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Copper and Copper Alloys

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Preface

Copper is mankind's oldest metal, dating back some 10,000 years. All of the great civilizations of the past, including the Sumerian, Egyptian, Greek, Roman, and Chinese, used copper and copper alloys (principally bronze and later brass) for both decorative and utilitarian purposes. From antiquity through the Middle Ages and the Renaissance, copper was used for military purposes, artistic applications such as church bells and statuary, tools, and numerous other functional objects. However, it was the Industrial Revolution that brought about a tremendous change in the production and consumption of copper and copper alloys. Electrical engineering in the modern industrial sense followed from Michael Faraday's discovery of electromagnetic induction in 1831, Werner von Siemens' invention of the electric dynamo in 1866, and Thomas Edison's invention of the electric light bulb in 1878 and his construction of the first electrical power generating plant in 1882. To this day, copper remains the key to modern power generation.

The industrial importance of copper in the 20th and 21st centuries has been extended by the ease with which it combines with other metals. Tin and zinc are and always have been the principal alloying elements, but many others—aluminum, nickel, beryllium, chromium, cadmium, manganese, etc.—form alloys with unique combinations of mechanical and physical properties and excellent corrosion and wear resistance. These attributes have contributed toward copper and its alloys being the material of choice for building construction (e.g., plumbing, wiring, and roofing), but have also led to the use of copper in many demanding engineering applications in the marine, automotive, chemical, and electronics industries. Continuing developments in superconductors, electric vehicles, solar heating, and large-scale desalination of water should ensure that copper remains an essential material in the future.

Recognizing the industrial importance of this metal, ASM International has devoted the eighth volume of the ASM Specialty Handbook series to the engineering aspects of copper and copper alloys. Divided into four major sections, this book describes the metallurgy and applications of wrought, cast, and powder metallurgy alloys; fabrication and finishing procedures; metallography, microstructures, and phase diagrams; and engineering properties and service characteristics. Although several excellent texts have been published on copper during the past 25 years, none can match the breadth of coverage offered in this Handbook.

The sustained growth and development of the copper industry can be attributed in large part to the following technical organizations: the Copper Development Association Inc. (CDA), the International Copper Association, Ltd. (ICA), and the Canadian Copper & Brass Development Association (CCBDA). ASM International wishes to express its thanks for the cooperation it received from these organizations during the course of this project. The editor also extends his appreciation to these organizations as well as the hard working and cooperative ASM Editorial and Library staffs. Lastly, the contributions of the many authors who have written articles on copper and copper alloys published in the ASM Handbook should also be recognized. Their respective works are acknowledged throughout this Handbook.

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Introduction and Overview

COPPER was first used by man more than 10,000 years ago. Small, decorative pendants and other items discovered in the Middle East have been dated about 8700 B.C. These objects were hammered to shape from nuggets of "native copper," pure copper found in conjunction with copper-bearing ores. The earliest artifacts known to be made from smelted metal were also copper. These were excavated in Anatolia (now Turkey) and have been dated as early as 7000 B.C. The discovery of a copper-tin alloy and its uses led to the *Bronze Age*, which began in the Middle East before 3000 B.C. More recent discoveries in Thailand, however, indicate that bronze technology was known in the Far East as early as 4500 B.C. The Bronze Age ended about 1200 B.C., after which iron technology (the *Iron Age*) became common.

Today, copper and copper alloys remain one of the major groups of commercial metals, ranking third behind only iron/steel and aluminum in production and consumption. They are widely used because of their excellent electrical and thermal conductivities, outstanding resistance to corrosion, ease of fabrication, and good strength and fatigue resistance. They are generally nonmagnetic. They can be readily soldered and brazed, and many coppers and copper alloys can be welded by various gas, arc, and resistance methods. For decorative parts, standard alloys having specific colors are readily available. Copper alloys can be polished and buffed to almost any desired texture and luster. They can be plated, coated with organic substances, or chemically colored to further extend the variety of available finishes.

Pure copper is used extensively for cables and wires, electrical contacts, and a wide variety of other parts that are required to pass electrical current. Coppers and certain brasses, bronzes, and cupronickels are used extensively for automobile radiators, heat exchangers, home heating systems, panels for absorbing solar energy, and various other applications requiring rapid conduction of heat across or along a metal section. Because of their outstanding ability to resist corrosion, coppers, brasses, some bronzes, and cupronickels are used for pipes, valves, and fittings in systems carrying potable water, process water, or other aqueous fluids.

In all classes of copper alloys, certain alloy compositions for wrought products have counterparts among the cast alloys; this enables the designer to make an initial alloy selection before deciding on the manufacturing process. Most wrought alloys are available in various cold-worked conditions, and the room-temperature strengths and fatigue resistances of these alloys depend on the amount of cold work as well as the alloy content. Typical applications of cold-worked wrought alloys (cold-worked tempers) include springs, fasteners, hardware, small gears, cams, electrical contacts, and components.

Certain types of parts, most notably plumbing fittings and valves, are produced by hot forging simply because no other fabrication process can produce the required shapes and properties as economically. Copper alloys containing 1 to 6% Pb are free-machining grades. These alloys are widely used for machined parts, especially those produced in screw machines.

Major Groups of Copper and Copper Alloys

The elements most commonly alloyed with copper are aluminum, nickel, silicon, tin, and zinc. Other elements and metals are alloyed in small quantities to improve certain material characteristics, such as corrosion resistance or machinability. Copper and its alloys are divided into nine major groups. These major groups are:

- *Coppers*, which contain a minimum of 99.3% Cu
- *High-copper alloys*, which contain up to 5% alloying elements
- *Copper-zinc alloys (brasses)*, which contain up to 40% Zn
- *Copper-tin alloys (phosphor bronzes)*, which contain up to 10% Sn and 0.2% P
- *Copper-aluminum alloys (aluminum bronzes)*, which contain up to 10% Al
- *Copper-silicon alloys (silicon bronzes)*, which contain up to 3% Si
- *Copper-nickel alloys*, which contain up to 30% Ni
- *Copper-zinc-nickel alloys (nickel silvers)*, which contain up to 27% Zn and 18% Ni
- *Special alloys*, which contain alloying elements to enhance a specific property or characteristic, for example, machinability

Alloys falling into these nine groups are identified by their Unified Numbering System (UNS) designation. Each designation consists of five numbers following the prefix letter "C." In this system, wrought alloys of copper are designated by numbers C1*xxxx* to C7*xxxx*, and cast alloys are designated C8*xxxx* to C9*xxxx*. A more detailed explanation of the UNS system can be found in the article "Standard Designations for Wrought and Cast Copper and Copper Alloys" in this Handbook. Some copper and copper alloys are also identified by descriptive names, for example, Muntz metal (Cu-40Zn). Such descriptive names are discussed in the section "Alloy Terminology" in this article.

Properties of Importance

Along with strength, fatigue resistance, and ability to take a good finish, the primary selection criteria for copper and copper alloys are:

- Electrical conductivity
- Thermal conductivity
- Corrosion resistance
- Color
- Ease of fabrication (See the section "Fabrication Characteristics" in this article for details.)

Electrical Conductivity

As shown in Table 1, a little more than 60% of all copper and copper alloys consumed in the United States are used because of electrical conductivity. The bulk of these applications are wire and cable, for example, telecommunications wire and cable, electronic wire and cable, building wire, magnet wire, power cable, and automotive wire and cable.

The electrical conductivity scale established in 1913 was based on a copper standard defined as 100%, and the electrical conductivity of any material is still expressed as percent IACS (International Annealed Copper Standard), equal to 100 times the ratio of the volume resistivity of the annealed copper standard (0.017241 μΩ · m) at 20 °C (68 °F) to the value measured for the material concerned. The

Table 1 Copper and copper alloy consumption in the United States by functional use in 1997

End use	Millions of pounds	%
Electrical conductivity	5023	61
Corrosion resistance	1701	20
Heat transfer	949	11
Structural capability	515	6
Aesthetics	131	2
Total	**8319**	**100**

Source: Copper Development Association Inc.

highest purity copper produced today (99.999% Cu) has been found to be 103% IACS. As shown in Table 2, only silver has a higher electrical conductivity than copper.

Effect of Temperature. Electrical conductivity is sensitive to temperature: for copper it drops from 800% IACS at –240 °C (–400 °F) to 38% IACS at 425 °C (800 °F).

Effect of Grain Size and Cold Working. The conductivity of copper is independent of its crystal orientation and does not vary significantly with grain size. Cold working an annealed copper to about 90% reduction can cause a drop of 2 to 3% IACS.

Table 2 Electrical conductivity values for various metals and alloys

Material	%IACS
Pure silver	106
Pure copper (99.999% Cu)	103.06
C10100 (oxygen-free electronic, OFE)	101
C10200 (oxygen-free, OF)	101
C11000 (electrolytic tough pitch, ETP)	101
C10700 (oxygen-free with Ag, OFS)	100
C11300 (tough pitch with Ag)	100
C10300 (OF extra-low P)	99
C12000 (phosphorus deoxidized, low-residual P, DLP)	98
C12900 (fire-refined tough pitch with Ag, FRSTP)	98
C18700 (Cu-0.8–1.5Pb)	96
C14700 (Cu-0.20–0.50S)	95
C14500 (Cu-0.40–0.7Te)	93
C15000 (Cu-0.10–0.20Zr)	93
C15700 (dispersion-strengthened with Al_2O_3)	93
C10800 (oxygen-free low-residual P, OFLP)	92
C16200 (Cu-0.7–1.2Cd)	90
C12200 (phosphorus deoxidized, high-residual P, DHP)	85
90Ag-10Cu	85
C18200 (Cu-0.6–1.2Cr)	80
C15760 (dispersion-strengthened with Al_2O_3)	78
Pure gold	73.4
Pure aluminum	65
C16500 (Cu-0.02Fe-0.50–0.7Sn-0.6–1.0Cd)	60
Al 1100 (O)	59
C21000 (Gilding, 95%)	56
C19100 (99.5% min Cu+Fe-Ni-Pb-Zn-Te-P)	55
C19500 (96.0% min Cu+Fe-Sn-Zn-Pb-P-Co)	50
Al 2024 (O)	50
C50500 (Cu-1.3Sn)	48
C17410 (beryllium copper, 0.3% Be)	45
Al 7075 (O)	45
Al 6061 (T6)	43
C31400 (leaded commercial bronze)	42
C22600 (jewelry bronze, 87.5%)	40
Pure magnesium	38.6
C23000 (Cu-15Zn)	37
Al 7075 (T6)	33
Pure tungsten	30
Zn-27Al-1.2Cu-0.015Mg	29.7
Al 5056 (O)	29
Pure zinc	28.27
C26000 (Cu-30Zn)	28
C42500 (Cu-9.5Zn-2Sn-0.2P)	28
C37700 (Cu-38Zn-2Pb)	27
Pure nickel	25.2
C17200 (beryllium copper, 2% Be)	22
Pure iron	17.6
C51000 (Cu-5Sn-0.2P)	15
1010 steel	14.5
Carbon steel (0.65% C)	9.5
C70600 (Cu-10Ni-1.4Fe)	9
C74500 (Cu-25Zn-10Ni)	9
C65500 (Cu-3Si)	7
C71500 (Cu-30Ni-0.5Fe)	4
Type 316 stainless steel	2.5

Note: Copper and copper alloys categorized as high-conductivity materials have conductivities ranging from ~50 to > 100% IACS.

Effect of Composition. All additives to pure copper reduce its electrical conductivity, depending upon the element and amount in solid solution. Only small decreases are caused by elements added in excess of solubility. The data in Table 3 show the solubility of each element in copper at room temperature and the degree to which each element decreases electrical conductivity by indicating the resistivity increase per 1 wt% added. There is a cumulative effect when more than one element is added. The drop in electrical conductivity caused by additions of commonly used alloying elements is illustrated by Fig. 1, which shows the strongly detrimental effects of phosphorus and iron and the relatively mild decreases caused by silver and zinc additions. Oxygen in standard-grade copper reacts with many impurities, yielding insoluble oxides and thereby greatly reducing the harmful effects. Where oxygen-free or deoxidized copper is used, impurity levels must be reduced below those in cathode copper to achieve >100% IACS.

Effect of Alloying and Condition. As with other metal systems, copper is intentionally alloyed to improve strength without unduly degrading ductility or workability. However, it should be recognized that additions of alloying elements also degrade electrical and thermal conductivity by various amounts, depending on the alloying element and the concentration and location in the microstructure (solid solution, precipitate, dispersoid). The choice of alloy and condition is most often based on the trade-off between strength and conductivity (Fig. 2). Figure 3 shows the general trade-off between strength and conductivity for solid-solution, dispersion, and precipitation hardening. The optimal trade-off is achieved by precipitation hardening, which is usually the most costly because of either the alloy additions or extra processing. Precipitation-hardening alloys exhibit increases in electrical conductivity along with increased strength during the aging heat treatment, as elements are removed from supersaturated solid solution to form precipitates of intermetallic compounds.

Table 3 Solubility limits and electrical resistivity effects of copper alloying elements

Element	Solubility at 293 K, wt%	Resistivity increase per 1 wt% addition, μΩ · cm
Ag	0.1	0.355
Al	9.4	2.22
As	6.5	5.67
Au	100	0.185
B	0.06	8.25
Be	0.2	4.57
Ca	…	4.77
Cd	0.5	0.172
Co	0.2	7.3
Cr	0.03	4.9
Fe	0.14	10.6
Ga	20	1.27
Ge	11	3.2
Hg	…	0.32
In	3	0.615
Ir	1.5	2
Mg	1	4.2
Mn	24	3.37
Ni	100	1.2
O	0.0002	21
P	0.5	14.3
Pb	0.02	1.02
Pd	40	9.57
Pt	100	0.635
Rh	20	1.5
S	<0.0025	18.6
Sb	2	2.9
Se	<0.002	8.5
Si	2	7
Sn	1.2	1.65
Te	<0.0005	4
Ti	0.4	21.6
Zn	30	0.286
Zr	<0.01	8

When additional demands are placed on the material—corrosion or oxidation resistance, for example—the combinations become more complex. Hence, understanding the properties demanded by a given application is of paramount importance.

Thermal Conductivity

Copper and its alloys are also good conductors of heat, making them ideal for heat-transfer applications, for example, radiators and heat exchangers. Changes in thermal conductivity generally follow those in electrical conductivity in accordance with the Wiedemann-Franz relationship, which states that thermal conductivity is proportional to the product of electrical conductivity and temperature. Table 4 compares the thermal conductivities of various metals and alloys.

Corrosion Resistance

Copper is a noble metal, but unlike gold and other precious metals, it can be attacked by common reagents and environments. Pure copper resists attack quite well under most corrosive conditions. Some copper alloys, however, have limited usefulness in certain environments because of hydrogen embrittlement or stress-corrosion cracking (SCC).

Hydrogen embrittlement is observed when tough pitch coppers, which are alloys containing cuprous oxide, are exposed to a reducing atmosphere. Most copper alloys are

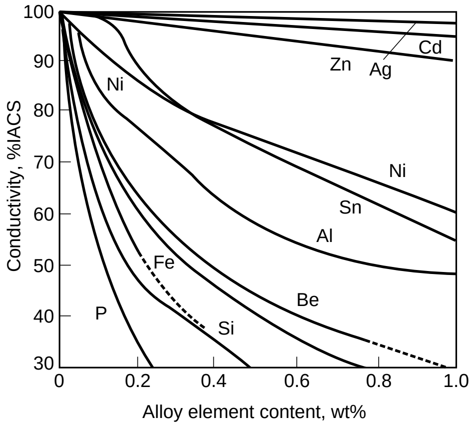

Fig. 1 Effect of alloying elements on the conductivity of oxygen-free high-conductivity copper

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deoxidized and thus are not subject to hydrogen embrittlement.

Stress-corrosion cracking most commonly occurs in brass that is exposed to ammonia or amines. Brasses containing more than 15% Zn are the most susceptible. Copper and most copper alloys that either do not contain zinc or are low in zinc content generally are not susceptible to SCC. Because SCC requires both tensile stress and a specific chemical species to be present at the same time, removal of either the stress or the chemical species can prevent cracking. Annealing or stress relieving after forming alleviates SCC by relieving residual stresses. Stress relieving is effective only if the parts are not subsequently bent or strained in service; such operations reintroduce stresses and resensitize the parts to SCC.

Table 4 Thermal conductivity values for various metals and alloys

Material	Thermal conductivity, W/m · K
Pure silver	428
Pure copper	398
C10100 (oxygen-free electronic, OFE)	391
C11000 (electrolytic tough pitch, ETP)	391
C10400 (oxygen-free with Ag)	388
C12200 (Cu-0.02P)	339
C18100 (Cu-0.04Mg-0.15Zr-0.8Cr)	324
Pure gold	317.9
Pure aluminum	247
Al 1100 (O)	222
C17410 (beryllium copper, 0.3% Be)	208
Al 2024 (O)	193
Al 6061 (O)	180
Al 6061 (T6)	167
Pure tungsten	160
Pure magnesium	155
Al 2024 (T6)	151
Al 7075 (T6)	130
C26000 (Cu-30Zn)	121
Al 5056 (O)	117
Pure zinc	113
C51100 (Cu-4.2Sn-0.2P)	84
Pure nickel	82.9
Pure iron	80.4
Pure cobalt	69.04
Pure tin	62.8
C61300 (Cu-6.8Al-2.5Fe-0.35Sn)	55
1020 carbon steel	51.9
C74500 (Cu-25Zn-10Ni)	45
Pure lead	33.6
C71500 (Cu-30Ni-0.5Fe)	29
Type 410 stainless steel	28.7
Pure carbon	23.9
Pure zirconium	21.1
Type 316 stainless steel	16.2
Pure titanium	11.4

Dealloying is another form of corrosion that affects zinc-containing copper alloys. In dealloying, the more active metal is selectively removed from an alloy, leaving behind a weak deposit of the more noble metal.

Copper-zinc alloys containing more than 15% Zn are susceptible to a dealloying process called dezincification. In the dezincification of brass, selective removal of zinc leaves a relatively porous and weak layer of copper and copper oxide. Corrosion of a similar nature continues beneath the primary corrosion layer, resulting in gradual replacement of sound brass by weak, porous copper. Unless arrested, dealloying eventually penetrates the metal, weakening it structurally and allowing liquids or gases to leak through the porous mass in the remaining structure.

A more detailed description of the corrosion resistance of copper can be found in the articles "Corrosion Behavior" and "Stress-Corrosion Cracking" in this Handbook.

Color

Copper and certain copper alloys are used for decorative purposes alone, or when a particular color and finish is combined with a desirable mechanical or physical property of the alloy. Table 5 lists the range of colors that can be obtained with standard copper alloys.

Fabrication Characteristics

As stated previously, ease of fabrication is one of the properties of importance for copper and copper alloys. These materials are generally capable of being shaped to the required form and dimensions by any of the common forming or forging processes, and they are readily assembled by any of the various joining processes. A brief review of the fabrication characteristics of copper and its alloys is given subsequently. More detailed information can be found in the articles contained in the Section "Fabrication and Finishing" in this Handbook.

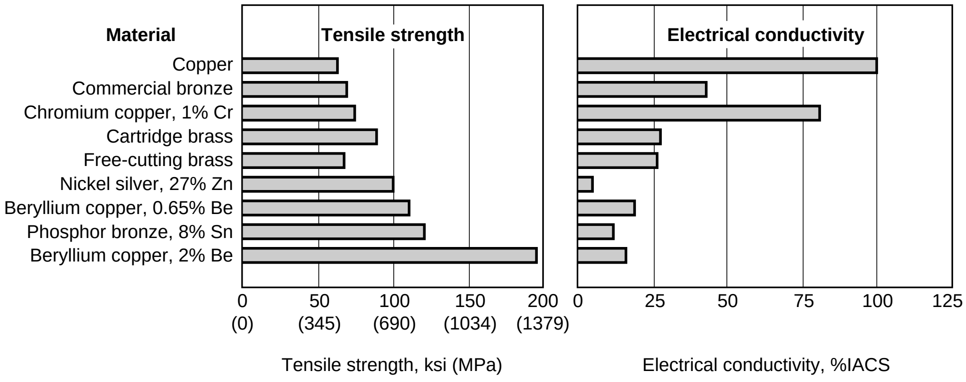

Fig. 2 Relationship between strength and electrical conductivity for copper and copper alloys

Workability. Copper and copper alloys are readily cast into cake (slabs of pure copper, generally 200 mm thick and up to 8.5 m long, or 8 in. by 28 ft), billet, rod, or plate—suitable for subsequent hot or cold processing into plate, sheet, rod, wire, or tube—via all the standard rolling, drawing, extrusion, forging, machining, and joining methods. Copper and copper alloy tubing can be made by the standard methods of piercing and tube drawing as well as by the continuous induction welding of strip. Copper is hot worked over the temperature range 750 to 875 °C (1400 to 1600 °F), annealed between cold working steps over the temperature range 375 to 650 °C (700 to 1200 °F), and is thermally stress relieved usually between 200 and 350 °C (390 and 660 °F). Copper and copper alloys owe their excellent fabricability to the face-centered cubic crystal structure and the twelve available dislocation slip systems. Many of the applications of copper and copper alloys take advantage of the work-hardening capability of the material, with the cold processing deformation of the final forming steps providing the required strength/ductility for direct use or for subsequent forming of stamped components. Copper is easily processible to more than 95% reduction in area. The amount of cold deformation between softening anneals is usually restricted to 90%

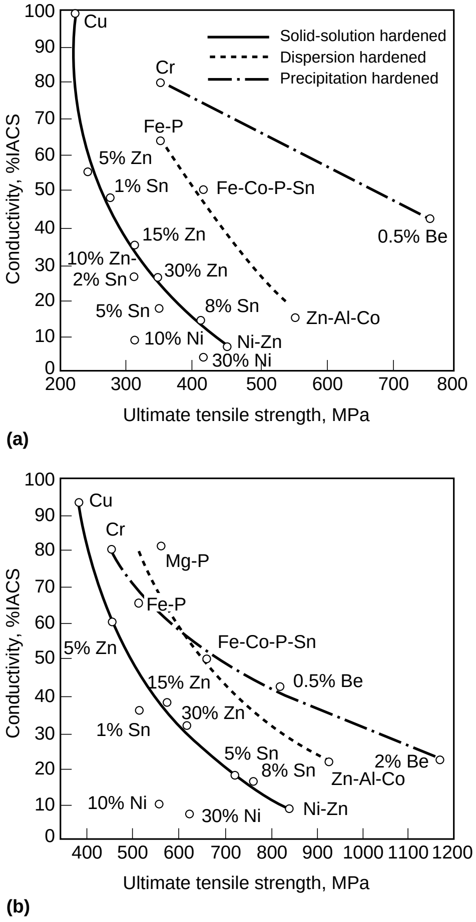

Fig. 3 Electrical conductivity as a function of tensile strength for (a) annealed and (b) 60% cold-reduced copper alloy strip

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maximum to avoid excessive crystallographic texturing, especially in rolling of sheet and strip.

Although copper obeys the Hall-Petch relationship and grain size can be readily controlled by processing parameters, work hardening is the only strengthening mechanism used with pure copper. Whether applied by processing to shape and thickness, as a rolled strip or drawn wire, or by forming into the finish component, as an electrical connector, the amount of work hardening applied is limited by the amount of ductility required by the application. Worked copper can be recrystallized by annealing at temperatures as low as 250 °C (480 °F), depending on the prior degree or cold work and the time at temperature. While this facilitates processing, it also means that softening resistance during long-time exposures at moderately elevated temperatures can be a concern, especially in electrical and electronic applications where resistance (I^2R) heating is a factor.

Weldability. Copper and copper alloys are most frequently welded using gas tungsten arc welding, especially for thin sections, because high localized heat input is important in materials with high thermal conductivity. In thicker sections, gas metal arc welding is preferred. The weldability varies among the different alloys for a variety of reasons, including the occurrence of hot cracking in the leaded (free-machining) alloys and unsound welds in alloys containing copper oxide. Tin and zinc both reduce the weldability of copper alloys. The presence in the alloy of residual phosphorus is beneficial to weldability because it combines with absorbed oxygen, thereby preventing the formation of copper oxide in the weld. Resistance welding is also widely used, particularly in alloys with low-thermal conductivity. Oxygen-bearing coppers can be subject to gassing and embrittlement, particularly in oxyacetylene welding.

Solderability. Copper is among the easiest of all engineering metals to solder. Oxides or tarnish films are easily removed by mild fluxing or precleaning in a dilute acid bath. A superior metallurgical bond is obtained with the use of a general-purpose solder composed of tin in the range of 35 to 60% and the balance lead. Alloys of copper exhibit a range of solderability, dependent upon the type and level of alloying addition and method of soldering.

The immersion test is one common method to evaluate solderability. It involves immersion of a substrate alloy in a molten solder bath. The sample after removal is graded on a scale of I to V, based on the surface characteristics of the solder coat. Variations in solderability are the result of the effect of alloying additions on formation of the metallurgical bond at the substrate-solder interface. Under these conditions, most copper alloys are easily solderable using mildly activated rosin fluxes. Table 6 ranks various representative alloy groups in order of decreasing solderability, showing the adverse effects of zinc and nickel.

For most conditions, the use of a more aggressive flux achieves the desired class I or II solderability, even for the alloys more difficult to solder. However, aggressive fluxes are not used for electronic applications. Soldering involving slower heating than in the immersion test amplifies the alloy effects noted in Table 6 or requires more severe fluxes to remove oxides.

Brazeability. The effects of alloying on brazing are similar to those for soldering, but because brazing is carried out at a higher temperature than soldering, the presence of reactive alloying elements intensifies the problem of detrimental oxide formation. Again, more aggressive fluxes and faster heating reduce the adverse effects caused by such alloy additions. Braze materials that melt at higher temperatures may also cause base-metal erosion or, in the case of the zinc brasses, give rise to zinc fuming, which degrades the structural integrity of the braze joint.

Machinability. All copper alloys are machinable in the sense that they can be cut with standard machine tooling. High-speed steel suffices for all but the hardest alloys. Carbide tooling can be used but is rarely necessary, and while grinding may be required for a few alloys in very hard tempers, these are not conditions to be expected in high-speed production. For mass-produced screw machine parts made from free-cutting brass or one of the other leaded copper alloys, high-speed steel is the standard tool material. Figure 4 compares the machining characteristics of copper alloys with those of an aluminum alloy and a free-machining steel.

Surface Finishes. For decorative parts, standard alloys in specific colors are readily available. Copper alloys can be polished and buffed to almost any desired texture and luster. They can be plated, coated with organic substances, or chemically colored to further extend the variety of available finishes.

Alloy Terminology

Although UNS designations have been incorporated in most relevant standards published by ASTM, American Society of Mechanical Engineers, Society of Automotive Engineers, and similar organizations, long-standing familiar alloys continue to be identified by traditional descriptive and/or colloquial names. Definitions of some of the more common examples are given subsequently for coppers, high-copper alloys, and copper-base alloys. It should be emphasized that these names should not be used whenever an alloy is cited on engineering drawings or purchase agreements.

Table 5 Standard color-controlled wrought copper alloys

UNS number	Common name	Color description
C11000	Electrolytic tough pitch copper	Soft pink
C21000	Gilding, 95%	Red-brown
C22000	Commercial bronze, 90%	Bronze-gold
C23000	Red brass, 85%	Tan-gold
C26000	Cartridge brass, 70%	Green-gold
C28000	Muntz metal, 60%	Light brown-gold
C63800	Aluminum bronze	Gold
C65500	High-silicon bronze, A	Lavender-brown
C70600	Copper-nickel, 10%	Soft lavender
C74500	Nickel silver, 65-10	Gray-white
C75200	Nickel silver, 65-18	Silver

Coppers and High-Copper Alloys

Coppers are metals that have a designated minimum copper content of 99.3% or higher. Dilute or high-copper alloys (~94% Cu min) contain small amounts of various alloying elements, such as beryllium, cadmium, or chromium, each having less than 8 at.% solubility. Because high-copper alloys retain the face-centered cubic α structure of copper, their physical properties are similar to those of the pure metal. Alloying generally serves to impart higher strength, thermal stability (resistance to softening), or other mechanical attributes while retaining sufficient electrical conductivity for the intended use. The term "modified copper" has also been used to describe metal for which the specified minimum copper content is less than 99.88% but not less than 99.3%, silver being counted as copper. This term is no longer recommended for usage.

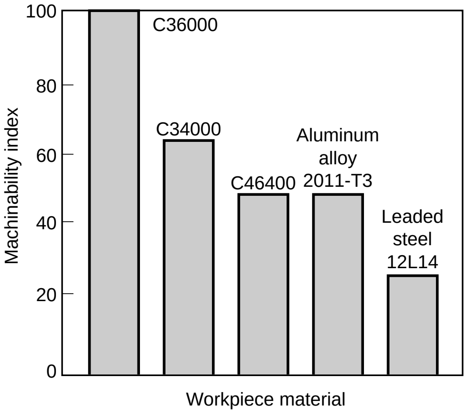

Fig. 4 Machinability ratings for copper alloys, aluminum alloy 2011, and a free-machining steel. The theoretical maximum machining rate for free-cutting brass (C36000) is five times higher than that of leaded low-carbon free-machining steel AISI 12L14 (UNS G12144). In this figure, production rates (determined by ASTM E 618) have been normalized and shown as a "machinability index."

Table 6 Solder immersion test ranking of copper alloys using a mildly activated rosin flux

Solder class	Alloys
I (best)	Cu and very dilute Cu alloys
II	Cu-10%Zn, Cu-Sn, Cu-Ni-Sn, Cu-Al-Si
III	Cu-Zn-Sn
IV	Cu-Ni
V (worst)	Cu-15 and 30% Zn, Cu-Zn-Ni

beryllium copper (C17000, C17200, and C17500). Precipitation-hardenable copper alloy containing varying amounts of beryllium (nominally 2% Be) and sometimes small amounts of cobalt, nickel, and iron. It is capable of being formed readily when in the soft (annealed) condition and heat treated to hardnesses and strengths approaching those of high-strength steels.

cadmium copper (C16200). A high-copper alloy containing up to 1.2% Cd for improved resistance to thermal softening and increased wear resistance.

cathode copper. A commercially pure copper electrolytically refined in cathode form.

chromium copper (C18200, C18400). A precipitation-hardening high-copper alloy containing up to 1.2% Cr for higher strength and improved thermal softening resistance, but with an electrical conductivity higher than 80% IACS.

electrolytic tough pitch copper (C11000). A commercially pure high-conductivity copper of any origin that has been refined by electrolytic deposition, then melted, oxidized, and brought to tough pitch or controlled low oxygen content, and finally cast into cakes, billets, wire bars, and so on, suitable for hot or cold working, or both.

fire-refined copper. A commercially pure copper of any origin or type that is finished by furnace refining without at any stage having been electrolytically refined.

high-conductivity copper. A copper that in the annealed condition, has a minimum electrical conductivity of 100% IACS.

oxygen-free copper (C10100, C10200). A commercially pure high-conductivity copper that has been produced in such manner as to contain no oxide or residual deoxidants. It has very high resistance to hydrogen embrittlement.

oxygen-free, silver-bearing copper (C10400, C10500, C10700). A commercially pure high-conductivity copper containing the designated element (silver) in amounts as agreed upon between the supplier and the consumer for the purpose of raising the thermal softening temperature.

phosphorus-deoxidized arsenical copper (C14200). A modified deoxidized copper containing the designated element (arsenic) in amounts as agreed upon between the supplier and the consumer mainly for the purpose of increasing corrosion resistance.

phosphorus-deoxidized copper, high-residual phosphorus (C12200). A commercially pure copper that has been deoxidized with phosphorus, leaving a relatively high residual phosphorus content. It is not susceptible to hydrogen embrittlement, but is of relatively low electrical conductivity due to the amount of phosphorus present.

phosphorus-deoxidized copper, low-residual phosphorus (C12000). A commercially pure copper that has been deoxidized with phosphorus in such a manner as to leave a very low residual phosphorus content. It is not readily susceptible to hydrogen embrittlement, and has an electrical conductivity slightly lower than that of high-conductivity copper.

phosphorus-deoxidized copper, tellurium-bearing (C14500, C14510). A modified deoxidized copper containing the designated element (tellurium) in amounts as agreed upon between the supplier and the consumer to improve machinability. The electrical conductivity is somewhat lower than that of electrolytic tough pitch copper.

silver-bearing copper. Any copper containing substantial amounts of silver, regardless of origin or treatment.

silver-bearing tough pitch copper (C11300, C11400, C11500, C11600). A commercially pure high-conductivity tough pitch copper containing silver in amounts agreed upon between the supplier and the consumer for the purpose of raising the thermal softening temperature.

tough pitch copper (C11000, C11030, C11100, C11300, C11400, C11500, C11600, C12900). Commercially pure or modified copper, either electrolytically, chemically, or fire refined, containing a controlled amount of oxygen for the purpose of obtaining a level set in the casting.

Copper Alloys

Copper alloys are metals with copper contents less than about 94%, but not less than 50%, and having no other element specified in excess of the copper content. An exception to this definition occurs in the case of some cast copper-lead alloys where the lead slightly exceeds the copper content in certain alloys that are commonly designated as copper alloys (e.g., alloy C98840 containing 44.0–58.0 Pb).

admiralty, inhibited (arsenical, antimonial, or phosphorized) (C44300, C44400, C44500, respectively). Admiralty modified by the addition of 0.02 to 0.10% of arsenic, antimony, or phosphorus to inhibit dezincification.

admiralty metal (C44200). An alloy containing nominally 71% Cu, 1% Sn, and 28% Zn, originally developed by the British Admiralty and generally available in tube, flat products, and wire. Its principal use is in heat exchanger and condenser tubes. An inhibitor may be added to increase the resistance to dezincification.

alpha. The name of a phase or of a certain range of copper alloys that contain one or more alloying elements dissolved in copper, the phase being a homogeneous solid solution.

alpha-beta brass. A series of copper-zinc alloys containing approximately 55 to 63% Cu and the remainder mostly, if not all, zinc and composed of crystals or grains of both the alpha and the beta phases.

aluminum brass (C68700). An alloy containing nominally 77.5% Cu, 2% Al, and 20.5% Zn with an inhibitor, available in tube form. Its principal use is in heat exchanger and condenser tubes.

aluminum bronzes (C60800–C64210). Copper alloys with aluminum as the principal alloying element, normally in the range of 3 to 15% with or without the additions of other elements.

architectural bronze (C38500). An alloy containing nominally 57% Cu, 3% Pb, and 40% Zn, generally available in extruded or drawn shapes and rod; used for architectural trim and for some mechanical applications. The alloy is not technically a bronze, but because of long usage the term "architectural bronze" has been used.

beta. The name of a second phase in the internal structure of certain copper alloys, generally harder and less ductile than the alpha phase. The beta phase renders the alloy more ductile when hot and less ductile when cold.

brass. Any copper alloy with zinc as the principal alloying element, with or without small quantities of some other elements.

bronze. Originally a term for copper alloys having tin as the only or principal alloying element. In modern usage the term *bronze* is seldom used alone, and the terms *phosphor bronze* or *tin bronze* are used for indicating copper-tin alloys. In fact, the term *bronze*, together with a suitable modifying adjective, has been extended to apply to any of a great variety of copper alloys.

cartridge brass, 70% (C26000). An alloy containing nominally 70% Cu and 30% Zn, and generally available in flat products, rod, wire, and tube.

commercial bronze, 90% (C22000). An alloy containing nominally 90% Cu and 10% Zn, generally available in flat products, wire, rod, and tube. The alloy is not technically a bronze, but because of long usage the term "commercial bronze" has been used.

copper-nickel (C70100–C72950). A copper alloy composed of copper and nickel with nickel content up to 40% and with small additions of elements such as iron and manganese. Also referred to as cupronickels.

cupronickels. See copper-nickel.

deep-drawing brass, drawing brass. Terms sometimes used, but not recommended, to denote non-leaded brasses at nominal copper content ranging from 65 to 70%. See preferred terms *cartridge brass*, 70%, and *yellow brass*.

engraver's brass. A term sometimes used, but not recommended, to denote *extra-high-leaded brass* and *high-leaded brass*.

extra-high-leaded brass (C35600). An alloy containing nominally 63% Cu, 2.5% Pb, and 34.5% Zn, generally available in flat rolled products, and used for engraving and other operations requiring considerable cutting.

forging brass (C37700). An alloy containing nominally 59% Cu, 2% Pb, and 39% Zn, generally available in rod, bar, tube, and shapes and recommended for fabrication by hot forging and hot pressing. It has excellent machinability, approaching that of *free-cutting brass*.

free-cutting brass (C36000). An alloy containing nominally 61.5% Cu, 3% Pb, and 35.5% Zn, generally available in rod and drawn bar and in extruded shapes. It is the most commonly used alloy for automatic screw machine work, or for other applications where material of maximum machinability is desired.

free-cutting Muntz metal (C37000). An alloy containing nominally 60% Cu, 1% Pb, and 39% Zn, generally available as tube. It is used for automatic screw machine products where maximum machinability is not necessary.

free-cutting phosphor bronze B-2 (C54400). An alloy containing nominally 88% Cu, 4% Sn, 4% Zn, and 4% Pb, generally available in rod and flat products.

gilding, 95% (C21000). An alloy containing nominally 95% Cu and 5% Zn, generally available in flat products, rod, and wire. The terms "commercial bronze, 95%" and "gilding metal" are not recommended.

hardware bronze. See preferred terms *leaded commercial bronze* and *leaded red brass*.

high brass. See preferred term *yellow brass*.

high-leaded brass (C34200, C35300). Alloys containing nominally 65% Cu, 2% Pb, and 33% Zn (C34200); and 62% Cu, 2% Pb, and 36% Zn (C35300), generally available in flat products and rod. They are used where easy stamping and machining are desired, as for instance, in clock and watch backs and gears and for engraving.

high-leaded brass (tube) (C33200). An alloy containing nominally 66% Cu, 1.6% Pb, and 32.4% Zn. It is recommended for automatic screw machine operations.

jewelry bronze, 87.5% (C22600). An alloy containing nominally 87.5% Cu and 12.5% Zn, having a rich golden color. It is used for costume jewelry, slide fasteners, and as a base for gold-filled articles. Variations may contain small amounts of tin.

leaded commercial bronze (C31400). An alloy containing nominally 89% Cu, 1.75% Pb, and 9.25% Zn, generally available in rod, shapes, and bar, and used extensively for hardware. The alloy is not technically a bronze, but because of long usage the term "leaded commercial bronze" has been used. Hardware bronze is a term formerly used to designate any one of a broad range of similar alloys; this term is not recommended.

leaded Muntz Metal (C36500). An alloy containing nominally 60% Cu, 0.6% Pb, and 39.4% Zn, generally used for condenser tube plates.

leaded naval brass (C48500). An alloy containing nominally 60% Cu, 0.75% Sn, 1.75% Pb, and 37.5% Zn, generally available in rod, shapes, and bar. This alloy has the equivalent strength and corrosion resistance of naval brass (C46400) plus considerably improved machinability.

leaded red brass (C32000). An alloy containing nominally 85% Cu, 2% Pb, and 13% Zn, generally available in rod and drawn bar. *Hardware bronze* is a term formerly used to designate any one of a broad range of similar alloys; this term is not recommended.

low brass, 80% (C24000). An alloy containing nominally 80% Cu and 20% Zn and generally available in flat products, rod, and wire.

low-leaded brass (C33500). An alloy containing nominally 65% Cu, 0.5% Pb, and 34.5% Zn, generally available in flat products. It is widely used for stamping and light drawing operations.

low-leaded brass (tube) (C33000). An alloy containing nominally 66% Cu, 0.5% Pb, and 33.5% Zn, and used where a combination of moderate machinability, strength, and ductility is required.

manganese bronze (A) (C67500). An alloy containing nominally 58.5% Cu, 1% Sn, 1.4% Fe, 0.1% Mn, and 39% Zn, generally available in rod, flat products, shapes, and wire. This alloy is appreciably harder and stronger than naval brass (C46400) and is, therefore, preferred to the latter for many structural uses. It is also an excellent brazing alloy.

medium-leaded brass (C34000). An alloy containing nominally 65% Cu, 1% Pb, and 34% Zn, generally available in flat products, rod, shapes, and wire, and used where a compromise between drawing properties and machinability is necessary.

Muntz metal (C28000). An alloy containing nominally 60% Cu and 40% Zn, and generally available in flat products, rod, wire, and tube. Named after George Muntz, who patented a process for the manufacture of 60Cu-40Zn brass in 1832.

naval brass (C46400). An alloy containing nominally 60% Cu, 0.75% Sn, and 39.25% Zn, generally available in rod, bar, wire, shapes, tube, and to some extent in flat products. It is used in marine construction where a strong, hard material is required.

nickel silver (C73500–C79800). Copper alloys containing nickel and zinc, formerly sometimes called German silver. These alloys are primarily used for their distinctive colors that range from yellow to silvery white.

Specific examples include:

- nickel silver, 65-10 (C74500). An alloy nominally containing 65% Cu, 10% Ni, and 25% Zn
- nickel silver, 65-18 (C75200). An alloy nominally containing 65% Cu, 18% Ni, and 17% Zn
- nickel silver, 65-15 (C75400). An alloy nominally containing 65% Cu, 15% Ni, and 20% Zn
- nickel silver, 65-12 (C75700). An alloy nominally containing 65% Cu, 12% Ni, and 23% Zn
- nickel silver, 55-18 (C77000). An alloy nominally containing 55% Cu, 18% Ni, and 27% Zn

phosphor bronzes (C50100–C52480). Copper alloys with tin as the principal alloying element, deoxidized with phosphorus. Various types are available in flat products, rod, tube, wire, and shapes, the most common ones containing nominally 1.25% to 10% Sn. Specific examples include (see also free-cutting phosphor bronze B-2):

- phosphor bronze, 1.25% E (C50500)
- phosphor bronze, 5% A (C51000)
- phosphor bronze, 8% C (C52100)
- phosphor bronze, 10% D (C52400)

platers' brass. A term sometimes used, but not recommended, to indicate specific alloys used as anodes for brass plating. These vary in composition from 80 to 90% Cu, 10 to 20% Zn, and sometimes 1 to 2% Sn.

radiator core brass. A term used to indicate strip brass or suitable characteristics for forming radiator cores. It is sometimes used, but not recommended, to designate a specific alloy.

red brass, 85% (C23000). An alloy containing nominally 85% Cu and 15% Zn, and generally available in flat products, rod, wire, and tube.

70-30 brass. A term sometimes used, but not recommended, for *cartridge brass*, 70% (C26000).

silicon bronze (C64700–C66100). Any copper alloy with silicon as the main alloying element, with or without additions of such elements as zinc, manganese, aluminum, iron, or nickel. The more commonly used silicon bronzes are:

- high-silicon bronze A (C65500), nominally containing 96% Cu and 3% Si
- low-silicon bronze B (C65100), nominally containing 97.7% Cu and 1.5% Si

spring brass. A term used to designate copper-zinc strip or wire in spring or harder tempers. It is sometimes used, but not recommended, to designate a specific alloy.

spring bronze. A term used to designate copper-tin strip, rod, or wire in spring or harder tempers. This term is sometimes used, but not recommended, to designate a specific alloy.

tin bronze. See *phosphor bronzes*

yellow brass (C26800, C27000). An alloy containing nominally 65% Cu and 35% Zn, and generally available in flat products, wire, and rod.

Temper Terminology

This section describes the terminology in general use for indicating the basic processes used to produce the different tempers in copper and copper alloy products. In the copper industry, the term "temper" refers to the metallurgical structure and properties of a product resulting from thermal or mechanical processing. A classification system (i.e., an alphanumeric code) of tempers can be found in the article "Standard Designations for Wrought and Cast Copper and Copper Alloys" in this Handbook.

anneal (annealing). A thermal treatment to change the properties or grain structure of a product. (1) When applied to a cold-worked product having a single phase: to produce softening by recrystallization or recrystallization and grain growth, with the accompanying changes in properties. (2) When applied to a cold-worked product having a single phase: to produce softening by changes in phase relationships that may include recrystallization and grain growth.

cold work. Controlled mechanical operations for changing the form or cross section of a product and for producing a strain-hardened product at temperatures below the recrystallization temperature.

drawn stress relieved (DSR). A thermal treatment of a cold-drawn product to reduce residual stress variations, thus reducing susceptibility of product to stress corrosion or season cracking, without significantly affecting its tensile strength or microstructure.

hot working. Controlled mechanical operations for shaping a product at temperatures above the recrystallization temperature.

order strengthening. A thermal treatment of a cold-worked product at a temperature below its recrystallization temperature causing ordering to occur to obtain an increase in yield strength.

precipitation heat treatment. A thermal treatment of a solution heat-treated product to produce property changes such as hardening, strengthening, and conductivity increase by precipitation of constituents from the supersaturated solid solution. This treatment has also been called "age hardened" and "precipitation hardened."

quench hardening. A treatment for copper-aluminum alloy products consisting of heating above the betatizing temperature followed by quenching to produce a hard martensitic structure.

solution heat treatment. A thermal treatment of a product to put alloying elements into solution in the base metal by heating into the temperature range of solid solubility, followed by cooling at a sufficient rate to retain them in a supersaturated solid solution.

spinodal heat treatment. A thermal treatment of a solution heat-treated product to produce property changes such as hardening, strengthening, and conductivity increase by spinodal decomposition of a solid solution. This treatment has also been called "age hardened," "spinodal hardened," or "spinodally decomposed."

strain hardening. The increase in strength and hardness and decrease in ductility as a result of permanent deformation of the structure by cold working.

stress relief. A treatment of a product to reduce residual stresses. (1) Stress relief by thermal treatment should be carried out without causing recrystallization. (2) Stress relief by mechanical treatment should be carried out without causing a significant change in size.

temper annealing. A thermal treatment above the eutectoid temperature for copper-aluminum alloy products to minimize the presence of the stable eutectoid structure.

tempering. A thermal treatment of a quench-hardened product to improve ductility.

thermal treatment. A controlled heating; time at maximum temperature-cooling cycle as needed to satisfy the property and grain structure requirements of the temper.

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The Copper Industry: Occurrence, Recovery, and Consumption

THE COPPER INDUSTRY in North America, broadly speaking, is composed of two segments: producers (mining, smelting, and refining companies) and fabricators (wire mills, brass mills, foundries, and powder plants). The end products of copper producers, the most important of which are refined copper cathode and wire rod, are sold almost entirely to copper fabricators. The end products of copper fabricators can be generally described as mill products and foundry products, and they consist of wire and cable, sheet, strip, plate, foil, rod, bar mechanical wire, tubing, forgings, extrusions, castings, and powder metallurgy (P/M) shapes. These products are sold to a wide variety of industrial users. Certain mill products—chiefly wire, cable, and most tubular products—are used without further metalworking. On the other hand, most flat-rolled products, rod, bar, mechanical wire, forgings, and castings go through multiple metalworking, machining, finishing, and/or assembly operations before emerging as finished products. Figure 1 is a simplified flow chart of the copper industry.

Production of Copper

Primary copper is produced from sulfide copper minerals and oxidized copper minerals. These materials are processed pyrometallurgically and/or hydrometallurgically to produce a high-purity electrorefined or electrowon copper containing less than 40 parts per million (ppm) impurities, which is suitable for all electrical, electronic, and mechanical uses. Secondary copper is produced from recycled scrap. Recycling of scrap accounts for approximately 40% of copper production worldwide.

Production of Copper from Sulfide Minerals

More than 90% of the primary copper in the Western world is produced from sulfide minerals, principally chalcopyrite ($CuFeS_2$), chalcocite (Cu_2S), and bornite (Cu_5FeS_4). The main processes used in the production of copper from sulfide ores are shown in Fig. 2. The mined ore, which contains only 0.5 to 2.0% Cu, is finely ground, and then is concentrated by flotation to form copper concentrates containing 25 to 30% Cu. The concentrates are then smelted at high temperatures (about 1250°C, or 2280°F) to form a molten mixture of copper and iron sulfide called *matte* containing up to 60% Cu. The molten matte is converted to *blister copper* (98.5% Cu) by oxidizing the remaining iron and sulfur in a converter. After removing the residual sulfur and oxygen in an anode furnace, copper anodes are cast and then refined electrolytically to produce high-purity copper cathode copper (99.95% Cu), which is suitable for most uses.

Smelting Processes. The reverberatory furnace (Fig. 3) is the oldest and most widely used smelting process. It consists of a refractory-lined chamber, typically 30 m (100 ft) long by 10 m

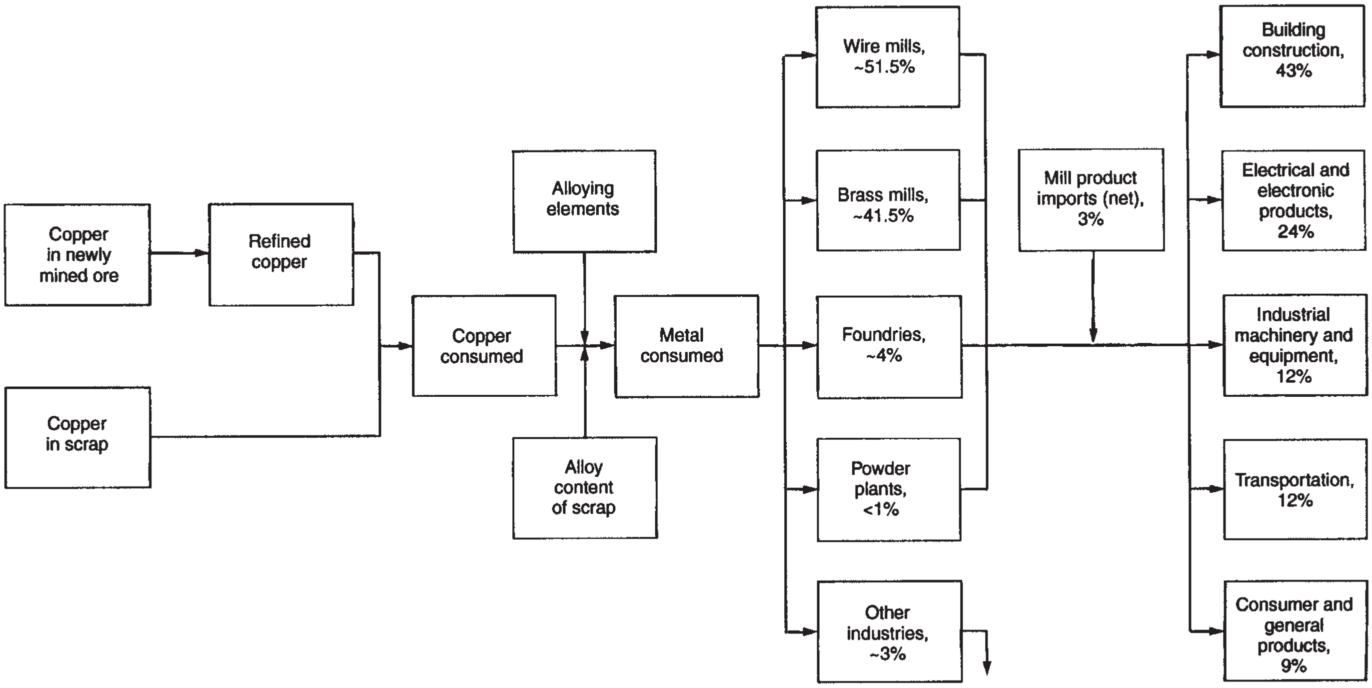

Fig. 1 Copper supply and consumption in the United States. See text for details. Source: Copper Development Association Inc.

(30 ft) wide, into which copper concentrates and silica flux are charged. Fuel-fired burners melt the charge, driving off the labile sulfur by the following reaction:

$$2CuFeS_2 \rightarrow Cu_2S \cdot 2FeS(l) + \tfrac{1}{2}S(g) \qquad \text{(Eq 1)}$$

Little iron sulfide is oxidized, so that fuel requirements are high, about 6.3×10^6 kJ per metric tonne (5.4×10^6 Btu per ton) of copper concentrate. Two molten layers are formed in the furnace: an upper layer slag of iron silicate with little copper (≤0.5% Cu), and a lower layer of matte (30 to 40% Cu). The slag and matte are drained separately from the furnace through tapholes into ladles. The slag is discarded, while matte is transferred to the converting step. The sulfur evolved during smelting leaves the furnace in a 1 to 2% SO_2 gas stream, which is too dilute for economic treatment.

Because the reverberatory furnace cannot meet current requirements for low-energy consumption and environmental standards, more efficient smelting processes have been developed since the 1960s. These processes use much less energy (typically 0.8 to 2.1×10^6 kJ per metric tonne of copper concentrate) and produce a strong SO_2 gas stream (10% SO_2) to reduce treatment costs. These processes use oxygen enrichment and oxidize more iron sulfide to generate more heat and produce mattes with higher copper levels (50 to 75% Cu). The smelting reaction for these processes can be represented by the following reaction:

$$\begin{aligned} &2CuFeS_2 + 2\alpha \cdot SiO_2 + (1 + 3\alpha)\, O_2 \\ &\quad \rightarrow Cu_2S \cdot 2(1 - \alpha)FeS + 2\alpha \cdot FeO \cdot SiO_2 \\ &\quad + (1 + 2\alpha)SO_2 \qquad \text{(Eq 2)} \end{aligned}$$

where α is the fraction of FeS reacted (typically, in the range $\alpha = 0.5$ to 0.9). As shown in Fig. 2, modern smelting processes fall into two categories: flash smelting and bath smelting. In flash smelting, dry concentrate is dispersed in an oxidizing gas stream, and the smelting reactions occur very rapidly as the particles fall down a reaction shaft (Fig. 4). The molten matte and slag are collected in a hearth, and the SO_2-containing gases exit via an uptake shaft. In bath smelting, moist concentrate is smelted continuously in a molten bath of matte and slag, which is vigorously stirred by the injection of air or oxygen-enriched air. In one commercial process reactor, the air is injected through tuyeres into a vessel similar to an elongated converter.

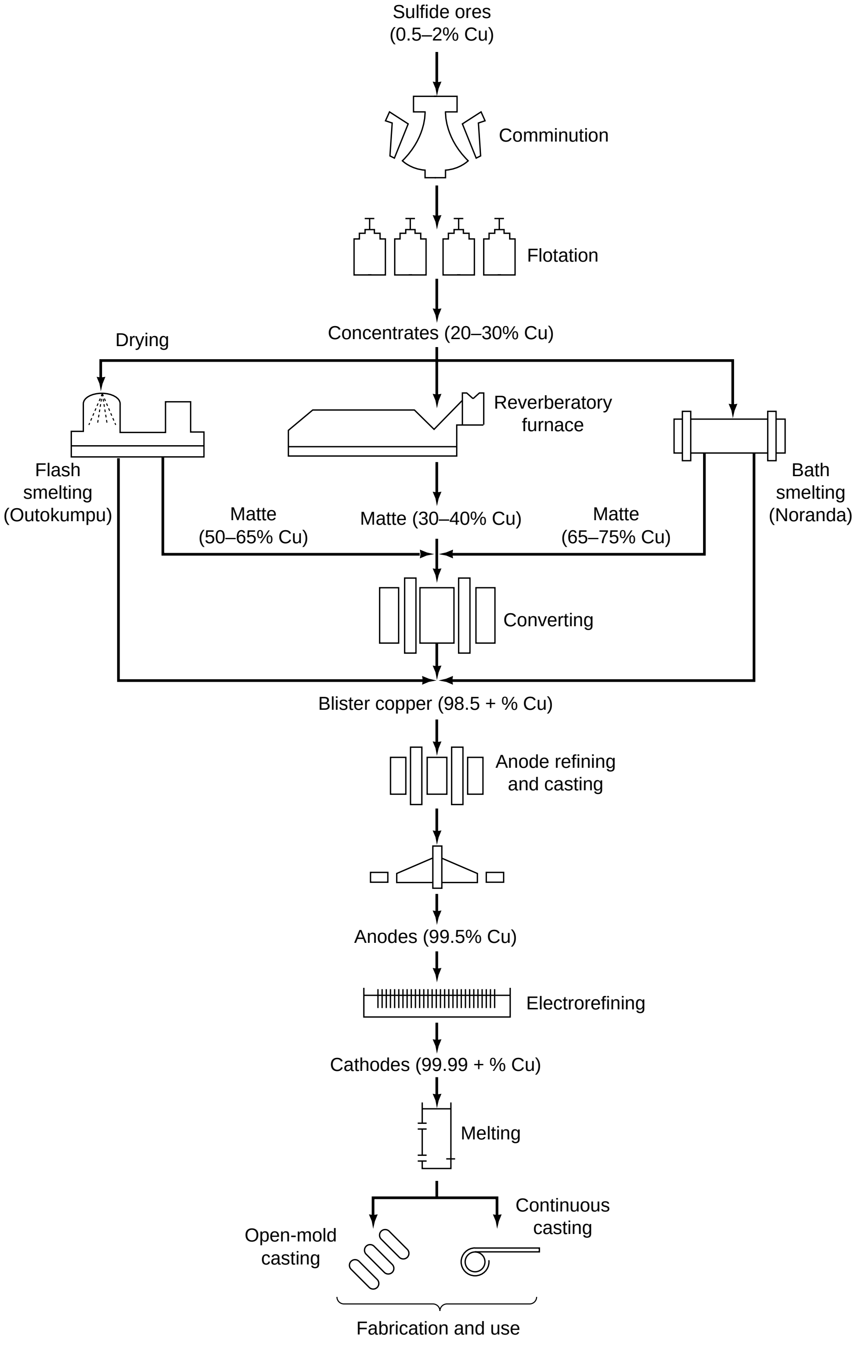

Fig. 2 Flow sheet of copper production from sulfide minerals

Matte Converting. The molten matte is converted to blister in Peirce-Smith converters (Fig. 5). The converter is a refractory-lined, cylindrical vessel, typically 10 m (30 ft) in length and 4 m (13 ft) in diameter. The converter can be rotated about its axis, and is fitted on one side with a row of approximately 50 tuyeres through which air is injected. The top of the converter has a large mouth for charging molten matte and removing slag and product copper. Converting is a batch operation; initially several ladles of matte are charged, the air turned on, and the converter rotated until the tuyeres are submerged. The air, bubbling violently through the bath, gradually oxidizes the matte in two stages. In the first or slag-forming stage, iron sulfide is oxidized and fluxed with silica to form a fluid slag by the following reaction:

$$\begin{aligned} &2FeS(l) + 2SiO_2(s) + 3O_2(g) \\ &\quad \rightarrow 2FeO \cdot SiO_2(l) + 2SO_2(g) \qquad \text{(Eq 3)} \end{aligned}$$

The converter slag contains some copper (1 to 5% Cu), and is recycled to the smelting furnace or treated in a separate process. When all the iron has been removed, the remaining copper sulfide is further oxidized to blister copper by the following reaction:

$$Cu_2S(l) + O_2(g) \rightarrow 2Cu(l) + SO_2(g) \qquad \text{(Eq 4)}$$

The converting process is sufficiently exothermic that no additional fuel is required. The blister copper from the converter is transferred by ladle to the anode furnace, where the residual sulfur and oxygen levels in the copper are reduced further. The copper is then cast into anodes for electrorefining.

Sulfur Fixation. Smelting and converting a typical copper concentrate generates over 0.50 metric tonne SO_2 per metric tonne concentrate

(0.55 ton SO_2 per ton concentrate) and the resulting SO_2 emissions must be controlled to meet local environmental standards. This is generally achieved by converting the SO_2 to sulfuric acid in a contact acid plant, as long as the SO_2 concentration exceeds 4% and a viable market for acid exists. If local conditions are favorable, it is also possible to make liquid SO_2 or elemental sulfur from strong SO_2 gases.

Electrorefining. The objective of electrorefining is to remove the remaining impurities in the anode copper (principally As, Bi, Ni, Pb, Sb, and Se) and produce a pure cathode copper (99.95 + % Cu). Also, many copper ores contain appreciable amounts of precious metals (Ag, Au, Pt, and so on), which are concentrated into the anode copper during smelting and are recovered as valuable by-products in electrorefining. The impure anodes are suspended alternately with pure copper cathodes in tanks through which an electrolyte of copper sulfate and free sulfuric acid is continuously circulated. When direct current is applied, the copper in the anodes is electrochemically dissolved and then plated as pure copper on the cathodes. Some of the anode impurities, such as arsenic and nickel, are less noble than copper and dissolve in the electrolyte, but they do not plate out at the cathode as long as their concentrations are controlled. The other impurities, such as silver, lead, and selenium, are virtually insoluble in the electrolyte and fall as slimes to the bottom of the tank. These slimes are recovered and processed for eventual recovery of selenium and the precious-metal values.

Production of Copper from Oxidized Minerals

About 10% of primary copper originates from oxidized copper ores, principally oxides, silicates, and sulfates. Oxidized copper ores are more effectively treated by hydrometallurgical processes. The ore is crushed, ground if necessary, and leached with dilute sulfuric acid, either by percolation through heaps of ore or by agitation in tanks. Copper is recovered from the resulting solution by either cementation or solvent extraction-electrowinning. In cementation, copper is precipitated by contact with scrap iron to form an impure cement copper, which is smelted, then refined. Solvent extraction-electrowinning has become the preferred process. In solvent extraction special organic reagents are used to selectively extract copper from solution. The resulting copper-containing organic phase is then stripped to give a pure and more concentrated aqueous copper solution for electrowinning. Electrowinning is similar to electrorefining, except that an inert anode is used and more energy is required. Although electrowon cathode copper is generally not as pure as electrorefined copper, it is still suitable for many applications.

One of the newest developments in hydrometallurgy is referred to as "bioleaching." In this emerging process, the copper concentrate is transported to a drum containing thermophillic bacteria and slightly acidic warm water. The resultant slurry is constantly stirred, allowing the bacteria to "eat" sulfur, arsenic, and other contaminants. In approximately four days a copper solution containing 30 g of pure copper for every liter of water is produced. this solution is subsequently electrolytically refined.

Production of Copper from Scrap

The box at the lower left in Fig. 1 represents the portion of the copper supply provided by scrap. In recent years, well over half the copper consumed in the United States has been derived

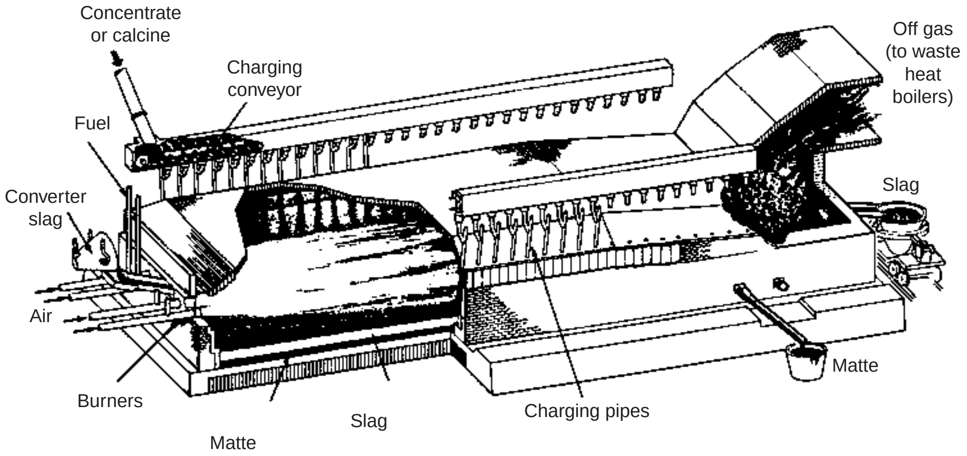

Fig. 3 Cutaway view of a reverberatory furnace for copper smelting

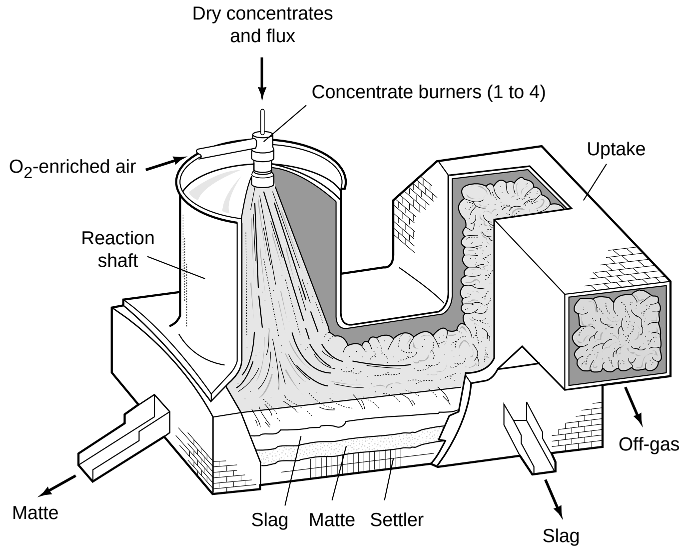

Fig. 4 Cutaway view of an oxygen-enriched flash-smelting furnace

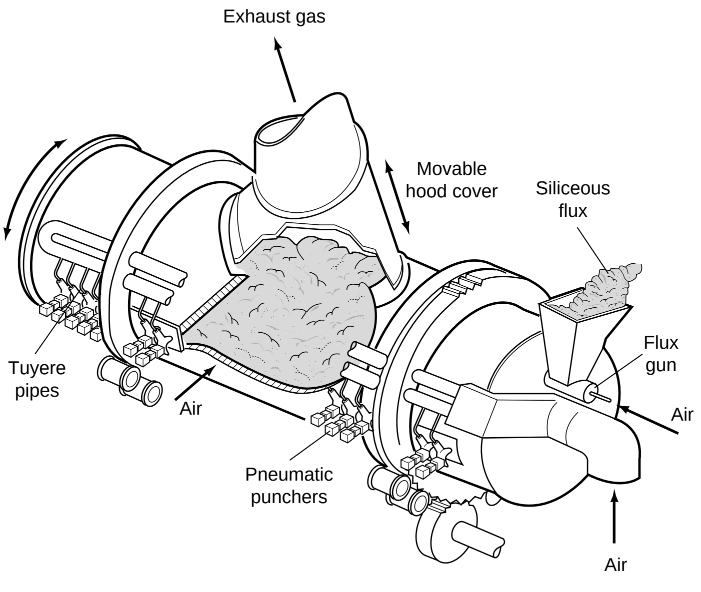

Fig. 5 Cutaway view of a horizontal side-blown Peirce-Smith converter for producing blister copper from matte

from recycled scrap, and this percentage has grown somewhat over the last three decades. Approximately 55% of this scrap has been *new scrap,* such as turnings from screw-machined rod, as opposed to *old scrap,* such as used electrical cable or auto radiators. Scrap recycled within a particular plant or company *(run-around scrap)* is not included in these statistics. About one-third of the scrap recycled in the United States is fed into the smelting or refining stream and quickly loses any identity. The remainder is consumed directly by brass mills; by ingot makers, whose main function is to process scrap into alloy ingot for use by foundries; by foundries themselves; by powder plants; and by others, such as the chemical, aluminum, and steel industries.

Copper Fabricators

The four classes of copper fabricators together account for ~97% of the total copper (including alloying metal) consumed each year in the United States (Fig. 1). Other industries, such as steel, aluminum, and chemical producers, consume the remaining 3%.

The share of metal consumed by wire rod mills has grown sharply over the last 35 years to the current level of ~51.5%; consumption by brass mills has dropped to 41.5%. Foundries account for about 4% of fabricated mill products, and powder plants use less than 1% of the U.S. supply of copper.

Wire mill products are destined for use as electrical conductors. Starting with wire rod, these mills cold draw the material (with necessary anneals) to final dimensions through a series of dies. The individual wires can be stranded and normally are insulated before being gathered into cable assemblies.

Brass mills melt and alloy feedstock to make strip, sheet, plate, tube, rod, bar, mechanical wire, forgings, and extrusions. Less than half the copper input to brass mills is refined; the rest is scrap. Fabricating processes such as hot rolling, cold rolling, extrusion, and drawing are employed to convert the melted and cast feedstock into mill products.

Approximately 45% of the output of U.S. brass mills is unalloyed copper and high-copper alloys, chiefly in such forms as plumbing and air conditioning tube, busbar and other heavy-gage current-carrying flat products, and roofing sheet. Copper alloys make up the remaining 55%. Free-cutting brass rod, which exhibits outstanding machinability and good corrosion resistance, and brass strip, which has high strength, good corrosion resistance, excellent formability, and good electrical properties, together constitute ~80% of the total tonnage of copper alloys shipped from U.S. brass mills. Other alloy types of major commercial significance include tin bronzes (phosphor bronzes), which are noted for their excellent cold-forming behavior and strength; tin brasses, known for outstanding corrosion resistance; copper-nickels, which are strong and particularly resistant to seawater; nickel silvers, which combine a silvery appearance with good formability and corrosion resistance; beryllium-coppers, which provide outstanding strength when hardened; and aluminum bronzes, which have high strength along with good resistance to oxidation, chemical attack, and mechanical abrasion.

Foundries use prealloyed ingot, scrap, and virgin metal as raw materials. Their chief products are shaped castings for many different industrial and consumer goods, the most important of which are plumbing products and industrial valves. Centrifugal and continuously cast products find major application as bearings, cylinders, and other symmetrical components. Powder plants produce powder and flake for further fabrication into powder metallurgy parts, chiefly small sintered porous bronze bearings.

Markets and Applications

The five major market categories shown at the far right in Fig. 1 constitute the chief customer industries of the copper fabricators. Of the chief customer industries, the largest is building construction, which, purchases large quantities of electrical wire, tubing, and parts for building hardware and for electrical, plumbing, heating, and air-conditioning systems. The second largest category is electrical and electronic products, including those for telecommunications, electronics, wiring de-vices, electric motors, and power utilities. The industrial machinery and equipment category includes industrial valves and fittings; industrial, chemical, and marine heat exchangers; and various other types of heavy equipment, off-road vehicles, and machine tools. Transportation applications include road vehicles, railroad equipment, and aircraft parts; automobile radiators and wiring harnesses are the most important products in this category. Finally, consumer and general products include electrical appliances, fasteners, ordnance, coinage, and jewelry. Table 1 provides a listing of the largest markets for copper and copper alloys in the United States. Additional information on the supply and consumption of copper can be found in statistical data available from the Copper Development Association Inc., the U.S. Geological Survey in the U.S. Department of the Interior, and the Bureau of the Census in the U. S. Department of Commerce.

Table 1 Recently published data on the leading copper markets in the United States

	Consumption	
Application	**lb × 10^6**	**%**
Building wire	1215	16
Plumbing and heating	1147	15.1
Air conditioning and commercial refrigeration	671	8.8
Power utilities	647	8.5
Telecommunications	544	7.2
Automotive (electrical)	511	6.7
In-plant equipment	500	6.6
Electronics	409	5.4
Automotive (nonelectrical)	276	3.6
Industrial valves and fittings	239	3.2
Lighting and wiring devices	231	3.1
All others	1201	15.8
Total	**7591**	**100**

Source: Copper Development Association Inc.

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Standard Designations for Wrought and Cast Copper and Copper Alloys

STANDARD DESIGNATION SYSTEMS for copper and copper alloys described in this article include:

- The Unified Numbering System (UNS) alloy designation system for wrought and cast copper and copper alloy products
- Temper designations for wrought and cast copper and copper alloy products
- International alloy and temper designation systems

Alloy Designations

In North America, the accepted designations for copper and copper alloys are now part of the Unified Numbering System (UNS) for Metals and Alloys (Ref 1), which is managed jointly by American Society for Testing and Materials (ASTM) and the Society of Automotive Engineers (SAE) International. Under the UNS system, coppers and copper alloys are designated by five-digit numbers preceded by the letter "C." The five-digit codes are based on, and supersede, an older three-digit system developed by the U.S. copper and brass industry. The older system was administered by the Copper Development Association (CDA), and alloys are still sometimes identified by their "CDA numbers." The UNS designations are simply two-digit extensions of the CDA numbers to accommodate new compositions. For example, free-cutting brass, once known as CDA Alloy No. 360, became UNS C36000. UNS designations have been incorporated in most relevant standards by ASTM, American Society of Mechanical Engineers (ASME), SAE, and similar organizations. Longstanding familiar alloys continue to be identified by descriptive names or trade names, but for the sake of clarity, UNS designations are preferred throughout industry for engineering drawings and purchase documents.

In the UNS system, numbers from C10000 through C79999 denote wrought alloys, while cast alloy designations range from C80000 through C99999. As shown in Table 1, within these two categories, the compositions are grouped into distinct families of coppers and copper alloys, including the six major branches—coppers, high-alloy coppers, brasses, bronzes, copper nickels, and nickel silvers. Alloys not falling into one of these six branches are classified as "other copper-zinc alloys" (wrought compositions) or "special alloys" (cast compositions). Table 2 lists the chemical compositions for 50 wrought coppers and 265 wrought copper alloys covered by UNS designations. Compositions for 148 cast coppers and copper alloys are listed in Table 3. The alloys described in Tables 2 and 3 are listed in CDA *Standard Designations for Wrought and Cast Copper and Copper Alloys*, 1999 edition. This publication is updated periodically with new alloys being added and alloys that are no longer produced being deleted.

Temper Designations

Copper alloys are also described by their *tempers,* which are terms that define metallurgical condition, heat treatment, and/or casting method. Copper alloys are said to have a harder temper if they have been cold worked, heat treated, or both, and a softer temper when they are in the as-hot-formed condition or when the effects of cold work and/or heat treatment have been removed by annealing. As usual, higher strength and hardness, that is, harder tempers, are gained at the expense of reduced ductility. Temper, as applied to heat treated copper alloys, carries exactly the opposite meaning than for heat treated steels where tempering generally implies softening (e.g., quenched and tempered steels).

Tempers for copper alloys are defined in ASTM B 601, "Standard Practice for Temper Designations for Copper and Copper Alloys—Wrought and Cast." As shown in Table 4, this standard establishes an alphanumeric code for use in designating product tempers. It should be noted, however, that the temper designations

Table 1 Generic classification of coppers and copper alloys

Generic name	UNS No.	Composition
Wrought alloys		
Coppers(a)	C10100–C15815	>99% Cu
High-copper alloys(b)	C16200–C19900	>96% Cu
Brasses	C20100–C28000	Cu-Zn
Leaded brasses	C31200–C38500	Cu-Zn-Pb
Tin brasses	C40400–C48600	Cu-Zn-Sn-Pb
Phosphor bronzes	C50100–C52480	Cu-Sn-P
Leaded phosphor bronzes	C53400–C54400	Cu-Sn-Pb-P
Copper-phosphorus and copper-silver-phosphorus alloys(c)	C55180–C55284	Cu-P-Ag
Aluminum bronzes	C60800–C64210	Cu-Al-Ni-Fe-Si-Sn
Silicon bronzes	C64700–C66100	Cu-Si-Sn
Other copper-zinc alloys	C66300–C69710	Cu-Zn-Mn-Fe-Sn-Al-Si-Co
Copper nickels	C70100–C72950	Cu-Ni-Fe
Nickel silvers	C73500–C79830	Cu-Ni-Zn
Cast alloys		
Coppers(a)	C80100–C81200	>99% Cu
High-copper alloys(d)	C81400–C82800	>94% Cu
Red and leaded red brasses	C83300–C83810	Cu-Sn-Zn-Pb (82–94% Cu)
Semi-red and leaded semi-red brasses	C84200–C84800	Cu-Sn-Zn-Pb (75–82% Cu)
Yellow and leaded yellow brasses	C85200–C85800	Cu-Zn-Pb
Manganese bronzes and leaded manganese bronzes(e)	C86100–C86800	Cu-Zn-Mn-Fe-Pb
Silicon brasses/bronzes	C87300–C87800	Cu-Zn-Si
Copper-bismuth and copper-bismuth-selenium alloys	C89320–C89940	Cu-Sn-Zn-Bi-Se
Tin bronzes	C90200–C91700	Cu-Sn-Zn
Leaded tin bronzes	C92200–C94500	Cu-Sn-Zn-Pb
Nickel-tin bronzes	C94700–C94900	Cu-Ni-Sn-Zn-Pb
Aluminum bronzes	C95200–C95900	Cu-Al-Fe-Ni
Copper nickels	C96200–C96950	Cu-Ni-Fe
Nickel silvers	C97300–C97800	Cu-Ni-Zn-Pb-Sn
Leaded coppers	C98200–C98840	Cu-Pb
Special alloys	C99300–C99750	Cu-Zn-Mn-Al-Fe-Co-Sn-Pb

(a) Metals that have a designated Cu content of 99.3% or higher. (b) For wrought products, those alloys with designated Cu contents less than 99.3%, but more than 96% that do not fall into any other copper alloy group. (c) Brazing filler metal alloys. (d) Cast high-copper alloys have designated Cu contents in excess of 94%, to which Ag may be added for special properties. (e) Also referred to as high-strength and leaded high-strength yellow brasses only imply specific mechanical properties when used in association with a particular alloy, product form, and size. For example, in order to specify a copper alloy correctly it is necessary to indicate (Ref 2):

- *UNS number,* for example, UNS C36000
- *Product form and size,* for example, 6.4 mm ($\frac{1}{4}$ in.) round rod
- *Temper,* for example, H02, $\frac{1}{2}$ hard

Properties vary considerably for different forms and tempers of the same alloy (Ref 2). For example, a 25 mm (1 in.) rod of free-cutting brass (UNS C36000) in the H02 temper has a yield strength of 310 MPa (45 ksi); whereas the same alloy produced as a 25 by 150 mm (1 by 6 in.) bar in the soft (O60) temper has a yield strength of only 138 MPa (20 ksi).

In addition, some copper alloys derive their mechanical properties from controlled grain sizes or through combinations of heat treatment and cold work. Tempers describing these metallurgical conditions are also listed in Table 4.

The choice of temper depends on the properties required and on the type of processing to be done (Ref 2). The $\frac{1}{2}$ hard (H02) cold-worked temper in Table 4 is most frequently specified for screw machine products because it combines the best levels of strength and ductility to suit both machinability and functional requirements.

Annealed tempers such as O50 or O60 refer to soft, formable structures ordinarily specified for cold-formed rather than machined products. Annealed alloys may have inferior machinability, with poor surface finishes, because of a tendency for chips to tear away from the work during cutting. This is observed particularly in single-phase metals such as pure copper, copper-nickels, and low-zinc brasses.

Lightly cold-worked tempers such as $\frac{1}{8}$ hard and $\frac{1}{4}$ hard give improved machinability yet retain sufficient ductility for forming operations. Hard, extra hard, and spring tempers produce maximum strength, but at the expense of ductility. Machinability, as measured by tool wear rates, usually (but not always) deteriorates in proportion to the hardness of the alloy.

Electrical and thermal conductivity vary with the degree of temper, but the nature and extent of the effect depends strongly on the type of alloy and its metallurgical condition. Chemical properties such as corrosion resistance and plateability are not strongly affected by temper, although residual cold-work-induced tensile stresses render some copper alloys more susceptible to stress-corrosion cracking than would be the case when the metals are in the annealed state.

Table 2 Chemical compositions of wrought coppers and copper alloys

Composition values are given as maximum percentages, unless shown as a range or minimum.

Coppers										
			Composition, wt%							
Copper No.	Designation	Description	Cu, min, (incl Ag), %	Ag, min		As	Sb	P	Te	Other named elements
				%	Troy oz					
C10100	OFE	Oxygen-free electronic	99.99(b)	…	…	0.0005	0.0004	0.0003	0.0002	(c)
C10200(a)	OF	Oxygen free	99.95	…	…	…	…	…	…	0.0010O
C10300	OFXLP	…	99.95(d)	…	…	…	…	0.001–0.005	…	…
C10400(a)	OFS	Oxygen-free with Ag	99.95	0.027	8	…	…	…	…	…
C10500(a)	OFS	Oxygen-free with Ag	99.95	0.034	10	…	…	…	…	…
C10700	OFS	Oxygen-free with Ag	99.95	0.085	25	…	…	…	…	…
C10800	OFLP	…	99.95(d)	…	…	…	…	0.005–0.012	…	…
C10920	…	…	99.90	…	…	…	…	…	…	0.02O
C10930	…	…	99.90	0.044	13	…	…	…	…	0.02O
C10940	…	…	99.90	0.085	25	…	…	…	…	0.02O
C11000(a)	ETP	Electrolytic tough pitch	99.90	…	…	…	…	…	…	(e)
C11010(a)	RHC	Remelted high conductivity	99.90	…	…	…	…	…	…	(e)
C11020(a)	FRHC	Fire-refined high conductivity	99.90	…	…	…	…	…	…	(e)
C11030(a)	CRTP	Chemically refined tough pitch	99.90	…	…	…	…	…	…	(e)
C11040(a)	…	…	99.90	…	…	0.0005	0.0004	…	0.0002	(f)
C11100(a)	…	Electrolytic tough pitch, anneal resistant	99.90	…	…	…	…	…	…	(g)
C11300(a)	STP	Tough pitch with Ag	99.90	0.027	8	…	…	…	…	(e)
C11400(a)	STP	Tough pitch with Ag	99.90	0.034	10	…	…	…	…	(e)
C11500(a)	STP	Tough pitch with Ag	99.90	0.054	16	…	…	…	…	(e)
C11600(a)	STP	Tough pitch with Ag	99.90	0.085	25	…	…	…	…	(e)
C11700	…	…	99.9(h)	…	…	…	…	0.04	…	0.004–0.02B
C12000	DLP	Phosphorus deoxidized, low residual phosphorus	99.90	…	…	…	…	0.004–0.012	…	…
C12100	…	…	99.90	0.014	4	…	…	0.005–0.012	…	…
C12200(a)	DHP	Phosphorus deoxidized, high residual phosphorus	…	99.9	…	…	…	…	0.015–0.040	…
C12210	…	…	99.90	…	…	…	…	0.015–0.025	…	…
C12220	…	…	99.9	…	…	…	…	0.040–0.065	…	…

(continued)

incl, including. (a) These are high conductivity coppers that have in the annealed condition a minimum conductivity of 100% International Annealed Copper Standard (IACS). (b) Copper is determined by the difference between the impurity total and 100%. (c) The following additional maximum limits apply: Bi, 1 ppm (0.0001%); Cd, 1 ppm (0.001%); Fe, 10 ppm (0.0010%); Pb, 5 ppm (0.0005%); Mn, 0.5 ppm (0.00005%); Hg, 1 ppm (0.0001%); Ni, 10 ppm (0.0010%); oxygen, 5 ppm (0.0005%); Se, 3 ppm (0.0003%); Ag, 25 ppm (0.0025%); S, 15 ppm (0.0015%); Sn, 2 ppm (0.0002%); Zn, 1 ppm (0.0001%). (d) Includes P. (e) The following additional maximum limits apply: Oxygen and trace elements can vary depending on the process. (f) Se, 2 ppm (0.0002%); Bi, 1.0 ppm (0.00010%); group total, Te + Se + Bi, 3 ppm (0.0003%). Sn, 5 ppm (0.0005%); Pb, 5 ppm (0.0005%); Fe, 10 ppm (0.0010%); Ni, 10 ppm (0.0010%); S, 15 ppm (0.0015%); Ag, 25 ppm (0.0025%); oxygen, 100-650 ppm (0.010–0.065%). The total maximum allowable of 65 ppm (0.0065%) does not include oxygen. (g) Small amounts of Cd or other elements can be added by agreement to improve the resistance to softening at elevated temperatures. (h) Includes B + P. (i) This includes oxygen-free copper that contains P in an agreed-upon amount. (j) Includes Te + Se. (k) Includes Cd. Deoxidized with lithium or other suitable agreed-upon elements. (l) Includes Cu + Ag + Sn. (m) Includes Te + Sn. (n) Includes oxygen-free or deoxidized grades with deoxidizers (such as phosphorus, boron, lithium, or other) in an agreed-upon amount. (o) All aluminum present as Al_2O_3; 0.04% oxygen present as Cu_2O with a negligible amount in solid solution with copper. (p) Cu + sum of named elements, 99.5% min. (q) Ni + Co, 0.20% min; Ni + Fe + Co, 0.6% max. (r) Includes Co. (s) Cu + sum of named elements, 99.9% min. (t) Cu + sum of named elements, 99.8% min. (u) Cu + sum of named elements, 99.7% min. (v) Cu + sum of named elements, 99.6% min. (w) For tube over 5 in. outside diameter, the Pb can be <0.20%. (x) For flat products, the iron is 0.10% max. (y) Cu, 61.0% min for rod. (z) Pb can be reduced to 1.0% by agreement. (aa) For tubular products, the minimum Sn content can be 0.9%. (bb) Cu + Sn + Fe + P, 99.5% min. (cc) Cu + sum of named elements, 99.85% min. (dd) When the product is for subsequent welding applications and is so specified by the purchaser, Cr, Cd, Zr, and Zn will each be 0.05% max. (ee) Fe content shall not exceed Ni content. (ff) Not including Co. (gg) Fe + Co, 1.8-2.3%. (hh) Al + Zn, 25.1-27.1%. (ii) The following additional maximum limits apply: When the product is for subsequent welding applications and is so specified by the purchaser, 0.50% Zn, 0.02% P, 0.02% Pb, 0.02% S (0.008% S for C71110), and 0.05% C. (jj) The following additional maximum limits apply: 0.02% C, 0.015% Si, 0.003% S, 0.002% Al, 0.001% P, 0.0005% Hg, 0.001% Ti, 0.001% Sb, 0.001% As, 0.001% Bi, 0.05% Co, 0.10% Mg, and 0.005% oxygen. For C70690, Co will be 0.02% max. (kk) The following maximum limits apply: 0.07% C, 0.15% Si, 0.024% S, 0.05% Al, and 0.03% P. (ll) 0.02% P, max; 0.25% Si, max; 0.01% S, max; 0.20-0.50% Ti. (mm) 0.005% Pb, max, for hot rolling. (nn) 0.05% Pb, max, for rod and wire. Source: Copper Development Association Inc.

Table 2 (continued)

Coppers										
			Composition, wt%							
				Ag, min						
Copper No.	Designation	Description	Cu, min, (incl Ag), %	%	Troy oz	As	Sb	P	Te	Other named elements
C12300	…	…	99.90	…	…	…	…	0.015–0.040	…	…
C12500	…	…	99.88	…	…	0.012	0.003	…	…	0.025Te+Se, 0.003Bi, 0.004Pb, 0.050Ni
C12510	…	…	99.9	…	…	…	0.003	0.03	…	0.025Te+Se, 0.005Bi, 0.020Pb, 0.050Ni, 0.05Fe, 0.05Sn, 0.080Zn
C12900	FRSTP	Fire-refined tough pitch with Ag	99.88	0.054	16	0.012	0.003	…	0.025(j)	0.050Ni, 0.003Bi, 0.004Pb
C14180	…	…	99.90	…	…	…	…	0.075	…	0.02Pb, 0.01Al
C14181	…	…	99.90	…	…	…	…	0.002	…	0.002Cd, 0.005C, 0.002Pb, 0.002Zn
C14200	DPA	Phosphorus deoxidized arsenical	99.4	…	…	0.15–50	…	0.015–0.040	…	…
C14300	…	Cadmium copper, deoxidized	99.90(k)	…	…	…	…	…	…	0.05–0.15Cd
C14410	…	…	99.90(l)	…	…	…	…	0.005–0.020	…	0.05Fe, 0.05Pb, 0.10–0.20Sn
C14415	…	…	99.96(l)	…	…	…	…	…	…	0.10–0.15Sn
C14420	…	…	99.90(m)	…	…	…	…	…	0.005–0.05	0.04–0.15Sn
C14500(n)	…	Tellurium bearing	99.90(m)	…	…	…	…	0.004–0.012	0.40–0.7	….
C14510	…	Tellurium bearing	99.90(m)	…	…	…	…	0.010–0.030	0.30–0.7	0.05Pb
C14520	DPTE	Phosphorus deoxidized, tellurium bearing	99.40(m)	…	…	…	…	0.004–0.020	0.40–0.7	…
C14530	…	…	99.90(j)(l)	…	…	…	…	0.001–0.010	0.003–0.023(j)	0.003–0.023Sn
C14700	…	Sulfur bearing	99.90(n)	…	…	…	…	0.002–0.005	…	0.20–0.50S
C15000	…	Zirconium copper	99.80	…	…	…	…	…	…	0.10–0.20Zr
C15100	…	…	99.82	…	…	…	…	…	…	0.005Al, 0.005Mn, 0.05–0.15Zr
C15500	…	…	99.75	0.027–0.10	8–30	…	…	0.040–0.080	…	0.08–0.13Mg

	Composition, wt%					
Copper No.	Cu (incl Ag), min	Al(o)	Fe	Pb	O(o)	Other named elements
C15715	99.62	0.13–0.17	0.01	0.01	0.12–0.19	…
C15715	99.62	0.13–0.17	0.01	0.01	0.12–0.19	…
C15720	99.52	0.18–0.22	0.01	0.01	0.16–0.24	…
C15725	99.43	0.23–0.27	0.01	0.01	0.20–0.28	…
C15760	98.77	0.58–0.62	0.01	0.01	0.52–0.59	…
C15815	97.82	0.13–0.17	0.01	0.01	0.19	1.2–1.8B

(continued)

incl, including. (a) These are high conductivity coppers that have in the annealed condition a minimum conductivity of 100% International Annealed Copper Standard (IACS). (b) Copper is determined by the difference between the impurity total and 100%. (c) The following additional maximum limits apply: Bi, 1 ppm (0.0001%); Cd, 1 ppm (0.001%); Fe, 10 ppm (0.0010%); Pb, 5 ppm (0.0005%); Mn, 0.5 ppm (0.00005%); Hg, 1 ppm (0.0001%); Ni, 10 ppm (0.0010%); oxygen, 5 ppm (0.0005%); Se, 3 ppm (0.0003%); Ag, 25 ppm (0.0025%); S, 15 ppm (0.0015%); Sn, 2 ppm (0.0002%); Zn, 1 ppm (0.0001%). (d) Includes P. (e) The following additional maximum limits apply: Oxygen and trace elements can vary depending on the process. (f) Se, 2 ppm (0.0002%); Bi, 1.0 ppm (0.00010%); group total, Te + Se + Bi, 3 ppm (0.0003%). Sn, 5 ppm (0.0005%); Pb, 5 ppm (0.0005%); Fe, 10 ppm (0.0010%); Ni, 10 ppm (0.0010%); S, 15 ppm (0.0015%); Ag, 25 ppm (0.0025%); oxygen, 100-650 ppm (0.010–0.065%). The total maximum allowable of 65 ppm (0.0065%) does not include oxygen. (g) Small amounts of Cd or other elements can be added by agreement to improve the resistance to softening at elevated temperatures. (h) Includes B + P. (i) This includes oxygen-free copper that contains P in an agreed-upon amount. (j) Includes Te + Se. (k) Includes Cd. Deoxidized with lithium or other suitable agreed-upon elements. (l) Includes Cu + Ag + Sn. (m) Includes Te + Sn. (n) Includes oxygen-free or deoxidized grades with deoxidizers (such as phosphorus, boron, lithium, or other) in an agreed-upon amount. (o) All aluminum present as Al_2O_3; 0.04% oxygen present as Cu_2O with a negligible amount in solid solution with copper. (p) Cu + sum of named elements, 99.5% min. (q) Ni + Co, 0.20% min; Ni + Fe + Co, 0.6% max. (r) Includes Co. (s) Cu + sum of named elements, 99.9% min. (t) Cu + sum of named elements, 99.8% min. (u) Cu + sum of named elements, 99.7% min. (v) Cu + sum of named elements, 99.6% min. (w) For tube over 5 in. outside diameter, the Pb can be <0.20%. (x) For flat products, the iron is 0.10% max. (y) Cu, 61.0% min for rod. (z) Pb can be reduced to 1.0% by agreement. (aa) For tubular products, the minimum Sn content can be 0.9%. (bb) Cu + Sn + Fe + P, 99.5% min. (cc) Cu + sum of named elements, 99.85% min. (dd) When the product is for subsequent welding applications and is so specified by the purchaser, Cr, Cd, Zr, and Zn will each be 0.05% max. (ee) Fe content shall not exceed Ni content. (ff) Not including Co. (gg) Fe + Co, 1.8-2.3%. (hh) Al + Zn, 25.1-27.1%. (ii) The following additional maximum limits apply: When the product is for subsequent welding applications and is so specified by the purchaser, 0.50% Zn, 0.02% P, 0.02% Pb, 0.02% S (0.008% S for C71110), and 0.05% C. (jj) The following additional maximum limits apply: 0.02% C, 0.015% Si, 0.003% S, 0.002% Al, 0.001% P, 0.0005% Hg, 0.001% Ti, 0.001% Sb, 0.001% As, 0.001% Bi, 0.05% Co, 0.10% Mg, and 0.005% oxygen. For C70690, Co will be 0.02% max. (kk) The following maximum limits apply: 0.07% C, 0.15% Si, 0.024% S, 0.05% Al, and 0.03% P. (ll) 0.02% P, max; 0.25% Si, max; 0.01% S, max; 0.20-0.50% Ti. (mm) 0.005% Pb, max, for hot rolling. (nn) 0.05% Pb, max, for rod and wire. Source: Copper Development Association Inc.

Table 2 (continued)

Alloys C16200—C19160 (high-copper alloys)

		Composition, wt%									
Copper alloy No.	**Previous trade name**	**Cu (incl Ag)**	**Fe**	**Sn**	**Ni**	**Co**	**Cr**	**Si**	**Be**	**Pb**	**Other named elements**
C16200	Cadmium copper	bal(p)	0.02	…	…	…	…	…	…	…	0.7–1.2Cd
C16500	…	bal(p)	0.02	0.50–0.7	…	…	…	…	…	…	0.6–1.0Cd
C17000	Beryllium copper	bal(p)	(q)	…	(q)	(q)	…	0.20	1.60–1.79	…	0.20Al
C17200	Beryllium copper	bal(p)	(q)	…	(q)	(q)	…	0.20	1.80–2.00	0.02	0.20Al
C17300	…	bal(p)	(q)	…	(q)	(q)	…	0.20	1.80–2.00	0.20–0.6	0.20Al
C17410	…	bal(p)	0.20	…	…	0.35–0.6	…	0.20	0.15–0.50	…	0.20Al
C17450	…	bal(p)	0.20	0.25	0.50–1.0	…	…	0.20	0.15–0.50	…	0.20Al
C17460	…	bal(p)	0.20	0.25	1.0–1.4	…	…	0.20	0.15–0.50	...	0.20Al, 0.10–0.50Zr
C17500	Beryllium copper	bal(p)	0.10	…	…	2.4–2.7	…	0.20	0.40–0.70	…	0.20Al
C17510	…	bal(p)	0.10	…	1.4–2.2	0.30	…	0.20	0.20–0.6	…	0.20Al
C17530	…	bal(p)	0.20	…	1.8–2.5(r)	…	…	0.20	0.20–0.40	…	0.6Al
C18000	…	bal(p)	0.15	…	1.8–3.0(r)	…	0.10–0.8	0.40–0.8	…	…	…
C18030	…	bal(s)	…	0.08–0.12	…	…	0.10–0.20	…	…	…	0.005–0.015P
C18040	…	bal(n)	…	0.20–0.30	…	…	0.25–0.35	…	…	…	0.005–0.015P, 0.05–0.15Zn
C18050	…	bal(t)	…	…	…	…	0.05–0.15	…	…	…	0.005–0.015Te
C18070	…	99.0(t)	…	…	…	…	0.15–0.40	0.02–0.07	…	…	0.01–0.40Ti
C18090	…	96.0 min(cc)	…	0.50–1.2	0.30–1.2	…	0.20–1.0	…	…	…	0.15–8Ti
C18100	…	98.7 min(p)	…	…	…	…	0.40–1.2	…	…	…	0.03–0.06Mg, 0.08–0.20Zr
C18135	…	bal(p)	…	…	…	…	0.20–0.6	…	…	…	0.20–0.6Cd
C18140	…	bal(p)	…	…	…	…	0.15–0.45	0.005–0.05	…	…	0.05–0.25Zr
C18150	…	bal(u)	…	…	…	…	0.50–1.5	…	…	…	0.05–0.25Zr
C18200	Chromium copper	bal(p)	0.10	…	…	…	0.06–1.2	0.10	…	0.05	…
C18400	Chromium copper	bal(p)	0.15	…	…	…	0.40–1.2	0.10	…	…	0.005As, 0.005Ca, 0.05Li, 0.05P, 0.7Zn
C18600	…	bal(p)	0.25–0.8	…	0.25	0.10	0.10–1.0	…	…	…	0.05–0.50Ti, 0.05–0.50Zr
C18610	…	bal(p)	0.10	…	0.25	0.25–0.8	0.10–1.0	…	…	…	0.05–0.50Ti, 0.05–0.50Zr
C18665	…	99.0 min	…	…	…	…	…	…	…	…	0.40–0.9Mg, 0.002–0.04P
C18700	…	bal(p)	…	…	…	…	…	…	…	0.8–1.5	…
C18835	…	99.0 min(p)	0.10	0.15–0.55	…	…	…	…	…	0.05	0.01P
C18900	…	bal(p)	…	0.6–0.9	…	…	…	0.15–0.40	…	0.02	0.05P, 0.01Al, 0.10–0.30Mn, 0.10Zn
C18980	…	98.0(p)	…	1.0	…	…	…	0.50	…	0.02	0.50Mn, 0.15P
C18990	…	bal(s)	…	1.8–2.2	…	…	0.10–0.20	…	…	…	0.005–0.015P
C19000	…	bal(p)	0.10	…	0.9–1.3	…	…	…	…	0.05	0.8Zn, 0.015–0.35P
C19010	…	bal(p)	…	…	0.8–1.8	…	…	0.15–0.35	…	…	0.01–0.05P
C19015	…	bal(t)	…	…	0.50–2.4	…	…	0.10–0.40	…	…	0.02–0.20P, 0.02–0.15Mg
C19020	…	bal(t)	…	0.30–0.9	0.50–3.0	…	…	…	…	…	0.01–0.20P, 0.35Mn+Si
C19025	…	bal(u)	…	0.7–1.1	0.8–1.2	…	…	…	…	…	0.03–0.07P
C19030	…	bal(u)	0.10	1.0–1.5	1.5–2.0	…	…	…	…	0.02	0.01–0.03P
C19100	…	bal(p)	0.20	…	0.9–1.3	…	…	…	…	0.10	0.50Zn, 0.35–0.6Te, 0.15–0.35P
C19140	…	bal(p)	0.05	0.05	0.8–1.2	…	…	…	…	0.40–0.8	0.50Zn
C19150	…	bal(p)	0.05	0.05	0.8–1.2	…	…	…	…	0.50–1.0	0.15–0.35P
C19160	…	bal(p)	0.05	0.05	0.8–1.2	…	…	…	…	0.8–1.2	0.50Zn, 0.15–0.35P

(continued)

incl, including. (a) These are high conductivity coppers that have in the annealed condition a minimum conductivity of 100% International Annealed Copper Standard (IACS). (b) Copper is determined by the difference between the impurity total and 100%. (c) The following additional maximum limits apply: Bi, 1 ppm (0.0001%); Cd, 1 ppm (0.001%); Fe, 10 ppm (0.0010%); Pb, 5 ppm (0.0005%); Mn, 0.5 ppm (0.00005%); Hg, 1 ppm (0.0001%); Ni, 10 ppm (0.0010%); oxygen, 5 ppm (0.0005%); Se, 3 ppm (0.0003%); Ag, 25 ppm (0.0025%); S, 15 ppm (0.0015%); Sn, 2 ppm (0.0002%); Zn, 1 ppm (0.0001%). (d) Includes P. (e) The following additional maximum limits apply: Oxygen and trace elements can vary depending on the process. (f) Se, 2 ppm (0.0002%); Bi, 1.0 ppm (0.00010%); group total, Te + Se + Bi, 3 ppm (0.0003%). Sn, 5 ppm (0.0005%); Pb, 5 ppm (0.0005%); Fe, 10 ppm (0.0010%); Ni, 10 ppm (0.0010%); S, 15 ppm (0.0015%); Ag, 25 ppm (0.0025%); oxygen, 100-650 ppm (0.010–0.065%). The total maximum allowable of 65 ppm (0.0065%) does not include oxygen. (g) Small amounts of Cd or other elements can be added by agreement to improve the resistance to softening at elevated temperatures. (h) Includes B + P. (i) This includes oxygen-free copper that contains P in an agreed-upon amount. (j) Includes Te + Se. (k) Includes Cd. Deoxidized with lithium or other suitable agreed-upon elements. (l) Includes Cu + Ag + Sn. (m) Includes Te + Sn. (n) Includes oxygen-free or deoxidized grades with deoxidizers (such as phosphorus, boron, lithium, or other) in an agreed-upon amount. (o) All aluminum present as Al_2O_3; 0.04% oxygen present as Cu_2O with a negligible amount in solid solution with copper. (p) Cu + sum of named elements, 99.5% min. (q) Ni + Co, 0.20% min; Ni + Fe + Co, 0.6% max. (r) Includes Co. (s) Cu + sum of named elements, 99.9% min. (t) Cu + sum of named elements, 99.8% min. (u) Cu + sum of named elements, 99.7% min. (v) Cu + sum of named elements, 99.6% min. (w) For tube over 5 in. outside diameter, the Pb can be <0.20%. (x) For flat products, the iron is 0.10% max. (y) Cu, 61.0% min for rod. (z) Pb can be reduced to 1.0% by agreement. (aa) For tubular products, the minimum Sn content can be 0.9%. (bb) Cu + Sn + Fe + P, 99.5% min. (cc) Cu + sum of named elements, 99.85% min. (dd) When the product is for subsequent welding applications and is so specified by the purchaser, Cr, Cd, Zr, and Zn will each be 0.05% max. (ee) Fe content shall not exceed Ni content. (ff) Not including Co. (gg) Fe + Co, 1.8-2.3%. (hh) Al + Zn, 25.1-27.1%. (ii) The following additional maximum limits apply: When the product is for subsequent welding applications and is so specified by the purchaser, 0.50% Zn, 0.02% P, 0.02% Pb, 0.02% S (0.008% S for C71110), and 0.05% C. (jj) The following additional maximum limits apply: 0.02% C, 0.015% Si, 0.003% S, 0.002% Al, 0.001% P, 0.0005% Hg, 0.001% Ti, 0.001% Sb, 0.001% As, 0.001% Bi, 0.05% Co, 0.10% Mg, and 0.005% oxygen. For C70690, Co will be 0.02% max. (kk) The following maximum limits apply: 0.07% C, 0.15% Si, 0.024% S, 0.05% Al, and 0.03% P. (ll) 0.02% P, max; 0.25% Si, max; 0.01% S, max; 0.20-0.50% Ti. (mm) 0.005% Pb, max, for hot rolling. (nn) 0.05% Pb, max, for rod and wire. Source: Copper Development Association Inc.

Table 2 (continued)

Alloys C19200–C19900 (high-copper alloys)

Copper alloy No.	Composition, wt%							
	Cu	Fe	Sn	Zn	Al	Pb	P	Other named elements
C19200	98.5 min(t)	0.8–1.2	…	0.20	…	…	0.01–0.04	…
C19210	bal(t)	0.05–0.15	…	…	…	…	0.025–0.040	…
C19220	bal(t)	0.10–0.30	0.05–0.10	…	…	…	0.03–0.07	0.005–0.015B, 0.10–0.25Ni
C19260	98.5 min(s)	0.40–0.8	…	…	…	…	…	0.20–0.40Ti, 0.20–0.15Mg
C19280	bal(t)	0.50–1.5	0.30–0.7	0.30–0.7	…	…	0.005–0.015	…
C19400	97.0 min	2.1–2.6	…	0.05–0.20	…	0.03	0.015–0.15	…
C19410	bal(t)	1.8–2.3	0.6–0.9	0.10–0.20	…	…	0.015–0.050	…
C19450	bal(t)	1.5–3.0	0.8–2.5	…	…	…	0.005–0.05	…
C19500	96.0 min(t)	1.0–2.0	0.10–1.0	0.20–0.02	0.02	0.02	0.01–0.35	0.30–1.3Co
C19520	96.6 min(t)	0.50–1.5	…	…	…	0.01–3.5	…	…
C19700	bal(t)	0.30–1.2	0.20	0.20	…	0.05	0.10–0.40	0.01–0.20Mg, 0.05Ni, 0.05Co, 0.05Mn
C19710	bal(p)	0.05–0.40	0.20	0.20	…	0.05	0.07–1.5	0.10Ni+Co, 0.05Mn, 0.03–0.06Mg
C19720	bal(p)	0.05–0.50	0.20	0.20	…	0.05	0.05–0.15	0.10Ni+Co, 0.05Mn, 0.06–0.20Mg
C19750	bal(t)	0.35–1.2	0.05–0.40	0.20	…	0.05	0.10–0.40	0.01–0.20Mg, 0.05Ni, 0.05Co, 0.05Mn
C19900	bal(p)	…	…	…	…	…	…	2.9–3.4Ti

Copper-zinc alloys (brasses)

Copper alloy No.	Previous trade name	Composition, wt%				
		Cu	Pb	Fe	Zn	Other named elements
C21000	Gilding, 95%	94.0–96.0(t)	0.03	0.05	bal	…
C22000	Commercial bronze, 90%	89.0–91.0(t)	0.05	0.05	bal	…
C22600	Jewelry bronze, 87.5%	86.0–89.0(t)	0.05	0.05	bal	…
C23000	Red brass, 85%	84.0–86.0(t)	0.05	0.05	bal	…
C23030	…	83.5–85.5(t)	0.05	0.05	bal	0.20–0.40Si
C23400	…	81.0–84.0(t)	0.05	0.05	bal	…
C24000	Low brass, 80%	78.5–81.5(t)	0.05	0.05	bal	…
C24080	…	78.0–82.0(t)	0.20	…	bal	0.10Al
C25600	…	71.0–73.0(u)	0.05	0.05	bal	…
C26000	Cartridge brass, 70%	68.5–71.5(u)	0.07	0.05	bal	…
C26130	…	68.5–71.5(u)	0.05	0.05	bal	0.02–0.08As
C26200	…	67.0–70.0(u)	0.07	0.05	bal	…
C26800	Yellow brass, 66%	64.0–68.5(u)	0.15	0.05	bal	…
C27000	Yellow brass, 65%	63.0–68.5(u)	0.10	0.07	bal	…
C27200	…	62.0–65.0(u)	0.07	0.07	bal	…
C27400	Yellow brass, 63%	61.0–64.0(u)	0.10	0.05	bal	…
C28000	Muntz metal, 60%	59.0–63.0(u)	0.30	0.07	bal	…

Copper-zinc-lead alloys (leaded brasses)

Copper alloy No.	Previous trade name	Composition, %				
		Cu	Pb	Fe	Zn	Other named elements
C31200	…	87.5–90.5(v)	0.7–1.2	0.10	bal	0.25Ni
C31400	Leaded commercial bronze	87.5–90.5(v)	1.3–2.5	0.10	bal	0.7Ni
C31600	Leaded commercial bronze (nickel-bearing)	87.5–90.5(v)	1.3–2.5	0.10	bal	0.7–1.2 Ni, 0.04–0.10P
C32000	Leaded red brass	83.5–86.5(v)	1.5–2.2	0.10	bal	0.25Ni
C33000	Low leaded brass (tube)	65.0–68.0(v)	0.25–0.7(w)	0.07	bal	…
C33200	High leaded brass (tube)	65.0–68.0(v)	1.5–2.5	0.07	bal	…
C33500	Low leaded brass	62.0–65.0(v)	0.25–0.7	0.15(x)	bal	…
C34000	Medium leaded brass, 64.5%	62.0–65.0(v)	0.8–1.5	0.15(x)	bal	…
C34200	High leaded brass, 64.5%	62.0–65.0(v)	1.5–2.5	0.15(x)	bal	…

(continued)

incl, including. (a) These are high conductivity coppers that have in the annealed condition a minimum conductivity of 100% International Annealed Copper Standard (IACS). (b) Copper is determined by the difference between the impurity total and 100%. (c) The following additional maximum limits apply: Bi, 1 ppm (0.0001%); Cd, 1 ppm (0.001%); Fe, 10 ppm (0.0010%); Pb, 5 ppm (0.0005%); Mn, 0.5 ppm (0.00005%); Hg, 1 ppm (0.0001%); Ni, 10 ppm (0.0010%); oxygen, 5 ppm (0.0005%); Se, 3 ppm (0.0003%); Ag, 25 ppm (0.0025%); S, 15 ppm (0.0015%); Sn, 2 ppm (0.0002%); Zn, 1 ppm (0.0001%). (d) Includes P. (e) The following additional maximum limits apply: Oxygen and trace elements can vary depending on the process. (f) Se, 2 ppm (0.0002%); Bi, 1.0 ppm (0.00010%); group total, Te + Se + Bi, 3 ppm (0.0003%). Sn, 5 ppm (0.0005%); Pb, 5 ppm (0.0005%); Fe, 10 ppm (0.0010%); Ni, 10 ppm (0.0010%); S, 15 ppm (0.0015%); Ag, 25 ppm (0.0025%); oxygen, 100-650 ppm (0.010–0.065%). The total maximum allowable of 65 ppm (0.0065%) does not include oxygen. (g) Small amounts of Cd or other elements can be added by agreement to improve the resistance to softening at elevated temperatures. (h) Includes B + P. (i) This includes oxygen-free copper that contains P in an agreed-upon amount. (j) Includes Te + Se. (k) Includes Cd. Deoxidized with lithium or other suitable agreed-upon elements. (l) Includes Cu + Ag + Sn. (m) Includes Te + Sn. (n) Includes oxygen-free or deoxidized grades with deoxidizers (such as phosphorus, boron, lithium, or other) in an agreed-upon amount. (o) All aluminum present as Al_2O_3; 0.04% oxygen present as Cu_2O with a negligible amount in solid solution with copper. (p) Cu + sum of named elements, 99.5% min. (q) Ni + Co, 0.20% min; Ni + Fe + Co, 0.6% max. (r) Includes Co. (s) Cu + sum of named elements, 99.9% min. (t) Cu + sum of named elements, 99.8% min. (u) Cu + sum of named elements, 99.7% min. (v) Cu + sum of named elements, 99.6% min. (w) For tube over 5 in. outside diameter, the Pb can be <0.20%. (x) For flat products, the iron is 0.10% max. (y) Cu, 61.0% min for rod. (z) Pb can be reduced to 1.0% by agreement. (aa) For tubular products, the minimum Sn content can be 0.9%. (bb) Cu + Sn + Fe + P, 99.5% min. (cc) Cu + sum of named elements, 99.85% min. (dd) When the product is for subsequent welding applications and is so specified by the purchaser, Cr, Cd, Zr, and Zn will each be 0.05% max. (ee) Fe content shall not exceed Ni content. (ff) Not including Co. (gg) Fe + Co, 1.8-2.3%. (hh) Al + Zn, 25.1-27.1%. (ii) The following additional maximum limits apply: When the product is for subsequent welding applications and is so specified by the purchaser, 0.50% Zn, 0.02% P, 0.02% Pb, 0.02% S (0.008% S for C71110), and 0.05% C. (jj) The following additional maximum limits apply: 0.02% C, 0.015% Si, 0.003% S, 0.002% Al, 0.001% P, 0.0005% Hg, 0.001% Ti, 0.001% Sb, 0.001% As, 0.001% Bi, 0.05% Co, 0.10% Mg, and 0.005% oxygen. For C70690, Co will be 0.02% max. (kk) The following maximum limits apply: 0.07% C, 0.15% Si, 0.024% S, 0.05% Al, and 0.03% P. (ll) 0.02% P, max; 0.25% Si, max; 0.01% S, max; 0.20-0.50% Ti. (mm) 0.005% Pb, max, for hot rolling. (nn) 0.05% Pb, max, for rod and wire. Source: Copper Development Association Inc.

Table 2 (continued)

Copper-zinc-lead alloys (leaded brasses)

Copper alloy No.	Previous trade name	Composition, %				
		Cu	Pb	Fe	Zn	Other named elements
C34500	…	62.0–65.0(v)	1.5–2.5	0.15	bal	…
C35000	Medium leaded brass, 62%	60.0–63.0(v)(y)	0.8–2.0	0.15(x)	bal	…
C35300	High leaded brass, 62%	60.0–63.0(p)(y)	1.5–2.5	0.15(x)	bal	…
C35330	…	60.5–64.0(p)	1.5–3.5(z)	…	bal	0.02–0.25As
C35600	Extra high leaded brass	60.0–63.0(p)	2.0–3.0	0.15(x)	bal	…
C36000	Free-cutting brass	60.0–63.0(p)	2.5–3.7	0.35	bal	…
C36500	Leaded Muntz metal, uninhibited	58.0–61.0(v)	0.25–0.7	0.15	bal	0.25Sn
C37000	Free-cutting Muntz metal	59.0–62.0(v)	0.8–1.5	0.15	bal	…
C37100	…	58.0–62.0(v)	0.6–1.2	0.15	bal	…
C37700	Forging brass	58.0–61.0(p)	1.5–2.5	0.30	bal	…
C37710	…	56.5–60.0(p)	1.0–3.0	0.30	bal	…
C38000	Architectural bronze, low leaded	55.0–60.0(p)	1.5–2.5	0.35	bal	0.50Al, 0.30Sn
C38500	Architectural bronze	55.0–59.0(p)	2.5–3.5	0.35	bal	…

Copper-zinc-tin alloys (tin brasses)

Copper alloy No.	Previous trade name	Composition, wt%						
		Cu	Pb	Fe	Sn	Zn	P	Other named elements
C40400	…	bal(u)	…	…	0.35–0.7	2.0–3.0	…	…
C40500	…	94.0–96.0(u)	0.05	0.05	0.7–1.3	bal	…	…
C40810	…	94.5–96.5(u)	0.05	0.08–0.12	1.8–2.2	bal	0.028–0.04	0.11–0.20Ni
C40850	…	94.5–96.5(u)	0.05	0.05–0.20	2.6–4.0	bal	0.02–0.04	0.05–0.20Ni
C40860	…	94.0–96.0(u)	0.05	0.01–0.05	1.7–2.3	bal	0.02–0.04	0.05–0.20Ni
C41000	…	91.0–93.0(u)	0.05	0.05	2.0–2.8	bal	…	…
C41100	…	89.0–92.0(u)	0.10	0.05	0.30–0.7	bal	…	…
C41120	…	89.0–92.0(u)	0.05	0.05–0.20	0.30–0.7	bal	0.02–0.05	0.05–0.20Ni
C41300	…	89.0–93.0(u)	0.10	0.05	0.7–1.3	bal	…	…
C41500	…	89.0–93.0(u)	0.10	0.05	1.5–2.2	bal	…	…
C42000	…	88.0–91.0(u)	…	…	1.5–2.0	bal	0.25	…
C42200	…	86.0–89.0(u)	0.05	0.05	0.8–1.4	bal	0.35	…
C42500	…	87.0–90.0(u)	0.05	0.05	1.5–3.0	bal	0.35	…
C42520	…	88.0–91.0(u)	0.05	0.05–0.20	1.5–3.0	bal	0.02–0.04	0.05–0.20Ni
C43000	…	84.0–87.0(u)	0.10	0.05	1.7–2.7	bal	…	…
C43400	…	84.0–87.0(u)	0.05	0.05	0.40–1.0	bal	…	…
C43500	…	79.0–83.0(u)	0.10	0.05	0.6–1.2	bal	…	…
C43600	…	80.0–83.0(u)	0.05	0.05	0.20–0.50	bal	…	…
C44300	Admiralty, arsenical	70.0–73.0(v)	0.07	0.06	0.8–1.2(aa)	bal	…	0.02–0.06As
C44400	Admiralty, antimonial	70.0–73.0(v)	0.07	0.06	0.8–1.2(aa)	bal	…	0.02–0.10Sb
C44500	Admiralty, phosphorized	70.0–73.0(v)	0.07	0.06	0.8–1.2(aa)	bal	0.02–0.10	…
C46200	Naval brass, 63.5%	62.0–65.0(v)	0.20	0.10	0.50–1.0	bal	…	…
C46400	Naval brass, uninhibited	59.0–62.0(v)	0.20	0.10	0.50–1.0	bal	…	…
C46500	Naval brass, arsenical	59.0–62.0(v)	0.20	0.10	0.50–1.0	bal	…	0.02–0.06As
C47000	Naval brass welding and brazing rod	57.0–61.0(v)	0.05	…	0.25–1.0	bal	…	0.01Al
C47940	…	63.0–66.0(v)	1.0–2.0	0.10–1.0	1.2–2.0	bal	…	0.10–0.50Ni (including Co)
C48200	Naval brass, medium leaded	59.0–62.0(v)	0.40–1.0	0.10	0.50–1.0	bal	…	…
C48500	Naval brass, high leaded	59.0–62.0(v)	1.3–2.2	0.10	0.50–1.0	bal	…	…
C48600	…	59.0–62.0(v)	1.0–2.5	…	0.8–1.5	bal	…	0.02–0.25As

Copper-tin-phosphorus alloys (phosphor bronzes)

Copper alloy No.	Previous trade name	Composition, wt%						
		Cu(p)	Pb	Fe	Sn	Zn	P	Other named elements
C50100	…	bal	0.05	0.05	0.50–0.8	…	0.01–0.05	…
C50200	…	bal	0.05	0.10	1.0–1.5	…	0.04	…
C50500	Phosphor bronze, 1.25% E	bal	0.05	0.10	1.0–1.7	0.30	0.03–0.35	…
C50510	…	bal(u)	…	…	1.0–1.5	0.10–0.25	0.02–0.07	0.15–0.40Ni
C50580	…	bal	0.05	0.05–0.20	1.0–1.7	0.30	0.02–0.10	0.05–0.20Ni
C50700	…	bal	0.05	0.10	1.5–2.0	…	0.30	…
C50710	…	bal	…	…	1.7–2.3	…	0.15	0.10–0.40Ni
C50715	…	bal(bb)	0.02	0.05–0.15	1.7–2.3	…	0.025–0.04	…

(continued)

incl, including. (a) These are high conductivity coppers that have in the annealed condition a minimum conductivity of 100% International Annealed Copper Standard (IACS). (b) Copper is determined by the difference between the impurity total and 100%. (c) The following additional maximum limits apply: Bi, 1 ppm (0.0001%); Cd, 1 ppm (0.001%); Fe, 10 ppm (0.0010%); Pb, 5 ppm (0.0005%); Mn, 0.5 ppm (0.00005%); Hg, 1 ppm (0.0001%); Ni, 10 ppm (0.0010%); oxygen, 5 ppm (0.0005%); Se, 3 ppm (0.0003%); Ag, 25 ppm (0.0025%); S, 15 ppm (0.0015%); Sn, 2 ppm (0.0002%); Zn, 1 ppm (0.0001%). (d) Includes P. (e) The following additional maximum limits apply: Oxygen and trace elements can vary depending on the process. (f) Se, 2 ppm (0.0002%); Bi, 1.0 ppm (0.00010%); group total, Te + Se + Bi, 3 ppm (0.0003%). Sn, 5 ppm (0.0005%); Pb, 5 ppm (0.0005%); Fe, 10 ppm (0.0010%); Ni, 10 ppm (0.0010%); S, 15 ppm (0.0015%); Ag, 25 ppm (0.0025%); oxygen, 100-650 ppm (0.010–0.065%). The total maximum allowable of 65 ppm (0.0065%) does not include oxygen. (g) Small amounts of Cd or other elements can be added by agreement to improve the resistance to softening at elevated temperatures. (h) Includes B + P. (i) This includes oxygen-free copper that contains P in an agreed-upon amount. (j) Includes Te + Se. (k) Includes Cd. Deoxidized with lithium or other suitable agreed-upon elements. (l) Includes Cu + Ag + Sn. (m) Includes Te + Sn. (n) Includes oxygen-free or deoxidized grades with deoxidizers (such as phosphorus, boron, lithium, or other) in an agreed-upon amount. (o) All aluminum present as Al_2O_3; 0.04% oxygen present as Cu_2O with a negligible amount in solid solution with copper. (p) Cu + sum of named elements, 99.5% min. (q) Ni + Co, 0.20% min; Ni + Fe + Co, 0.6% max. (r) Includes Co. (s) Cu + sum of named elements, 99.9% min. (t) Cu + sum of named elements, 99.8% min. (u) Cu + sum of named elements, 99.7% min. (v) Cu + sum of named elements, 99.6% min. (w) For tube over 5 in. outside diameter, the Pb can be <0.20%. (x) For flat products, the iron is 0.10% max. (y) Cu, 61.0% min for rod. (z) Pb can be reduced to 1.0% by agreement. (aa) For tubular products, the minimum Sn content can be 0.9%. (bb) Cu + Sn + Fe + P, 99.5% min. (cc) Cu + sum of named elements, 99.85% min. (dd) When the product is for subsequent welding applications and is so specified by the purchaser, Cr, Cd, Zr, and Zn will each be 0.05% max. (ee) Fe content shall not exceed Ni content. (ff) Not including Co. (gg) Fe + Co, 1.8-2.3%. (hh) Al + Zn, 25.1-27.1%. (ii) The following additional maximum limits apply: When the product is for subsequent welding applications and is so specified by the purchaser, 0.50% Zn, 0.02% P, 0.02% Pb, 0.02% S (0.008% S for C71110), and 0.05% C. (jj) The following additional maximum limits apply: 0.02% C, 0.015% Si, 0.003% S, 0.002% Al, 0.001% P, 0.0005% Hg, 0.001% Ti, 0.001% Sb, 0.001% As, 0.001% Bi, 0.05% Co, 0.10% Mg, and 0.005% oxygen. For C70690, Co will be 0.02% max. (kk) The following maximum limits apply: 0.07% C, 0.15% Si, 0.024% S, 0.05% Al, and 0.03% P. (ll) 0.02% P, max; 0.25% Si, max; 0.01% S, max; 0.20-0.50% Ti. (mm) 0.005% Pb, max, for hot rolling. (nn) 0.05% Pb, max, for rod and wire. Source: Copper Development Association Inc.

Table 2 (continued)

Copper-tin-phosphorus alloys (phosphor bronzes)

		Composition, wt%						
Copper alloy No.	Previous trade name	Cu(p)	Pb	Fe	Sn	Zn	P	Other named elements
C50725	…	94.0 min(p)	0.02	0.05–0.20	1.5–2.5	1.5–3.0	0.02–0.06	…
C50780	…	bal(p)	0.05	0.05–0.20	1.7–2.3	…	0.02–0.10	0.05–0.20Ni
C50900	…	bal	0.05	0.10	2.5–3.8	0.30	0.03–0.30	…
C51000	Phosphor bronze, 5% A	bal	0.05	0.10	4.2–5.8	0.30	0.03–0.35	…
C51080	…	bal(p)	0.05	0.05–0.20	4.8–5.8	0.30	0.02–0.10	0.05–0.20Ni
C51100	…	bal	0.05	0.10	3.5–4.9	0.30	0.03–0.35	…
C51800	Phosphor bronze	bal	0.02	…	4.0–6.0	…	0.10–0.35	0.01Al
C51900	…	bal	0.05	0.10	5.0–7.0	0.30	0.03–0.35	…
C52100	Phosphor bronze, 8% C	bal	0.05	0.10	7.0–9.0	0.20	0.03–0.35	…
C52400	Phosphor bronze, 10% D	bal	0.05	0.10	9.0–11.0	0.20	0.03–0.35	…
C52480	…	bal	0.05	0.05–0.20	9.0–11.0	0.30	0.02–0.10	0.05–0.20Ni

Copper-tin-lead phosphorus alloys (leaded phosphor bronzes)

		Composition, wt%					
Copper alloy No.	Previous trade name	Cu(p)	Pb	Fe	Sn	Zn	P
C53400	Phosphor bronze B-1	bal	0.8–1.2	0.10	3.5–5.8	0.30	0.03–0.35
C54400	Phosphor bronze B-2	bal	3.5–4.5	0.10	3.5–4.5	1.5–4.5	0.01–0.50

Copper-phosphorus and copper-silver-phosphorus alloys (brazing alloys)

	Composition, wt%		
Copper alloy No.	Cu(cc)	Ag	P
C55180	bal	…	4.8–5.2
C55181	bal	…	7.0–7.5
C55280	bal	1.8–2.2	6.8–7.2
C55281	bal	4.8–5.2	5.8–6.2
C55282	bal	4.8–5.2	6.5–7.0
C55283	bal	5.8–6.2	7.0–7.5
C55284	bal	14.5–15.5	4.8–5.2

Copper-aluminum alloys (aluminum bronzes)

	Composition, wt%									
Copper alloy No.	Cu (incl Ag) (p)	Pb	Fe	Sn	Zn	Al	Mn	Si	Ni (incl Co)	Other named elements
C60800	bal	0.10	0.10	…	…	5.0–6.5	…	…	…	0.02–0.35As
C61000	bal	0.02	0.50	…	0.20	6.0–8.5	…	0.10	…	…
C61300	bal(t)	0.01	2.0–3.0	0.20–0.50	0.10(dd)	6.0–7.5	0.20	0.10	0.15	0.015P(dd)
C61400	bal	0.01	1.5–3.5	…	0.20	6.0–8.0	1.0	…	…	0.015P
C61500	bal	0.015	…	…	…	7.7–8.3	…	…	1.8–2.2	…
C61550	bal	0.05	0.20	0.05	0.8	5.5–6.5	1.0	…	1.5–2.5	…
C61800	bal	0.02	0.50–1.5	…	0.02	8.5–11.0	…	0.10	…	…
C61900	bal	0.02	3.0–4.5	0.6	0.8	8.5–10.0	…	…	…	…
C62200	bal	0.02	3.0–4.2	…	0.02	11.0–12.0	…	0.10	…	…
C62300	bal	…	2.0–4.0	0.6	…	8.5–10.0	0.50	0.25	1.0	…
C62400	bal	…	2.0–4.5	0.20	…	10.0–11.5	0.30	0.25	…	…
C62500	bal	…	3.5–5.5	…	…	12.5–13.5	2.0	…	…	…
C62580	bal	0.02	3.0–5.0	…	0.02	12.0–13.0	…	0.04	…	…
C62581	bal	0.02	3.0–5.0	…	0.02	13.0–14.0	…	0.04	…	…
C62582	bal	0.02	3.0–5.0	…	0.02	14.0–15.0	…	0.04	…	…
C63000	bal	…	2.0–4.0	0.20	0.30	9.0–11.0	1.5	0.25	4.0–5.5	…
C63010	78.0 min(t)	…	2.0–3.5	0.20	0.30	9.7–10.9	1.5	…	4.5–5.5	…
C63020	74.5 min	0.03	4.0–5.5	0.25	0.30	10.0–11.0	1.5	…	4.2–6.0	0.20Co, 0.05Cr
C63200	bal	0.02	3.5–4.3(ee)	…	…	8.7–9.5	1.2–2.0	0.10	4.0–4.8(ee)	…
C63280	bal	0.02	3.0–5.0	…	…	8.5–9.5	0.6–3.5	…	4.0–5.5	…
C63380	bal	0.02	2.0–4.0	…	0.15	7.0–8.5	11.0–14.0	0.10	1.5–3.0	…
C63400	bal	0.05	0.15	0.20	0.50	2.6–3.2	…	0.25–0.45	0.15	0.15As
C63600	bal	0.05	0.15	0.20	0.50	3.0–4.0	…	0.7–1.3	0.15	0.15As
C63800	bal	0.05	0.20	…	0.8	2.5–3.1	0.10	1.5–2.1	0.20(ff)	0.25–0.55Co
C64200	bal	0.05	0.30	0.20	0.50	6.3–7.6	0.10	1.5–2.2	0.25	0.15As
C64210	bal	0.05	0.30	0.20	0.50	6.3–7.0	0.10	1.5–2.0	0.25	0.15As

(continued)

incl, including. (a) These are high conductivity coppers that have in the annealed condition a minimum conductivity of 100% International Annealed Copper Standard (IACS). (b) Copper is determined by the difference between the impurity total and 100%. (c) The following additional maximum limits apply: Bi, 1 ppm (0.0001%); Cd, 1 ppm (0.001%); Fe, 10 ppm (0.0010%); Pb, 5 ppm (0.0005%); Mn, 0.5 ppm (0.00005%); Hg, 1 ppm (0.0001%); Ni, 10 ppm (0.0010%); oxygen, 5 ppm (0.0005%); Se, 3 ppm (0.0003%); Ag, 25 ppm (0.0025%); S, 15 ppm (0.0015%); Sn, 2 ppm (0.0002%); Zn, 1 ppm (0.0001%). (d) Includes P. (e) The following additional maximum limits apply: Oxygen and trace elements can vary depending on the process. (f) Se, 2 ppm (0.0002%); Bi, 1.0 ppm (0.00010%); group total, Te + Se + Bi, 3 ppm (0.0003%). Sn, 5 ppm (0.0005%); Pb, 5 ppm (0.0005%); Fe, 10 ppm (0.0010%); Ni, 10 ppm (0.0010%); S, 15 ppm (0.0015%); Ag, 25 ppm (0.0025%); oxygen, 100-650 ppm (0.010–0.065%). The total maximum allowable of 65 ppm (0.0065%) does not include oxygen. (g) Small amounts of Cd or other elements can be added by agreement to improve the resistance to softening at elevated temperatures. (h) Includes B + P. (i) This includes oxygen-free copper that contains P in an agreed-upon amount. (j) Includes Te + Se. (k) Includes Cd. Deoxidized with lithium or other suitable agreed-upon elements. (l) Includes Cu + Ag + Sn. (m) Includes Te + Sn. (n) Includes oxygen-free or deoxidized grades with deoxidizers (such as phosphorus, boron, lithium, or other) in an agreed-upon amount. (o) All aluminum present as Al_2O_3; 0.04% oxygen present as Cu_2O with a negligible amount in solid solution with copper. (p) Cu + sum of named elements, 99.5% min. (q) Ni + Co, 0.20% min; Ni + Fe + Co, 0.6% max. (r) Includes Co. (s) Cu + sum of named elements, 99.9% min. (t) Cu + sum of named elements, 99.8% min. (u) Cu + sum of named elements, 99.7% min. (v) Cu + sum of named elements, 99.6% min. (w) For tube over 5 in. outside diameter, the Pb can be <0.20%. (x) For flat products, the iron is 0.10% max. (y) Cu, 61.0% min for rod. (z) Pb can be reduced to 1.0% by agreement. (aa) For tubular products, the minimum Sn content can be 0.9%. (bb) Cu + Sn + Fe + P, 99.5% min. (cc) Cu + sum of named elements, 99.85% min. (dd) When the product is for subsequent welding applications and is so specified by the purchaser, Cr, Cd, Zr, and Zn will each be 0.05% max. (ee) Fe content shall not exceed Ni content. (ff) Not including Co. (gg) Fe + Co, 1.8-2.3%. (hh) Al + Zn, 25.1-27.1%. (ii) The following additional maximum limits apply: When the product is for subsequent welding applications and is so specified by the purchaser, 0.50% Zn, 0.02% P, 0.02% Pb, 0.02% S (0.008% S for C71110), and 0.05% C. (jj) The following additional maximum limits apply: 0.02% C, 0.015% Si, 0.003% S, 0.002% Al, 0.001% P, 0.0005% Hg, 0.001% Ti, 0.001% Sb, 0.001% As, 0.001% Bi, 0.05% Co, 0.10% Mg, and 0.005% oxygen. For C70690, Co will be 0.02% max. (kk) The following maximum limits apply: 0.07% C, 0.15% Si, 0.024% S, 0.05% Al, and 0.03% P. (ll) 0.02% P, max; 0.25% Si, max; 0.01% S, max; 0.20-0.50% Ti. (mm) 0.005% Pb, max, for hot rolling. (nn) 0.05% Pb, max, for rod and wire. Source: Copper Development Association Inc.

Table 2 (continued)

Copper-silicon alloys (silicon bronzes)

Copper alloy No.	Previous trade name	Composition, wt%								
		Cu(p) (incl Ag)	Pb	Fe	Sn	Zn	Mn	Si	Ni (incl Co)	Other named elements
C64700	…	bal	0.10	0.10	…	0.50	…	0.40–0.8	1.6–2.2	…
C64710	…	95.0 min	…	…	…	0.20–0.50	0.10	0.50–0.9	2.9–3.5	…
C64730	…	93.5 min	…	…	1.0–1.5	0.20–0.50	0.10	0.50–0.9	2.9–3.5	…
C64900	…	bal	0.05	0.10	1.2–1.6	0.20	…	0.8–1.2	0.10	0.10Al
C65100	Low silicon bronze B	bal	0.05	0.8	…	1.5	0.7	0.8–2.0	…	…
C65400	…	bal	0.05	…	1.2–1.9	0.50	…	2.7–3.4	…	0.01–0.12Cr
C65500	High silicon bronze A	bal	0.05	0.8	…	1.5	0.50–1.3	2.8–3.8	0.6	…
C65600	…	bal	0.02	0.50	1.5	1.5	1.5	2.8–4.0	…	0.01Al
C66100	…	bal	0.20–0.8	0.25	…	1.5	1.5	2.8–3.5	…	…

Other copper-zinc alloys

Copper alloy No.	Previous trade name	Composition, wt%									
		Cu(p) (incl Ag)	Pb	Fe	Sn	Zn	Ni (incl Co)	Al	Mn	Si	Other named elements
C66300	…	84.5–87.5	0.05	1.4–2.4	1.5–3.0	bal	…	…	…	…	0.35P, 0.20Co
C66400	…	bal	0.015	1.3–1.7(gg)	0.05	11.00–12.0	…	…	…	…	0.30–0.7Co(gg)
C66410	…	bal	0.015	1.8–2.3	0.05	11.0–12.0	…	…	…	…	…
C66700	Manganese brass	68.5–71.5	0.07	0.10	…	bal	…	…	0.8–1.5	…	…
C66800	…	60.0–63.0	0.50	0.35	0.30	bal	0.25	0.25	2.0–3.5	0.50–1.5	…
C66900	…	62.5–64.5(t)	0.05	0.25	…	bal	…	…	11.5–12.5	…	…
C66950	…	bal	0.01	0.50	…	14.0–15.0	…	1.0–1.5	14.0–15.0	…	…
C67000	Manganese bronze B	63.0–68.0	0.20	2.0–4.0	0.50	bal	…	3.0–6.0	2.5–5.0	…	…
C67300	…	58.0–63.0	0.40–3.0	0.50	0.30	bal	0.25	0.25	2.0–3.5	0.50–1.5	…
C67400	…	57.0–60.0	0.50	0.35	0.30	bal	0.25	0.50–2.0	2.0–3.5	0.50–1.5	…
C67420	…	57.0–58.5	0.25–0.8	0.15–0.55	0.35	bal	0.25	1.0–2.0	1.5–2.5	0.25–0.7	…
C67500	Manganese bronze A	57.0–60.0	0.20	0.8–2.0	0.50–1.5	bal	…	0.25	0.05–0.50	…	…
C67600	…	57.0–60.0	0.50–1.0	0.40–1.3	0.50–1.5	bal	…	…	0.05–0.50	…	…
C68000	Bronze, low fuming (nickel)	56.0–60.0	0.05	0.25–1.25	0.75–1.10	bal	0.20–0.8	0.01	0.01–0.50	0.04–0.15	…
C68100	Bronze, low fuming	56.0–60.0	0.05	0.25–1.25	0.75–1.10	bal	…	0.01	0.01–0.50	0.04–0.15	…
C68700	Aluminum brass, arsenical	76.0–79.0	0.07	0.06	…	bal	…	1.8–2.5	…	…	0.02–0.06As
C68800	…	bal	0.05	0.20	…	21.3–24.1(hh)	…	3.0–3.8(hh)	…	…	0.25–0.55Co
C69050	…	70.0–75.0	…	…	…	bal	0.50–1.5	3.0–4.0	…	0.10–0.6	0.01–0.20Zr
C69100	…	81.0–84.0	0.05	0.25	0.10	bal	0.8–1.4	0.7–1.2	0.10 min	0.8–1.3	…
C69400	Silicon red brass	80.0–83.0	0.30	0.20	…	bal	…	…	…	3.5–4.5	…
C69430	…	80.0–83.0	0.30	0.20	…	bal	…	…	…	3.5–4.5	0.03–0.06As
C69700	…	75.0–80.0	0.50–1.5	0.20	…	bal	…	…	0.40	2.5–3.5	…
C69710	…	75.0–80.0	0.50–1.5	0.20	…	bal	…	…	0.40	2.5–3.5	0.03–0.06As

Copper-nickel alloys

Copper alloy No.	Previous trade name	Composition, wt%						
		Cu (incl Ag)	Pb	Fe	Zn	Ni (incl Co)	Sn	Mn	Other named elements
C70100	…	bal(p)	…	0.05	0.25	3.0–4.0	…	0.50	…
C70200	…	bal(p)	0.05	0.10	…	2.0–3.0	…	0.40	…
C70230	…	bal(p)	…	…	0.50–2.0	2.2–3.2	0.10–0.50	…	0.10Ag+B, 0.40–0.8Si
C70250	…	bal(p)	0.05	0.20	1.0	2.2–4.2	…	0.10	0.05–0.30Mg, 0.25–1.2Si
C70260	…	bal(p)	…	…	…	1.0–3.0	…	…	0.20–0.7Si, 0.010P
C70280	…	bal(p)	0.02	0.015	0.30	1.3–1.7	1.0–1.5	…	0.02–0.04P, 0.22–0.30Si
C70290	…	bal(p)	0.02	0.015	0.30	1.3–1.7	2.1–2.7	…	0.02–0.04P, 0.22–0.30Si
C70400	Copper-nickel, 5%	rem(p)	0.05	1.3–1.71.0	1.0	4.8–6.2	…	0.30–0.8	…
C70500	Copper-nickel, 7%	bal(p)	0.05	0.10	0.20	5.8–7.8	…	0.15	…
C70600	Copper-nickel, 10%	bal(p)	0.05(ii)	1.0–1.8	1.0(ii)	9.0–11.0	…	1.0	(ii)
C70610	…	bal(p)	0.01	1.0–2.0	…	10.0–11.0	…	0.50–1.0	0.05S, 0.05C
C70620	…	86.5(p)	0.02	1.0–1.8	0.50	9.0–11.0	…	1.0	0.05C, 0.02P, 0.02S
C70690	…	bal(p)	0.001	0.005	0.001	9.0–11.0	…	0.001	(jj)
C70700	…	bal(p)	…	0.05	…	9.5–10.5	…	0.50	…

(continued)

incl, including. (a) These are high conductivity coppers that have in the annealed condition a minimum conductivity of 100% International Annealed Copper Standard (IACS). (b) Copper is determined by the difference between the impurity total and 100%. (c) The following additional maximum limits apply: Bi, 1 ppm (0.0001%); Cd, 1 ppm (0.001%); Fe, 10 ppm (0.0010%); Pb, 5 ppm (0.0005%); Mn, 0.5 ppm (0.00005%); Hg, 1 ppm (0.0001%); Ni, 10 ppm (0.0010%); oxygen, 5 ppm (0.0005%); Se, 3 ppm (0.0003%); Ag, 25 ppm (0.0025%); S, 15 ppm (0.0015%); Sn, 2 ppm (0.0002%); Zn, 1 ppm (0.0001%). (d) Includes P. (e) The following additional maximum limits apply: Oxygen and trace elements can vary depending on the process. (f) Se, 2 ppm (0.0002%); Bi, 1.0 ppm (0.00010%); group total, Te + Se + Bi, 3 ppm (0.0003%). Sn, 5 ppm (0.0005%); Pb, 5 ppm (0.0005%); Fe, 10 ppm (0.0010%); Ni, 10 ppm (0.0010%); S, 15 ppm (0.0015%); Ag, 25 ppm (0.0025%); oxygen, 100-650 ppm (0.010–0.065%). The total maximum allowable of 65 ppm (0.0065%) does not include oxygen. (g) Small amounts of Cd or other elements can be added by agreement to improve the resistance to softening at elevated temperatures. (h) Includes B + P. (i) This includes oxygen-free copper that contains P in an agreed-upon amount. (j) Includes Te + Se. (k) Includes Cd. Deoxidized with lithium or other suitable agreed-upon elements. (l) Includes Cu + Ag + Sn. (m) Includes Te + Sn. (n) Includes oxygen-free or deoxidized grades with deoxidizers (such as phosphorus, boron, lithium, or other) in an agreed-upon amount. (o) All aluminum present as Al_2O_3; 0.04% oxygen present as Cu_2O with a negligible amount in solid solution with copper. (p) Cu + sum of named elements, 99.5% min. (q) Ni + Co, 0.20% min; Ni + Fe + Co, 0.6% max. (r) Includes Co. (s) Cu + sum of named elements, 99.9% min. (t) Cu + sum of named elements, 99.8% min. (u) Cu + sum of named elements, 99.7% min. (v) Cu + sum of named elements, 99.6% min. (w) For tube over 5 in. outside diameter, the Pb can be <0.20%. (x) For flat products, the iron is 0.10% max. (y) Cu, 61.0% min for rod. (z) Pb can be reduced to 1.0% by agreement. (aa) For tubular products, the minimum Sn content can be 0.9%. (bb) Cu + Sn + Fe + P, 99.5% min. (cc) Cu + sum of named elements, 99.85% min. (dd) When the product is for subsequent welding applications and is so specified by the purchaser, Cr, Cd, Zr, and Zn will each be 0.05% max. (ee) Fe content shall not exceed Ni content. (ff) Not including Co. (gg) Fe + Co, 1.8-2.3%. (hh) Al + Zn, 25.1-27.1%. (ii) The following additional maximum limits apply: When the product is for subsequent welding applications and is so specified by the purchaser, 0.50% Zn, 0.02% P, 0.02% Pb, 0.02% S (0.008% S for C71110), and 0.05% C. (jj) The following additional maximum limits apply: 0.02% C, 0.015% Si, 0.003% S, 0.002% Al, 0.001% P, 0.0005% Hg, 0.001% Ti, 0.001% Sb, 0.001% As, 0.001% Bi, 0.05% Co, 0.10% Mg, and 0.005% oxygen. For C70690, Co will be 0.02% max. (kk) The following maximum limits apply: 0.07% C, 0.15% Si, 0.024% S, 0.05% Al, and 0.03% P. (ll) 0.02% P, max; 0.25% Si, max; 0.01% S, max; 0.20-0.50% Ti. (mm) 0.005% Pb, max, for hot rolling. (nn) 0.05% Pb, max, for rod and wire. Source: Copper Development Association Inc.

Table 2 (continued)

Copper-nickel alloys

Copper alloy No.	Previous trade name	Composition, wt%							
		Cu (incl Ag)	Pb	Fe	Zn	Ni (incl Co)	Sn	Mn	Other named elements
C70800	Copper-nickel, 11%	bal(p)	0.05	0.10	0.20	10.5–12.5	…	0.15	…
C71000	Copper-nickel, 20%	bal(p)	0.05	1.0	1.0	19.0–23.0	…	1.0	…
C71100	…	bal(p)	0.05	0.10	0.20	22.0–24.0	…	0.15	…
C71300	…	bal(p)	0.05	0.20	1.0	23.5–26.5	…	1.0	…
C71500	Copper-nickel, 30%	bal(p)	0.05(ii)	0.40–1.0	1.0(ii)	29.0–33.0	…	1.0	(ii)
C71520	…	65.0 min(p)	0.02	0.40–1.0	0.50	29.0–33.0	…	1.0	0.05C, 0.02P, 0.02S
C71580	…	bal(p)	0.05	0.50	0.05	29.0–33.0	…	0.30	(kk)
C71581	…	bal(p)	0.02	0.40–0.7	…	29.0–32.0	…	1.0	(ll)
C71590	…	bal	0.001	0.15	0.001	29.0–31.0	0.001	0.50	(jj)
C71640	…	bal(p)	0.01	1.7–2.3	…	29.0–32.0	…	1.5–2.5	0.03S, 0.06C
C71700	…	bal(p)	…	0.40–1.0	…	29.0–33.0	…	…	0.30–0.7Be
C71900	…	bal(p)	0.015	0.50	0.05	28.0–33.0	…	0.20–1.0	2.2–3.0Cr, 0.02–0.35Zr, 0.01–0.20Ti, 0.04C, 0.25Si, 0.15S, 0.02P
C72150	…	bal(p)	0.05	0.10	0.20	43.0–46.0	…	0.05	0.10C, 0.50Si
C72200	…	bal(t)	0.05(ii)	0.50–1.0	1.0(ii)	15.0–18.0	…	1.0	0.30–0.7Cr, 0.03Si, 0.03Ti (ii)
C72420	…	bal(u)	0.02	0.7–1.2	0.20	13.5–16.5	0.10	3.5–5.5	1.0–2.0Al, 0.50Cr, 0.15Si, 0.05Mg, 0.15S, 0.01P 0.05C
C72500	…	bal(t)	0.05	0.6	0.50	8.5–10.5	1.8–2.8	0.20	…
C72650	…	bal(u)	0.01	0.10	0.10	7.0–8.0	4.5–5.5	0.10	…
C72700	…	bal(u)	0.02	0.50	0.50	8.5–9.5	5.5–6.5	0.5–0.30	0.10Nb, 0.15Mg
C72800	…	bal(u)	0.005	0.50	1.0	9.5–10.5	7.5–8.5	0.05–0.30	0.10Al, 0.001B, 0.001Bi, 0.10–0.30Nb, 0.005–0.15Mg, 0.005P, 0.0025S, 0.02Sb, 0.05Si, 0.01Ti
C72900	…	bal(u)	0.02(mm)	0.50	0.50	14.5–15.5	7.5–8.5	0.30	0.10Nb, 0.15Mg
C72950	…	bal(u)	0.05	0.6	…	20.0–22.0	4.5–5.7	0.6	…

Copper-nickel-zinc alloys (nickel silvers)

Copper alloy No.	Previous trade name	Composition, wt%					
		Cu(p) (incl Ag)	Pb	Fe	Zn	Ni (incl Co)	Mn	Other named elements
C73500	…	70.5–73.5	0.10	0.25	bal	16.5–19.5	0.50	…
C74000	…	69.0–73.5	0.10	0.25	bal	9.0–11.0	0.50	…
C74300	…	63.0–66.0	0.10	0.25	bal	7.0–9.0	0.50	…
C74400	…	62.0–66.0	0.05	0.05	bal	2.0–4.0	…	…
C74500	Nickel silver, 65-10	63.5–66.5	0.10(nn)	0.25	bal	9.0–11.0	0.50	…
C75200	Nickel silver, 65-18	63.5–66.5	0.05	0.25	bal	16.5–19.5	0.50	…
C75400	Nickel silver, 65-15	63.5–66.5	0.10	0.25	bal	14.0–16.0	0.50	…
C75700	Nickel silver, 65-12	63.5–66.5	0.05	0.25	bal	11.0–13.0	0.50	…
C76000	…	60.0–63.0	0.10	0.25	bal	16.5–19.5	0.50	…
C76200	…	57.0–61.0	0.10	0.25	bal	11.0–13.5	0.50	…
C76400	…	58.5–61.5	0.05	0.25	bal	16.5–19.5	0.50	…
C76700	Nickel silver, 56.5-15	55.0–58.0	…	…	bal	14.0–16.0	0.50	…
C77000	Nickel silver, 55-18	53.5–56.5	0.05	0.25	bal	16.5–19.5.	0.50	…
C77300	…	46.0–50.0	0.05	…	bal	9.0–11.0	…	0.01Al, 0.25P, 0.04–0.25Si
C77400	…	43.0–47.0	0.20	…	bal	9.0–11.0	…	…
C78200	…	63.0–67.0	1.5–2.5	0.35	bal	7.0–9.0	0.50	…
C79000	…	63.0–67.0	1.5–2.2	0.35	bal	11.0–13.0	0.50	…
C79200	…	59.0–66.5	0.8–1.4	0.25	bal	11.0–13.0	0.50	…
C79800	…	45.5–48.5	1.5–2.5	0.25	bal	9.0–11.0	1.5–2.5	…
C79830	…	45.5–47.0	1.0–2.5	0.45	bal	9.0–10.5	0.15–0.55	…

incl, including. (a) These are high conductivity coppers that have in the annealed condition a minimum conductivity of 100% International Annealed Copper Standard (IACS). (b) Copper is determined by the difference between the impurity total and 100%. (c) The following additional maximum limits apply: Bi, 1 ppm (0.0001%); Cd, 1 ppm (0.001%); Fe, 10 ppm (0.0010%); Pb, 5 ppm (0.0005%); Mn, 0.5 ppm (0.00005%); Hg, 1 ppm (0.0001%); Ni, 10 ppm (0.0010%); oxygen, 5 ppm (0.0005%); Se, 3 ppm (0.0003%); Ag, 25 ppm (0.0025%); S, 15 ppm (0.0015%); Sn, 2 ppm (0.0002%); Zn, 1 ppm (0.0001%). (d) Includes P. (e) The following additional maximum limits apply: Oxygen and trace elements can vary depending on the process. (f) Se, 2 ppm (0.0002%); Bi, 1.0 ppm (0.00010%); group total, Te + Se + Bi, 3 ppm (0.0003%). Sn, 5 ppm (0.0005%); Pb, 5 ppm (0.0005%); Fe, 10 ppm (0.0010%); Ni, 10 ppm (0.0010%); S, 15 ppm (0.0015%); Ag, 25 ppm (0.0025%); oxygen, 100-650 ppm (0.010–0.065%). The total maximum allowable of 65 ppm (0.0065%) does not include oxygen. (g) Small amounts of Cd or other elements can be added by agreement to improve the resistance to softening at elevated temperatures. (h) Includes B + P. (i) This includes oxygen-free copper that contains P in an agreed-upon amount. (j) Includes Te + Se. (k) Includes Cd. Deoxidized with lithium or other suitable agreed-upon elements. (l) Includes Cu + Ag + Sn. (m) Includes Te + Sn. (n) Includes oxygen-free or deoxidized grades with deoxidizers (such as phosphorus, boron, lithium, or other) in an agreed-upon amount. (o) All aluminum present as Al_2O_3; 0.04% oxygen present as Cu_2O with a negligible amount in solid solution with copper. (p) Cu + sum of named elements, 99.5% min. (q) Ni + Co, 0.20% min; Ni + Fe + Co, 0.6% max. (r) Includes Co. (s) Cu + sum of named elements, 99.9% min. (t) Cu + sum of named elements, 99.8% min. (u) Cu + sum of named elements, 99.7% min. (v) Cu + sum of named elements, 99.6% min. (w) For tube over 5 in. outside diameter, the Pb can be <0.20%. (x) For flat products, the iron is 0.10% max. (y) Cu, 61.0% min for rod. (z) Pb can be reduced to 1.0% by agreement. (aa) For tubular products, the minimum Sn content can be 0.9%. (bb) Cu + Sn + Fe + P, 99.5% min. (cc) Cu + sum of named elements, 99.85% min. (dd) When the product is for subsequent welding applications and is so specified by the purchaser, Cr, Cd, Zr, and Zn will each be 0.05% max. (ee) Fe content shall not exceed Ni content. (ff) Not including Co. (gg) Fe + Co, 1.8-2.3%. (hh) Al + Zn, 25.1-27.1%. (ii) The following additional maximum limits apply: When the product is for subsequent welding applications and is so specified by the purchaser, 0.50% Zn, 0.02% P, 0.02% Pb, 0.02% S (0.008% S for C71110), and 0.05% C. (jj) The following additional maximum limits apply: 0.02% C, 0.015% Si, 0.003% S, 0.002% Al, 0.001% P, 0.0005% Hg, 0.001% Ti, 0.001% Sb, 0.001% As, 0.001% Bi, 0.05% Co, 0.10% Mg, and 0.005% oxygen. For C70690, Co will be 0.02% max. (kk) The following maximum limits apply: 0.07% C, 0.15% Si, 0.024% S, 0.05% Al, and 0.03% P. (ll) 0.02% P, max; 0.25% Si, max; 0.01% S, max; 0.20-0.50% Ti. (mm) 0.005% Pb, max, for hot rolling. (nn) 0.05% Pb, max, for rod and wire. Source: Copper Development Association Inc.

Table 3 Chemical compositions of cast coppers and copper alloys

Composition values are given as maximum percentages, unless shown as a range or minimum.

Coppers

Copper No.	Cu (incl Ag), % min	P	Total other elements
C80100	99.95	…	…
C80410	99.9	…	0.10
C81100	99.70	…	…
C81200	99.9	0.045–0.065	…

High-copper alloys

Copper alloy No.	Cu (a)	Be	Co	Si	Ni	Fe	Al	Sn	Pb	Zn	Cr
C81400	bal	0.02–0.10	…	…	…	…	…	…	…	…	0.6–1.0
C81500	bal	…	…	0.15	…	0.10	0.10	0.10	0.02	0.10	0.40–1.5
C81540	95.1 min(b)	…	…	0.40–0.8	2.0–3.0(c)	0.15	0.10	0.10	0.02	0.10	0.10–0.6
C82000	bal	0.45–0.8	2.40–2.70(c)	0.15	0.20	0.10	0.10	0.10	0.02	0.10	0.10
C82200	bal	0.35–0.8	0.30	…	1.0–2.0	…	…	…	…	…	…
C82400	bal	1.60–1.85	0.20–0.65	…	0.20	0.20	0.15	0.10	0.02	0.10	0.10
C82500	bal	1.90–2.25	0.35–0.70(c)	0.20–0.35	0.20	0.25	0.15	0.10	0.02	0.10	0.10
C82510	bal	1.90–2.15	1.0–1.2	0.20–0.35	0.20	0.25	0.15	0.10	0.02	0.10	0.10
C82600	bal	2.25–2.55	0.35–0.65	0.20–0.35	0.20	0.25	0.15	0.10	0.02	0.10	0.10
C82700	bal	2.35–2.55	…	0.15	1.0–1.5	0.25	0.15	0.10	0.02	0.10	0.10
C82800	bal	2.50–2.85	0.35–0.70(c)	0.20–0.35	0.20	0.25	0.15	0.10	0.02	0.10	0.10

Red and leaded red brasses

Copper alloy No.	Cu(d)(e)	Sn	Pb	Zn	Fe	Sb	As	Ni (incl Co)	S	P(f)	Al	Si
C83300	92.0–94.0	1.0–2.0	1.0–2.0	2.0–6.0	…	…	…	…	…	…	…	…
C83400	88.0–92.0	0.20	0.50	8.0–12.0	0.25	0.25	…	1.0	0.08	0.03	0.005	0.005
C83450	87.0–89.0	2.0–3.5	1.5–3.0	5.5–7.5	0.30	0.25	…	0.8–2.0	0.08	0.03	0.005	0.005
C83500	86.0–88.0	5.5–6.5	3.5–5.5	1.0–2.5	0.25	0.25	…	0.50–1.0	0.08	0.03	0.005	0.005
C83600	84.0–86.0	4.0–6.0	4.0–6.0	4.0–6.0	0.30	0.25	…	1.0	0.08	0.05	0.005	0.005
C83800	82.0–83.8	3.3–4.2	5.0–7.0	5.0–8.0	0.30	0.25	…	1.0	0.08	0.03	0.005	0.005
C83810	bal	2.0–3.5	4.0–6.0	7.5–9.5	0.50(g)	(g)	(g)	2.0	…	…	0.005	0.10

Semi-red and leaded semi-red brasses

Copper alloy No.	Cu(d)(e)	Sn	Pb	Zn	Fe	Sb	Ni (incl Co)	S	P(f)	Al	Si	Bi
C84200	78.0–82.0	4.0–6.0	2.0–3.0	10.0–16.0	0.40	0.25	0.8	0.08	0.05	0.005	0.005	…
C84400	78.0–82.0	2.3–3.5	6.0–8.0	7.0–10.0	0.40	0.25	1.0	0.08	0.02	0.005	0.005	…
C84410	bal	3.0–4.5	7.0–9.0	7.0–11.0	(h)	(h)	1.0	…	…	0.01	0.20	0.05
C84500	77.0–79.0	2.0–4.0	6.0–7.5	10.0–14.0	0.40	0.25	1.0	0.08	0.02	0.005	0.005	…
C84800	75.0–77.0	2.0–3.0	5.5–7.0	13.0–17.0	0.40	0.25	1.0	0.08	0.02	0.005	0.005	…

Yellow and leaded yellow brasses

Copper alloy No.	Cu(d)	Sn	Pb	Zn	Fe	Sb	Ni (incl Co)	Mn	As	S	P	Al	Si
C85200	70.0–74.0(i)	0.7–2.0	1.5–3.8	20.0–27.0	0.6	0.20	1.0	…	…	0.05	0.02	0.005	0.05
C85400	65.0–70.0(j)	0.50–1.5	1.5–3.8	24.0–32.0	0.7	…	1.0	…	…	…	…	0.35	0.05
C85500	59.0–63.0(i)	0.20	0.20	bal	0.20	…	0.20	0.20	…	…	…	…	…
C85700	58.0–64.0(k)	0.50–1.5	0.8–1.5	32.0–40.0	0.7	…	1.0	…	…	…	…	0.8	0.05
C85800	57.0 min(k)	1.5	1.5	31.0–41.0	0.50	0.05	0.50	0.25	0.05	0.05	0.01	0.55	0.25

Manganese bronze and leaded manganese bronze alloys

Copper alloy No.	Cu(d)(l)	Sn	Pb	Zn	Fe	Ni (incl Co)	Al	Mn	Si
C86100	66.0–68.0	0.20	0.20	bal	2.0–4.0	…	4.5–5.5	2.5–5.0	…
C86200	60.0–66.0	0.20	0.20	22.0–28.0	2.0–4.0	1.0	3.0–4.9	2.5–5.0	…
C86300	60.0–66.0	0.20	0.20	22.0–28.0	2.0–4.0	1.0	5.0–7.5	2.5–5.0	…
C86400	56.0–62.0	0.50–1.5	0.50–1.5	34.0–42.0	0.40–2.0	1.0	0.50–1.5	0.10–1.5	…
C86500	55.0–60.0	1.0	0.40	36.0–42.0	0.40–2.0	1.0	0.50–1.5	0.10–1.5	…
C86550	57.0 min	1.0	0.50	bal	0.7–2.0	1.0	0.50–2.5	0.10–3.0	0.10
C86700	55.0–60.0	1.5	0.50–1.5	30.0–38.0	1.0–3.0	1.0	1.0–3.0	0.10–3.5	…
C86800	53.5–57.0	1.0	0.20	bal	1.0–2.5	2.5–4.0	2.0	2.5–4.0	…

(continued)

incl, including. bal, balance. (a) Cu + sum of named elements, 99.5% min. (b) Includes Ag. (c) Ni + Co. (d) In determining copper min, copper can be calculated as Cu + Ni. (e) Cu + sum of named elements, 99.3% min. (f) For continuous castings, P will be 1.5%, max. (g) Fe + Sb + As will be 0.50% max. (h) Fe + Sb + As will be 0.8% max. (i) Cu + sum of named elements, 99.1% min. (j) Cu + sum of named elements, 98.9% min. (k) Cu + sum of named elements, 98.7% min. (l) Cu + sum of named elements, 99.0% min. (m) Cu + sum of named elements, 99.2% min. (n) 0.01–2.0% as any single or combination of Ce, La or other rare earth* elements, as agreed upon. *ASM International definition: one of the group of chemically similar metals with atomic numbers 57 through 71, commonly referred to as lanthanides. (o) Bi:Se ≥ 2:1. (p) Cu + sum of named elements, 99.4% min. (q) Cu + sum of named elements, 99.7% min. (r) Fe shall be 0.35% max, when used for steel-backed bearings. (s) For continuous castings, S will be 0.25% max. (t) The mechanical properties of C94700 (heat treated) may not be attainable if the lead content exceeds 0.01%. (u) Cu + sum of named elements, 99.8% min. (v) Fe content shall not exceed Ni content. (w) When the product or casting is intended for subsequent welding applications, and so specified by the purchaser, the Nb content will be 0.40% max. (x) The following additional maximum impurity limits will apply: 0.10% Al, 0.001% B, 0.001% Bi, 0.005–0.15% Mg, 0.005% P, 0.0025% S, 0.02% Sb, 7.5–8.5% Sn, 0.01% Ti, 1.0% Zn. (y) Cu + sum of named elements, 99.6% min. (z) Pb and Ag can be adjusted to modify the alloy hardness. (aa) Includes Co. Source: Copper Development Association

Table 3 (continued)

Silicon bronzes and silicon brasses

Copper alloy No.	Cu(a)	Sn	Pb	Zn	Fe	Al	Si	Mn	Mg	Ni (incl Co)	S	Other named elements
C87300	94.0min	…	0.20	0.25	0.20	…	3.5–4.5	0.8–1.5	…	…	…	…
C87400	79.0min(m)	…	1.0	12.0–16.0	…	0.8	2.5–4.0	…	…	…	…	…
C87500	79.0min	…	0.50	12.0–16.0	…	0.50	3.0–5.0	…	…	…	…	…
C87600	88.0min	…	0.50	4.0–7.0	0.20	…	3.5–5.5	0.25	…	…	…	…
C87610	90.0min	…	0.20	3.0–5.0	0.20	…	3.0–5.0	0.25	…	…	…	…
C87800	80.0min	0.25	0.15	12.0–16.0	0.15	0.15	3.8–4.2	0.15	0.01	0.20	0.05	0.01P, 0.05As, 0.05Sb

Copper-bismuth and copper-bismuth-selenium alloys

Copper alloy No.	Cu	Sn	Pb	Zn	Fe	Sb	Ni (incl Co)	S	P	Al	Si	Bi	Se	Other named elements
C89320	87.0–91.0(a)	5.0–7.0	0.09	1.0	0.20	0.35	1.0	0.08	0.30	0.005	0.005	4.0–6.0	…	…
C89325	84.0–88.0(l)	9.0–11.0	0.10	1.0	0.15	0.50	1.0	0.08	0.10	0.005	0.005	2.7–3.7	…	(n)
C89510	86.0–88.0(a)	4.0–6.0	0.25	4.0–6.0	0.30	0.25	1.0	0.08	0.05	0.005	0.005	0.50–1.5	0.35–0.7	…
C89520	85.0–87.0(a)	5.0–6.0	0.25	4.0–6.0	0.30	0.25	1.0	0.08	0.05	0.005	0.005	1.6–2.2	0.8–1.2	(o)
C89831	87.0–91.0(l)	2.7–3.7	0.10	2.0–4.0	0.30	0.25	1.0	0.08	0.050	0.005	0.005	2.7–3.7	…	(n)
C89833	87.0–91.0(l)	4.0–6.0	0.10	2.0–4.0	0.30	0.25	1.0	0.08	0.050	0.005	0.005	1.7–2.7	…	(n)
C89835	85.0–89.0(l)	6.0–7.5	0.10	2.0–4.0	0.20	0.35	1.0	0.08	0.10	0.005	0.005	1.7–2.7	…	(n)
C89837	84.0–88.0(a)	3.0–4.0	0.10	6.0–10.0	0.30	0.25	1.0	0.08	0.050	0.005	0.005	0.7–1.2	…	(n)
C89550	58.0–64.0(a)	0.50–1.5	0.20	32.0–40.0	0.7	…	1.0	…	…	0.30–0.7	…	0.7–2.0	0.07–0.25	…
C89844	83.0–86.0(a)	3.0–5.0	0.20	7.0–10.0	0.30	0.25	1.0	0.08	0.05	0.005	0.005	2.0–4.0	…	…
C89940	64.0–68.0(a)	3.0–5.0	0.01	3.0–5.0	0.7–2.0	0.10	20.0–23.0	0.05	0.10–0.15	0.005	0.15	4.0–5.5	…	0.20Mn

Tin bronzes

Copper alloy No.	Cu(d)(p)	Sn	Pb	Zn	Fe	Sb	Ni (incl Co)	S	P(f)	Al	Si
C90200	91.0–94.0	6.0–8.0	0.30	0.50	0.20	0.20	0.50	0.05	0.05	0.005	0.005
C90300	86.0–89.0	7.5–9.0	0.30	3.0–5.0	0.20	0.20	1.0	0.05	0.05	0.005	0.005
C90500	86.0–89.0(q)	9.0–11.0	0.30	1.0–3.0	0.20	0.20	1.0	0.05	0.05	0.005	0.005
C90700	88.0–90.0	10.0–12.0	0.50	0.50	0.15	0.20	0.50	0.05	0.30	0.005	0.005
C90710	bal	10.0–12.0	0.25	0.05	0.10	0.20	0.10	0.05	0.05–1.2	0.005	0.005
C90800	85.0–89.0	11.0–13.0	0.25	0.25	0.15	0.20	0.50	0.05	0.30	0.005	0.005
C90810	bal	11.0–13.0	0.25	0.30	0.15	0.20	0.50	0.05	0.15–0.8	0.005	0.005
C90900	86.0–89.0	12.0–14.0	0.25	0.25	0.15	0.20	0.50	0.05	0.05	0.005	0.005
C91000	84.0–86.0	14.0–16.0	0.20	1.5	0.10	0.20	0.8	0.05	0.05	0.005	0.005
C91100	82.0–85.0	15.0–17.0	0.25	0.25	0.25	0.20	0.50	0.05	1.0	0.005	0.005
C91300	79.0–82.0	18.0–20.0	0.25	0.25	0.25	0.20	0.50	0.05	1.0	0.005	0.005
C91600	86.0–89.0	9.7–10.8	0.25	0.25	0.20	0.20	1.2–2.0	0.05	0.30	0.005	0.005
C91700	84.0–87.0	11.3–12.5	0.25	0.25	0.20	0.20	1.2–2.0	0.05	0.30	0.005	0.005

Leaded tin bronzes

Copper alloy No.	Cu(d)(e)	Sn	Pb	Zn	Fe	Sb	Ni (incl Co)	S	P(f)	Al	Si	Mn
C92200	86.0–90.0	5.5–6.5	1.0–2.0	3.0–5.0	0.25	0.25	1.0	0.05	0.05	0.005	0.005	…
C92210	86.0–89.0	4.5–5.5	1.7–2.5	3.0–4.5	0.25	0.20	0.7–1.0	0.05	0.03	0.005	0.005	…
C92220	86.0–88.0(d)	5.0–6.0	1.5–2.5	3.0–5.5	0.25	…	0.50–1.0	…	0.05	…	…	…
C92300	85.0–89.0	7.5–9.0	0.30–1.0	2.5–5.0	0.25	0.25	1.0	0.05	0.05	0.005	0.005	…
C92310	bal	7.5–9.0	0.30–1.5	3.5–4.5	…	…	1.0	…	…	0.005	0.005	0.03
C92400	86.0–89.0	9.0–11.0	1.0–2.5	1.0–3.0	0.25	0.25	1.0	0.05	0.05	0.005	0.005	…
C92410	bal	6.0–8.0	2.5–3.5	1.5–3.0	0.20	0.25	0.20	…	…	0.005	0.005	0.05
C92500	85.0–88.0	10.0–12.0	1.0–1.5	0.50	0.30	0.25	0.8–1.5	0.05	0.30	0.005	0.005	…
C92600	86.0–88.5	9.3–10.5	0.8–1.5	1.3–2.5	0.20	0.25	0.7	0.05	0.03	0.005	0.005	…
C92610	bal	9.5–10.5	0.30–1.5	1.7–2.8	0.15	…	1.0	…	…	0.005	0.005	0.03
C92700	86.0–89.0	9.0–11.0	1.0–2.5	0.7	0.20	0.25	1.0	0.05	0.25	0.005	0.005	…
C92710	bal	9.0–11.0	4.0–6.0	1.0	0.20	0.25	2.0	0.05	0.10	0.005	0.005	…
C92800	78.0–82.0	15.0–17.0	4.0–6.0	0.8	0.20	0.25	0.8	0.05	0.05	0.005	0.005	…
C92810	78.0–82.0	12.0–14.0	4.0–6.0	0.50	0.50	0.25	0.8–1.2	0.05	0.05	0.005	0.005	…
C92900	82.0–86.0	9.0–11.0	2.0–3.2	0.25	0.20	0.25	2.8–4.0	0.05	0.50	0.005	0.005	…

High-leaded tin bronzes

Copper alloy No.	Cu	Sn	Pb	Zn	Fe	Sb	Ni (incl Co)	S	P(f)	Al	Si
C93100	bal(d)(l)	6.5–8.5	2.0–5.0	2.0	0.25	0.25	1.0	0.05	0.30	0.005	0.005
C93200	81.0–85.0(d)(l)	6.3–7.5	6.0–8.0	1.0–4.0	0.20	0.35	1.0	0.08	0.15	0.005	0.005
C93400	82.0–85.0(d)(l)	7.0–9.0	7.0–9.0	0.8	0.20	0.50	1.0	0.08	0.50	0.005	0.005

(continued)

incl, including. bal, balance. (a) Cu + sum of named elements, 99.5% min. (b) Includes Ag. (c) Ni + Co. (d) In determining copper min, copper can be calculated as Cu + Ni. (e) Cu + sum of named elements, 99.3% min. (f) For continuous castings, P will be 1.5%, max. (g) Fe + Sb + As will be 0.50% max. (h) Fe + Sb + As will be 0.8% max. (i) Cu + sum of named elements, 99.1% min. (j) Cu + sum of named elements, 98.9% min. (k) Cu + sum of named elements, 98.7% min. (l) Cu + sum of named elements, 99.0% min. (m) Cu + sum of named elements, 99.2% min. (n) 0.01–2.0% as any single or combination of Ce, La or other rare earth* elements, as agreed upon. *ASM International definition: one of the group of chemically similar metals with atomic numbers 57 through 71, commonly referred to as lanthanides. (o) Bi:Se ≥ 2:1. (p) Cu + sum of named elements, 99.4% min. (q) Cu + sum of named elements, 99.7% min. (r) Fe shall be 0.35% max, when used for steel-backed bearings. (s) For continuous castings, S will be 0.25% max. (t) The mechanical properties of C94700 (heat treated) may not be attainable if the lead content exceeds 0.01%. (u) Cu + sum of named elements, 99.8% min. (v) Fe content shall not exceed Ni content. (w) When the product or casting is intended for subsequent welding applications, and so specified by the purchaser, the Nb content will be 0.40% max. (x) The following additional maximum impurity limits will apply: 0.10% Al, 0.001% B, 0.001% Bi, 0.005–0.15% Mg, 0.005% P, 0.0025% S, 0.02% Sb, 7.5–8.5% Sn, 0.01% Ti, 1.0% Zn. (y) Cu + sum of named elements, 99.6% min. (z) Pb and Ag can be adjusted to modify the alloy hardness. (aa) Includes Co. Source: Copper Development Association

Table 3 (continued)

High-leaded tin bronzes

Copper alloy No.	Cu	Sn	Pb	Zn	Fe	Sb	Ni (incl Co)	S	P(f)	Al	Si
C93500	83.0–86.0(d)(l)	4.3–6.0	8.0–10.0	2.0	0.20	0.30	1.0	0.08	0.05	0.005	0.005
C93600	79.0–83.0(e)	6.0–8.0	11.0–13.0	1.0	0.20	0.55	1.0	0.08	0.15	0.005	0.005
C93700	78.0–82.0(l)	9.0–11.0	8.0–11.0	0.8	0.7(r)	0.50	0.50	0.08	0.10	0.005	0.005
C93720	83.0min(l)	3.5–4.5	7.0–9.0	4.0	0.7	0.50	0.50	…	0.10	…	…
C93800	75.0–79.0(l)	6.3–7.5	13.0–16.0	0.8	0.15	0.8	1.0	0.08	0.05	0.005	0.005
C93900	76.5–79.5(j)	5.0–7.0	14.0–18.0	1.5	0.40	0.50	0.8	0.08	1.5	0.005	0.005
C94000	69.0–72.0(k)	12.0–14.0	14.0–16.0	0.50	0.25	0.50	0.50–1.0	0.08(s)	0.05	0.005	0.005
C94100	72.0–79.0(k)	4.5–6.5	18.0–22.0	1.0	0.25	0.8	1.0	0.08(s)	0.05	0.005	0.005
C94300	67.0–72.0(l)	4.5–6.0	23.0–27.0	0.8	0.15	0.8	1.0	0.08(s)	0.08	0.005	0.005
C94310	bal(l)	1.5–3.0	27.0–34.0	0.50	0.50	0.50	0.25–1.0	…	0.05	…	…
C94320	bal(l)	4.0–7.0	24.0–32.0	…	0.35	…	…	…	…	…	…
C94330	68.5–75.5(l)	3.0–4.0	21.0–25.0	3.0	0.7	0.50	0.50	…	0.10	…	…
C94400	bal(l)	7.0–9.0	9.0–12.0	0.8	0.15	0.8	1.0	0.08	0.50	0.005	0.005
C94500	bal(l)	6.0–8.0	16.0–22.0	1.2	0.15	0.8	1.0	0.08	0.05	0.005	0.005

Nickel-tin bronzes

Copper alloy No.	Cu	Sn	Pb	Zn	Fe	Sb	Ni (incl Co)	Mn	S	P	Al	Si
C94700	85.0–90.0(k)	4.5–6.0	0.10(t)	1.0–2.5	0.25	0.15	4.5–6.0	0.20	0.05	0.05	0.005	0.005
C94800	84.0–89.0(k)	4.5–6.0	0.30–1.0	1.0–2.5	0.25	0.15	4.5–6.0	0.20	0.05	0.05	0.005	0.005
C94900	79.0–81.0(p)	4.0–6.0	4.0–6.0	4.0–6.0	0.30	0.25	4.0–6.0	0.10	0.08	0.05	0.005	0.005

Aluminum bronzes

Copper alloy No.	Cu, min	Pb	Fe	Ni (incl Co)	Al	Mn	Mg	Si	Zn	Sn	Other named elements
C95200	86.0(l)	…	2.5–4.0	…	8.5–9.5	…	…	…	…	…	…
C95210	86.0(l)	0.05	2.5–4.0	1.0	8.5–9.5	1.0	0.05	0.25	0.50	0.10	…
C95220	bal(a)	…	2.5–4.0	2.5	9.5–10.5	0.50	…	…	…	…	…
C95300	86.0(l)	…	0.8–1.5	…	9.0–11.0	…	…	…	…	…	…
C95400	83.0(a)	…	3.0–5.0	1.5	10.0–11.5	0.50	…	…	…	…	…
C95410	83.0(a)	…	3.0–5.0	1.5–2.5	10.0–11.5	0.50	…	…	…	…	…
C95420	83.5(a)	…	3.0–4.3	0.50	10.5–12.0	0.50	…	…	…	…	…
C95500	78.0(a)	…	3.0–5.0	3.0–5.5	10.0–11.5	3.5	…	…	…	…	…
C95510	78.0(u)	…	2.0–3.5	4.5–5.5	9.7–10.9	1.5	…	…	0.30	0.20	…
C95520	74.5(a)	0.03	4.0–5.5	4.2–6.0	10.5–11.5	1.5	…	0.15	0.30	0.25	0.20Co, 0.05Cr
C95600	88.0(l)	…	…	0.25	6.0–8.0	…	…	1.8–3.2	…	…	…
C95700	71.0(a)	…	2.0–4.0	1.5–3.0	7.0–8.5	11.0–14.0	…	0.10	…	…	…
C95710	71.0(a)	0.05	2.0–4.0	1.5–3.0	7.0–8.5	11.0–14.0	…	0.15	0.50	1.0	0.05P
C95720	73.0(a)	0.03	1.5–3.5	3.0–6.0	6.0–8.0	12.0–15.0	…	0.10	0.10	0.10	0.20Cr
C95800	79.0(a)	0.03	3.5–4.5(v)	4.0–5.0(v)	8.5–9.5	0.8–1.5	…	0.10	…	…	…
C95810	79.0(a)	0.10	3.5–4.5(v)	4.0–5.0(v)	8.5–9.5	0.8–1.5	0.05	0.10	0.50	…	…
C95820	77.5(a)	0.02	4.0–5.0	4.5–5.8	9.0–10.0	1.5	…	0.10	0.20	0.20	…
C95900	bal(a)	…	3.0–5.0	0.50	12.0–13.5	1.5	…	…	…	…	…

Copper-nickels

Copper alloy No.	Cu(a)	Pb	Fe	Ni (incl Co)	Mn	Si	Nb	C	Be	Other named elements
C96200	bal	0.01	1.0–1.8	9.0–11.0	1.5	0.50	1.0(w)	0.10	…	0.02S, 0.02P
C96300	bal	0.01	0.50–1.5	18.0–22.0	0.25–1.5	0.50	0.50–1.5	0.15	…	0.02S, 0.02P
C96400	bal	0.01	0.25–1.5	28.0–32.0	1.5	0.50	0.50–1.5	0.15	…	0.02S, 0.02P
C96600	bal	0.01	0.8–1.1	29.0–33.0	1.0	0.15	…	…	0.40–0.7	…
C97600	bal	0.01	0.40–1.0	29.0–33.0	0.40–1.0	0.15	…	…	1.1–1.2	0.15–0.35Zr, 0.15–0.35Ti
C96800	bal	0.005	0.50	9.5–10.5	0.05–0.30	0.05	0.10–0.30	…	…	(x)
C96900	bal	0.02	0.50	14.5–15.5	0.05–0.30	…	0.10	…	…	0.15Mg, 7.5–8.5Sn, 0.50Zn
C96950	bal	0.02	0.50	11.0–15.5	0.05–0.40	0.30	0.10	…	…	5.8–8.5Sn, 0.15Mg

(continued)

incl, including. bal, balance. (a) Cu + sum of named elements, 99.5% min. (b) Includes Ag. (c) Ni + Co. (d) In determining copper min, copper can be calculated as Cu + Ni. (e) Cu + sum of named elements, 99.3% min. (f) For continuous castings, P will be 1.5%, max. (g) Fe + Sb + As will be 0.50% max. (h) Fe + Sb + As will be 0.8% max. (i) Cu + sum of named elements, 99.1% min. (j) Cu + sum of named elements, 98.9% min. (k) Cu + sum of named elements, 98.7% min. (l) Cu + sum of named elements, 99.0% min. (m) Cu + sum of named elements, 99.2% min. (n) 0.01–2.0% as any single or combination of Ce, La or other rare earth* elements, as agreed upon. *ASM International definition: one of the group of chemically similar metals with atomic numbers 57 through 71, commonly referred to as lanthanides. (o) Bi:Se ≥ 2:1. (p) Cu + sum of named elements, 99.4% min. (q) Cu + sum of named elements, 99.7% min. (r) Fe shall be 0.35% max, when used for steel-backed bearings. (s) For continuous castings, S will be 0.25% max. (t) The mechanical properties of C94700 (heat treated) may not be attainable if the lead content exceeds 0.01%. (u) Cu + sum of named elements, 99.8% min. (v) Fe content shall not exceed Ni content. (w) When the product or casting is intended for subsequent welding applications, and so specified by the purchaser, the Nb content will be 0.40% max. (x) The following additional maximum impurity limits will apply: 0.10% Al, 0.001% B, 0.001% Bi, 0.005–0.15% Mg, 0.005% P, 0.0025% S, 0.02% Sb, 7.5–8.5% Sn, 0.01% Ti, 1.0% Zn. (y) Cu + sum of named elements, 99.6% min. (z) Pb and Ag can be adjusted to modify the alloy hardness. (aa) Includes Co. Source: Copper Development Association

Table 3 (continued)

Nickel silvers

Copper alloy No.	Cu	Sn	Pb	Zn	Fe	Sb	Ni (incl Co)	S	P	Al	Mn	Si
C97300	53.0–58.0(l)	1.5–3.0	8.0–11.0	17.0–25.0	1.5	0.35	11.0–14.0	0.08	0.05	0.005	0.50	0.15
C97400	58.0–61.0(l)	2.5–3.5	4.5–5.5	bal	1.5	…	15.5–17.0	…	…	…	0.50	…
C97600	63.0–67.0(q)	3.5–4.5	3.0–5.0	3.0–9.0	1.5	0.25	19.0–21.5	0.08	0.05	0.005	1.0	0.15
C97800	64.0–67.0(y)	4.0–5.5	1.0–2.5	1.0–4.0	1.5	0.20	24.0–27.0	0.08	0.05	0.005	1.0	0.15

Copper-lead alloys

Copper alloy No.	Cu	Sn	Pb	Ag	Zn	P	Fe	NI	Sb
C98200	bal(a)	0.6–2.0	21.0–27.0	…	0.50	0.10	0.7	0.50	0.50
C98400	bal(a)	0.50	26.0–33.0	1.5	0.50	0.10	0.7	0.50	0.50
C98600	60.0–70.0	0.50	30.0–40.0	1.5	…	…	0.35	…	…
C98800	56.5–62.5(b)	0.25	37.5–42.5(z)	5.5(z)	0.10	0.02	0.35	…	…
C98820	bal	1.0–5.0	40.0–44.0	…	…	…	0.35	…	…
C98840	bal	1.0–5.0	44.0–58.0	…	…	…	0.35	…	…

Special alloys

Copper alloy No.	Other designations	Cu(q)	Sn	Pb	Ni	Fe	Al	Co	Si	Mn	Other named elements
C99300	Incramet 800	bal	0.05	0.02	13.5–16.5	0.40–1.0	10.7–11.5	1.0–2.0	0.02	…	…
C99350	…	bal	…	0.15	14.5–16.0(aa)	1.0	9.5–10.5	…	…	0.25	7.5–9.5Zn
C99400	…	bal	…	0.25	1.0–3.5	1.0–3.0	0.50–2.0	…	0.50–2.0	0.50	0.50–5.0Zn
C99500	…	bal	…	0.25	3.5–5.5	3.0–5.0	0.50–2.0	…	0.50–2.0	0.50	0.50–2.0Zn
C99600	Incramute 1	bal	0.10	0.02	0.20	0.20	1.0–2.8	0.20	0.10	39.0–45.0	0.20Zn, 0.05C
C99700	…	54.0 min	1.0	2.0	4.0–6.0	1.0	0.50–3.0	…	…	11.0–15.0	19.0–25.0Zn
C99750	…	55.0–61.0	0.50–2.5	…	5.0	1.0	0.25–3.0	…	…	17.0–23.0	17.0–23.0Zn

incl, including. bal, balance. (a) Cu + sum of named elements, 99.5% min. (b) Includes Ag. (c) Ni + Co. (d) In determining copper min, copper can be calculated as Cu + Ni. (e) Cu + sum of named elements, 99.3% min. (f) For continuous castings, P will be 1.5%, max. (g) Fe + Sb + As will be 0.50% max. (h) Fe + Sb + As will be 0.8% max. (i) Cu + sum of named elements, 99.1% min. (j) Cu + sum of named elements, 98.9% min. (k) Cu + sum of named elements, 98.7% min. (l) Cu + sum of named elements, 99.0% min. (m) Cu + sum of named elements, 99.2% min. (n) 0.01–2.0% as any single or combination of Ce, La or other rare earth* elements, as agreed upon. *ASM International definition: one of the group of chemically similar metals with atomic numbers 57 through 71, commonly referred to as lanthanides. (o) Bi:Se ≥ 2:1. (p) Cu + sum of named elements, 99.4% min. (q) Cu + sum of named elements, 99.7% min. (r) Fe shall be 0.35% max, when used for steel-backed bearings. (s) For continuous castings, S will be 0.25% max. (t) The mechanical properties of C94700 (heat treated) may not be attainable if the lead content exceeds 0.01%. (u) Cu + sum of named elements, 99.8% min. (v) Fe content shall not exceed Ni content. (w) When the product or casting is intended for subsequent welding applications, and so specified by the purchaser, the Nb content will be 0.40% max. (x) The following additional maximum impurity limits will apply: 0.10% Al, 0.001% B, 0.001% Bi, 0.005–0.15% Mg, 0.005% P, 0.0025% S, 0.02% Sb, 7.5–8.5% Sn, 0.01% Ti, 1.0% Zn. (y) Cu + sum of named elements, 99.6% min. (z) Pb and Ag can be adjusted to modify the alloy hardness. (aa) Includes Co. Source: Copper Development Association

Table 4 ASTM B 601 temper designation codes for copper and copper alloys

Temper designation	Temper name or material condition
Cold-worked tempers(a)	
H00	1/8 hard
H01	1/4 hard
H02	1/2 hard
H03	3/4 hard
H04	Hard
H06	Extra hard
H08	Spring
H10	Extra spring
H12	Special spring
H13	Ultra spring
H14	Super spring
Cold worked tempers(b)	
H50	Extruded and drawn
H52	Pierced and drawn
H55	Light drawn; light cold rolled
H58	Drawn general purpose
H60	Cold heading; forming
H63	Rivet
H64	Screw
H66	Bolt
H70	Bending
H80	Hard drawn
H85	Medium-hard-drawn electrical wire
H86	Hard-drawn electrical wire
H90	As finned
Cold worked and stress-relieved tempers	
HR01	H01 and stress relieved
HR02	H02 and stress relieved
HR04	H04 and stress relieved
Cold worked and stress-relieved tempers	
HR06	H06 and stress relieved
HR08	H08 and stress relieved
HR10	H10 and stress relieved
HR20	As finned
HR50	Drawn and stress relieved
Cold rolled and order-strengthened temper(c)	
HT04	H04 and order heat treated
HT08	H08 and order heat treated
As-manufactured tempers	
M01	As-sand cast
M02	As-centrifugal cast
M03	As-plaster case
M04	As-pressure die cast
M05	As-permanent mold cast
M06	As-investment cast
M07	As-continuous cast
M10	As-hot forged and air cooled
M11	As-forged and quenched
M20	As-hot rolled
M25	As-hot rolled and rerolled
M30	As-hot extruded
M40	As-hot pierced
M45	As-hot pierced and rerolled
Annealed tempers(d)	
O10	Cast and annealed (homogenized)
O11	As-cast and precipitation heat treated
O20	Hot forged and annealed
O25	Hot rolled and annealed

(continued)

(a) Cold-worked tempers to meet standard requirements based on cold rolling or cold drawing. (b) Cold-worked tempers to meet standard requirements based on temper names applicable to specific products. (c) Tempers produced by controlled amounts of cold work followed by a thermal treatment to produce order strengthening. (d) Annealed to meet specific mechanical property requirements. (e) Annealed to meet prescribed nominal average grain size. (f) Tempers of heat-treated materials as supplied by the mill resulting from combinations of cold work and precipitation heat treatment or spinodal heat treatment. (g) Tempers to meet standard requirements based on cold rolling or cold drawing. (h) Tempers of fully finished tubing that has been drawn or annealed to produce specified mechanical properties or that has been annealed to produce a prescribed nominal average grain size are commonly identified by the appropriate H, O, or OS temper designation

Table 4 (continued)

Temper designation	Temper name or material condition
Annealed tempers(d)	
O30	Hot extruded and annealed
O31	Extruded and precipitation heat treated
O40	Hot pierced and annealed
O50	Light annealed
O60	Soft annealed
O61	Annealed
O65	Drawing annealed
O68	Deep-drawing annealed
O70	Dead-soft annealed
O80	Annealed to temper, 1/8 hard
O81	Annealed to temper, 1/4 hard
O82	Annealed to temper, 1/2 hard
Annealed tempers(e)	
OS005	Average grain size, 0.005 mm
OS010	Average grain size, 0.010 mm
OS015	Average grain size, 0.015 mm
OS025	Average grain size, 0.025 mm
OS035	Average grain size, 0.035 mm
OS045	Average grain size, 0.045 mm
OS050	Average grain size, 0.050 mm
OS060	Average grain size, 0.060 mm
OS065	Average grain size, 0.065 mm
OS070	Average grain size, 0.070 mm
OS100	Average grain size, 0.100 mm
OS120	Average grain size, 0.120 mm
OS150	Average grain size, 0.150 mm
OS200	Average grain size, 0.200 mm
Solution-treated temper	
TB00	Solution heat treated
Solution-treated and cold-worked tempers	
TD00	TB00 cold worked to 1/8 hard
TD01	TB00 cold worked to 1/4 hard
TD02	TB00 cold worked to 1/2 hard
TD03	TB00 cold worked to 3/4 hard
TD04	TB00 cold worked to full hard
Solution-treated and precipitation-hardened temper	
TF00	TB00 and precipitation hardened
TF01	TB00 and precipitation-hardened plate–low hardness
TF02	TB00 and precipitation-hardened plate–high hardness
Cold-worked and precipitation-hardened tempers	
TH01	TD01 and precipitation hardened
TH02	TD02 and precipitation hardened
TH03	TD03 and precipitation hardened
TH04	TD04 and precipitation hardened
Precipitation-hardened or spinodal-heat-treated and cold-worked tempers	
TL00	TF00 cold worked to 1/8 hard
TL01	TF00 cold worked to 1/4 hard
TL02	TF00 cold worked to 1/2 hard
TL04	TF00 cold worked to full hard
TL08	TF00 cold worked to spring
TL10	TF00 cold worked to extra spring
Mill-hardened tempers(f)	
TM00	AM
TM01	1/4 HM
TM02	1/2 HM
TM03	3/4 HM
TM04	HM
TM06	XHM
TM08	XHMS
Quench-hardened tempers	
TQ00	Quench hardened
TQ30	Quench hardened and tempered
TQ50	Quench hardened and temper annealed
TQ55	Quench hardened and temper annealed, cold drawn and stress relieved
TQ75	Interrupted quench hardened
Precipitation-hardened or spinodal-heat-treated, cold-worked, and thermal-stress-relieved tempers	
TR01	TL01 and stress relieved
TR02	TL02 and stress relieved
TR04	TL04 and stress relieved
Solution-treated, cold-worked, and spinodal-heat-treated tempers(g)	
TS00	1/8 hard and spinodal hardened
TS01	1/4 hard and spinodal hardened
TS02	1/2 hard and spinodal hardened
TS03	3/4 hard and spinodal hardened
TS04	Hard and spinodal hardened
TS06	Extra hard and spinodal hardened
TS08	Spring and spinodal hardened
TS10	Extra spring and spinodal hardened
TS12	Special spring and spinodal hardened
TS13	Ultra spring and spinodal hardened
TS14	Super spring and spinodal hardened
Solution-treated and spinodal-heat-treated temper	
TX00	Spinodal hardened
Tempers of welded tubing(h)	
WH00	Welded and drawn to 1/8 hard
WH01	Welded and drawn to 1/4 hard
WH02	Welded and drawn to 1/2 hard
WH03	Welded and drawn to 3/4 hard
WH04	Welded and drawn to full hard
WH06	Welded and drawn to extra hard
WH55	Welded and cold reduced or light drawn
WH58	Welded and cold reduced or light drawn–general purpose
WH80	Welded and reduced or hard drawn
WM00	As welded from H00 (1/8-hard) strip
WM01	As welded from H01 (1/4-hard) strip
WM02	As welded from H02 (1/2-hard) strip
WM03	As welded from H03 (3/4-hard) strip
WM04	As welded from H04 (full-hard) strip
WM06	As welded from H06 (extra-hard) strip
WM08	As welded from H08 (spring) strip
WM10	As welded from H10 (extra-spring) strip
WM15	WM50 and stress relieved
WM20	WM00 and stress relieved
WM21	WM01 and stress relieved
WM22	WM02 and stress relieved
WM50	As welded from annealed strip
WO50	Welded and light annealed
WO60	Welded and soft annealed
WO61	Welded and annealed
WR00	WM00; drawn and stress relieved
WR01	WM01; drawn and stress relieved
WR02	WM02; drawn and stress relieved
WR03	WM03; drawn and stress relieved
WR04	WM04; drawn and stress relieved
WR06	WM06; drawn and stress relieved

(a) Cold-worked tempers to meet standard requirements based on cold rolling or cold drawing. (b) Cold-worked tempers to meet standard requirements based on temper names applicable to specific products. (c) Tempers produced by controlled amounts of cold work followed by a thermal treatment to produce order strengthening. (d) Annealed to meet specific mechanical property requirements. (e) Annealed to meet prescribed nominal average grain size. (f) Tempers of heat-treated materials as supplied by the mill resulting from combinations of cold work and precipitation heat treatment or spinodal heat treatment. (g) Tempers to meet standard requirements based on cold rolling or cold drawing. (h) Tempers of fully finished tubing that has been drawn or annealed to produce specified mechanical properties or that has been annealed to produce a prescribed nominal average grain size are commonly identified by the appropriate H, O, or OS temper designation

International Alloy and Temper Designations

International Alloy Designations. A common designation system used within the International Organization for Standardization (ISO) is a compositional system described in ISO 1190 Part 1, based on the element symbols and the descending order of magnitude of alloying elements. For example, a leaded brass containing 60% Cu and 2% Pb is designated CuZn38Pb2. Because this system is unwieldy when used to describe complex alloys, a European numbering system has been formulated by the Comité Européen de Normalisation (CEN). CEN/TC 132 describes a six-digit alpha-numerical system. The first letter, "C," indicates a copper alloy. A second letter was introduced to indicate the material state (i.e., "W" for a wrought material, "C" for castings, and "M" for master alloys). Three numbers are then used to identify the material, and final third letter is used to identify the classification of individual copper material groups and to enlarge the capacity of the designation system. A summary of the preferred number ranges and letters allocated by the CEN numbering system to the different copper alloy groups is shown in Table 5.

Tables 6 and 7 cross reference some International Organization for Standardization (ISO), British Standard, Comité Européen de Normalisation (CEN), and near-equivalent UNS designations. Additional information on international designation systems for coppers and copper alloys is available from the CDA.

International Temper Designations. For temper designations, CEN/TC 133 covering copper and copper alloys has agreed to use a system similar to that already established by Deutsches Institut für Normung (DIN) indicating the minimum value of specified properties. Letter symbols for property designations are as follows:

A	Elongation
B	Spring bending limit
G	Grain size
H	Hardness (HB for castings, HV for wrought products)
M	As-manufactured, that is,without specified mechanical properties
R	Tensile strength
Y	0.2% proof stress (yield strength)

For example, tensile strength R250 indicates the minimum of 250 MPa (36 ksi), a hardness of H090 indicates a value of 90 (Vickers for wrought materials and Brinell for cast), and Y140 indicates a 0.2% proof stress of 140 MPa (20 ksi). This designation system meets the requirements of the wide variety of customers who have individual needs for special properties to ensure fitness for purpose, but do not need to know the way in which a temper was originally produced.

Table 5 Summary of preferred designators for copper alloys in the Comité Européen de Normalisation system

Material groups	Number ranges available for positions 3, 4, and 5	Final letter, designating material group	Number range allocated to materials preferred by CEN
Copper	001–999	A	001–049A
	001–999	B	050–099B
Miscellaneous copper alloys	001–999	C	100–149C
	001–999	D	150–199D
	001–999	E	200–249E
	001–999	F	250–299F
Copper-aluminum alloys	001–999	G	300–349G
Copper-nickel alloys	001–999	H	350–399H
Copper-nickel-zinc alloys	001–999	J	400–449J
Copper-tin alloys	001–999	K	459–499K
Copper-zinc alloys, binary	001–999	L	500–549L
	001–999	M	550–599M
Copper-zinc-lead alloys	001–999	N	600–649N
	001–999	P	650–699P
Copper-zinc alloys, complex	001–999	R	700–749R
	001–999		750–799S
Copper material not standardized by CEN/TC 133	800–999	A-S(a)	800–999(a)

(a) Letter as appropriate for the material group

Table 6 Cross-reference for ISO, British Standard, CEN, and UNS wrought copper and copper alloy designations

ISO	British Standard	CEN	UNS
Coppers			
Cu-ETP1	C100	CW003A	…
Cu-ETP	C101	CW004A	C11000
Cu-Ag(0.04)	C101	CW011A	…
Cu-Ag(0.07)	…	CW012A	…
Cu-Ag(0.10)	…	CW013A	…
Cu-FRHC	C102	CW005A	C11020
Cu-HCP	…	CW021A	…
Cu-DLP	…	CW023A	C12000
Cu-FRTP	C104	CW006A	C12500
CuAs	C105	…	…
Cu-DHP	C106	CW024A	C12200
CuAsP	C107	…	C14200
Cu-Ag(0.04P)	…	CW014A	…
Cu-Ag(0.07P)	…	CW015A	…
Cu-Ag(0.10P)	…	CW016A	…
Cu-OF1	…	CW007A	…
Cu-OF	C103	CW008A	C10200
Cu-OFE	C110	CW009A	C10100
Cu-OFS	C103	…	…
Cu-PHCE	…	CW022A	…
High-alloy coppers			
CuCd1	C108	…	C16200
CuCdSn	…	…	…
CuCr1	CC101	CW105C	C18200
CuCr1Zr	CC102	CW106C	…
CuNi1Si	…	CW109C	C19010
CuNi2Si	…	CW111C	C70250
CuNi3Si1	…	CW112C	C70320
CuNi4AlSi	…	…	…
CuNi1P	C113	CW108C	…
CuBe1.7	…	CW100C	…
CuBe2	CB101	CW101C	C17200
CuBe2CoNi	…	…	…
CuBe2Pb	…	CW102C	C17300
CuNi2Be	…	CW110C	C17510
CuCo2Be	C112	CW104C	C17500
CuCo1Ni1Be	…	CW103C	…
CuZr	…	CW120C	C15000
CuSi1	…	CW115C	C65100
CuSi3Mn1	CS101	CW116C	C65500
CuSn0.15	…	CW117C	…

(continued)

Source: Copper Development Association

Table 6 (continued)

ISO	British Standard	CEN	UNS
High-alloy coppers			
CuTeP	C109	CW118C	C14500
CuSP	C111	CW114C	C14700
CuPb1P	…	CW113C	C18700
Brasses (Cu-Zn alloys)			
CuZn5	CZ125	CW500L	C21000
CuZn10	CZ101	CW501L	C22000
CuZn15	CZ102	CW502L	C23000
CuZn20	CZ103	CW503L	C24000
CuZn28	…	CW504L	…
CuZn30	CZ106	CW505L	C26000
CuZn33	…	CW506L	C26800
CuZn35	…	…	C27000
CuZn36	CZ107	CW507L	C27200
CuZn37	CZ108	CW508L	C27400
CuZn40	CZ109	CW509L	C28000
Leaded brasses			
CuZn9Pb2	…	…	C31400
CuZn20Pb	CZ104	…	…
CuZn35Pb1	CZ118	CW600N	C34000
CuZn35Pb2	CZ119	CW601N	C34200
CuZn36Pb3	CZ124	CW603N	C36000
CuZn36Pb2As	CZ132	CW602N	…
CuZn37Pb0.5	…	CW604N	C33500
CuZn37Pb1	…	CW605N	C35000
CuZn37Pb2	CZ131	CW606N	C35300
CuZn38Pb1	CZ129	CW607N	C35000
CuZn38Pb2	CZ128	CW608N	C37700
CuZn38Pb4	CZ121-Pb4	CW609N	…
CuZn39Pb0.5	CZ137	CW610N	C36500
CuZn39Pb1	CZ129	CW611N	C37100
CuZn39Pb2	CZ120	CW612N	C37700
CuZn39Pb2Sn	…	CW613N	C48500
CuZn39Pb3	CZ121-Pb3	CW614N	C38500
CuZn39Pb3Sn	…	CW615N	…
CuZn40Pb	CZ123	…	…
CuZn40Pb2	CZ122	CW617N	C38010
CuZn40Pb2Sn	…	CW619N	…
CuZn43Pb2	CZ130	CW623N	…
CuZn40Pb1Al	…	CW616N	…
CuZn40Pb2Al	…	CW618N	…
CuZn41Pb1Al	…	CW620N	…
CuZn42PbAl	…	CW621N	…
CuZn43Pb1Al	…	CW622N	C38000
CuZn43Pb2Al	CZ130	CW624N	…
Special copper-zinc alloys			
CuZn13AlNiSi	CZ127	CW700R	…
CuZn19Sn	…	CW701R	C43500
CuZn23Al3Co	…	CW703R	…
CuZn28Sn1Al	CZ111	…	…
CuZn20Al2As	CZ110	CW702R	…
CuZn29As	CZ105	…	…
CuZn30As	CZ126	CW707R	…
CuZn31Si1	…	CW708R	…
CuZn32Pb2AsFeSi	…	CW709R	…
CuZn36Pb2Sn1	CZ134	CW711R	C48400
CuZn37Pb1Sn1	…	CW714R	C48200
CuZn38Sn1	CZ112	…	…
CuZn38Sn1As	…	CW717R	…
CuZn39Sn1	CZ133	CW719R	C46400
CuZn36Sn1Pb	…	CW712R	C48200
CuZn39Mn1AlPbSi	…	CW718R	…
CuZn37Mn3Al2PbSi	CZ135	CW713R	C67420
CuZn40Mn1Pb1	CZ136	CW720R	…
CuZn38Mn1Al	…	CW716R	…
CuZn38AlFeNiPbSn	…	CW715R	…
Special copper-zinc alloys			
CuZn40Mn1Pb1AlFeSn	CZ114	CW721R	…
CuZn40Mn1Pb1FeSn	CZ115	CW722R	…
CuZn40Mn2Fe1	…	CW723R	…
CuZn35Ni3Mn2AlPb	…	CW710R	…
CuZn25Al5Fe2Mn2Pb	CZ116	CW705R	C67000
Nickel silvers			
CuNi10Zn27	NS103	CW401J	C74500
CuNi10Zn28Pb1	NS111	…	…
CuNi12Zn24	NS104	CW403J	C75700
CuNi12Zn25Pb1	…	CW404J	C79200
CuNi12Zn29	…	CW405J	…
CuNi12Zn30Pb1	…	CW406J	C79000
CuNi14Zn44Pb	NS102	…	…
CuNi15Zn21	NS105	…	…
CuNi18Zn20	NS106	CW409J	C75200
CuNi18Zn19Pb1	NS113	CW408J	C67300
CuNi18Zn27	NS107	CW410J	C77000
CuNi20Zn17	NS108	…	…
CuNi25Zn18	NS109	…	…
CuNi7Zn39Pb3Mn2	…	CW400J	…
CuNi10Zn42Pb2	NS101	CW402J	C79830
CuNi12Zn38Mn5Pb2	…	CW407J	…
Copper-tin alloys			
CuSn4	PB101	CW450K	C51100
CuSn4TeP	…	CW457K	…
CuSn4Pb2P	…	CW455K	C53200
CuSn4Pb4Zn4	…	CW456L	…
CuSn5	PB102	CW451K	C51000
CuSn5PB1	…	CW458K	C53400
CuSn5Te	…	…	…
CuSn6	PB103	CW452K	C51900
CuSn8	…	CW453K	…
CuSn8P	PB104	CW459K	C52100
CuSn3Zn9	…	CW454K	…
Copper-nickel alloys			
CuNi5Fe	CN101	…	C70400
CuNiSn	…	…	…
CuNi9Sn2	…	CW351H	C72500
CuNi10Fe1Mn	CN102	CW352H	C70600
CuNi15	CN103	…	C70900
CuNi20	CN104	…	C71000
CuNi25	CN105	CW350H	C71300
CuNi30Mn1Fe	CN107	CW354H	C71500
CuNi30Fe2Mn2	CN108	CW353H	C71640
CuNi45	…	…	…
Copper-aluminum alloys (aluminum bronzes)			
CuAl5	CA101	…	…
CuAl6Si2Fe	CA107	CW301G	…
CuAl7Si2	…	CW302G	C64200
CuAl7	CA102	…	C61400
CuAl7Fe3	…	…	…
CuAl8Fe3	CA106	CW303G	C62300
CuAl9	CA103	…	…
CuAl9Pb	…	…	…
CuAl9Ni3Fe2	…	CW304G	…
CuAl9Fe2Ni2Mn2	…	…	…
CuAl10Fe1	…	CW305G	C61800
CuAl10Fe3Mn2	…	CW306G	…
CuAl10Ni5Fe4	CA104	CW307G	C63000
CuAl10Fe3Ni7Mn2	CA105	…	…
CuAl10Fe3Ni5Mn2	…	…	…
CuAl10Fe5Ni5Mn2	…	…	…
CuAl11Fe6Ni6	…	CW308G	…
CuMn12Al8Fe3Ni2	…	…	…

Source: Copper Development Association

Table 7 Cross-reference for ISO, British Standard, CEN, and UNS cast copper and copper alloy designations

ISO	British Standard	CEN	UNS
High-conductivity coppers			
Cu-C	HCC1	CC040A	…
G-CuSn	…	…	…
CuCr1-C	CC1-TF	CC140C	…
G-CuNiP	…	…	…
G-CuNi2Si	…	…	…
G-CuCo2Be	…	…	…
G-CuBe	…	…	…
Brasses (Cu-Zn alloys)			
CuZn15As-C	SCB6	CC760S	…
G-CuSn25Pb3Sn2	SCB1	…	C85200
CuZn33Pb2-C	SCB3	CC750S	…
G-CuZn36Sn	SCB4	…	…
CuZn39Pb1Al-C	DCB3	CC754S	C85700
CuZn39Pb1AlB-C (fine grained)	DCB3a	CC755S	C85700
G-CuZn40PB	PCB1	…	…
CuZn38Al-C	DCB1	CC767S	C85700
CuZn37Al1-C	…	CC766S	…
CuZn35Pb2Al-C(As 0.15)	DZR1	CC752S	…
CuZn33Pb2Si-C	DZR2	CC751S	…
CuZn37Pb2Ni1AlFe-C	…	CC753S	…
Special copper-zinc alloys (high tensile brasses)			
CuZn35Mn2Al1Fe1-C	HTB1	CC765S	C86400
CuZn32Al2Mn2Fe1-C	HTB1 (Pb)	CC763S	C86700
CuZn34Mn3Al2Fe1-C	…	CC764S	…
CuZn25Al5Mn4Fe3-C	HTB3	CC762S	C86200
CuZn37Pb2Ni1AlFe-C	…	CC753S	…
CuZn16Si4-C	…	CC761S	C87400
Copper-tin-phosphorus alloys			
CuSn11P-C	PB1	CC481K	…
G-CuSn11	CT1	…	…
CuSn10-C	…	CC480K	…
CuSn12-C	PB2	CC483K	…
CuSn12Ni-C	CT2	CC484K	C91700
Copper-tin-phosphorus alloys			
CuSn11Pb2-C	PB4	CC482K	C92700
G-CuSn8Pb4Zn1	LPB1	…	C93100
Copper-tin-lead alloys (leaded bronzes)			
CuSn5Pb9-C	LB4	CC494K	C93500
CuSn10Pb10-C	LB2	CC495K	C93700
CuSn7Pb15-C	LB1	CC496K	C93800
CuSn5Pb20-C	LB5	CC497L	C94300
Copper-tin-zinc-lead alloys (gunmetals)			
G-CuSn10Zn2	G1	…	C90200
G-CuSn8Zn4Pb	G2	…	C90300
G-CuSn7Ni5Zn3	G3	…	…
CuSn3Zn8Pb5-C	LG1	CC490K	C83800
CuSn5Zn5Pb5-C	LG2	CC491K	C83600
G-CuSn7Pb4Zn2	LG3	…	C92200
CuSn7Zn2Pb3-C	LG4	CC492K	…
CuSn7Zn4Pb7-C	…	CC493L	…
Copper-nickel alloys			
CuNi30Cr2FeMnSi-C	CN1	CC382H	…
CuNi30Fe1Mn1NbSi-C	CN2	CC383H	…
CuNi10Fe1Mn1-C	…	CC380H	…
CuNi30Fe1Mn1-C	…	CC381H	…
Copper-aluminum alloys (aluminum bronzes)			
CuAl9-C	…	CC330G	…
G-CuAl9Fe2Mn3	…	…	…
CuAl10Fe2-C	AB1	CC331G	C95200
CuAl10Ni3Fe2-C	…	CC332G	…
CuAl10Fe5Ni5-C	AB2	CC333G	C95500
G-CuAl6Si2Fe	AB3	…	…
G-CuAl11Fe5Ni5Mn2	…	…	…
CuAl11Fe6Ni6-C	…	CC334G	…
CuMn11Al8Fe3Ni3-C	CMA1	CC212E	…
G-CuMn13Al9Fe3Ni3	CMA2	…	…

Source: Copper Development Association

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Physical Metallurgy: Heat Treatment, Structure, and Properties

COPPER AND COPPER ALLOYS have a wide range of properties that account for their extensive use as engineering materials. As described in the article "Introduction and Overview" in this Handbook, their high electrical and thermal conductivity, ease of fabrication, and excellent corrosion resistance under certain conditions are three characteristics that make them attractive.

The most common use of copper is in applications requiring high electrical conductivity, and the reason that this element (or its alloys) is preferred is illustrated in Table 1. (Although silver has a slight advantage over copper in this respect, it is more expensive.) Attaining high conductivity requires the use of copper in the "pure" form, and therefore in this article commercially pure copper is discussed first. Because the electrical conductivity of copper is very impurity-sensitive, considerable attention is paid to the effects of minor amounts of other elements present. The brasses, copper-zinc alloys that are essentially noted for their formability, are then discussed. The bronzes—copper-tin and copper-aluminum alloys—are described next, and finally the age-hardening copper-beryllium alloys are addressed. Although there are many other copper-base alloys of importance, the alloy systems chosen for close examination serve well to demonstrate the variety of alloys available and the principles of physical metallurgy associated with copper-base alloys.

A comment about the use of the terms "brass" and "bronze" is in order here. Generally, brass means copper-zinc alloys. However, bronze is used to describe many different copper-base alloys, and an attempt is sometimes made to distinguish them (e.g., aluminum bronze, a Cu-Al alloy). In any case, it is difficult to employ the two terms, brass and bronze, without being very careful to modify them when referring to specific alloys. Therefore, in this article, these terms are not employed extensively.

Commercially Pure Copper

There are several grades of commercially pure copper, the variety reflecting mainly the need for high-electrical conductivity but with other properties. For example, solid-solution elements will strengthen pure copper but lower the electrical conductivity; thus, some alloys have a chemical composition that strives for a balance between these two effects. In this section, only three commercially pure copper alloys, which are widely used mainly for their high electrical conductivity, are examined in some detail: deoxidized copper, oxygen-free copper, and tough pitch copper.

Any disturbance of the periodicity of the copper lattice will scatter electrons and hence decrease the electrical conductivity. Solute elements in the copper lattice, with their different atomic size, cause locally elastically strained regions and hence decrease conductivity. This is the major effect of impurities. However, if the second element combines with the copper to form a second phase (e.g., Cu_2O), then the presence of this second phase usually reduces the conductivity mainly because there is less volume of the copper to carry the current. This effect is not as important as when the second element is in solid solution.

Effect of Impurities on Conductivity. Figure 1 shows the effect of various solutes on the resistivity of copper. Note that silver, lead, zinc, and cadmium increase the resistivity/decrease the conductivity only slightly, whereas phosphorus has a potent effect. Note also that these curves cover the range up to only 0.1 wt%, showing that the impurity levels of importance are quite low. Now, in the manufacture of pure copper from the ore, these elements are present from the ore itself, and most are reduced to acceptable levels, usually by selective oxidation. That is, most of these elements have a greater affinity for oxygen than for copper, and hence in liquid copper will react with oxygen more readily than with copper, forming oxides that are transferred to a slag layer that is immiscible with the liquid copper. Once these elements are

Table 1 Electrical and thermal conductivity of copper and several other commercially pure metals at 20 °C (68 °F)

Metal	Relative electrical conductivity (copper = 100)	Relative thermal conductivity (copper = 100)
Silver	106	108
Copper	100	100
Gold	72	76
Aluminum	62	56
Magnesium	39	41
Zinc	29	29
Nickel	25	15
Cadmium	23	24
Cobalt	18	17
Iron	17	17
Steel	13–17	13–17
Platinum	16	18
Tin	15	17
Lead	8	9
Antimony	4.5	5

Source: Ref 1

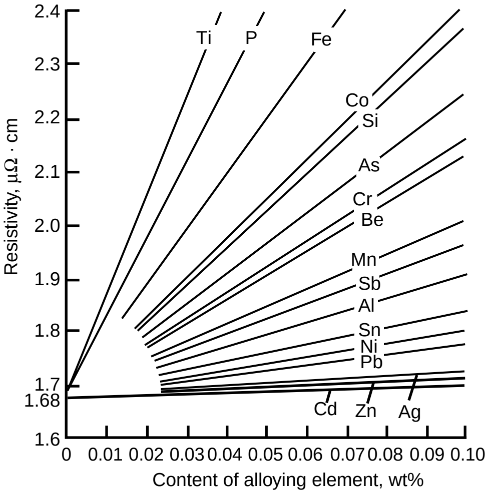

Fig. 1 Effects of alloying elements on electrical resistivity of copper. Note: an increase in resistivity, ρ, is equivalent to a decrease in electrical conductivity, σ, because the electrical conductivity of a material is simply the reciprocal of the resistivity, or σ = 1/ρ. Source: Ref 2

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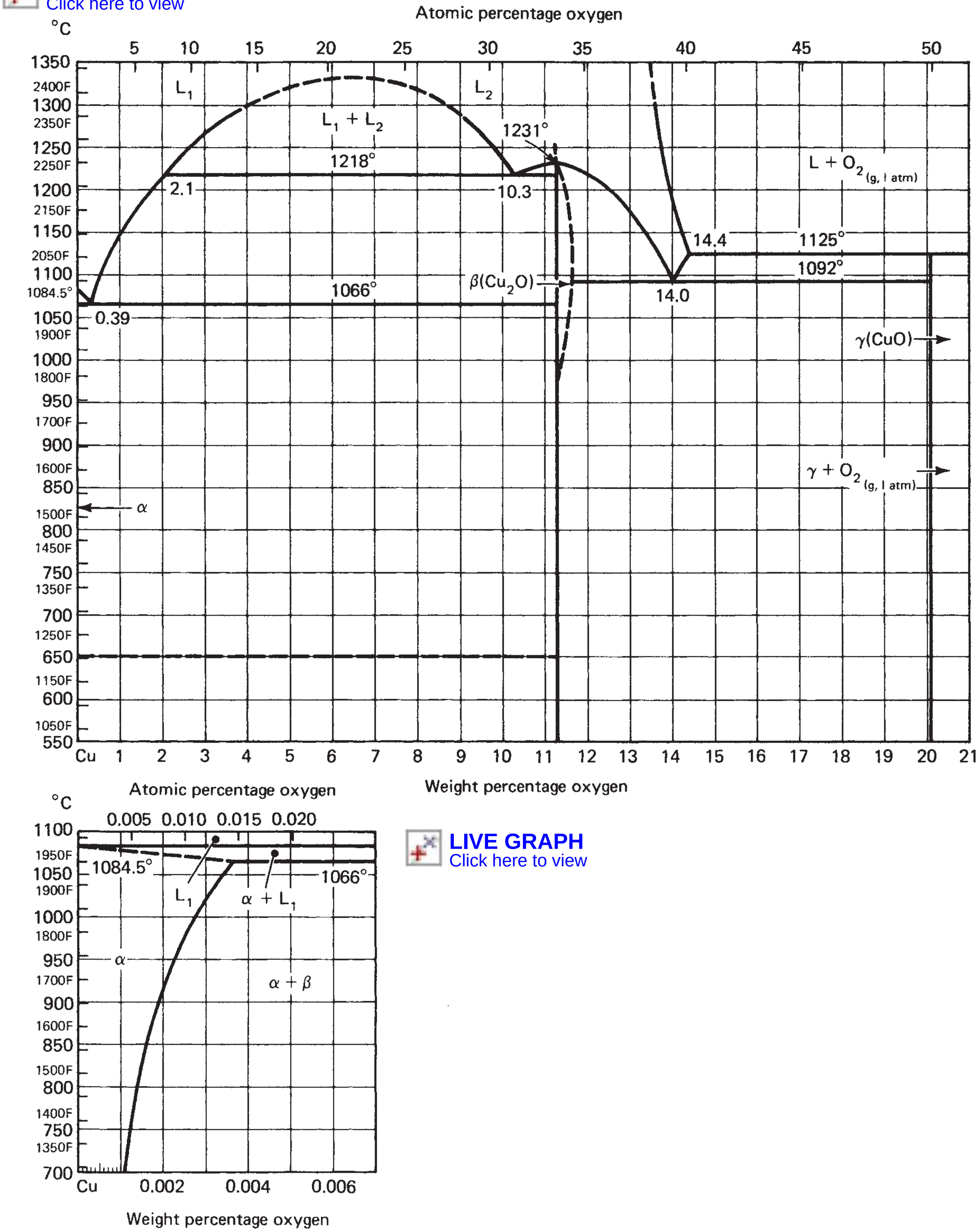

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Fig. 2 The copper-oxygen phase diagram. See text for details.

reduced to low values, then oxygen will be present in the liquid copper. Upon solidification, this oxygen has an effect on the conductivity, and hence it must be contended with.

The copper-oxygen phase diagram is shown in Fig. 2. In the range of interest, the alloys undergo an eutectic reaction, forming upon cooling the copper-rich terminal solid solution (α) and the oxide Cu_2O. Note that in the solid state the solubility of oxygen is quite low, so that invariably most of the oxygen is in the oxide. The eutectic composition is 0.39% O.

In the as-cast condition, the structure, if the oxygen content is below 0.39%, will consist of primary α crystals showing coring and eutectic solid. Figure 3 shows typical microstructures. After extensive plastic deformation and annealing, the eutectic structure loses its identity, and the oxides may appear as elongated inclusions, as shown in Fig. 4. The effect of these oxide inclusions on mechanical properties is slight, as shown in Fig. 5. Here the effects of cold working and of subsequent annealing on tensile-mechanical properties and on hardness show lit-

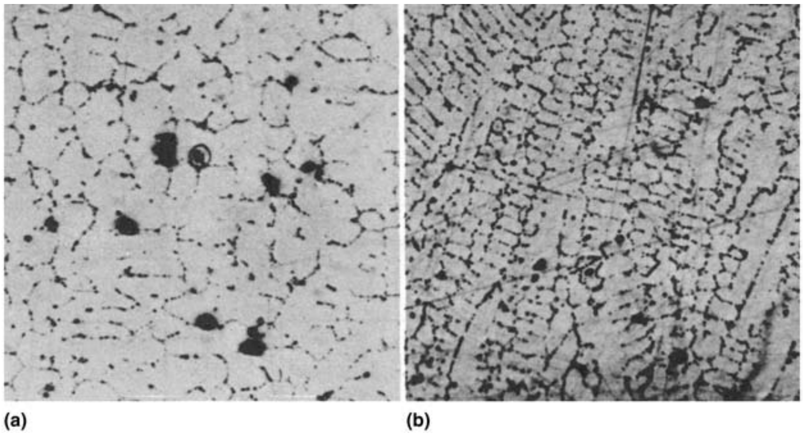

Fig. 3 Microstructures typical of as-cast copper-oxygen alloys. The light areas are the copper dendrite cells, outlined by the dark Cu-Cu_2O eutectic network. The larger black regions are shrinkage voids. (a) 0.05% O. (b) 0.09% O. Both as polished (not etched); 100×

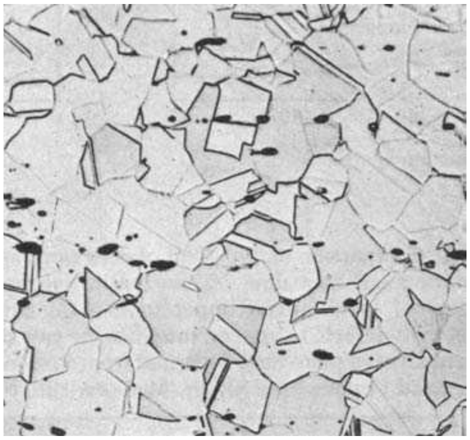

Fig. 4 Microstructure typical of wrought and then annealed copper-oxygen alloys. This is electrolytic tough pitch copper that has been hot rolled. The dark particles are Cu_2O inclusions. 250×

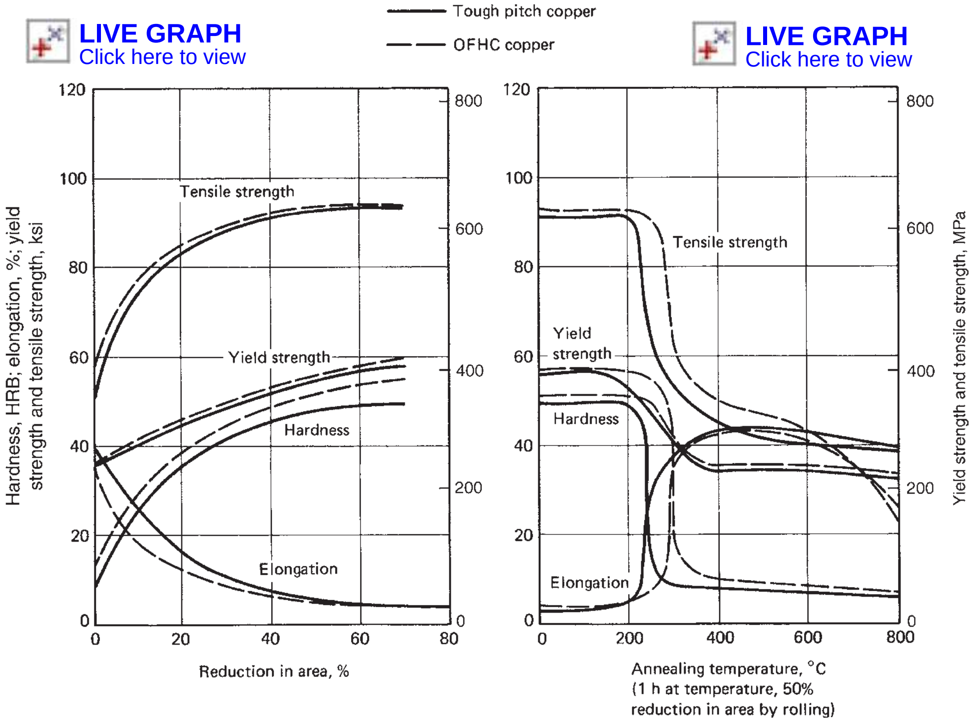

Fig. 5 Comparison of the effect of cold working (by rolling at 25 °C, or 75 °F) and subsequent annealing on the tensile mechanical properties and hardness of tough pitch copper (0.05% O) and oxygen-free, high-conductivity (OFHC) copper. Note that the two materials are affected in essentially the same way. Source: Ref 3

tle difference between tough pitch copper with about 0.05% O and oxygen-free, high-conductivity copper with essentially no oxygen. (These two grades of copper are discussed shortly.) Figure 6 shows that increasing the amount of Cu_2O does lower the impact energy, although the material remains relatively tough. However, where extensive plastic deformation is required in fabrication, a copper containing lower oxygen may have to be used.

The grades of commercially pure copper available are related to the refining processes used. The most common practice is to take concentrated copper sulfides and pass oxygen (usually as air) through the molten material, effecting separation of an impure copper product known as *blister copper*. This product contains sufficient impurities that it must be further refined to obtain usable industrial copper. One method is to melt the blister copper and further oxidize the molten copper to remove most impurities to an immiscible liquid slag or to vaporize them. This method is usable because of the greater affinity of the impurities for the oxygen dissolved in the liquid copper than for the copper itself. To effect removal of these elements to a sufficiently low value, however, requires using excess oxygen, so after these impurities are lowered to an acceptable level, oxygen remains dissolved in the liquid copper and may also be present as Cu_2O if the solubility of oxygen is exceeded (Fig. 2). Thus, the oxygen must then be lowered to an acceptable level. This is accomplished by the use of reducing gases, which convert the dissolved oxygen to gaseous oxides and reduce the Cu_2O back to copper. If only pure copper remains, shrinkage during solidification leaves a depression on the surface of a test ingot. However, if some oxygen is present, Cu_2O forms during solidification, along with the low oxygen content copper (α). (See the phase diagram in Fig. 2.) The oxide has a density of about 6 g/cm^3 compared to ~9 g/cm^3 for pure copper, and hence when the copper-oxygen liquid freezes, less contraction occurs than if the liquid were pure copper. That is, the formation of the less-dense oxide compensates partially for the volume decrease when the solid copper forms from the liquid. In addition, some dissolved hydrogen is released and also compensates for contraction. If the test ingot shows little shrinkage of the surface upon freezing, then the copper is called *tough pitch*. The oxygen content is about 0.05%, nearly all present in the solidified copper as Cu_2O (about 0.5% Cu_2O present). Note from the phase diagram shown in Fig. 2 that 0.05% O will give upon solidification primary α (almost pure copper) and a small amount of eutectic solid consisting of α and Cu_2O. This is shown in the microstructures in Fig. 3.

If oxygen-bearing copper is heated above approximately 400 °C (750 °F) in a hydrogen-containing atmosphere (or in some cases other reducing gases), the hydrogen dissolves readily in the copper and then diffuses rapidly. On encountering the Cu_2O particles, the following reaction occurs:

$$\underset{\substack{\text{(dissolved}\\\text{in copper}\\\text{lattice)}}}{2\,\underline{\mathrm{H}}} + \mathrm{Cu_2O} \leftrightarrow 2\,\mathrm{Cu} + \underset{\text{(gas)}}{\mathrm{H_2O}}$$

The H_2O molecules formed combine readily into gas (steam) pockets, as these molecules are

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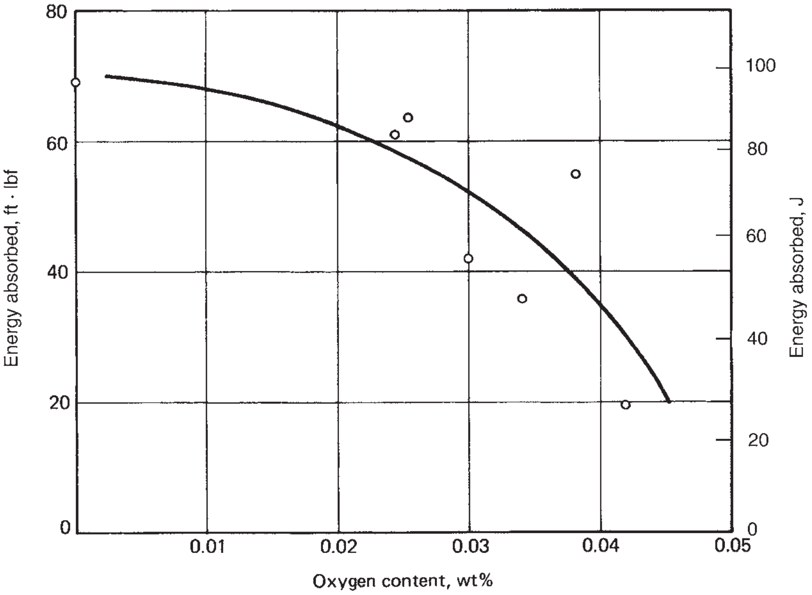

Fig. 6 Average Charpy impact energy at 20 °C (68 °F) for electrolytic tough pitch copper of different oxygen contents. The datum at zero oxygen is for oxygen-free copper. Source: Ref 4

insoluble in the copper. This leaves a porous structure, and the strength is reduced drastically. Thus, in manufacturing copper tubing and pipe, if annealing is to be in hydrogen to reduce oxidation, tough pitch copper cannot be used. Figure 7 is a microstructure showing void formation due to heating in hydrogen.

There are two important reasons why tough pitch copper with the Cu_2O particles is undesirable: such copper cannot be used in reducing gases at elevated temperatures, and fabrication, especially by cold working, may be difficult. One method of reducing the oxygen content is to add to the molten copper an element that has a greater affinity for oxygen than for copper. One element commonly used is phosphorus. In the molten state, it will readily react with essentially all of the dissolved oxygen to form phosphorus oxide, which will pass into the immiscible slag. It is difficult, however, to control the reaction so that the amount of phosphorus added is just sufficient to combine with the oxygen but not leave any unreacted phosphorus dissolved in the copper. A practical compromise must be made, and this leads to the presence of some excess phosphorus, which then after solidification shows up dissolved in the solid copper lattice. There are different grades of phosphorus-deoxidized copper, depending upon the amount of residual phosphorus. *Phosphorus-deoxidized, low-residual phosphorus* contains from 0.01 to 0.04% P. According to Fig. 1, this should lead to a significant reduction in the electrical conductivity, and this is substantiated by the values in Table 2. The phosphorus-deoxidized copper has an electrical resistivity about 15% higher than that of tough pitch copper (15% lower conductivity). Thus, this copper is more widely used for piping and tubing than for electrical applications.

If high electrical conductivity and a low concentration of Cu_2O are desired, it is common to use *oxygen-free electronic copper*, previously referred to as oxygen-free, high-conductivity copper. This copper is made by very carefully controlling deoxidation during refining, so that both the residual oxygen content and the deoxidizer content are low. Table 2 shows that this copper has an electrical resistivity about the same as that of tough pitch copper, but a much lower oxygen (and hence Cu_2O) content. Thus, this copper can be used where extensive cold working is involved and can be heat treated in reducing gases, whereas, as described previously, tough pitch copper cannot.

Note that all three commercially pure coppers in Table 2 have the same hardness. Thus the presence of Cu_2O and of solute atoms in the lattice has negligible effect on the strength properties, but they have a potent effect on the electrical resistivity and also on the thermal conductivity. Also, recall that tough pitch copper is desirable because the solidification shrinkage is small, so that the ingot solidifies with a rather flat top. Ingots cast from oxygen-free or from deoxidized copper will have on top a large "pipe," or shrinkage cavity, and this portion will have to be removed before hot working the ingot, contributing to scrap loss.

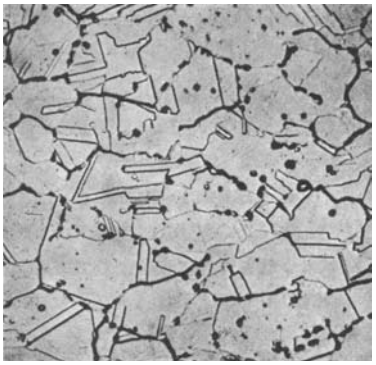

Fig. 7 Microstructure of a wrought tough pitch copper sample that has been heated in hydrogen (2 min at 850 °C, or 1560 °F) to form water vapor pockets, which impair the mechanical properties. 300×. Source: Ref 5

Table 2 Approximate oxygen content and properties of three commercially pure coppers and a silver-bearing copper

	Copper content, wt%	Oxygen content, wt%	Others, wt%	Electrical resistivity at 20 °C (68 °F), mΩ/mm^2	Thermal conductivity at 20 °C (68 °F), W/m · K	Hardness, HRF
Tough pitch copper	99.0 min (Cu + Ag)	0.04–0.05	…	58.6	226	40
Deoxidized low-phosphorus copper	99.90	0.01	0.004–0.012 P	49.3	196	40
Oxygen-free electronic copper	99.99 min	0.001 max	…	58.6	226	40
Silver-bearing	99.90	…	0.03–0.05 Ag (10–15 oz per ton)	58.0	226	40

Source: Ref 6

These commercially pure coppers were chosen to illustrate the principles involved in the uses of the pure coppers. There are many reasons that specifications call for control of specific elements and that alloying additions are made to copper. Two examples are examined below.

Example 1: Effect of Lead Content. As discussed earlier, one advantage of touch pitch copper is that it solidifies with a flat top on the ingot, so that the entire ingot can be hot worked. A chemical-composition specification on electrolytic tough pitch copper is that lead should not be present in amounts greater than 0.005% if the copper is to be hot worked. The reason for this can be seen by examining the copper-lead phase diagram shown in Fig. 8. The melting points of copper and lead differ greatly, and there is an eutectic at 99.94% Pb. From 326 to 955 °C (619–1751 °F), a two-phase region exists with lead-rich liquid in equilibrium with the copper-rich, terminal solid solution. The solubility of lead in solid copper is extremely small, being about 0.007%. Thus, if the lead content of the copper exceeds this value, upon heating the copper to the hot-working range (500–900 °C, or 930–1650 °F), the alloy is in the two-phase region. The liquid wets the a grain boundaries and forms a film on them, and upon hot working, the alloy disintegrates. (This effect is called *hot shortness*.) For this reason, the chemical specification of lead in tough pitch copper is set at 0.005% maximum.

Example 2: Effect of Silver Additions. The silver-bearing copper is an interesting example of the reason for the addition of a specific element. In many electrical applications, strength is required and is obtained by cold working. However, copper has a rather low recrystallization temperature (e.g., 140 °C, or 284 °F), and it is desirable to alloy it with an element that will raise the recrystallization temperature and yet retain usable electrical conductivity. Figure 1 shows that the element that reduces the electrical conductivity least is silver; the addition of about 0.05% reduces the conductivity only about 1%. However, in most solid solutions the addition of only a very small amount of solute reduces the atom mobility and hence increases the recrystallization temperature. Figure 9 shows the effect of several solutes on the recrystallization temperature of copper, and it is seen that the addition of 0.05% Ag increases this temperature from 140 to about 340 °C (284–645 °F). Although some of the other elements have a comparable effect, they very markedly lower the electrical conductivity (Fig. 1). Thus, silver is the most obvious element to add to retard softening of cold-worked copper and yet retain excellent electrical conductivity. Table 2 compares properties of a silver-bearing copper with those of the three commercial coppers previously discussed. Note the high electrical and thermal conductivity.

Copper-Zinc Alloys

Copper-zinc solid-solution alloys are probably the most widely used copper-base alloys. They retain the good corrosion resistance and formability of copper but are considerably stronger. Zinc is hexagonal close-packed, so the solubility in copper cannot be complete. However, copper is face-centered cubic, a close-packed structure, and the atom size difference is only about 4%, so extensive solubility is expected. The phase diagram is shown in Fig. 10, where it is seen that the maximum solubility of zinc in copper is about 38%, and at 20 °C (68 °F) it is about 35%. (The dashed lines indicate that equilibrium is slow to attain, so that the solubility boundary at about 200 °C, or 390 °F, is valid at 20 °C, or 68 °F). Note that four intermetallic compounds form in this system.

It is useful to examine the size difference between copper and solute atoms to predict the extent of solid-solution strengthening. A large size difference should favor strengthening, but this usually causes limited solubility. Thus the more usable solutes for solid-solution strengthening are those for which the size difference is modest and the solubility large. Table 3 lists the atom size difference for several solutes, along with the approximate maximum solubility. Note that zinc has the best combination of size difference and solubility (except for gold, which is expensive).

The data in Table 3 are consistent with the data in Fig. 11, which show the effect of several solutes on the critical resolved shear stress, which is the shear stress on a crystallographic plane in a certain direction that causes slip (Ref 11). Those elements that show strong strengthening of copper generally have low solubility. For example, the solubility of indium is only about 1 at.%. (Note in Table 3 that tin is an attractive possibility, and Fig. 11 shows that it has a significant strengthening effect; the copper-tin alloys are discussed subsequently.) The effect of zinc is not as potent as that of several of the other solutes, but its high solubility allows

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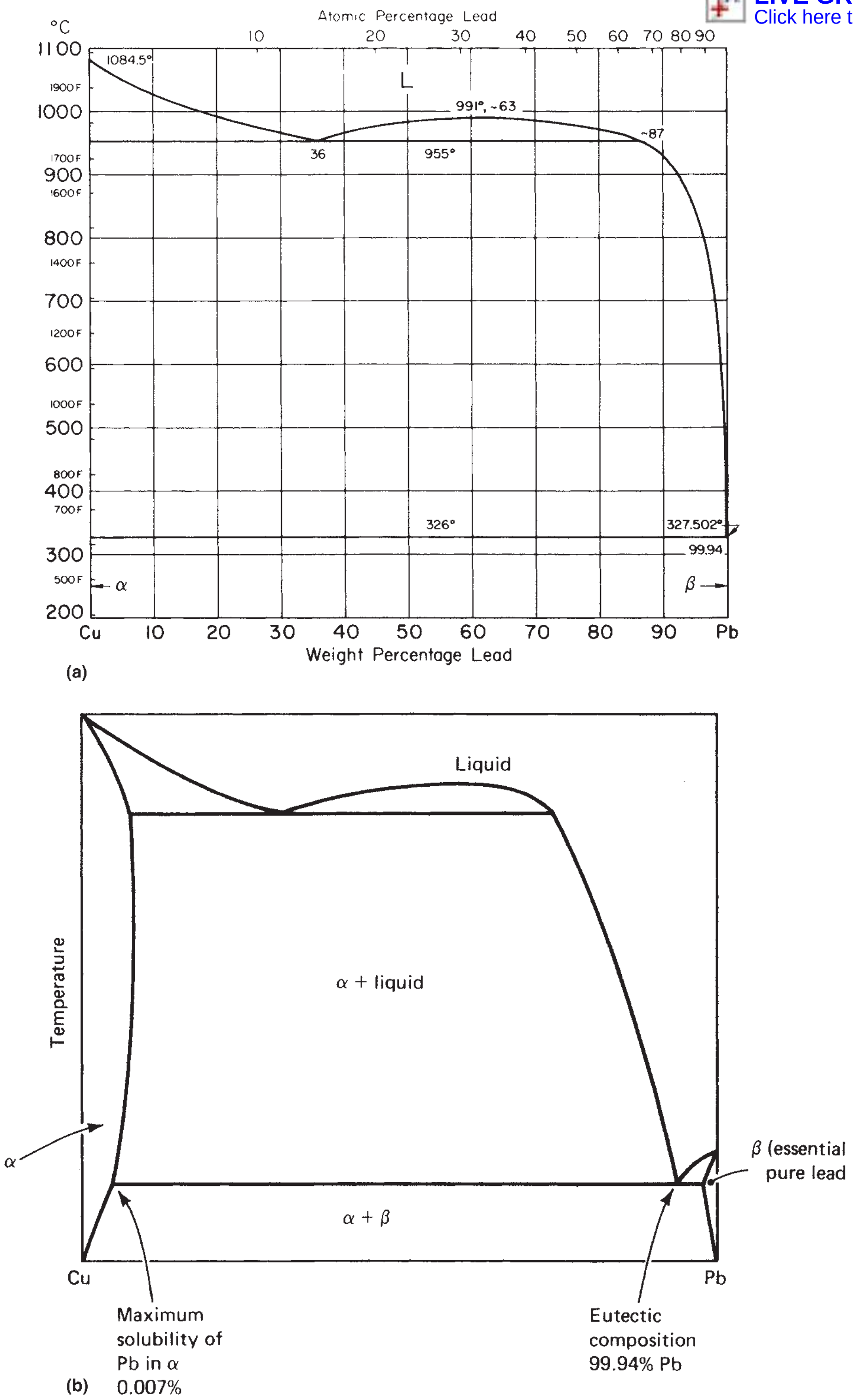

Fig. 8 (a) The copper-lead phase diagram. The schematic diagram in (b) shows more clearly the location of the eutectic at almost pure lead and the low solubility of lead in copper.

the strengthening to be significant at contents in the 30% range (Fig. 12).

Factors Influencing Fabrication Characteristics

One of the main uses of copper is in fabricating intricate shapes by deformation (such as deep drawing). The copper-zinc solid-solution alloys have the advantage that they retain this deformation ease yet have higher strength than copper. Figure 13 shows the tensile strength and elongation at fracture (at 20 °C, or 68 °F) of commercially pure copper and several commercial copper-zinc alloys as a function of the amount of cold rolling. Note that even in the initial, annealed condition the copper-zinc alloys containing 20 and 30% Zn show a greater elongation than pure copper and the alloys with less zinc.

Although the copper-zinc alloys are stronger than copper, they work harden at a lower rate (Fig. 14), and necking occurs at a higher strain. Thus upon forcing these alloys into a die, the metal can be deformed extensively before the danger of necking appears, leading to an undesirable local dimensional change and to fracture. Note also in Fig. 13 that the 20 and 30% Zn alloys retain their superiority as they are cold worked, although all of the alloys show less ductility with increasing cold deformation.

From the viewpoint of fabrication by deformation, the sensitivity of the elongation to the grain size, as illustrated by Fig. 15, is quite important. If the grain size becomes approximately the same as, or exceeds, the thickness of the tensile specimen (or the sheet in the case of the data in Fig. 15), then there are few or no grain boundaries to inhibit slip and contribute to work hardening, and as the grain size increases the metal shows less elongation at fracture. Thus control of grain size *before* cold deformation is quite important, and the prior annealing processes must be carefully regulated to yield a fine grain size (see the article “Heat Treating” in this Handbook for additional information).

How these mechanical properties are related to the ease of fabrication by cold deformation operations is addressed next. To illustrate the relationship, deep drawing is considered. The response of the metal to drawing depends upon a number of factors, such as loading rate, lubrication, and die radius. The description given here is simplified and is designed to illustrate only the general aspects of the process. One type of deep drawing is depicted schematically in Fig. 16(a). Here a circular blank is drawn into a cup. The blank is forced into a die by a punch, and in the case shown, the clearance between the die and punch is the same as the thickness of the blank. During cold working, density changes only slightly so that as the punch forces the metal into the opening, the tube elongates. (Compare step 3 with step 4.) As the metal is drawn into the die, the thickness does not change and plastic strain occurs only tangentially and longitudinally (plain strain). A continued force must be exerted to cause the metal to flow, and the material must have sufficient strength to withstand the longitudinal force and the ability to plastically strain without necking to prevent thinning of the wall of the tube.

As the diameter of the circular blank increases, necessary to form a longer tube, the force required to form the tube is greater than for a smaller-diameter blank (Fig. 16b). this is because a greater volume of metal is forced into the same die opening. A measure of drawability of a metal is the maximum ratio of the diameter of the blank to that of the punch (*drawing ratio*) allowable without fracture or wrinkling. Table 4 shows the drawing ratio for pure copper and for a Cu-30Zn alloy (cartridge brass) for various amounts of prior work. Note that both materials retain their deformation ability quite well as the degree of prior cold work increases.

In the drawing operation in Fig. 16 it is obvious that a wrinkling effect will occur. To avoid this, it is common to use a plate on the blank to maintain the thickness constant and to force the blank to move horizontally (for the configuration in Fig. 16) into the die. Also, the clearance between the die and the punch can be less than the blank thickness, so that the tube height is increased. All of these factors complicate the flow analysis and clearly point out that a material with high ductility and high strength is required.

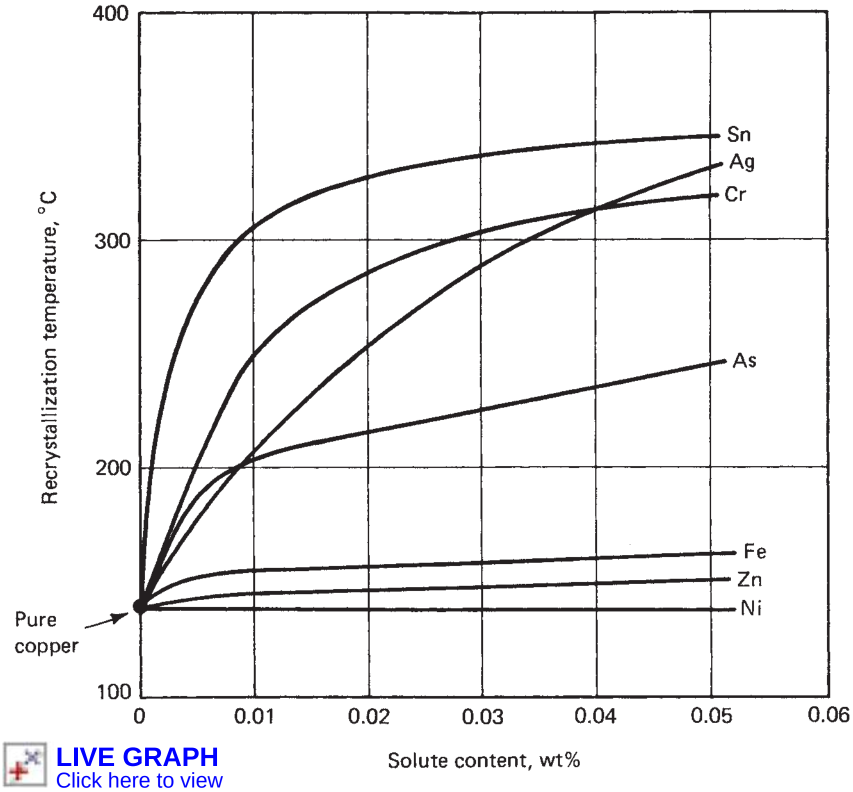

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Fig. 9 Effect of solute content on the recrystallization temperature of pure copper. These data are for oxygen-free copper, but quite similar curves are obtained for tough pitch copper. The samples were annealed for 30 min at 600 °C (1110 °F) then cold rolled at 20 °C (68 °F) to a reduction in thickness of 75%. Note that pure copper has a recrystallization temperature of 140 °C (285 °F). Source: Ref 7

Table 3 Approximate atom diameter size difference and approximate solubility in copper of several solutes

Solute	Approximate atom diameter size difference, % $(d_{Cu} - d_M)/d_{Cu}$	Approximate solubility in Cu, wt%
Oxygen	+113	0
Beryllium	+14	2
Aluminum	–11	9
Silicon	+9	5
Phosphorus	+70	2
Nickel	+2	100
Zinc	–4	39
Arsenic	+2	8
Silver	–11	8
Cadmium	–14	3
Tin	–15	15
Antimony	–12	11
Gold	–11	100
Bismuth	–18	0
Lead	–27	0

Table 4 Drawability of pure copper and Cu-30Zn alloy

	Approximate % reduction in thickness by rolling at 20 °C (68 °F) (temper designation)	Maximum drawing ratio using hemispherical punch
High-conductivity copper	0 (O)	2.20
	11 (1/4 H)	2.17
	21 (1/2 H)	2.12
	37 (H)	1.72
70/30 brass	0 (O)	2.17
	11 (1/4 H)	2.12
	21 (1/2 H)	2.07
	37 (H)	1.80

Drawability is maximum ratio of the diameter of a circular blank to that of the punch: see Fig. 16. Source: Ref 13

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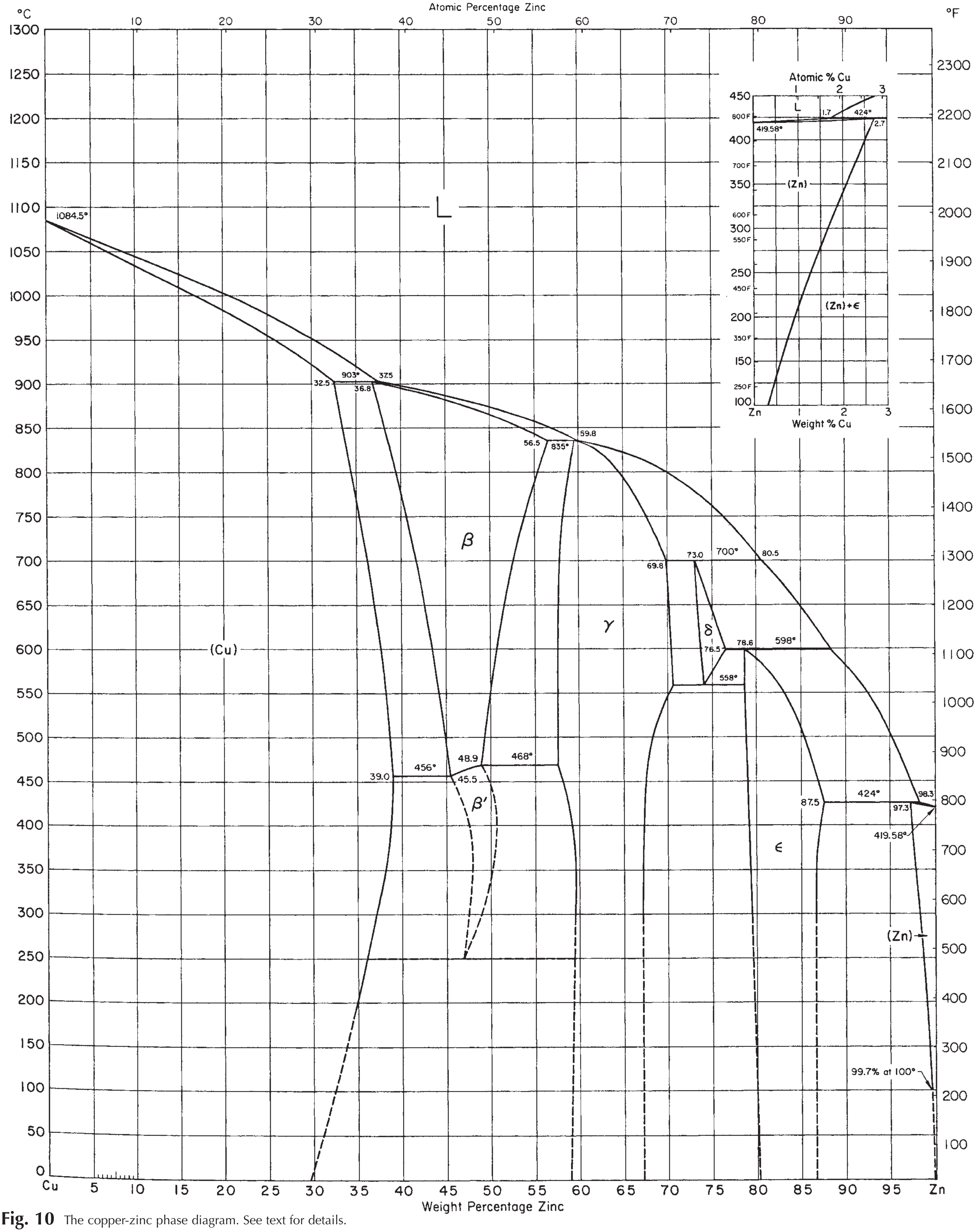

Fig. 10 The copper-zinc phase diagram. See text for details.

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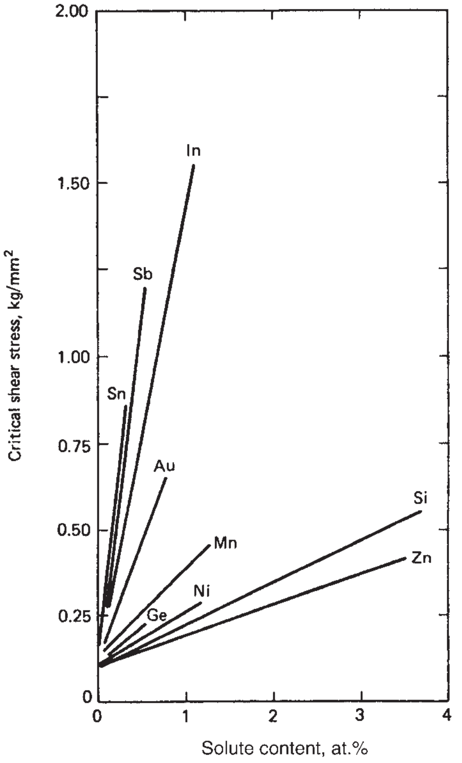

Fig. 11 Approximate effect of solute content on the critical resolved shear stress at 20 °C (68 °F) of dilute copper-base solid solutions. Source: Ref 8–10

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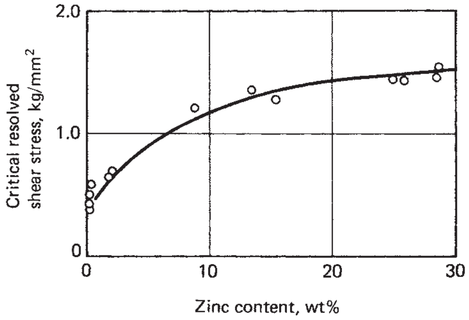

Fig. 12 Effect of zinc content on the critical resolved shear stress at 20 °C (68 °F) of copper-zinc solid-solution alloys. Source: Ref 9

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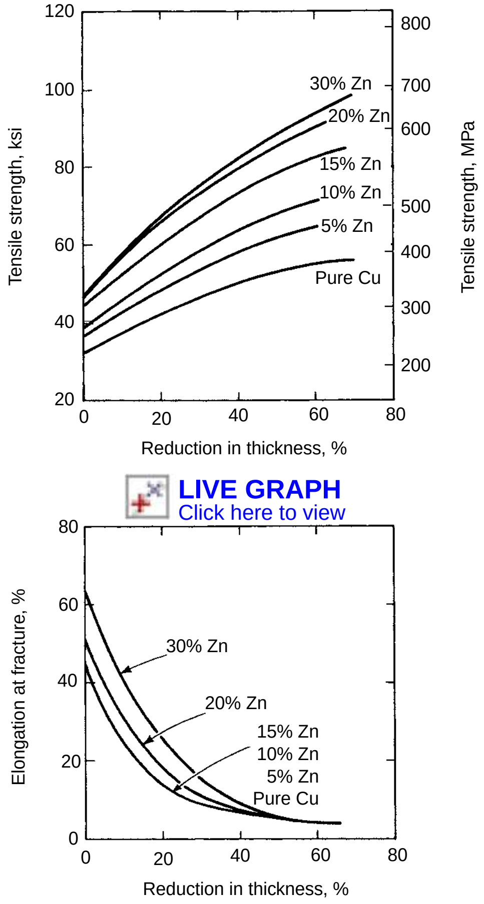

Pure copper . . electrolytic tough pitch (ETP) copper	15% Zn . . . red brass
5% Zn . . . . gilding	20% Zn . . . low brass
10% Zn . . . . . . commercial bronze	30% Zn . . . cartridge brass

Fig. 13 Effect of cold rolling at 20 °C (68 °F) on the tensile strength and elongation at fracture of 1 mm (0.040 in.) thick sheet of copper and copper-zinc single-phase commercial alloys

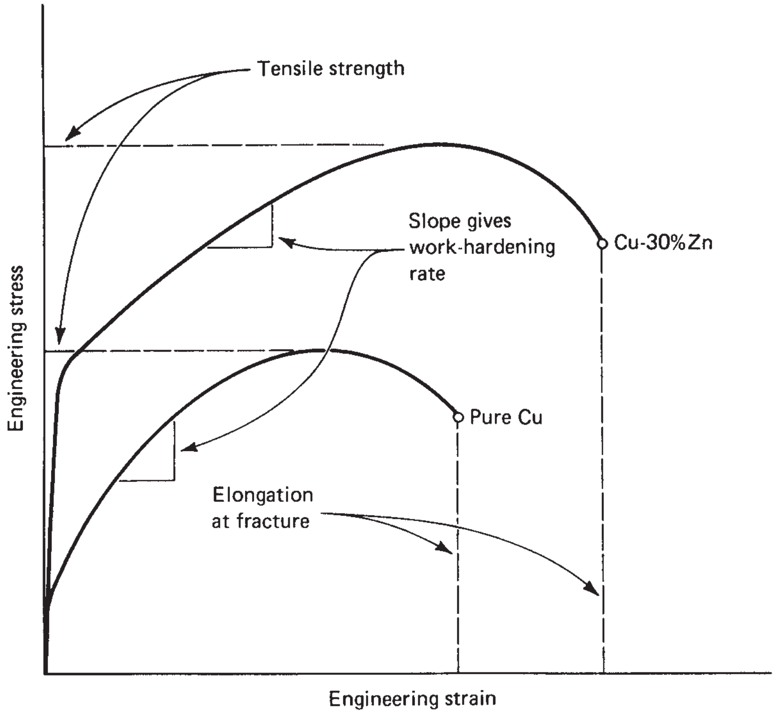

Fig. 14 Schematic engineering stress–engineering strain curves for pure copper and a Cu-30Zn solid solution alloy, showing that the alloy has a higher tensile strength and a lower work-hardening rate, necks at a higher strain, and has a greater fracture strain (elongation at fracture).

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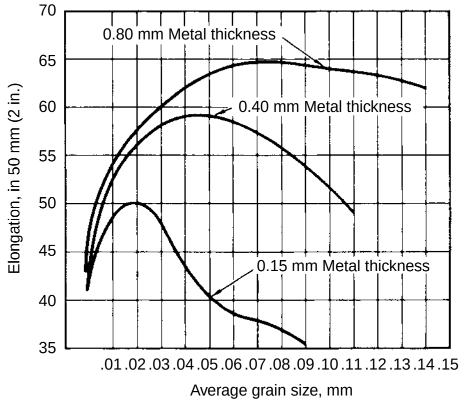

Fig. 15 Influence of initial grain size and sheet thickness on the elongation at fracture for the commercial alloy cartridge brass (Cu-30Zn). Source: Ref 12

Effect of Beta (β) Phase on Structure and Properties

The higher-zinc alloys in which the β phase is present (Fig. 10) are now examined. These alloys have rather complex phase transformations, which give rise to a variety of microstructures and hence properties. Their usefulness relies on excellent hot workability and excellent machinability. To illustrate these alloys, the 60Cu-40Zn alloy is discussed in some detail. This alloy is essentially the commercial alloy Muntz metal.

Structure. The β phase is referred to as an intermetallic compound, meaning a phase based on an approximate stoichiometry of the elements. Thus, note in Fig. 10 that the β phase is approximately centered at copper-zinc. However, the chemical composition of intermetallic compounds can usually be varied from the stoichiometric ratio and yet retain the crystal structure of the compound. For the β phase in the copper-zinc system, at 800 °C (1472 °F) it is stable from about 39 to 55% Zn. This range decreases as the temperature is lowered, being stable only from 45 to 49% Zn at 500 °C (932 °F).

The β phase is body-centered cubic, and, in spite of the approximate stoichiometry, at temperatures above about 470 °C (880 °F) the copper and zinc atoms are located at random on the lattice sites. There is a binding energy between the copper and the zinc atoms, and hence a tendency for the atoms to take on preferential positions relative to each other in the lattice. However, at high temperatures the thermal energy, in the form of lattice vibrations, is sufficient to keep the atoms dispersed randomly on the lattice sites. As the temperature decreases, the vibrations are reduced, and a temperature is reached (called the critical temperature) below which this preferential siting occurs. The phase is then said to be ordered (long-range ordered), or to have formed a *superlattice*. This is the β' phase in Fig. 10. The crystal structure is shown in Fig. 17.

The critical temperature for the ordering process is dependent upon the composition of the β phase, and this is the line shown in Fig. 10 separating the β and the β' (the ordered structure) region. The lines extending into the $\alpha + \beta$ and into the $\beta + \gamma$ regions give the critical temperature for the β phase in equilibrium with either α or γ.

Figure 10 shows that the β' phase undergoes a eutectoid reaction at 250 °C (482 °F), forming α and γ. However, note that the phase boundaries are shown dashed, indicating considerable experimental uncertainty in their location. Also, the eutectoid reaction requires considerable time to initiate. Therefore the phase boundaries shown in the phase diagram in Fig. 18 can be used. Here, the β' phase is considered stable to 20 °C (68 °F).

The process by which the ordered structure forms from the disordered lattice can be quite complex and in some alloys is not well understood. However, a simplified description of a possible process is useful in pointing out some factors that might affect mechanical properties. Figure 19(a) depicts a (110) plane for a 50 at.% Zn-Cu alloy. The atoms are placed randomly in the schematic drawing. The picture in Fig. 19(a) would change with time, as the lattice thermal vibrations would allow atoms to move from one lattice site to another. This would occur mainly by vacancy movement, but the vacancies are not shown in the figure and they are neglected for simplicity in the following description.

The description in Fig. 19(a) typifies that of the alloy above the critical temperature. However, as the temperature is lowered below the critical temperature, the lattice vibrations no longer are sufficiently strong to overcome the attraction between the copper and the zinc atoms, and if the atoms become arranged as they are in Fig. 17, the configuration will be stable. Now, in spite of the fact that the arrangement in Fig. 19(a) was achieved by placing the closed and open circles randomly on the array, small regions can be found that have the ordered structure. When the alloy is cooled below the critical temperature, these regions act as nuclei for the ordering process. In Fig. 19(b) are shown two perfectly ordered regions in the random arrangement. Only these two act as nuclei. For these to grow, atoms at the interface must relocate to extend the arrangement. The required atom exchanges, shown by the arrows in Fig. 19(b), lead to the perfectly ordered regions increasing their size as shown in Fig. 19(c). These small ordered regions are call *domains*.

For the domains to grow further requires the atoms in the disordered material right at the domain-disordered lattice (or $\beta'-\beta$) interface to continue to rearrange in order to propagate the correct arrangement. If the atoms are moved as indicated in Fig. 19(d), the two domains eventually contact. However, note that the particular choice of the original domain nucleus leads to a mismatch at the interface of the two domains. Such an interface is called an antiphase *domain boundary*.

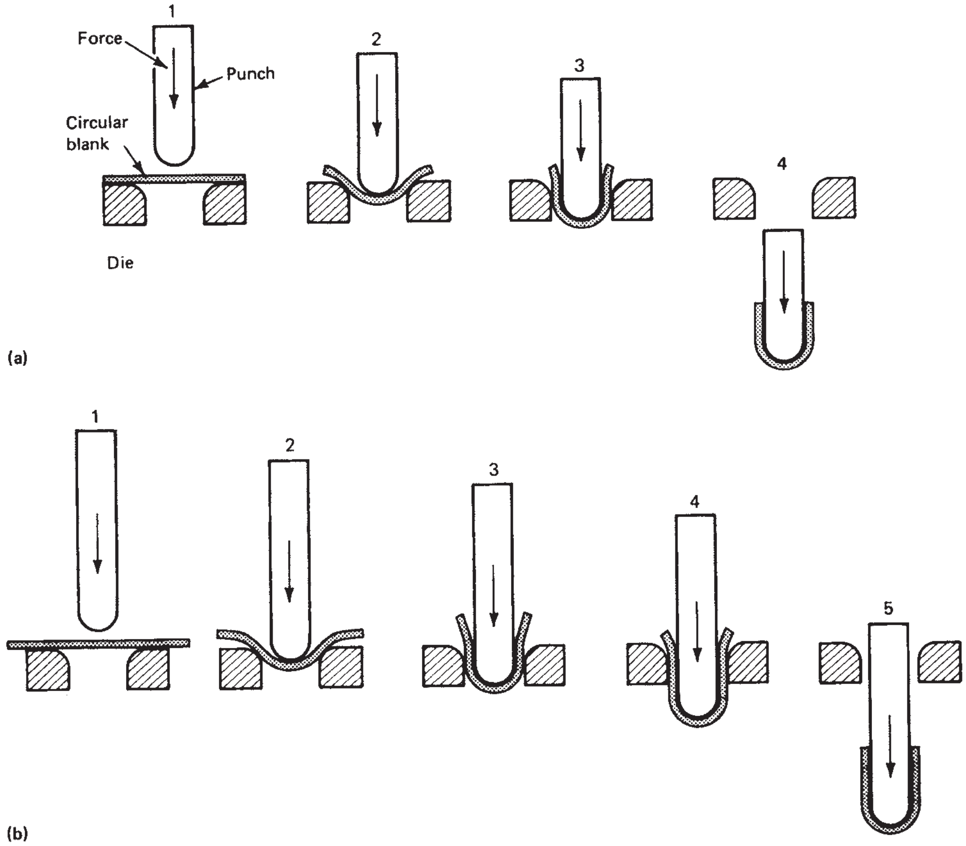

Fig. 16 (a) Schematic illustration of a drawing operation. If the ratio of the diameter of the circular blank to that of the punch increases (b), the force to draw the tube increases, and the wall of the tube must withstand more force. This ratio of diameters is called the drawing ratio, and the maximum ratio that will withstand fracture is a measure of drawability. Some data are given in Table 4.

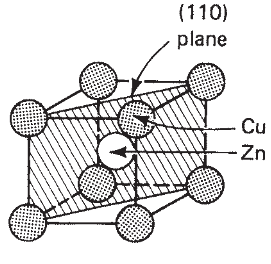

Fig. 17 The ordered (superlattice) β' phase for the exact composition of equal numbers of atoms of copper and zinc (about 49 wt% Zn). The unit cell could just as well have been drawn with a copper atom in the center and zinc atoms on the corners.

The perfection of the order within a domain is referred to as the *degree of order*. For example, each of the domains depicted in Fig. 19(d) is perfectly ordered (with degree of order $S = 1$). If a few copper and zinc atoms swapped positions, the degree of order would be less than perfect (S between 1 and 0). If the arrangement were random, $S = 0$. In the β' structure, the equilibrium degree of order is essentially unity below about 250 °C (480 °F), and approaches zero as the critical temperature is approached. However, the actual degree of order in an alloy may be influenced by the heat treatment.

Two characteristics can be established here. One is that in the copper-zinc β phase, even rapid cooling from β cannot suppress the ordering. This is reasonable from the description in Fig. 19, as it is expected that many nuclei exist and that only a few atom exchanges will bring the domains into contact, with the alloy locally completely ordered. The other characteristic is that a fine domain size should be established, with many antiphase boundaries. This should contribute to strengthening.

Properties. Some mechanical properties of the β' phase are now examined. Figure 20 shows that the strength of the ordered β' can be increased by aging in the intermediate temperature range (200–500 °C, or 390–930 °F) below the critical temperature. This reflects the influence of the heat treatment on the degree of order and on the domain structure. Figure 21 shows the influence of cooling rate from the β region on the hardness. Very slow cooling should induce the equilibrium amount of order and allow development of a relatively coarse domain size. Increased cooling rate from the β region should develop a fine domain size and perhaps allow less than the equilibrium amount of order to develop. This fine domain size is probably responsible for the increased hardness as the cooling rate increases. Again, it is necessary to remember that even very rapid cooling cannot suppress the ordering; it just develops a very fine domain size.

The data in Fig. 22 show that above the critical temperature, the ductility and toughness of the β-composition alloys increase markedly. Thus, the high-temperature, disordered β phase deforms much easier than the ordered β' structure. One important characteristic of copper-zinc alloys containing β and α is that they show better hot workability (but not cold workability) than alloys consisting of only the α phase.

With this brief description of the β and β' phases, the Cu-40Zn alloy is considered. The β' alloy is not suitable for commercial use, as it is brittle. However, alloys in which the β' phase coexists with the ductile α phase are useful. The Cu-40Zn alloy can be heat treated at high temperature so that it is all β. The structure developed at lower temperatures depends upon the heat treatment, as this controls the precipitation and formation of the α phase. If the alloy is cooled slowly from 800 °C (1470 °F), the phase diagram (Fig. 18) shows that at 20 °C (68 °F) the alloy should consist of approximately equal amounts of α and β'. Figure 23 shows a typical microstructure. The α phase can be identified by the presence of annealing twins, characteristic of the face-centered cubic structure.

The curves on the right-hand side of Fig. 24 show that the amount of β' influences the hardness. The alloy was cooled slowly from 700 °C (1290 °F), where it was mostly β, to 20 °C (68 °F), then reheated to temperature for 30 min, followed by rapid cooling. Upon heating at 800 °C (1470 °F), the structure is all β, and

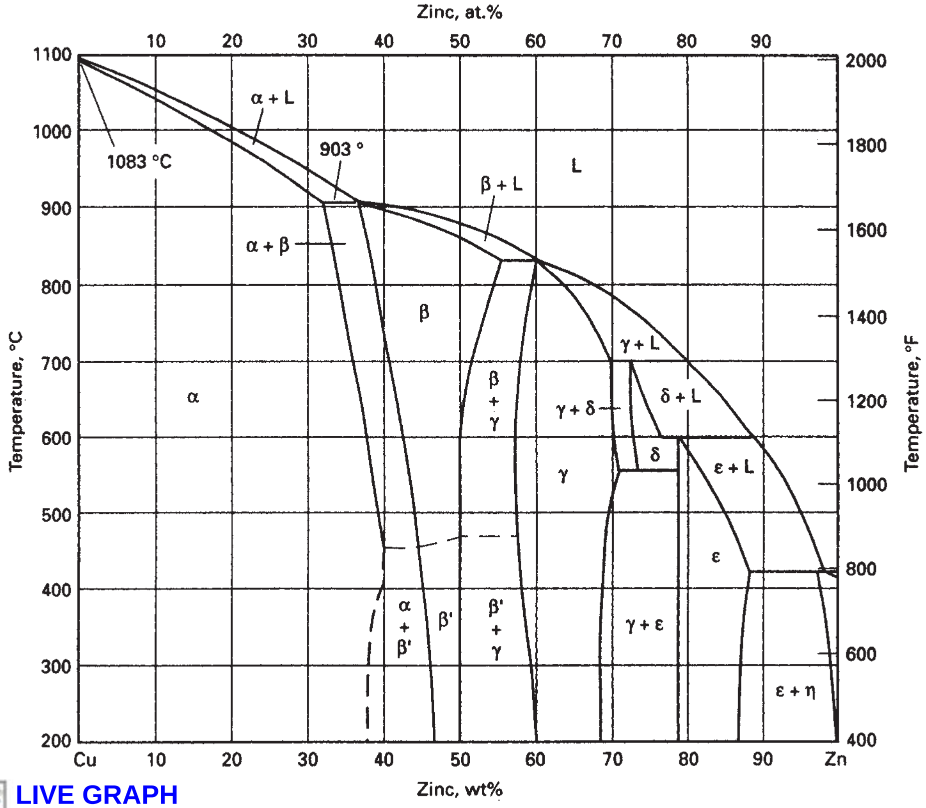

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Fig. 18 The copper-zinc phase diagram in which the β' phase is stable below the critical temperature. This diagram is used in discussing the heat treatment of alloys containing the β' phase.

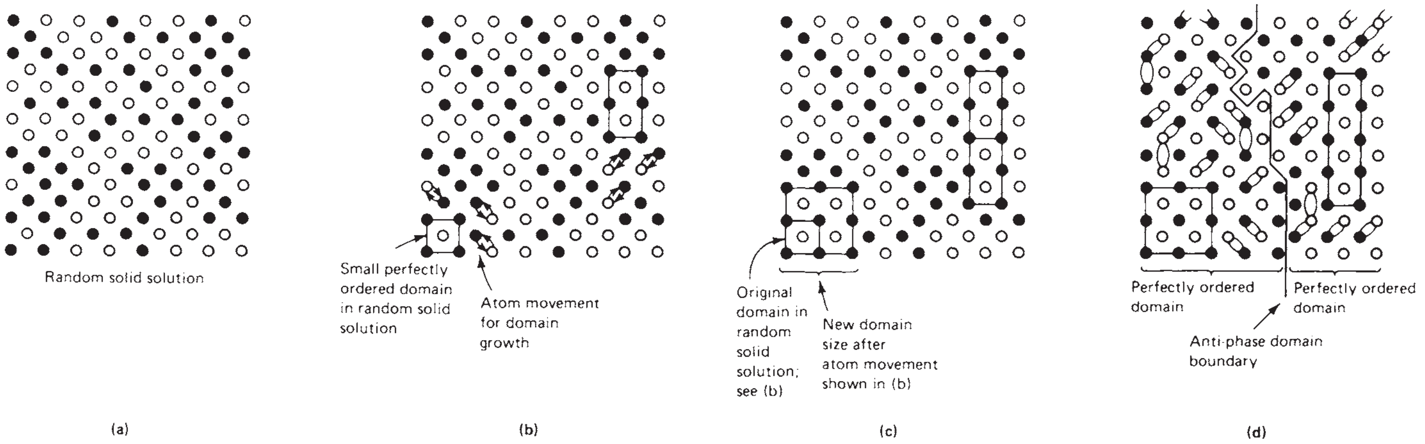

Fig. 19 Schematic illustration of a possible mechanism of the formation of two ordered domains. The plane shown is a (110) type (see Fig. 17).

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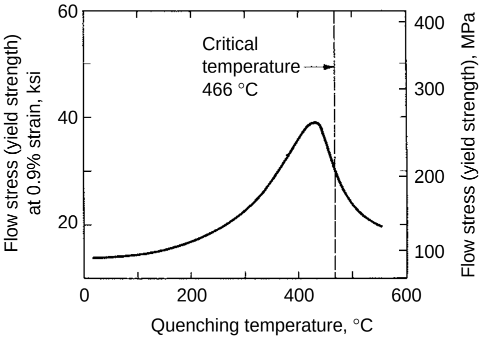

Fig. 20 Yield strength as a function of quenching temperature for β brass (Cu-49.5Zn). The alloy was originally slowly cooled from 500 °C to 25 °C (930–75 °F) (giving a completely ordered structure), reheated for 15 min at temperature, then water quenched. In this condition the flow stress was measured at 25 °C (75 °F). From 20 to about 200 °C (68–390 °F) the alloy is essentially in the condition obtained by slow cooling from 500 °C, which is why the strength is about the same. However, from 200 to about 500 °C (390–930 °F) the degree of order depends on the temperature and hence affects the strength measured after quenching. Source: Ref 14

Table 5 Mechanical properties typical of cartridge brass (Cu-30Zn) and Muntz metal (Cu-40Zn)

	Tensile strength		Yield strength		
Alloy	MPa	ksi	MPa	ksi	Elongation, %
Cartridge brass	305–895	44–130	75–450	11–65	63-3
Muntz metal	395–510	57–74	145–380	21–55	52-10

	Approximate properties for specific treatments			
	Tensile strength			
Alloy	MPa	ksi	Elongation, %	Hardness, HRB
Cartridge brass				
Annealed	345–415	50–60	65–50	10–50
Annealed + 40% cold work	550–620	80–90	8–5	84–90
Annealed + 70% cold work	655–725	95–105	4	92–95
Muntz metal				
Annealed	365–395	53–57	55–47	30–38
Annealed + 40% cold work	550–620	80–90	10–5	85–90
Annealed + 70% cold work	695–710	101–103	6–4	93

Source: Ref 3

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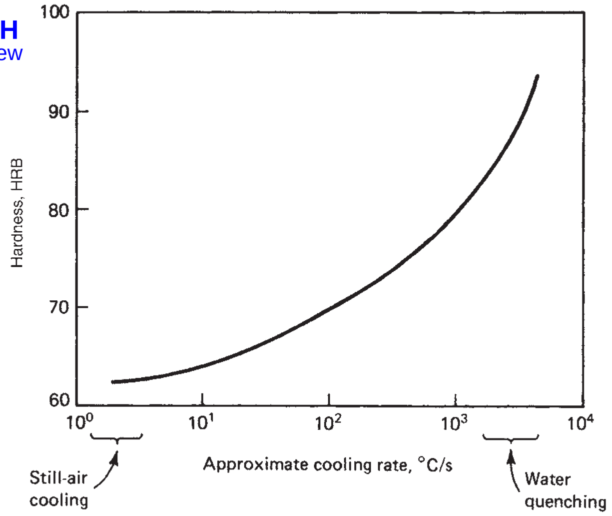

Fig. 21 Effect of cooling rate from 500 °C (930 °F) on the hardness at 25 °C (75 °F) of β brass (Cu-47Zn). The alloy was held for 15 min at 500 °C (930 °F), then cooled in different media. The cooling rates shown are estimated, ranging from water quenching to cooling in still air. Source: Ref 15

Table 6 Effect of aging on the strength of a Cu-10Sn alloy

Property	As-cast	Cast, then annealed for 10 h at 760 °C (1400 °F), water quenched, aged 5 h at 315 °C (600 °F)
Yield strength, MPa (ksi)	145 (21)	140 (20)
Tensile strength, MPa (ksi)	305 (44)	295 (43)
Elongation, %	25	25
Hardness, HB	62	60

Source: Ref 22

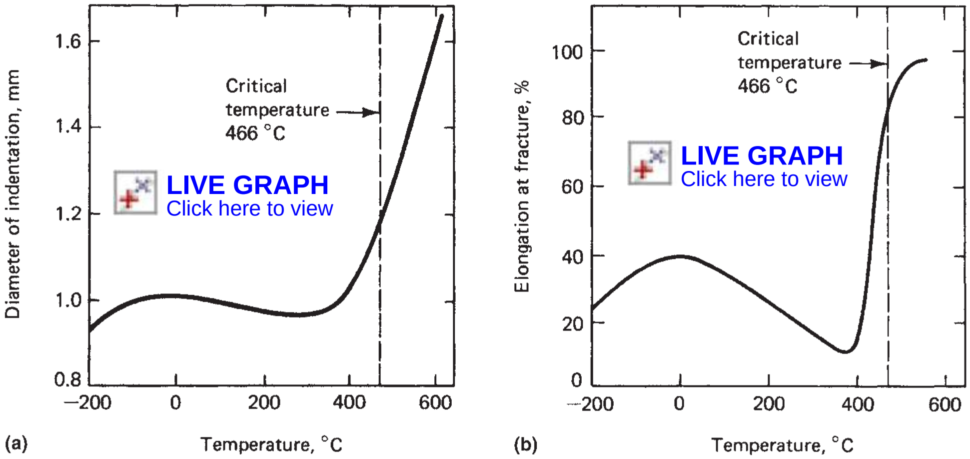

Fig. 22 Increased ductility of β brass (approximately Cu-49Zn) above the critical temperature. (a) Plot of the diameter of the impression of a steel ball dropped from a constant height, giving the impact hardness. Source: Ref 16. (b) Plot of the elongation at fracture in a tension test. Source: Ref 17

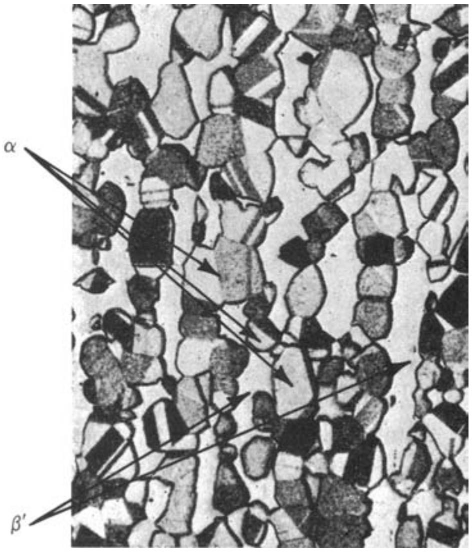

Fig. 23 Typical microstructure of annealed Muntz metal (Cu-40Zn). The clear, white regions are the β′, and the dark and gray regions showing annealing twins are α. Light micrograph; 250×. Source: Ref 18

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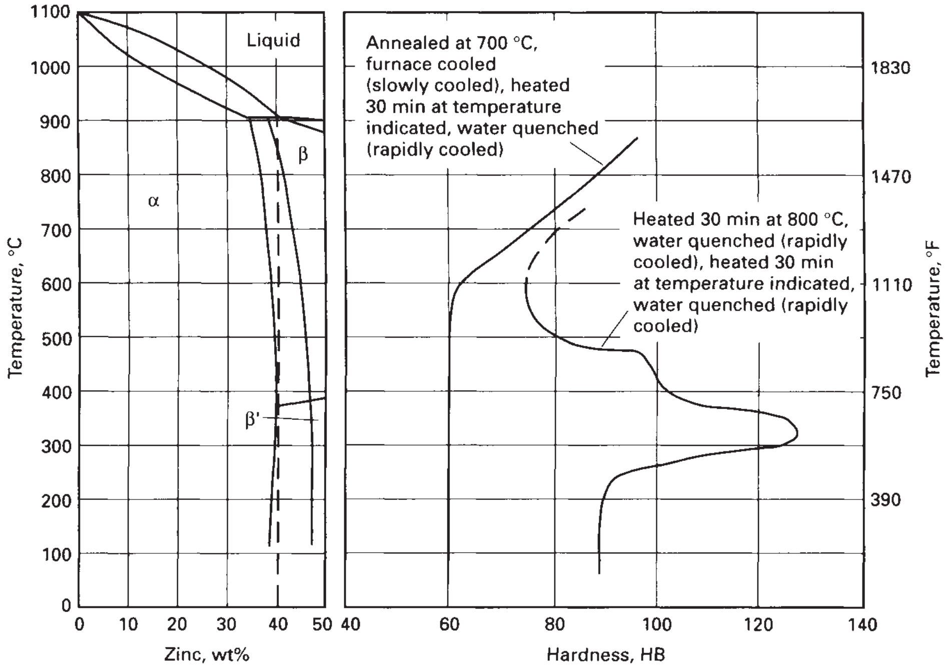
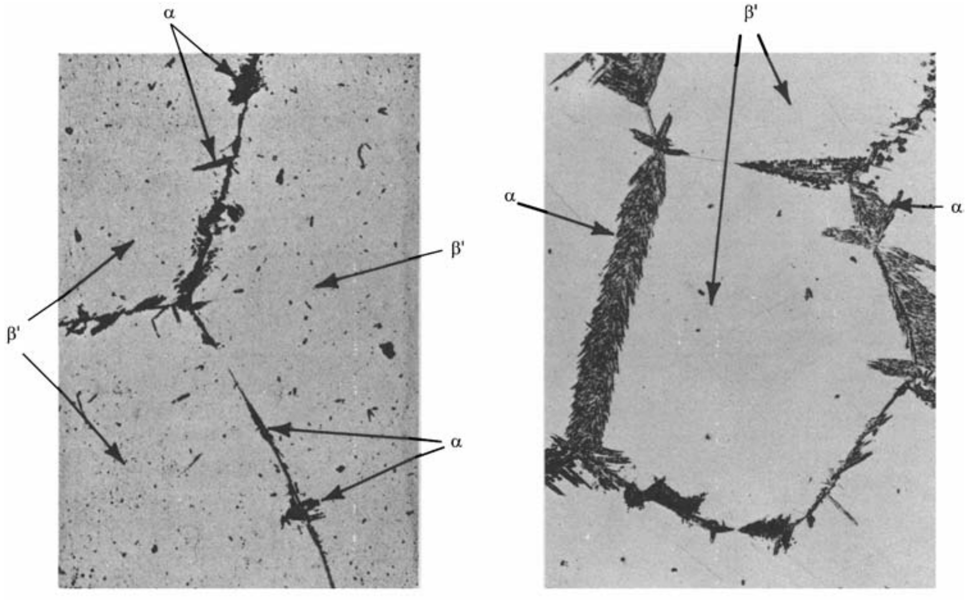


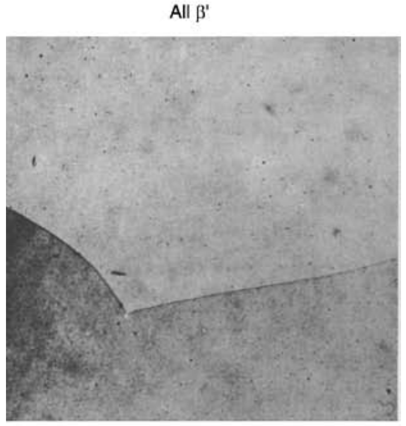
Fig. 24 Influence of heat treatment on the hardness at 20 °C (68 °F) of a Cu-40Zn alloy. Source: Ref 19



(a)

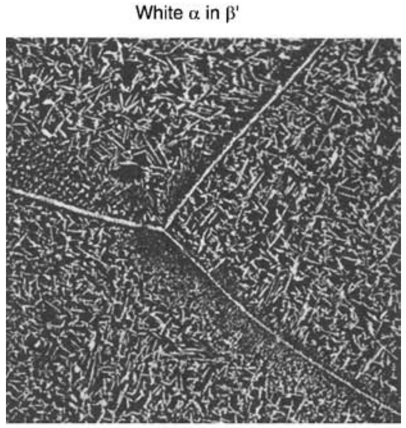
(b)

Fig. 25 Microstructures typical of Cu-40Zn alloys cooled rapidly from the β region to 20 °C (68 °F). Even rapid cooling has not prevented some α from forming. (a) Cu-40Zn alloy, quenched into ice water from 825 °C (1520 °F). Source: Ref 20. (b) Quenched Muntz metal. Both are light micrographs; 100×



Quenched from 800 °C

(a)



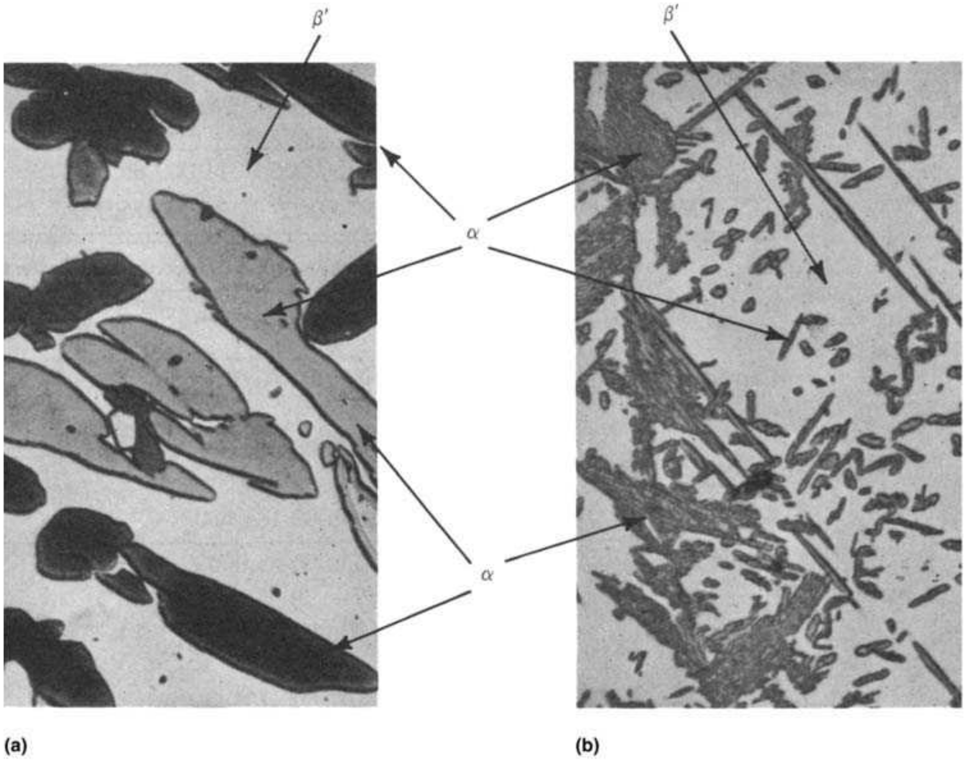
Quenched from 800 °C,
reheated for 30 min
at 400 °C

(b)

Quenched from 800 ° C,
reheated for 30 min
at 600 °C

(c)

Fig. 26 Microstructures of Cu-42Zn alloy quenched from the β region, then reheated to develop an α precipitate structure. The higher reheating temperature gives a coarser structure and hence a softer material. (a) All β′. Quenched from 800 °C (1470 °F). (b) White α in β′. Quenched from 800 °C (1470 °F), reheated for 30 min at 400 °C (750 °F). (c) White α in β′. Quenched from 800 °C (1470 °F), reheated for 30 min at 600 °C (1110 °F). All three are light micrographs; 100×. Source: Ref 5



(a) (b)

Fig. 27 Microstructure of a Cu-43Zn alloy after cooling from 700 °C (1290 °F), the β region. (a) Furnace cooled. (b) Air cooled. Both are light micrographs; 90×. Source: Ref 21

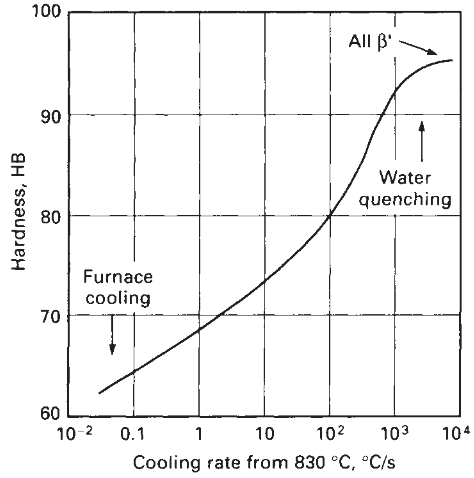


Fig. 28 Effect of cooling rate from the β region on the hardness of a Cu-40Zn alloy. Source: Ref 19

upon cooling rapidly little α forms. However, the β orders to β′, giving a hardness around 90 HB. Reheating for 30 min in the lower temperature range, 20 to 500 °C (68–930 °F), was not sufficient to significantly affect the originally slowly cooled structure, and the hardness remains constant. In this temperature range, the structure is approximately equal amounts of α and β′. However, as the temperature increases from 500 °C (930 °F), 30 minutes is sufficient time to allow the equilibrium amounts and α and β to form. Thus, as the temperature increases, increasing amounts of β and decreasing amounts of α are present at temperature, giving increasing amounts of β′ upon cooling rapidly to 20 °C (68 °F), and hence a rise in hardness.

If the Cu-40Zn alloy is cooled rapidly to 20 °C (68 °F) after sufficient holding (e.g., 30 min) above about 750 °C (1380 °F), a structure of essentially all β′ is obtained. Often some α is observed to have formed in the β grain boundaries, and the morphology will vary somewhat depending upon the exact cooling rate. Usually, the α is present as "needles" emanating from the boundaries, with a clear crystallographic relation between the α and the β′ in which it has formed. Figure 25 shows two examples.

Upon reheating β′ in the intermediate temperature range, the morphology of the α formed will vary depending upon the exact heat treatment. Also, recall that reheating will influence the change in the ordered structure. Both changes affect properties, and the hardness can be increased considerably by judicious treatment. In Figure 24 are shown hardness data for a Cu-40Zn alloy after reheating for 30 min following initial treatment of quenching from 800 °C (1470 °F), giving a structure similar to those in Fig. 25. Supposedly the maximum hardness obtained by treatment around 300 °C (570 °F) is caused by the formation of a fine α precipitate and some changes in the ordered β′ phase. The type of microstructures obtained for such heat treatments is illustrated in Fig. 26 for a Cu-42Zn alloy. In this alloy the zinc content is suffi-

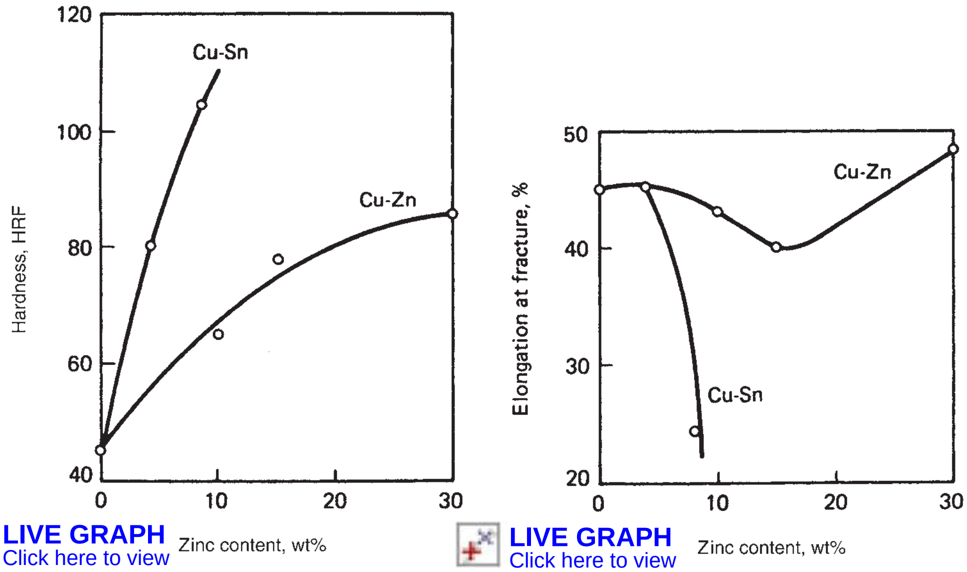


Fig. 29 Comparison of the effect of zinc and tin on the hardness of the binary solid solutions. Tin has a greater solid-solution strengthening effect than zinc but the elongation decreases, so that copper-tin alloys are not as readily fabricated as copper-zinc alloys. Source: Ref 3

Table 7 Mechanical properties of copper-zinc and Cu-Zn-Sn solid solution alloys, illustrating the strengthening effect of tin (grain size 0.015 mm)

	Yield strength		Tensile strength			
Alloy	MPa	ksi	MPa	ksi	Elongation, %	Hardness, HRF
Cu-10Zn	105	15	275	40	44	65
Cu-9.5Zn-0.5Sn	125	18	310	45	43	70
Cu-30Zn	205	30	395	57	48	86
Cu-29Zn-1Sn	230	33	400	58	40	87

Source: Ref 3

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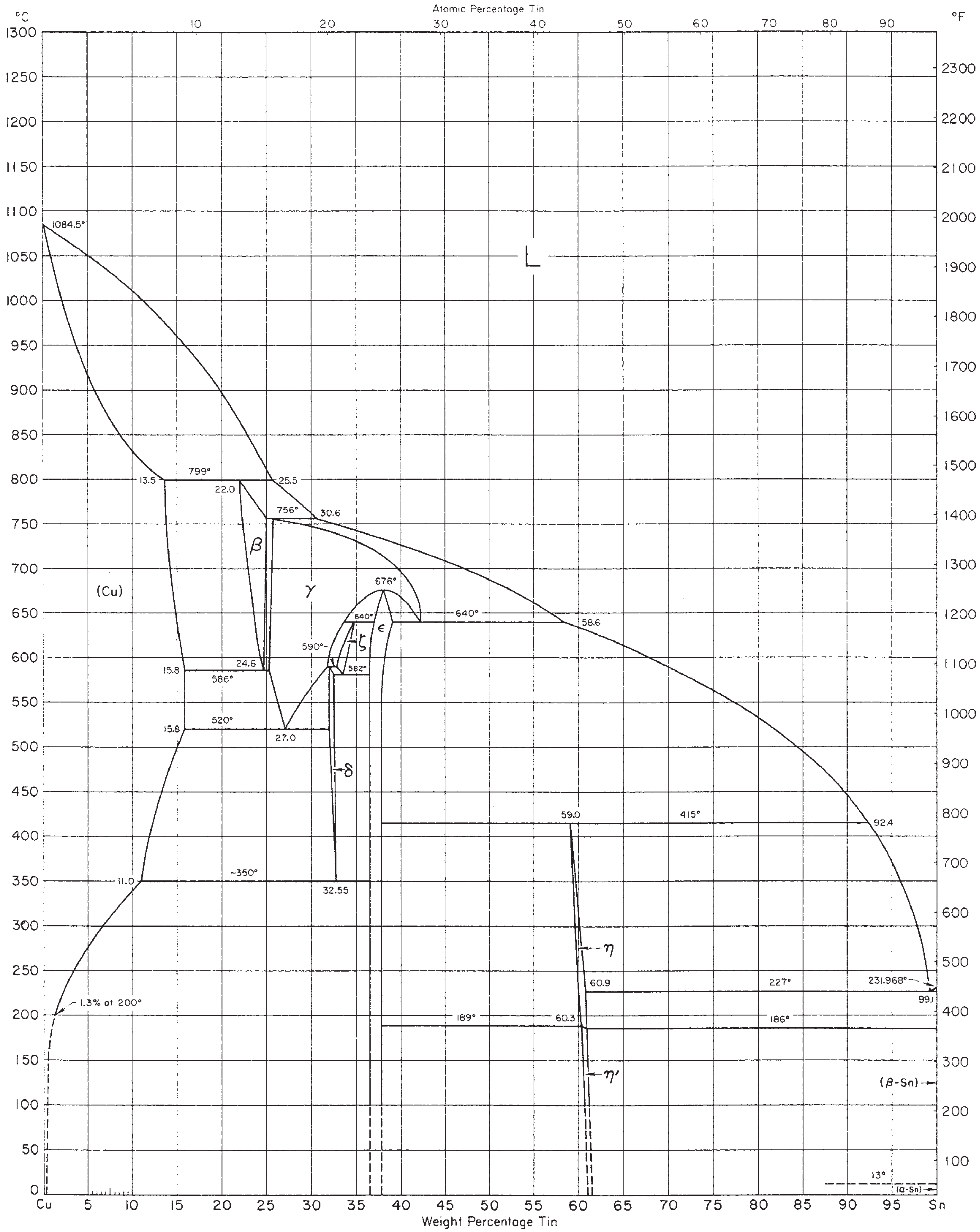

Fig. 30 The copper-tin phase diagram. See text for details.

ciently high to completely suppress any α formation upon rapid cooling from β, giving at 25 °C (75 °F) only β′ (Fig. 26a). Reheating for 30 min at 400 °C (750 °F) gives a fine α precipitate on the β′ grain boundaries, and a fine intercrystalline precipitate of α (Fig. 26b). Reheating for 30 min at a higher temperature, 600 °C (1110 °F), gives a coarser α structure, shown in Fig. 26(c).

If the rate of cooling from the α region is quite slow (several hours to 20 °C, or 68 °F), then α nucleates at a high temperature where the nucleation rate is low, and the α crystals grow relatively large as few crystals nucleate. This gives a rather coarse structure, typified by Fig. 27(a). As the cooling rate increases, the nucleation rate increases, but the individual α crystals do not have time to grow large before the temperature is too low for significant growth to continue. This gives a finer structure (Fig. 27b) and will increase strength. Eventually, the cooling rate becomes sufficient to suppress the formation of α altogether, giving a structure entirely of highly unstable β′ at 20 °C (68 °F). As was shown in Fig. 25, however, it is difficult in the Cu-40Zn alloy to completely suppress some α formation even upon rapid cooling. Figure 28 illustrates the influence of cooling rate from β on the hardness.

Table 5 presents the range of properties usually available for the commercial alloy Muntz metal, which contains 40% Zn, and for commercial cartridge brass, which contains 30% Zn. In the 30% Zn alloy the range is obtained by choice of the amount of cold work and of the annealing treatment. In the 40% Zn alloy, the range is achieved by cold working and by annealing. However, in this alloy the annealing and cooling rate from the high temperature affect the α structure and the ordered β′ structure, which affect the hardness.

Again, alloys that consist of all β′ are too brittle for industrial use, but the lower-zinc alloys with structures of α + β′ are usable. However, the data in Table 5 show that the Cu-40Zn alloy is not preferred because of strength. Instead, the β phase has excellent hot workability, and thus the 40% Zn alloy is frequently chosen to fabricate objects by hot working. Further, it is found that the 40% Zn alloy has better machinability than the 30% Zn alloy, although the latter is considered to have good machinability. This characteristic of the 40% Zn alloy is believed to be due to the presence of the brittle β′, allowing removal of material with less energy consumption and the development of a fine surface finish.

Copper-Tin Alloys

Examination of Table 3 reveals that tin is a solute that has a large size difference and reasonably high solubility, so that the copper-tin solid solutions should have quite usable strength. Indeed, the copper-tin solid solutions are considerably stronger than the copper-zinc alloys in dilute solutions (Fig. 11), and Fig. 29 shows that a Cu-8Sn alloy is harder than a Cu-30Zn alloy. However, note in Fig. 29 that the

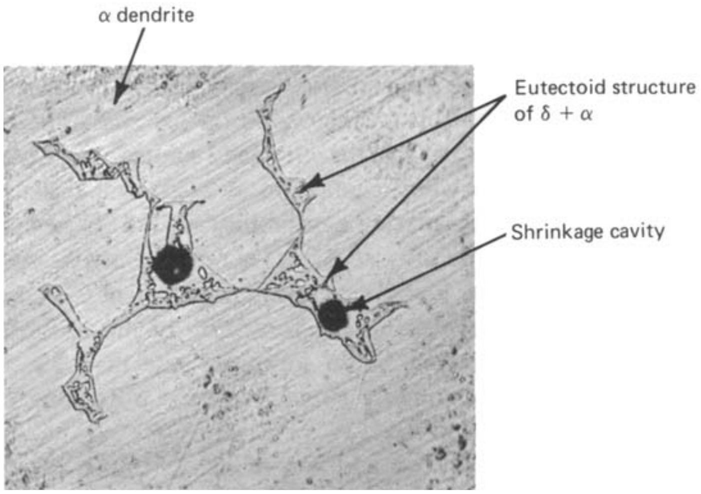

Fig. 31 Microstructure of a Cu-10Sn alloy in the as-cast condition showing the presence of the δ phase. Light micrograph; 500×. Source: Ref 23

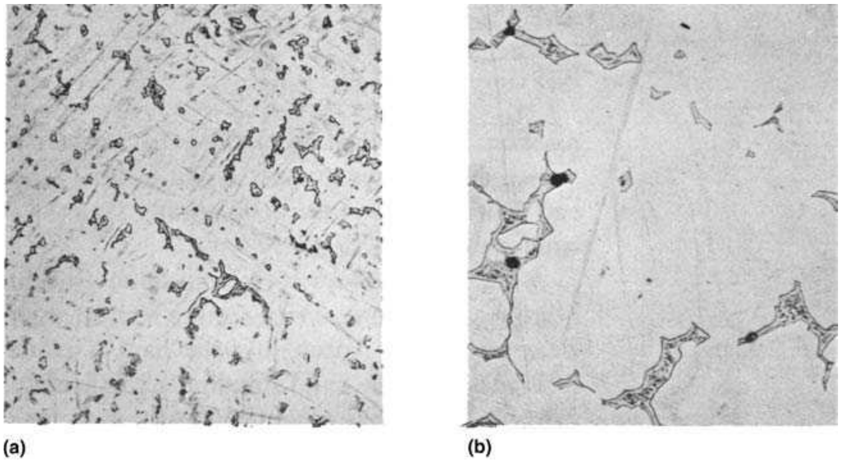

Fig. 32 Affect of cooling rate on microstructure of Cu-10Sn alloys. The faster cooling (chill cast) alloy (a) has formed considerably finer α dendrites than the sand cast alloy (b). Both light micrographs; 200×. Source: Ref 23

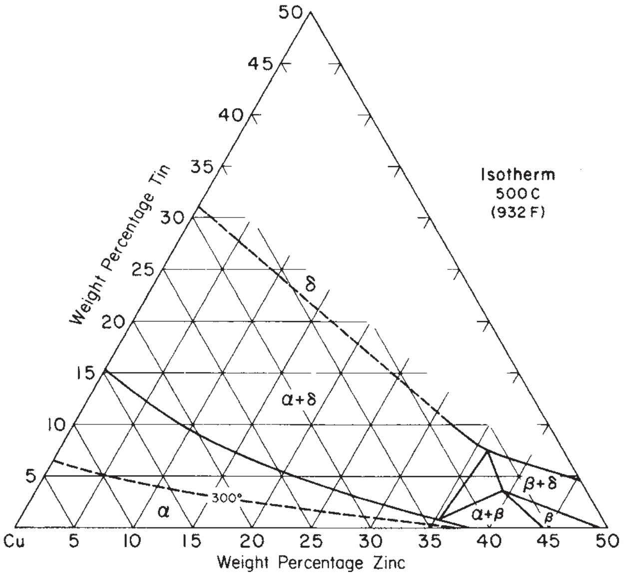

Fig. 33 Isotherm at 500 °C (932 °F) for the copper-rich corner of the Cu-Zn-Sn phase diagram. The α solubility boundary at 300 °C (572 °F) is also shown.

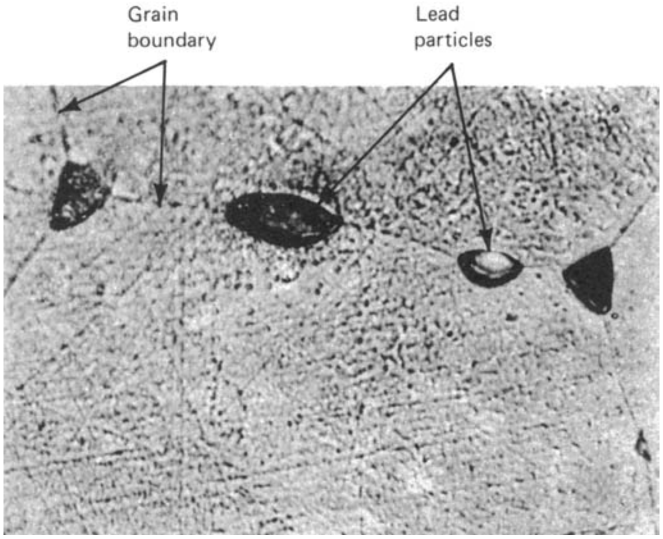

Fig. 34 Microstructure of a Cu-3Pb alloy, showing the configuration of the lead particles typical of leaded copper-base alloys. Light micrograph; 1000×. Source: Ref 24

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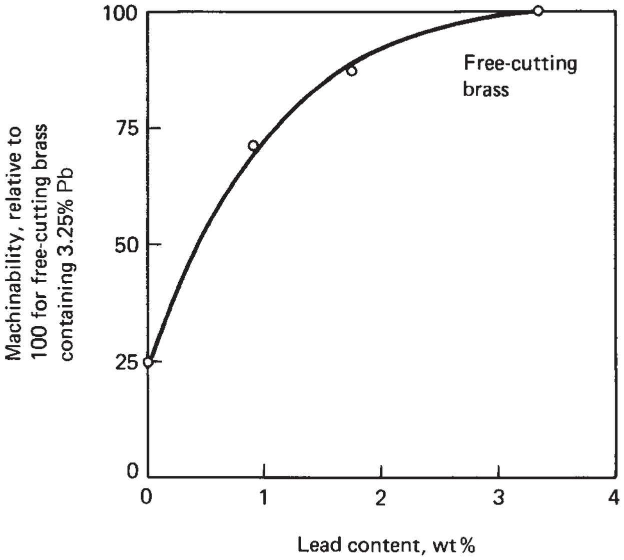

Fig. 35 Effect of lead content on the machinability of yellow brass (Cu-33Zn). All the lead is present as undissolved particles. Source: Ref 18

elongation decreases with increasing tin content. Although the Cu-8Sn alloy is quite ductile, it does not have nearly the workability of a Cu-30Zn solid-solution alloy.

The copper-tin phase diagram in Fig. 30 shows that the solubility of tin decreases markedly with decreasing temperature. However, below about 300 °C (570 °F) the rate of precipitation of ε is low, so that alloys up to about 10% Sn will be single-phase α after proper homogenization and cooling to 25 °C (75 °F). It also appears that these alloys would be precipitation hardenable, since δ has a high hardness. But the precipitation process is quite slow, so that the time for precipitation is too long to make such a treatment commercially feasible. The data in Table 6 show that aging a Cu-10Sn alloy for 5 h produces no significant difference in tensile properties and hardness from the as-cast condition.

The wide temperature range between the liquidus and solidus makes these alloys very susceptible to coring. Also, cast alloys with tin contents as low as 8% Sn frequently contain δ, a result of the fact that coring allows the outside of the α dendrites to attain about 13.5% Sn. This composition of α will react with the liquid to form some β by a peritectic reaction. This β then decomposes by a eutectoid reaction to α and γ; the γ then decomposes to form α and δ. This sequence can be quite complex and dependent upon the cooling rate. Figure 31 shows an as-cast microstructure of a copper-tin alloy.

The copper-tin alloys containing up to 10% Sn (and higher) are used for bearing applications, which require high strength to support heavy loads and wear resistance. Apparently, the hard δ phase is important in the wear resistance, and the solid-solution strengthening allows the development of strength. These alloys are frequently used for bearing applications in the as-cast condition, with no subsequent heat treatment, so the initial properties are dependent upon the development of δ during the solidification process. If the alloy is to be used in the as-cast condition, then the properties can only be controlled by the casting process. The main factor is the primary α grain size, and the δ-containing structure. The primary α grain size can be reduced by increasing the nucleation rate from the liquid, either by inoculation or by increasing the cooling rate. The effect of the cooling rate is shown in Fig. 32, where the faster cooling has formed considerably finer α dendrites.

Copper-Zinc-Tin Alloys

The solid-solution strengthening effect of zinc on copper should be enhanced by substituting some tin for zinc. The ternary phase diagram (Fig. 33) shows that the combined solutes have extensive solubility in α. For example, an alloy containing 10% Zn will dissolve up to about 9% Sn at 500 °C (932 °F); however, the solubility at 300 °C (572 °F) is only 4%. For a 30% Zn alloy, the solubility at 300 °C (572 °F) is only about %. Although the solubility of tin in α in the lower-zinc alloys is sufficient to make the addition of tin attractive, the problem of the formation of the brittle δ phase during casting limits the amount of tin to values less than 2%. However, even low tin contents measurably strengthen the copper-zinc binary alloys, as shown by the data in Table 7.

The addition of zinc to copper-tin alloys improves the soundness of the castings by affecting the solidification process. This has led to a group of alloys popular for making castings that must be pressure tight, such as for high-pressure water valves.

Copper-Base Leaded Alloys

It was pointed out in the section "Commercially Pure Copper" that the amount of lead must be kept low to be able to hot work copper (and also the brasses), because if the quite low solubility of lead in copper is exceeded, a lead-rich liquid film wets the grain boundaries, reducing the strength. However, if the lead content exceeds approximately 0.5%, at 25 °C (75 °F) the lead is essentially all located along the grain

Table 8 Effect of heat treatment on hardness for a Cu-11.8Al (eutectoid) alloy and a Cu-10.2Al alloy

	Cu-11.8Al		Cu-10.2Al	
Heat treatment	Structure produced	Brinell hardness	Structure produced	Brinell hardness
Slowly cooled (furnace cooled)	Pearlite ($a + Y_2$)	220	Primary a + pearlite ($a + Y_2$)	150
Rapidly cooled (water quenched)	All-β martensite	150	All-β martensite	240
Rapidly cooled, then tempered 30 min(a)	$a + Y_2$	240	$a + Y_2$	110

(a) Cu-11.8Al tempered at 500 °C (930 °F); Cu-10.2Al, at 350 °C (660 °F). Source: Ref 19

Table 9 Effect of heat treatment on some mechanical properties of a Cu-9.8Al alloy

	Approximate properties		
Heat treatment	Hardness, HB	Elongation, %	Izod impact energy, kgf · m
Quenched from 900 °C (1650 °F)	155	7	4
Annealed at 650 to 700 °C (1200–1290 °F)	110	40	5
Annealed at less than 570 °C (1060 °F)	115	30	1.5

Source: Ref 19

Table 10 Some mechanical properties of a Cu-1.9Be alloy for four different treatments

Treatment	Hardness	0.2% yield strength, MPa	0.2% yield strength, ksi	Tensile strength, MPa	Tensile strength, ksi	Elongation, %
Solution annealed for 8 min at 800 °C (1470 °F), water quenched	61 HRB	255	37	490	71	56
Solution annealed for 8 min at 800 °C (1470 °F), water quenched, then cold rolled to a reduction in thickness of 38%	100 HRB	740	107	795	115	5
Solution annealed treatment, then aged for 3h at 345 °C (655 °F)	42 HRC	1160	168	1290	187	4
Solution annealed treatment, cold worked 38%, then aged for 2 h at 345 °C (655 °F)	42 HRC	1220	177	1370	199	3

Source: Ref 27

boundaries as separated particles, not spread along the grain boundaries. A typical microstructure is shown in Fig. 34. The leaded alloys usually do not have good hot-working characteristics, but they can be cold worked and safely annealed. The important advantage of adding lead is that the machinability greatly improves. Since many objects manufactured from copper-base alloys are machined, this is an important consideration. The effect is illustrated in Fig. 35. Thus, there are numerous commercial copper-base alloys that are leaded for machinability.

It is important to realize that the lead is very finely distributed. According to the copper-lead phase diagram (Fig. 8), upon solidification of an alloy containing from 0.5 to 3% Pb, just prior to the completion of freezing, the structure will consist mainly of α crystals with a small amount of liquid of monoeutectic composition (36% Pb). This liquid will freeze by forming simultaneously more α and lead-rich liquid. Upon further cooling, this liquid rejects more copper, which forms on the already existing α crystals, until at 326 °C (619 °F), the liquid, almost pure lead now, undergoes an eutectic reaction, forming almost all pure lead. Thus in the as-cast alloy, these lead particles are trapped between the primary α dendrites. However, upon hot working, or cold working and annealing, the original α crystals lose their identity, and the lead particles are found in the configuration shown in Fig. 34. To give a fine and uniform distribution of the lead particles, the solidification process must be controlled to give a fine α grain

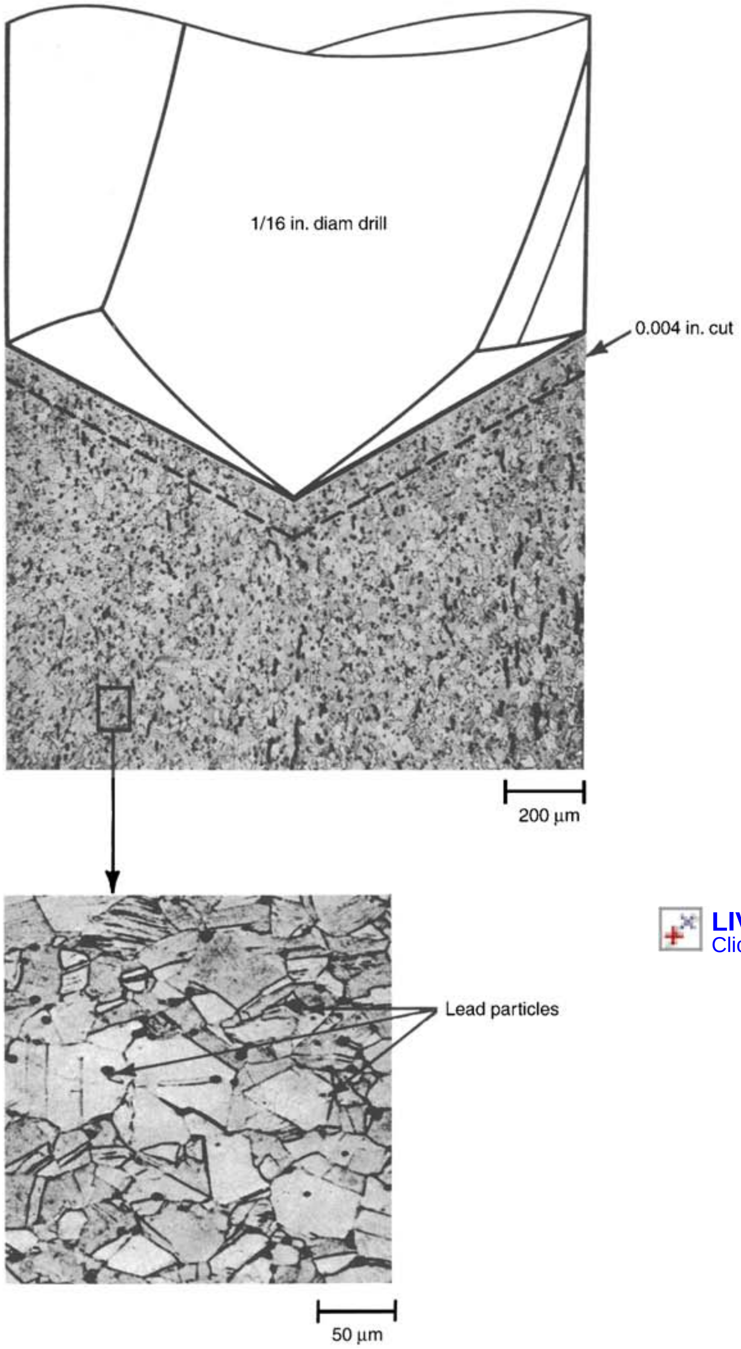

Fig. 36 Schematic illustration of the amount of material removed when a $\frac{1}{16}$ in. diameter drill penetrates 0.004 in. The number of lead particles in the volume of material removed is about 150,000 for an alloy containing 3% Pb, with the particle size shown in the higher-magnification photograph. Source: Ref 5, 18

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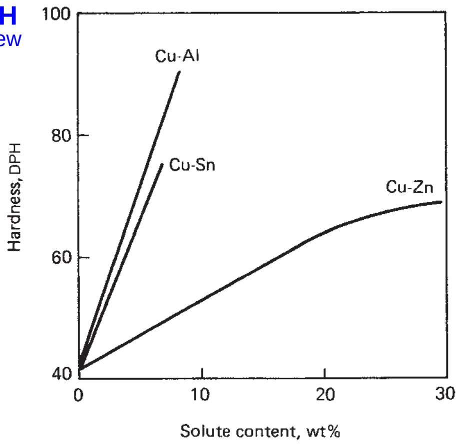

Fig. 37 Comparison of the effect of aluminum, tin, and zinc as solid-solution strengtheners of copper. Source: Ref 25

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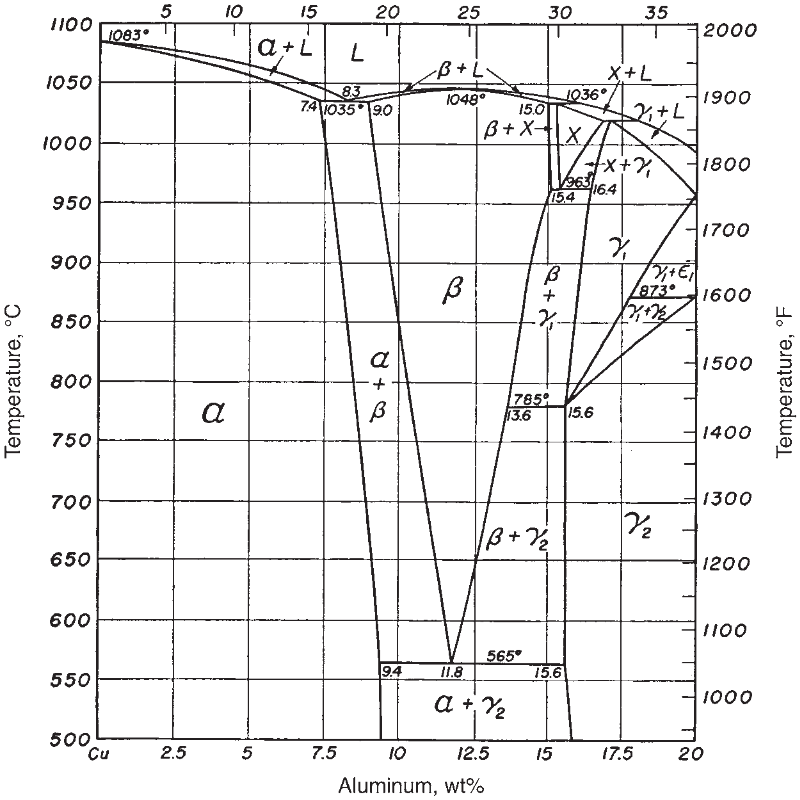

Fig. 38 Copper-rich end of the copper-aluminum phase diagram

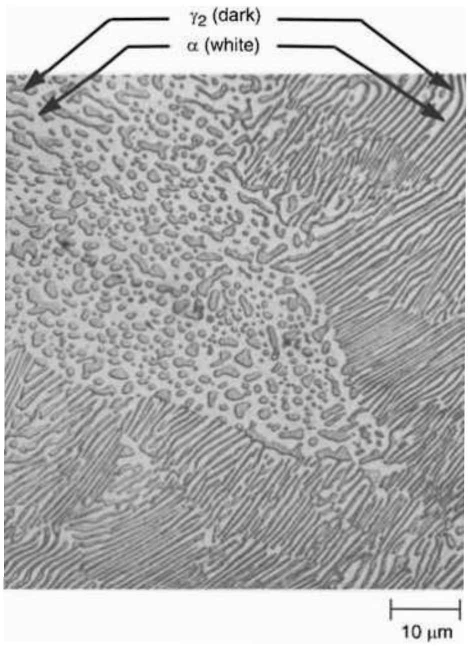

Fig. 39 Microstructure of a Cu-11.8Al alloy, homogenized at 800 °C (1470 °F) for 2 h, then cooled slowly in the furnace. The structure is pearlite of alternate plates of α and γ_2. The α is the white phase, and the γ_2 is the dark.

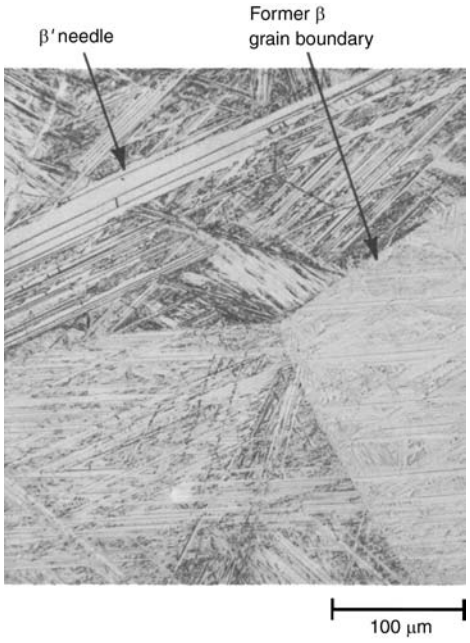

Fig. 40 Microstructure of a Cu-11.8Al alloy, homogenized for 2 h at 800 °C (1470 °F), then cooled rapidly (water quenched). The structure is thin needles of martensite, β′.

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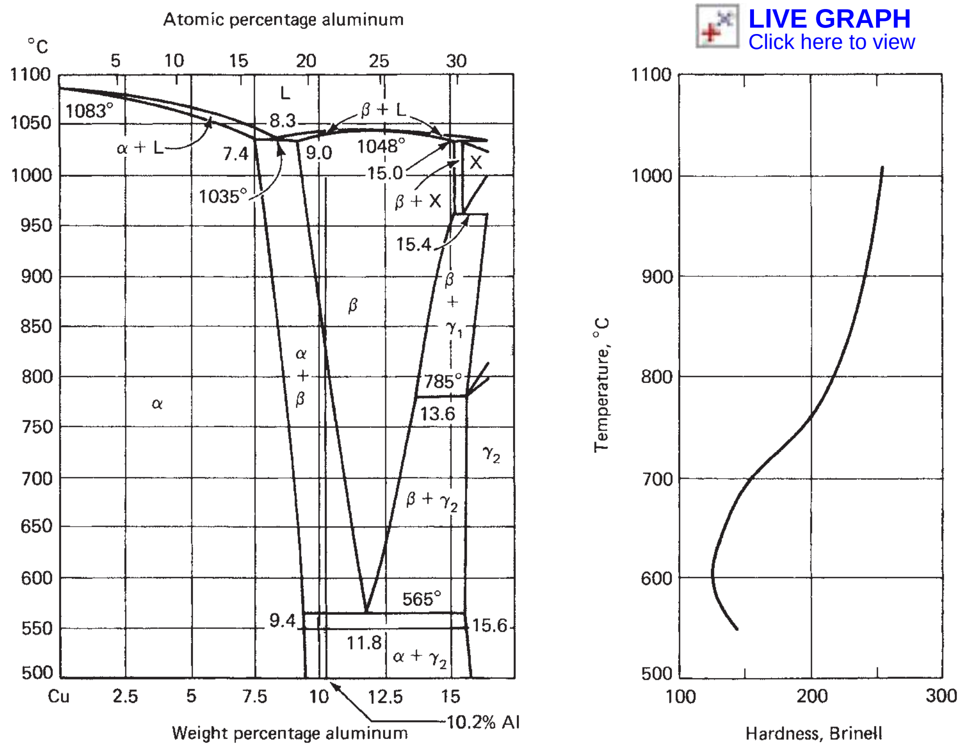

Fig. 41 Effect of quenching temperature on the hardness of a Cu-10.2Al alloy. The samples were initially heat treated to give a primary α and α + γ_2 eutectoid structure, heated at indicated temperatures for 30 min, then quenched. Source: Ref 19

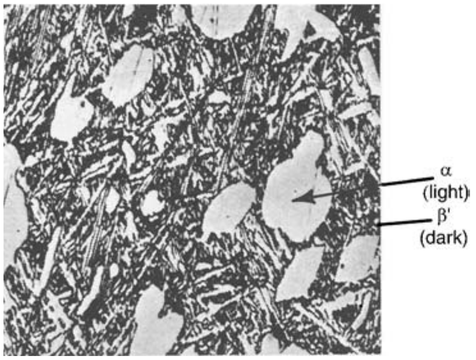

Fig. 42 Microstructure of a Cu-10.2Al alloy quenched from 750 °C (1380 °F), giving a structure of α and β′. 200×. Source: Ref 19

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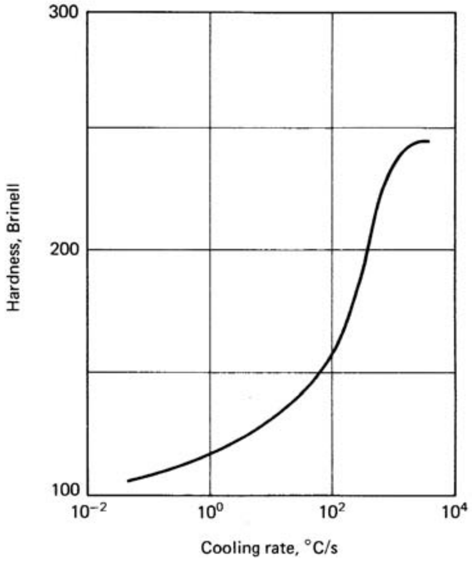

Fig. 43 Effect of cooling rate from 900 °C (1650 °F) on the hardness of a Cu-10.2Al alloy. Source: Ref 19

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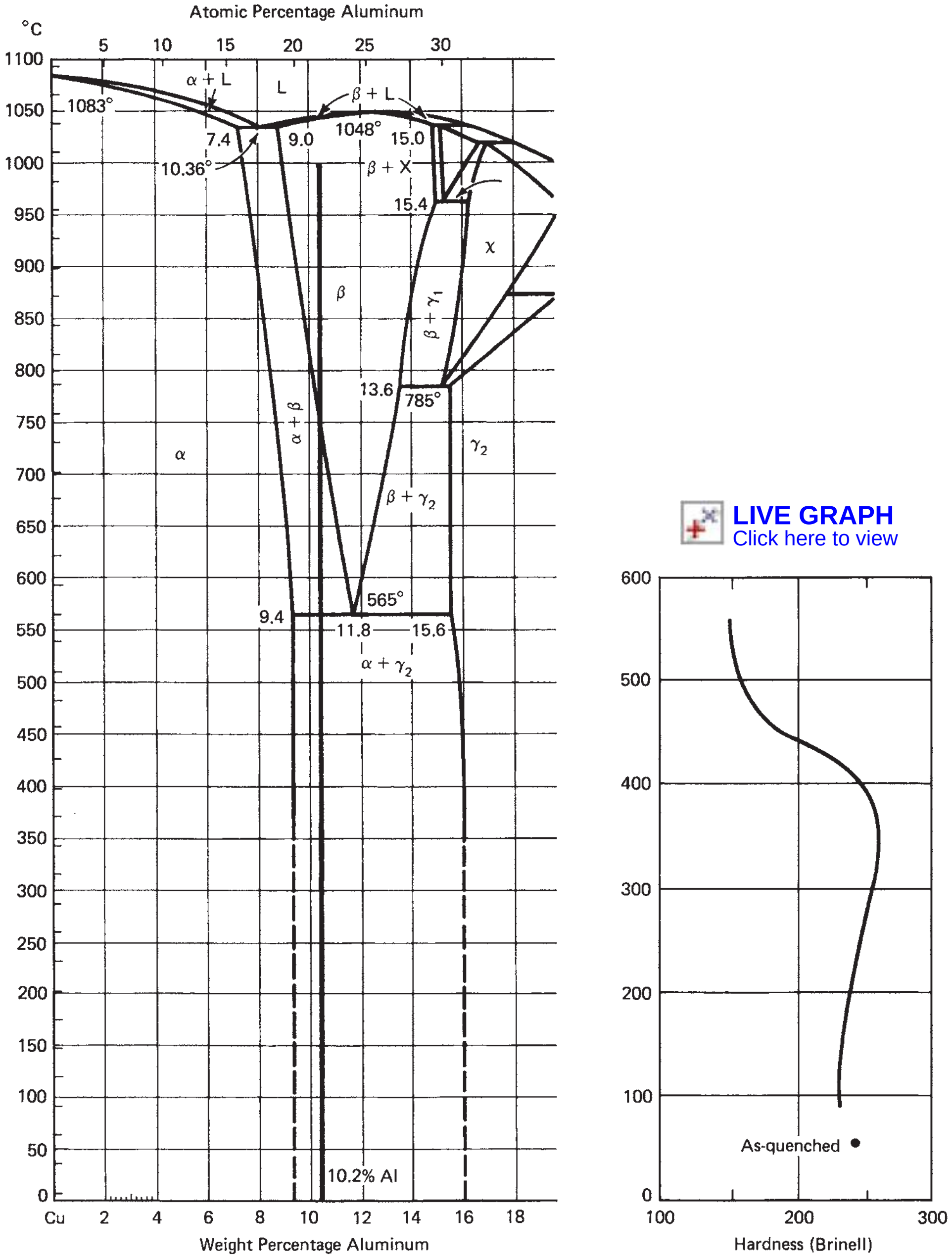


Fig. 44 Effect of tempering (for 30 min) on the hardness of a Cu-10.2Al alloy. The alloy was initially quenched from 900 °C (1650 °F). Source: Ref 19

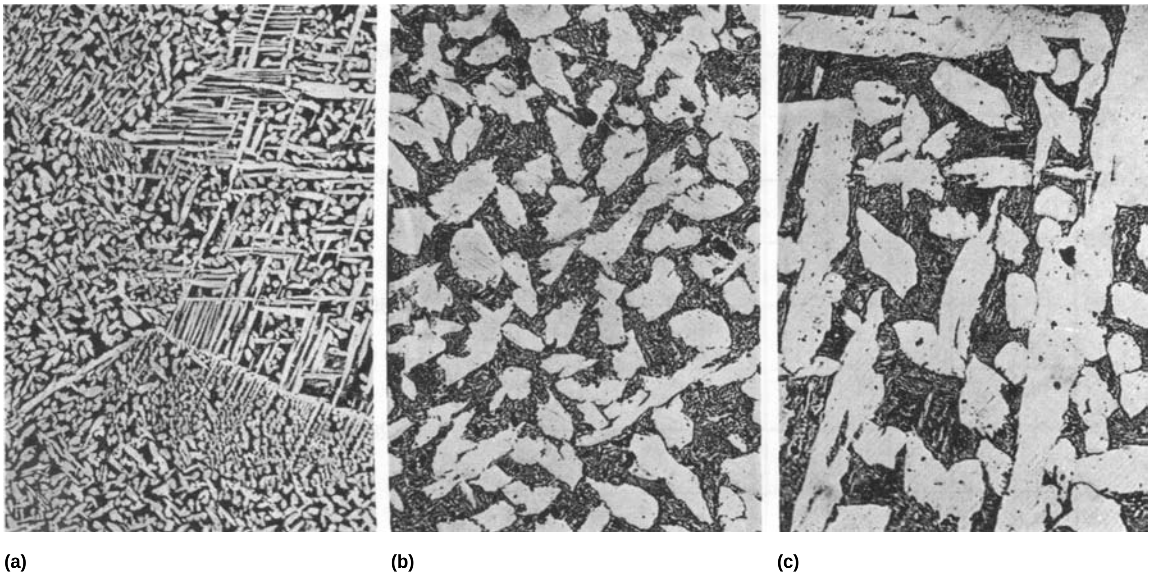
Table 11 Recommended heat treatments for some commercial cast and wrought copper-beryllium alloys

Alloy designation	Chemical composition, wt%	Solution treatment(a)	Aging treatment for maximum hardness
Cast alloys			
C82400	98Cu-1.7Be-0.3Co	800–815 °C (1470 –1500 °F)	3 h at 345 °C (655 °F)
C82500	97.2Cu-2Be-0.5Co-0.25Si	790–800 °C (1455–1470 °F)	3 h at 345 °C (655 °F)
C82600	97Cu-2.4Be-0.5Co	790–800 °C (1455–1470 °F)	3 h at 345 °C (655 °F)
C82800	96.6Cu-2.6Be-0.5Co-0.3Si	790–800 °C (1455–1470 °F)	3 h at 345 °C (655 °F)
Wrought alloys			
C17000	98Cu-1.7Be-0.3Co	775–800 °C (1425–1470 °F)	1 to 3 h at 315 to 345 °C (600–655 °F), depending upon amount of cold working prior to aging
C17200	Cu-1.9Be-0.3Co	760–790 °C (1400–1455 °F)	1 to 3 h at 315 to 345 °C (600–655 °F), depending upon amount of cold working prior to aging

(a) Time depends upon thickness of part. Allow 1 h for each 25 mm (1 in.) of thickness.

size, and freezing must be sufficiently rapid so as not to allow the lead-rich liquid to separate under gravity but instead be trapped by the α dendrites.

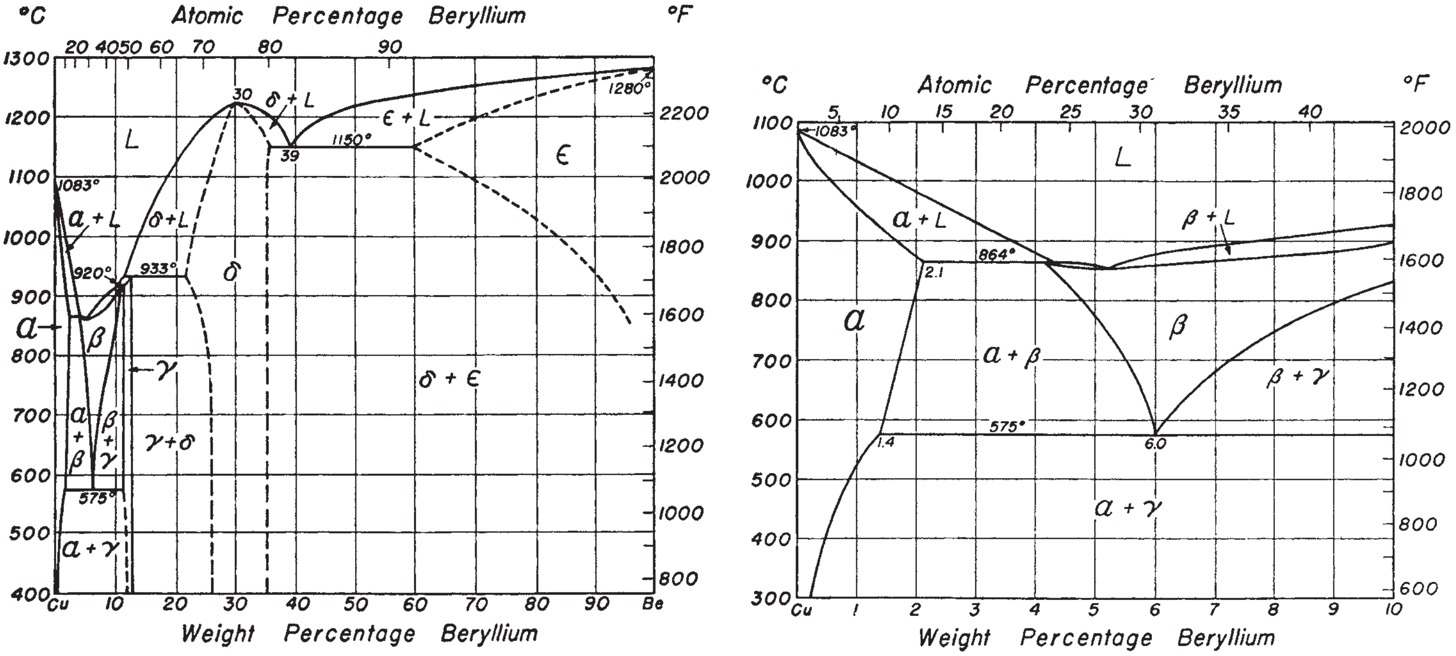
To appreciate the fineness of the distribution of the lead particles, note that for particles similar in size to those shown in Fig. 34, an alloy containing about 3% Pb will have a particle density of about 10^{10} particles per cubic inch of material. If a $^{1}/_{16}$ in. diameter drill removes about 0.004 in. of this material in one revolution, the volume of material removed by the drill will contain about 150,000 lead particles (see Fig. 36). Thus, the cutting edge of the drill encounters a large number of lead particles during the one revolution. The finely



(a) (b) (c)

Specimen	Tensile strength		Yield strength		Elongation, %	Hardness, HB
	MPa	ksi	MPa	ksi		
Chill cast 22 mm (⅞ in.) bar (Fig. 45a)	620	90	275	40	15	140
Ear of chilled test block (Fig. 45b)	520	75	255	37	12	140
Ear of sand cast test block (Fig. 45c)	415	60	295	43	8	160

Fig. 45 Microstructures (light micrographs) and properties of a Cu-10.5Al-1.0Fe alloy that was cooled at different rates from the liquid. The magnification is about 100×. The light areas are primary α, and the dark background consists of unresolved decomposition products of β, which are either β′ martensite or α and γ_2, depending on the cooling rate. (a) Chill cast 22 mm (⅞i n.) bar. (b) Ear of chilled test block. (c) Ear of sand cast test block. Source: Ref 26



(a) (b)

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Fig. 46 (a) The copper-beryllium phase diagram. (b) Copper-rich end of the copper-beryllium diagram divided lead makes the alloy relatively brittle and weak on a microscopic scale, as the lead particles are weak, and the cutting tool more easily fractures the matrix material separating the weak lead particles. In addition, the lead acts as a lubricant, so that less energy is required for machining.

Copper-Aluminum Alloys

In a general sense, the copper-aluminum phase diagram is similar to that for copper-zinc. There is a rather high solubility of aluminum in copper, and several intermetallic compounds occur for higher aluminum contents, some of which have the same crystal structure and stoichiometry as ones in the copper-zinc system. With a high atom-size difference combined with a relatively high maximum solubility (Table 3), it would be expected that commercial copper-aluminum alloys that are solid solutions would be available because of their strength. Figure 37 shows that aluminum is indeed a potent strengthener, and there are two common commercial copper-aluminum alloys (5 and 8% Al) that are solid solutions, their heat treatments involving only the conventional homogenization of the as-cast structure and annealing of the cold-worked structure.

Figure 38 shows the copper-rich portion of the copper-aluminum phase diagram. The phases established at 500 °C (932 °F) are essentially those at lower temperatures, unless extremely long annealing times are employed. Note that alloys with aluminum contents above about 8% are subject to the formation of β at high temperature, which, upon slow cooling, undergoes a eutectoid reaction to α and γ_2. Therefore, this eutectoid reaction is examined briefly, followed by a discussion of a specific commercial alloy (Cu-10Al) whose composition allows α, β, and γ_2 to be present.

The Eutectoid Reaction. The β phase is body-centered cubic, like the β phase in the copper-zinc system (Fig. 10), and the γ_2 phase is similar to that of γ. The eutectoid composition is

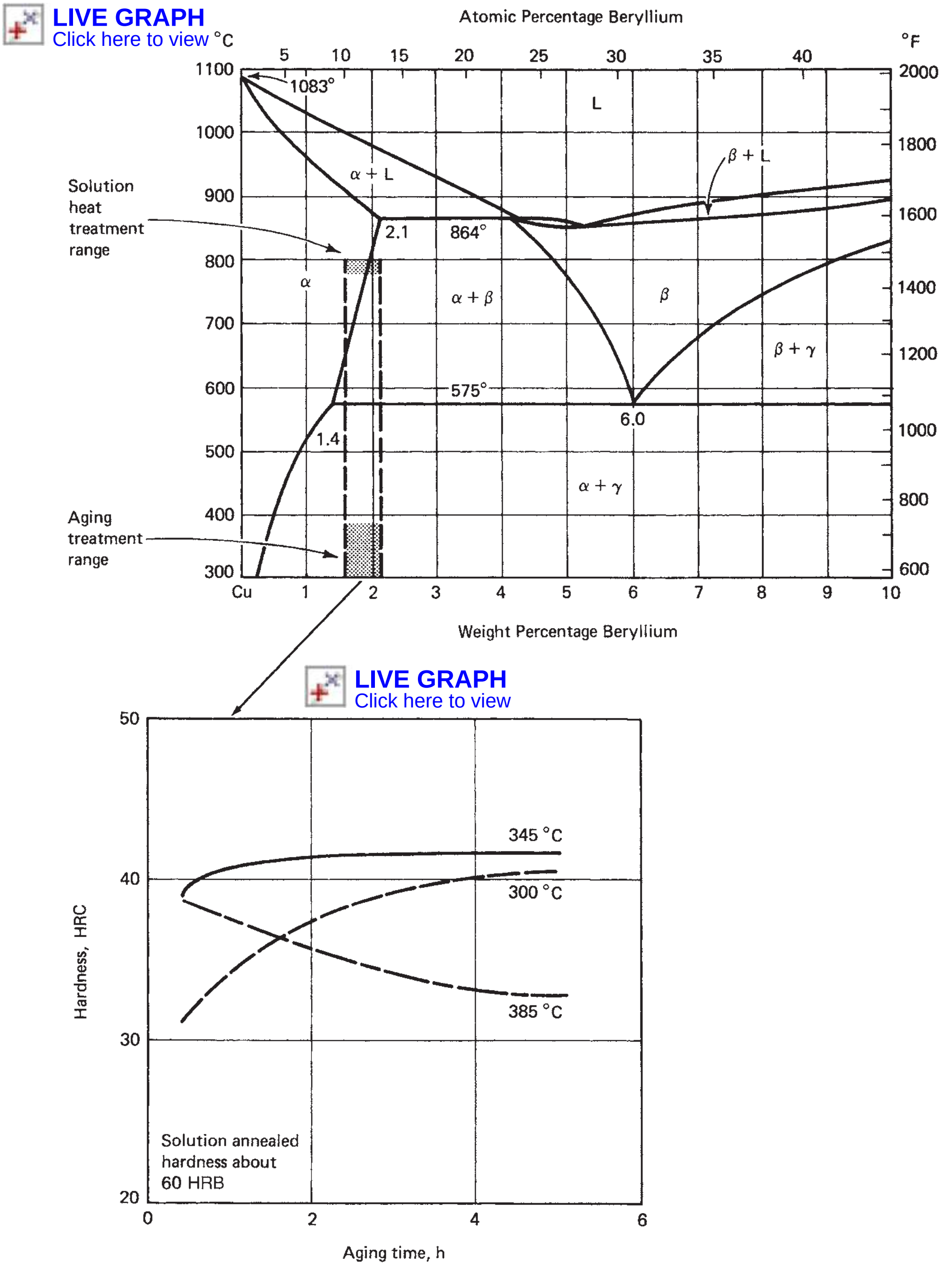

Fig. 47 Age-hardening response of a Cu-1.9Be alloy. It was solution heat treated for about 8 min at 800 °C (1470 °F), then water quenched, giving a hardness of approximately 60 HRB. Source: Ref 27

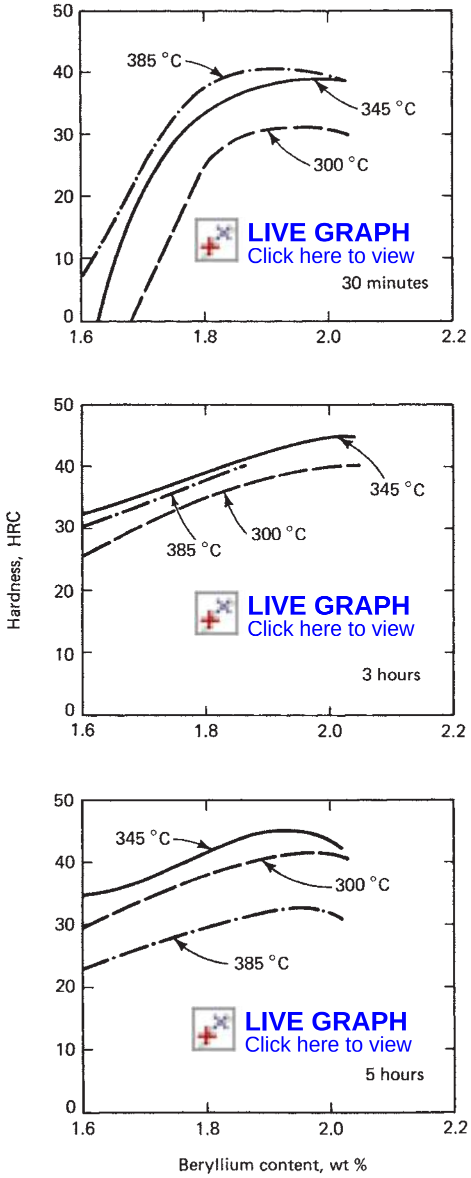

Fig. 48 Effect of beryllium content, aging temperature, and aging time on the precipitation hardening of copper-beryllium alloys. Source: Ref 27

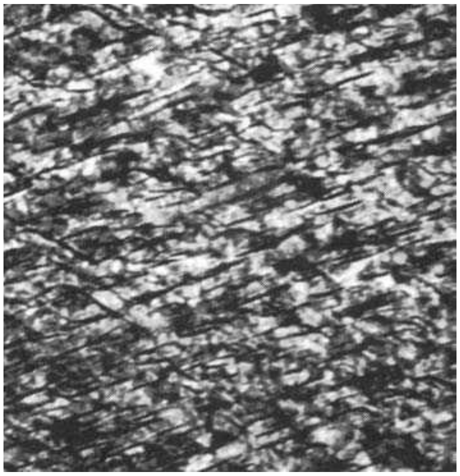

Fig. 49 Microstructure of a Cu-2Be alloy solution treated at 800 °C (1470 °F), water quenched, then aged at 350 °C (660 °F) for 4 h. The dark lines are the metastable precipitate. Transmission electron micrograph; 70,000×. Source: Ref 28

at 11.8% Al, and upon cooling an alloy of this composition slowly (e.g., 50 °C/h, or 90 °F/h) after homogenization in the β region (e.g., 1 h at 800 °C, or 1470 °F), the α and γ_2 phases form in an alternate-layer configuration. This is similar in appearance to the eutectoid structure in iron-carbon alloys, where the morphology is called pearlite, and this term is used here to describe this eutectoid structure. Figure 39 shows a microstructure typical of the eutectoid alloy after slowly cooling from β.

Rapid cooling from β might be expected to suppress the eutectoid reaction and to leave retained β at 20 °C (68 °F). This structure then would decompose very slowly and, for practical purposes, be stable at this temperature. Then the properties of β could be utilized for the development of alloys. However, as in steels (iron-carbon alloys), the β undergoes a transformation to another phase (β′) even upon the most rapid cooling practical. This is a nonequilibrium phase, not shown on the phase diagram. It has a hexagonal crystal structure and is ordered. It forms by a martensite reaction (as in steels), with the β decomposing into long needles. Upon rapid cooling, when a temperature of about 380 °C (715 °F) (the martensite start temperature, M_s) is reached, these needles begin to appear with great speed in the β; as cooling toward 20 °C (68 °F) continues, the remaining β decomposes into these fine needles. The final structure is illustrated in Fig. 40.

Now in steels, martensite is the hardest structure. For example, in a eutectoid alloy, Fe-0.8C, the slowly cooled steel will have a hardness (typically) of about 20 HRC, whereas the martensite structure will be 65 HRC. Hence the use of quenching for hardening in steels. However, in the copper-aluminum eutectoid alloy here, the martensite will be approximately 70 HRB, and the pearlite formed after cooling slowly will be approximately 80 HRB. Thus, the slowly cooled product is slightly harder than that formed upon rapid cooling. This hardness change reflects the influence of the very hard γ_2 on the hardness of the structure.

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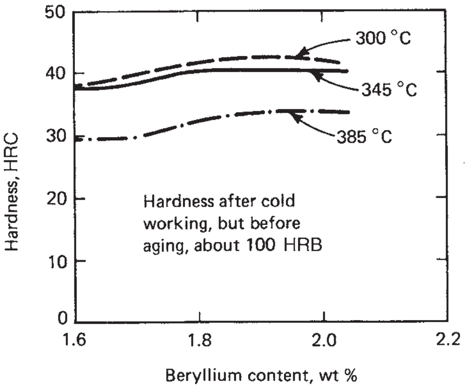

Fig. 50 Effect of cold working on the aging response of copper-beryllium alloys. The alloys were solution annealed at 800 °C (1470 °F) for 10 min, water quenched, then reduced in thickness about 40% by rolling, then aged for 3 h. Source: Ref 27

Also, in steels the hardness of the martensite is reduced by heating the alloy below the eutectoid temperature to convert the martensite to the equilibrium phases, a heat treatment called tempering. However, in the copper-aluminum alloy here, heating the β′ martensite below the eutectoid temperature (565 °C, or 1049 °F, as shown in Fig. 38) will increase the hardness. If the martensite has a hardness of approximately 70 HRB, then heating around 500 °C (930 °F) for 30 min will increase the hardness to about 90.

Physical Metallurgy of the Cu-10Al Alloy. Table 8 lists the hardness and structure for different heat treatments for the eutectoid alloy. For comparison, also shown are the hardness and structure for a 10% Al alloy for similar heat treatments. This 10% Al alloy is now examined in some detail.

Figure 41 shows the effect of the quenching temperature on the hardness of a Cu-10Al alloy. Heating above about 850 °C (1560 °F) results in a structure that is all β, and hence upon quenching, an all-martensite structure is formed, with a hardness of about 250 HB. The microstructure would be similar to that in Fig. 40. Holding below about 850 °C (1560 °F) results in increasing amounts of β existing with the α, and hence the quenched alloy has an increasing amount of the soft α present, decreasing the Brinell hardness to about 120. A microstructure typical to that for the alloy quenched from the α–β region is shown in Fig. 42.

If, instead of quenching from the β region, the Cu-10Al alloy is cooled slowly (e.g., furnace cooled), a large amount (about 50% by a mass balance calculation) or primary α will form, and the rest of the structure will be the eutectoid pearlite. Even though the pearlite is harder than the β′ martensite, the large amount of the soft α makes the alloy soft for this heat treatment. As the cooling rate decreases from rapid cooling, increasing amounts of the soft α and decreasing amounts of martensite appear, and the hardness decreases (Fig. 43).

Tempering of the quenched Cu-10Al alloy results in an increase in hardness if the alloy is tempered around 350 °C (660 °F), but a decrease in hardness when tempered at higher temperatures (Fig. 44). The increase is due to the formation of a fine dispersion of the hard γ_2 in the softer α. However, at sufficiently high tempering temperatures (i.e., above about 400 °C, or 750 °F), the tempering time is sufficient to allow coarsening of the γ_2, and the hardness decreases.

Table 8 shows that the eutectoid Cu-11.8Al alloy was hardest if the structure was α + γ_2, formed either by cooling slowly from β or by tempering the β′ martensite. However, increasing aluminum content decreases the hardness of the β′ martensite (although it is not clear why). Thus, the Cu-10Al alloy is hardest with the least amount of soft α, and the maximum amount of β′. This is in the quenched condition.

The data in Fig. 41, 43, and 44 show that a copper-aluminum alloy containing approximately 10% Al would have the highest hardness when water quenched from the β region, or when water quenched and tempered below approximately 400 °C (750 °F). However, the toughness for these heat-treated conditions must be considered. Table 9 shows that annealing below approximately 600 °C (1110 °F) will embrittle the alloy. Note that the elongation at fracture indicates considerable toughness, but upon impact loading, the alloy is considerably more brittle than for the other two heat treatments listed. (Note that these data are for a 9.8% Al alloy). Thus, a heat-treating recommendation for a Cu-9Al bronze for most commercial purposes calls for annealing at 650 °C (1200 °F), and then quench. Annealing below 570 °C (1060 °F) should be avoided along with cooling too slowly from the annealing temperature.

It must be borne in mind that the properties of these copper-aluminum alloys that involve primary α depend quite sensitively upon the primary α grain size and shape. This is demonstrated by the microstructures in Fig. 45. This alloy was cooled from the liquid at different rates, which affected not only the original β grain size, but the subsequent α grain size that formed upon cooling into the α + β region. The cooling rate also affects the decomposition of the β. Note in the figure that the finer the primary α structure, the greater the tensile strength. However, the complex structure brings about some unpredicted effects on properties. The hardness is almost unaffected, and the structure with the coarser primary α grain size has the least ductility. This structure was the most slowly cooled of the three sections of the casting, and hence the decomposition of β into the more brittle α + γ_2 structure was favored.

Copper-Beryllium Alloys

Table 3 shows that there is a size difference between beryllium and copper comparable to that between copper and aluminum or tin.

Figure 46 shows that the solubility is quite limited, so that the addition of beryllium for solid-solution strengthening is not favorable. However, alloys containing greater than 1.5% Be might be precipitation hardenable, since around 800 °C (1470 °F) they will be single-phase α (or α + β), and at lower temperature, the γ (copper-beryllium) phase will precipitate from α. Indeed, in this alloy remarkable precipitation strengthening occurs, with hardness values above 40 HRC. (To place this in perspective, this is the range normally associated with steels.)

These copper-beryllium alloys show precipitation-hardening behavior similar to that observed for copper-aluminum alloys. Figure 47 illustrates the effect of aging time and of aging temperature. For this Cu-1.9Be alloy, the optimal aging temperature is around 350 °C (660 °F).

The data in Fig. 48 show that for maximum hardness the beryllium content should be between 1.8 and 2.0%. The aging temperature should be around 350 °C (660 °F), and the aging time can be between 3 and 5 h. Note that the aging temperature, aging time, and beryllium content are all rather flexible, and yet an approximate maximum hardness of about 40–45 HRC can be attained.

As in many other precipitation processes, the equilibrium precipitate γ is preceded by the formation of a metastable phase. The hardening is caused by the precipitation of this phase in an extremely finely dispersed manner, as illustrated in Fig. 49. The precipitates are disks from 200 to 400 atoms in diameter, and approximately 50 atoms thick, and very close together. As shown in Fig. 47, these alloys will overage as the structure coarsens, and the equilibrium precipitate forms.

The recrystallization temperature for these alloys is in the range of 500 °C (930 °F) and above. If these alloys are solution annealed, then cold worked prior to aging in the range 300 to 385 °C (570–725 °F), the precipitation process will occur before recrystallization (and hence softening) can occur. The effect of such a treatment on hardness is shown in Fig. 50. Note that the hardness in this condition is not significantly different from that of the aged material without prior cold working. However, the data in Table 10 show that the yield and tensile strength are greatly enhanced by prior cold working. Note that in the aged condition, with or without prior cold work, the ductility is quite low.

The commercial precipitation-hardening copper-beryllium alloys have alloy additions other than beryllium. Many contain some cobalt, which forms an insoluble beryllium-cobalt compound that inhibits grain growth during solution annealing. Also, the cast alloys have additions that act as grain refiners to control the as-cast grain size. Table 11 gives the recommended heat treatment for some of the commercial copper-beryllium alloys. Note that the solution treatment and the aging treatment are essentially independent of the exact alloy, which would be predicted from the data in Fig. 49 and 50 (as discussed previously).

In heat treating, some precautions should be taken. One is to avoid using too high a solution temperature, as partial melting may occur, and upon cooling the β phase will form, which is difficult to dissolve upon subsequent solution annealing. The other is to avoid too low a solution temperature, because β will form at the solution temperature. Its formation lowers the beryllium content of the α, and the hardening response is reduced. Also, this β is difficult to redissolve by resolution annealing. Also, if the alloy is not cooled sufficiently rapidly from the solution temperature, then some β may form during cooling. Thus, control of the water quenching must be maintained.

ACKNOWLEDGMENT

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Wrought Copper and Copper Alloys

WROUGHT COPPER AND COPPER ALLOYS comprise one of the largest families of engineering materials. In North America alone, there are currently more than 275 recognized "standard" wrought grades. Best known for high conductivity and corrosion resistance, this large and diverse group of materials also offers a wide range of mechanical and physical properties, often in unique combinations.

Designating Copper and Its Alloys

A copper or copper alloy is identified by product form (sheet or rod, for example), temper, and composition. Some are produced in all product forms, while others are limited to one or two. The temper of a material describes both its mechanical state and its properties. A temper designation system for copper and its alloys is detailed in ASTM B 601, "Standard Practice for Temper Designations for Copper and Copper Alloys—Wrought and Cast."

Under the Unified Numbering System (UNS), copper and copper alloys are designated by five-digit numbers preceded by the letter "C." The format is essentially the Copper Development Association's former three-digit system expanded to accommodate new compositions. Using the UNS system, numbers ranging from C10000 through C79999 denote wrought alloys.

More detailed information on both the temper and UNS designations for copper alloys can be found in the article "Standard Designations for Wrought and Cast Copper and Copper Alloys" in this Handbook. International standards and designations are also discussed in the same article.

Wrought Copper and Copper Alloy Families

The most common way to catalog copper and copper alloys is to divide them into six families: coppers, high-copper (or dilute) alloys, brasses, bronzes, copper-nickels, and nickel silvers. The first family, the coppers, is essentially commercially pure copper, which ordinarily is soft and ductile and contains less than about 0.7% total impurities. The high-copper alloys contain small amounts of various alloying elements, such as beryllium, cadmium, chromium, and iron, each having less than 8 at.% solid solubility; these elements modify one or more of the basic properties of copper. Each of the remaining families contains one of five major alloying elements as its primary alloying ingredient:

Family	Alloying element	Solid solubility(a), at.%
Brasses	Zinc	37
Phosphor bronzes	Tin	9
Aluminum bronzes	Aluminum	19
Silicon bronzes	Silicon	8
Copper-nickels, nickel silvers	Nickel	100

(a) At 20 °C (70 °F)

The purpose of adding alloying elements to copper is to optimize the strength, ductility (formability), and thermal stability, without inducing unacceptable loss in fabricability, electrical/thermal conductivity, or corrosion resistance. Copper alloys show excellent hot and cold ductility, although usually not to the same degree as the unalloyed parent metal. Even alloys with large amounts of solution-hardening elements—zinc, aluminum, tin, and silicon—that show rapid work hardening are readily commercially processed beyond 50% cold work before a softening anneal is required to permit additional processing. The amount of cold working and the annealing parameters must be balanced to control grain size and crystallographic texturing. These two parameters are controlled to provide annealed strip products at finish gage that have the formability needed in the severe forming and deep drawing commonly done in commercial production of copper, brass, and other copper alloy hardware and cylindrical tubular products.

Table 1 lists nominal compositions, product forms, and mechanical property ranges for wrought coppers and copper alloys. Physical properties of representative wrought alloys are listed in Table 2. Tables 3 through 6 list wrought copper alloys ranked by their tensile strength, yield strength, electrical conductivity, and thermal conductivity, respectively. Additional property data can be found in the article "Properties of Wrought Copper and Copper Alloys" in this Handbook.

Coppers

Wrought coppers (C10100 to C15999) must contain at least 99.3% Cu, but may include residual deoxidizers or minor alloying elements. The normally soft, ductile metals can be strengthened by cold working. However, exposure to elevated temperatures readily anneals the cold-worked microstructure. Coppers are inherently resistant to atmospheric and aqueous corrosion, and are relatively insensitive to stress-corrosion cracking (SCC). Their most important characteristic is superior electrical conductivity. They are primarily used for electrical and electronic products.

Oxygen-free coppers (C10100 to C10700) are generally reserved for applications requiring the highest electrical conductivity. Their conductivity is at least 100% IACS (Inter-national Annealed Copper Standard, as described in the "Introduction and Overview" to this Handbook). Electrolytic tough pitch copper (C11000) is commonly used for electrical wire and cable, as well as for roofing and architectural trim, while phosphorus-deoxidized copper (C12200) is the standard material for household water tube. Oxygen-free and deoxidized coppers can be welded without danger of embrittlement.

Silver imparts modest annealing resistance to copper without significantly affecting its electrical conductivity. This is why coppers containing residual silver have been used for electrical products that must not soften as a result of exposure to soldering temperatures. Arsenic, cadmium, and zirconium-coppers (C14200, C14300, and C15000, respectively) have similar properties. Cadmium also imparts wear resistance, a useful property for sliding electrical contacts. Arsenic improves resistance to corrosion and high-temperature oxidation, which are required for products such as heat-exchanger tubing. Tellurium-bearing coppers (C14500 and C14510) and sulfur-bearing copper (C14700) are free-machining, and are supplied as rods for making high-conductivity parts by screw machining.

Coppers C15715 through C15760 are dispersion-strengthened with aluminum oxide to inhibit softening at elevated temperatures. The combination of thermal stability and high electrical conductivity is useful in applications such as heavy-duty electrical connectors, vacuum tube components, and resistance welding electrodes. More detailed information on dispersion-strengthened alloys can be found in the article "Powder Metallurgy Copper and Copper Alloys" in this Handbook.

High-Copper Alloys

As stated earlier, the high-copper or dilute alloys (C16200 to C19900) contain ~94% Cu

Table 1 Nominal compositions, product forms, and properties of commonly used wrought copper and copper alloys

Alloy number (and name)	Nominal composition, %	Commercial forms (a)	Mechanical properties(b) Tensile strength MPa	Tensile strength ksi	Yield strength MPa	Yield strength ksi	Elongation in 50 mm (2 in.) (b), %	Machinability rating(c), %
C10100 (oxygen-free electronic copper)	99.99 Cu	F, R, W, T, P, S	221–455	32–66	69–365	10–53	55–4	20
C10200 (oxygen-free copper)	99.95 Cu	F, R, W, T, P, S	221–455	32–66	69–365	10–53	55–4	20
C10300 (oxygen-free extra-low-phosphorus copper)	99.95 Cu, 0.003 P	F, R, T, P, S	221–379	32–55	69–345	10–50	50–6	20
C10400, C10500, C10700 (oxygen-free silver-bearing copper)	99.95 Cu(d)	F, R, W, S	221–455	32–66	69–365	10–53	55–4	20
C10800 (oxygen-free low-phosphorus copper)	99.95 Cu, 0.009 P	F, R, T, P	221–379	32–55	69–345	10–50	50–4	20
C11000 (electrolytic tough pitch copper)	99.90 Cu, 0.04 O	F, R, W, T, P, S	221–455	32–66	69–365	10–53	55–4	20
C11100 (electrolytic tough pitch anneal-resistant copper)	99.90 Cu, 0.04 O, 0.01 Cd	W	455	66	…	…	1.5 in 1500 mm (60 in.)	20
C11300, C11400, C11500, C11600 (silver-bearing tough pitch copper)	99.90 Cu, 0.04 O, Ag(e)	F, R, W, T, S	221–455	32–66	69–365	10–53	55–4	20
C12000, C12100	99.9 Cu(f)	F, T, P	221–393	32–57	69–365	10–53	55–4	20
C12200 (phosphorus-deoxidized copper, high residual phosphorus)	99.90 Cu, 0.02 P	F, R, T, P	221–379	32–55	69–345	10–50	45–8	20
C12500, C12700, C12800, C12900, C13000 (fire-refined tough pitch with silver)	99.88 Cu(g)	F, R, W, S	221–462	32–67	69–365	10–53	55–4	20
C14200 (phosphorus-deoxidized arsenical copper)	99.68 Cu, 0.3 As, 0.02 P	F, R, T	221–379	32–55	69–345	10–50	45–8	20
C14300	99.9 Cu, 0.1 Cd	F	221–400	32–58	76–386	11–56	42–1	20
C14310	99.8 Cu, 0.2 Cd	F	221–400	32–58	76–386	11–56	42–1	20
C14500 (phosphorus-deoxidized tellurium-bearing copper)	99.5 Cu, 0.50 Te, 0.008 P	F, R, W, T	221–386	32–56	69–352	10–51	50–3	85
C14700 (sulfur-bearing copper)	99.6 Cu, 0.40 S	R, W	221–393	32–57	69–379	10–55	52–8	85
C15000 (zirconium-copper)	99.8 Cu, 0.15 Zr	R, W	200–524	29–76	41–496	6–72	54–1.5	20
C15100	99.82 Cu, 0.1 Zr	F	262–469	38–68	69–455	10–66	36–2	20
C15500	99.75 Cu, 0.06 P, 0.11 Mg, Ag(h)	F	276–552	40–80	124–496	18–72	40–3	20
C15710	99.8 Cu, 0.2 Al_2O_3	R, W	324–724	47–105	268–689	39–100	20–10	…
C15720	99.6 Cu, 0.4 Al_2O_3	F, R	462–614	67–89	365–586	53–85	20–3.5	…
C15735	99.3 Cu, 0.7 Al_2O_3	R	483–586	70–85	414–565	60–82	16–10	…
C15760	98.9 Cu, 1.1 Al_2O_3	F, R	483–648	70–94	386–552	56–80	20–8	…
C16200 (cadmium-copper)	99.0 Cu, 1.0 Cd	F, R, W	241–689	35–100	48–476	7–69	57–1	20
C16500	98.6 Cu, 0.8 Cd, 0.6 Sn	F, R, W	276–655	40–95	97–490	14–71	53–1.5	20
C17000 (beryllium-copper)	99.5 Cu, 1.7 Be, 0.20 Co	F, R	483–1310	70–190	221–1172	32–170	45–3	20
C17200 (beryllium-copper)	99.5 Cu, 1.9 Be, 0.20 Co	F, R, W, T, P, S	469–1462	68–212	172–1344	25–195	48–1	20
C17300 (beryllium-copper)	99.5 Cu, 1.9 Be, 0.40 Pb	R	469–1479	68–200	172–1255	25–182	48–3	50
C17400	99.5 Cu, 0.3 Be, 0.25 Co	F	620–793	90–115	172–758	25–110	12–4	20
C17500 (copper-cobalt-beryllium alloy)	99.5 Cu, 2.5 Co, 0.6 Be	F, R	310–793	45–115	172–758	25–110	28–5	…
C18200, C18400, C18500 (chromium-copper)	99.5 Cu(i)	F, W, R, S, T	234–593	34–86	97–531	14–77	40–5	20
C18700 (leaded copper)	99.0 Cu, 1.0 Pb	R	221–379	32–55	69–345	10–50	45–8	85
C18900	98.75 Cu, 0.75 Sn, 0.3 Si, 0.20 Mn	R, W	262–655	38–95	62–359	9–52	48–14	20
C19000 (copper-nickel-phosphorus alloy)	98.7 Cu, 1.1 Ni, 0.25 P	F, R, W	262–793	38–115	138–552	20–80	50–2	30
C19100 (copper-nickel-phosphorus-tellurium alloy)	98.15 Cu, 1.1 Ni, 0.50 Te, 0.25 P	R, F	248–717	36–104	69–634	10–92	27–6	75
C19200	98.97 Cu, 1.0 Fe, 0.03 P	F, T	255–531	37–77	76–510	11–74	40–2	20
C19400	97.5 Cu, 2.4 Fe, 0.13 Zn, 0.03 P	F	310–524	45–76	165–503	24–73	32–2	20
C19500	97.0 Cu, 1.5 Fe, 0.6 Sn, 0.10 P, 0.80 Co	F	552–669	80–97	448–655	65–95	15–2	20
C19700	99 Cu, 0.6 Fe, 0.2 P, 0.05 Mg	F	344–517	50–75	165–503	24–73	32–2	20
C21000 (gilding, 95%)	95.0 Cu, 5.0 Zn	F, W	234–441	34–64	69–400	10–58	45–4	20
C22000 (commercial bronze, 90%)	90.0 Cu, 10.0 Zn	F, R, W, T	255–496	37–72	69–427	10–62	50–3	20
C22600 (jewelry bronze, 87.5%)	87.5 Cu, 12.5 Zn	F, W	269–669	39–97	76–427	11–62	46–3	30
C23000 (red brass, 85%)	85.0 Cu, 15.0 Zn	F, W, T, P	269–724	39–105	69–434	10–63	55–3	30
C24000 (low brass, 80%)	80.0 Cu, 20.0 Zn	F, W	290–862	42–125	83–448	12–65	55–3	30
C26000 (cartridge brass, 70%)	70.0 Cu, 30.0 Zn	F, R, W, T	303–896	44–130	76–448	11–65	66–3	30
C26800, C27000 (yellow brass)	65.0 Cu, 35.0 Zn	F, R, W	317–883	46–128	97–427	14–62	65–3	30
C28000 (Muntz metal)	60.0 Cu, 40.0 Zn	F, R, T	372–510	54–74	145–379	21–55	52–10	40
C31400 (leaded commercial bronze)	89.0 Cu, 1.75 Pb, 9.25 Zn	F, R	255–414	37–60	83–379	12–55	45–10	80
C31600 (leaded commercial bronze, nickel-bearing)	89.0 Cu, 1.9 Pb, 1.0 Ni, 8.1 Zn	F, R	255–462	37–67	83–407	12–59	45–12	80
C33000 (low-leaded brass tube)	66.0 Cu, 0.5 Pb, 33.5 Zn	T	324–517	47–75	103–414	15–60	60–7	60
C33200 (high-leaded brass tube)	66.0 Cu, 1.6 Pb, 32.4 Zn	T	359–517	52–75	138–414	20–60	50–7	80
C33500 (low-leaded brass)	65.0 Cu, 0.5 Pb, 34.5 Zn	F	317–510	46–74	97–414	14–60	65–8	60
C34000 (medium-leaded brass)	65.0 Cu, 1.0 Pb, 34.0 Zn	F, R, W, S	324–607	47–88	103–414	15–60	60–7	70
C34200 (high-leaded brass)	64.5 Cu, 2.0 Pb, 33.5 Zn	F, R	338–586	49–85	117–427	17–62	52–5	90
C34900	62.2 Cu, 0.35 Pb, 37.45 Zn	R, W	365–469	53–68	110–379	16–55	72–18	50

(continued)

(a) F, flat products; R, rod; W, wire; T, tube; P, pipe; S, shapes. (b) Ranges are from softest to hardest commercial forms. The strength of the standard copper alloys depends on the temper (annealed grain size or degree of cold work) and the section thickness of the mill product. Ranges cover standard tempers for each alloy. (c) Based on 100% for C36000. (d) C10400, 250 g/Mg (8 oz/ton) Ag; C10500, 310 g/Mg (10 oz/ton); C10700, 780 g/Mg (25 oz/ton). (e) C11300, 250 g/Mg (8 oz/ton) Ag; C11400, 310 g/Mg (10 oz/ton); C11500, 500 g/Mg (16 oz/ton); C11600, 780 g/Mg (25 oz/ton). (f) C12000, 0.008 P; C12100, 0.008 P and 125 g/Mg (4 oz/ton) Ag. (g) C12700, 250 g/Mg (8 oz/ton) Ag; C12800, 500 g/Mg (10 oz/ton); C12900, 500 g/Mg (16 oz/ton); C13000, 780 g/Mg (25 oz/ton). (h) 260 g/Mg (8.30 oz/ton) Ag. (i) C18200, 0.9 Cr; C18400, 0.8 Cr; C18500, 0.7 Cr. (j) Values are for as-hot-rolled material. (k) Values are for as-extruded material. (l) Rod, 61.0 Cu min. Source: Copper Development Association Inc.

Table 1 (continued)

Alloy number (and name)	Nominal composition, %	Commercial forms (a)	Mechanical properties(b)				Elongation in 50 mm (2 in.) (b), %	Machinability rating(c), %
			Tensile strength		Yield strength			
			MPa	ksi	MPa	ksi		
C35000 (medium-leaded brass)	62.5 Cu, 1.1 Pb, 36.4 Zn	F, R	310–655	45–95	90–483	13–70	66–1	70
C35300 (high-leaded brass)	62.0 Cu, 1.8 Pb, 36.2 Zn	F, R	338–586	49–85	117–427	17–62	52–5	90
C35600 (extra-high-leaded brass)	63.0 Cu, 2.5 Pb, 34.5 Zn	F	338–510	49–74	117–414	17–60	50–7	100
C36000 (free-cutting brass)	61.5 Cu, 3.0 Pb, 35.5 Zn	F, R, S	338–469	49–68	124–310	18–45	53–18	100
C36500 to C36800 (leaded Muntz metal)(j)	60.0 Cu(l), 0.6 Pb, 39.4 Zn	F	372	54	138	20	45	60
C37000 (free-cutting Muntz metal)	60.0 Cu, 1.0 Pb, 39.0 Zn	T	372–552	54–80	138–414	20–60	40–6	70
C37700 (forging brass)(k)	59.0 Cu, 2.0 Pb, 39.0 Zn	R, S	359	52	138	20	45	80
C38500 (architectural bronze)(k)	57.0 Cu, 3.0 Pb, 40.0 Zn	R, S	414	60	138	20	30	90
C40500	95 Cu, 1 Sn, 4 Zn	F	269–538	39–78	83–483	12–70	49–3	20
C40800	95 Cu, 2 Sn, 3 Zn	F	290–545	42–79	90–517	13–75	43–3	20
C41100	91 Cu, 0.5 Sn, 8.5 Zn	F, W	269–731	39–106	76–496	11–72	13–2	20
C41300	90.0 Cu, 1.0 Sn, 9.0 Zn	F, R, W	283–724	41–105	83–565	12–82	45–2	20
C41500	91 Cu, 1.8 Sn, 7.2 Zn	F	317–558	46–81	117–517	17–75	44–2	30
C42200	87.5 Cu, 1.1 Sn, 11.4 Zn	F	296–607	43–88	103–517	15–75	46–2	30
C42500	88.5 Cu, 2.0 Sn, 9.5 Zn	F	310–634	45–92	124–524	18–76	49–2	30
C43000	87.0 Cu, 2.2 Sn, 10.8 Zn	F	317–648	46–94	124–503	18–73	55–3	30
C43400	85.0 Cu, 0.7 Sn, 14.3 Zn	F	310–607	45–88	103–517	15–75	49–3	30
C43500	81.0 Cu, 0.9 Sn 18.1 Zn	F, T	317–552	46–80	110–469	16–68	46–7	30
C44300, C44400, C44500 (inhibited admiralty)	71.0 Cu, 28.0 Zn, 1.0 Sn	F, W, T	331–379	48–55	124–152	18–22	65–60	30
C46400 to C46700 (naval brass)	60.0 Cu, 39.25 Zn, 0.75 Sn	F, R, T, S	379–607	55–88	172–455	25–66	50–17	30
C48200 (naval brass, medium-leaded)	60.5 Cu, 0.7 Pb, 0.8 Sn, 38.0 Zn	F, R, S	386–517	56–75	172–365	25–53	43–15	50
C48500 (leaded naval brass)	60.0 Cu, 1.75 Pb, 37.5 Zn, 0.75 Sn	F, R, S	379–531	55–77	172–365	25–53	40–15	70
C50500 (phosphor bronze, 1.25% E)	98.75 Cu, 1.25 Sn, trace P	F, W	276–545	40–79	97–345	14–50	48–4	20
C51000 (phosphor bronze, 5% A)	95.0 Cu, 5.0 Sn, trace P	F, R, W, T	324–965	47–140	131–552	19–80	64–2	20
C51100	95.6 Cu, 4.2 Sn, 0.2 P	F	317–710	46–103	345–552	50–80	48–2	20
C52100 (phosphor bronze, 8% C)	92.0 Cu, 8.0 Sn, trace P	F, R, W	379–965	55–140	165–552	24–80	70–2	20
C52400 (phosphor bronze, 10% D)	90.0 Cu, 10.0 Sn, trace P	F, R, W	455–1014	66–147	193 (Annealed)	28	70–3	20
C54400 (free-cutting phosphor bronze)	88.0 Cu, 4.0 Pb, 4.0 Zn, 4.0 Sn	F, R	303–517	44–75	131–434	19–63	50–16	80
C60800 (aluminum bronze, 5%)	95.0 Cu, 5.0 Al	T	414	60	186	27	55	20
C61000	92.0 Cu, 8.0 Al	R, W	483–552	70–80	207–379	30–55	65–25	20
C61300	92.65 Cu, 0.35 Sn, 7.0 Al	F, R, T, P, S	483–586	70–85	207–400	30–58	42–35	30
C61400 (aluminum bronze, D)	91.0 Cu, 7.0 Al, 2.0 Fe	F, R, W, T, P, S	524–614	76–89	228–414	33–60	45–32	20
C61500	90.0 Cu, 8.0 Al, 2.0 Ni	F	483–1000	70–145	152–965	22–140	55–1	30
C61800	89.0 Cu, 1.0 Fe, 10.0 Al	R	552–586	80–85	269–293	39–42.5	28–23	40
C61900	86.5 Cu, 4.0 Fe, 9.5 Al	F	634–1048	92–152	338–1000	49–145	30–1	…
C62300	87.0 Cu, 3.0 Fe, 10.0 Al	F, R	517–676	75–98	241–359	35–52	35–22	50
C62400	86.0 Cu, 3.0 Fe, 11.0 Al	F, R	621–724	90–105	276–359	40–52	18–14	50
C62500(k)	82.7 Cu, 4.3 Fe, 13.0 Al	F, R	689	100	379	55	1	20
C63000	82.0 Cu, 3.0 Fe, 10.0 Al, 5.0 Ni	F, R	621–814	90–118	345–517	50–75	20–15	30
C63200	82.0 Cu, 4.0 Fe, 9.0 Al, 5.0 Ni	F, R	621–724	90–105	310–365	45–53	25–20	30
C63600	95.5 Cu, 3.5 Al, 1.0 Si	R, W	414–579	60–84	…	…	64–29	40
C63800	95.0 Cu, 2.8 Al, 1.8 Si, 0.40 Co	F	565–896	82–130	372–786	54–114	36–4	…
C64200	91.2 Cu, 7.0 Al	F, R	517–703	75–102	241–469	35–68	32–22	60
C65100 (low-silicon bronze, B)	98.5 Cu, 1.5 Si	R, W, T	276–655	40–95	103–476	15–69	55–11	30
C65400	95.44 Cu, 3 Si, 1.5 Sn, 0.06 Cr	F	276–793	40–115	130–744	20–108	40–3	20
C65500 (high-silicon bronze, A)	97.0 Cu, 3.0 Si	F, R, W, T	386–1000	56–145	145–483	21–70	63–3	30
C66700 (manganese brass)	70.0 Cu, 28.8 Zn, 1.2 Mn	F, W	315–689	45.8–100	83–638	12–92.5	60–2	30
C67400	58.5 Cu, 36.5 Zn, 1.2 Al, 2.8 Mn, 1.0 Sn	F, R	483–634	70–92	234–379	34–55	28–20	25
C67500 (manganese bronze, A)	58.5 Cu, 1.4 Fe, 39.0 Zn, 1.0 Sn, 0.1 Mn	R, S	448–579	65–84	207–414	30–60	33–19	30
C68700 (aluminum brass, arsenical)	77.5 Cu, 20.5 Zn, 2.0 Al, 0.1 As	T	414	60	186	27	55	30
C68800	73.5 Cu, 22.7 Zn, 3.4 Al, 0.40 Co	F	565–889	82–129	379–786	55–114	36–2	…
C69000	73.3 Cu, 3.4 Al, 0.6 Ni, 22.7 Zn	F	496–896	72–130	345–807	50–117	40–2	…
C69400 (silicon red brass)	81.5 Cu, 14.5 Zn, 4.0 Si	R	552–689	80–100	276–393	40–57	25–20	30
C70250	96.2 Cu, 3 Ni, 0.65 Si, 0.15 Mg	F	586–758	85–110	552–784	80–105	40–3	20
C70400	92.4 Cu, 1.5 Fe, 5.5 Ni, 0.6 Mn	F, T	262–531	38–77	276–524	40–76	46–2	20
C70600 (copper-nickel, 10%)	88.7 Cu, 1.3 Fe, 10.0 Ni	F, T	303–414	44–60	110–393	16–57	42–10	20
C71000 (copper-nickel, 20%)	79.0 Cu, 21.0 Ni	F, W, T	338–655	49–95	90–586	13–85	40–3	20
C71300	75 Cu, 25 Ni	F	338–655	49–95	90–586	13–85	40–3	20
C71500 (copper-nickel, 30%)	70.0 Cu, 30.0 Ni	F, R, T	372–517	54–75	138–483	20–70	45–15	20
C71700	67.8 Cu, 0.7 Fe, 31.0 Ni, 0.5 Be	F, R, W	483–1379	70–200	207–1241	30–180	40–4	20
C72500	88.2 Cu, 9.5 Ni, 2.3 Sn	F, R, W, T	379–827	55–120	152–745	22–108	35–1	20
C73500	72.0 Cu, 10.0 Zn, 18.0 Ni	F, R, W, T	345–758	50–110	103–579	15–84	37–1	20
C74500 (nickel silver, 65-10)	65.0 Cu, 25.0 Zn, 10.0 Ni	F, W	338–896	49–130	124–524	18–76	50–1	20
C75200 (nickel silver, 65-18)	65.0 Cu, 17.0 Zn, 18.0 Ni	F, R, W	386–710	56–103	172–621	25–90	45–3	20
C75400 (nickel silver, 65-15)	65.0 Cu, 20.0 Zn, 15.0 Ni	F	365–634	53–92	124–545	18–79	43–2	20

(continued)

(a) F, flat products; R, rod; W, wire; T, tube; P, pipe; S, shapes. (b) Ranges are from softest to hardest commercial forms. The strength of the standard copper alloys depends on the temper (annealed grain size or degree of cold work) and the section thickness of the mill product. Ranges cover standard tempers for each alloy. (c) Based on 100% for C36000. (d) C10400, 250 g/Mg (8 oz/ton) Ag; C10500, 310 g/Mg (10 oz/ton); C10700, 780 g/Mg (25 oz/ton). (e) C11300, 250 g/Mg (8 oz/ton) Ag; C11400, 310 g/Mg (10 oz/ton); C11500, 500 g/Mg (16 oz/ton); C11600, 780 g/Mg (25 oz/ton). (f) C12000, 0.008 P; C12100, 0.008 P and 125 g/Mg (4 oz/ton) Ag. (g) C12700, 250 g/Mg (8 oz/ton) Ag; C12800, 500 g/Mg (10 oz/ton); C12900, 500 g/Mg (16 oz/ton); C13000, 780 g/Mg (25 oz/ton). (h) 260 g/Mg (8.30 oz/ton) Ag. (i) C18200, 0.9 Cr; C18400, 0.8 Cr; C18500, 0.7 Cr. (j) Values are for as-hot-rolled material. (k) Values are for as-extruded material. (l) Rod, 61.0 Cu min. Source: Copper Development Association Inc.

Table 1 (continued)

Alloy number (and name)	Nominal composition, %	Commercial forms (a)	Mechanical properties(b)				Elongation in 50 mm (2 in.) (b), %	Machinability rating(c), %
			Tensile strength		Yield strength			
			MPa	ksi	MPa	ksi		
C75700 (nickel silver, 65-12)	65.0 Cu, 23.0 Zn, 12.0 Ni	F, W	359–641	52–93	124–545	18–79	48–2	20
C76200	59.0 Cu, 29.0 Zn, 12.0 Ni	F, T	393–841	57–122	145–758	21–110	50–1	…
C77000 (nickel silver, 55-18)	55.0 Cu, 27.0 Zn, 18.0 Ni	F, R, W	414–1000	60–145	186–621	27–90	40–2	30
C72200	82.0 Cu, 16.0 Ni, 0.5 Cr, 0.8 Fe, 0.5 Mn	F, T	317–483	46–70	124–455	18–66	46–6	…
C78200 (leaded nickel silver, 65-8-2)	65.0 Cu, 2.0 Pb, 25.0 Zn, 8.0 Ni	F	365–627	53–91	159–524	23–76	40–3	60

(a) F, flat products; R, rod; W, wire; T, tube; P, pipe; S, shapes. (b) Ranges are from softest to hardest commercial forms. The strength of the standard copper alloys depends on the temper (annealed grain size or degree of cold work) and the section thickness of the mill product. Ranges cover standard tempers for each alloy. (c) Based on 100% for C36000. (d) C10400, 250 g/Mg (8 oz/ton) Ag; C10500, 310 g/Mg (10 oz/ton); C10700, 780 g/Mg (25 oz/ton). (e) C11300, 250 g/Mg (8 oz/ton) Ag; C11400, 310 g/Mg (10 oz/ton); C11500, 500 g/Mg (16 oz/ton); C11600, 780 g/Mg (25 oz/ton). (f) C12000, 0.008 P; C12100, 0.008 P and 125 g/Mg (4 oz/ton) Ag. (g) C12700, 250 g/Mg (8 oz/ton) Ag; C12800, 500 g/Mg (10 oz/ton); C12900, 500 g/Mg (16 oz/ton); C13000, 780 g/Mg (25 oz/ton). (h) 260 g/Mg (8.30 oz/ton) Ag. (i) C18200, 0.9 Cr; C18400, 0.8 Cr; C18500, 0.7 Cr. (j) Values are for as-hot-rolled material. (k) Values are for as-extruded material. (l) Rod, 61.0 Cu min. Source: Copper Development Association Inc.

Table 2 Physical properties of representative wrought copper alloys

UNS No.	Nominal composition, %	Density, g/cm^3 (lb/in.^{3})	Coefficient of thermal expansion, 10^{-6}/°C (10^{-6}/°F), 20–300 °C (70–570 °F)	Thermal conductivity, W/m · K, at 20 °C (Btu/ft^2/ft/h/°F, at 70 °F)	Electrical conductivity, %IACS, at 20 °C (70 °F)	Specific heat, cal/g · °C, at 20 °C, or Btu/lb · °F, at 70 °F
Coppers (C10100–C15999)						
C10200	99.95 Cu	8.94 (0.323)	17.7 (9.8)	391 (226)	101	0.092
C11000	99.9 Cu	8.94 (0.323)	17.7 (9.8)	391 (226)	101	0.092
C12200	99.90 Cu, 0.02 P	8.94 (0.323)	17.7 (9.8)	339 (196)	85	0.092
C15760	Cu, 0.6 Al, 0.57 O	8.80 (0.318)	16.6 (9.2)	322 (186)	78	0.092
High-copper alloys (C16200–C19199)						
C17200	98.1 Cu, 1.9 Be, 0.2 (Ni + Co) min	8.25 (0.298)	17.8 (9.9)	107 (62)	22	0.10
C17410	Cu, 0.5 Co, 0.3 Be	8.80 (0.318)	17.7 (9.8)	208 (120)	45	0.08
C18100	Cu, 0.04 Mg, 0.15 Zr, 0.8 Cr	8.83 (0.319)	19.4 (10.7)	324 (187)	80	0.094
C19400	97.4 Cu, 2.4 Fe, 0.13 Zn, 0.04 P	8.91 (0.322)	17.9 (9.2)	262 (150)	65	0.092
C19500	97 Cu, 1.5 Fe, 0.6 Sn, 0.1 P, 0.8 Co	8.92 (0.322)	16.9 (9.4)	197 (115)	50	0.092
Copper-zinc alloys (brasses, C21000–C28000)						
C23000	85 Cu, 15 Zn	8.74 (0.316)	18.7 (10.4)	159 (92)	37	0.09
C26000	70 Cu, 30 Zn	8.52 (0.308)	20.1 (11.1)	121 (70)	28	0.09
C28000	60 Cu, 40 Zn	8.39 (0.303)	21.0 (11.6)	123 (71)	28	0.09
Copper-zinc-lead alloys (leaded brasses, C31200–C38500)						
C34500	63.5 Cu, 34.5 Zn, 2 Pb	8.49 (0.307)	20.3 (11.3)	116 (67)	26	0.09
C35300	61.5 Cu, 36.5 Zn, 2.8 Pb	8.47 (0.306)	20.4 (11.3)	116 (67)	26	0.09
C36000	61.5 Cu, 35.4 Zn, 3.1 Pb	8.50 (0.307)	20.6 (11.4)	116 (67)	26	0.09
C37700	59.5 Cu, 38 Zn, 2 Pb	8.44 (0.305)	20.8 (11.5)	119 (69)	27	0.09
Copper-zinc-tin alloys (tin brasses, C40400–C48600)						
C42500	88.5 Cu, 9.5 Zn, 2 Sn, 0.2 P	8.78 (0.317)	18.4 (10.2)	121 (69)	28	0.09
C44400	71 Cu, 28 Zn, 1 Sn, 0.02 Sb min	8.53 (0.308)	20.2 (11.2)	109 (64)	28	0.09
C46400	60 Cu, 39.2 Zn, 0.8 Sn	8.41 (0.304)	21.3 (11.8)	116 (67)	26	0.09
Copper-tin-phosphorus alloys (phosphor bronzes, C50100–C54200)						
C50500	98.7 Cu, 1.3 Sn	8.89 (0.321)	17.8 (9.9)	87 (50)	48	0.09
C51000	94.8 Cu, 5 Sn, 0.2 P	8.86 (0.320)	17.9 (9.9)	69 (40)	15	0.09
C51100	95.6 Cu, 4.2 Sn, 0.2 P	8.86 (0.320)	17.8 (9.9)	84 (48.4)	20	0.09
Copper-tin-lead-phosphorus alloys (leaded phosphor bronzes, C53400–C53500)						
C54400	88 Cu, 4 Sn, 4 Pb, 4 Zn, 0.5 P max	8.88 (0.321)	17.4 (9.6)	87 (50)	19	0.09
Copper-aluminum alloys (aluminum bronzes, C60800–C64210)						
C61300	90.3 Cu, 6.8 Al, 2.5 Fe, 0.35 Sn	7.94 (0.287)	16.3 (9.0)	55 (32)	12	0.09
C63000	82 Cu, 10 Al, 5 (Ni + Co), 3 Fe	7.58 (0.274)	16.3 (9.0)	39 (22)	7	0.09
C63020	74.5 Cu min., 10.5 Al, 5 Ni, 4.75 Fe	7.45 (0.269)	16.3 (9.0)	47 (27)	6	…
C63800	95 Cu, 2.8 Al, 1.8 Si, 0.4 Co	8.28 (0.299)	17.1 (9.5)	41 (23)	10	0.09
Copper-silicon alloys (silicon bronzes, C64700–C66100)						
C65500	97 Cu, 3 Si	8.52 (0.308)	18.0 (10.0)	36 (21)	7	0.09
Other copper-zinc alloys (C66400–C69710)						
C67500	58.5 Cu, 39 Zn, 1.4 Fe, 1 Sn, 0.1 Mn	8.36 (0.302)	21.3 (11.8)	105 (61)	24	0.09
C69400	81.5 Cu, 14.5 Zn, 4 Si	8.19 (0.296)	20.3 (11.2)	26 (15)	6	0.09
Copper-nickel alloys (copper-nickels, C70100–C72950)						
C70600	88.6 Cu, 10 Ni, 1.4 Fe	8.94 (0.323)	17.1 (9.5)	45 (26)	9	0.09
C71500	69.5 Cu, 30 Ni, 0.5 Fe	8.94 (0.323)	16.2 (9.0)	29 (17)	4	0.09
C72200	82.2 Cu, 16.5 (Ni + Co), 0.8 Fe, 0.5 Cr	8.94 (0.323)	15.8 (8.8)	34 (20)	6.5	0.094
Copper-zinc-nickel alloys (nickel silvers, C73500–C79800)						
C74500	65 Cu, 25 Zn, 10 Ni	8.69 (0.314)	16.4 (9.1)	45 (26)	9	0.09
C77000	55 Cu, 27 Zn, 18 Ni	8.70 (0.314)	16.7 (9.3)	29 (17)	5.5	0.09

Table 3 Copper alloys (rod form) ranked by tensile strength

UNS No.	Size		Condition	Tensile strength	
	mm	in.		MPa	ksi
C17200, C17300	<9.5	<0.375	TH04	1485	215
	9.5–25.4	0.375–1	TH04	1413	205
	76	3	TH04	1380	200
	All sizes		TF00	1310	190
C63020	≤25.4	≤1	TQ30, quenched and tempered	1000	145
	>25.4	>1	TQ30, quenched and tempered	965	140
C17500, C17510	<76.2	<3	TH04	896	130
C17200, C17300	<9.5	<0.375	TD04	862	125
	9.5–25.4	0.375–1	TD04	827	120
C17410	<9.5	<0.375	TH04	827	120
C17500, C17510	All sizes		TF00	825	120
C63000	25.4	1	Half hard, H02, 10%	814	118
	50.8	2	Half hard, H02, 10%	793	115
C17200, C17300	25.4–76.2	1–3	TD04	760	110
C63000	76.2	3	Half hard, H02, 10%	772	112
C65500	25.4	1	Extra hard, 50%	745	108
C62400	25.4	1	Half hard, H02, 10%	724	105
C63200	25.4	1	Light anneal, O50	724	105
C19100	3.2	0.125	Spring, TH04, 75%, heat treated	717	104
C63200	50.8	2	Light anneal, O50	710	103
	76.2	3	Light anneal, O50	703	102
C64200	19	0.750	Hard, H04, 15%	703	102
C64700	12.7	0.500	Drawn and aged	703	102
C18000	25.4	1	TH04	690	100
C19150	1.3–9.5	0.05–0.375	TH04	690	100
C62500	All sizes		As extruded, M30	690	100
C63000	101.6	4	As extruded, M30	690	100
C69400	19	0.750	Eighth hard, H00, 7%	690	100
C62300	12.7	0.500	Half hard, H02, 15%	676	98
	25.4	1	Half hard, H02, 15%	655	95
C62400	50.8–76.2	2–3	Half hard, H02, 10%	655	95
C19100	9.5	0.375	Spring, TH04, 60%	648	94
C64200	38	1.500	Hard, H04, 10%	641	93
C62300	50.8	2	Half hard, H02, 15%	634	92
C64200	12.7	0.500	Light anneal, O50	634	92
C65500	25.4	1	Hard, H04, 36%	634	92
C65600	25.4	1	Hard, H04	634	92
C67400	19	0.750	Half hard, HR02, stress relieved 1 h at 550 °F (288 °C)	634	92
C15760	7	0.275	Cold worked 74%	621	90
C19150	9.5–12.7	0.375–0.500	TH04	621	90
C62400	101.6	4	As extruded, M30	621	90
C64200	19	0.750	Light anneal, O50	621	90
C65100	25.4	1	Extra hard, H06, 50%	621	90
C66100	25.4	1	Hard, H04	621	90
C69400	12.7	0.500	Soft anneal, O60	621	90
C15760	7	0.275	Annealed at 600 °F (316 °C)	614	89
C62300	76.2	3	Half hard, H02, 15%	600	87
C18200, C18400	4	0.156	Solution heat treated, cold worked 90% and aged, TD01	593	86
C61400	25.4	1	Hard, H04	586	85
C61300	12.7	0.500	Hard, H04, 25%	586	85
C61800	25.4	1	Half hard, H02, 15%	586	85
C69400	25.4	1	Soft anneal, O60	586	85
C69430	25.4	1	Hard, H04	586	85
C15760	7	0.275	Annealed at 1200 °F (649 °C)	579	84
C19100	3.2	0.250	Hard, TH04, 35%, heat treated	579	84
C67500	25.4	1	Half hard, H02, 20%	579	84
C15760	12.7	0.500	Cold worked 14%	572	83
C61800	50.8	2	Half hard, H02, 15%	565	82
C61400	25.4	1	Hard, H04	565	82
C61300	25.4	1	Hard, H04, 25%	565	82
C15760	13.7	0.540	As consolidated, M30	552	80
C19100	12.7	0.500	Hard, TH04, 35%, heat treated	552	80
C24000	7.9	0.312	Hard, H04	552	80
C46400	6.35	0.250	Half hard, H02, 20%	552	80
C52100	12.7	0.500	Half hard, H02, 20%	552	80
C61300	50.8	2	Hard, H04, 25%	552	80
C61400	50.8	2	Hard, H04	552	80
C61800	76.2	3	Half hard, H02	552	80
C69400	50.8	2	Soft anneal, O60	552	80
C75700	≤25.4	≤1	Hard, H04	552	80
C18150	25.4	1	Hard and precipitation heat treated, TH04	538	78
C19100	25.4	1	Hard, TH04, 30%, heat treated	538	78
C65500	25.4	1	Half hard, H02, 20%	538	78
C16500	12.7	0.500	Extra hard, H06, 67%	531	77
C18200, C18400	13	0.500	Solution heat treated, cold worked 50%, aged and cold worked 6%	531	77
	12.7	0.500	Solution heat treated, cold worked 60.5% and aged at 842 °F (450 °C)	531	77
C67500	25.4	1	Quarter hard, H01, 10%	531	77

(continued)

Source: Copper Development Association Inc.

Table 3 (continued)

UNS No.	Size mm	Size in.	Condition	Tensile strength MPa	Tensile strength ksi
C15760	7	0.275	Annealed 1800 °F (982 °C)	524	76
C17200, C17300	All sizes		TB00	760	75
C17500, C17510	<76.2	<3	TD04	760	75
C46400, C48200, C48500	25.4	1	Half hard, H02, 20%	517	75
C51000	12.7	0.500	Half hard, H02, 20%	517	75
C54400	12.7	0.500	Hard, H04, 35%	517	75
C62300	101.6	4	As extruded, M30	517	75
C64200	19	0.750	As extruded, M30	517	75
C67300	25.4	1		517	75
C67600	25.4	1	Half hard, H02	517	75
C71500	25.4	1	Half hard, H02, 20%	517	75
C18200, C18400	4	0.156	Solution heat treated and cold worked 91%, TD01	510	74
C16200	12.7	0.500	Hard, H04	503	73
C15715	7	0.275	Cold worked 94%	496	72
C15760	64	2.500	As consolidated, M30	496	72
C18200, C18400	25.4	1	Solution heat treated and aged, TF00	496	72
C28000	25.4	1	Quarter hard, H01	496	72
C67500	50.8	2	Quarter hard, H01, 10%	496	72
C79200	19	0.750	Hard, H04	496	72
C18135	0.500	12.7	Solution heat treated, cold worked 40% and aged, TH01	483	70
C18200, C18400	12.7	0.500	Solution heat treated and aged at 932 °F (500 °C), 3 h, TF00	483	70
	50.8	2	Solution heat treated and aged, TF00	483	70
C23000	7.9	0.312	Hard, H04	483	70
C26000, C26130, C26200	25.4	1	Half hard, H02, 20%	483	70
C32000	25.4	1	Hard, H04	483	70
C34500	25.4	1	Half hard, H02	483	70
C35000	12.7	0.500	Half hard, H02, 20%	483	70
C46200	25.4	1	Half hard, H02	483	70
C46400	6.35	0.250	Quarter hard, H01, 10%	483	70
C48200	50.8	2	Half hard, H02, 15%	483	70
C51000	25.4	1	Half hard, H02, 20%	483	70
C61000	19	0.750	Hard, H04	483	70
C65100	25.4	1	Hard, H04, 36%	483	70
C67400	19	0.750	Soft anneal, O60	483	70
C69710	25.4	1	Hard, H04	483	70
C75200	12.7	0.500	Half hard, H02, 20%	483	70
C46400, C48200, C48500	25.4	1	Quarter hard, H01, 8%	476	69
C18135	50.8	2	Solution heat treated, cold worked 30% and aged	476	69
C15000	9.5	0.375	Solution heat treated, cold worked 80%, aged and cold worked 44%	469	68
C35600, C36000	6.35	0.250	Half hard, H02, 25%	469	68
C54400	25.4	1	Hard, H04, 25%	469	68
C15000	0.500	12.7	Solution heat treated, cold worked 56%, aged and cold worked 47%	462	67
C15715	7	0.275	Annealed 600 °F (316 °C)	462	67
C22600	7.9	0.312	Hard, H04	462	67
C31600	12.7	0.500	Hard, H04, 38%	462	67
C46400, C48200	50.8	2	Quarter hard, H01, 8%	462	67
C15715	12.7	0.500	Cold worked 80%	455	66
C16500	12.7	0.500	Hard, H04, 35%	448	65
C18200, C18400	76.2	3	Solution heat treated and aged	448	65
C31600	25.4	1	Hard, H04, 38%	448	65
C67500	25.4	1	Soft anneal, O60	448	65
C15000	15.9	0.625	Solution heat treated, cold worked 61%, aged and cold worked 31%	441	64
	19	0.750	Solution heat treated, cold worked 50%, aged and cold worked 34%	434	63
C46400	6.35–25.4	0.250–1	Light annealed, O50	434	63
C48200	76.2	3	Quarter hard, H01, 4%	434	63
C48200	25.4	1	Light annealed, O50	434	63
C18135	12.7	0.500	Solution heat treated, cold worked 40% and aged	427	62
C15000	22.2	0.875	Solution heat treated, cold worked 48%, aged and cold worked	427	62
	25.4	1	Solution heat treated, cold worked 48%, aged and cold worked 47%	427	62
	5.2	0.204	Solution heat treated, aged and cold worked 76%, TD01	427	62
C15715	19	0.750	Cold worked 55%	427	62
C46400, C48200	50.8	2	Light annealed, O50	427	62
C18135	50.8	2	Solution heat treated, cold worked 30% and aged	421	61
C15000	31.2	1.250	Solution heat treated, cold worked 32%, aged and cold worked 17%	414	60
C15725	All sizes		As consolidated, M30	414	60
C31400	6.35	0.250	Half hard, H02, 37%	414	60
C15715	7	0.275	Annealed 1200 °F (649 °C), O61	407	59
C16200	12.7	0.500	Half hard, H02, 25%	400	58
C35000	12.7	0.500	Quarter hard, H01, 10%	400	58
C34200, C35300, C35330, C35600, C36000	25.4	1	Half hard, H02, 20%	400	58
C46400	6.35	0.250	Soft anneal, O60	400	58
C65500	25.4	1	Grain size 0.050 mm, OS050	400	58
C14700	9.5	0.375	Extra hard, H06, 56%	393	57
C15715	29	1.125	As consolidated, M30	393	57
	7	0.275	Annealed 1800 °F (982 °C), O61	393	57
C18200, C18400	12.7	0.500	Solution treated and cold worked 60.5%, TD01	393	57
C46400, C48200, C48500	25.4	1	Soft anneal, O60	393	57

(continued)

Source: Copper Development Association Inc.

Table 3 (continued)

	Size			Tensile strength	
UNS No.	mm	in.	Condition	MPa	ksi
C32000	25.4	1	Half hard, H02, 25%	386	56
C46400, C48200	50.8	2	Soft anneal, O60	386	56
C75200	12.7	0.500	Grain size 0.035 mm, OS035	386	56
C10100, C10200, C10300, C10400, C10500, C10700, C10800, C11000, C11300, C11400, C11500, C11600, C12000, C12100	6.35	0.250	Hard, H04, 40%	379	55
C18200, C18400	101.6	4.0	Solution heat treated and aged, TF00	379	55
C18700	3.2	0.125	Hard, H04, 50%	379	55
C21000	7.9	0.312	Hard, H04	379	55
C26000, C26130, C26200, C26800, C27000	25.4	1	Eighth hard, H00, 6%	379	55
C31400	12.7	0.500	Half hard, H02, 25%	379	55
C34000	25.4	1	Quarter hard, H01, 10%	379	55
C35000	12.7	0.500	Grain size 0.015 mm, OS015	379	55
C35600, C36000	50.8	2	Half hard, H02, 15%	379	55
C28000	25.4	1	Soft anneal, O60	372	54
C14500, C14520, C18700	6.35	0.250	Hard, H04, 45%	365	53
C28000, C37700	25.4	1	As extruded, M30	358	52
C31400	25.4	1	Half hard, H02, 20%	358	52
C34000	25.4	1	Grain size 0.025 mm, OS025	345	50
C35600, C36000	25.4	1	Soft anneal O60	338	49
C10100, C10200, C10300, C10400, C10500, C10700, C10800, C11000, C11300, C11400, C11500, C11600, C12000, C12100, C12900	25.4	1	Hard, H04, 35%	331	48
C14500, C14520	12.7–25.4	0.500–1	Hard, H04, 35%	331	48
C18700	25.4	1	Hard, H04, 35%	331	48
	12.7	0.500	Hard, H04, 35%	331	48
C26000, C26130, C26200, C26800, C27000	25.4	1	Grain size 0.050 mm, OS050	331	48
C35000	12.7	0.500	Grain size 0.050 mm, OS015	331	48
C14700	6.35	0.250	Hard, H04, 36%	331	48
	12.7	0.500	Hard, H04, 35%	331	48
C70600	≤64	≤2.500	Annealed, O61	324	47
C14700	25.4	1	Hard, H04, 29%	317	46
C10100, C10200, C10400, C10500, C10700, C10800, C11000, C11300, C11400, C11500, C11600, C12000, C12100	50.8	2	Hard, H04, 16%	310	45
C12200	25.4	1	Hard, H04	310	45
C17500, C17510	All sizes		TB00	310	45
C18200, C18400	12.7	0.500	TB00	310	45
C22000	12.7	0.500	Eighth hard, H00	310	45
C14500, C14520	6.35–12.7	0.250–0.500	Half hard, H02, 20%	296	43
C14700	12.7	0.500	Half hard, H02, 20%	296	43
C18700	6.35	0.250	Half hard, H02, 20%	296	43
C14500, C14520	25.4	1	Half hard, H02, 20%	290	42
	50.8	2	Half hard, H02, 15%	290	42
C14700	41	1.625	Hard, H04, 25%	290	42
C18700	25.4	1	Half hard, H02, 20%	290	42
C15000	…	…	Mill annealed and cold worked 10%	283	41
C14700	44	1.75	Hard, H04, 24%	276	40
C16500	12.7	0.500	Grain size 0.050 mm, OS050	276	40
C22000	12.7	0.500	Grain size 0.035 mm	276	40
C19150	>9.5	>0.375	TD04	276	40
C32000	25.4	1	Grain size 0.050, OS050	276	40
C65100	25.4	1	Grain size 0.035 mm, OS035	276	40
C14500, C14520, C14700	12.7	0.500	Eighth hard, H00, 6%	262	38
C31400, C31600	25.4	1	Grain size 0.050 mm, OS050	255	37
C16200	12.7	0.500	Grain size 0.025 mm, OS025	248	36
	12.7	0.500	Grain size 0.050 mm , OS050	241	35
C14500, C14520, C14700	12.7	0.500	Grain size 0.015 mm, OS015	228	33
C10100, C10200, C10400, C10500, C10700, C11000, C11300, C11400, C11500, C11600, C12000, C12100, C12900	25.4	1	As hot rolled, M20	221	32
C10100, C10200, C10400, C10500, C10700, C11000, C11300, C11400, C11500, C11600, C12000, C12100, C12900, C14500, C14520, C18700	25.4	1	Grain size 0.050 mm, OS050	221	32
C14700	12.7	0.500	Grain size 0.050 mm, OS050	221	32

Source: Copper Development Association Inc.

Table 4 Copper alloys (rod form) ranked by 0.5% extension yield strength

UNS No.	Size		Condition	Yield strength (0.5% extension)	
	mm	in.		MPa	ksi
C64700	12.7	0.500	Drawn and aged	621	90
C19150	1.3–9.5	0.050–0.375	TH04	585	85
C18200, C18400	4	0.156	Solution heat treated, cold worked 91%, TD01	531	77
C19100	3.2	0.125	Spring, TH04, 75%	531	77
	9.5	0.375	Spring, heat treated, TH04	517	75
C19150	9.5–12.7	0.375–0.5	TH04	517	75
C63000	25.4	1	Half hard, H02, 10%	517	75
C18200, C18400	4	0.156	Solution heat treated, cold worked 90% & aged, TH01	503	73
C19100	6.35	0.250	Hard, heat treated, TH04, 35%	503	73
C16500	12.7	0.500	Extra hard, H06, 67%	492	71
C19100	12.7	0.500	Hard, heat treated, TH04, 35%	483	70
C71500	25.4	1	Half hard, H02, 20%	483	70
C16200	12.7	0.500	Hard, H04	474	69
C19100	25.4	1	Hard, heat treated, TH04, 30%	469	68
C64200	19	0.750	Hard, H04, 15%	469	68
C18200, C18400	12.7	0.500	Solution heat treated, cold worked 60.5%, aged, cold worked 6%	462	67
C65100	25.4	1	Extra hard, 50%	462	67
C18200, C18400	25.4–50.8	1–2	Solution heat treated and aged, TF00	448	65
	12.7	0.500	Solution heat treated, cold worked 60.5%, aged at 842 °F (450 °C) 3h, TH01	448	65
C51000, C52100	12.7	0.500	Half hard, H02, 20%	448	65
C63000	50.8	2	Half hard, H02, 10%	446	65
C15000	9.5	0.375	Solution heat treated, cold worked 80%, aged, cold worked 44%	441	64
C24000	7.9	0.312	Hard, H04	434	63
C15000	12.7	0.500	Solution heat treated, cold worked 56%, aged, cold worked 47%	434	63
C54400	12.7	0.500	Hard 35%	434	63
C18135	50.8	2	Solution heat treated, cold worked 30% & aged	432	63
C15000	16	0.625	Solution treated, cold worked 61%, aged, cold worked 31%	427	62
C63000	76.2	3	Half hard, H02, 10%	427	62
C79200	19	0.750	Hard, H04	427	62
C18135	12.7	0.500	Solution heat treated, cold worked 40% & aged	421	61
C15000	19	0.750	Solution treated, cold worked 50%, aged, cold worked 34%	421	61
	25.4	1	Solution treated, cold worked 48%, aged & cold worked 47%	414	60
	22	0.875	Solution treated, cold worked 48%, aged & cold worked 52%	414	60
C32000	25.4	1	Hard, H04	414	60
C63000	101.6	4	As extruded, M30	414	60
C64200	38	1.5	Hard, H04, 10%	414	60
C67500	25.4	1	Half hard, H02, 20%	414	60
C75200	12.7	0.500	Half hard, H02, 20%	414	60
C65500	25.4	1	Extra hard, H06, 50%	414	60
C31600	12.7	0.500	Hard, H04, 38%	407	59
C15000	32	1.250	Solution treated, cold worked 32%, aged & cold worked 17%	400	58
C34500	25.4	1	Half hard, H02	400	58
C51000	25.4	1	Half hard, H02, 20%	400	58
C61300	12.7	0.500	Hard, H04, 25%	400	58
C64200	12.7	0.500	Light anneal, O50	400	58
C31600	25.4	1	Hard, H04, 38%	393	57
C46400	6.35	0.250	Half hard, H02, 20%	393	57
C54400	25.4	1	Hard, H04, 25%	393	57
C69400	19	0.750	Eighth hard, H00, 7%	393	57
C15000	5.2	0.204	76% reduction after aging	386	56
C18200, C18400	12.7	0.500	Solution heat treated & cold worked 60.5%, TD01	386	56
C14700	9.5	0.375	Extra hard, H06, 56%	379	55
C16500	12.7	0.500	Hard, 35%	379	55
C18200, C18400	76.2	3	Solution heat treated and aged, TF00	379	55
	12.7	0.500	Solution heat treated and aged at 932 °F (500 °C) 3h, TF00	379	55
C31400	6.35	0.250	Half hard, H02, 37%	379	55
C61300	25.4	1	Hard, H04, 25%	379	55
C62500	All sizes		As extruded, M30	379	55
C64200	19	0.750	Light anneal, O50	379	55
C65100	25.4	1	Hard, H04, 36%	379	55
C65500	25.4	1	Hard, H04, 36%	379	55
C65600, C66100	25.4	1	Hard, H04	379	55
C67300	≤25.4	≤1		379	55
C67400	19	0.750	Half hard, stress relieved 1h at 550 °F (288 °C), HR50	379	55
C18135	12.7	0.500	Solution heat treated, cold worked 40% & aged, TH01	365	53
	50.8	2	Solution heat treated, cold worked 30% & aged, TH01	365	53
C46400	25.4	1	Half hard, H02, 20%	365	53
C48200	25.4	1	Half hard, H02, 20%	365	53
C48500	25.4	1	Half hard, H02, 20%	365	53
C63200	25.4	1	Light annealed, O50	365	53
C75700	≤25.4	≤1	Hard, H04	365	53
C23000	7.9	0.312	Hard, H04	359	52
C26000, C26130, C26200	25.4	1	Half hard, H02, 20%	359	52
C35000	12.7	0.500	Half hard, H02, 20%	359	52
C35600, C36000	6.35	0.250	Half hard, H02, 25%	359	52

(continued)

Source: Copper Development Association Inc.

Table 4 (continued)

	Size			Yield strength (0.5% extension)	
UNS No.	mm	in.	Condition	MPa	ksi
C48200	50.8	2	Half hard, H02, 15%	359	52
C62300	12.7	0.500	Half hard, H02, 15%	359	52
C62400	25.4	1	Half hard, H02, 10%	359	52
C63200	50.8	2	Light anneal, O50	359	52
	76.2	3	Light anneal, O50	352	51
C10100, C10200, C10400, C10500, C10700, C10800, C11000, C11300, C11400, C11500, C11600, C12000, C12100	6.35	0.250	Hard, H04, 40%	345	50
C18700	3.2	0.125	Hard, H04, 50%	345	50
C22600	7.9	0.312	Hard, H04	345	50
C28000	25.4	1	Quarter hard, H01	345	50
C31400	12.7	0.500	Half hard, H02, 25%	345	50
C46200	25.4	1	Half hard, H02	345	50
C62300	25.4	1	Half hard, H02, 15%	345	50
C69430	25.4	1	Hard, H04	345	50
C14500, C14520, C18700	6.35	0.250	Hard, H04, 45%	338	49
C46400	6.35	0.250	Quarter hard, H01, 10%	331	48
C61300	50.8	2	Hard, H04, 25%	331	48
C62300	50.8	2	Half hard, H02, 15%	331	48
C62400	50.8	2	Half hard, H02, 10%	331	48
	76.2	3	Half hard, 10%	324	47
C32000	25.4	1	Half hard, 25%	317	46
C46400, C48200, C48500	25.4	1	Quarter hard, H01, 8%	317	46
C16200	12.7	0.500	Half hard, H02, 25%	310	45
C31400, C34200, C35600, C36000	25.4	1	Half hard, H02, 20%	310	45
C61400	12.7	0.500	Hard, H04	310	45
C62300	76.2	3	Half hard, H02, 15%	310	45
C65500	25.4	1	Half hard, H02, 20%	310	45
C67500	25.4	1	Quarter hard, H01, 10%	310	45
C67600	25.4	1	Half hard, H02	310	45
C69400	12.7	0.500	Soft anneal, O60	310	45
C10100, C10200, C10300, C10400, C10500, C10700, C10800, C11000, C11300, C11400, C11500, C11600, C12000, C12100, C12900	25.4	1	Hard, H04, 35%	303	44
C14500, C14520	12.7–25.4	0.500–1.0	Hard, H04, 35%	303	44
C14700	12.7	0.500	Hard, H04, 35%	303	44
	6.35	0.250	Hard, H04, 36%	303	44
C18700	12.7	0.500	Hard, H04, 35%	303	44
C35000	12.7	0.500	Quarter hard, H01, 10%	303	44
C35600, C36000	50.8	2	Half hard, H02, 15%	303	44
C14700	25.4	1	Hard, H04, 29%	296	43
C18200, C18400	101.6	4	Solution heat treated and aged, TF00	296	43
C69400	25.4	1	Soft anneal, O60	296	43
C18700	25.4	1	Hard, H04, 35%	290	42
C34000	25.4	1	Quarter hard, H01, 10%	290	42
C61800	25.4	1	Half hard, H02, 15%	290	42
C67500	50.8	2	Quarter hard, H01, 10%	290	42
C10100, C10200, C10300	50.8	2	Hard, H04, 16%	276	40
C10400, C10500, C10700, C10800, C11000, C11300, C11400, C11500, C11600, C12000, C12100	50.8	2	Hard, H04, 16%	276	40
C14500, C14520	6.35–25.4	0.250–1	Half hard, 20%	276	40
C14700	12.7	0.500	Half hard, H02, 20%	276	40
C18700	6.35	0.250	Half hard, H02, 20%	276	40
C26000, C26130, C26200, C26800, C27000	25.4	1	Eighth hard, H00, 6%	276	40
C46400, C48200	50.8	2	Quarter hard, H01, 8%	276	40
C12200, C61400, C69710	25.4	1	Hard, H04	276	40
C62400	101.6	4	As extruded, M30	276	40
C69400	50.8	2	Soft anneal, O60	276	40
C14500, C14520	50.8	2	Half hard, H02, 15%	269	39
C61800	76.2	3	Half hard, H02	269	39
	50.8	2	Half hard, H02, 15%	269	39
C14700	41	1.625	Hard, H04, 25%	262	38
C18700	25.4	1	Half hard, H02, 20%	262	38
C14700	44	1.750	Hard, H04, 24%	248	36
C15000	6.35	0.250	Mill annealed and cold worked, 10%	248	36
C21000	7.9	0.312	Hard, H04	241	35
C22000	12.7	0.500	Eighth hard, H00	241	35

(continued)

Source: Copper Development Association Inc.

Table 4 (continued)

UNS No.	Size		Condition	Yield strength (0.5% extension)	
	mm	in.		MPa	ksi
C61400	50.8	2	Hard, H04	241	35
C62300	101.6	4	As extruded, M30	241	35
C64200	19	0.750	As extruded, M30	241	35
C67400	19	0.750	Soft anneal, O60	234	34
C70600	≤6.4	≤2.5	Annealed, O61	234	34
C48200	76.2	3	Quarter hard, H01, 4%	228	33
C14500, C14520	12.7	0.500	Eighth hard, 6%	207	30
C14700	12.7	0.500	Eighth hard, 6%	207	30
C46400	6.35–25.4	0.250–1	Light annealed, O50	207	30
C48200	25.4	1	Light annealed, O50	207	30
C67500	25.4	1	Soft anneal, O60	207	30
C46400, C48200	50.8	2	Light annealed, O50	193	28
C46400	6.35	0.250	Soft annealed, O60	186	27
C35000	12.7	0.500	Grain size 0.015 mm, OS015	172	25
C46400, C48200	25.4–50.8	1–2	Soft annealed, O60	172	25
C48500	25.4	1	Soft annealed, O60	172	25
C75200	12.7	0.500	Grain size 0.035 mm, OS035	172	25
C65500	25.4	1	Grain size 0.050 mm, OS050	152	22
C28000	25.4	1	Soft annealed, O60	145	21
C28000, C37700	25.4	1	As extruded, M30	138	20
C34000	25.4	1	Grain size 0.025 mm, OS025	131	19
C35600, C36000	25.4	1	Soft annealed, O60	131	18
C26000, C26130, C26200, C26800, C27000, C32000	25.4	1	Grain size 0.050 mm, OS050	110	16
C35000	12.7	0.500	Grain size 0.050 mm, OS050	110	16
C65100	25.4	1	Grain size 0.035 mm, OS035	103	15
C16500	12.7	0.500	Grain size 0.050 mm, OS050	97	14
C18200, C18400	All sizes		Solution heat treated, TB00	97	14
C22000	12.7	0.500	Grain size 0.035, OS035	97	14
C16200	12.7	0.500	Grain size 0.025 mm, OS025	83	12
C31400, C31600	25.4	1	Grain size 0.050 mm, OS050	83	12
C14500, C14520, C14700	12.7	0.500	Grain size 0.015 mm, OS015	76	11
C10100, C10200, C10400, C10500, C10600, C10700, C11000, C11300, C11400, C11500, C12000, C12100, C12900	25.4	1	As hot rolled, grain size 0.050 mm, OS050	69	10
C14500, C14520	25.4	1	Grain size 0.050 mm, OS050	69	10
C14700	12.7	0.500	Grain size 0.050 mm, OS050	69	10
C18700	25.4	1	Grain size 0.050 mm, OS050	69	10
C16200	12.7	0.500	Grain size 0.050 mm, OS050	48	7

Source: Copper Development Association Inc.

and small amounts of various alloying elements such as beryllium, cadmium, chromium, or iron, each having less than 8 at.% solid solubility. Some high-copper alloys also contain up to ~2% of nickel, cobalt, and tin. Because dilute copper alloys retain the face-centered cubic (fcc) α-structure of copper, their physical properties are similar to those of the pure metal. Alloying generally serves to impart higher strength, thermal stability, or other mechanical attributes, while retaining sufficient electrical conductivity for the intended use.

Recent interest in applications for these high-copper alloys has focused on electrical/electronic connectors and integrated-circuit (IC) lead frames. Alloys for electronic components used in the increasingly severe, automotive under-the-hood environment, for example, require a formidable combination of properties: high stress-relaxation resistance between 135 and 200 °C (275 and 390 °F) to maintain adequate contact pressure; good electrical conductivity to minimize Joule heating; high plateability without reacting with contact coatings; sufficient and consistent deformation characteristics; and economy (Ref 1). Figure 1 shows the strength and electrical conductivity requirement for under-the-hood applications.

Traditional materials such as copper (C11000), cartridge brass (C26000), phosphor bronze (C51000), tin brass (C42500), and cobalt-modified aluminum brass (C68800) will continue to be used for garden-variety connectors. Improved alloys such as zirconium-copper (C15100), Cu-Fe-P alloy C19700, and Cu-Ni-Si alloy C70250 will capture the more demanding applications (Ref 2). However, beryllium-coppers (C17000 to C17510) will probably continue as the materials of choice for military and other severe duty connectors.

The traditional nickel-iron IC lead frame alloys have given way, at least for plastic dual-in-line packages, to the higher conductivity, Cu-Fe-Zn-P alloy C19400. Packages requiring higher strength use alloy C19500, which contains strength-enhancing additions of tin and cobalt. If high heat dissipation is needed, alloy C15100 is recommended. The recently improved tempers of alloys C19400 and C70250 are candidates for applications requiring very high strength in thin sections (Ref 2). Lead frame materials are described in the article "Applications" in this Handbook.

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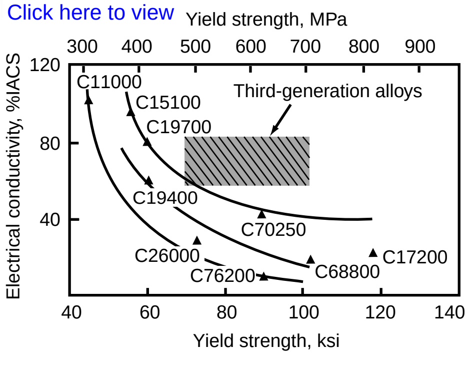

Fig. 1 Strength versus electrical conductivity for selected copper alloys. Both strength and conductivity are prerequisites for electrical connector alloys. In automotive under-the-hood applications, conventional materials (lower left curve) have largely been replaced by copper alloys with improved properties (middle and upper curves). However, future vehicles will require a third generation of materials (shaded area). Source: Ref 1

Heavy-duty electromechanical products, such as circuit breaker components and resistance welding equipment, can be specified in precipitation-hardenable chromium-coppers such as C18000 and C18100. For highest strength, however, the beryllium-coppers are the material of choice. Alloys containing nominally 2% Be (the "gold" alloys, C17000 to C17300) can be age hardened to an ultimate tensile strength (UTS) exceeding 1380 MPa (200 ksi), while the lower-beryllium "red" alloys, C17410 to C17510, aren't as strong (UTS around 830 MPa, or 120 ksi), but have high conductivity. Various combinations of strength and conductivity can be developed by appropriate overaging treatments. Figure 2 compares the strength and electrical conductivity relationships of various copper alloys, including beryllium-copper alloys C17000, C17200, C17410, and C17510.

Brasses

The common brasses (C21000 to C28000) are copper alloys in which zinc is the principal alloying element. Low-zinc alloys, such as gilding (C21000), retain the fcc a-structure, while high-zinc brasses (>39% Zn), such as Muntz metal (C28000), contain mostly the hard body-centered cubic β-phase. Brasses containing between 32 and 39% Zn may have a duplex α + β-structure, which makes them easier to hot work and machine. Increasing zinc content produces stronger and "springier" alloys, at the expense of a moderate decrease in corrosion resistance. Although produced in all product forms, brasses are primarily used as sheet, for stampings (springs, and components of electrical switches and sockets, for example); as tube, for lamp components, drain pipe, and plumbing goods; and as rod, for cold-headed fasteners and forgings.

Table 5 Copper alloys ranked by electrical conductivity

UNS No.	Electrical conductivity, %IACS at 20 °C (68 °F)
C10100, C10200, C11000	101
C10400, C10500, C10700, C11300, C11400, C11500, C11600	100
C10300	99
C12000, C12100, C12900	98
C18700	96
C14700	95
C14500, C15000, C15715	93
C10800, C18135	92
C16200	90
C15725	87
C12200, C14520	85
C18100, C18200, C18400	80
C15760	78
C16500	60
C21000	56
C19100, C19150	55
C17410, C17500, C17510	45
C22000	44
C31400	42
C22600	40
C64700	38
C23000	37
C32000	36
C50700	35
C24000, C31600	32
C26000, C26130, C26200, C28000, C38500	28
C26800, C27000, C37000, C37700	27
C33500, C34000, C34200, C34500, C35000, C35300, C35330, C35600, C36000, C46400, C48200, C48500	26
C46200	25
C67500	24
C67400	23
C17200, C17300, C67000, C67600	22
C54400	19
C51000, C61000	15
C61400	14
C52100, C61800	13
C61300, C62300, C62400, C65100	12
C62500	10
C70600, C74500	9
C64200, C69710, C75700, C79200	8
C63000, C63200, C65500, C75400	7
C65600, C66100, C63020, C69400, C75200	6
C71500	4

Source: Copper Development Association Inc.

Table 6 Copper alloys ranked by thermal conductivity

UNS No.	Thermal conductivity at 20 °C (68 °F) W/m · K	Btu/ft^2/ft/h/°F
C10100, C10200, C11000	391	226
C10400, C10500, C10700, C11300, C11400, C11500, C11600	388	224
C10300, C12000, C12100	386	223
C12900, C18700	377	218
C14700	374	216
C15000	367	212
C15715	365	211
C18135	363	210
C16200	360	208
C14500	355	205
C10800	349	202
C15725	344	199
C12200	339	196
C18100, C18200, C18400	324	187
C15760	322	186
C16500	253	146
C19100	251	145
C21000	234	135
C17410, C17500, C17510, C19150	208	120
C22000	189	109
C31400	180	104
C22600	173	100
C64700	168	97
C50700	164	95
C23000	159	92
C32000	156	90
C24000, C31600	140	81
C28000, C38500	123	71
C26000, C26130, C26200	121	70
C37000, C37700	119	69
C26800, C27000, C33500, C34000, C34200, C34500, C35000, C35300, C35330, C35600, C36000, C46400, C48200, C48500	116	67
C46200	111	64
C17200, C17300	107	62
C67500	106	61
C67400	100	58
C67000, C67600	99	57
C54400	87	50
C51000, C61000	69	40
C61400	67	39
C61800	64	37
C52100	62	36
C62400	59	34
C65100	57	33
C61300	55	32
C62300	54	31
C62500, C63020	47	27
C64200, C70600, C74500	45	26
C69710, C75700, C79200	40	23
C63000	38	22
C65500, C75400	36	21
C63200, C65600, C66100	35	20
C75200	33	19
C71500	29	17
C69400, C69430	26	15

Source: Copper Development Association Inc.

The corrosion resistance of brass is adequate for service in most atmospheric environments. However, the alloys are subject to dezincification in stagnant, acidic aqueous environments, and may fail by SCC in the presence of moist ammonia, amines, and mercury compounds. Electrical conductivity of brass is reasonably high, ranging from 56% IACS for C21000 to 28% IACS for high-zinc alloys. The cartridge brass (C26000) used in common electrical hardware has a conductivity of 28% IACS. (The conductivities of carbon steel and austenitic stainless steel are about 8.5% and 2.3% IACS, respectively.)

Alloy selection among the brasses is normally made on the basis of formability (C26000 is generally regarded as having optimal forming characteristics), corrosion resistance (which favors low-zinc alloys that have more copper-like properties), or color (which ranges from reddish pink to pale yellow, depending on zinc content). Hot forged products, if they must be lead-free, should be made from duplex alloys, or mostly-b-phase compositions such as alloy C28000.

Leaded (Cu-Zn-Pb) Brasses. The lead in wrought leaded brasses (C31200 to C38500) provides high machinability by acting as a microscopic chip breaker and tool lubricant. Leaded brasses are produced primarily as rod, bar, shapes, and mechanical tubing. The alloys have the same atmospheric corrosion resistance as their unleaded counterparts. Alloy C35330 also contains arsenic to inhibit dezincification.

Free-cutting brass (C36000) containing ~3% Pb is normally the first choice for a copper-base screw-machine material. The theoretical machinability of the alloy is more than five times that of leaded low-carbon steel (American Iron and Steel Institute (AISI) 12L14), which the brass approaches in terms of mechanical properties and far surpasses in corrosion resistance. With the high scrap value of turnings, and no need for expensive electroplating, the total cost of brass screw-machine products can be significantly lower than that of leaded-steel parts. For products that require both machining and cold forming, reduced-lead (~2% Pb) copper alloys such as C34500 or C35300 should be considered (Ref 4).

Alloy C37700 is primarily specified for corrosion-resistant forgings, such as valves and fittings, architectural hardware, and specialty fasteners. A modest lead content (~2% Pb) makes the alloy free-cutting. Like most brasses, it can be finished to a high luster and readily accepts decorative electroplated coatings.

Tin (Cu-Zn-Sn) brasses (C40400 to C48600) are essentially high-zinc brasses containing tin for better corrosion resistance and somewhat higher strength. Tin, like arsenic, antimony, and phosphorus, reduces susceptibility to dezincification. These economical alloys have properties somewhat better than those of the straight copper-zinc brasses.

Tin brasses have good hot forgeability and reasonably good cold formability. In rod form, they can be cold headed to produce high-

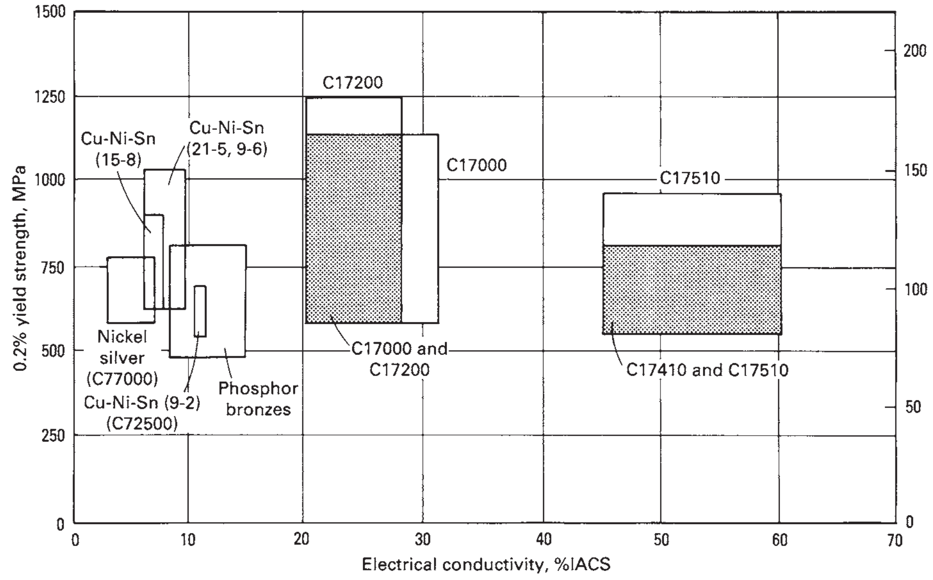

Fig. 2 Strength and electrical conductivity relationships in selected copper alloys. Each box represents the range of properties spanned by available tempers of the indicated alloy. Source: Ref 3

strength fasteners and similar parts. Leaded alloys C48200 and C48500 are free machining. Alloy C42500 is supplied as strip for fabricating into electrical connectors, springs, and related products. The admiralty brasses (C44300, C44400, and C44500) and naval brasses (C46400, C46500, and C46600) are used for corrosion-resistant mechanical products. Leaded naval brasses (C48200 and C48500) are supplied in rod form for marine hardware, pump shafts, valve stems, and corrosion-resistant screw-machine parts.

Copper-Zinc Alloys (C66300 to C69710). These miscellaneous copper-zinc alloys form a subgroup of high-strength brasses in which mechanical properties are enhanced by additions of manganese, iron, tin, aluminum, silicon, and/or cobalt. The alloys display a wide range of properties, but they are best known for their combination of high strength and moderately high corrosion resistance. Alloy C67300 is a familiar bearing material best used at high speeds and medium loads. It machines well and has reasonably good corrosion resistance. Alloy C68800 in strip form is a common electrical connector material.

Bronzes

Bronzes are copper alloys in which the major alloying addition is neither zinc nor nickel. Although there are exceptions, bronzes are generally classified by their major alloying element or elements.

Tin (Cu-Sn-P) bronzes (C50100 to C52480), also commonly referred to as phosphor bronzes, have superb spring qualities, high fatigue resistance, excellent formability and solderability, and high corrosion resistance. They are primarily produced as strip for electrical products. Other uses include corrosion-resistant bellows, diaphragms, and spring washers.

Leaded (Cu-Sn-P-Pb) tin or phosphor bronzes (C53400 and C54400) combine high strength and fatigue resistance with good machinability, high wear resistance, and excellent corrosion resistance, especially in seawater. They are frequently used for sleeve bearings, thrust washers, cam followers, and similar parts. Leaded tin bronze bearings resist pounding, but should be used against hardened journals (300 to 400 HB min), and only in applications where reliable lubrication is assured.

Aluminum (Cu-Al) bronzes (C60800 to C64210) are best known for their combination of high strength and excellent corrosion resistance. Their stress-corrosion fatigue resistance exceeds that of austenitic stainless steels. They are readily weldable, and can be machined or ground, although good lubrication and cooling are essential to obtain fine surface finishes.

Aluminum bronzes containing less than about 9.5% Al are hardened through a combination of solid-solution strengthening, cold work, and the precipitation of an iron-rich phase. Tensile strengths range between 480 and 690 MPa (70 and 100 ksi), depending on composition and temper. High-aluminum alloys (9 to 11% Al), such as C63000 and C63020, can be quenched and tempered much like steels to produce tensile strengths higher than 1000 MPa (145ksi).

Aluminum bronzes have a very wide range of applications. Common uses include marine hardware, shafts, and pump and valve components for handling seawater, sour mine waters, nonoxidizing acids, and industrial process fluids. The good wear resistance of the alloys makes them excellent choices for heavy-duty sleeve bearings and machine-tool ways. Because the aluminum reduces density in addition to raising strength, these bronzes have relatively high strength-to-weight ratios. This explains why nickel-aluminum bronze (C63020) is sometimes substituted for beryllium-copper in aircraft landing-gear bearings.

Silicon (Cu-Si) bronzes (C64700 to C66100) resemble the lower-aluminum bronzes in mechanical properties, having nominal tensile strengths up to about 690 MPa (100 ksi). The alloys exhibit the good corrosion resistance characteristic of all copper metals, although their resistance to SCC is somewhat lower than that of the aluminum bronzes. Silicon bronzes are produced in relatively low volumes for products such as hydraulic fluid lines, high-strength fasteners, wear plates, and marine and pole-line hardware. The alloys have excellent weldability, and are commonly used as welding filler wire.

Copper-Nickel Alloys

The copper-nickel alloys (C70100 to C72950) inhabit the copper-rich end of the binary copper-nickel system that also includes the Monel (67Ni-30Cu) alloys, and their properties are similar to nickel-rich alloys. Copper-nickels are among the most corrosion resistant and thermally stable of all the copper alloys, and are virtually immune to SCC. Like nickel-base alloys, copper-nickels exhibit high oxidation resistance in steam and moist air. Their moderate to high strength is retained well at elevated temperatures.

Low-nickel alloys (2 to 4% Ni) are used in strip form for electrical/electronic products, where strength, thermal stability, and good bend formability are needed. Alloys C70600 (10% Ni), C72200 (16% Ni, plus iron and chromium), and C71500 (30% Ni) are mostly produced as tubes for condensers in ships and seacoast power stations. Rod and plate are used for a variety of marine products, including valves, pumps, fittings, and fouling-resistant sheathing for ship hulls and offshore oil/gas platforms (Ref 5–8).

Nickel Silvers. These Cu-Ni-Zn alloys (C73500 to C79830) can be thought of as nickel brasses, because they generally contain more zinc than nickel. Nickel silvers combine good corrosion resistance with moderately high strength, which accounts for their wide use in food and beverage handling equipment. Their attractive silver luster is exploited for decorative hardware, electroplated tableware, optical and photographic equipment, and musical instruments.

Strengthening Mechanisms for Wrought Copper Alloys

Solution Hardening. Copper can be hardened by the various common methods without unduly impairing ductility or electrical conductivity. The metallurgy of copper alloys is suited for using, singly or in combination, the various common strengthening mechanisms: solid solution and work hardening, as well as dispersed particle and precipitation hardening. The commonly used solid-solution hardening elements are zinc, nickel, manganese, aluminum, tin and silicon, listed in approximate order of increasing effectiveness. Commercial alloys represent the entire range of available solid-solution compositions of each element up to 35% Zn, and up to (and even beyond) 50% Ni, 50% Mn, 9% Al,

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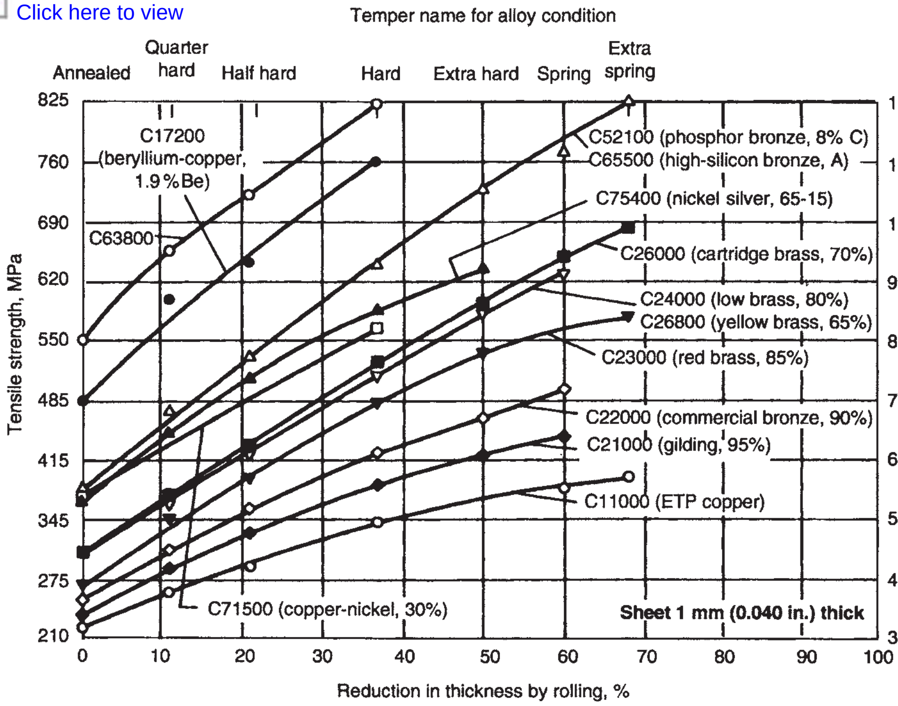

Fig. 3 Tensile strength of single-phase copper alloys as affected by percentage reduction in thickness by rolling (temper). Curves of lesser slope indicate a low rate of work hardening and a higher capacity for redrawing. ETP, electrolytic tough pitch

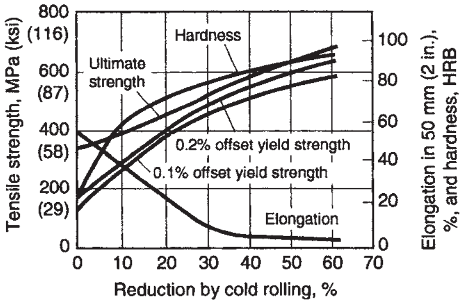

Fig. 4 The effect of cold rolling on the strength, hardness, and ductility of annealed copper alloy C26000 when it is cold rolled in varying amounts up to 62% reduction in thickness

11% Sn, and 4% Si. The relative amount of solution strengthening obtained from each element or particular combination of elements is determined by the ability of the solute to interfere with dislocation motion and is reflected in the work-hardening rate starting with the annealed condition, as illustrated by the increase in tensile strength with cold work shown in Fig. 3.

Work hardening is the principal hardening mechanism applied to most copper alloys, the degree of which depends on the type and amount of alloying element and whether the alloying element remains in solid solution or forms a dispersoid or precipitate phase. Even those alloys that are commercially age hardenable are often provided in the mill-hardened tempers; that is, they have been processed with cold work preceding and/or following an age-hardening heat treatment. For the leaner alloys (below ~12% Zn, or ~3% Al, for example), processing generates dislocations that develop into entanglements and into cells, with some narrow shear band formation beyond ~65% cold reduction in thickness. After ~90% cold work, the distinct "copper" or "metal" deformation crystallographic texture begins to develop. With the richer solid-solution alloys that lower the stacking-fault energy, planar slip is the dominant dislocation mechanism, with associated higher work hardening. Beyond ~40% cold work in these richer alloys, stacking faults, shear banding, and deformation twinning become important deformation mechanisms that, beyond 90% cold work, lead to the "brass" or "alloy" type of crystallographic deformation texture and accompanying anisotropy of properties. Figure 4 shows the variation in tensile properties with cold working of an annealed Cu-30Zn alloy (C26000). The degree of work hardening seen with cold working several selected single-phase copper alloys is illustrated by the cold-rolling curves in Fig. 3. Many copper alloys are used in wrought forms in a worked temper, chosen for the desired combination of work-hardened strength and formability, either for direct use in service or for subsequent component fabrication.

Dispersion strengthening is used in copper alloys for hardening, controlling grain size, and providing softening resistance, as exemplified by iron particles in copper-iron alloys, C19200 or C19400, and in aluminum bronzes, C61300 or C63380. Cobalt silicide particles in alloy C63800 (Cu-2.8Al-1.8Si-0.4Co), for example, provide fine-grain control and dispersion hardening to give this alloy high strength with reasonably good formability. Alloy C63800 offers an annealed tensile strength of 570 MPa (82 ksi) and rolled temper tensile strengths of 660 to 900 MPa (96 to 130 ksi). Alloys offering exceptionally good thermal stability have been developed using powder metallurgy techniques to incorporate dispersions of fine Al_2O_3 particles (3 to 12 nm in size) in a basic copper matrix, which is finish processed to rod, wire, or strip products. This family of alloys, C15715 to C15760, can resist softening up to and above 800 °C (1472 °F). More detailed information on oxide-dispersion-strengthened copper alloys is found in the article "Powder Metallurgy Copper and Copper Alloys" in this Handbook.

Precipitation Hardening. Age-hardening mechanisms are used in those few but important copper systems that offer a decreasing solubility for hardening phases. The beryllium-copper system offers a series of wrought and cast age-hardening alloys, UNS C17000 to C17530 and C82000 to C82800. The wrought alloys contain 0.2 to 2.0% Be and 0.3 to 2.7% Co (or up to 2.2% Ni). They are solution heat treated in the 760 to 955 °C (1400 to 1750 °F) range and age hardened to produce the beryllium-rich coherent precipitates when aged in the 260 to 565 °C (500 to 1050 °F) range, with the specific temperature being chosen for the particular alloy and desired property combination (Fig. 5). The precipitation sequence during aging consists of the formation of solute-rich G-P zones, followed in sequence by coherent platelets of the metastable intermediate phases γ' and γ''. Overaging is marked by the appearance of the B2 ordered equilibrium γ-BeCu phase as particles within grains and along grain boundaries, large enough to be seen in the light microscope. The cobalt and nickel additions form dispersoids of equilibrium (Cu, Co, or Ni)Be that restrict grain growth during solution annealing in the two-phase field at elevated temperatures (Fig. 5b). A cold-working step following solution annealing is often used to increase the age-hardening response. Alloy C17200 (Cu-1.8Be-0.4Co), for example, can be processed to reach high strength; that is, tensile strengths after solutionization (470 MPa, or 68 ksi), after cold rolling to the hard temper (755 MPa, or 110 ksi), and after aging (1415 MPa, or 205 ksi). While they are commercially available in the heat-treatable (solutionized) condition, the beryllium-copper alloys are commonly provided in the mill-hardened temper with the optimal strength/ductility/conductivity combination suitable for the application.

Other age-hardening copper alloys include the chromium-coppers, which contain 0.4 to 1.2% Cr (C18100, C18200, and C18400); these alloys produce arrays of pure chromium precipitates and dispersoid particles when aged. The Cu-Ni-Si alloys, C64700 and C70250, age harden by precipitating the Ni_2Si intermetallic phase. Each of these alloys, including the beryllium-coppers, can be thermomechanically processed to provide unique combinations of strength, formability, electrical conductivity, softening resistance, and stress-relaxation resistance.

Spinodal Hardening. Alloys in the ternary Cu-Ni-Sn system, which lie in the range of Cu-4Ni-4Sn to Cu-15Ni-8Sn, exhibit the phenom-

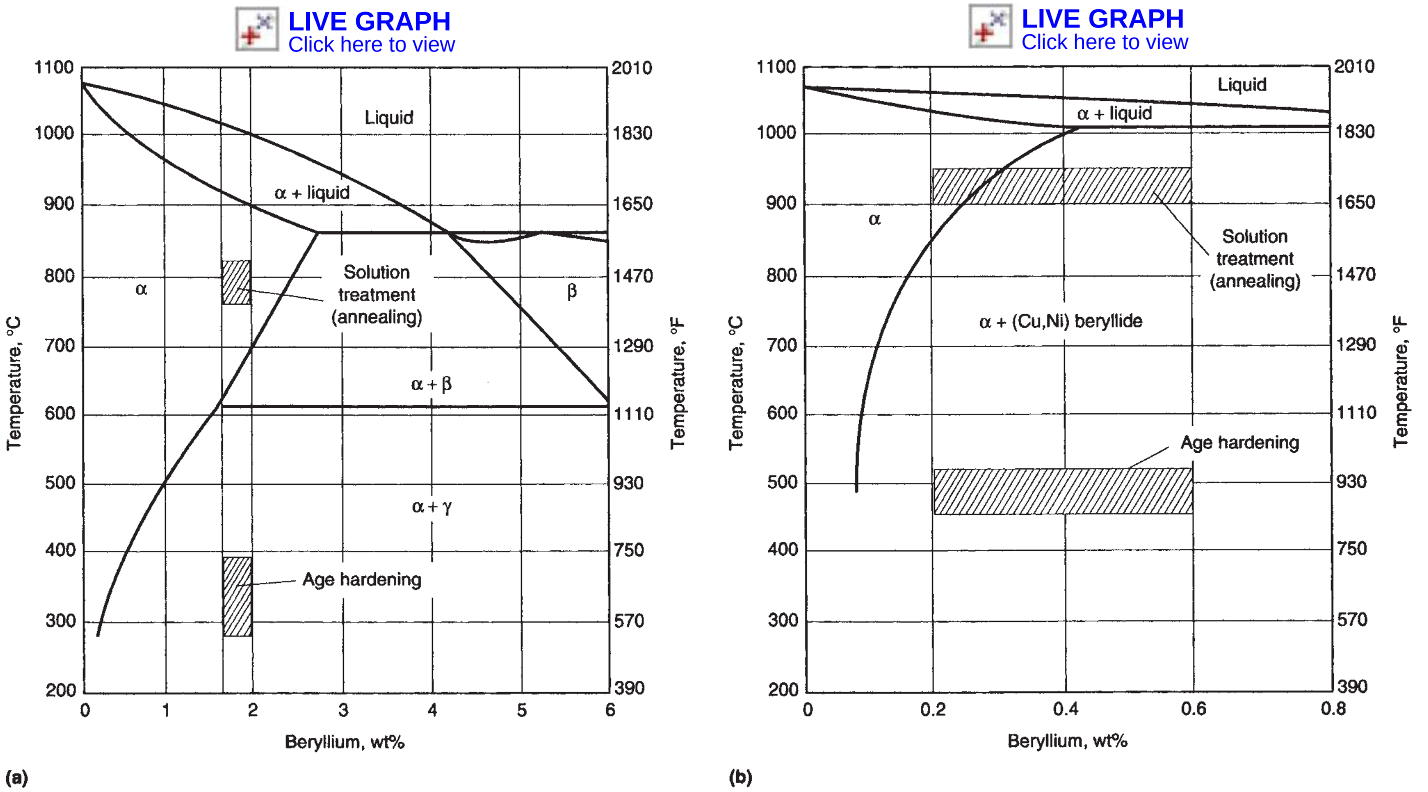

Fig. 5 Phase diagrams for beryllium-copper alloys. (a) Binary composition for high-strength alloys such as C17200. (b) Pseudobinary composition for C17510, a high-conductivity alloy

enon known as spinodal decomposition. A number of commercial alloys have been developed, the most important of which are C72700 and C72900.

Spinodal decomposition is similar to an age-hardening reaction and involves quenching and subsequent heat treatment, but instead of precipitates forming by a conventional nucleation and growth mechanism, regular variations in composition occur in the lattice with an extremely fine spacing between them. The two constituents have the same crystal structure but different lattice parameters. The strain hardening produced leads to particularly good mechanical properties, and no distortion occurs during the heat treatment.

Classification of Wrought Copper Products

Wrought copper and copper alloy products are broadly classified as refinery shapes, wire mill products, and brass mill products.

Refinery shapes are the products of primary copper producers. Along with recycled and re-refined scrap, they are the starting materials for the production of wrought (wire mill and brass mill) products, foundry products, and powder products (foundry and powder products are described elsewhere in this Handbook). Refinery shapes include:

- Cathodes
- Wire rod
- Billets
- Cakes
- Ingots

Wire Mill Products are destined for use as electrical conductors. Starting with wire rod, these mills cold draw the material (with necessary anneals) to final dimensions through a series of dies. The individual wires can be stranded and normally are insulated before being gathered into cable assemblies.

Brass Mill Products. Brass mills melt and alloy feedstock to make sheet, strip, plate, foil, tube, pipe, rod, bar, mechanical wire, forgings, and extrusions. Less than half of the copper input to brass mills is refined; the rest is scrap. Fabricating processes such as hot rolling, cold rolling, extrusion, and drawing are employed to convert the melted and cast feedstock into mill products.

Refinery Shapes

Copper is brought into the market initially in the form of cathodes, which are the end result of the extraction and electrolytic refining process (see the article "The Copper Industry: Occurrence, Recovery, and Consumption" in this Handbook). The cathodes are then converted into wire rod, billets, cakes, or ingots. These refinery shapes are further processed in wire mills and brass mills.

Cathodes are thick sheets (Fig. 6) of pure copper ($\sim$99.98% Cu) that weigh between 90 and 155 kg (200 and 342 lb). Sizes range between 960 and 1240 mm long by 767 to 925 mm wide and 4 to 16 mm thick (roughly 3 ft by 4 ft by $\frac{1}{4}$ in.). Compositional limits have been established for both electrorefined and electrowon cathodes by various international trading centers and standards organizations (see, for example, ASTM B 115, "Specification for Electrolytic Cathode Copper").

Most copper cathodes are sold for wire and cable production. They are continuously cast into wire rod as a precursor to wire drawing. They are also cast into billets, cakes, or ingots as pure copper or alloyed with other metals.

Wire rods are round, hexagonal, or octagonal sections about 8 mm ($\frac{5}{16}$ in.) in diameter that are furnished in coils (Fig. 7) or straight lengths. Both copper producers and wire mills produce continuously cast wire rod. Continuously cast wire rod meets the requirements of ASTM B 49, "Specification for Rod Drawing Stock for Electrical Purposes."

Continuously cast wire rod has completely replaced wire bar, which was the traditional starting material for wire production. The main advantage of continuous cast wire rod is that it is available in coils whose size is limited only by the capacity of the coil handling equipment either in the rod or the wire drawing plant. By contrast, wire bar is limited to about 115 kg (250 lb), requiring frequent butt welding of the small wire coils to produce larger coil sizes. Coils as large as 4545 kg (10,000 lb) can be produced by continuously casting wire rod.

Billets are continuously cast 9 m (30 ft) long logs about 200 mm (8 in.) in diameter of pure copper or of copper alloys. Billets are sawed into shorter lengths that are extruded and then drawn as tube, rod, and bar stock of various sizes and shapes. Rod stock is used for forging.

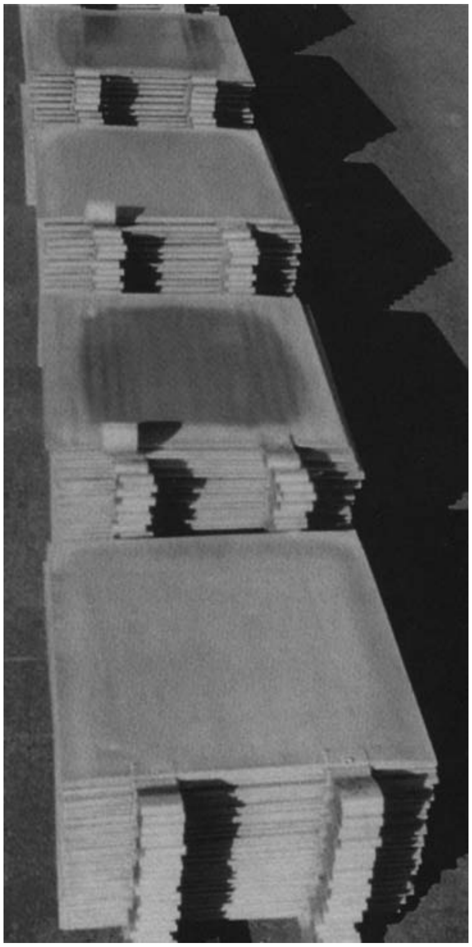

Fig. 6 Copper cathodes, as produced in an electrolytic refinery

Cakes. Continuous or semicontinuous casting is used to produce cast cake for conversion into plate, sheet, strip, and foil by hot or cold rolling. Cake has a slablike configuration—about 8.5 m (28 ft) long and 200 mm (8 in.) thick.

Ingots are bricks of pure copper or copper alloys that are chill cast in metallic molds. They may be used by mills for alloying with other metals or used by foundries for casting. Requirements for ingots are outlined in ASTM B 30, "Specification for Copper-Base Alloys in Ingot Form."

Wire Mill Products

Wire mills produce electrical conductors. Products include round and flat wire, stranded wire, and coated wire. Wires can be in the form of single filaments, multiple filaments, or cable (a group of insulated conductors twisted, or stranded, together). Major markets include building wire and cable, magnet wire, telecommunications wire and cable, power cable, automotive wire and cable, and other wire and cable products such as apparatus wire, cord sets, and electronic wire and cable. See the article "Applications" in this Handbook for additional information on markets for wire and cable.

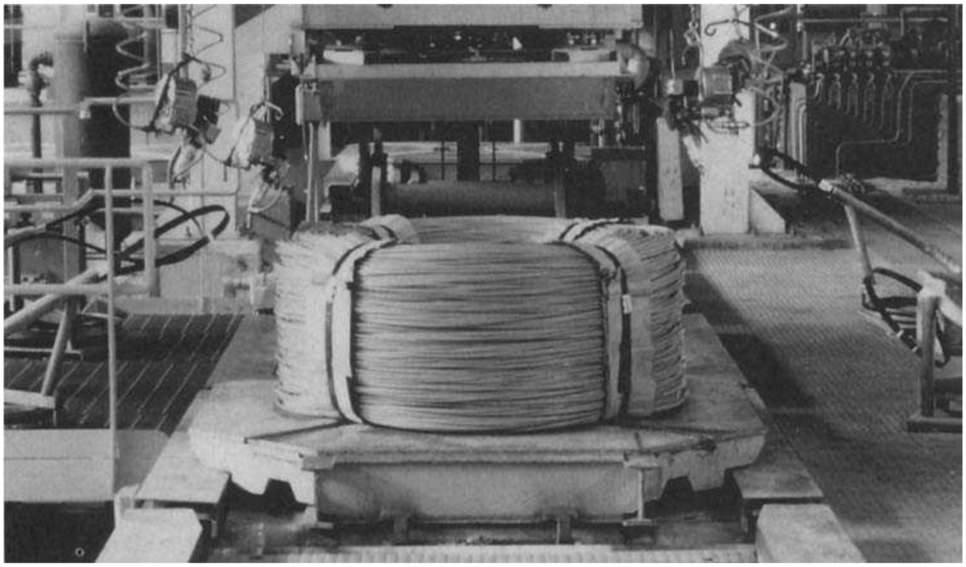

Fig. 7 Copper wire rod—the principal intermediate product for wire manufacture

Classification of Copper Conductors

Copper metals used for electrical conductors fall into three general categories: high-conductivity coppers, high-copper alloys, and electrical bronzes.

High-conductivity coppers are covered by ASTM B 5, "Specification for Electrolytic Tough Pitch Copper Refinery Shapes," and ASTM B 170, "Specification for Oxygen-Free Electrolytic Copper—Refinery Shapes." Oxygen-free copper employs special manufacturing techniques to avoid hydrogen embrittlement when exposed to elevated temperatures and reducing atmospheres.

High-copper alloys are specialty coppers produced by adding minimal amounts of hardening agents (such as chromium, cadmium zirconium, or beryllium). These are used in applications where resistance to thermal softening is required.

Electrical Bronzes. A series of bronzes has been developed for use as conductors; these alloys are covered by ASTM B 105, "Specification for Hard-Drawn Copper Alloy Wires for Electric Conductors." These bronzes are intended to provide better corrosion resistance and higher tensile strengths than standard conductor coppers. There are nine conductor bronzes, designated 8.5 to 85 in accordance with their electrical conductivities, as given below:

ASTM B 105 alloy designation	Alternative alloy types
8.5	Cu-Si-Fe, Cu-Si-Mn, Cu-Si-Zn, Cu-Si-Sn-Fe, Cu-Si-Sn-Zn
13	Cu-Al-Sn, Cu-Al-Si-Sn, Cu-Si-Sn
15	Cu-Al-Si, Cu-Al-Sn, Cu-Al-Si-Sn, Cu-Si-Sn
20	Cu-Sn
30	Cu-Sn, Cu-Zn-Sn
40(a)	Cu-Sn, Cu-Sn-Cd
55(a)	Cu-Sn-Cd
65(a)	Cu-Sn, Cu-Sn-Cd
80(a)	Cu-Cd
85	Cu-Cd

(a) Normally used for trolley-wire applications in either a round or grooved cross-sectional configuration, as set forth in ASTM B 9

The compositions of these alloys must be within the total limits prescribed in the following table, and no alloy may contain more than the allowed maximum of any constituent other than copper.

Element	Composition limit, % max
Fe	0.75
Mn	0.75
Cd	1.50
Si	3.00
Al	3.50
Sn	5.00
Zn	10.50
Cu	89.00 min
Sum of above elements	**99.50 min**

Classification of Wire and Cable

Round Wire. Standard nominal diameters and cross-sectional areas of solid round copper wires used as electrical conductors are prescribed in ASTM B 258, "Specification for Standard Nominal Diameters and Cross-Sectional Areas of AWG Sizes of Solid Round Wires Used as Electrical Conductors." Wire sizes have almost always been designated in the American Wire Gauge (AWG) system. This system is based on fixed diameters for two wire sizes (4/0 and 36 AWG, respectively) with a geometric progression of wire diameters for the 38 intermediate gages and for gages smaller than 36 AWG (see Table 7). This is an inverse series in which a higher number denotes a smaller wire diameter. Each increase of one AWG number is approximately equivalent to a 20.7% reduction in cross-sectional area.

ASTM B 3, "Specification for Soft or Annealed Copper Wire," specifies soft (or annealed) copper wire with a maximum volumetric resistivity of $0.017241\ \Omega \cdot \text{mm}^2/\text{m}$ at 20 °C (68 °F), which corresponds to a maximum weight-basis resistivity of $875.20\ \Omega \cdot \text{lb/mile}^2$ when the density is $8.89\ \text{g/cm}^3$. This type of copper is used as the IACS for electrical conductivity. Table 7 lists some properties of annealed copper wire for various AWG sizes. Tensile strengths are not specified for annealed copper wire.

Hard-drawn copper wire and hard-drawn copper alloy wire for electrical purposes are specified in ASTM B 1 and B 105, respectively. ASTM B 1, "Specification for Hard-Drawn Copper Wire," specifies hard-drawn round wire that has been reduced at least four AWG numbers (60% reduction in area). Table 8 lists the mechanical properties of hard-drawn copper wire and several hard-drawn copper alloy wires. The electrical resistivity and conductivity of these hard-drawn wires at 20 °C (68 °F) are as follows:

Alloy (hard drawn)	Maximum resistivity		Conductivity (volume basis), %IACS
	$\Omega \cdot \text{mm}^2/\text{m}$	$\Omega \cdot \text{lb/mile}^2$	
Copper			
(ASTM B 1) wire with diameter of:			
8.25 to 11.68 mm (0.325 to 0.460 in.)	0.017745	900.77	97.16
1.02 to <8.25mm (0.0403 to <0.325 in.)	0.017930	910.15	96.16
Copper alloys			
(ASTM B 105):			
C65100	0.20284	10,169.0	8.5
C51000	0.13263	6,649.0	13
C50700	0.057471	2,917.3	30
C16500	0.031348	1,591.3	55
C19600	0.023299	1,182.7	74
C16200	0.021552	1,094.0	80

Square and Rectangular Wire. ASTM B 48 specifies soft (annealed) square and rectangular copper wire.

Stranded wire is normally used in electrical applications where some degree of flexing is encountered either in service or during installation. In order of increasing flexibility, the common forms of stranded wire are: concentric lay, unilay, rope lay, and bunched.

Concentric-lay stranded wire and cable are composed of a central wire surrounded by one or more layers of helically laid wires, with the direction of lay reversed in successive layers, and with the length of lay increased for each successive layer. The outer layer usually has a left-hand lay.

ASTM B 8 establishes five classes of concentric-lay stranded wire and cable, from AA (the coarsest) to D (the finest). Details of concentric-lay constructions are given in Table 9.

Unilay stranded wire is composed of a central core surrounded by more than one layer of helically laid wires, all layers having a common lay length and direction. This type of wire sometimes is referred to as "smooth bunch." The layers usually have a left-hand lay.

Rope-lay stranded wire and cable are composed of a stranded member (or members) as a central core, around which are laid one or more helical layers of similar stranded members. The members may be concentric or bunch stranded. ASTM B 173 and B 172 establish five classes of rope-lay stranded conductors: classes G and H, which have concentric members; and classes I, K, and M, which have bunched members. Construction details are shown in Tables 10 and 11. These cables are normally used to make large, flexible conductors for portable service, such as mining cable or apparatus cable.

Bunch stranded wire is composed of any number of wires twisted together in the same direction without regard to geometric arrangement of the individual strands. ASTM B 174 provides for five classes (I, J, K, L, and M); these conductors are commonly used in flexible cords, hookup wires, and special flexible welding conductors. Typical construction details are given in Table 12.

Tin-Coated Wire. Solid and stranded wires are available with tin coatings. These are manufactured to the latest revisions of ASTM B 33, which covers soft or annealed tinned-copper wires, and B 246, which covers hard-drawn or medium-hard-drawn tinned-copper wires. Characteristics of tinned, round, solid wire are given in Table 13.

Fabrication of Wire Rod

Continuous cast wire rod is generally rolled to intermediate before it is processed into wire. Processing steps include cleaning, wiredrawing, annealing, coating, stranding, and/or insulating and jacketing.

Preparation of Rod. In order to provide a wire of good surface quality, it is necessary to have clean wire rod with a smooth, oxide-free surface. Conventional hot-rolled rod must be cleaned in a separate operation, but with the advent of continuous casting, which provides better surface quality, a separate cleaning operation is not required. Instead, the rod passes through a cleaning station as it exits from the rolling mill.

The standard method for cleaning copper wire rod is pickling in hot 20% sulfuric acid followed by rinsing in water. When fine wire is being produced, it is necessary to provide rod of even better surface quality. This can be achieved in a number of ways. One is by open-flame annealing of cold-drawn rod—that is, heating to 700 °C (1300 °F) in an oxidizing atmosphere. This eliminates shallow discontinuities. A more common practice, especially for fine magnet-wire applications, is die shaving, where rod is drawn through a circular cutting die made of steel or carbide to remove approximately 0.13 mm (0.005 in.) from the entire surface of the rod. A further refinement of this cleaning operation for rod made from conventionally cast wirebar involves scalping the top surface of cast wirebar and subsequently die shaving the hot-rolled bar.

Wiredrawing. Single-die machines called bull blocks are used for drawing special heavy sections such as trolley wire. Drawing speeds range from about 1 to 2.5 m/s (200 to 500 ft/min). Tallow is generally used as the lubricant, and the wire is drawn through hardened steel or tungsten carbide dies. In some instances, multiple-draft tandem bull blocks (in sets of 3 or 5 passes) are used instead of single-draft machines.

Tandem drawing machines having 10 to 12 dies for each machine are used for breakdown of hot-rolled or continuous-cast copper rod. The rod is reduced in diameter from 8.3 mm (0.325 in.) to about 2 mm (0.08 in.) by drawing it through dies at speeds up to 25 m/s (5000 ft/min). The drawing machine operates continuously; the operator merely welds the end of each rod coil to the start of the next coil.

Intermediate and fine wires are drawn on smaller machines that have 12 to 20 or more dies each. The wire is reduced in steps of 20 to 25% in cross-sectional area. Intermediate machines can produce wire as small as 0.5 mm (0.020 in.) in diameter, and fine wire machines can produce wire in diameters from 0.5 mm (0.020 in.) to less than 0.25 mm (0.010 in.). Drawing speeds are typically 25 to 30 m/s (5000 to 6000 ft/min) and may be even higher.

All drawing is performed with a copious supply of lubricant to cool the wire and prevent rapid die wear. Traditional lubricants are soap and fat emulsions, which are fed to all machines from a central reservoir. Breakdown of rod usually requires a lubricant concentration of about 7%; drawing of intermediate and fine wires, concentrations of 2 to 3%. Synthetic lubricants are becoming more widely accepted.

Drawn wire is collected on reels or stem packs, depending on the next operation. Fine wire is collected on reels carrying as little as 4.5 kg (10 lb); large-diameter wire, on stem packs carrying up to 450 kg (1000 lb). To ensure continuous operation, many drawing machines are equipped with dual take-up systems. When one reel is filled, the machine automatically flips the wire onto an adjacent empty reel and simultaneously cuts the wire. This permits the operator to unload the full reel and replace it with an empty one without stopping the wiredrawing operation.

Production of Flat or Rectangular Wire. Depending on size and quantity, flat or rectangular wire is drawn on bull block machines or Turk's-head machines, or is rolled on tandem rolling mills with horizontal and vertical rolls. Larger quantities are produced by rolling, smaller quantities by drawing.

Annealing. Wiredrawing, like any other cold-working operation, increases tensile strength and reduces ductility of copper. Although it is possible to cold work copper up to 99% reduction in area, copper wire usually is annealed after 90% reduction.

In some plants, electrical-resistance heating methods are used to fully anneal copper wire as it exits from the drawing machines. Wire coming directly from drawing passes over suitably spaced contact pulleys that carry the electrical current necessary to heat the wire above its recrystallization temperature in less than a second.

In plants where batch annealing is practiced, drawn wire is treated either in a continuous tunnel furnace, where reels travel through a neutral or slightly reducing atmosphere and are annealed during transit, or in batch bell furnaces under a similar protective atmosphere. Annealing temperatures range from 400 to 600 °C (750 to 1100 °F) depending chiefly on wire diameter and reel weight.

Wire Coating. Four basic coatings are used on copper conductors for electrical applications:

- Lead, or lead alloy (80Pb-20Sn), ASTM B 189
- Nickel, ASTM B 355
- Silver, ASTM B 298
- Tin, ASTM B 33

Coatings are applied to:

- Retain solderability for hookup-wire applications
- Provide a barrier between the copper and insulation materials, such as rubber, that would react with the copper and adhere to it (thus making it difficult to strip insulation from the wire to make an electrical connection)

Table 7 Sizes of round wire in the American Wire Gauge (AWG) system and the properties of solid annealed copper wire (ASTM B 3)

	Conductor diameter		Conductor area at 20 °C (68 °F)		Annealed copper (ASTM B 3)			
					Net weight (a)			
Conductor size, AWG	mm	in.	mm^2	circular mils	kg/km	lb/1000 ft	Elongation(b), %	Nominal resistance(c), Ω/1000 ft (305 m)
4/0	11.684	0.4600	107.0	211,600	953.2	640.5	35	0.0490
3/0	10.404	0.4096	85.0	167,800	755.7	507.8	35	0.06180
2/0	9.266	0.3648	67.4	133,100	599.4	402.8	35	0.07792
1/0	8.252	0.3249	53.5	105,600	475.5	319.5	35	0.09821
1	7.348	0.2893	42.4	83,690	377.0	253.3	30	0.1239
2	6.543	0.2576	33.6	66,360	299.0	200.9	30	0.1563
3	5.827	0.2294	26.7	52,620	237.1	159.3	30	0.1971
4	5.189	0.2043	21.2	41,740	188.0	126.3	30	0.2485
5	4.620	0.1819	16.8	33,090	149.1	100.2	30	0.3134
6	4.115	0.1620	13.3	26,240	118.2	79.44	30	0.3952
7	3.665	0.1443	10.5	20,820	93.8	63.03	30	0.4981
8	3.264	0.1285	8.37	16,510	74.4	49.98	30	0.6281
9	2.906	0.1144	6.63	13,090	59.0	39.62	30	0.7923
10	2.588	0.1019	5.26	10,380	46.8	31.43	25	0.9992
11	2.304	0.0907	4.17	8,230	37.1	24.9	25	1.26
12	2.052	0.0808	3.31	6,530	29.5	19.8	25	1.59
13	1.829	0.0720	2.63	5,180	23.4	15.7	25	2.00
14	1.628	0.0641	2.08	4,110	18.5	12.4	25	2.52
15	1.450	0.0571	1.65	3,260	14.7	9.87	25	3.18
16	1.290	0.0508	1.31	2,580	11.6	7.81	25	4.02
17	1.151	0.0453	1.04	2,050	9.24	6.21	25	5.06
18	1.024	0.0403	0.823	1,620	7.32	4.92	25	6.40
19	0.912	0.0359	0.654	1,290	5.80	3.90	25	8.04
20	0.813	0.0320	0.517	1,020	4.61	3.10	25	10.2
21	0.724	0.0285	0.411	812	3.66	2.46	25	12.8
22	0.643	0.0253	0.324	640	2.89	1.94	25	16.2
23	0.574	0.0226	0.259	511	2.31	1.55	25	20.3
24	0.511	0.0201	0.205	404	1.82	1.22	20	25.7
25	0.455	0.0179	0.162	320	1.44	0.970	20	32.4
26	0.404	0.0159	0.128	253	1.14	0.765	20	41.0
27	0.361	0.0142	0.102	202	0.908	0.610	20	51.4
28	0.320	0.0126	0.081	159	0.716	0.481	20	65.2
29	0.287	0.0113	0.065	128	0.576	0.387	20	81.0
30	0.254	0.0100	0.051	100	0.451	0.303	15	104.0
31	0.226	0.0089	0.040	79.2	0.357	0.240	15	131.0
32	0.203	0.0080	0.032	64.0	0.289	0.194	15	162.0
33	0.180	0.0071	0.026	50.4	0.228	0.153	15	206.0
34	0.160	0.0063	0.020	39.7	0.179	0.120	15	261.0
35	0.142	0.0056	0.016	31.4	0.141	0.0949	15	330.0
36	0.127	0.0050	0.013	25.0	0.113	0.0757	15	415.0
37	0.114	0.0045	0.010	20.2	0.0912	0.0613	15	513.0
38	0.102	0.0040	0.0081	16.0	0.0720	0.0484	15	648.0
39	0.089	0.0035	0.0062	12.2	0.0552	0.0371	15	850.0
40	0.079	0.0031	0.0049	9.61	0.0433	0.0291	15	1,079.0
41	0.071	0.0028	0.0040	7.84	0.0353	0.0237	15(d)	1,323.0
42	0.0635	0.0025	0.0032	6.25	0.0281	0.0189	15(d)	1,659.0
43	0.056	0.0022	0.0023	4.48	0.0219	0.0147	15(d)	2,143.0
44	0.050	0.0020	0.0020	4.00	0.0180	0.0121	15(d)	2,593.0
45	0.045	0.00176	0.0016	3.10	0.0140	0.00938	(d)	3,345.6
46	0.040	0.00157	0.00125	2.46	0.0111	0.00745	(d)	4,216.0
47	0.036	0.00140	0.00099	1.96	0.00882	0.00593	(d)	5,291.6
48	0.031	0.00124	0.00078	1.54	0.00673	0.00466	(d)	6,734.7
49	0.028	0.00111	0.00062	1.23	0.00554	0.00372	(d)	8,432.1
50	0.025	0.00099	0.00050	0.980	0.00442	0.00297	(d)	10,583
51	0.022	0.00088	0.00039	0.774	0.00348	0.00234	(d)	13,400
52	0.020	0.00078	0.00031	0.608	0.00274	0.00184	(d)	17,058
53	0.018	0.00070	0.00025	0.490	0.00220	0.00148	(d)	21,166
54	0.016	0.00062	0.00019	0.384	0.00173	0.00116	(d)	27,009
55	0.014	0.00055	0.00015	0.302	0.00136	0.000914	(d)	34,342
56	0.012	0.00049	0.00012	0.240	0.00108	0.000726	(d)	43,214

(a) Based on a density of 8.89 g/cm^3 at 20 °C (68 °F). (b) Minimum elongation in 250 mm (10 in.). (c) Based on a resistivity value of 0.017241 Ω · mm^2/m (875 · 20 Ω · lb/mile^2), which is the resistivity for the International Annealed Copper Standard (IACS) of electrical conductivity. (d) Elongation not specified in ASTM B 3

Table 8 Tensile properties of hard-drawn copper and copper alloy round wire

Conductor size, AWG	Hard-drawn copper wire (ASTM B 1)					Minimum tensile strength of hard-drawn copper alloy wire (ASTM B 105)												ASTM B 105 minimum elongation(b),
	Nominal tensile strength(a)		Nominal elongation(b)	Nominal breaking strength		C65100		C51000		C50700		C16500		C19600		C16200		
	MPa	ksi	%	N	lbf	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	%
4/0	340	49.0	3.8	36,220	8,143	…	…	…	…	…	…	…	…	…	…	…	…	…
3/0	350	51.0	3.3	29,900	6,720	…	…	…	…	…	…	…	…	…	…	…	…	…
2/0	365	52.8	2.8	24,550	5,519	…	…	…	…	…	…	…	…	…	…	…	…	…
1/0	375	54.5	2.4	20,095	4,518	…	…	…	…	…	…	…	…	…	…	…	…	…
1	385	56.1	2.2	17,290	3,888	672	97.5	707	102.5	510	74.0	524	76.0	510	74.0	496	72.0	2.2
2	395	57.6	2.0	13,350	3,002	716	103.8	750	108.8	552	80.0	536	77.8	520	75.5	507	73.5	2.0
3	405	59	1.8	10,850	2,439	741	107.5	776	112.5	586	85.0	547	79.3	534	77.5	517	75.0	1.8
4	415	60.1	1.7	8,762	1,970	760	110.2	794	115.2	614	89.0	558	80.9	545	79.0	527	76.4	1.6
5	420	61.2	1.6	7,072	1,590	774	112.2	808	117.2	638	92.5	568	82.4	552	80.0	534	77.5	1.5
6	430	62.1	1.4	5,693	1,280	786	114.0	820	119.0	654	94.8	579	84.0	558	81.0	542	78.6	1.4
7	435	63	1.3	4,580	1,030	795	115.3	829	120.3	665	96.5	590	85.5	568	82.4	550	79.8	1.3
8	440	63.7	1.3	3,674	826.1	804	116.6	836	121.6	675	97.9	600	87.0	576	83.5	558	81.0	1.3
9	445	64.3	1.2	2,940	660.9	812	117.8	847	122.8	683	99.0	610	88.5	583	84.6	567	82.2	1.2
10	445	64.9	1.2	2,354	529.3	820	118.9	854	123.9	690	100.1	620	90.0	590	85.5	575	83.4	1.2
11	450	65.4	1.1	1,880	423	826	119.8	860	124.8	698	101.2	630	91.3	597	86.6	583	84.6	1.2
12	455	65.7	1.1	1,500	337	832	120.6	866	125.6	705	102.2	638	92.6	605	87.7	591	85.7	1.1
13	455	65.9	1.1	1,190	268	836	121.2	870	126.2	710	103.0	647	93.8	612	88.8	598	86.8	1.1
14	455	66.2	1.0	952	214	839	121.7	874	126.7	715	103.7	655	95.0	619	89.8	605	87.8	1.1
15	460	66.4	1.0	756	170	843	122.2	877	127.2	720	104.4	662	96.0	625	90.6	612	88.7	1.0
16	460	66.6	1.0	600	135	845	122.5	879	127.5	725	105.2	669	97.0	634	92.0	617	89.5	1.0
17	460	66.8	1.0	480	108	847	122.8	881	127.8	730	105.9	676	98.0	640	92.8	623	90.3	1.0
18	460	67.0	1.0	380	85.5	848	123.0	883	128.0	735	106.6	680	98.6	645	93.5	627	91.0	0.9
19	463	67.2	…	302	68.0	849	123.2	884	128.2	740	107.3	683	99.0	648	94.0	632	91.6	0.9
20	465	67.4	…	241	54.2	852	123.5	886	128.5	745	108.0	686	99.5	652	94.5	636	92.2	0.9
21	467	67.7	…	192	43.2	…	…	…	…	…	…	…	…	…	…	…	…	…
22	468	67.9	…	152	34.1	…	…	…	…	…	…	…	…	…	…	…	…	…
23	470	68.1	…	121	27.3	…	…	…	…	…	…	…	…	…	…	…	…	…
24	471	68.3	…	96.5	21.7	…	…	…	…	…	…	…	…	…	…	…	…	…
25	473	68.6	…	77.0	17.3	…	…	…	…	…	…	…	…	…	…	…	…	…
26	474	68.8	…	60.9	13.7	…	…	…	…	…	…	…	…	…	…	…	…	…
27	476	69.0	…	48.5	10.9	…	…	…	…	…	…	…	…	…	…	…	…	…
28	478	69.3	…	38.4	8.64	…	…	…	…	…	…	…	…	…	…	…	…	…
29	479	69.4	…	31.0	6.96	…	…	…	…	…	…	…	…	…	…	…	…	…
30	481	69.7	…	24.3	5.47	…	…	…	…	…	…	…	…	…	…	…	…	…
31	482	69.9	…	19.3	4.35	…	…	…	…	…	…	…	…	…	…	…	…	…
32	484	70.2	…	15.7	3.53	…	…	…	…	…	…	…	…	…	…	…	…	…
33	485	70.4	…	12.4	2.79	…	…	…	…	…	…	…	…	…	…	…	…	…
34	487	70.6	…	9.79	2.20	…	…	…	…	…	…	…	…	…	…	…	…	…
35	489	70.9	…	7.78	1.75	…	…	…	…	…	…	…	…	…	…	…	…	…
36	490	71.1	…	6.23	1.40	…	…	…	…	…	…	…	…	…	…	…	…	…
37	492	71.3	…	5.03	1.13	…	…	…	…	…	…	…	…	…	…	…	…	…
38	493	71.5	…	4.39	0.898	…	…	…	…	…	…	…	…	…	…	…	…	…
39	495	71.8	…	3.07	0.691	…	…	…	…	…	…	…	…	…	…	…	…	…
40–44	496	72.0	…	2.42–1.00	0.543–0.226	…	…	…	…	…	…	…	…	…	…	…	…	…

(a) Tensile strengths cannot always be met if wire is drawn into coils of less than 480 mm (19 in.). (b) Elongation in 250 mm (10 in.)

- Prevent oxidation of the copper during high-temperature service

Tin-lead alloy coatings and pure tin coatings are the most common; nickel and silver are used for specialty and high-temperature applications.

Copper wire can be coated by hot dipping in a molten metal bath, electroplating, or cladding. With the advent of continuous processes, electroplating has become the dominant process, especially because it can be done "on line" following the wiredrawing operation.

Stranded wire is produced by twisting or braiding several wires together to provide a flexible cable. (For a description of various strand constructions, see the section of this article entitled "Classification of Wire and Cable.") Different degrees of flexibility for a given current-carrying capacity can be achieved by varying the number, size, and arrangement of individual wires. Solid wire, concentric strand, rope strand, and bunched strand provide increasing degrees of flexibility; within the last three categories, a larger number of finer wires provides greater flexibility.

Stranded copper wire and cable are made on machines known as bunchers or stranders. Conventional bunchers are used for stranding small-diameter wires (34 AWG up to 10 AWG). Individual wires are payed off reels located alongside the equipment and are fed over flyer arms that rotate about the take-up reel to twist the wires. The rotational speed of the arm relative to the take-up speed controls the length of lay in the bunch. For small, portable, flexible cables, individual wires are usually 30 to 34 AWG, and there may be as many as 150 wires in each cable.

A tubular buncher has up to 18 wire-payoff reels mounted inside the unit. Wire is taken off each reel while it remains in a horizontal plane, is threaded along a tubular barrel, and is twisted together with other wires by a rotating action of the barrel. At the take-up end, the strand passes through a closing die to form the final bunch configuration. The finished strand is wound onto a reel that also remains within the machine.

Supply reels in conventional stranders for large-diameter wire are fixed onto a rotating frame within the equipment and revolve about the axis of the finished conductor. There are two basic types of machines. In one, known as a rigid-frame strander, individual supply reels are mounted in such a way that each wire receives a full twist for every revolution of the strander. In the other, known as a planetary strander, the wire receives no twist as the frame rotates.

These types of stranders are comprised of multiple bays, with the first bay carrying six reels and subsequent bays carrying increasing multiples of six. The core wire in the center of the strand is payed off externally. It passes through the machine center and individual wires are laid over it. In this manner, strands with up to 127 wires are produced in one or

Table 9 Characteristics of concentric-lay stranded copper conductors specified in ASTM B 8

			Class AA		Class A		Class B		Class C		Class D	
Conductor size, circular mils or AWG	Nominal weight (a), lb/1000 ft	Nominal resistance(b), Ω/1000 ft(a)	Number of wires	Diameter of individual wires(a), mils	Number of wires	Diameter of individual wires(a), mils	Number of wires	Diameter of individual wires(a), mils	Number of wires	Diameter of individual wires(a), mils	Number of wires	Diameter of individual wires(a), mils
5,000,000	15,890	0.002 178	…	…	169	172.0	217	151.8	271	135.8	271	135.8
4,500,000	14,300	0.002 420	…	…	169	163.2	217	144.0	271	128.9	271	128.9
4,000,000	12,590	0.002 696	…	…	169	153.8	217	135.8	271	121.5	271	121.5
3,500,000	11,020	0.003 082	…	…	127	166.0	169	143.9	217	127.0	271	113.6
3,000,000	9,353	0.003 561	…	…	127	153.7	169	133.2	217	117.6	271	105.2
2,500,000	7,794	0.004 278	…	…	91	165.7	127	140.3	169	121.6	217	107.3
2,000,000	6,175	0.005 289	…	…	91	148.2	127	125.5	169	108.8	217	96.0
1,900,000	5,886	0.005 568	…	…	91	144.5	127	122.3	169	106.0	217	93.6
1,800,000	5,558	0.005 877	…	…	91	140.6	127	119.1	169	103.2	217	91.1
1,750,000	6,403	0.006 045	…	…	91	138.7	127	117.4	169	101.8	217	89.8
1,700,000	5,249	0.006 223	…	…	91	136.7	127	115.7	169	100.3	217	88.5
1,600,000	4,940	0.006 612	…	…	91	132.6	127	112.2	169	97.3	217	85.9
1,500,000	4,631	0.007 052	…	…	61	156.6	91	128.4	127	108.7	169	94.2
1,400,000	4,323	0.007 556	…	…	61	151.5	91	124.0	127	105.0	169	91.0
1,300,000	4,014	0.008 137	…	…	61	146.0	91	119.5	127	101.2	169	87.7
1,250,000	3,859	0.008 463	…	…	61	143.1	91	117.2	127	99.2	169	86.0
1,200,000	3,705	0.008 815	…	…	61	140.3	91	114.8	127	97.2	169	84.3
1,100,000	3,396	0.009 617	…	…	61	134.3	91	109.9	127	93.1	169	80.7
1,000,000	3,088	0.010 88	37	164.4	61	128.0	61	128.0	91	104.8	127	88.7
900,000	2,779	0.011 75	37	156.0	61	121.5	61	121.5	91	99.4	127	84.2
800,000	2,470	0.013 22	37	147.0	61	114.5	61	114.5	91	93.8	127	79.4
750,000	2,316	0.014 10	37	142.4	61	110.9	61	110.9	91	90.8	127	76.8
700,000	2,161	0.015 11	37	137.5	61	107.1	61	107.1	91	87.7	127	74.2
650,000	2,007	0.016 27	37	132.5	61	103.2	61	103.2	91	84.5	127	71.5
600,000	1,853	0.017 63	37	127.3	37	127.3	61	99.2	91	81.2	127	68.7
550,000	1,698	0.019 23	37	121.9	37	121.9	61	95.0	91	77.7	127	65.8
500,000	1,544	0.021 16	19	162.2	37	116.2	37	116.2	61	90.5	91	74.1
450,000	1,389	0.023 51	19	153.9	37	110.3	37	110.3	61	85.9	91	70.3
400,000	1,235	0.026 45	19	145.1	19	145.1	37	104.0	61	81.0	91	66.3
350,000	1,081	0.030 22	12	170.8	19	135.7	37	97.3	61	75.7	91	62.0
300,000	926.3	0.035 26	12	158.1	19	125.7	37	90.0	61	70.1	91	57.4
250,000	771.9	0.042 31	12	144.3	19	114.6	37	82.2	61	64.0	91	52.4
4/0	653.3	0.049 99	7	173.9	7	173.9	19	105.5	37	75.6	61	58.9
3/0	518.1	0.063 04	7	154.8	7	154.8	19	94.0	37	67.3	61	52.4
2/0	410.9	0.079 48	7	137.9	7	137.9	19	83.7	37	60.0	61	46.7
1/0	326.0	0.100 2	7	122.8	7	122.8	19	74.5	37	53.4	…	…
1	258.4	0.126 4	3	167.0	7	109.3	19	66.4	37	47.6	…	…
2	204.9	0.159 4	3	148.7	7	97.4	7	57.4	19	59.1	…	…
3	162.5	0.201 0	3	132.5	7	86.7	7	86.7	19	52.6	…	…
4	128.9	0.253 4	3	118.0	7	77.2	7	77.2	19	48.9	…	…
5	102.2	0.319 7	…	…	…	…	7	68.8	19	41.7	…	…
6	81.05	0.403 1	…	…	…	…	7	61.2	19	37.2	…	…
7	64.28	0.508 1	…	…	…	…	7	54.5	19	33.1	…	…
8	50.98	0.640 7	…	…	…	…	7	48.6	19	29.5	…	…
9	40.42	0.808 1	…	…	…	…	7	43.2	19	28.2	…	…

(a) Units used in ASTM B 8 specification. (b) Uncoated wire

two passes through the machine, depending on its capacity for stranding individual wires.

Normally, hard-drawn copper is stranded on a planetary machine so that the strand will not be as springy and will tend to stay bunched rather than spring open when it is cut off. The finished product is wound onto a power-driven external reel that maintains a prescribed amount of tension on the stranded wire.

Insulation and Jacketing

Of the three broad categories of insulation—polymeric, enamel, and paper-and-oil—polymeric insulation is the most widely used.

Polymeric Insulation. The most common polymers are polyvinyl chloride (PVC), polyethylene, ethylene propylene rubber (EPR), silicone rubber, polytetrafluoroethylene (PTFE), and fluorinated ethylene propylene (FEP). Polyimide coatings are used where fire resistance is of prime importance, such as in wiring harnesses for manned space vehicles. Natural rubber was used, but this has been supplanted by synthetics such as butyl rubber and EPR. Synthetic rubbers are used wherever good flexibility must be maintained, such as in welding or mining cable.

Many varieties of PVC are made, including several that are flame resistant. PVC has good dielectric strength and flexibility, and is one of the least expensive conventional insulating and jacketing materials. It is used mainly for communication wire, control cable, building wire, and low-voltage power cables. PVC insulation is normally selected for applications requiring continuous operation at temperatures up to 75 °C (165 °F).

Polyethylene, because of its low and stable dielectric constant, is specified when better electrical properties are required. It resists abrasion and solvents. It is used chiefly for hookup wire, communication wire, and high-voltage cable. Cross-linked polyethylene (XLPE), which is made by adding organic peroxides to polyethylene and then vulcanizing the mixture, yields better heat resistance, better mechanical properties, better aging characteristics, and freedom from environmental stress cracking. Special compounding can provide flame resistance in XLPE. Typical uses include building wire, control cables, and power cables. The usual maximum sustained operating temperature is 90 °C (200 °F).

PTFE and FEP are used to insulate jet aircraft wire, electronic equipment wire, and specialty control cables, where heat resistance, solvent resistance, and high reliability are important. These electrical cables can operate at temperatures up to 250 °C (480 °F).

All of the polymeric compounds are applied over copper conductors by hot extrusion. The extruders are machines that convert pellets or powders of thermoplastic polymers into continuous covers. The insulating compound is loaded into a hopper that feeds into a long, heated chamber. A continuously revolving screw moves the pellets into the hot zone where the polymer softens and becomes fluid. At the end of the chamber, molten compound is forced out through a small die over the moving conductor, which also passes through the die opening. As the insulated conductor leaves the extruder it is water cooled and taken up on reels. Cables jacketed with EPR and XLPE go through a vulcanizing chamber prior to cooling to complete the cross-linking process.

Enamel Film Insulation. Film-coated wire, usually fine magnet wire, is composed of a metallic conductor coated with a thin, flexible enamel film. These insulated conductors are used for electromagnetic coils in electrical devices and must be capable of withstanding high breakdown voltages. Temperature ratings range from 105 to 220 °C (220 to 425 °F), depending on enamel composition. The most commonly used enamels are based on polyvinyl acetals, polyesters, and epoxy resins.

Equipment for enamel coating of wire often is custom built, but standard lines are available. Basically, systems are designed to insulate large numbers of wires simultaneously. Wires are passed through an enamel applicator that deposits a controlled thickness of liquid enamel onto the wire. Then the wire travels through a series of ovens to cure the coating, and finished wire is collected on spools. In order to build up a heavy coating of enamel, it may be necessary to pass wires through the system several times. Some manufacturers have used powder-coating methods. These avoid evolution of solvents, which is characteristic of curing conventional enamels, and thus make it easier for the manufacturer to meet Occupational Safety and Health Administration and Environmental Protection Agency standards. Electrostatic sprayers, fluidized beds, and other experimental devices are used to apply the coatings.

Paper-and-Oil Insulation. Cellulose is one of the oldest materials for electrical insulation and is still used for certain applications. Oil-impregnated cellulose paper is used to insulate high-voltage cables for critical power-distribution applications. The paper, which may be applied in tape form, is wound helically around the conductors using special machines in which six to twelve paper-filled pads are held in a cage that rotates around the cable. Paper layers are wrapped alternately in opposite directions, free of twist. Paper-wrapped cables then are placed inside special impregnating tanks to fill the pores in the paper with oil and to ensure that all air has been expelled from the wrapped cable.

The other major use of paper insulation is for flat magnet wire. In this application, magnet-wire strip (with a width-to-thickness ratio greater than 50 to 1) is helically wrapped with one or more layers of overlapping tapes. These may be bonded to the conductor with adhesives or varnishes. The insulation provides highly reliable mechanical separation under conditions of electrical overload.

Table 10 Characteristics of rope-lay stranded copper conductors having uncoated or tinned concentric members specified in ASTM B 173

	Class G				Class H			
Conductor sizes, circular mils or AWG	Diameter of individual wires(a), mils	Number of ropes	Number of wires each rope	Net weight(a), lb/1000 ft	Diameter of individual wires(a), mil	Number of ropess	Number of wires each rope	Net weight(a), lb/1000 ft
5,000,000	65.7	61	19	16,052	53.8	91	19	15,057
4,500,000	62.3	61	19	14,434	51.0	91	19	14,429
4,000,000	58.7	61	19	12,814	48.1	91	19	12,835
3,500,000	55.0	61	19	11,249	45.0	91	19	11,234
3,000,000	50.9	61	19	9,635	41.7	91	19	9,647
2,500,000	59.6	37	19	8,012	46.4	61	19	8,006
2,000,000	53.3	37	19	6,408	41.5	61	19	6,405
1,900,000	52.0	37	19	6,099	40.5	61	19	6,100
1,800,000	50.6	37	19	5,775	39.4	61	19	5,773
1,750,000	49.9	37	19	5,617	38.9	61	19	5,627
1,700,000	49.2	37	19	5,460	38.3	61	19	5,455
1,600,000	47.7	37	19	5,132	37.2	61	19	5,146
1,500,000	59.3	61	7	4,772	46.2	37	19	4,815
1,400,000	57.3	61	7	4,456	44.6	37	19	4,487
1,300,000	55.2	61	7	4,135	43.0	37	19	4,171
1,250,000	54.1	61	7	3,972	42.2	37	19	4,017
1,200,000	53.0	61	7	3,814	41.3	37	19	3,847
1,100,000	50.8	61	7	3,502	39.6	37	19	3,537
1,000,000	48.4	61	7	3,179	37.7	37	19	3,206
900,000	45.9	61	7	2,859	35.8	37	19	2,891
800,000	43.3	61	7	2,544	33.7	37	19	2,562
750,000	41.9	61	7	2,383	32.7	37	19	2,412
700,000	40.5	61	7	2,226	31.6	37	19	2,252
650,000	39.0	61	7	2,064	30.4	37	19	2,085
600,000	37.5	61	7	1,908	29.2	37	19	1,923
550,000	35.9	61	7	1,749	28.0	37	19	1,768
500,000	43.9	37	7	1,579	34.2	61	7	1,587
450,000	41.7	37	7	1,425	32.5	61	7	1,433
400,000	39.3	37	7	1,265	30.6	61	7	1,271
350,000	36.8	37	7	1,109	28.6	61	7	1,110
300,000	34.0	37	7	947.1	26.5	61	7	953.0
250,000	31.1	37	7	792.4	24.2	61	7	794.8
4/0	39.9	19	7	666.6	28.6	37	7	670.1
3/0	35.5	19	7	527.7	25.5	37	7	532.7
2/0	31.6	19	7	418.1	22.7	37	7	422.2
1/0	28.2	19	7	333.0	20.7	37	7	334.3
1	25.1	19	7	263.8	18.0	37	7	265.4
2	36.8	7	7	206.9	22.3	19	7	208.2
3	37.8	7	7	164.4	19.9	19	7	165.8
4	29.2	7	7	130.3	17.7	19	7	131.2
5	26.0	7	7	103.3	15.8	19	7	104.5
6	23.1	7	7	81.52	14.0	19	7	82.06
7	20.6	7	7	64.83	12.5	19	7	65.42
8	18.4	7	7	51.72	11.1	19	7	51.59
9	15.3	7	7	40.59	9.9	19	7	41.04
10	14.6	7	7	32.57	…	…	…	…
12	11.5	7	7	20.20	…	…	…	…
14	9.2	7	7	12.93	…	…	…	…

(a) Units used in ASTM B 173

Flat-Rolled Products

Flat-rolled brass mill products include sheet, strip, plate, and foil. Sheets are flat-rolled products up to and including approximately 4.8 mm (0.188 in.) thick and over 500 mm (20 in.) wide. Strip is defined as any flat product other than flat wire. Thickness follows the range for sheet, although strip is furnished in widths between 32 and 305 mm (1.25 and 12 in.) with drawn or rolled edges. Plate is defined as flat product that is more than 4.8 mm (0.188 in.) thick and over 300 mm (12 in.) wide. Dimensional ranges for flat-rolled products are given in Table 14.

Flat-rolled coppers are used in the manufacture of products ranging from roofing sheet to coinage and electrical components. Product is supplied in the annealed condition and in a range of as-rolled tempers. Tempers based on grain size are also available. The choice of grade and temper depends on the intended application.

Copper-alloy strip is also manufactured in a range of tempers from soft to extra spring. Again, the choice of temper depends on the application and the degree of deformation required to manufacture the finished product. Simple electrical springs, for example, may be stamped from hard temper strip, while complex-shaped connectors and lead frames may require softer starting material.

General requirements for wrought copper and copper alloy plate, sheet, and strip are covered by ASTM B 248. Other ASTM specifications for flat-rolled products are listed in Table 15.

Copper foil, which is nominally less than 0.50 mm (0.2 in.), is produced by rolling, electroplating, or electroless plating. Foil is primarily used in the manufacture of printed circuit boards (see the article "Applications" in this Handbook). In general, the rolled foil product is used in applications where flexibility is required. Typical foil properties are listed in Table 16.

Table 11 Characteristics of rope-lay stranded copper conductor shaving uncoated or tinned bunched members specified in ASTM B 172

Conductor size, circular mils or AWG	Class of strand	Construction and wire size, AWG	Total number of wires	Approximate diameter, in.	Net weight, lb/1000 ft
1,000,000	I	19 × 7 × 19/24	2,527	1.290	3306
	K	37 × 7 × 39/30	10,101	1.329	3272
	M	61 × 7 × 59/34	25,193	1.353	3239
900,000	I	19 × 7 × 17/24	2,261	1.217	2959
	K	37 × 7 × 35/30	9,065	1.255	2936
	M	61 × 7 × 53/34	22,631	1.279	2909
800,000	I	19 × 7 × 15/24	1,995	1.140	2611
	K	19 × 7 × 60/30	7,980	1.174	2585
	M	61 × 7 × 47/34	20,069	1.200	2580
750,000	I	19 × 7 × 14/24	1,862	1.099	2437
	K	19 × 7 × 57/30	7,581	1.143	2455
	M	61 × 7 × 44/34	18,788	1.160	2415
700,000	I	19 × 7 × 13/24	1,729	1.057	2262
	K	19 × 7 × 52/30	6,916	1.089	2240
	M	61 × 7 × 41/34	17,507	1.117	2251
650,000	I	19 × 7 × 12/24	1,596	1.014	2088
	K	19 × 7 × 49/30	6,517	1.056	2111
	M	61 × 7 × 38/34	16,226	1.074	2086
600,000	I	7 × 7 × 30/24	1,470	0.971	1906
	K	19 × 7 × 45/30	5,985	1.010	1938
	M	61 × 7 × 35/34	14,945	1.028	1921
550,000	I	7 × 7 × 28/24	1,372	0.936	1779
	K	19 × 7 × 41/30	5,453	0.961	1766
	M	61 × 7 × 32/34	13,664	0.981	1757
500,000	I	7 × 7 × 25/24	1,225	0.882	1588
	K	19 × 7 × 38/30	5,054	0.924	1637
	M	37 × 7 × 49/34	12,691	0.900	1631
450,000	I	7 × 7 × 23/24	1,127	0.845	1461
	K	19 × 7 × 34/30	4,522	0.871	1465
	M	37 × 7 × 44/34	11,396	0.892	1465
400,000	I	7 × 7 × 20/24	980	0.785	1270
	K	19 × 7 × 30/30	3,990	0.816	1292
	M	37 × 7 × 39/34	10,101	0.837	1298
350,000	I	7 × 7 × 18/24	882	0.743	1143
	K	19 × 7 × 26/30	3,458	0.757	1120
	M	37 × 7 × 34/34	8,806	0.779	1132
300,000	I	7 × 7 × 15/24	735	0.675	953
	K	7 × 7 × 61/30	2,989	0.701	959
	M	19 × 7 × 57/34	7,581	0.720	975
250,000	I	7 × 7 × 13/24	637	0.626	826
250,000	K	7 × 7 × 61/30	2,499	0.638	802
	M	19 × 7 × 48/34	6,384	0.658	821
4/0	I	19 × 28/24	532	0.569	683
	K	7 × 7 × 43/30	2,107	0.584	676
	M	19 × 7 × 40/34	5,320	0.598	684
3/0	I	19 × 22/24	418	0.502	537
	K	7 × 7 × 34/30	1,666	0.516	535
	M	19 × 7 × 32/34	4,256	0.532	547
2/0	I	19 × 18/24	342	0.452	439
	K	7 × 7 × 27/30	1,323	0.457	424
	M	19 × 7 × 25/34	3,325	0.467	427
1/0	I	19 × 14/24	266	0.396	342
	K	19 × 56/30	1,064	0.408	338
	M	7 × 7 × 54/34	2,646	0.414	337
1	I	7 × 30/24	210	0.350	267
	K	19 × 44/30	836	0.359	266
	M	7 × 7 × 43/34	2,107	0.368	268
2	I	7 × 23/24	161	0.304	205
	K	19 × 35/30	665	0.319	211
	M	7 × 7 × 34/34	1,666	0.325	212
3	I	7 × 19/24	133	0.275	169
	K	19 × 28/30	532	0.283	169
	M	7 × 7 × 27/34	1,323	0.288	168
4	I	7 × 15/24	105	0.243	134
	K	7 × 60/30	420	0.250	132
	M	19 × 56/34	1,064	0.257	134
5	I	7 × 12/24	84	0.216	107
	K	7 × 48/30	336	0.223	106
	M	19 × 44/34	836	0.226	105
6	I	7 × 9/24	63	0.186	80
	K	7 × 38/30	266	0.197	84
	M	19 × 35/34	665	0.201	84
7	K	7 × 30/30	210	0.174	66
	M	19 × 28/34	532	0.178	67
8	K	7 × /30	168	0.155	53
	M	7 × 60/34	420	0.158	53
9	K	7 × 19/30	133	0.137	42
	M	7 × 48/34	336	0.140	42
10	M	7 × 37/34	259	0.122	33
12	M	7 × 24/34	168	0.097	21

Table 12 Characteristics of bunch stranded copper conductors having uncoated or tinned members specified in ASTM B 174

Conductor size, AWG	Class of strand	Number and size of wire, AWG	Approximate diameter, in.	Approximate weight, lb/1000 ft
7	I	52/24	0.168	64.9
8	I	41/24	0.148	51.1
9	I	33/24	0.132	41.2
10	I	26/24	0.117	32.4
	J	65/28	0.118	31.9
	K	104/30	0.120	32.1
12	J	41/28	0.093	20.1
	K	65/30	0.094	20.1
	L	104/32	0.096	20.6
14	J	26/28	0.073	12.7
	K	41/30	0.074	12.7
	L	65/32	0.075	12.8
	M	104/34	0.076	12.7
16	J	16/28	0.057	7.84
	K	26/30	0.058	8.03
	L	41/32	0.059	8.10
	M	65/34	0.059	7.97
18	J	10/28	0.044	4.90
	K	16/30	0.045	4.94
	L	26/32	0.046	5.14
	M	41/34	0.046	5.02
20	J	7/28	0.038	3.43
	K	10/30	0.035	3.09
	L	16/32	0.036	3.16
	M	26/34	0.037	3.19

The Manufacture of Sheet and Strip

The manufacture of sheet and strip in the modern brass mill begins with one of two basic casting processes:

- Vertical direct-chill (DC) semicontinuous casting
- Horizontal continuous casting

The vertical DC semicontinuous casting process is used to produce slabs of large cross section, which are subsequently reheated, hot rolled into heavy gage strip, and coiled. The continuous casting process uses a horizontal mold and casts a thin, rectangular section in much longer lengths that are coiled directly without hot rolling. The coils, in either case, then have their surfaces milled to remove any defects from casting or hot rolling. The next set of operations provides the desired final gage and temper by a series of cold-rolling, annealing, and cleaning operations. Finally, the sheet or strip may be slit into narrower widths, leveled, edge rolled or otherwise treated, and packaged for shipment.

Hot Rolling of Slabs

The rolling of slab into sheet or strip products is performed for reduction in thickness and/or grain refinement. The initial rolling of slabs is for grain refinement as well as to begin reduction in thickness. For copper and copper alloys that can be hot worked, the quickest and most economical method of reduction is hot rolling.

To prepare the slab for hot rolling, the top or gate end is trimmed by sawing and then it is conveyed into a furnace for heating. Slabs or bars of the same alloy are grouped together in a lot and processed through the furnace and the hot mill. The furnace temperature and the time for each bar to pass through the furnace are adjusted in order to allow the bar to reach the appropriate temperature throughout its thickness, length, and width by the time it passes through to the exit conveyor.

Temperature control is an important factor in hot rolling. Hot rolling can be accomplished only within a certain temperature range for each alloy. The bars will be damaged and have to be scrapped if hot rolling is attempted at a temperature that is too high or too low. Further, for all alloys, the grain size of the hot-rolled product is determined by the temperature at the last rolling pass. Subsequent processing (that is, cold working and annealing) to meet specified properties is dependent on this grain size. In some alloys, elements go into solution above certain temperatures and then precipitate out at lower temperatures. By completing hot rolling at a temperature above the precipitation temperature and quenching in a high-pressure water spray, solution heat treatment can be accomplished. This also affects both the physical and the mechanical properties attained in subsequent processing.

The roll stand used for hot rolling is a very sturdy mill having two rolls (two-high) whose direction of rotation can be rapidly reversed so the strip can be passed back and forth between them. The large horizontal rolls that reduce the thickness are supplemented by a pair of vertical edging rolls. The vertical rolls are needed to maintain the proper width by rolling edges because an appreciable spread in width takes place during hot rolling. The rolls are water cooled to avoid overheating, which would cause the surfaces to crack and check. Further, a polishing stone continuously dresses the rolls as they operate. As the thickness is reduced, the bar length increases proportionately. After the final rolling pass, the metal is spray cooled and coiled. Rolling temperatures and the percent of reduction per pass are designed to suit each alloy.

Milling or Scalping

Along with continuous casting, an equipment development that significantly advanced production is the high-speed coil milling machine. All coppers and copper alloys, produced with the good surface expected of brass mill sheet and strip, have their surfaces removed or scalped by a machining operation after breakdown rolling to remove all surface oxides remaining from

Table 13 Characteristics of tinned, solid, round copper wire specified in ASTM B 33, B 246, B 258

		Soft (annealed) wire		Hard-drawn wire	
Conductor size, AWG	Net weight, lb/1000 ft	Nominal resistance, V/1000 ft	Minimum elongation(a), %	Nominal resistance, Ω/1000 ft	Minimum breaking strength, lbf
2	200.9	0.1609	25	…	…
3	159.3	0.2028	25	…	…
4	126.3	0.2557	25	0.2680	1773
5	100.2	0.3226	25	0.3380	1432
6	79.44	0.4067	25	0.4263	1152
7	63.03	0.5127	25	0.5372	927.3
8	49.98	0.6465	25	0.6776	743.1
9	39.62	0.8154	25	0.8545	595.1
10	31.43	1.039	20	1.087	476.1
11	24.9	1.31	20	1.37	381.0
12	19.8	1.65	20	1.73	303.0
13	15.7	2.08	20	2.18	241.0
14	12.4	2.62	20	2.74	192.0
15	9.87	3.31	20	3.46	153.0
16	7.81	4.18	20	4.37	121.0
17	6.21	5.26	20	…	…
18	4.92	6.66	20	…	…
19	3.90	8.36	20	…	…
20	3.10	10.6	20	…	…
21	2.46	13.3	20	…	…
22	1.94	16.9	20	…	…
23	1.55	21.1	20	…	…
24	1.22	26.7	15	…	…
25	0.970	34.4	15	…	…
26	0.765	43.5	15	…	…
27	0.610	54.5	15	…	…
28	0.481	69.3	15	…	…
29	0.387	86.1	15	…	…
30	0.303	110.0	10	…	…
31	0.204	141.0	10	…	…
32	0.194	174.0	10	…	…
33	0.153	221.0	10	…	…
34	0.120	281.0	10	…	…

(a) In 250 mm (10 in.)

Table 14 Flat products (including rectangles and squares) furnished in rolls or in straight lengths

	Products available at a given width			
Thickness, in.	≤1.25 in.	>1.25 to 12 in.	>12 to 24 in.	>24 in.
≤0.188	Strip(a)	…	…	…
	Flat wire(b) (including square wire)	Strip	…	Sheet
>0.188	Bar(c)	…	Plate	…

(a) Product originally produced with slit, sheared, or sawed edges, whether or not such edges are subsequently rolled or drawn. (b) Product with all surfaces rolled or drawn, without previously having been slit, sheared, or sawed. (c) When bar is ordered, it is particularly desirable that the type of edge be specified. Source: Copper Development Association Inc.

Table 15 ASTM specifications for copper and copper alloy flat-rolled products

Specification	Product description
B 36	Brass plate, sheet, strip, and rolled bar
B 96 and B 96M (metric)	Copper-silicon alloy plate, sheet, strip, and rolled bar for general purposes
B 103	Phosphor bronze plate, sheet, strip, and rolled bar
B 121	Leaded brass plate, sheet, strip, and rolled bar
B 122	Copper-nickel-tin alloy, copper-nickel-zinc alloy (nickel silver), and copper-nickel alloy plate, sheet, strip, and rolled bar
B 152 and B 152M (metric)	Copper sheet, strip, plate, and rolled bar
B 169 and B 169M (metric)	Aluminum bronze plate, sheet, strip, and rolled bar
B 194	Copper-beryllium alloy plate, sheet, strip, and rolled bar
B 291	Copper-zinc-manganese alloy (manganese brass) sheet and strip
B 422	Copper-aluminum-silicon-cobalt alloy, copper-nickel-aluminum-silicon alloy, copper-nickel-aluminum-magnesium alloy sheet and strip
B 465	Copper-iron alloy plate, sheet, strip, and rolled bar
B 534	Copper-cobalt-beryllium alloy, copper-nickel-beryllium alloy plate, sheet, strip, and rolled bar
B 591	Copper-zinc-tin alloy plate, sheet, strip, and rolled bar
B 592	Copper-zinc-aluminum-cobalt or nickel-alloy plate, sheet, strip, and rolled bar
B 694	Copper, copper alloy, and copper-clad stainless steel sheet and strip for electrical cable shielding
B 740	Copper-nickel-tin spinodal alloy strip

casting or hot rolling. This operation is accomplished in a specially designed milling machine having rolls with inset blades that cut or mill away the surface layer of metal. The capability of this machine to handle the product in coiled form means that a much longer bar can be conveniently and economically milled.

Following hot rolling the DC cast bars are coil milled, and after careful surface inspection are ready to be applied on orders for processing to final gage, temper, and width.

Continuous-cast bars arrive at this stage by a somewhat different processing path. The coiled cast bars are annealed to provide a stress-free structure of maximum ductility. They are then cold rolled to work the structure sufficiently, so a fully recrystallized wrought grain structure will develop in the subsequent anneal. The bars are then scalped by milling. Both hot-reduced and cold-reduced milled bars are typically in the thickness range of 7.5 to 10 mm (0.300 to 0.400 in.).

Cold Rolling to Final Thickness

The sequence of operations for processing metal from milled condition to finish thickness or gage is designed to meet specified requirements for each application.

The earliest stages of cold rolling and annealing are designed to achieve the largest practical reduction in thickness (limits to the amount of reduction are discussed in the section "Effect on Properties" in this article). In the final rolling operations, where the strip is brought to finish gage, the cold reductions are designed to meet the specified property (temper) requirement. Meeting the tensile strength requirement, which is the basic mechanical property requirement for rolled tempers, is accomplished by cold rolling to the appropriate ready-to-finish gage, annealing to the desired grain size, and then rolling to finish gage. The percent reduction between ready-to-finish and finish gage is chosen to provide the amount of work hardening needed to produce the tensile strength required. Unavoidable small variations in thickness at both ready-to-finish and finish gages and in grain size from the ready-to-finish anneal require that the tensile strength requirement be given as a range, rather than a single value.

Rolling Mills. All thickness reduction is accomplished by cold rolling, and a variety of rolling mills are used. Cold rolling of coppers and copper alloys into sheet and strip of excellent quality requires a combination of skillful workmanship, knowledge, and good rolling mills. To keep cost as low as possible and competitive, the reduction in thickness to final gage needs to be accomplished in the fewest operations compatible with quality requirements. The basic problem is to reduce the thickness as much as possible in each rolling operation while maintaining uniformity of thickness across the width and length of a coil that is 60 to 180 m (200 to 600 ft) long at the first rolling pass and could be 7500 m (25,000 ft) long if rolled to 0.1 mm (0.004 in.) finish gage. Coupled with the need to maintain uniformity of thickness through all processing stages is the need to maintain flatness across the width and length of the coiled metal. Metal with uniformity of flatness across and along its length is described as having good shape. It is free of humps, waves, and buckles.

A rolling mill is capable of applying a large, but still limited, force upon the surfaces of the metal as it passes between the rolls to reduce its thickness. The applied force is spread across the contact area of the rolls on the metal. The larger the contact area, the smaller the force that is applied per unit of area and the smaller the reduction in thickness that can be achieved per pass through the rolls. Rolls of small diameter will have a small contact area, and greater force per unit of area. Small-diameter work rolls are most desirable for providing maximum use of roll force in reducing metal thickness, but they lack the stiffness required. The wider the metal to be rolled, the longer the rolls, and the greater the tendency for the rolls to bend or spring. To overcome the tendency, four-high and cluster rolling mills are used for cold rolling in the brass mill.

Four-high rolling mills (Fig. 8a) contain a pair of work rolls of relatively small diameter (for example, 300 mm, or 12 in.). A second pair of rolls, of large diameter (for example, 900 mm, or 36 in.), is placed above and below the work rolls in the stand to back them up and prevent them from springing. This arrangement allows the advantage of the small contact area of small work rolls and the transmittal of high force through the large backup rolls, while maintaining the rigidity required for gage control. The minimum size of the work rolls is limited by the forces in rolling, which tend to bow them backward or forward during rolling.

Cluster rolling mills (for example, Sendzimir mills) were designed to counteract both the vertical and horizontal elements of the rolling forces and thus enable the use of minimum-diameter work rolls (Fig. 8b). In cluster mills the work rolls are backed up by a cluster of backup rolls placed with respect to the work rolls so they contain the rolling forces and prevent bending or springing of the work rolls. By the use of such rolling mills, the thickness from width edge to edge across the 600 to 915 mm (24 to 36 in.) metal coils can be kept uniform through each gage reduction by rolling. This edge-to-edge gage control contributes to the maintenance of good shape. Good shape contributes to the production of flat, straight metal when slitting to the final specified width needed by the consumer.

Table 16 Typical copper foil properties

Temper designation	Material and condition	Nominal weight, g/m^2	Tensile strength, min MPa	Tensile strength, min ksi	Elongation in 50 mm, min, %
…	Electrodeposited	153	105	15	3
		305 and over	205	30	3
O61	Rolled and annealed	153	105	15	5
		305	140	20	10
		610 and over	170	25	20
H00	Light cold rolled	610 and over	220	32	5
H08	As rolled	All weights	345	50	…

The control equipment included in the rolling mill is a feature that bears directly on control of the gage from end to end of a coil of metal during rolling. For thickness control during high-speed rolling, continuous measurement of this dimension is a necessity. Rolling mills are equipped with x-ray and beta-ray instruments, which continuously gage the metal and provide a continuous readout of thickness. There are also control devices that actuate the screws in the roll housings and automatically open or close the gap between the work rolls to adjust the thickness being produced as required. These gages may also adjust back tension and forward tension applied by payoff and recoil arbors to effect changes in the thickness of the rolled metal.

Roll Lubricants. Rolling also exerts considerable influence on the surface quality of the metal. Work rolls are made of hardened steel, much harder than the copper alloy being rolled. As the rolls squeeze the metal to reduce its thickness, forward and backward slip between the rolls and the metal surfaces takes place. The frictional forces between the roll and metal surfaces, if direct contact was made, would tear the surface of the metal and load the roll surfaces with bits of the metal. To avoid damaging the surfaces in this manner, the metal and roll surfaces are flooded with cushioning lubricants. The selection of roll lubricants that will provide the protection needed without staining the metal, will be readily removable from the metal surfaces, and will not interfere with the rolling mill performance is an important engineering function that influences the economic production of high-quality copper alloy strip.

Effect on Properties. The more metal is cold worked, the harder and stronger it becomes. The hardening that occurs when copper and copper alloys are cold rolled allows each of them to be produced with a range of strengths or tempers that are suitable for a variety of applications. Starting with annealed temper, the metal will increase in strength approximately proportionally by the amount of reduction by cold rolling. A series of standard cold-rolled tempers for each copper and copper alloy has been established. A typical plot of reduction versus tensile properties and hardness is shown in Fig. 4 for C26000 (cartridge brass). Figure 3 shows the variation of tensile strength and elongation for various degrees of reduction (and the associated rolling "temper" name).

For each of the coppers and copper alloys there are limits to the amount of cold reduction that is desirable before annealing the metal to provide a recrystallized soft structure for further cold reduction. Some alloys, such as the phosphor bronzes, the high-zinc-content nickel silvers, and the aluminum-containing high-zinc brasses work harden rapidly. As they are cold rolled, they quickly become too hard for further reduction and must be annealed.

With large amounts of cold reduction prior to annealing, some coppers and copper alloys will develop differences in their strength and ductility when these properties are measured along the direction of rolling, compared to measurements across the direction of rolling. This directionality in mechanical properties arises from the fact that the normal random orientation of the atomic planes from grain to grain is gradually forced into a pattern conforming to the constant working of the metal in one direction. This directionality can affect the fabricability and final performance of the strip or sheet. Its control requires that the amount of reduction between anneals and the temperature of successive anneals be carefully controlled.

Annealing

The basic purpose of annealing is recrystallization and softening to prepare the metal for further cold working in the mill or by the consumer. Anneals are usually designed to produce a chosen grain size for a specified tensile strength, which in annealed copper and copper alloys is largely dependent on grain size, with few exceptions. The effect of grain size on the tensile strength of copper and brass strip is shown in Fig. 9. The effect of grain size on the elongation of C26000 is shown in Fig. 10.

Besides strength, grain size also affects workability, the control of directionality, and surface roughness. The consistent performance of the metal in subsequent cold working is dependent on grain-size uniformity. All these factors are considered when selecting the grain size to be established by any of the anneals included in the processing of each coil. Table 17 lists recommended applications of grain size ranges. Uniformity of grain size is influenced by the type of annealing furnaces and the method of operation. Each type of annealing method has certain advantages and disadvantages.

Coil Annealing. When annealing coiled metal, heat from the furnace must be absorbed through the coil surface and then penetrate to the innermost wraps, mostly by conduction. Temperature tends to vary in the coil with distance from the heat-absorbing surfaces. Coil annealing must be carefully controlled by slowly applying heat at a rate that will avoid overheating the surface, while the temperature of the inner wraps rises and equalizes with that of the outer wraps.

Coil annealing may be done in a roller hearth furnace where the coils are slowly moved through the furnace as they are gradually heated to the annealing temperature. This type of furnace usually does not have a prepared atmosphere, but the products of combustion fill the furnace and reduce the metal oxidation rate. More commonly, coil annealing is done in bell furnaces where a controlled atmosphere can be maintained. The annealing unit consists of a base on which the coils are stacked. Under the base is a fan for circulating the hot gases through the load, to provide more uniform and rapid heating. Surrounding the base is a trough, which may be filled with water, oil, or some other material to seal the inner hood when it is placed over the metal load to enclose it for atmosphere control.

In this type of batch annealing, bell furnaces capable of annealing up to 45 Mg (100,000 lb) of metal at a time are used. After the metal is stacked on the base, temperature-control thermocouples are placed throughout the load to continuously measure the temperature. The inner hood or retort is placed over the load and sealed. Controlled atmosphere begins to flow through the hood, purging the air. The furnace is placed over the hood and heating is begun.

In the well-equipped brass mill, large groups of such annealing units may be connected to a central process-control computer. As the furnace and load thermocouples measure the temperatures and relay them to the control unit, the heat input is constantly adjusted to maintain temperature uniformity in the load. This controlled temperature rise also allows roll lubricants to vaporize and be carried off before the metal gets so hot that surfaces can be harmed. After the metal has reached the annealing temperature, it is held there for a short period or soaked to provide maximum uniformity. Then the furnace is turned off and removed, and the metal cools in the controlled atmosphere under the inner hood. Cooling may be aided by a cooling cover containing a water spray system. The inner hood is not removed until the metal temperature is low enough that no discoloring or oxidation of the metal takes place.

The controlled atmosphere is produced in gas-cracking units. Combustible gases are burned with sufficient air to oxidize all the gaseous elements. The products of this combustion are then refined, and all gases that would be harmful to the metal surfaces are removed by chemical means. Those remaining pass into the annealing hoods, where they expel the air and protect the metal during annealing. For most coppers and copper alloys a slightly oxidizing atmosphere is desirable. For copper alloy C11000, the atmosphere must be nearly free of hydrogen and the annealing temperature low enough to avoid hydrogen embrittlement. For alloys containing zinc, the small amount of oxygen in the atmosphere

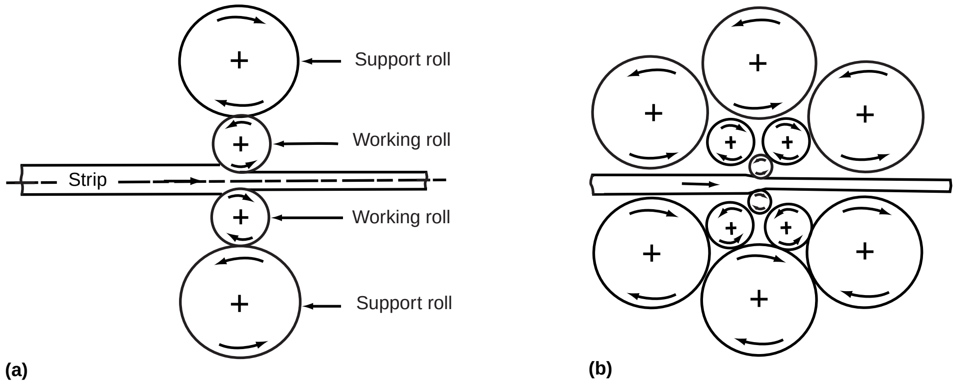

Fig. 8 Typical roll arrangements for precision cold rolling of copper sheet and strip. (a) Four-high mill. (b) Cluster mill

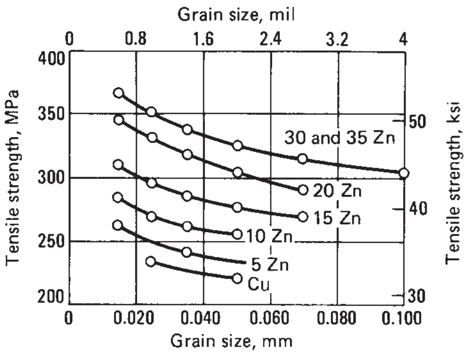

Fig. 9 Effect of grain size on tensile strength of annealed 0.040 in. strip of copper and brasses of designated zinc contents

LIVE GRAPH
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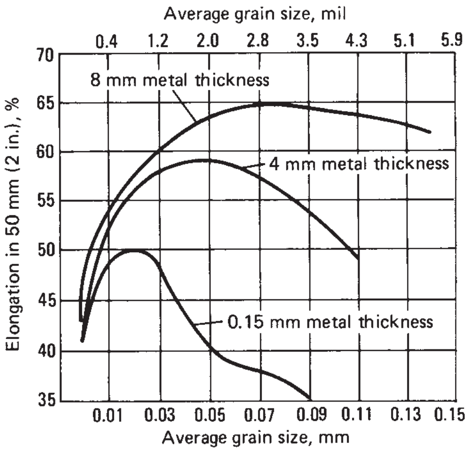

Fig. 10 Effect of grain size on elongation of annealed 0.040 in. strip of copper and brasses of designated zinc contents

LIVE GRAPH
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combines with the zinc fumes given off and prevents them from attacking the metal parts in the annealing unit. The oxide film that forms on the surface is very thin and readily removed in the subsequent cleaning processes.

Advantages and Disadvantages. One of the advantages of coil annealing in a controlled atmosphere furnace is that the surface of the metal can be readily restored to its natural color by appropriate cleaning following the anneal. The rather rare exception is when an abnormally high annealing temperature is required that causes excessive oxidation or dezincification of a high-zinc brass. Special cleaning methods that remove surface metal are then required to correct this condition. The more common situation is that annealing is done in a well-controlled atmosphere and followed by normal cleaning practices. This produces a metal surface uniform in color and free from detrimental oxides.

A disadvantage of coil annealing is that large coils of some alloys in thinner gages can be easily damaged. When the coiled metal is heated, it expands and the coil wraps get tighter. One wrap can become welded to the next because of the high temperature and pressure encountered, usually making the coil unsuitable for further processing. Coil annealing is also time consuming. A large bell furnace full of metal may require from 24 to 40 h to complete an annealing cycle; additional time is needed for cleaning, done as a separate operation.

Continuous Strand Annealing. In the late 1940s continuous strand, or strip annealing, lines came into use in brass mills. From these early beginnings, the high-speed vertical strip annealers were developed in the 1960s. Annealing lines of this type are used for annealing copper and copper alloy strip in thicknesses from under 0.25 mm to over 3 mm (0.010 to over 0.125 in.). When several such lines are available, a variety of thickness ranges can be rapidly annealed, providing great flexibility in production scheduling and enabling fast delivery of finished strip.

Because every foot of a coil is exposed to the same temperature as it passes through the strip-annealing furnaces, grain size from end to end should be uniform. Furnace instrumentation continuously records the furnace temperature and controls the heat input. Strip speed through the furnace is similarly monitored. The combination of furnace temperature and speed determines the temperature attained in the metal, and, therefore, the grain size. Samples commonly are cut from each end of each coil after strip or coil annealing, and the grain size or mechanical properties are determined as a further control on the quality uniformity of the product.

The continuous-strip anneal lines include payoff reels, a stitcher for joining the front end of a coil to the trailing end of the preceding one, a degreaser for removing roll lubricants, looping towers for metal storage, a seven-story-high vertical furnace that includes a heating zone, a controlled-atmosphere cooling zone, and a water quench tank. This is followed by acid cleaning tanks, a water rinse, a drying oven, and a reel for recoiling the metal. The fact that the metal is uncoiled before passing through the furnace removes annealing limitations on coil length. Degreasing units remove roll lubricants from the metal surfaces before the metal enters the furnace, so a clean, uniform surface is presented for annealing. The metal passes over a large roller outside the furnace at the top and does not touch anything inside while it is being heated. It then passes under another large roller at the bottom in the cooling water tank. This arrangement avoids any possibility of surface damage to the hot metal, which was common in the earlier horizontal-strip anneal furnaces. Although the furnace temperature is high, the metal is exposed to it for only a few seconds.

The furnace atmosphere may consist of hot burned gases that are blown against the strip surfaces to heat the metal. The metal is rapidly and uniformly raised to the annealing temperature as it passes through the heating zone of the furnace, and is then cooled rapidly by cold burned gases as it passes through the cooling zone, still protected from excessive oxidation.

Table 17 Available grain-size ranges and recommended applications

Average grain size, mm	Type of press operation and surface characteristics
0.005–0.015	Shallow forming or stamping. Parts will have good strength and very smooth surface. Also used for very thin metal
0.010–0.025	Stampings and shallow drawn parts. Parts will have high strength and smooth surface. General use for metal under 0.25 mm (0.010 in.) thick
0.015–0.030	Shallow drawn parts, stampings, and deep drawn parts that require buffable surfaces. General use for gages under 0.3 mm (0.012 in.)
0.020–0.035	This grain-size range includes the largest average grain that will produce parts essentially free of orange peel. For this reason it is used for all sorts of drawn parts produced from brass up to 0.8 mm (0.032 in.) thick.
0.025–0.040	Brass with 0.040 mm average grain size begins to show some roughening of the surface when severely stretched. Good deep drawing quality for 0.4 to 0.5 mm (0.015 to 0.020 in.) gage range
0.030–0.050	Drawn parts from 0.4 to 0.635 mm (0.015 to 0.025 in.) thick brass requiring relatively good surface, or stamped parts requiring no polishing or buffing
0.040–0.060	Commonly used grain-size range for general applications for deep and shallow drawings of parts from brass in 0.5 to 1.0 mm (0.020 to 0.040 in.) gages. Moderate orange peel may develop on drawn surfaces.
0.050–0.080, 0.060–0.090, 0.070–0.120	Large average-grain-size ranges are used for deep drawing of difficult shapes or deep drawing parts for gages 1.0 mm (0.040 in.) and greater. Drawn parts will have rough surfaces with orange peel except where smoothed by ironing.

Following a water quench, which completes the cooling cycle, the metal passes through the cleaning tanks. A normal cleaning solution is dilute sulfuric acid, which dissolves most of the oxide film left on the metal by annealing. As noted earlier, the atmosphere in the furnace must be slightly oxidizing to prevent zinc fumes from attacking the furnace steel framework. For most coppers and copper alloys this small amount of surface oxidation is not detrimental after normal cleaning, and they are regularly strip annealed throughout processing, including finish gage. They have a faintly different color than does bell-annealed and cleaned metal, but the difference is so slight that it is insignificant in most applications. In fact, brasses containing 15% or more of zinc have surfaces that many users feel are better suited for later fabricating if the strip has been continuously annealed. The metal surface holds lubricants well and has a low coefficient of friction against tool steels, making it desirable for press forming and deep drawing. It is likely that some zinc oxide remains on the surface and acts as a natural lubricant. After acid cleaning, rinsing, and drying, the surface is usually coated with a detergent solution or a light sulfur-free oil to protect it during handling in transit.

Stress-relief heat treatments are sometimes required after the harder rolling tempers such as extra hard, spring, and extra spring. Although the internal residual stresses left in the strip, from edge to edge and along the length, from this severe working are relatively uniform, small variations sometimes exist that can cause a difference in spring-back during subsequent forming operations. To reduce such residual-stress variations, the metal is heated to a temperature below the recrystallization temperature, usually between 200 and 350 °C (390 and 660 °F), and held there for 0.5 to 1 h. Such treatment results in a product with uniform spring-back.

Heating for stress relief also can change other properties. In phosphor bronzes tensile elongation is increased and strength slightly decreased. These changes are an advantage in the case of difficult-to-form parts requiring maximum strength. In the high-zinc alloys, stress-relief heat treatment increases strength and decreases tensile elongation. In this case, the formability may be decreased.

Cleaning

As noted, following each anneal or heat treatment the metal is cleaned. After cleaning in the appropriate solution the metal is thoroughly washed in water, including brushing with wire or synthetic brushes when needed. The rinse water usually contains a tarnish inhibitor, such as tolutriazole or benzotriazole, to protect the metal. For product at finish gage the rinse tank has a detergent solution added that further protects the metal when dried and also lubricates it slightly to reduce the danger of friction scratches during coiling and uncoiling. Squeegee rolls are used to remove the bulk of the rinse water, and drying ovens in the cleaning lines complete the job.

If desired for subsequent working, annealed strip can also be coated with a film of light nontarnishing oil for protection and lubrication. Metal that is finished in a rolled temper will normally contain a light film of rolling lubricant on the surfaces to protect and lubricate it during coiling and uncoiling and in transit.

Slitting, Cutting, and Leveling

Following the final rolling or the final annealing and cleaning, the strip or sheet product is slit to its final width. Slitting is accomplished by opposing rotary discs mounted on rotating arbors. These knife sets mesh as the metal passes between them and shear it into a variety of widths. Slitter knife sets are assembled on arbors. The sets are assemblies of disc knives, cylindrical metal and rubber fillers, and shims. Clearance between the opposing knife edges must be exact for the thickness, alloy, and temper of the metal to be slit. The distance between knife edges on each arbor must be set accurately to cut the specified width within the tolerance allowed. Knife edges must be sharp and continuously lubricated. Dull knives or incorrect clearance between knives for the particular material being slit causes distorted or burred edges.

Camber, that is, departure from edgewise straightness, has often been attributed incorrectly to poor slitting practice. It is true that strips can be pulled crooked when slitting a large number of them from a wide bar, because the slit strips are sometimes fanned out for subsequent coiling using divider plates. This difficulty is diminished on slitters equipped with over-arm separators because strips need not be fanned out as much. This kind of problem can be anticipated, and, if necessary, the bar split at an intermediate stage in processing prior to the final slitting, so fewer cuts are made in this last operation.

Instead of slitting practice, it is the maintenance of good shape during each of the rolling operations that is most important in the control of camber. If good control of thickness across the width is maintained at each rolling operation, the edges and centers of the bar will have elongated uniformly, and when narrow strips are slit they will remain satisfactorily straight.

The shape of the slit edge of strip depends to a great extent on the properties of the metal being slit. The metal may be thick, soft, and ductile, at one extreme of shearing characteristics, to thin, hard, and brittle, at the other extreme. Between these fall all the variations that are characteristic of the gage, alloy, and temper required for the final application. A certain amount of edge distortion cannot be avoided when slitting thick, soft metals (Fig. 11). Even with the best slitter setup, the cross section of a narrow strip will tend to have a "loaf" shape. By contrast, thin, hard phosphor bronze or nickel silver in narrow widths will have a cross section of rectangular shape with square cut edges. Leaded brasses shear cleanly because the lead, present as microscopic globules, lowers the ductility and shear strength. It is for this purpose—ease of cutting and machinability—that lead is added to copper alloys.

As the metal comes from the slitter, both edges of each strip, if distorted, will be distorted in the same direction. The immediately adjacent strips will have edges distorted in the opposite direction. There are some applications for which it is desirable that any edge distortions be in the same direction relative to the part being produced. The user recognizes that the edges of every other coil will be opposite and arranges to uncoil either over or under the coil so the edge condition entering the press is always the same (Fig. 12).

Coil set, the curvature that remains in a strip when it is unwound from a coil, is an inherent characteristic. The degree of this coil set is dependent on a number of factors. The final coiling operation takes place after slitting, and some measure of control over coil set can be exercised at this process stage. However, there are frequently other considerations that also have a bearing. For annealed tempers and the lightly cold-rolled tempers such as quarter hard and half hard, coil set may be established during final coiling. The degree of set will be lowest when the largest inside diameter compatible with the specified gage and weight can be used. For the harder rolled tempers and lighter gages, the coil set is actually controlled in the final rolling operation, rather than during coiling, and is usually kept to a minimum.

Processing operations after final slitting are occasionally required. Blanking and edge rolling are two such operations.

Blanking of squares or rectangles is generally done by cutting to length. The metal is first flattened and then cut to length on a flying shear. If the tolerance on length cannot be achieved on the automatic cutting lines, the cut lengths are resheared by hand. When circular blanks are required, they are die cut on a press. The tolerances for the diameter of circular blanks are the same as those for slit metal of corresponding width.

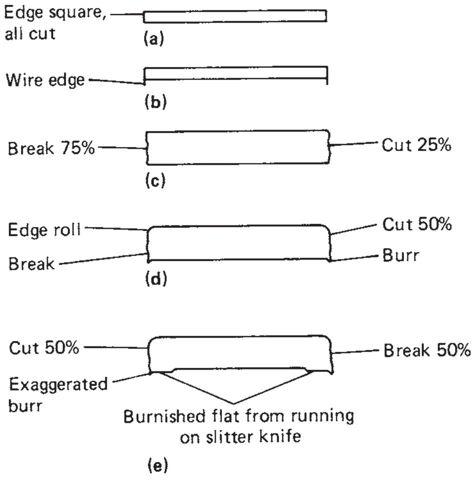

Fig. 11 The different edge contours that can result from slitting, depending on thickness, temper, and alloy. (a) Thin gages; all alloys. Edges square with almost no break. (b) Thin gages. On soft metal, set must be adjusted to avoid wire edges. (c) Heavy gages; hard metal; all alloys. Edges square with 25% cut balanced break. (d) Heavy gages; soft metal; all alloys. Edges square with slight roll. (e) As a rule, the heavy-gage, high copper alloys have greatest tendency to roll and burr.

Edge rolling can produce rolled square edges, rounded edges, rounded corners, or rolled full-rounded edges. It can only be done on a limited range of gage, width, and temper combinations. Properties and tolerances are generally the same as those for similar slit-edge products.

Tubular Products

Tube and pipe made of copper or copper alloys are used extensively for carrying potable water in buildings and homes. These brass mill products also are used throughout the oil, chemical, and process industries to carry diverse fluids, ranging from various natural and process waters, to seawater, to an extremely broad range of strong and dilute organic and inorganic chemicals. In the automotive and aerospace industries, copper tube is used for hydraulic lines, heat exchangers (such as automotive radiators), air conditioning systems, and various formed or machined fittings. In marine service, copper tube and pipe are used to carry potable water, seawater, and other fluids, but their chief application is in tube bundles for condensers, economizers, and auxiliary heat exchangers. Copper tube and pipe are used in food and beverage industries to carry process fluids for beet and cane sugar refining, for brewing of beer, and for many other food-processing operations. In the building trades, copper tube is used widely for heating and air conditioning systems in homes, commercial buildings, and industrial plants and offices. Table 18 summarizes the copper alloys that are standard tube alloys, and gives ASTM specifications and typical uses for each of the alloys. As indicated in Table 18, copper and copper alloy tubing is available in seamless and welded forms.

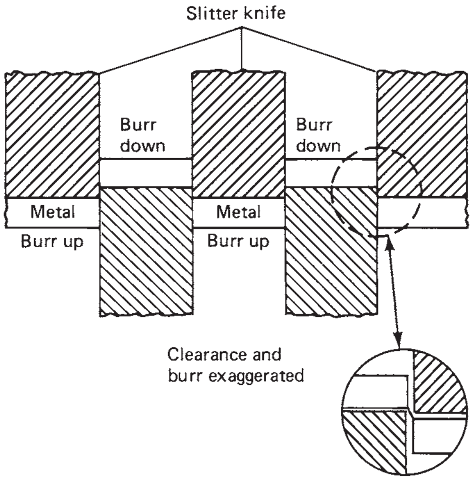

Fig. 12 Burr up/burr down relationship in slitting setup. Such burrs are never excessive on strip released for shipment.

Joints

Joints in copper tube and pipe are made in various ways. Permanent joints can be made by brazing or welding. Semipermanent joints are made most often by soldering, usually in conjunction with standard socket-type solder fittings, but threaded joints also can be considered semipermanent joints for pipe. Detachable joints are almost always some form of mechanical joint—flared joints, flange-and-gasket joints, and joints made using any of a wide variety of specially designed compression fittings (Fig. 13) are all common.

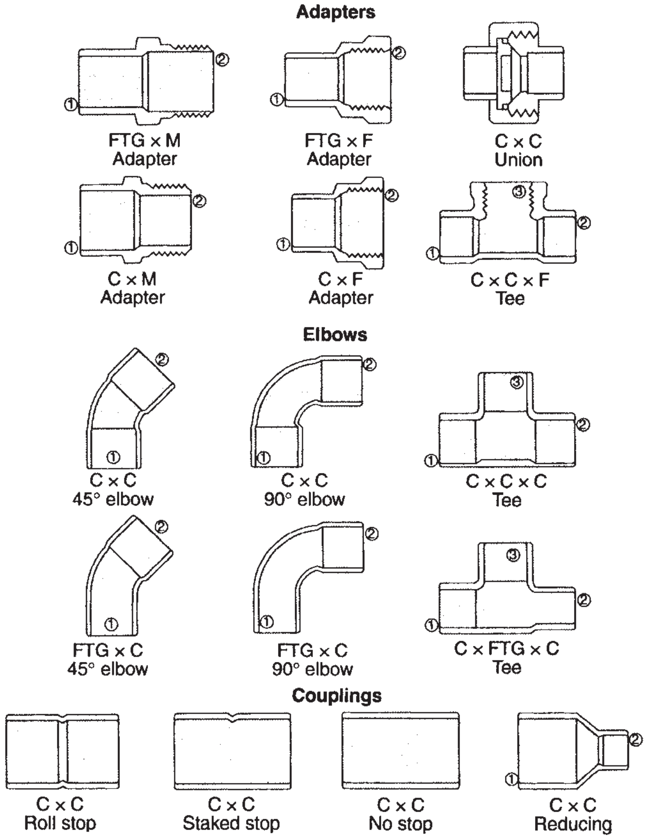

Fig. 13 Selected pressure fittings for copper tubular products. Source: Ref 9

Properties of Tube

As with most wrought products, the mechanical properties of copper tube depend on prior processing. With copper, it is not so much the methods used to produce tube, but rather the resulting metallurgical condition that has the greatest bearing on properties. Table 19 summarizes tensile properties for the standard tube alloys in their most widely used conditions. Information on other properties of tube alloys can be found in the data compilations for the individual alloys; see the article "Properties of Wrought Coppers and Copper Alloys" in this Handbook.

Production of Tube Shells

Copper tubular products are typically produced from shells made by extruding or piercing copper billets.

Extrusion of copper and copper alloy tube shells is done by heating a billet of material above the recrystallization temperature, and then forcing material through an orifice in a die and over a mandrel held in position with the die orifice. The clearance between mandrel and die determines the wall thickness of the extruded tube shell.

In extrusion, the die is located at one end of the container section of an extrusion press; the metal to be extruded is driven through the die by a ram, which enters the container from the end opposite the die. Tube shells are produced either by starting with a hollow billet or by a two-step operation in which a solid billet is first pierced and then extruded.

Table 18 Copper tube alloys and typical applications

UNS No.	Alloy type	ASTM specifications	Typical uses
C10200	Oxygen-free copper	B 68, B 75, B 88, B 111, B 188, B 280, B 359, B 372, B 395, B 447	Bus tube, conductors, wave guides
C12200	Phosphorus deoxidized copper	B 68, B 75, B 88, B 111, B 280, B 306, B 359, B 360, B 395, B 447, B 543	Water tubes; condenser, evaporator and heat-exchanger tubes; air conditioning and refrigeration, gas, heater and oil burner lines; plumbing pipe and steam tubes; brewery and distillery tubes; gasoline, hydraulic and oil lines; rotating bands
C19200	Copper	B 111, B 359, B 395, B 469	Automotive hydraulic brake lines; flexible hose
C23000	Red brass, 85%	B 111, B 135, B 359, B 395, B 543	Condenser and heat-exchanger tubes, flexible hose; plumbing pipe; pump lines
C26000	Cartridge brass, 70%	B 135	Plumbing brass goods
C33000	Low-leaded brass (tube)	B 135	Pump and power cylinders and liners; plumbing brass goods
C36000	Free-cutting brass	…	Screw-machine parts; plumbing goods
C43500	Tin brass	…	Bourdon tubes; musical instruments
C44300, C44400, and C44500	Inhibited admiralty metal	B 111, B 359, B 395	Condenser, evaporator and heat-exchanger tubes; distiller tubes
C46400, C46500, C46600, and C46700	Naval brass	…	Marine hardware, nuts
C60800	Aluminum bronze, 5%	B 111, B 359, B 395	Condenser, evaporator and heat-exchanger tubes; distiller tubes
C65100	Silicon bronze B	B 315	Heat-exchanger tubes; electrical conduits
C65500	Silicon bronze A	B 315	Chemical equipment, heat-exchanger tubes; piston rings
C68700	Arsenical aluminum brass	B 111, B 359, B 395	Condenser, evaporator and heat-exchanger tubes; distiller tubes
C70600	Copper-nickel, 10%	B 111, B 359, B 395, B 466, B 467, B 543, B 552	Condenser, evaporator and heat-exchanger tubes; salt water piping; distiller tubes
C71500	Copper-nickel, 30%	B 111, B 359, B 395, B 446, B 467, B 543, B 552	Condenser, evaporator and heat-exchanger tubes; distiller tubes; salt water piping

Extrusion pressure varies with alloy composition. C36000 (61.5Cu-3Pb-35.5Zn) requires a relatively low pressure, whereas C26000 (70Cu-30Zn) and C44300 (71.5Cu-1Sn-27.5Zn-0.06As) require the highest pressure of all the brasses. Most of the coppers require an extrusion pressure intermediate between those for C26000 and C36000. C71500 (70Cu-30Ni) requires a very high extrusion pressure.

Extrusion pressure also depends on billet temperature, extrusion ratio (the ratio of the cross-sectional area of the billet to that of the extruded section), speed of extrusion, and degree of lubrication. The flow of metal during extrusion depends on many factors, including copper content of the metal, amount of lubricant, and die design.

Rotary piercing on a Mannesmann mill is another method commonly used to produce seamless pipe and tube from copper and certain copper alloys. Piercing is the most severe forming operation customarily applied to metals. The process takes advantage of tensile stresses that develop at the center of a billet when it is subjected to compressive forces around its periphery. In rotary piercing, one end of a heated cylindrical billet is fed between rotating work rolls that lie in a horizontal plane and are inclined at an angle to the axis of the billet (Fig. 14). Guide rolls beneath the billet prevent it from dropping from between the work rolls. Because the work rolls are set at an angle to each other as well as to the billet, the billet is simultaneously rotated and driven forward toward the piercing plug, which is held in position between the work rolls.

The opening between work rolls is set smaller than the billet, and the resultant pressure acting around the periphery of the billet opens up tensile cracks, and then a rough hole, at the center of the billet just in front of the piercing plug. The piercing plug assists in further opening the axial hole in the center of the billet, smoothes the wall of the hole, and controls the wall thickness of the formed tube.

Table 19 Typical mechanical properties for copper alloy tube(a)

Temper	Tensile strength MPa	Tensile strength ksi	Yield strength(b) MPa	Yield strength(b) ksi	Elongation(c), %
C10200					
OS050	220	32	69	10	45
OS025	235	34	76	11	45
H55	275	40	220	32	25
H80	380	55	345	50	8
C12200					
OS050	220	32	69	10	45
OS025	235	34	76	11	45
H55	275	40	220	32	25
H80	380	55	345	50	8
C19200					
H55(d)	290	42	205(e)	30(e)	35
C23000					
OS050	275	40	83	12	55
OS015	305	44	125	18	45
H55	345	50	275	40	30
H80	485	70	400	58	8
C26000					
OS050	325	47	105	15	65
OS025	360	52	140	20	55
H80	540	78	440	64	8
C33000					
OS050	325	47	105	15	60
OS025	360	52	140	20	50
H80	515	75	415	60	7
C43500					
OS035	315	46	110	16	46
H80	515	75	415	60	10
C44300, C44400, C44500					
OS025	365	53	150	22	65
C46400, C46500, C46600, C46700(f)					
H80	605	88	455	66	18
C60800					
OS025	415	60	185	27	55
C65100					
OS015	310	45	140	20	55
H80	450	65	275	40	20
C65500					
OS050	395	57	…	…	70
H80	640	93	…	…	22
C68700					
OS025	415	60	185	27	55
C70600					
OS025	305	44	110	16	42
H55	415	60	395	57	10
C71500					
OS025	415	60	170	25	45

(a) Tube size: 25 mm (1 in.) outside diameter (OD) by 1.65 mm (0.065 in.) wall. (b) 0.5% extension under load. (c) In 50 mm (2 in.). (d) Tube size: 4.8 mm (0.1875 in.) OD by 0.76 mm (0.030 in.) wall. (e) 0.2% offset. (f) Tube size: 9.5 mm (0.375 in.) OD by 2.5 mm (0.097 in.) wall

Copper and plain alpha brasses can be pierced, provided the lead content is held to less than 0.01%. Alpha-beta brasses can tolerate higher levels of lead without adversely affecting their ability to be pierced.

When piercing brass, close temperature control must be maintained because the range in which brass can be pierced is narrow. Each alloy has a characteristic temperature range within which it is sufficiently plastic for piercing to take place. Below this range, the central hole does not open up properly under the applied peripheral forces. Overheating may lead to cracked surfaces. Suggested piercing temperatures for various alloys are as follows:

UNS number	Piercing temperature °C	Piercing temperature °F
C11000	815–870	1500–1600
C12200	815–870	1500–1600
C22000	815–870	1500–1600
C23000	815–870	1500–1600
C26000	760–790	1400–1450
C28000	705–760	1300–1400
C46400	730–790	1350–1450

Production of Finished Tubes

Cold drawing of extruded or pierced tube shells to smaller sizes is done on draw blocks for coppers and on draw benches for brasses and other alloys. With either type of machine, the metal is cold worked by pulling the tube through a die that reduces the diameter. Concurrently, wall thickness is reduced by drawing over a plug or mandrel that may be either fixed or floating. Cold drawing increases the strength of the mate-

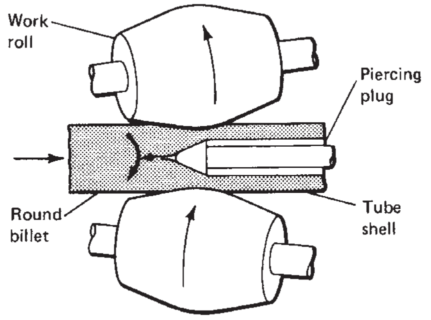

Fig. 14 Schematic diagram of metal piercing. Arrows indicate direction of motion.

rial and simultaneously reduces ductility. Tube size is reduced—outside diameter, inside diameter, wall thickness, and cross-sectional area all are smaller after drawing. Because the metal work hardens, tubes may be annealed at intermediate stages when drawing to small sizes. However, coppers are so ductile that they frequently can be drawn to finished size without intermediate annealing.

Tube reducing is an alternative process for cold sizing of tube. In tube reducing, semicircular grooved dies are rolled or rocked back and forth along the tube while a tapered mandrel inside the tube controls the inside diameter and wall thickness. The process yields tube having very accurate dimensions and better concentricity than can be achieved by tube drawing.

The grooves in the tube-reducing dies are tapered, one end of the grooved section being somewhat larger than the outside diameter of the tube to be sized. As the dies are rocked, the tube is pinched against the tapered mandrel, which reduces wall thickness and increases tube length. The tube is fed longitudinally, and rotated on its axis to distribute the cold work uniformly around the circumference. Feeding and rotating are synchronized with die motion and take place after the dies have completed their forward stroke.

Tube reducing may be used for all alloys that can be drawn on draw benches. Slight changes in die design and operating conditions may be required to accommodate different alloys. Small-diameter tube may be produced by block or bench drawing following tube reducing.

Product Specifications

Copper tube and pipe are available in a wide variety of nominal diameters and wall thicknesses, from small-diameter capillary tube to 300 mm (12 in.) nominal-diameter pipe. To a certain extent, dimensions and tolerances for copper tube and pipe depend on the type of service for which they are intended. The standard dimensions and tolerances for several kinds of copper tube and pipe are given in the ASTM specifications listed in Table 20, along with other requirements for the tubular products. Seamless copper tube for automotive applications ($\frac{1}{8}$ to $\frac{3}{4}$ in. nominal diameter) is covered by Society of Automotive Engineers J528. Requirements for copper tube and pipe to be used in condensers, heat exchangers, economizers, and similar unfired pressure vessels are given in the American Society of Mechanical Engineers (ASME) specifications listed in Table 20. (ASME materials specifications are almost always identical to ASTM specifications having the same numerical designation; for example, ASME SB111 is identical to ASTM B 111.) Certain tube alloys are covered in Aerospace Material Specifications (AMS), which apply to materials for aerospace applications. These are given below:

AMS specifications	Product	Copper alloy
4555	Seamless brass tube, light annealed	C26000, C33000
4558	Seamless brass tube, drawn	C33200
4625	Phosphor bronze, hard temper	C51000
4640	Aluminum bronze	C63000
4665	Seamless silicon bronze tube, annealed	C65500

Table 20 ASTM and ASME specifications for copper tube and pipe

Tubular product	ASTM	ASME
Seamless pipe and tube		
Seamless copper alloy (C69100) pipe and tube	B 706	…
Seamless pipe and tube, copper-nickel alloy(a)	B 466	
	B 466M(a)	SB466
Seamless pipe and tube, copper-silicon alloy	B 315	SB315
Seamless pipe and tube, for electrical conductors	B 188	…
Seamless pipe, standard sizes	B 42	…
Seamless pipe, threadless	B 302	…
Seamless tube		
Seamless copper alloy tubes (C19200 and C70600), for pressure applications	B 469	…
Seamless copper-nickel tubes, for desalting plants	B 552	…
Seamless tube(a)	B 75	SB75
	B 75M(a)	…
Seamless tube, brass(a)	B 135	
	B 135M(a)	SB135
Seamless tube, bright annealed(a)	B 68	…
	B 68M(a)	…
Seamless tube, capillary, hard drawn	B 360	…
Seamless tube, condenser and heat exchanger(a)	B 111, B 395	SB111, SB395
	B 111M(a)	…
	B 395M(a)	…
Seamless tube, condenser and heat exchanger, with integral fins(a)	B 359	SB359
	B 359M(a)	…
Seamless tube, for air conditioning and refrigeration service	B 280	…
Seamless tube, drainage	B 306	…
Seamless tube, general requirements(a)	B 251	…
	B 251M(a)	…
Seamless tube, rectangular waveguide	B 372	…
Seamless tube, water(a)	B 88	…
	B 88M(a)	…
Welded pipe and tube		
Hard temper welded copper tube (C21000), for general plumbing and fluid conveyance	B 642	…
Welded brass tube, for general application	B 587	…
Welded copper tube, for air conditioning-refrigeration	B 640	…
Welded pipe and tube, copper-nickel alloy	B 467	SB467
Welded tube, C10800 and 12000(a)	B 543	SB543
	B 543M(a)	…
Welded tube, all other coppers	B 447	…

(a) Suffix "M" indicates a metric specification.

Rod, Bar, and Shapes

For the copper metals, rod is defined as a round, hexagonal, or octagonal product. Bar refers to square or rectangular cross sections, while shapes can have oval, half-round, geometric, or custom-ordered profiles. Examples of rod and bar products are shown in Fig. 15, and a variety of specialty shapes are shown in Fig. 16. The three basic product forms are differentiated from wire in that they are sold in straight lengths, whereas wire is sold in coils.

Specifications and Properties. General requirements for wrought copper and copper alloy rod, bar, shaped, and forgings are outlined in ASTM B 249. Other ASTM for rod, bar, and shapes are listed in Table 21. Tensile and yield properties for rod are listed in Tables 3 and 4.

Forming. Bending and rotary swaging of copper and copper alloy rod, bar, and shapes are discussed in the article "Forming" in this Handbook.

Forgings

Copper-base forgings represent a relatively small but important class of products. Forgings are typically moderate-size products, such as valves, fittings, mechanical devices, and architectural hardware, rarely exceeding 90 kg (200 lb). Because forgings tend to be somewhat more costly than comparably sized castings, forged products are usually reserved for applications in which special qualities are needed.

Strong, Tough Structures. Forging of copper metals is performed hot, and the severe deformation involved produces a dense, fibrous grain structure that gives the products excellent mechanical properties. Forgings are therefore preferred for thin-walled pressure-retaining devices, such as valves and fittings.

Fine Surface Finishes. Copper-base forgings can be expected to have surface finishes as fine as at least 32 μm (125 μin.). Finer finishes are possible in many cases, but this depends very much on the size and shape of the product. In general, better surface finishes are easier to obtain on smaller products.

Consistent Dimensions, Close Tolerances. Copper-base forgings can be made to precise dimensions and to sections thinner than 3.2 mm (0.125 in.); however, section sizes are normally limited by the features of the part in question. Typical commercial tolerances fall between ±0.2 and ±0.4 mm (±0.008 and ±0.015 in.), depending on configuration, in forgings weighing less than about 0.9 kg (2 lb). Tolerances are slightly wider in heavier forgings, but dimensions can be held as tight as ±0.025 mm (±0.001 in.) in special cases. Flatness tolerances are typically on the order of 0.12 mm/25 mm (0.005 in./in.) for the first 25 mm and 0.075 mm/25 mm (0.003 in./in.) thereafter.

Intricate detail and sharp lettering makes forging the preferred method of manufacture for decorative and architectural products, such as doorplates.

Lower Environmental Risk. Unlike sand casting, forging produces neither hazardous fumes nor residues that require expensive clean up or special disposal. There is no waste, and all unused metal is recycled to make new alloy.

Cost Considerations. Forgings are usually more costly than castings, but there are exceptions. Forging dies cost about one-half as much as dies for pressure die casting (a competing process). Also, forging dies are usually a one-time expense to the customer, whereas the maintenance, repair, and replacement of casting dies are usually the customer's responsibility. Finally, forgings use significantly less metal per part than castings or screw-machine products because forged products can be made with thinner walls and lighter sections. Forging also generates less runaround scrap, thereby reducing energy consumption.

Materials. Ideal forging characteristics include low force requirements, little tendency to crack, and good surface finishes. Forging brass, C37700, is by far the most commonly used alloy. It is a leaded yellow brass containing sufficient beta phase to provide high-temperature ductility. Forging brass also contains about 2% Pb, making it free machining. Other commonly forged copper alloys include naval brass (C46400), lead naval brass (C48500), electrolytic tough pitch copper (C11000), tellurium-copper (C14500), manganese bronze (C67500), and aluminum-silicon bronze (C64200). More detailed information on the forging characteristics of forging alloys can be found in the article "Forging and Extrusion" in this Handbook.

Specifications for copper and copper alloy forging alloys include ASTM B 124 (see Table 21), B 283 (die forgings—hot pressed), and B 570 (beryllium-copper forgings and extrusions).

Table 21 ASTM specifications for copper rod, bar, and shapes

Product	ASTM(a)	Alloy
Bar, bus bar, rod, shapes	B 187/B 187M	Copper
Forging, rod, bar, shapes	B 124/B 124M	Copper and copper alloys
Rod	B 453/B 453M	Leaded brass
Rod, bar, shapes	B 16/B 16M	Free-cutting brass
Rod, bar, shapes	B 301/B 301M	Free-cutting copper
Rod, bar, shapes	B 21/B 21M	Naval brass
Rod, bar, shapes	B 150/B 150M	Aluminum bronze
Rod, bar	B 196/B 196M	Beryllium-copper
Rod, bar	B 441	Alloy C17500
Rod, bar	B 411	Copper-nickel-silicon alloy
Rod, bar	B 151/B 151M	Nickel silver
Rod, bar, shapes	B 98/B 98M	Copper-silicon alloy
Rod, bar, shapes	B 140/B 140M	Leaded red brass or hardware bronze
Rod	B 371	Copper-zinc-silicon alloy
Rod, bar, shapes	B 138/B 138M	Manganese bronze
Rod, bar, shapes	B 139/B 139M	Phosphor bronze

(a) The suffix "M" indicates a metric specification.

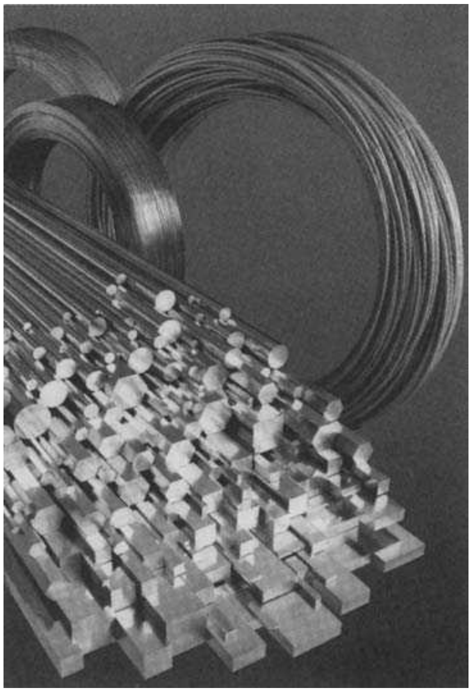

Fig. 15 Examples of copper bar and rod products

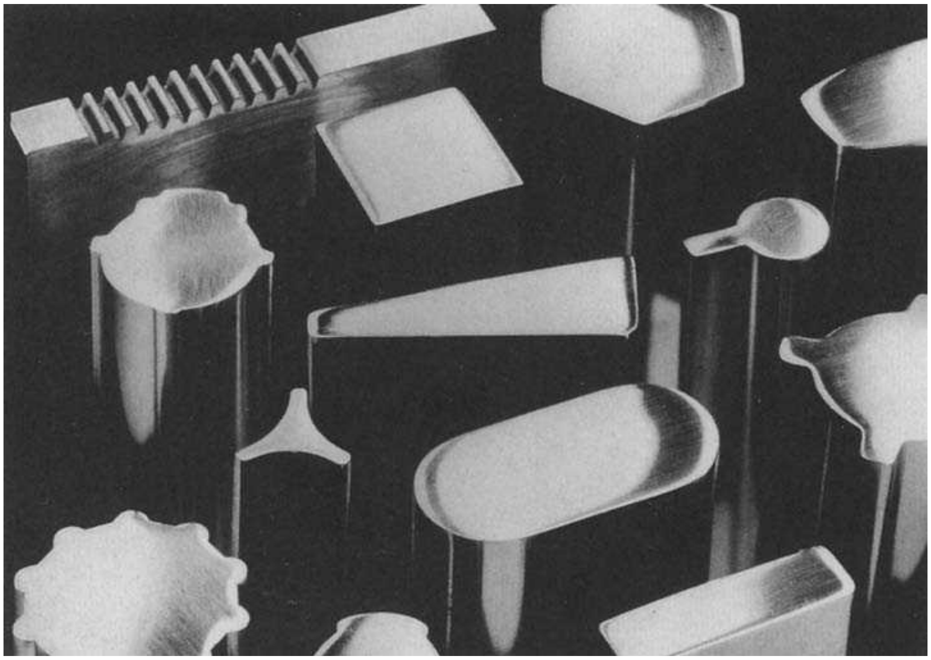

Fig. 16 Examples of copper custom shapes

ACKNOWLEDGMENTS

This article was adapted from:

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Cast Copper and Copper Alloys

COPPER CASTING ALLOYS are primarily selected for either their corrosion resistance or their combination of corrosion resistance and mechanical properties. These materials also feature good castability, high machinability, and, compared with other corrosion-resistant alloys, reasonable cost. Additional benefits include biofouling resistance—important in marine applications—and a spectrum of attractive colors. Many of the alloys also have favorable tribological properties, which explains their widespread use for sleeve bearings, wear plates, gears, and wear-prone components.

Copper Casting Alloy Families

The copper-base casting alloys are designated in the Unified Numbering System (UNS) with numbers ranging from C80000 to C99999 (see the article "Standard Designations for Wrought and Cast Copper and Copper Alloys" in this Handbook). Also, copper alloys in cast form are sometimes classified according to their freezing range (that is, the temperature range between the liquidus and solidus temperatures). The freezing range of various copper alloys is discussed in the section "Control of Solidification" in this article.

Cast versus Wrought Compositions

Compositions of copper casting alloys (Table 1) may differ from those of their wrought counterparts for various reasons. Generally, casting permits greater latitude in the use of alloying elements because the effects of composition on hot- or cold-working properties are not important. However, imbalances among certain elements, and trace amounts of certain impurities in some alloys, will diminish castability and can result in castings of lower quality.

Lead Additions. Lead is commonly added to many cast copper alloys. As shown in Table 1, many alloys have lead contents of 5% or more. Alloys containing such high percentages of lead are not suited to hot working, but they offer several advantages as castings. Because of the low solubility of lead in copper, true alloying does not occur to any measurable degree. During the solidification of castings, some constituents in a given alloy form crystals at higher temperatures relative to others, resulting in treelike structures called dendrites. The small spaces between the dendrites can interconnect to form micropores. This microporosity is a consequence of the solidification process. The role of lead is to seal these intradendritic pores. This results in a pressure-tight casting, which is important for fluid-handling applications.

Lead also allows the machining of castings to be performed at higher speeds without the aid of coolants because it acts as a lubricant for cutting-tool edges and promotes the formation of small, discontinuous chips that easily can be cleared. This results in improved machine surface finishes. Lead also plays a role in providing lubricity during service as in cast copper bearings and bushings. Lead does not have an adverse effect on strength unless present in high concentrations, but it does reduce ductility. Although lead-containing copper alloys can be soldered and brazed, they cannot be welded.

Coppers and High-Copper Alloys

Cast coppers (C80100–C81200) are high-purity metals containing at least 99.3% Cu. (Wrought coppers have a slightly higher minimum copper content.) Trace amounts of silver or phosphorus (a deoxidizer) may be present. Silver imparts annealing resistance, while phosphorus facilitates welding. Neither element affects electrical conductivity significantly when present in such small concentrations. Electrical conductivity can be as high as 100% IACS, while thermal conductivity can reach 391 W/m · K (226 Btu/ft^2/ft/h/°F). Coppers have very modest strength and cannot be hardened by heat treatment.

Oxygen-free copper (C80100) has the highest electrical and thermal conductivity among the cast copper alloys, but it is essentially identical to phosphorus-deoxidized copper (C81200) in other respects. Both oxygen-free and deoxidized coppers are readily weldable.

Ironically, while copper alloys are among the most easily cast engineering materials, unalloyed copper presents a number of casting difficulties: coarse, often columnar grain structures; rough surfaces; and a tendency to form shrinkage cavities. Although these problems can be overcome by proper foundry practice, use of cast pure copper is generally reserved for applications that demand the highest electrical and/or thermal conductivities. Typical products include large electrical connectors and water-cooled, hot-metal handling equipment such as blast-furnace tuyeres.

High-Copper Alloys. Compared with pure copper, the dilute alloys (C81400–C82800) have significantly higher strengths, higher hardness and wear resistance, higher fatigue resistance, and better castability, yet they retain most of the electrical and thermal conductivity of pure copper. Corrosion and oxidation resistance of these alloys are as good or better than those of pure copper, because alloying improves the chemical and mechanical properties of their protective oxide films. Within their useful temperature range, which extends from the cryogenic region to 400 °C (750 °F), depending on composition, no other engineering materials can match their combination of conductivity, strength, and corrosion resistance.

Chromium-Copper. Several of the high-copper alloys can be age hardened. In the fully aged condition, the strength of chromium-copper (C81500) is roughly twice that of pure copper, and its electrical conductivity remains higher than 80% IACS. Chromium-copper is used for electromechanical products such as welding-machine clamps, resistance welding electrodes, and high-strength electrical cable connectors.

Beryllium Copper Grades. The age-hardening beryllium coppers can be further categorized as high-conductivity alloys, such as C82200 (nominally 0.6% Be), and high-strength grades, such as C82500 (2% Be). Alloy selection depends on whether electrical or mechanical properties are more important. In the fully aged condition (TF00 temper), the high-conductivity alloy develops about 60% of the strength, but twice the conductivity, of the high-strength alloy.

Beryllium coppers are relatively expensive, but they can be very cost effective when properly used. Plastic injection molds, a common application, are a good example. Copper-beryllium casting alloys have high fluidity and can reproduce fine details in master patterns. Their high conductivity enables high production speed, while their good corrosion/oxidation resistance promotes long die life. Other applications for beryllium copper alloys include inlet guide vanes for helicopter turbine engines (C82200), pitot tube housings for high-speed aircraft, golf club heads (C82500), and components of undersea-cable repeater housings.

Brasses

Brasses (C83300–C87900 and C89320–C89940) are copper alloys in which zinc is the dominant alloying addition. Because of their excellent castability, relatively low cost, and

Table 1 Compositions, uses, and characteristics of copper alloy castings

UNS No.	Other designations, descriptive names (former SAE No.)	Applicable casting processes(a)	Composition(b), wt%						
			Cu	Sn	Pb	Zn	Ni	Fe	Other
Coppers: High-purity coppers with excellent electrical and thermal conductivities. Deoxidation of C81200 improves weldability.									
C80100	Oxygen-free copper	S, C, CL, PM, I, P	99.95(c)	…	…	…	…	…	…
C81100	High-conductivity copper	S, C, CL, PM, I, P	99.70(c)	…	…	…	…	…	…
C81200	High-conductivity copper	S, C, CL, PM, I, P	99.9(c)	…	…	…	…	…	0.045–0.065P
High-copper alloys: Relatively high-strength coppers with good electrical and thermal conductivity. Strength generally inversely proportional to conductivities. Used where good combination of strength and conductivity is needed, as in resistance welding electrodes, switch blades and components, dies, clutch rings, brake drums, as well as bearings and bushings. Beryllium coppers have highest strength of all copper alloys and are used in bearings, mechanical products, and nonsparking safety tools.									
C81400	70C	S, C, CL, PM, I, P	98.5 min(d)	…	…	…	…	…	0.02–0.10 Be, 0.6–1.0 Cr
C81500	Chromium-copper	S, C, CL, PM, I, P	98.0 min(d)	0.10	0.02	0.10	…	0.10	0.15 Si, 0.10 Al, 0.40–1.5 Cr
C81540	Chromium-copper	S, C, CL, PM, I, P	95.1 min(d)(e)	0.10	0.02	0.10	2.0–3.0(f)	0.15	0.40–0.8 Si, 0.10 Al, 0.10–0.6 Cr
C82000	10C	S, C, CL, PM, I, P, D	bal(d)	0.10	0.02	0.10	0.20	0.10	0.10 Al, 0.10 Cr, 0.15 Si, 2.40–2.70 Co(f), 0.45–0.8 Be
C82200	35C, 53B	S, C, CL, PM, I, P	bal(d)	…	…	…	1.0–2.0	…	0.35–0.80 Be, 0.30 Co
C82400	165C	S, C, CL, PM, I, P, D	bal(d)	0.10	0.02	0.10	0.20	0.20	0.20–0.65 Co, 1.60–1.85 Be, 0.15 Al, 0.10 Cr
C82500	20C	S, C, CL, PM, I, P, D	bal(d)	0.10	0.02	0.10	0.20	0.25	1.90–2.25 Be, 0.35–0.70 Co(f), 0.20–0.35 Si, 0.15 Al, 0.10 Cr
C82510	Increased-Co 20C	S, C, CL, PM, I, P, D	bal(d)	0.10	0.02	0.10	0.20	0.25	1.90–2.15 Be, 1.0–1.2 Co(f), 0.20–0.35 Si, 0.15 Al, 0.10 Cr
C82600	245C	S, C, CL, PM, I, P, D	bal(d)	0.10	0.02	0.10	0.20	0.25	2.25–2.55 Be, 0.35–0.65 Co, 0.20–0.35 Si, 0.15 Al, 0.10 Cr
C82700	Ni-Be-Cu	S, C, CL, PM, I, P	bal(d)	0.10	0.02	0.10	1.0–1.5	0.25	2.35–2.55 Be, 0.15 Si, 0.15 Al, 0.10 Cr
C82800	275C	S, C, CL, PM, I, P, D	bal(d)	0.10	0.02	0.10	0.20	0.25	2.50–2.85 Be, 0.35–0.70 Co(f), 0.20–0.35 Si, 0.15 Al, 0.10 Cr
Cu-Sn-Zn and Cu-Sn-Zn-Pb alloys (red and leaded red brasses): High-copper brasses with reasonable electrical conductivity and moderate strength. Used for electrical hardware, including cable connectors									
C83300	131, contact metal	S, C, CL	92.0–94.0(g)(h)	1.0–2.0	1.0–2.0	2.0–6.0	…	…	…
C83400	407.5, commercial bronze 90/10, gilding metal	S, C, CL	88.0–92.0(g)(h)	0.20	0.50	8.0–12.0	1.0	0.25	0.25 Sb, 0.08 S, 0.03 P, 0.005 Si, 0.005 Al
C83450	Nickel-bearing leaded red brass	S, C, CL	87.0–89.0(g)(h)	2.0–3.5	1.5–3.0	5.5–7.5	0.8–2.0(i)	0.30	0.25 Sb, 0.08 S, 0.03 P(j), 0.005 Al, 0.005 Si
C83500	Leaded nickel-bearing tin bronze	S, C, CL	86.0–88.0(g)(h)	5.5–6.5	3.5–5.5	1.0–2.5	0.50–1.0(i)	0.25	0.25 Sb, 0.08 S, 0.03 P(j), 0.005 Al, 0.005 Si
Cu-Sn-Zn and Cu-Sn-Zn-Pb alloys (red and leaded red brasses): Good corrosion resistance, excellent castability, and moderate strength. Lead content ensures pressure tightness. Alloy C83600 is one of the most important cast alloys, widely used for plumbing fittings and other water-service goods. Alloy C83800 has slightly lower strength, but is essentially similar in properties and application.									
C83600	115, 85-5-5-5, composition bronze, ounce metal, (SAE 40)	S, C, CL	84.0–86.0(g)(h)	4.0–6.0	4.0–6.0	4.0–6.0	1.0(i)	0.30	0.25 Sb, 0.08 S, 0.05 P(j), 0.005 Al, 0.005 Si
C83800	120, 83-4-6-7, commercial red brass, hydraulic bronze	S, C, CL	82.0–83.8(g)(h)	3.3–4.2	5.0–7.0	5.0–8.0	1.0(i)	0.30	0.25 Sb, 0.08 S, 0.03 P(j), 0.005 Al, 0.005 Si
C83810	Nickel-bearing leaded red brass	S, C, CL	bal(g)(h)	2.0–3.5	4.0–6.0	7.5–9.5	2.0(i)	0.50(k)	Sb(k), As(k), 0.005 Al, 0.10 Si
Cu-Sn-Zn-Pb alloys (leaded semired brasses): General-purpose alloys for plumbing and hardware goods. Good machinability and pressure tightness. Alloy C84400 is the most popular plumbing alloy in U.S. Markets.									
C84200	101, 80-5-2½-12½	S, C, CL	78.0–82.0(g)(h)	4.0–6.0	2.0–3.0	10.0–16.0	0.8(i)	0.40	0.25 Sb, 0.08 S, 0.05 P(j), 0.005 Al, 0.005 Si
C84400	123, 81-3-7-9, valve composition, 81 metal	S, C, CL	78.0–82.0(g)(h)	2.3–3.5	6.0–8.0	7.0–10.0	1.0(i)	0.40	0.25 Sb, 0.08 S, 0.02 P(j), 0.005 Al, 0.005 Si
C84410	…	S, C, CL	bal(g)(1)	3.0–4.5	7.0–9.0	7.0–11.0	1.0(i)	(m)	Sb(m), 0.01 Al, 0.20 Si, 0.05 Bi
C84500	125, 78 metal	S, C, CL	77.0–79.0(g)(h)	2.0–4.0	6.0–7.5	10.0–14.0	1.0(i)	0.40	0.25 Sb, 0.08 S, 0.02 P(j), 0.005 Al, 0.005 Si
C84800	130, 76-3-6-15, 76 metal	S, C, CL	75.0–77.0(g)(h)	2.0–3.0	5.5–7.0	13.0–17.0	1.0(i)	0.40	0.25 Sb, 0.08 S, 0.02 P(j), 0.005 Al, 0.005 Si

(continued)

(a) Casting processes: S, sand; D, die; C, continuous; I, investment; PM, permanent mold; CL, centrifugal; and P, plaster. (b) Composition values are given as maximum percentages, unless shown as a range or minimum. (c) Including Ag, % min. (d) Cu + sum of named elements, 99.5% min. (e) Includes Ag. (f) Ni + Co. (g) In determining copper min, copper can be calculated as Cu + Ni. (h) Cu + sum of named elements, 99.3% min. (i) Including Co. (j) For continuous castings, P is 1.5% max. (k) Fe + Sb + As is 0.50% max. (l) Cu + sum of named elements, 99.2% min. (m) Fe + Sb +As is 0.8% max. (n) Cu + sum of named elements, 99.1% min. (o) Cu + sum of named elements, 98.7% min. (p) Cu + sum of named elements, 99.0% min. (q) Cu + sum of named elements, 99.4% min. (r) Cu + sum of named elements, 99.7% min. (s) Fe is 0.35% max, when used for steel-backed bearings. (t) Cu + sum of named elements, 98.9% min. (u) For continuous castings, S is 0.25% max. (v) The mechanical properties of C94700 (heat treated) may not be attainable if the lead content exceeds 0.01%. (w) Cu + sum of named elements, 99.8% min. (x) Fe content should not exceed Ni content. (y) The following additional maximum impurity limits shall apply: 0.10% Al, 0.001% B, 0.001% Bi, 0.005–0.15% Mg, 0.005% P, 0.0025% S, 0.02% Sb, 7.5–8.5% Sn, 0.01% T, and 1.0% Zn. (z)Cu + sum of named elements, 99.6% min. (aa) Pb and Ag can be adjusted to modify the alloy hardness. Source: Copper Development Association Inc.

Table 1 (continued)

UNS No.	Other designations, descriptive names (former SAE No.)	Applicable casting processes(a)	Composition(b), wt% Cu	Sn	Pb	Zn	Ni	Fe	Other
Copper-zinc and Cu-Zn-Pb alloys (yellow and leaded yellow brasses): Low-cost, low-to-moderate strength, general-purpose casting alloys with good machinability, adequate corrosion resistance for many water-service applications including marine hardware and automotive cooling systems. Some compositions are amenable to permanent mold and die casting processes.									
C85200	400, 72-1-3-24, high copper yellow brass	S, C, CL	70.0–74.0(g)(n)	0.7–2.0	1.5–3.8	20.0–27.0	1.0(i)	0.6	0.20 Sb, 0.05 S, 0.02 P, 0.005 Al, 0.05 Si
C85400	403, 67-1-3-29, commercial No. 1 yellow brass	S, C, CL, PM, I, P	65.0–70.0(g)(o)	0.50–1.5	1.5–3.8	24.0–32.0	1.0(i)	0.7	0.35 Al, 0.05 Si
C85500	60-40 yellow brass	S, C, CL	59.0–63.0(g)(o)	0.20	0.20	bal	0.20(i)	0.20	0.20 Mn
C85700	405.2, 63-1-1-35, B2, permanent mold brass	S, C, CL, PM, I, P	58.0–64.0(g)(n)	0.50–1.5	0.80–1.5	32.0–40.0	1.0(i)	0.7	0.8 Al, 0.05Si
C85800	405.1, die casting yellow brass	S, C, CL, PM, I, P, D	57.0 min(g)(o)	1.5	1.5	31.0–41.0	0.50(i)	0.50	0.05 Sb, 0.25 Mn, 0.05 As, 0.05 S, 0.01 P, 0.55 Al, 0.25 Si
Manganese bronze and leaded manganese bronze alloys (high-strength and leaded-high-strength yellow brasses): Alloys with high mechanical strength, good corrosion resistance, and favorable castability. Can be machined, but with the exception of C86400 and C86700, are less readily machined than leaded compositions. Alloy C86300 can attain tensile strengths exceeding 115 ksi (793 MPa). Used for mechanical devices: gears, levers, brackets, and valve and pump components for fresh and seawater service. When used for high-strength bearings, alloys C86300 and C86400 require hardened shafts.									
C86100	423, 90,000 tensile manganese bronze	S, CL, PM, I, P	66.0–68.0(g)(p)	0.20	0.20	bal	…	2.0–4.0	4.5–5.5 Al, 2.5–5.5 Mn
C86200	423, 95,000 tensile manganese bronze, (SAE 430 A)	S, C, CL, PM, I, P, D	60.0–66.0(g)(p)	0.20	0.20	22.0–28.0	1.0(i)	2.0–4.0	3.0–4.9 Al, 2.5–5.0 Mn
C86300	424, 110,000 tensile manganese bronze, (SAE 430 B)	S, C, CL, PM, I, P	60.0–66.0(g)(p)	0.20	0.20	22.0–28.0	1.0(i)	2.0–4.0	5.0–7.5 Al, 2.5–5.0 Mn
C86400	420, 60,000 tensile manganese bronze	S, C, CL, PM, I, P, D	56.0–62.0(g)(p)	0.50–1.5	0.50–1.5	34.0–42.0	1.0(i)	0.40–2.0	0.50–1.5 Al, 0.10–1.5 Mn
C86500	421, 65,000 tensile manganese bronze, (SAE 43)	S, C, CL, PM, I, P	55.0–60.0(e)(m)	1.0	0.40	36.0–42.0	1.0(i)	0.40–2.0	0.50–1.5 Al, 0.10–1.5 Mn
C86700	422, 80,000 tensile manganese bronze	S, C, CL, PM, I, P	55.0–60.0(g)(p)	1.5	0.50–1.5	30.0–38.0	1.0(i)	1.0–3.0	1.0–3.0 Al, 0.10–3.5 Mn
C86800	Nickel-manganese bronze	S, C, CL, PM, I, P	53.5–57.0(g)(p)	1.0	0.20	bal	2.5–4.0(i)	1.0–2.5	2.0 Al, 2.5–4.0 Mn
Copper-silicon alloys (silicon bronzes and silicon brasses): Moderate to high-strength alloys with good corrosion resistance and favorable casting properties. Used for mechanical products and pump components where combination of strength and corrosion resistance is important. Similar compositions are commonly die and/or permanent mold cast in Europe and the United Kingdom.									
C87300	95-1-4, silicon bronze	S, C, CL, PM, I, P	94.0 min(d)	…	0.20	0.25	…	0.20	3.5–4.5 Si, 0.80–1.5 Mn
C87400	500	S, CL, PM, I, P, D	79.0 min(d)	…	1.0	12.0–16.0	…	…	0.80 Al, 2.5–4.0 Si
C87500	500	S, CL, PM, I, P, D	79.0 min(d)	…	0.50	12.0–16.0	…	…	0.50 Al, 3.0–5.0 Si
C87600	500, low zinc silicon brass	S, CL, PM, I, P, D	88.0 min(d)	…	0.50	4.0–7.0	…	0.20	3.5–5.5 Si, 0.25 Mn
C87610	…	S, CL, PM, I, P, D	90.0 min(d)	…	0.20	3.0–5.0	…	0.20	3.0–5.0 Si, 0.25 Mn
C87800	500, die cast silicon brass	S, CL, PM, I, P, D	80.0 min(d)	0.25	0.15	12.0–16.0	0.20(i)	0.15	0.15 Al, 3.8–4.2 Si, 0.15 Mn, 0.01 Mg, 0.05 S, 0.01 P, 0.05 As, 0.05 Sb
Copper-bismuth and Cu-Bi-Se brasses: Good lubricity and machinability with very low lead. Meets potable water standards. Used for bearings and bushings, plumbing fixtures, valves, and fittings for potable water and food processing.									
C89510	SeBiLOY I	S	86.0–88.08	4.0–6.0	0.25	4.0–6.0	1.0(f)	…	0.5–1.5 Bi, 0.35–0.7 Se
C89520	SeBiLOY II	S	85.0–87.0	5.0–6.0	0.25	4.0–6.0	1.0(f)	…	1.6–2.2 Bi, 0.8–1.1 Se
C89550	SeBiLOY III	PM	58.0–64.0	0.5–1.5	0.20	32.0–40.0	1.0(f)	0.7	0.30–0.7 Al, 0.7–1.0 Bi, 0.07–0.25 Se
Copper-tin alloys (tin bronzes): Hard, strong alloys with good corrosion resistance, especially against seawater. As bearings, they are wear resistant and resist pounding well. Moderately machinable. Widely used for gears, wormwheels, bearings, marine fittings, piston rings, and pump components.									
C90200	242, 93-7-0-0	S, C, CL, PM, I, P	91.0–94.0(g)(q)	6.0–8.0	0.30	0.50	0.50(i)	0.20	0.20 Sb, 0.05 S, 0.05 P(j), 0.005 Al, 0.005 Si
C90300	225, 88-8-0-4, Navy "G" bronze, (SAE 620)	S, C, CL, PM, I, P	86.0–89.0(g)(q)	7.5–9.0	0.30	3.0–5.0	1.0(i)	0.20	0.20 Sb, 0.05 S, 0.05 P(j), 0.005 Al, 0.005 Si
C90500	210, 88-10-0-2, gun metal, (SAE 62)	S, C, CL, PM, I, P	86.0–89.0(g)(r)	9.0–11.0	0.30	1.0–3.0	1.0(i)	0.20	0.20 Sb, 0.05 S, 0.05 P(j), 0.005 Al, 0.005 Si
C90700	205, 89-11, (SAE 65)	S, C, CL, PM, I, P	88.0–90.0(g)(q)	10.0–12.0	0.50	0.50	0.50(i)	0.15	0.20 Sb, 0.05 S, 0.30 P(j), 0.005 Al, 0.005 Si
C90710	…	S, C, CL, PM, I, P	bal(g)(q)	10.0–12.0	0.25	0.05	0.10(i)	0.10	0.20 Sb, 0.05 S, 0.05–1.2 P(j), 0.005 Al, 0.005 Si
C90800	…	S, C, CL, PM, I, P	85.0–89.0(g)(q)	11.0–13.0	0.25	0.25	0.50(i)	0.15	0.20 Sb, 0.05 S, 0.30 P(j), 0.005 Al, 0.005 Si
C90810	…	S, C, CL, PM, I, P	bal(g)(q)	11.0–13.0	0.25	0.30	0.50(i)	0.15	0.20 Sb, 0.05 S, 0.15–0.8 P(j), 0.005 Al, 0.005 Si

(continued)

(a) Casting processes: S, sand; D, die; C, continuous; I, investment; PM, permanent mold; CL, centrifugal; and P, plaster. (b) Composition values are given as maximum percentages, unless shown as a range or minimum. (c) Including Ag, % min. (d) Cu + sum of named elements, 99.5% min. (e) Includes Ag. (f) Ni + Co. (g) In determining copper min, copper can be calculated as Cu + Ni. (h) Cu + sum of named elements, 99.3% min. (i) Including Co. (j) For continuous castings, P is 1.5% max. (k) Fe + Sb + As is 0.50% max. (l) Cu + sum of named elements, 99.2% min. (m) Fe + Sb +As is 0.8% max. (n) Cu + sum of named elements, 99.1% min. (o) Cu + sum of named elements, 98.7% min. (p) Cu + sum of named elements, 99.0% min. (q) Cu + sum of named elements, 99.4% min. (r) Cu + sum of named elements, 99.7% min. (s) Fe is 0.35% max, when used for steel-backed bearings. (t) Cu + sum of named elements, 98.9% min. (u) For continuous castings, S is 0.25% max. (v) The mechanical properties of C94700 (heat treated) may not be attainable if the lead content exceeds 0.01%. (w) Cu + sum of named elements, 99.8% min. (x) Fe content should not exceed Ni content. (y) The following additional maximum impurity limits shall apply: 0.10% Al, 0.001% B, 0.001% Bi, 0.005–0.15% Mg, 0.005% P, 0.0025% S, 0.02% Sb, 7.5–8.5% Sn, 0.01% T, and 1.0% Zn. (z)Cu + sum of named elements, 99.6% min. (aa) Pb and Ag can be adjusted to modify the alloy hardness. Source: Copper Development Association Inc.

Table 1 (continued)

UNS No.	Other designations, descriptive names (former SAE No.)	Applicable casting processes(a)	Composition(b), wt%						
			Cu	Sn	Pb	Zn	Ni	Fe	Other
Copper-tin alloys (tin bronzes) (continued)									
C90900	199, 87-13-0-0	S, C, CL, PM, I, P	86.0–89.0(g)(q)	12.0–14.0	0.25	0.25	0.50(i)	0.15	0.20 Sb, 0.05 S, 0.05 P(j), 0.005 Al, 0.005 Si
C91000	197, 85-14-0-1	S, C, CL, PM, I, P	84.0–86.0(g)(q)	14.0–16.0	0.20	1.5	0.80(i)	0.10	0.20 Sb, 0.05 S, 0.05 P(j), 0.005 Al, 0.005 Si
C91100	84-16-0-0	S, C, CL, PM, I, P	82.0–85.0(g)(q)	15.0–17.0	0.25	0.25	0.50(i)	0.25	0.20 Sb, 0.05 S, 1.0 P(j), 0.005 Al, 0.005 Si
C91300	194, 81-19	S, C, CL, PM, I, P	79.0–82.0(g)(q)	18.0–20.0	0.25	0.25	0.50(i)	0.25	0.20 Sb, 0.05 S, 1.0 P(j), 0.005 Al, 0.005 Si
C91600	205N, 88-10½,0-0-1½, nickel gear bronze	S, C, CL, PM, I, P	86.0–89.0(g)(q)	9.7–10.8	0.25	0.25	1.2–2.0(i)	0.20	0.20 Sb, 0.05 S, 0.30 P(j), 0.005 Al, 0.005 Si
C91700	86½-12-0-0-1½, nickel gear bronze	S, C, CL, PM, I, P	84.0–87.0(g)(q)	11.3–12.5	0.25	0.25	1.20–2.0(i)	0.20	0.20 Sb, 0.05 S, 0.30 P(j), 0.005 Al, 0.005 Si
Cu-Sn-Pb alloys (leaded tin bronzes): Lead improves machinability in these tin bronzes, but does not materially affect mechanical properties. The alloys are essentially free-cutting versions of the tin bronzes, above, and have similar properties and uses.									
C92200	245, 88-6-1½-4½, Navy "M" bronze, steam bronze, (SAE 622)	S, C, CL, PM, I, P	86.0–90.0(g)(h)	5.5–6.5	1.0–2.0	3.0–5.0	1.0(i)	0.25	0.25 Sb, 0.05 S, 0.05 P(j), 0.005 Al, 0.005 Si
C92210	…	…	86.0–89.0(g)(h)	4.5–5.5	1.7–2.5	3.0–4.5	0.7–1.0	0.25	0.25 Sb, 0.05 S, 0.03 P, 0.005 Al, 0.005 Si
C92300	230, 87-8-1-4, leaded "G" bronze	S, C, CL, PM, I, P	85.0–89.0(g)(h)	7.5–9.0	0.30–1.0	2.5–5.0	1.0(i)	0.25	0.25 Sb, 0.05 S, 0.05 P(j), 0.005 Al, 0.005 Si
C92310	…	S, C, CL, PM, I, P	bal(g)(h)	7.5–8.5	0.30–1.5	3.5–4.5	1.0(i)	…	0.03 Mn, 0.005 Al, 0.005 Si
C92400	…	S, C, CL, PM, I, P	86.0–89.0(g)(h)	9.0–11.0	1.0–2.5	1.0–3.0	1.0(i)	0.25	0.25 Sb, 0.05 S, 0.05 P(j), 0.005 Al, 0.005 Si
C92410	…	S, C, CL, PM, I, P	bal(g)(h)	6.0–8.0	2.5–3.5	1.5–3.0	0.20(i)	0.20	0.25 Sb, 0.05 Mn, 0.005 Al, 0.005 Si
C92500	200, 87-11-1-0-1, (SAE 640)	S, C, CL, PM, I, P	85.0–88.0(g)	10.0–12.0	1.0–1.5	0.50	0.8–1.5(i)	0.30	0.25 Sb, 0.05 S, 0.30 P(j), 0.005 Al, 0.005 Si
C92600	215, 87-10-1-2	S, C, CL, PM, I, P	86.0–88.50(g)(h)	9.3–10.5	0.8–1.5	1.3–2.5	0.7(i)	0.20	0.25 Sb, 0.05 S, 0.03 P(j), 0.005 Al, 0.005 Si
C92610	…	S, C, CL, PM, I, P	bal(g)(h)	9.5–10.5	0.30–1.5	1.7–2.8	1.0(i)	0.15	0.005 Al, 0.005 Si, 0.03 Mn
C92700	206, 88-10-2-0, (SAE 63)	S, C, CL, PM, I, P	86.0–89.0(g)(h)	9.0–11.0	1.0–2.5	0.7	1.0(i)	0.20	0.25 Sb, 0.05 S, 0.25 P(j), 0.005 Al, 0.005 Si
C92710	…	S, C, CL, PM, I, P	bal(g)(h)	9.0–11.0	4.0–6.0	1.0	2.0(i)	0.20	0.25 Sb, 0.05 S, 0.10 P(j), 0.005 Al, 0.005 Si
C92800	295, 79-16-5-0 ring metal	S, C, CL, PM, I, P	78.0–82.0(g)(h)	15.0–17.0	4.0–6.0	0.8	0.80(i)	0.20	0.25 Sb, 0.05 S, 0.05 P(j), 0.005 Al, 0.005 Si
C92810	…	S, C, CL, PM, I, P	78.0–82.0(g)	12.0–14.0	4.0–6.0	0.50	0.8–1.2(i)	0.50	0.25 Sb, 0.05 S, 0.05 P(j), 0.005 Al, 0.005 Si
C92900	84-10-2½-0-3½, leaded nickel tin bronze	S, C, CL, PM, I, P	82.0–86.0(g)	9.0–11.0	2.0–3.2	0.25	2.8–4.0(i)	0.20	0.25 Sb, 0.05 S, 0.50 P(j), 0.005 Al, 0.005 Si
Cu-Sn-Pb alloys (high leaded tin bronzes): Most commonly used bearing alloys, found in bearings operating at moderate to high speeds, as in electric motors and appliances. Alloy C93200 is considered the workhorse alloy of the series. Alloy C93600 has improved machining and antiseizing properties. C93800 noted for good corrosion resistance against concentrations of sulfuric acid below 78%. Alloy C94100 is especially good under boundary lubricated conditions.									
C93100	…	S, C, CL, PM, I, P	bal(g)(p)	6.5–8.5	2.0–5.0	2.0	1.0(i)	0.25	0.25 Sb, 0.05 S, 0.30 P(j), 0.005 Al, 0.005 Si
C93200	315, 83-7-7-3, bearing bronze, (SAE 660)	S, C, CL, PM, I, P	81.0–85.0(g)(p)	6.3–7.5	6.0–8.0	1.0–4.0	1.0(i)	0.20	0.35 Sb, 0.08 S, 0.15 P(j), 0.005 Al, 0.005 Si
C93400	311, 84-8-8-0	S, C, CL, PM, I, P	82.0–85.0(g)(p)	7.0–9.0	7.0–9.0	0.8	1.0(i)	0.20	0.50 Sb, 0.08 S, 0.50 P(j), 0.005 Al, 0.005 Si
C93500	326, 85-5-9-1, (SAE 66)	S, C, CL, PM, I, P	83.0–86.0(g)(p)	4.3–6.0	8.0–10.0	2.0	1.0(i)	0.20	0.30 Sb, 0.08 S, 0.05 P(j), 0.005 Al, 0.005 Si
C93600	…	S, C, CL, PM, I, P	79.0–83.0(h)	6.0–8.0	11.0–13.0	1.0	1.0(i)	0.20	0.55 Sb, 0.08 S, 0.15 P(j), 0.005 Al, 0.005 Si
C93700	305, 80-10-10, bushing and bearing bronze, (SAE 64)	S, C, CL, PM, I, P	78.0–82.0(p)	9.0–11.0	8.0–11.0	0.8	0.50(i)	0.7(s)	0.50 Sb, 0.08 S, 0.10 P(j), 0.005 Al, 0.005 Si
C93720	…	S, C, CL, PM, I, P	83.0 min(p)	3.5–4.5	7.0–9.0	4.0	0.50(i)	0.7	0.50 Sb, 0.10 P(j)
C93800	319, 78-7-15, anti-acid metal, (SAE 67)	S, C, CL, PM, I, P	75.0–79.0(p)	6.3–7.5	13.0–16.0	0.8	1.0(i)	0.15	0.8 Sb, 0.08 S, 0.05 P(j), 0.005 Al, 0.005 Si
C93900	79-6-15	S, C, CL, PM, I, P	76.5–79.5(t)	5.0–7.0	14.0–18.0	1.5	0.8(i)	0.40	0.50 Sb, 0.08 S, 1.5 P(j), 0.005 Al, 0.005 Si
C94000	…	S, C, CL, PM, I, P	69.0–72.0(o)	12.0–14.0	14.0–16.0	0.50	0.50–1.0(i)	0.25	0.50 Sb, 0.08 S(u), 0.05 P(j), 0.005 Al, 0.005 Si
C94100	…	S, C, CL, PM, I, P	72.0–79.0(o)	4.5–6.5	18.0–22.0	1.0	1.0(i)	0.25	0.8 Sb, 0.08 S(u), 0.05 P(j), 0.005 Al, 0.005 Si
C94300	…	S, C, CL, PM, I, P	67.0–72.0(p)	4.5–6.0	23.0–27.0	0.8	1.0(i)	0.15	0.80 Sb, 0.08 S(u), 0.08 P(j), 0.005 Al, 0.005 Si

(continued)

(a) Casting processes: S, sand; D, die; C, continuous; I, investment; PM, permanent mold; CL, centrifugal; and P, plaster. (b) Composition values are given as maximum percentages, unless shown as a range or minimum. (c) Including Ag, % min. (d) Cu + sum of named elements, 99.5% min. (e) Includes Ag. (f) Ni + Co. (g) In determining copper min, copper can be calculated as Cu + Ni. (h) Cu + sum of named elements, 99.3% min. (i) Including Co. (j) For continuous castings, P is 1.5% max. (k) Fe + Sb + As is 0.50% max. (l) Cu + sum of named elements, 99.2% min. (m) Fe + Sb +As is 0.8% max. (n) Cu + sum of named elements, 99.1% min. (o) Cu + sum of named elements, 98.7% min. (p) Cu + sum of named elements, 99.0% min. (q) Cu + sum of named elements, 99.4% min. (r) Cu + sum of named elements, 99.7% min. (s) Fe is 0.35% max, when used for steel-backed bearings. (t) Cu + sum of named elements, 98.9% min. (u) For continuous castings, S is 0.25% max. (v) The mechanical properties of C94700 (heat treated) may not be attainable if the lead content exceeds 0.01%. (w) Cu + sum of named elements, 99.8% min. (x) Fe content should not exceed Ni content. (y) The following additional maximum impurity limits shall apply: 0.10% Al, 0.001% B, 0.001% Bi, 0.005–0.15% Mg, 0.005% P, 0.0025% S, 0.02% Sb, 7.5–8.5% Sn, 0.01% T, and 1.0% Zn. (z)Cu + sum of named elements, 99.6% min. (aa) Pb and Ag can be adjusted to modify the alloy hardness. Source: Copper Development Association Inc.

Table 1 (continued)

UNS No.	Other designations, descriptive names (former SAE No.)	Applicable casting processes(a)	Composition(b), wt%						
			Cu	Sn	Pb	Zn	Ni	Fe	Other
Cu-Sn-Pb alloys (high leaded tin bronzes) (continued)									
C94310	…	S, C, CL, PM, I, P	bal(p)	1.50–3.0	27.0–34.0	0.50	0.25–1.0(i)	0.50	0.50 Sb, 0.05 P(j)
C94320	…	S, C, CL, PM, I, P	bal(p)	4.0–7.0	24.0–32.0	…	…	0.35	…
C94330	…	S, C, CL, PM, I, P	68.5–75.5(p)	3.0–4.0	21.0–25.0	3.0	0.50(i)	0.7	0.50 Sb, 0.10 P(j)
C94400	312, 81-8-11, phosphor bronze	S, C, CL, PM, I, P	bal(p)	7.0–9.0	9.0–12.0	0.8	1.0(i)	0.15	0.08 Sb, 0.08 S, 0.50 P(j), 0.005 Al, 0.005 Si
C94500	321, 73-7-20, medium bronze	S, C, CL, PM, I, P	bal(p)	6.0–8.0	16.0–22.0	1.2	1.0(i)	0.15	0.80 Sb, 0.08 S, 0.05 P, 0.005 Al, 0.005 Si
Cu-Sn-Ni alloys (nickel-tin bronzes): High-strength structural castings. Easy to cast, pressure tight. Corrosion and wear resistant. C94700 is heat treatable. Alloys used for bearings, worm gears, valve stems and nuts, impellers, screw conveyors, roller bearing cages, and railway electrification hardware.									
C94700	88-5-0-2-5	S, C, CL, PM, I, P	85.0–90.0(o)	4.5–6.0	0.10(v)	1.0–2.5	4.5–6.0(i)	0.25	0.15 Sb, 0.20 Mn, 0.05 S, 0.05 P, 0.005 Al, 0.005 Si
C94800	87-5-1-2-5, leaded nickel-tin bronze	S, C, CL, PM, I, P	84.0–89.0(o)	4.5–6.0	0.30–1.0	1.0–2.5	4.5–6.0(i)	0.25	0.15 Sb, 0.20 Mn, 0.05 S, 0.05 P, 0.005 Al, 0.005 Si
C94900	leaded nickel-tin bronze	S, C, CL, PM, I, P	79.0–81.0(p)	4.0–6.0(i)	4.0–6.0	4.0–6.0	4.0–6.0(i)	0.30	0.25 Sb, 0.10 Mn, 0.08 S, 0.05 P, 0.005 Al, 0.005 Si
Cu-Al-Fe and Cu-Al-Fe-Ni alloys (aluminum bronzes): The aluminum bronzes are characterized by high strength and excellent corrosion resistance. Alloys containing more than 9.5% Al can be heat treated, some to tensile strengths exceeding 120 ksi (827 MPa). Uses include a variety of heavy-duty mechanical and structural products including gears, worm drives, valve guides, and seats. Excellent heavy-duty bearing alloys, but do not tolerate misalignment or dirty lubricants and generally should be used against hardened steel shafts, with both shaft and bearing machined to fine surface finishes.									
C95200	415, 88-3-9, aluminum bronze 9A, (SAE 68a)	S, C, CL, PM, I, P	86.0 min(p)	…	…	…	…	2.5–4.0	8.5–9.5 Al
C95210	…	S, C, CL, PM, I, P	86.0 min(p)	0.10	0.05	0.50	1.0(i)	2.5–4.0	8.5–9.5 Al, 1.0 Mn, 0.05 Mg, 0.25 Si
C95220	…	S, C, CL, PM, I, P	bal(p)	…	…	…	2.5(i)	2.5–4.0	9.5–10.5 Al, 0.50 Mn
C95300	415, 89-1-10, aluminum bronze 9B, (SAE 68b)	S, C, CL, PM, I, P	83.0 min(p)	…	…	…	…	0.8–1.5	9.0–11.0 Al
C95400	415, 85-4-11, aluminum bronze 9C	S, C, CL, PM, I, P	83.0 min(d)	…	…	…	1.5(i)	3.0–5.0	10.0–11.5 Al, 0.50 Mn
C95410	…	S, C, CL, PM, I, P	83.0 min(d)	…	…	…	1.5–2.5(i)	3.0–5.0	10.0–11.5 Al, 0.50 Mn
C95420	…	S, C, CL, PM, I, P	83.5 min(d)	…	…	…	0.50(i)	3.0–4.3	10.5–12.0 Al, 0.50 Mn
C95500	415, 81-4-4-11, aluminum bronze 9D	S, C, CL, PM, I, P	78.0 min(d)	…	…	…	3.0–5.5(i)	3.0–5.0	10.0–11.5 Al, 3.5 Mn
C95510	Nickel-aluminum bronze	S, C, CL, PM, I, P	78.0 min(w)	0.20	…	0.30	4.5–5.5(i)	2.0–3.5	9.7–10.9 Al, 1.5 Mn
C95520	Nickel-aluminum bronze	S, C, CL, PM, I, P	74.5 min(d)	0.25	0.03	0.30	4.2–6.0(i)	4.0–5.5	10.5–11.5 Al, 1.5 Mn, 0.15 Si, 0.20 Co, 0.05 Cr
C95600	91-2-7, aluminum-silicon bronze	S, C, CL, PM, I, P	88.0 min(p)	…	…	…	0.25(i)	…	6.0–8.0 Al, 1.8–3.2 Si
C95700	75-3-8-2-12, manganese-aluminum bronze	S, C, CL, PM, I, P	71.0 min(d)	…	…	…	1.5–3.0(i)	2.0–4.0	7.0–8.5 Al, 11.0–14.0 Mn, 0.10 Si
C95710	Manganese-aluminum bronze	S, C, CL, PM, I, P	71.0 min(d)	1.0	0.05	0.50	1.5–3.0(i)	2.0–4.0	7.0–8.5 Al, 11.0–14.0 Mn, 0.15 Si, 0.05 P
C95800	415, 81-5-4-9-1, α nickel-aluminum bronze. propeller bronze	S, C, CL, PM, I, P	79.0 min(d)	…	0.03	…	4.0–5.0(i)(x)	3.5–4.5(x)	8.5–9.5 Al, 0.8–1.5 Mn, 0.10 Si
C95810	Nickel-aluminum bronze	S, C, CL, PM, I, P	79.0 min(d)	…	0.10	0.50	4.0–5.0(i)(x)	3.5–4.5(x)	8.5–9.5 Al, 0.8–1.5 Mn, 0.05 Mg, 0.10 Si
C95900	…	S, C, CL, PM, I, P	bal(d)	…	…	…	0.50(i)	3.0–5.0	12.0–13.5 Al, 1.5 Mn
Cu-Ni-Fe alloys (copper-nickels): Excellent corrosion resistance, especially against seawater. High strength and toughness from low to elevated temperatures. Very widely used in marine applications, as pump and valve components, fittings, flanges, etc. Beryllium-containing alloys can be heat treated to approximately 110 ksi (758 MPa).									
C96200	90-10 copper-nickel	S, C, CL, PM, I, P	bal(d)	…	0.01	…	9.0–11.0(i)	1.0–1.8	1.5 Mn, 0.50 Si, 0.5–1.0 Nb, 0.10 C, 0.02 S, 0.02 P
C96300	80-20 copper-nickel	S, C, CL, PM, I, P	bal(d)	…	0.01	…	18.0–22.0(i)	0.50–1.5	0.25–1.5 Mn, 0.50 Si, 0.50–1.5 Nb, 0.15 C, 0.02 S, 0.02 P
C96400	70-30 copper-nickel	S, C, CL, PM, I, P	bal(d)	…	0.01	…	28.0–32.0(i)	0.25–1.5	1.5 Mn, 0.50 Si, 0.50–1.5 Nb, 0.15 C, 0.02 S, 0.02 P
C96600	717C, Be-Cu-Ni	S, C, CL, PM, I, P	bal(d)	…	0.01	…	29.0–33.0(i)	0.8–1.1	1.0 Mn, 0.15 Si, 0.40–0.7 Be
C96700	Be-Zr-Ti-Cu-Ni	S, C, CL, PM, I, P	bal(d)	…	0.01	…	29.0–33.0(i)	0.40–0.70	0.40–0.70 Mn, 0.15 Si, 1.1–1.2 Be, 0.15–0.35 Zr, 0.15–0.35 Ti
C96800	Spinodal alloy	S, C, CL, PM, I, P	bal(d)	…	0.005	…	9.5–10.5(i)	0.50	0.05–0.30 Mn, 0.05 Si, 0.10–0.30 Nb(y)
C96900	Spinodal alloy	S, C, CL, PM, I, P	bal(d)	7.5–8.5	0.02	0.50	14.5–15.5(i)	0.50	0.05–0.30 Mn, 0.10 Nb, 0.15 Mg

(continued)

(a) Casting processes: S, sand; D, die; C, continuous; I, investment; PM, permanent mold; CL, centrifugal; and P, plaster. (b) Composition values are given as maximum percentages, unless shown as a range or minimum. (c) Including Ag, % min. (d) Cu + sum of named elements, 99.5% min. (e) Includes Ag. (f) Ni + Co. (g) In determining copper min, copper can be calculated as Cu + Ni. (h) Cu + sum of named elements, 99.3% min. (i) Including Co. (j) For continuous castings, P is 1.5% max. (k) Fe + Sb + As is 0.50% max. (l) Cu + sum of named elements, 99.2% min. (m) Fe + Sb +As is 0.8% max. (n) Cu + sum of named elements, 99.1% min. (o) Cu + sum of named elements, 98.7% min. (p) Cu + sum of named elements, 99.0% min. (q) Cu + sum of named elements, 99.4% min. (r) Cu + sum of named elements, 99.7% min. (s) Fe is 0.35% max, when used for steel-backed bearings. (t) Cu + sum of named elements, 98.9% min. (u) For continuous castings, S is 0.25% max. (v) The mechanical properties of C94700 (heat treated) may not be attainable if the lead content exceeds 0.01%. (w) Cu + sum of named elements, 99.8% min. (x) Fe content should not exceed Ni content. (y) The following additional maximumß impurity limits shall apply: 0.10% Al, 0.001% B, 0.001% Bi, 0.005–0.15% Mg, 0.005% P, 0.0025% S, 0.02% Sb, 7.5–8.5% Sn, 0.01% T, and 1.0% Zn. (z)Cu + sum of named elements, 99.6% min. (aa) Pb and Ag can be adjusted to modify the alloy hardness. Source: Copper Development Association Inc.

Table 1 (continued)

	Other designations, descriptive names	Applicable casting	Composition(b), wt%						
UNS No.	(former SAE No.)	processes(a)	Cu	Sn	Pb	Zn	Ni	Fe	Other
Cu-Ni-Zn alloys (nickel silvers): Moderately strong alloys with very good corrosion resistance and a pleasing silver color. Used in valves, fittings, and other components for dairy equipment and as architectural and decorative trim.									
C97300	56-2-10-20-12, 12% nickel silver	S, C, CL, PM, I, P	53.0–58.0(p)	1.5–3.0	8.0–11.0	17.0–25.0	11.0–14.0(i)	1.5	0.35 Sb, 0.08 S, 0.05 P, 0.005 Al, 0.50 Mn, 0.15 Si
C97400	59-3-5-17-16, 15% nickel silver	S, C, CL, PM, I, P	58.0–61.0(p)	2.5–3.5	4.5–5.5	bal	15.5–17.0(i)	1.5	0.50 Mn
C97600	64-4-4-8-20, 20% nickel silver, dairy metal	S, C, CL, PM, I, P	63.0–67.0(r)	3.5–4.5	3.0–5.0	3.0–9.0	19.0–21.5(i)	1.5	0.25 Sb, 0.08 S, 0.05 P, 0.005 Al, 1.0 Mn, 0.15 Si
C97800	66-5-2-2-25, 25% nickel silver	S, C, CL, PM, I, P	64.0–67.0(z)	4.0–5.5	1.0–2.5	1.0–4.0	24.0–27.0(i)	1.5	0.20 Sb, 0.08 S, 0.05 P, 0.005 Al, 1.0 Mn, 0.15 Si
Copper-lead alloys (leaded coppers): Ultrahigh lead alloys for special-purpose bearings. Alloys have relatively low strength and poor impact properties and generally require reinforcement.									
C98200	Leaded copper, 25% SAE 49	S, C	bal(d)	0.6–2.0	21.0–27.0	0.50	0.50	0.7	0.10 P, 0.50 Sb
C98400	Leaded copper, 30%	S, C	bal(d)	0.50	26.0–33.0	0.50	0.50	0.7	1.5 Ag, 0.10 P, 0.50 Sb
C98600	Leaded copper, 35% SAE 480	S, C	60.0–70.0	0.50	30.0–40.0	…	…	0.35	1.5 Ag
C98800	Leaded copper, 40% SAE 481	S, C	56.5–62.5(e)	0.25	37.5–42.5(aa)	0.10	…	0.35	5.5 Ag(aa), 0.02 P
C98820	Leaded copper, 42% SAE 484	S, C	bal	1.0–5.0	40.0–44.0	…	…	0.35	…
C98840	Leaded copper, 50% SAE 485	S, C	bal	1.0–5.0	44.0–58.0	…	…	0.35	…
Special alloys: Alloys specifically designed for glassmaking molds, but also used for marine hardware.									
C99300	Incramet 800	S, C, CL	bal(r)	0.05	0.02	…	13.5–16.5	0.40–1.0	10.7–11.5 Al, 1.0–2.0 Co, 0.02 Si
C99350	Cu-Ni-Al-Zn alloy	S, C, CL	bal(r)	…	0.15	7.5–9.5	14.5–16.0(i)	1.0	9.5–10.5 Al, 0.25 Mn
Special alloys: Moderate-strength alloys with good resistance to dezincification and dealuminification. Used in various products for marine (especially outboard) and mining equipment.									
C99400	Nondezincification alloy, NDZ	S, C, CL, I, P	bal(r)	…	0.25	0.50–5.0	1.0–3.5	1.0–3.0	0.50–2.0 Al, 0.50–2.0 Si, 0.50 Mn
C99500	Cu-Ni-Al-Zn-Fe alloy	S, C, CL	bal(r)	…	0.25	0.50–2.0	3.5–5.5	3.0–5.0	0.50–2.0 Al, 0.50–2.0 Si, 0.50 Mn
Special alloys: Special-purpose alloys with exceptionally high damping capacity.									
C99600	Incramute 1	S, C, CL	bal(r)	0.10	0.02	0.20	0.20	0.20	1.0–2.8 Al, 0.20 Co, 0.10 Si, 39.0–45.0Mn, 0.05 C
C99700	White manganese brass	S, CL, PM, I, P, D	54.0 min(r)	1.0	2.0	19.0–25.0	4.0–6.0	1.0	0.50–3.0 Al, 11.0–15.0 Mn
C99750	Cu-Zn-Mn	S, PM, I, P, D	55.0–61.0(r)	0.50–2.5	…	17.0–23.0	5.0	1.0	0.25–3.0 Al, 17.0–23.0 Mn

(a) Casting processes: S, sand; D, die; C, continuous; I, investment; PM, permanent mold; CL, centrifugal; and P, plaster. (b) Composition values are given as maximum percentages, unless shown as a range or minimum. (c) Including Ag, % min. (d) Cu + sum of named elements, 99.5% min. (e) Includes Ag. (f) Ni + Co. (g) In determining copper min, copper can be calculated as Cu + Ni. (h) Cu + sum of named elements, 99.3% min. (i) Including Co. (j) For continuous castings, P is 1.5% max. (k) Fe + Sb + As is 0.50% max. (l) Cu + sum of named elements, 99.2% min. (m) Fe + Sb +As is 0.8% max. (n) Cu + sum of named elements, 99.1% min. (o) Cu + sum of named elements, 98.7% min. (p) Cu + sum of named elements, 99.0% min. (q) Cu + sum of named elements, 99.4% min. (r) Cu + sum of named elements, 99.7% min. (s) Fe is 0.35% max, when used for steel-backed bearings. (t) Cu + sum of named elements, 98.9% min. (u) For continuous castings, S is 0.25% max. (v) The mechanical properties of C94700 (heat treated) may not be attainable if the lead content exceeds 0.01%. (w) Cu + sum of named elements, 99.8% min. (x) Fe content should not exceed Ni content. (y) The following additional maximum impurity limits shall apply: 0.10% Al, 0.001% B, 0.001% Bi, 0.005–0.15% Mg, 0.005% P, 0.0025% S, 0.02% Sb, 7.5–8.5% Sn, 0.01% T, and 1.0% Zn. (z)Cu + sum of named elements, 99.6% min. (aa) Pb and Ag can be adjusted to modify the alloy hardness. Source: Copper Development Association Inc.

favorable combination of strength and corrosion resistance, brasses are by far the most commonly cast copper alloys. There are six subcategories of cast brasses: red and leaded red, semired and leaded semired, yellow and leaded yellow, high-strength and leaded high-strength yellow (manganese bronzes), silicon brasses/silicon bronzes, and copper-bismuth (Cu-Bi) and copper-selenium-bismuth (Cu-Se-Bi) brasses.

Red and Leaded Red Brasses. The cast red brasses (C83300–C83810) are alloys of copper, zinc, tin, and in some cases, lead. A "red" copperlike color is evident in alloys containing less than about 8% Zn. These moderate-strength alloys retain the face-centered cubic (α) structure of pure copper. Their electrical conductivity, while not extremely high, is adequate for electromechanical equipment such as pole-line hardware. The leaded red brasses may contain up to 7% Pb. The primary function of the element is to provide pressure tightness by sealing the interdendritic shrinkage pores that form as these wide-freezing-range alloys solidify. Lead also improves machinability, but high levels of the element diminish mechanical properties, particularly at elevated temperatures.

With their high aqueous and atmospheric corrosion resistance, the red brasses are widely used for plumbing goods, valves, fittings, pump housings and impellers, water meters, plaques and statuary, and countless other products. The workhorse alloy is C83600, which is also known as 85-5-5-5 (85Cu-5Sn-5Pb-5Zn), ounce metal, and composition metal. C83600 has been used commercially for several hundred years and currently accounts for more tonnage than any other copper casting alloy.

Semired and leaded semired brasses (C84200–C84800) differ from the red brasses primarily by their higher zinc contents, which range up to 15%. Zinc reduces corrosion resistance (and cost) somewhat compared with red brasses, but it has little effect on strength. Higher zinc also lightens alloy color. The microstructure remains mostly single-phase α, although some body-centered cubic β phase may appear as a result of coring. The leaded alloys C84400 and C84800 are the most widely used members of this family. Like the red brasses, the semired alloys are primarily specified for plumbing fixtures, fittings, and low-pressure valves.

The yellow and leaded yellow brasses (C85200–C85800) span a broad range of zinc contents (20–40%). As a result, the alloys have microstructures that range from essentially all-α to ones with substantial amounts of the hard β phase. Properties vary accordingly, since β is a potent strengthener. Although β slightly impairs room-temperature ductility, it also markedly improves ductility at temperatures approaching the solidus. This feature is put to use in alloy C85800 (40% Zn), which is suitable for both permanent mold casting and pressure die casting because it can accommodate the high shrinkage strains that arise in rigid molds.

Yellow brasses have a pleasing light color and can be polished to a high luster. Their corrosion resistance and cost are somewhat lower than those of the semired brasses, but properties are well suited for the architectural trim, decorative hardware, and plumbing fixtures for which these alloys are commonly used. The most widely used yellow brasses are C85200, C85400, and C85700. Alloy C85700 is essentially a cast version of the familiar 60Cu-40Zn Muntz metal (C28000).

High-Strength Brasses. Also called manganese bronzes and high-tensile brasses, these Cu-Zn-Fe-Al-Mn alloys (C86100–C86800) are among the strongest (as-cast) copper-base materials. The mechanical properties of the high-strength yellow brasses derive primarily from a high β phase content. Beta is stable in binary alloys containing more than 39.5% Zn, but strong β stabilizers such as aluminum promote its presence at lower zinc contents, as in alloys C86200 (25% Zn, 4% Al) and C86300 (26% Zn, 6% Al). Additional strength is provided by iron, a grain refiner that appears as precipitates of an iron-rich intermetallic compound. Manganese also contributes to strength, but its principal functions may have more to do with castability. The high-zinc, low-aluminum alloys C86400 and C86500 have duplex (α + β) structures. Their mechanical properties fall between those of yellow brasses and fully β alloys such as C86200 and C86300.

The high-strength yellow brasses are mainly used for gears, bolts, valve stems, bridge trunnions, and other mechanical products requiring high-strength, good wear resistance, and reasonably good corrosion resistance. Where economically feasible, however, the high-strength brasses have increasingly been replaced by the more corrosion-resistant and equally strong aluminum bronzes.

Silicon Brasses/Bronzes. The foundry characteristics of silicon brasses (C87300–C87900) include favorably low melting points and high fluidity. They are amenable to most casting methods, including permanent mold and pressure die casting processes. Castings exhibit moderate strength and very good aqueous and atmospheric corrosion resistance, although susceptibility to stress-corrosion cracking (SCC) in severe environments has been reported. Silicon brasses have been considered as possible lead-free replacements for common plumbing brasses, but limited machinability restricts their wide-spread acceptance. Current applications include bearings, gears, pole-line hardware, and intricately shaped pump and valve components.

Copper-Bismuth and Cu-Se-Bi Brasses. The copper-bismuth and Cu-Se-Bi (SeBiLoy) red brasses (alloys C89510 and C89520, respectively) are low-lead sand-cast alloys that are used in food process and potable water applications such as faucets and other plumbing fixtures. These alloys were developed to minimize lead leaching into potable water and to replicate the high machinability and pressure tightness of leaded brass.

A selenium-bismuth-containing yellow brass (C89550) has also been developed for the permanent mold casting process. It too was developed for use in potable water systems.

Bronzes

Under the UNS system, the term bronze (C90200–C95900) applies to a broad class of alloys in which the principal alloying element is neither zinc nor nickel. There are four broad categories of bronzes: tin bronzes, leaded and high-leaded tin bronzes, nickel-tin bronzes, and aluminum bronzes.

Tin Bronzes. Tin is a potent solid-solution strengthener in copper. It also increases corrosion resistance, as the hundreds of surviving Bronze Age relics dramatically illustrate. In fact, current tin bronzes (C90200–C91700) are not materially different from those cast more than 3500 years ago in Europe and China.

Binary copper-tin alloys retain the α solid solution up to 15.8% Sn at 520 °C (968 °F), and while the solubility of tin is much lower at room temperature, low-temperature transformations are very sluggish and can usually be ignored. Tin broadens the freezing range far more than zinc does, and the tin bronzes therefore tend to undergo an extended mushy stage during solidification. Castings must be designed with this behavior in mind.

Tin bronzes are stronger and more ductile than red and semired brasses and are useable at higher temperatures than leaded alloys. Their high wear resistance and low friction coefficient against steel are useful in bearings, gears, and piston rings. Other applications include valves, fittings, and bells. Alloys C90300 and C90500 can be used for pressure-retaining products at temperatures up to 260 °C (500 °F).

Leaded Tin Bronzes. The principal functions of lead in copper-tin and Cu-Sn-Zn alloys are to improve machinability and pressure tightness. With proper foundry practice, most copper alloys can produce pressure-tight castings, but extended-freezing-range alloys such as the high-tin bronzes often require some lead to seal interconnected microporosity. As little as 1% Pb is usually sufficient, although more may be present if it is needed to improve machinability or bearing properties. Lead does reduce tensile strength and ductility; however, the amount added can be balanced with regard to machinability and strength requirements.

Many mechanical products are routinely cast in leaded tin bronzes (C92200–C92900). Alloys C92200 (Navy "M" bronze, steam bronze) and C92300 (Navy "G" bronze) are specified for corrosion-resistant valves, fittings, and other pressure-retaining products. C92200 may be used for pressure-retaining parts at temperatures up to 290 °C (550 °F), whereas alloy C92300 is limited to temperatures below 260 °C (500 °F) as a precaution against a form of embrittlement that can occur at higher temperatures. Alloys C92600 through C92900, which contain 10% Sn, are slightly stronger and more corrosion resistant than leaner alloys such as C92200. None of the leaded alloys can be welded, but all can be soldered and many can be brazed, provided they can cool without constraint so as to avoid hot shortness (brittleness).

High-leaded tin bronzes (C93100–C94500) are primarily used for sleeve bearings. Should the flow of lubricant in such bearings be interrupted, lead exudes from the alloy, smears over the surface of the journal, and prevents galling and seizing, at least temporarily. This "slow-fail" feature is one of the principal advantages that leaded-bronze sleeve bearings hold over rolling-element bearings.

The nickel-tin bronzes C94700 and C94800 combine strength (585 MPa, or 85 ksi, tensile strength) and toughness with good bearing properties and high corrosion resistance. They are amenable to most foundry processes, including permanent mold and investment (precision) casting. Bearings, rings, and gear blanks can be produced by centrifugal and/or continuous casting. The alloys are soft and ductile in the as-cast or solution-annealed and quenched condition, but low-temperature aging (at 315 °C, or 600 °F) causes a spinodal decomposition that sharply raises mechanical properties. The alloys find numerous uses as specialty bearings, pistons, nozzles, shifter forks, feed mechanisms, mechanical actuators, and machinery components.

Aluminum bronzes (95200–C95900) are best known for their combination of exceptional corrosion resistance; high mechanical strength, toughness, and wear resistance; and good casting and welding characteristics. They comprise a large family of alloys ranging from ductile, moderate-strength grades to some of the strongest copper-base compositions available. Alloys with less than about 9.25% Al display primarily α-phase microstructures, which can be strengthened via precipitation of iron- or nickel-rich phases. Alloys with more than about 8.5% Al can contain mixtures of several phases in the as-cast condition. The nature and occurrence of these phases are controlled by composition, cooling rate, and heat treatment.

Simple aluminum bronzes such as C95200 to C95500 are actually Cu-Al-Fe ternary alloys. Of these, C95300, C95400, and C95500 can be quenched and tempered, although C95400, the most widely used of the three, is usually not heat treated.

Alloy C95600 is a silicon-aluminum bronze with reportedly improved machinability and bearing properties. C95700 is a high-strength Mn-Ni-Fe-Al bronze originally developed as a marine propeller alloy. It has largely been

Table 2 Water-velocity guidelines for copper alloy castings

	Peripheral velocity	
UNS No.	m/s	ft/s
C83600	<9.1	<30
C87600	<9.1	<30
C90300	<13.7	<45
C92200	<13.7	<45
C95200	<22.8	<75
C86500	<22.8	<75
C95500	>22.8	>75
C95700	>22.8	>75
C95800	>22.8	>75

Note: Velocity guidelines for cast copper alloys in pumps and propellers operating in seawater replaced in this application by C95800, a nickel-aluminum bronze. Alloy C95800 cannot be heat treated to improve mechanical properties, but it is commonly temper annealed to enhance its corrosion resistance.

The corrosion resistance of aluminum bronzes is generally very high, especially in seawater, chlorides, and dilute acids, including sulfuric, phosphoric, hydrochloric, and hydrofluoric. Aluminum bronzes are much less susceptible to crevice corrosion than stainless steels, and resist both pitting and SCC. Largely because of the high alumina (Al_2O_3) content of their protective corrosion-product films, aluminum bronzes have very high erosion-corrosion and cavitation resistance. The data in Table 2 show that aluminum bronzes can tolerate water velocities more than twice as high as the limits for other copper alloys.

Aluminum bronzes have a wide range of uses. They have replaced other copper-base alloys in traditional applications such as pump and valve components, bearings, and wear rings. In many other cases, they have proven to be technically viable and cost-effective alternatives to stainless steels and nickel-base alloys. Because the alloys resist biofouling, they are widely used in marine equipment, such as seawater piping, fittings, valves, pumps, propellers, and propeller hubs. Other applications include: bearings and pump/valve components in the chemical process industries, wear rings for hydroelectric turbines, and large-diameter landing-gear bearings for commercial and military aircraft.

Other Alloys

Copper-Nickel Alloys. The copper-nickel binary system includes the copper nickels (C96200–C96900) at its copper-rich end and the Monel alloys (e.g., Ni-30Cu) in its nickel-rich section. Copper nickels, also called cupronickels, are solid-solution alloys to which iron, chromium, niobium, and/or manganese are added for improved strength and corrosion resistance, particularly under conditions of high-velocity liquid flow. They are noted for their exceptional corrosion resistance in seawater and for their virtual immunity to SCC in media that attack other copper alloys (ammonia, amines, and nitrites, for example). Biofouling resistance is highest in low-nickel alloys such as C96200 (10% Ni), but other properties generally improve with higher nickel content. Highest corrosion resistance is observed in C96400 (30% Ni). Since nickel content strongly affects alloy price, use of these alloys should be justified by the severity of service conditions and the required product life.

Copper-nickel alloys are typically used aboard ships, on offshore platforms, and in coastal power plants. They are acknowledged to be the best materials for evaporative desalination plants. Cast copper-nickels have also been considered as candidate materials for spent-nuclear-fuel burial containers, along with pure copper and aluminum bronze.

Nickel Silvers. These Cu-Sn-Pb-Zn-Ni alloys (C97300–C97800), some of which are actually leaded nickel brasses, are named for their bright silvery luster. They have low to moderate strength, depending on grade. The alloys exhibit high fluidity during casting and can reproduce fine details. Tin and nickel impart good aqueous corrosion resistance, while lead provides pressure tightness and machinability. The nickel silvers are often thought of as ornamental alloys, and architectural trim and musical-instrument valves are indeed two of their better-known uses. However, alloy C97600 (20% Ni), which has a nominal as-cast tensile strength of 310 MPa (45 ksi), is also used for marine hardware and low-pressure valves and fittings for the food, dairy, and beverage industries.

Leaded coppers (C98200–C98840) are essentially pure copper or high-copper alloys containing lead. The leaded coppers offer the moderate corrosion resistance and high conductivity of the copper alloys, in addition to the lubricity and low-friction characteristics of high-leaded bronzes. Applications include auto main and connecting rod bearings.

Special alloys (C99300–C99750) are those with unique characteristics, such as C99300 (Incramet 800), which has high oxidation resistance due to aluminum, good thermal fatigue resistance, and high hot hardness. This alloy was developed for glass processing including glassmaking molds and plate glass rolls. Other alloys falling under the "special alloy" category include the manganese white brasses (C99700 and C99750), which are used in musical instrument components, decorative hardware requiring silver color, and components that have good damping characteristics and attenuate noise well.

Table 3 Foundry properties of the principal copper alloys for sand casting

UNS No.	Common name	Shrinkage allowance, %	Approximate liquidus temperature		Castability rating(a)	Fluidity rating(a)
			˚C	˚F		
C83600	Leaded red brass	5.7	1010	1850	2	6
C84400	Leaded semired brass	2.0	980	1795	2	6
C84800	Leaded semired brass	1.4	955	1750	2	6
C85400	Leaded yellow brass	1.5–1.8	940	1725	4	3
C85800	Yellow brass	2.0	925	1700	4	3
C86300	Manganese bronze	2.3	920	1690	5	2
C86500	Manganese bronze	1.9	880	1615	4	2
C87200	Silicon bronze	1.8–2.0	…	…	5	3
C87500	Silicon brass	1.9	915	1680	4	1
C90300	Tin bronze	1.5–1.8	980	1795	3	6
C92200	Leaded tin bronze	1.5	990	1810	3	6
C93700	High-lead tin bronze	2.0	930	1705	2	6
C94300	High-lead tin bronze	1.5	925	1700	6	7
C95300	Aluminum bronze	1.6	1045	1910	8	3
C95800	Aluminum bronze	1.6	1060	1940	8	3
C97600	Nickel-silver	2.0	1145	2090	8	7
C97800	Nickel-silver	1.6	1180	2160	8	7

(a) Relative rating for casting in sand molds. The alloys are ranked from 1–8 in both overall castability and fluidity; 1 is the highest or best possible rating.

Selection Criteria

The choice of an alloy for any casting usually depends on the following factors:

- Castability
- Properties, including mechanical properties, corrosion resistance, and electrical and thermal conductivities
- Machinability
- Cost

Castability

Castability should not be confused with fluidity, which is only a measure of the distance to which a metal will flow before solidifying. Fluidity is thus one factor determining the ability of a molten alloy to completely fill a mold cavity in every detail. Castability, on the other hand, is a general term relating to the ability to reproduce fine detail on a surface. Colloquially, good castability refers to the ease with which an alloy responds to ordinary foundry practice without requiring special techniques for gating, risering, melting, sand conditioning, or any of the other factors involved in making good castings. High fluidity often ensures good castability, but it is not solely responsible for that quality in a casting alloy.

The castability of alloys is generally influenced by their shrinkage characteristics and their freezing range (which is not necessarily related directly to shrinkage). Classification of copper casting alloys according to a narrow or wide freezing range is discussed in the article "Melting and Casting" in this Handbook and in the section "Control of Solidification" in this article.

Foundry alloys are also classified as high-shrinkage or low-shrinkage alloys. The former class includes the manganese bronzes, aluminum bronzes, silicon bronzes, silicon brasses, and some nickel-silvers. They are more fluid than the low-shrinkage red brasses, more easily poured, and give high-grade castings in the sand, permanent mold, plaster, die, and centrifugal casting processes. With high-shrinkage alloys, careful design is necessary to promote directional solidification, avoid abrupt changes in cross section, avoid notches (by using generous fillets), and properly place gates and risers; all of these design precautions help avoid internal shrinks and cracks. Turbulent pouring must be avoided to prevent the formation of dross becoming entrapped in the casting. Liberal use of risers or exothermic compounds ensures adequate molten metal to feed all sections of the casting. Table 3 presents foundry characteristics of selected standard alloys, including a comparative ranking of both fluidity and overall castability for sand casting; number 1 represents the highest castability or fluidity ranking.

All copper alloys can be successfully cast in sand. Sand casting allows the greatest flexibility in casting size and shape and is the most economical casting method if only a few castings are made (die casting is more economical above ~50,000 units). Permanent mold casting is best suited for tin, silicon, aluminum, and manganese bronzes and for yellow brasses. Die casting is well suited for yellow brasses, but increasing amounts of permanent mold alloys are also being die cast. Size is a definite limitation for both methods, although large slabs weighing as much as 4500 kg (10,000 lb) have been cast in permanent molds. Brass die castings generally weigh less than 0.2 kg (0.5 lb) and seldom exceed 0.9 kg (2 lb). The limitation of size is due to the reduced die life with larger castings.

Virtually all copper alloys can be cast successfully by the centrifugal casting process. Castings of almost every size from less than 100 g to more than 22,000 kg (<0.25 to >50,000 lb) have been made.

Because of their low lead contents, aluminum bronzes, yellow brasses, manganese bronzes, low-nickel bronzes, and silicon brasses and bronzes are best adapted to plaster mold casting. For most of these alloys, lead should be held to a minimum because it reacts with the calcium sulfate in the plaster, resulting in discoloration of the surface of the casting and increased cleaning and machining costs. Size is a limitation on plaster mold casting, although aluminum bronze castings that weigh as little as 100 g (0.25 lb) have been made by the lost-wax process, and castings that weigh more than 150 kg (330 lb) have been made by conventional plaster molding.

Control of Solidification. Production of consistently sound castings requires an understanding of the solidification characteristics of the alloys as well as knowledge of relative magnitudes of shrinkage. The actual amount of contraction during solidification does not differ greatly from alloy to alloy. Its distribution, however, is a function of the freezing range and the temperature gradient in critical sections. Manganese and aluminum bronzes are similar to steel in that their freezing ranges are quite narrow—about 40 and 14 °C (70 and 25 °F), respectively. Large castings can be made by the same conventional methods used for steel, as long as proper attention is given to placement of gates and risers—both those for controlling directional solidification and those for feeding the primary central shrinkage cavity.

Tin bronzes have wider freezing ranges (~165 °C, or 300 °F, for C83600). Alloys with such wide freezing ranges form a mushy zone during solidification, resulting in interdendritic shrinkage or microshrinkage. Because feeding cannot take place properly under these conditions, porosity results in the affected sections. In overcoming this effect, design and riser placement, plus the use of chills, are important. Another means of overcoming interdendritic shrinkage is to maintain close temperature control of the metal during pouring and to provide for rapid solidification. These requirements limit section thickness and pouring temperatures, and this practice requires a gating system that will ensure directional solidification. Sections up to 25 mm (1 in.) in thickness are routinely cast. Sections up to 50 mm (2 in.) thick can be cast, but only with difficulty and under carefully controlled conditions. A bronze with a narrow solidification (freezing) range and good directional solidification characteristics is recommended for castings having section thicknesses greater than about 25 mm (1 in.).

It is difficult to achieve directional solidification in complex castings. The most effective and most easily used device is the chill. For irregular sections, chills must be shaped to fit the contour of the section of the mold in which they are placed. Insulating pads and riser sleeves sometimes are effective in slowing down the solidification rate in certain areas to maintain directional solidification. Further information on the casting of copper alloys is given in the article "Melting and Casting" in this Handbook.

Mechanical Properties

Most copper-base casting alloys containing tin, lead, or zinc have only moderate tensile and yield strengths, low-to-medium hardness, and high elongation. When higher tensile or yield strength is required, the aluminum bronzes, manganese bronzes, silicon brasses, silicon bronzes, and some nickel-silvers are used instead. Most of the higher-strength alloys have better-than-average resistance to corrosion and wear. Mechanical properties of copper-base casting alloys are presented in Table 4. (Throughout this discussion, as well as in Table 4, the mechanical properties quoted are for sand cast test bars, unless otherwise noted. Properties of the castings themselves may be lower, depending on section size and process-design variables.)

Tensile strengths for cast test bars of aluminum bronzes and manganese bronzes range from 450 to 900 MPa (65–130 ksi), depending on composition; some aluminum bronzes attain maximum tensile strength only after heat treatment.

Although manganese and aluminum bronzes are often used for the same applications, the manganese bronzes are handled more easily in the foundry. As-cast tensile strengths as high as 800 MPa (115 ksi) and elongations of 15 to 20% can be obtained readily in sand castings; slightly higher values are possible in centrifugal castings. Stresses can be relieved at 175 to 200 °C (350–400 °F). Lead can be added to the lower-strength manganese bronzes to increase machinability, but at the expense of tensile strength and elongation. Lead content should not exceed 0.1% in high-strength manganese bronzes. Although manganese bronzes range in hardness from 125 to 250 HB, they are readily machined.

Tin is added to the low-strength manganese bronzes to enhance resistance to dezincification, but it should be limited to 0.1% in high-strength manganese bronzes unless sacrifices in strength and ductility can be accepted.

Manganese bronzes are specified for marine propellers and fittings, pinions, ball bearing races, worm wheels, gear shift forks, and architectural work. Manganese bronzes are also used for rolling mill screw-down nuts and slippers, bridge trunnions, gears, and bearings, all of which require high strength and hardness.

Various cast aluminum bronzes contain 9 to 14% Al and lesser amounts of iron, manganese, or nickel. They have a very narrow solidification range; therefore, they have a greater need for adequate gating and risering than do most other copper casting alloys and thus are more difficult to cast. A wide range of properties can be obtained with these alloys, especially after heat treatment, but close control of composition is necessary. Like the manganese bronzes, aluminum bronzes can develop tensile strengths well over 700 MPa (100 ksi).

Most aluminum bronzes contain from 0.75 to 4% Fe to refine grain structure and increase strength. Alloys containing from 8 to 9.5% Al cannot be heat treated unless other elements (such as nickel or manganese) in amounts over 2% are added as well. They have higher tensile strengths and greater ductility and toughness than any of the ordinary tin bronzes. Applications include valve nuts, cam bearings, impellers, hangers in pickling baths, agitators, crane gears, and connecting rods.

The heat treatable aluminum bronzes contain from 9.5 to 11.5% Al; they also contain iron, with or without nickel or manganese. These castings are quenched in water or oil from temperatures between 760 and 925 °C (1400 and 1700 °F) and tempered at 425 to 650 °C (800–1200 °F), depending on the exact composition and the required properties.

From the range of properties shown in Table 4, it can be seen that all the maximum properties cannot be obtained in any one aluminum bronze. In general, alloys with higher tensile strengths, yield strengths, and hardnesses have lower values of elongation. Typical applications of the higher-hardness alloys are rolling mill screwdown nuts and slippers, worm gears, bushings, slides, impellers, nonsparking tools, valves, and dies.

Aluminum bronzes resist corrosion in many substances, including pickling solutions. When corrosion occurs, it often proceeds by preferential attack of the aluminum-rich phases. Duplex $\alpha + \beta$ aluminum bronzes are more susceptible to preferential attack of the aluminum-rich phases than are the all-α aluminum bronzes.

Aluminum bronzes have fatigue limits that are considerably greater than those of manganese bronze or any other cast copper alloy. Unlike copper-zinc and Cu-Sn-Pb-Zn alloys, the mechanical properties of aluminum and manganese bronzes do not decrease with increases in

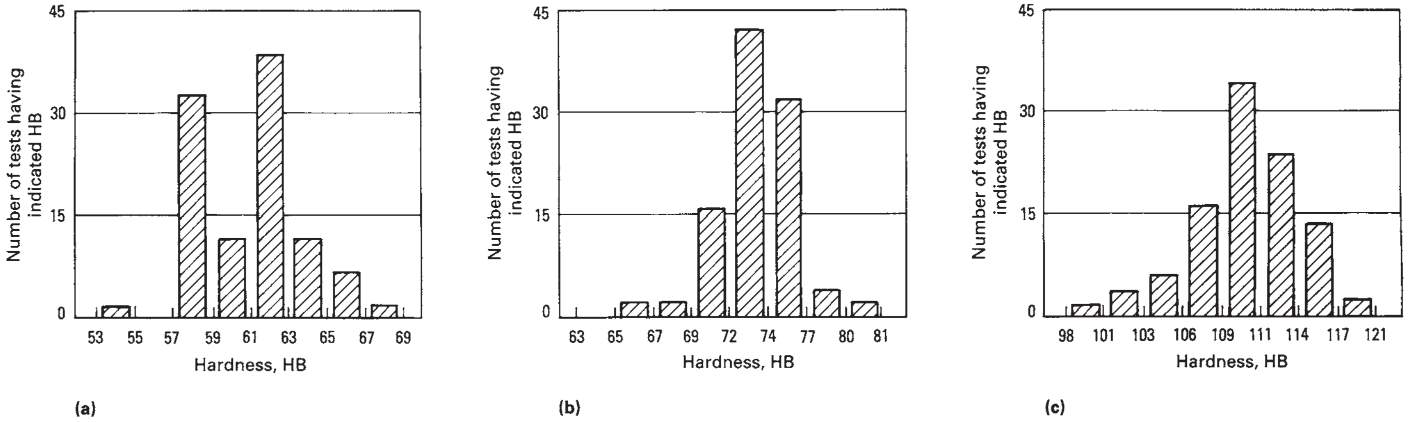

Fig. 1 Distribution of hardness over 100 tests for three copper casting alloys of different tensile strengths. (a) C83600. Tensile strength, 235–260 MPa (34–38 ksi); 500 kg (1100 lbf) load. (b) C90300. Tensile strength, 275–325 MPa (40–47 ksi); 500 kg (1100 lbf) load. (c) C87500. Tensile strength, 420–500 MPa (61–72 ksi); 1500 kg (3300 lbf) load

casting cross section. This is because these alloys have narrow freezing ranges, which result in denser structures when castings are properly designed and properly fed.

Whereas manganese bronzes experience hot shortness above 230 °C (450 °F), aluminum bronzes can be used at temperatures as high as 400 °C (750 °F) for short periods of time without an appreciable loss in strength. For example, a room-temperature tensile strength of 540 MPa (78 ksi) declines to 529 MPa (76.7 ksi) at 260 °C (500 °F), 460 MPa (67 ksi) at 400 °C (750 °F), and 400 MPa (58 ksi) at 540 °C (1000 °F). Corresponding elongation values change from 28% to 32, 35, and 25%, respectively.

Unlike manganese bronzes, many aluminum bronzes increase in yield strength and hardness but decrease in tensile strength and elongation upon slow cooling in the mold. Whereas some manganese bronzes precipitate a relatively soft phase during slow cooling, aluminum bronzes precipitate a hard constituent rather rapidly within the narrow temperature range of 565 to 480 °C (1050–900 °F). Therefore, large castings, or smaller castings that are cooled slowly, will have properties different from those of small castings cooled relatively rapidly. The same phenomenon occurs upon heat treating the hardenable aluminum bronzes. Cooling slowly through the critical temperature range after quenching, or tempering at temperatures within this range, will decrease elongation. An addition of 2 to 5% Ni greatly diminishes this effect.

Nickel brasses, silicon brasses, and silicon bronzes, although generally higher in strength than red metal alloys, are used more for their corrosion resistance.

Distributions of hardness and tensile strength data for separately cast test bars of three different alloys are shown in Fig. 1.

Properties of Test Bars. The mechanical properties of separately cast test bars often differ widely from those of production castings poured at the same time, particularly when the thickness of the casting differs markedly from that of the test bar.

The mechanical properties of tin bronzes are particularly affected by variations in casting section size. With increasing section sizes up to about 50 mm (2 in.), the mechanical properties—both strength and elongation—of the castings themselves are progressively lower than the corresponding properties of separately cast test bars. Elongation is particularly affected; for some tin bronzes, elongation of a 50 mm (2 in.) section may be as little as $^1/_{10}$ that of a 10 mm (0.4 in.) section or of a separately cast test bar.

The metallurgical behavior of many copper alloy systems is complex. The cooling rate (a function of casting section size) directly influences grain size, segregation, and interdendritic shrinkage; these factors, in turn, affect the mechanical properties of the cast metal. Therefore, molding and casting techniques are based on metallurgical characteristics as well as on casting shape.

Property Rankings. Tables 5 to 7 list copper casting alloys ranked by tensile strength, yield strength, and compressive strength, respectively. Unless otherwise noted, the data are typical for sand cast test specimens. An explanation of the temper designations given in Tables 5 to 7 can be found in the article "Standard Designations for Wrought and Cast Copper and Copper Alloys" in this Handbook.

Corrosion Resistance

In Table 8, the relative corrosion resistance in a wide variety of liquids and gases is given for 14 different classes of copper casting alloys. Certain generalizations can be drawn from an examination of these data. In many liquids, the yellow brasses do not have corrosion resistance as high as that of the other copper alloys. However, the high strength of the yellow brasses may make them more desirable even though some corrosion may be encountered. Corrosion of these alloys often takes place by dezincification; if this is a problem, alloys with copper contents of 80% or more must be selected.

Often, experience must be relied on for the proper selection of alloys. Laboratory tests are only guides because they fail to duplicate or approximate the conditions that will be encountered in service. When used in a "recommended" service application (see Table 8), copper metals generally give adequate service life. However, the table can only serve as a guide, and it should be used judiciously. Additional information on the corrosion of copper alloys is given in the articles "Corrosion Behavior" and "Stress-Corrosion Cracking" in this Handbook.

Atmospheric Corrosion. Copper alloy castings have been used for centuries for their superior resistance to atmospheric corrosion. Resistance is afforded by the formation of a coating or patina of basic copper sulfate, which ultimately reacts further to form some basic copper carbonate. The sulfate is virtually insoluble in water and thus affords good protection.

Liquid Corrosion. Copper alloy castings are widely used for their superior corrosion resistance in many liquid media. Their resistance to corrosion in liquids, like their resistance to atmospheric corrosion, is increased by the formation of a stable, adherent reaction product. If the coating is removed by chemical or mechanical means, corrosion resistance is reduced, and this reduction often is severe. Thus, rapid corrosion takes place in aerated mineral acids or under conditions of severe agitation, impingement, or high-velocity flow.

Copper metals are attacked by strong organic and inorganic acids and, to some extent, by weak organic acids. Although a copper metal may not visibly corrode, even a minute quantity of copper ions in the solution is not acceptable in certain applications. This is particularly true for food products, in which adverse color or taste can develop.

Ammonium hydroxide attacks all copper alloys severely, and these alloys are not recommended where ammonium ions may be formed. Copper metals are generally satisfactory for applications involving neutral organic compounds, including petroleum products, solvents, and animal and vegetable products. However, in the presence of moisture, certain of these materials may form acids, which in turn may attack a copper metal.

Table 4 Mechanical properties of copper casting alloys

	Tensile strength								Yield strength								Elongation, in 50 mm (2 in.), %				Hardness	
	As-cast (sand)				After heat treatment				As-cast (sand)				After heat treatment				As-cast (sand)		After heat treatment		As-cast (sand)	After heat treatment
	MPa		ksi		MPa		ksi		MPa		ksi		MPa		ksi							
UNS No.	Min	Typ	Min	Typ	Min	Typ	Min	Typ	Min	Typ	Min	Typ	Min	Typ	Min	Typ	Min	Typ	Min	Typ	Typ	Typ
C80100	130(a)	170	19(a)	25					45(a)(c)(d)	62(c)(d)	6.5(a)(c)(d)	9(c)(d)					20(a)	40			44(f)	
C80300	130	170	19	25					45(c)(d)	62(c)(d)	6.5(c)(d)	9(c)(d)					20	40			44(f)	
C80500	130	170	19	25					45(c)(d)	62(c)(d)	6.5(c)(d)	9(c)(d)					20	40			44(f)	
C80700	130	170	19	25					45(c)(d)	62(c)(d)	6.5(c)(d)	9(c)(d)					20	40			44(f)	
C80900	130	170	19	25					45(c)(d)	62(c)(d)	6.5(c)(d)	9(c)(d)					20	40			44(f)	
C81100	130	170	19	25					45(c)(d)	62(c)(d)	6.5(c)(d)	9(c)(d)					20	40			44(f)	
C81300					365(a)		53(a)						250(a)(d)		36(a)(d)			11(a)			89(f)	
C81400						365		53						250(d)		36(d)				11		B69(e)
C81500					310(a)	350	45(a)	51					240(a)(c)	275(c)	35(a)(c)	40(c)			12(a)	17		105(f)
C81700					585(a)	635	85(a)	92					425(a)(d)	470(d)	62(a)(d)	68(d)			5(a)	8		217(g)
C81800				50	620	705	90	102				25(d)	480(d)	515(d)	70(d)	75(d)		20	3	8	B55(e)	B96(e)
C82000				50	655	690	95	100				20(d)	480(d)	515(d)	70(d)	75(d)		20	3	8	B55(e)	B95(e)
C82100					585(a)	635	85(a)	92					425(a)(d)	470(d)	62(a)(d)	68(d)			5(a)	8		217(g)
C82200				57	620(a)	655	90(a)	95				30(d)	480(a)(d)	515(d)	70(a)(d)	75(d)		20	5(a)	8	B60(e)	B96(e)
C82400		495		72	1000	1035	145	150		255(d)		37(d)	930(d)	965(d)	135(d)	140(d)		20	0	1	B78(e)	C38(e)
C82500		550		80	1070	1105	155	160		310(d)		45(d)	795(d)		115(d)			20	0	1	B82(e)	C40(e)
C82600		565		82	1105	1140	160	165		325(d)		47(d)	1035(d)	1070(d)	150(d)	155(d)		20	0	1	B83(e)	C43(e)
C82700					1070		155						895(d)		130(d)				0			
C82800		670		97	1035	1140	150	165		380(d)		55(d)	760(d)	1000(d)	110(d)	145(d)		20	0	1	B85(e)	C45(e)
C83300		220		32						69(c)		10(c)						35			35(f)	
C83400		240		35						69(c)		10(c)						30			F50(e)	
C83600	205	255	30	37					95(c)	115(c)	14(c)	17(c)					20	30			60(f)	
C83800	205	240	30	35					90(c)	110(c)	13(c)	16(c)					20	25			60(f)	
C84200	195	240	28	35						95(c)		14(c)					15	27			60(f)	
C84400	200	235	29	34					90(c)	105(c)	13(c)	15(c)					18	26			55(f)	
C84500	200	240	29	35					90(c)	95(c)	13(c)	14(c)					16	28			55(f)	
C84800	195	250	28	36					85(c)	95(c)	12(c)	14(c)					16	30			55(f)	
C85200	240	260	35	38					85(c)	90(c)	12(c)	13(c)					25	35			45(f)	
C85400	205	235	30	34					75(c)	85(c)	11(c)	12(c)					20	35			50(f)	
C85500	380	415	55	60						160(c)		23(c)					25	40			B55(e)	
C85700	275	345	40	50					19(c)	125(c)	14(c)	18(c)					15	40			75(f)	
C85800		380(h)		55(h)						205(d)(h)		30(d)(h)						15(h)			B55(e)(h)	
C86100	620	655	90	95					310(c)(d)	345(c)(d)	45(c)(d)	50(c)(d)					18	20			180(g)	
C86200	620	655	90	95					310(d)	330(d)	45(d)	48(d)					18	20			180(g)	
C86300	760	795	110	115					415(c)	450(c)	60(c)	65(c)					12	15			225(g)	
									415(d)	570(d)	60(d)	83(d)										
C86400	415	450	60	65					140(c)(d)	170(c)(d)	20(c)(d)	25(c)(d)					15	20			90(f)	
																					105(g)	
C86500	450	490	65	71					170(c)(d)	195(c)(d)	25(c)(d)	28(c)(d)					20	30			100(f)	
C86700	550	585	80	85					220(c)	290(c)	32(c)	42(c)					15	20			B80(e)	
C86800	540	565	78	82					240(c)	260(c)	35(c)	38(c)					18	22			80(g)	
C87400	345	380	50	55					145(c)	165(c)	21(c)	24(c)					18	30			70(f)	
C87500	415	460	60	67					165(c)	205(c)	24(c)	30(c)					16	21			115(f)	
C87600	415	455	60	66					205(c)	220(c)	30(c)	32(c)					16	20			B76(e)	
C87800		585(h)		85(h)						345(d)(h)		50(d)(h)						25(h)			B85(e)(h)	
C87900		480(h)		70(h)						240(d)(h)		35(d)(h)						25(h)			B70(e)(h)	
C89510		205		30						125(c)		18(c)						12			55(f)	
C89520	170	205	25	30					125(c)	140(c)	18(c)	20(c)					6	10			54(f)	

(continued)

Min, minimum; Typ, typical. (a) Suggested value. (b) These values are not for heat treated material, but are values for centrifugal or permanent mold castings. (c) 0.5% extension under load. (d) 0.2% offset. (e) Rockwell hardness. (f) Brinell hardness, 500 kg. (g) Brinell hardness, 3000 kg. (h) Values are for die castings not sand castings. Source: Canadian Copper & Brass Development Association

Table 4 (continued)

	Tensile strength								Yield strength								Elongation, in 50 mm (2 in.), %				Hardness	
	As-cast (sand)				After heat treatment				As-cast (sand)				After heat treatment				As-cast (sand)		After heat treatment		As-cast (sand)	After heat treatment
	MPa		ksi		MPa		ksi		MPa		ksi		MPa		ksi							
UNS No.	Min	Typ	Min	Typ	Min	Typ	Min	Typ	Min	Typ	Min	Typ	Min	Typ	Min	Typ	Min	Typ	Min	Typ	Typ	Typ
C90200		260		38						110(c)		16(c)						30			70(f)	
C90300	275	310	40	45					125(c)	145(c)	18(c)	21(c)					20	30			70(f)	
C90500	275	310	40	45					125(c)	150(c)	18(c)	22(c)					20	25			75(f)	
C90700	240	305	35	44		380(b)		55(b)	125(c)	150(c)	18(c)	22(c)		205(b)(c)		30(b)(c)	10	20		16(b)	80(f)	102(b)(f)
C90900		275		40						140(c)		20(c)						15			90(f)	
C91000	205	220	30	32						170(c)		25(c)					1	2			105(f)	
C91100		240		35						170(c)		25(c)						2			135(g)	
C91300		240		35						205(c)		30(c)						0.5			170(g)	
C91600	240	305	35	44	310(b)	415(b)	45(b)	60(b)	115(c)	150(c)	17(c)	22(c)	170(b)(c)	220(b)(c)	25(b)(c)	32(b)(c)	10	16	10(b)	16(b)	85(f)	106(b)(f)
C91700	240	305	35	44	345(b)	415(b)	50(b)	60(b)	115(c)	150(c)	17(c)	22(c)	195(b)(c)	220(b)(c)	28(b)(c)	32(b)(c)	10	16	12(b)	16(b)	85(f)	106(b)(f)
C92200	235	275	34	40					110(c)	140(c)	16(c)	20(c)					24	30			65(f)	
C92300	250	275	36	40					110(c)	140(c)	16(c)	20(c)					18	25			70(f)	
C92500	240	305	35	44						140(c)		20(c)					10	20			80(f)	
C92600	275	305	40	44					125(c)	140(c)	18(c)	20(c)					20	30			F78(e)	
C92700	240	290	35	42						145(c)		21(c)					10	20			77(f)	
C92800		275		40						205(c)		30(c)						1			B80(e)	
C93200	205	240	30	35					95(c)	125(c)	14(c)	18(c)					15	20			65(f)	
C93400	170	220	25	32					85(c)	110(c)	12(c)	16(c)					8	20			60(f)	
C93500	195	220	28	32					85(c)	110(c)	12(c)	16(c)					15	20			60(f)	
C93700	205	240	30	35					85(c)	125(c)	12(c)	18(c)					15	20			60(f)	
C93800	180	205	26	30					95(c)	110(c)	14(c)	16(c)					12	18			55(f)	
C93900	170	220	25	32					110(c)	150(c)	16(c)	22(c)					5	7			63(f)	
C94300	165	185	24	27						90(c)		13(c)					10	15			48(f)	
C94400		220		32						110(c)		16(c)						18			55(f)	
C94500		170		25						85(c)		12(c)						12			50(f)	
C94700	310	345	45	50	515	585	75	85	140(c)	160(c)	20(c)	23(c)	345(c)	415(c)	50(c)	60(c)	25	35	5	10	85(f)	180(g)
C94800	275	310	40	45		415		60	140(c)	160(c)	20(c)	23(c)		205(c)		30(c)	20	35		8	80(f)	120(f)
C95200	450	550	65	80					170(c)	185(c)	25(c)	27(c)					20	35			125(g)	
C95300	450	515	65	75	550	585	80	85	170(c)	185(c)	25(c)	27(c)	275(c)	290(c)	40(c)	42(c)	20	25	12	15	140(g)	174(g)
C95400	515	585	75	85	620	725	90	105	205(c)	240(c)	30(c)	35(c)	310(c)	370(c)	45(c)	54(c)	12	18	6	8	170(g)	195(g)
C95500	620	690	90	100	760	825	110	120	275(c)	305(c)	40(c)	44(c)	415(c)	470(c)	60(c)	68(c)	6	12	5	10	195(g)	230(g)
C95600	415	515	60	75					195(c)	235(c)	28(c)	34(c)					10	18			140(g)	
C95700	620	655	90	95					275(c)	310(c)	40(c)	45(c)					20	26			180(g)	
C95800	585	655	85	95					240(c)	260(c)	35(c)	38(c)					15	25			159(g)	
C96200	310		45						170(c)		25(c)						20					
C96300	515		75						380(c)		55(c)						10				150(f)	
C96400	415	470	60	68					220(c)	255(c)	32(c)	37(c)					20	28			140(g)	
C96600						760		110		480(d)		70(d)								7		230(g)
C97300	205	240	30	35					105(c)	115(c)	15(c)	17(c)					8	20			55(f)	
C97400	205	260	30	38					110(c)	115(c)	16(c)	17(c)					8	20			70(f)	
C97600	275	310	40	45					115(c)	165(c)	17(c)	24(c)					10	20			80(f)	
C97800	345	380	50	55					150(c)	205(c)	22(c)	30(c)					10	15			130(g)	
C99300		655		95						380(c)		55(c)						2			200(g)	
C99400	415	455	60	66		545		79	205(c)	235(c)	30(c)	34(c)		370(c)		54(c)	20	25	14.1	17.6	125(g)	170(g)
C99500	480		70			595		86	275(c)		40(c)			425(c)		62(c)	12			8	145(f)	196(f)
C99700		380		55						170(c)		25(c)						25			110(g)	

Min, minimum; Typ, typical. (a) Suggested value. (b) These values are not for heat treated material, but are values for centrifugal or permanent mold castings. (c) 0.5% extension under load. (d) 0.2% offset. (e) Rockwell hardness. (f) Brinell hardness, 500 kg. (g) Brinell hardness, 3000 kg. (h) Values are for die castings not sand castings. Source: Canadian Copper & Brass Development Association

Table 5 Copper casting alloys ranked by typical tensile strength

UNS No.	Casting process(a)	Temper	Tensile strength MPa	Tensile strength ksi
C82600, C82800	S	TF00	1138	165
C82500	S	TF00	1103	160
C82400	S	TF00	1068	155
C82800	S	O11	862	125
C82500, C82600	S	O11	827	120
C95500	S, CL	TQ50	827	120
C96600	S	TF00	827	120
C86300	S	M01	821	119
C95400	S, CL	TQ50	724	105
C95410	S	TQ50	724	105
C82400	S	O11	690	100
C95500	S, CL	M01, M02	690	100
C82000	S	TF00	662	96
C82200	S	TF00	655	95
C86100	S	M01	655	95
C86200	S, CL, C	M01, M02, M07	655	95
C95700, C99300	S	M01	655	95
C95800	S, CL	M01, M02	655	95
C99500	S	TF00	593	86
C86700, C95410	S	M01	586	85
C87800	D	M04	586	85
C94700	S, C	TX00	586	85
C95300	S, CL, C	TQ50	586	85
C95400	S, CL	M01, M02	586	85
C86800	S	M01	565	82
C82600, C82800	S	M01	552	80
C82800	S	TB00	552	80
C95200	S, CL	M01, M02	552	80
C99400	S	TF00	545	79
C82500, C95600	S	M01	517	75
C95300	S, CL	M01, M02	517	75
C96600	S	TB00	517	75
C99750	S	TQ50	517	75
C86500	S, CL	M01, M02	490	71
C82600	S	TB00	483	70
C96400	S	M01	469	68
C87500	S, CL	M01, M02	462	67
C87600, C99400	S	M01	455	66
C82000, C82200	S	O11	448	65
C86400, C99750	S	M01	448	65
C99700	D	M04	448	65
C82400, C82500	S	TB00	414	60
C85500	S	M01	414	60
C91600, C91700	CL, PM	M02, M05	414	60
C94800	S	TX00	414	60
C85800	D	M04	379	55
C87300, C87400	S, CL	M01, M02	379	55
C90700	CL, PM	M02, M05	379	55
C97800, C99700	S	M01	379	55
C81400	S	TF00	365	53
C81500	S	TF00	352	51
C82000, C82200	S	M01	345	50
C85700	S, CL	M01, M02	345	50
C94700	S, C	M01, M07	345	50
C82000	S	TB00	324	47
C92900	S, PM, C	M01, M05, M07	324	47
C82200	S	TB00	310	45
C90300	S, CL	M01, M02	310	45
C90500	S, CL	M01, M02	310	45
C94800	S, C	M01, M07	310	45
C97600	S	M01	310	45
C90700, C92500	S	M01	303	44
C91600, C91700, C92600	S	M01	303	44
C92700	S	M01	290	42
C90900, C92800	S	M01	276	40
C92200, C92300	S, CL	M01, M02	276	40
C85200	S, CL	M01, M02	262	38
C90200, C97400	S	M01	262	38
C83600	S, CL	M01, M02	255	37
C84800	S	M01	255	37
C83400, C84200, C84500, C91100, C91300, C97300	S	M01	241	35
C83800, C93200, C93700	S, CL	M01, M02	241	35
C84400	S	M01	234	34
C85400	S, CL	M01, M02	234	34
C93800	CL	M02	228	33
C83300, C91000, C93400	S	M01	221	32
C93500	S, CL	M01, M02	221	32
C93900	C	M07	221	32
C94400	S	M01	221	32
C81400	S	M01	207	30
C93800	S, CL	M01, M02	207	30
C94300	S	M01	186	27
C80100, C81100, C94500	S	M01	172	25

(a) Casting processes: S, sand; D, die; C, continuous, I, investment; CL, centrifugal; P, plaster; PM, permanent mold. Source: Copper Development Association Inc.

Table 6 Copper casting alloys ranked by typical yield strength

UNS No.	Temper	Yield strength MPa	Yield strength ksi
0.2% offset			
C82600, C82800	TF00	1069	155
C82500	TF00	1034	150
C82400	TF00	1000	145
C82800	O11	758	110
C82500, C82600	O11	724	105
C82400	O11	551	80
C82000, C82200	TF00	517	75
C86300	M01	462	67
C82600, C82800, C86100, C87800	M01	345	50
C86200	M01	331	48
C82200	O11	276	40
C82500	M01	276	40
C99750	TF00	276	40
C82000	O11	255	37
C81400	TF00	248	36
C82800	TB00	241	35
C82600	TB00	207	30
C85800	M04	207	30
C86500	M01	193	28
C82500	TB00	172	25
C82200, C86400	M01	172	25
C82000	M01	138	20
C82400	TB00	138	20
C93700	M01	110	16
C82000	TB00	103	15
C81400	M01	83	12
C82200	TB00	83	12
0.5% extension			
C96600	TF00	517	75
C95500	TQ50	469	68
C99500	TF00	427	62
C94700	TX00	414	60
C99300	M01	379	55
C95400, C95410	TQ50	372	54
C99400	TF00	372	54
C95700	M01	310	45
C95500	M01	303	44
C86700	M01	290	42
C95300	TQ50	290	42
C81500	TF00	276	40
C99750	TQ50	276	40
C86800, C95800	M01	262	38
C96600	TB00	262	38
C96400	M01	255	37
C95400, C95410	M01	241	35
C95600, C99400	M01	234	34
C87600, C99750	M01	221	32
C91600, C91700	M02, M05	221	32
C95400	M07	221	32
C87500, C91300, C92800, C97800	M01	207	30
C90700	M02, M05	207	30
C94800	TX00	207	30
C86500	M01	200	29
C95200, C95300	M01	186	27
C99700	M04	186	27
C92900	M01	179	26
C87300, C91000, C91100, C99700	M01	172	25
C87400, C97600	M01	165	24
C85500, C94700, C94800	M01	159	23
C90500, C90700, C91600, C91700	M01	152	22
C93900	M07	152	22
C90300, C92700	M01	145	21
C90900, C92200, C92300, C92500, C92600	M01	138	20
C93800	M02	138	20
C85700, C93200, C93700	M01	124	18
C83600, C97300, C97400	M01	117	17
C83800, C90200, C93400, C93500, C93800, C94400	M01	110	16
C84400	M01	103	15
C84200, C84500, C84800	M01	97	14
C85200, C94300	M01	90	13
C85400, C94500	M01	83	12
C83300, C83400	M01	69	10
C80100, C81100	M01	62	9

Source: Copper Development Association Inc.

Table 7 Copper casting alloys ranked by compressive strength

UNS No.	Temper	Compressive strength(a) MPa	Compressive strength(a) ksi
0.1% set			
C86300	M01	414	60
C86100, C86200	M01	345	50
C95300	TQ50	241	35
C99750	M01	193	28
C87500, C95200	M01	186	27
C86500	M01	166	24
C86400	M01	152	22
C95300	M01	138	20
C93800	M02	131	19
C87300	M01	124	18
C92200	M01	103	15
C83600	M01	97	14
C84500, C90300, C93500, C93700	M01	90	13
C83800, C92600, C93800	M01	83	12
C94300	M01	76	11
C92300	M01	69	10
C85200, C85400	M01	62	9
1% set			
C90500	M01	276	40
C99750	M01	262	38
C97600	M01	207	30
C86300	M01	241	30
C95300	TQ50	241	35
C92200, C95300	M01	138	20
C84500	M01	110	16
10% set			
C95500	TQ50	1034	150
C95700	M01	1034	150
C95400, C95410	TQ50	827	120
C95500	M01	827	120
C95400, C95410, C95800	M01	690	100
C86300	M01	669	97
C95300	TQ50	621	90
C86400	M01	600	87
C95300	M01	572	83
C86500	M01	545	79
C87500	M01	517	75
C99750	M01	496	72
C95200	M01	483	70
C87300, C87600	M01	414	60
C97600	M01	393	57
C92900	M01	345	50
C93400	M01	331	48
C93700	M01	324	47
C93200	M01	317	46
C94400	M01	303	44
C92600	M01	276	40
C83600, C92200, C93800	M01	262	38
C96200	M01	255	37
C94500	M01	248	36
C92300	M01	241	35
C84500, C84800	M01	234	34
C85200	M01	207	30
C83800	M01	200	29
C85400	M01	193	28
C94300	M01	159	23

(a) Stress required to produce the indicated percent permanent engineering strain (set) in a 3.2 mm (0.125 in.) thick compression specimen. Source: Copper Development Association Inc.

Table 8 Corrosion ratings of cast copper metals in various media

Ratings: A, recommended; B, acceptable; C, not recommended

Corrosive medium	Copper	Tin bronze	Leaded tin bronze	High-lead tin bronze	Leaded red brass	Leaded semired brass	Leaded yellow brass	Leaded high-strength yellow brass	High-strength yellow brass	Aluminum bronze	Leaded nickel brass	Leaded nickel bronze	Silicon bronze	Silicon brass
Acetate solvents	B	A	A	A	A	A	B	A	A	A	A	A	A	B
Acetic acid														
20%	A	C	B	C	B	C	C	C	C	A	C	A	A	B
50%	A	C	B	C	B	C	C	C	C	A	C	B	A	B
Glacial	A	A	A	C	A	C	C	C	C	A	B	B	A	A
Acetone	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Acetylene(a)	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Alcohols(b)	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Aluminum chloride	C	C	C	C	C	C	C	C	C	B	C	C	C	C
Aluminum sulfate	B	B	B	B	B	C	C	C	C	A	C	C	A	A
Ammonia, moist gas	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Ammonia, moisture-free	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Ammonium chloride	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Ammonium hydroxide	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Ammonium nitrate	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Ammonium sulfate	B	B	B	B	B	C	C	C	C	A	C	C	A	A
Aniline and aniline dyes	C	C	C	C	C	C	C	C	C	B	C	C	C	C
Asphalt	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Barium chloride	A	A	A	A	A	C	C	C	C	A	A	A	A	C
Barium sulfide	C	C	C	C	C	C	C	C	B	C	C	C	C	C
Beer(b)	A	A	B	B	B	C	C	C	A	A	C	A	A	B
Beet sugar syrup	A	A	B	B	B	A	A	A	B	A	A	A	B	B
Benzine	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Benzol	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Boric acid	A	A	A	A	A	A	A	B	A	A	A	A	A	A
Butane	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Calcium bisulfite	A	A	B	B	B	C	C	C	C	A	B	A	A	B
Calcium chloride, acid	B	B	B	B	B	B	C	C	C	A	C	C	A	C
Calcium chloride, alkaline	C	C	C	C	C	C	C	C	C	A	C	A	C	B
Calcium hydroxide	C	C	C	C	C	C	C	C	C	B	C	C	C	C
Calcium hypochlorite	C	C	B	B	B	C	C	C	C	B	C	C	C	C
Cane sugar syrups	A	A	B	A	B	A	A	A	A	A	A	A	A	B
Carbonated beverages(b)	A	C	C	C	C	C	C	C	C	A	C	C	A	C
Carbon dioxide, dry	A	A	A	A	A	A	A	A	A	A	A	A	A	A

(continued)

(a) Acetylene forms an explosive compound with copper when moist or when certain impurities are present and the gas is under pressure. Alloys containing less than 65% Cu are satisfactory under this use. When gas is not under pressure, other copper alloys are satisfactory. (b) Copper and copper alloys resist corrosion by most food products. Traces of copper may be dissolved and affect taste or color. In such cases, copper metals often are tin coated.

Table 8 (continued)

Corrosive medium	Copper	Tin bronze	Leaded tin bronze	High-lead tin bronze	Leaded red brass	Leaded semired brass	Leaded yellow brass	Leaded high-strength yellow brass	High-strength yellow brass	Aluminum bronze	Leaded nickel brass	Leaded nickel bronze	Silicon bronze	Silicon brass
Carbon dioxide, moist(b)	B	B	B	C	B	C	C	C	C	A	C	A	A	B
Carbon tetrachloride, dry	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Carbon tetrachloride, moist	B	B	B	B	B	B	B	B	B	B	B	A	A	A
Chlorine, dry	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Chlorine, moist	C	C	B	B	B	C	C	C	C	C	C	C	C	C
Chromic acid	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Citric acid	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Copper sulfate	B	A	A	A	A	C	C	C	C	B	B	B	A	A
Cottonseed oil(b)	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Creosote	B	B	B	B	B	C	C	C	C	A	B	B	B	B
Ethers	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Ethylene glycol	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Ferric chloride, sulfate	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Ferrous chloride, sulfate	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Formaldehyde	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Formic acid	A	A	A	A	A	B	B	B	B	A	B	B	B	C
Freon	A	A	A	A	A	A	A	A	A	A	A	A	A	B
Fuel oil	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Furfural	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Gasoline	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Gelatin(b)	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Glucose	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Glue	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Glycerin	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Hydrochloric or muriatic acid	C	C	C	C	C	C	C	C	C	B	C	C	C	C
Hydrofluoric acid	B	B	B	B	B	B	B	B	B	A	B	B	B	B
Hydrofluosilicic acid	B	B	B	B	B	C	C	C	C	B	C	C	B	C
Hydrogen	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Hydrogen peroxide	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Hydrogen sulfide, dry	C	C	C	C	C	C	C	C	C	B	C	C	B	C
Hydrogen sulfide, moist	C	C	C	C	C	C	C	C	C	B	C	C	C	C
Lacquers	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Lacquer thinners	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Lactic acid	A	A	A	A	A	C	C	C	C	A	C	C	A	C
Linseed oil	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Liquors														
Black	B	B	B	B	B	C	C	C	C	B	C	C	B	B
Green	C	C	C	C	C	C	C	C	C	B	C	C	C	B
White	C	C	C	C	C	C	C	C	C	A	C	C	C	B
Magnesium chloride	A	A	A	A	A	C	C	C	C	A	C	C	A	B
Magnesium hydroxide	B	B	B	B	B	B	B	B	B	A	B	B	B	B
Magnesium sulfate	A	A	A	A	B	C	C	C	C	A	C	B	A	B
Mercury and mercury salts	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Milk(b)	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Molasses(b)	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Natural gas	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Nickel chloride	A	A	A	A	A	C	C	C	C	B	C	C	A	C
Nickel sulfate	A	A	A	A	A	C	C	C	C	A	C	C	A	C
Nitric acid	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Oleic acid	A	A	B	B	B	C	C	C	C	A	C	A	A	B
Oxalic acid	A	A	B	B	B	C	C	C	C	A	C	A	A	B
Phosphoric acid	A	A	A	A	A	C	C	C	C	A	C	A	A	A
Picric acid	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Potassium chloride	A	A	A	A	A	C	C	C	C	A	C	C	A	C
Potassium cyanide	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Potassium hydroxide	C	C	C	C	C	C	C	C	C	A	C	C	C	C
Potassium sulfate	A	A	A	A	A	C	C	C	C	A	C	C	A	C
Propane gas	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Seawater	A	A	A	A	A	C	C	C	C	A	C	C	B	B
Soap solutions	A	A	A	A	B	C	C	C	C	A	C	C	A	C
Sodium bicarbonate	A	A	A	A	A	A	A	A	A	A	A	A	A	B
Sodium bisulfate	C	C	C	C	C	C	C	C	C	A	C	C	C	C
Sodium carbonate	C	A	A	A	A	C	C	C	C	A	C	C	C	A
Sodium chloride	A	A	A	A	A	B	C	C	C	A	C	C	A	C
Sodium cyanide	C	C	C	C	C	C	C	C	C	B	C	C	C	C
Sodium hydroxide	C	C	C	C	C	C	C	C	C	A	C	C	C	C

(continued)

(a) Acetylene forms an explosive compound with copper when moist or when certain impurities are present and the gas is under pressure. Alloys containing less than 65% Cu are satisfactory under this use. When gas is not under pressure, other copper alloys are satisfactory. (b) Copper and copper alloys resist corrosion by most food products. Traces of copper may be dissolved and affect taste or color. In such cases, copper metals often are tin coated.

Table 8 (continued)

Corrosive medium	Copper	Tin bronze	Leaded tin bronze	High-lead tin bronze	Leaded red brass	Leaded semired brass	Leaded yellow brass	Leaded high-strength yellow brass	High-strength yellow brass	Aluminum bronze	Leaded nickel brass	Leaded nickel bronze	Silicon bronze	Silicon brass
Sodium hypochlorite	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Sodium nitrate	B	B	B	B	B	B	B	B	B	A	B	B	A	A
Sodium peroxide	B	B	B	B	B	B	B	B	B	B	B	B	B	B
Sodium phosphate	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Sodium sulfate, silicate	A	A	B	B	B	B	C	C	C	A	C	C	A	B
Sodium sulfide, thiosulfate	C	C	C	C	C	C	C	C	C	B	C	C	C	C
Stearic acid	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Sulfur, solid	C	C	C	C	C	C	C	C	C	A	C	C	C	C
Sulfur chloride	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Sulfur dioxide, dry	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Sulfur dioxide, moist	A	A	A	B	B	C	C	C	C	A	C	C	A	B
Sulfur trioxide, dry	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Sulfuric acid														
78% or less	B	B	B	B	B	C	C	C	C	A	C	C	B	B
78–90%	C	C	C	C	C	C	C	C	C	B	C	C	C	C
90–95%	C	C	C	C	C	C	C	C	C	B	C	C	C	C
Fuming	C	C	C	C	C	C	C	C	C	A	C	C	C	C
Tannic acid	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Tartaric acid	B	A	A	A	A	A	A	A	A	A	A	A	A	A
Toluene	B	B	A	A	A	B	B	B	B	B	B	B	B	A
Trichlorethylene, dry	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Trichlorethylene, moist	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Turpentine	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Varnish	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Vinegar	A	A	B	B	B	C	C	C	C	B	C	C	A	B
Water, acid mine	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Water, condensate	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Water, potable	A	A	A	A	A	A	B	B	B	A	A	A	A	A
Whiskey(b)	A	A	C	C	C	C	C	C	C	A	C	C	A	C
Zinc chloride	C	C	C	C	C	C	C	C	C	B	C	C	B	C
Zinc sulfate	A	A	A	A	A	C	C	C	C	B	C	A	A	C

(a) Acetylene forms an explosive compound with copper when moist or when certain impurities are present and the gas is under pressure. Alloys containing less than 65% Cu are satisfactory under this use. When gas is not under pressure, other copper alloys are satisfactory. (b) Copper and copper alloys resist corrosion by most food products. Traces of copper may be dissolved and affect taste or color. In such cases, copper metals often are tin coated.

In aqueous solutions, attack is accelerated by dissolved oxygen and carbon dioxide. Thus, although copper alloys are widely used for plumbing goods, they are attacked by many natural waters, especially the very soft waters with high oxygen and carbon dioxide contents. In these waters, carbonic acid is formed, which prevents the development of a resistant layer or dissolves any previously formed layer. Dezincification of high-zinc alloys frequently results if they are used indiscriminately in freshwater service.

Electrical and Thermal Conductivity

Electrical and thermal conductivity of any casting will invariably be lower than for wrought metal of the same composition. Copper castings are used in the electrical industry for their current-carrying capacity, and they are used for water-cooled parts of melting and refining furnaces because of their high thermal conductivity. However, for a copper casting to be sound and have electrical or thermal conductivity of at least 85%, care must be taken in melting and casting. The ordinary deoxidizers (silicon, tin, zinc, aluminum, and phosphorus) cannot be used because small residual amounts lower electrical and thermal conductivity drastically. Calcium boride or lithium will help to produce sound castings with high conductivity.

Cast copper is soft and low in strength. Increased strength and hardness and good conductivity can be obtained with heat treated alloys containing silicon, cobalt, chromium, nickel, and beryllium in various combinations. These alloys, however, are expensive and less readily available than the standardized alloys. Table 9 presents some of the properties of these alloys after heat treatment. Tables 10 and 11 rank copper casting alloys according to their electrical and thermal conductivities, respectively.

Machinability

As a class, cast copper alloys are relatively easy to machine, compared with steels, and far easier to machine than stainless steels, nickel-base alloys, and titanium, their major competitors for corrosion-resistant products. Machinability ratings of copper castings can be separated into three groups:

- Leaded free-cutting copper castings with machinability ratings greater than about 70
- Intermediate machinable alloys with machinability ratings between about 30 and 70
- Difficult-to-machine alloys with machinability ratings below 30

The relative machinability of alloys belonging to the three groups is shown in Table 12. Additional information on machining of copper castings can be found in the article "Machining" in this Handbook.

Free-cutting alloys containing more than about 2% Pb are the easiest to machine. These alloys form small, fragmented machining chips that literally burst away from the cutting tool, generating very little heat and making possible the high machining speeds for which the free-cutting alloys are known. Tool wear is minimal, and surface finishes are generally excellent.

Highly machinable low-lead copper castings containing bismuth and selenium have also been developed. Like lead, bismuth is nearly insolu-

Table 9 Composition and typical properties of heat-treated copper casting alloys of high strength and conductivity

UNS No.	Nominal composition	Tensile strength		Yield strength		Elongation, %	Hardness	Electrical conductivity, % IACS
		MPa	ksi	MPa	ksi			
C81400	99Cu-0.8Cr-0.06Be	365	53	250	36	11	69 HRB	70
C81500	99Cu-1Cr	350	51	275	40	17	105 HB	85
C81800	97Cu-1.5Co-Ag-0.4Be	705	102	515	75	8	96 HRB	48
C82000	97Cu-2.5Co-0.5Be	660	96	515	75	6	96 HRB	48
C82200	98Cu-1.5Ni-0.5Be	655	95	515	75	7	96 HRB	48
C82500	97Cu-2Be-0.5Co-0.3Si	1105	160	1035	150	1	43 HRC	20
C82800	96.6Cu-2.6Be-0.5Co-0.3Si	1140	165	1070	155	1	46 HRC	18

ble in copper and copper alloys and, also like lead, it causes machining chips to break up into small, easily removed particles. Selenium enhances the effect of bismuth in brasses; therefore, it reduces the amount of bismuth needed to achieve the desired improvement in machinability. Unlike lead-containing alloys, bismuth-selenium-containing alloys are not known to be toxic to humans.

Intermediate Machinable Alloys. Alloys of the second group contain two or more phases (the free-cutting alloys contain a single copper-rich phase plus lead). Generally, the secondary phases are harder or more brittle than the matrix. Examples include unleaded yellow brasses, manganese bronzes, silicon brasses and bronzes, and nickel silvers. These alloys form short, brittle, tightly curled chips that tend to break into manageable segments. Surface finishes can be quite good for multiphase alloys; however, cutting speeds will be lower and tool wear higher than with free-cutting grades.

Table 10 Copper casting alloys ranked by electrical conductivity

UNS No.	Electrical conductivity, %IACS at 20 °C (68 °F)
C80100	100
C81100	92
C81500	82
C81400	60
C82200	45
C82000	45
C83400	44
C83300	32
C85500	26
C82400	25
C85700, C86500	22
C82500, C85800	20
C82700	20
C85400	20
C86400	19
C82600	19
C82800, C85200	18
C86700	17
C84500	16
C84200, C84400, C84800	16
C93500	15
C83600, C83800	15
C92200	14
C90200, C95300, C95400, C95410	13
C92300, C93200, C93400, C94800, C99400	12
C90300	12
C90500, C92700	11
C93800, C93900	11
C95200, C96200	11
C93700	10
C91600, C91700, C94400, C94500, C99400	10
C99500	10
C90700	10
C91000	9
C92900, C94300	9
C86800, C92600, C99300	9
C91100, C95500, C95600	8
C86100, C86200	8
C86300	8
C95800	7
C91300	7
C87400, C87500, C87800	7
C96300	6
C87300, C87600	6
C97300	6
C97400	6
C97600	5
C96400	5
C97800	4
C96600	4
C95700	3
C99700	3
C99750	2

Source: Copper Development Association Inc.

Table 11 Copper casting alloys ranked by thermal conductivity

UNS No.	Thermal conductivity W/m · K at 293 K	Thermal conductivity Btu/ft^2/ft/h/°F at 68 °F
C80100	391	226
C81100	346	200
C81500	315	182
C81400, C82000	259	150
C83400	188	109
C82200	183	106
C82400	133	76.9
C82500, C82700	130	74.9
C82600	126	73.0
C82800	123	70.8
C85500	116	67.0
C86400	88.3	51.0
C85400	87.9	50.8
C86500	85.3	49.6
C85200, C85700, C85800	83.9	48.5
C90300, C90500, C92300	74.8	43.2
C83800, C84200, C84400	72.4	41.8
C83600, C84500, C84800	72.0	41.6
C90700, C91600, C91700	70.6	40.8
C93500	70.4	40.7
C92200	69.6	40.2
C95300	62.8	36.3
C94300	62.7	36.2
C90200	62.3	36.0
C95400, C95410	58.7	33.9
C92900, C93200, C93400	58.2	33.6
C94700	54.0	31.2
C93800, C93900, C94400, C94500	52.3	30.2
C95200	50.4	29.1
C92700	47.0	27.2
C93700	46.9	27.1
C96200	45.2	26.1
C99300	43.9	25.4
C95500	41.9	24.2
C94800, C95600	38.6	22.3
C96300	36.8	21.3
C95800	36.0	20.8
C86100, C86200, C86300	35.5	20.5
C96600	30.1	17.4
C97300	28.6	16.5
C96400	28.5	16.4
C87300, C87600	28.4	16.4
C87400, C87500, C87800	27.7	16.0
C97400	27.3	15.8
C97800	25.4	14.7
C97600	31.4	13.0
C95700	12.1	7.0

Source: Copper Development Association Inc.

Difficult-to-Machine Alloys. The third group is made up of the unleaded single-phase α alloys, which include high-conductivity coppers, high-copper alloys such as chromium copper and the beryllium coppers, tin bronzes, red brasses, aluminum bronzes, and copper nickels. The properties of the alloys range from soft and ductile to very strong and tough, which leads to some variation in machinability among members of this group. There is, however, a general tendency to form long, stringy chips that interfere with high-speed machining operations. In addition, pure copper and high-nickel alloys tend to weld to the tool face. This impairs surface finish.

Cost Considerations

During the design of a copper alloy casting, foundry personnel or the design engineer must choose a method of producing internal cavities. There is no general rule for choosing between cored and coreless designs. A cost analysis will determine which is the more economical method of producing the casting, although frequently the choice can be decided by past experience.

For example, costs were compared for producing a small (13 mm, or ½ in.) valve disk both

Table 12 Machinability ratings of copper casting alloys

Wrought aluminum alloy 2011-T3 and free-machining steel 12L14 are included for comparisons.

UNS No.	Machinability rating
Group 1 free-cutting alloys	
C83800, C84400, C84500, C84800	90
C89520	85
C83600	84
C84200, C85200, C85400, C85500, C85700, C85800, C93700, C93800, C93900, C94300, C94400, C94500, C99700, C99750	80
C89510	75
C92800, C93200, C93400, C93500, C97300, C97600	70
Group 2 intermediate machinable alloys	
C86400	65
C83400, C95400, C95410, C95600, C97400, C97800	60
C86700, C95300	55
C87400, C87500, C94800(a), C95500, C95700, C99400, C99500, 2011-T3(A1)	50
C92700	45
C92200, C92300	42
C87300, C87600, C87800, C92600, C92900, C94800(b)	40
C83300	35
C81700, C82000, C82200, C82400, C82500, C82600, C82700, C82800, C85300, C86100, C86200, C86800, C90300, C90500, C92500, C94700(a)	30
Difficult-to-machine alloys	
C86500	26
12L14 (Steel)	21
C81300, C81400, C81500, C81800, C90200, C90700, C90900, C91000, C91600, C91700, C94700(b), C95200, C95800, C96400, C96600, C99300	20
C96300	15
C80100, C81100, C91100, C91300, C96200	10
C86800, C86300	8

(a) M01 temper. (b) TF00 temper. Source: Copper Development Association Inc.

as a cored casting and as a machined casting (internal cavities made without cores). The machined casting could be produced for about 78% of the cost of making the identical casting using dry sand cores—a savings of 22% in favor of the machined casting. In a similar instance, producing a larger (38 mm, or 1 $\frac{1}{2}$ in.) valve disk as a cored casting that required only a minimal amount of machining saved more than 8% in overall cost compared to producing the same valve disk without cores. Thus, for two closely related parts, a difference in manufacturing economy may exist when all cost factors are taken into account.

Applications

Copper alloy castings are used in applications that require superior corrosion resistance, good bearing-surface qualities, high thermal or electrical conductivity, and other special properties. These applications may be divided into six principal groups:

- Plumbing hardware, pump parts, and valves and fittings
- Bearings and bushings
- Gears
- Marine castings
- Electrical components
- Architectural and ornamental parts

Figure 2 illustrates the wide variety of intricate shapes and sizes into which copper and its alloys are typically cast.

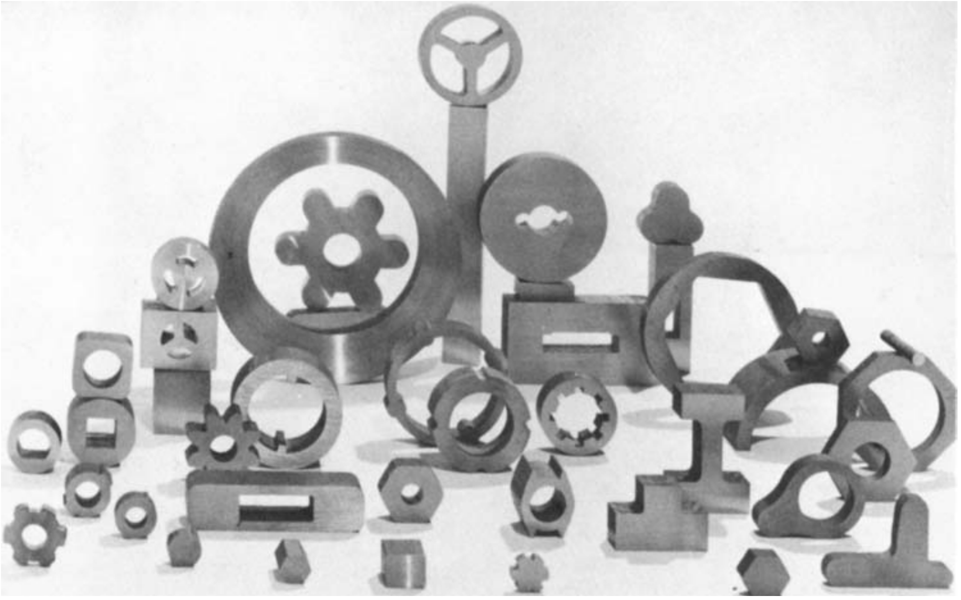

Fig. 2 Variety of intricate shapes and sizes obtained using continuous casting methods to produce brass and bronze alloy parts

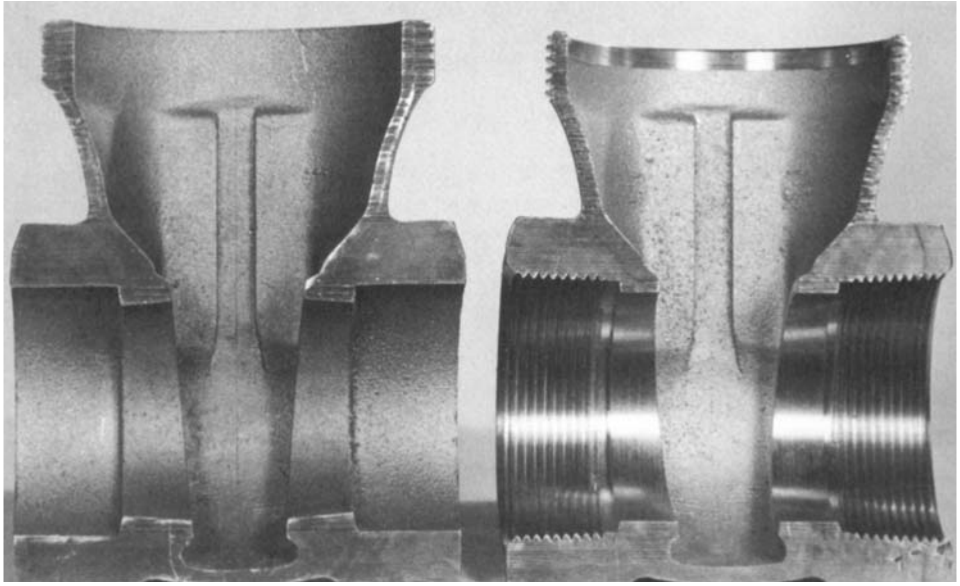

Fig. 3 Cutaway views of an as-cast and finish machined/threaded body of a 50 mm (2 in.) gate valve-union bonnet assembly rated at 1.0 MPa (150 psi). The body section was sand cast of C83600 alloy (Cu–5Sn–5Pb–5Zn composition) and weighs 2.4 kg (5.2 lb).

Plumbing Hardware, Pump Parts, Valves, and Fittings. The requirements for such fluid-handling components are pressure tightness to avoid leakage; reasonable mechanical strength at low, room, and high temperatures to avoid bursting; good corrosion resistance; and ease of machining. In addition, for a pleasing appearance, as in water fixtures, the parts must be easily platable.

Plumbing fixtures and pump parts for the waterworks industry are usually produced in red brasses and semired brasses (alloys C83300–C84800). Yellow brass (C85200) is sometimes used to cast plumbing fixtures. Similarly, pump parts are cast in silicon bronze (C87200).

A variety of alloys, however, are used to produce valves and fittings. These alloys are specified in ASTM B 763 (copper alloy sand castings for valve applications), and the list includes semired brasses, leaded semired brasses, silicon bronzes, silicon brasses, tin bronzes, leaded tin bronzes, high-leaded tin bronzes, nickel-tin bronzes, leaded nickel-tin bronzes, aluminum bronzes, leaded nickel bronzes, and so on.

Parts that do not require high strength are usually produced in red brasses, semired brasses, tin bronzes, and so forth, but when higher strength is required, the nickel-tin bronzes, high-strength yellow brasses, and so on, are preferred. For example, the valve stem in a control valve is cast in nickel-tin bronze (alloy C94700), whereas the facing is cast in alloy C83600 (Fig. 3).

Equipment for handling more corrosive fluids, such as crude oil and salt water encountered in the oil field industry, is different from that of the waterworks industry. The requirements are corrosion resistance, pressure tightness, and better mechanical properties. The aluminum bronzes are widely used in the oil field industry to meet these requirements. Similar specifications apply to valves used in hydroelectric generating plants (Fig. 4). One such example is the reciprocating pump, in which all areas exposed to the corrosive fluids being pumped are made of aluminum bronzes (C95300 or C95800). Check valves and diaphragm backs for use in oil wells and chemical-processing equipment are cast in nickel-tin bronze (C94700).

The requirements for pressure-tight valves and fittings for different gases are higher than those for liquids. Such components can still be produced in the semired brass (C83600). However, care must be exercised in the casting process to ensure that shrinkage porosity is avoided.

Pump parts, valves, and fittings are also produced for marine application (see the section "Marine Castings" below).

Bearings and Bushings. Copper alloys have long been used for bearings because of their combination of moderate-to-high strength, corrosion resistance, and either wear resistance or self-lubrication properties. The choice of an alloy depends on required corrosion resistance and fatigue strength, rigidity of backing material, lubrication, thicknesses of bearing material, load, speed of rotation, atmospheric conditions, and other factors. Copper alloys may be cast into plain bearings, cast on steel backs, cast on rolled strip, made into sintered powder metallurgy shapes, or pressed and sintered onto a backing material.

Three groups of alloys are used for bearings and wear-resistant applications:

- Phosphor bronzes (copper-tin)
- Copper-tin-lead (low-zinc) alloys
- Manganese, aluminum, and silicon bronzes

Some of these applications are described below.

Phosphor bronzes (Cu-Sn-P or Cu-Sn-Pb-P alloys) have residual phosphorus, ranging from a few hundredths of 1% (for deoxidation and slight hardening) to a maximum of 1%, which imparts great hardness. Often nickel is added to refine grain size and disperse the lead. Phosphor bronzes of higher tin content, such as C91100 and C91300, are used in bridge turntables, where loads are high and rotational movement is slow.

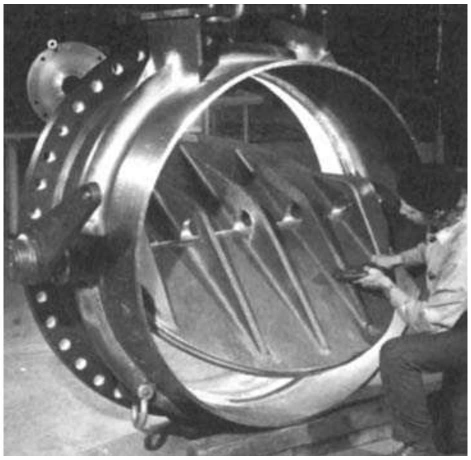

Fig. 4 A 1.37 m (54 in.) diam aluminum bronze stop valve for power-generation cooling loop applications using a centrifugally cast body and a sand cast disk assembly. Seating surface is cold-rolled plate welded to the valve body with aluminum bronze spooled wire.

Fig. 5 Centrifugally cast aluminum bronze worm gear blanks being inspected

High-leaded tin bronzes are used when a softer metal is required at slow-to-moderate speeds and at loads not exceeding 5.5 MPa (800 psi). Alloys of this type include C93200, C93500, C93700, and C94100. C93700 is widely used in machine tools, electrical and railroad equipment, steel mill machinery, and automotive applications. Alloys C93200 and C93500 are less costly than C93700 and are used chiefly for replacement bearings in machinery. Alloy C93800 (15% Pb) and C94300 (24% Pb) are used when high loads are encountered under conditions of poor or nonexistent lubrication; under corrosion conditions, such as in mining equipment (pumps and car bearings); or in dusty atmospheres, as in stone-crushing operations and cement plants. These alloys replace the tin bronzes or low-leaded tin bronzes when operating conditions are unsuitable for alloys containing little or no lead.

Aluminum bronzes with 8 to 9% Al are used widely for bushings and bearings in light-duty or high-speed machinery. Aluminum bronzes containing 11% Al, either as cast or heat treated, are suitable for heavy-duty service (such as valve guides, rolling mill bearings, nuts, and slippers) and precision machinery applications.

Gears. When gears are highly loaded and well lubricated the tin bronzes and nickel-tin bronzes are used. Specification ASTM B 427 (gear bronze alloy castings) gives the chemical compositions and mechanical properties of the five commonly used alloys—namely, C90700, C90800, C91600, C91700, and C92900. These are particularly advantageous when operating against hardened steel. It appears that the dispersion hardening of the δ phase in a solution-hardened matrix (by tin) provides the required strength. There is enough ductility to permit corrosion of minor misalignment with the hard steel mating part. Also, because of the dissimilarity of materials, no galling or scuffing is encountered.

When lubrication is irregular or omitted as in chemical applications, leaded materials are used. One such alloy is the leaded nickel-tin bronze containing Cu-20Pb-5Ni-5Sn. For gears exposed to harsh atmospheric conditions, manganese bronze (alloy C86500) has been successful.

Some typical applications are worm gears for rolling mills (alloy C91700), worm gears for oil well equipment (alloy C90700), and gearing of the stripper crane that removes the ingot from the ingot mold in the steel making industry (alloy C91700). Aluminum bronze is also used in worm gear applications (Fig. 5).

Marine Castings. The selection of materials for marine applications such as ship construction, desalination plants, and so forth, is governed by surrounding corrosive environments, which may include salt water, fresh water, or various corrosive cargoes such as oils, chemicals, and so on. Copper alloys generally give the greatest service life per dollar because of their excellent corrosion resistance in fresh water, salt water, alkaline solutions (except those containing ammonia), and many organic chemicals. The most commonly used alloys are the high-strength copper-nickels (both Cu-10Ni and Cu-30Ni, that is, alloys C96200 and C96400), aluminum bronzes (especially the nickel-aluminum bronze, alloy C95800, and Mn-Ni-Al bronzes, alloy C95700), and manganese bronzes (alloys C86100, C86200, C86400, C86500, and C86800). These are used in pump bodies, valves, tees, elbows, propellers (Fig. 6), propeller shafts, propeller hubs (Fig. 7), hull gear, impellers, turbines, and the like.

The most important alloys to cast propellers are the nickel-aluminum bronzes (C95800),

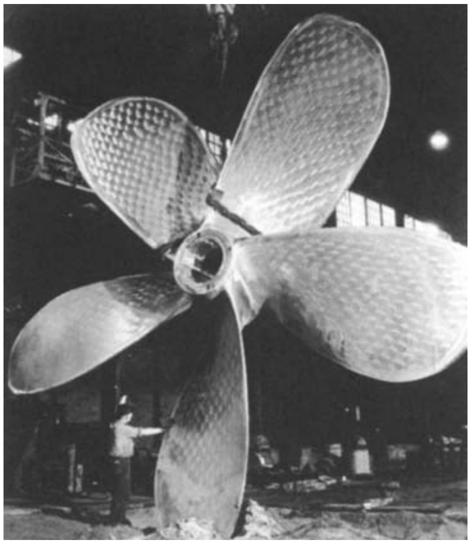

Fig. 6 Propeller for a 114,000 ton tanker measures 7.5 m (24.7 ft) in diameter and weighs 37.52 Mg (82,725 lb). Part was machined and polished from a single 53.75 Mg (118,500 lb) nickel-aluminum bronze casting.

Fig. 7 Vertical centrifugally cast ship propeller hub for controllable-pitch propeller blades is made of nickel-aluminum bronze, weighs 8.44 Mg (18,600 lb), and measures 1575 mm (62 in.) in diameter and 1270 mm (50 in.) in length.

Fig. 8 Twelve-foot-high bronze sand casting of the Great Seal of the United States located in lobby of the Federal Deposit Insurance Corporation building in Washington, D.C. Weight, 1.8 Mg (4000 lb)

Mn-Ni-Al bronzes (C95700), and manganese bronzes or high-strength yellow brasses (C86500). Manganese bronze propellers dezincify in salt water, and the aluminum bronzes should be preferred for such applications. Bearings for propellers and ship rudders, however, are produced in tin and leaded-tin bronzes such as alloys C90500 and C92200.

Electrical Components. Copper and copper alloys are used extensively in the electrical industry because of their current carrying capacity. They are used for substation, transformer, and pole hardware components for power transmission, plating and welding of electrical-equipment parts, and turbine runners for hydroelectric-power generation.

Cast copper is soft and low in strength. Increased strength and hardness and good conductivity can be obtained with heat treated alloys containing beryllium, nickel, chromium, and so on, in various combinations.

Pure copper and beryllium-copper are used to cast complex shapes for current conductors, often with water-cooled passages. Conductivity of the fittings is not important, the principal requirements being corrosion resistance and strength. Such fittings can be produced in leaded red brasses (alloys C83300 or C83600), heat treated nickel-tin bronze (alloy C94700), or manganese bronze (alloy C86500).

Beryllium-copper (alloy C82500) is also used to cast carriers for plating work and a variety of shapes and sizes for the welding industry.

Aluminum bronzes are the most important alloys for producing components for the hydroelectric-power generation plants because of their good corrosion resistance. Although parts have been produced from alloys C95200 and C95400, heat treated nickel-aluminum bronze (alloy C95800) and Mn-Ni-Al bronzes (alloy C95700) are the most useful because of their resistance to dealuminification.

Architectural and Ornamental Applications. The aesthetic applications of copper-base alloys in artistic, musical, and ornamental work are due to their excellent corrosion resistance, remarkable castability, and variety of colors. Bronze statues are cast in silicon bronze alloy (UNS C87200) because it has good fluidity and is free from pitting and corrosion, and the development of an adherent patina reduces the corrosion rate. Figure 8, a bronze casting that dominates the lobby of a federal building in Washington, D.C., shows the fine detail that can be produced using copper in ornamental applications. For this reason, yellow and leaded yellow brasses (alloys C85200, C85300, C85400, C85500, and C85700) are also used for a variety of internal and external hardware. Church bells are usually cast in copper-tin alloys containing about 19% Sn. These alloys contain a network of the brittle δ phase in the matrix, which reduces the damping capacity and produces a better tone.

A complete range of colors, from red to bronze and gold to silvery yellow and silver can be obtained by adjusting the composition. The artist can take advantage of these color combinations to produce ornamental castings such as door handles in red and semired brasses (C83600 and C84400), yellow and leaded yellow brasses, and nickel silvers (alloys C97300, C97400, C97600, and C97800).

ACKNOWLEDGMENTS

This article was adapted from:

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Powder Metallurgy Copper and Copper Alloys

COPPER AND COPPER-BASE POWDERS follow only iron and steel in volume of powder used in powder metallurgy (P/M) parts fabrication. Of the 25,240 short tons of copper or copper alloy powder shipped in North America, approximately 45% is used in the manufacture of self-lubricating bearings. Other important applications for copper and copper-base P/M materials include structural parts, electrical parts, friction materials, brushes, filters, additives to iron powders (alloying as well as infiltration), catalysts, paints, and pigments. Table 1 summarizes these and other applications for copper-base powder metals.

This article reviews the characteristics, properties, and applications of copper and copper-base P/M materials/parts. In general, physical properties and mechanical properties of near-full (theoretical) density copper and copper alloy P/M structural parts are comparable to cast and wrought copper-base materials of similar composition. However, P/M copper parts vary in density from the low density typical of self-lubricating bearings or filters to the near-full density of electrical parts. The physical and mechanical properties depend greatly on the density as a percentage of theoretical density.

The Powder Processing Route

Powder processing of copper and copper alloys, like that of other P/M systems, involves powder production, blending/mixing of additives such as die lubricants with the powder, and powder consolidation, for example, conventional (press and sinter) processing. As shown in Fig. 1, a number of secondary, or optional, operations can also be carried out.

Production of Copper Powders

Copper powders of 99+% purity are commercially available. The four major methods of producing such copper powders are:

- Atomization
- Oxide reduction
- Hydrometallurgy
- Electrolysis

Of these methods, atomization and oxide reduction are presently practiced on a large scale globally. Hydrometallurgical and electrolytic copper powders have not been manufactured in the United States since the early 1980s, but they are produced in Europe and Japan.

Table 2 shows a comparison of some of the typical fundamental powder characteristics of commercial copper powders made by the four production processes. Each process produces a unique particle shape and surface area. More detailed information on the powder production methods listed previously as well as relevant powder property data can be found in the article "Powder Metallurgy Processing" in this Handbook.

Production of Copper Alloy Powders

Alloy powders are available in various compositions, including brasses, nickel silvers, tin bronzes, aluminum bronzes, and beryllium bronzes. Alloy powders are produced by either (1) preblending copper powders with other elemental powders such as tin, zinc, or nickel or (2) prealloying during powder production.

Preblending. Preblended powders are mixtures of selected compositions, with or without lubricant, that form the desired alloy during sintering. The most common P/M copper alloy made with preblended powders is tin bronze used in self-lubricating bearings. Typical bronze composition is 90Cu-10Sn, often containing up to 1.5% graphite. Some "dilute" bronze bearings contain various amounts of iron replacing some of the copper and tin. Copper-lead and steel-backed Cu-Pb-Sn materials, used to replace solid bronze bearings, also use preblended powders because lead is virtually insoluble in copper and cannot be prealloyed. Friction materials used in brakes and clutches contain disparate materials such as copper with several other components including lead, tin, iron, graphite, molybdenum disulfide, oxides, and so forth. These can only be made by using preblended powders.

Prealloying. Prealloyed powders are generally produced by melting the constituents to form a homogeneous alloy and atomizing the alloy melt by the methods similar to those used for the production of copper powder. They can also be produced by sintering preblended powders and grinding the materials to attain the desired powder characteristics. Some typical commercial prealloyed powders are discussed subsequently.

Brass and Nickel Silver. Air atomization is generally used for making prealloyed powders of brass and nickel silver for use in high-density (>7.0 g/cm^3) components. The low surface tension of the molten alloys of these compositions renders the particle shape sufficiently irregular to make the powders compactible. Reduction of oxides is not necessary for the standard P/M grades of brass and nickel silver powders.

Commercial prealloyed brass and nickel silver powders are available in leaded and nonleaded compositions. Commercial brass alloys range from 90Cu-10Zn to 65Cu-35Zn. Leaded versions of 80Cu-20Zn and 70Cu-30Zn are most commonly used for the manufacture of sintered structural parts that may require secondary machining operations. The only commercially available nickel silver powder has a nominal composition of 65Cu-18Ni-17Zn, which is modified by addition of lead when improved machinability is required.

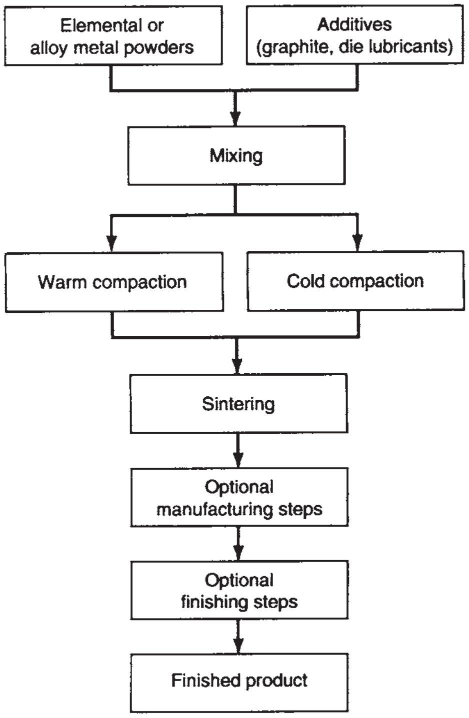


Fig. 1 Conventional press-and-sinter processing sequence for fabricating copper-base P/M materials

Table 1 Applications of copper-base powders

Application	Powder type
Automotive and machinery	
Bearings and bushings	Bronze, copper-lead, and copper-lead-tin
Brake bands and linings	Copper, brass, copper-lead, copper-lead-tin
Bushings	Bronze
Control panels/instruments	Nickel-silver
Counterweights	Copper-tungsten
Chemical and industrial	
Chemical catalyst	Copper
Filters	Bronze
Flame arrestors	Bronze
Fungicide additive	Copper
Soil conditioning	Copper
Valves and pumps	Copper-nickel
Coatings and paints	
Antifouling paints	Copper
Conductive paints and plastics	Copper and brass
Decorative paints	Copper, brass, bronze
Lacquers	Brass, bronze
Mechanical (peen) plating	Copper, brass
Spray coating	Copper, brass
Vacuum metallizing	Copper
Construction hardware	
Conductive and nonsparking floors	Copper
Decorative plastics	Copper, bronze, and brass
Domestic water filters	Brass
Locks and keys	Brass, bronze
Nuts	Brass
Pipe joint compounds	Copper
Electrical and electronic	
Brushes	Copper
Brush holders	Nickel-silver
Contacts	ODS Copper
Electrical and electronic	
Heatsinks	Copper
Printed circuits	Copper
Semiconductor stud bases	Copper, dispersion-strengthened copper
Telephone components	Brass, bronze
Switch and contactor components	Copper, brass
Incandescent lamps	ODS Copper
X-ray, microwave tube parts	ODS Copper
Lubricants	
Antigalling pipe joint compounds	Copper
Copper lubricants	Copper
Plastic-filled metal	Copper, bronze
Self-lubricating (oil-filled) parts	Bronze
Manufacturing and machining	
Abrasive wheel bonding	Copper
Brazing compounds	Copper, bronze, brass
Electrodischarge machining	Copper
Eletrochemical machining	Copper
Resistance welding electrodes	Copper, dispersion-strengthened copper
Ordnance	
Armor-piercing cores	Copper
Fuse parts	Brass
Projectile rotating bands	Copper, brass
Other equipment or uses	
Business machines	Brass
Coins, metals, medallions	Copper-nickel
Cordless devices	Copper
Fingernail polish	Copper
Lawn and garden equipment	Bronze
Photographic equipment	Bronze, brass, nickel-silver

Table 2 Characteristics of commercial copper powders

	Composition, %				
Type of powder	Copper	Oxygen	Acid insolubles	Particle shape	Surface area
Electrolytic	99.1–99.8	0.1–0.8	0.03 max	Dendritic	Medium to high
Oxide reduced	99.3–99.6	0.2–0.6	0.03–0.1	Irregular; porous	Medium
Water atomized	99.3–99.7	0.1–0.3	0.01–0.03	Irregular to spherical; solid	Low
Hydrometallurgical	97–99.5	0.2–0.8	0.03–0.8	Irregular agglomerates	Very high

Bronze. Prealloyed bronze powders are not used widely for structural parts fabrication because their nodular particle form and high apparent density result in low green strength. However, blends of such powders with irregular copper powders and phosphorus-copper yield sintered parts with good mechanical properties. Table 3 shows typical properties of commercial grades of prealloyed brass, bronze, and nickel silver powders.

Powder Consolidation

Compaction. The consolidation of copper or copper alloy powder is usually performed in a closed die although other means such as roll compaction, isostatic compaction, extrusion, or forging can be used. Different materials require different compacting pressures. For example, pure copper P/M parts are produced with relatively low pressures, for example, 205 to 250 MPa (15 to 18 tsi). The objective is to permit the escape of gases and water vapor formed by the internal reduction of oxides during subsequent sintering. Compacting pressures that are too high will prevent proper sintering of the center of the compact and reduce the electrical conductivity and the strength. Recommended pressures for various copper-base materials/parts are described subsequently and in the article "Powder Metallurgy Processing" in this Handbook.

Sintering. The compacted parts are sintered at elevated temperature and under protective conditions to avoid oxidation. During this process, the powder particles are metallurgically bonded to each other. Typical sintering times and temperatures are also listed subsequently and described in the article "Powder Metallurgy Processing" in this Handbook.

Secondary Operations

A variety of secondary manufacturing and finishing operations may be required to complete the part, to improve properties, or to calibrate dimensional tolerances. Examples include sizing, repressing, coining, oil impregnation, machining, plating, deburring, and joining.

Pure Copper P/M Parts

Pure copper P/M parts are used mainly in electrical and electronic applications because of their high electrical conductivity. It is essential to use very pure copper powders (≥99.95% purity) or to bring about the precipitation of soluble impurities during sintering. As little as 0.023% Fe in solid solution in copper lowers its conductivity to 86% of that of pure copper. Small amounts of iron mechanically mixed with the copper powder lower the conductivity much less, unless the iron dissolves in the copper during sintering. If high-purity copper is used, or if soluble impurities are precipitated during sintering, it is possible to obtain the strength and conductivity values shown in Fig. 2.

Conductivity is directly related to porosity; the greater the void content (lower the density), the lower the conductivity. Electrical conductivity of pure copper parts pressed at moderate pressures of 205 to 250 MPa (15 to 18 tsi) and sintered at 800 to 900 °C (1500 to 1650 °F) varies from 80 to 90% International Annealed Copper Standard (IACS) on a scale where conductivity of solid annealed copper is 100% IACS. the conductivity of solid copper can be reached or approached in P/M copper parts by sintering the pressed parts at higher temperatures, such as 930 to 1030 °C (1700 to 1900 °F), followed by repressing, coining, or forging.

Typical applications of pure copper parts in which high electrical conductivity is required include commutator rings, contacts, shading

Table 3 Physical properties of typical brass, bronze, and nickel silver alloy powders

Property	Brass(a)	Bronze(a)	Nickel silver(a)(b)
Sieve analysis, %			
+ 100 mesh	2.0 max	2.0 max	2.0 max
− 100 + 200	15–35	15–35	15–35
− 200 + 325	15–35	15–35	15–35
− 325	60 max	60 max	60 max
Physical properties			
Apparent density	3.0–3.2	3.3–3.5	3.0–3.2
Flow rate, s/50 g	24–26	…	…
Mechanical properties			
Green density(c) at 415 MPa (30 tsi), g/cm^3	7.6	7.4	7.6
Green strength(c) at 415 MPa (30 tsi), MPa (psi)	10–12 (1500–1700)	10–12 (1500–1700)	9.6–11 (1400–1600)

(a) Nominal mesh sizes, brass, −60 mesh; bronze, −60 mesh; nickel silver, −100 mesh. (b) Contains no lead. (c) Compressibility and green strength data of powders lubricated with 0.5% lithium stearate.

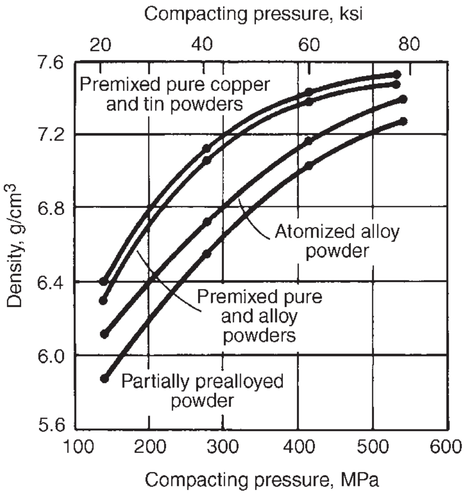


Fig. 3 Pressing characteristics of premixed and prealloyed 90Cu-10Sn powders. Source: Ref 2

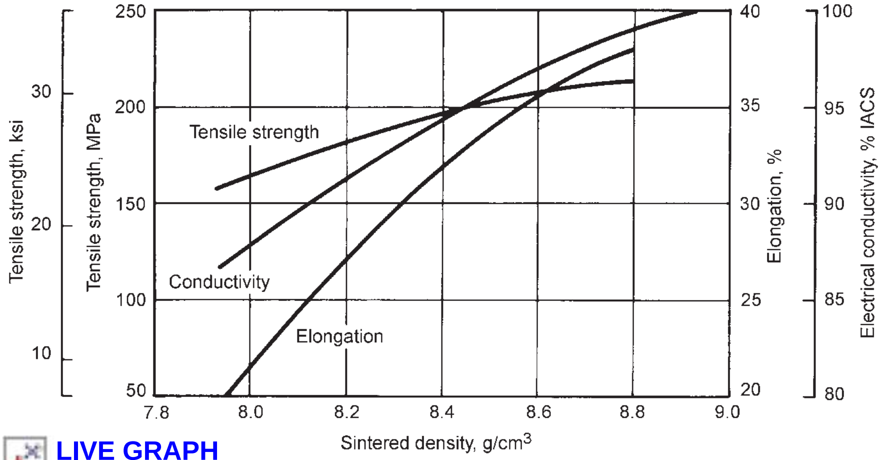


Fig. 2 Effect of density on electrical conductivity and tensile strength properties of P/M copper. Source: Ref 1

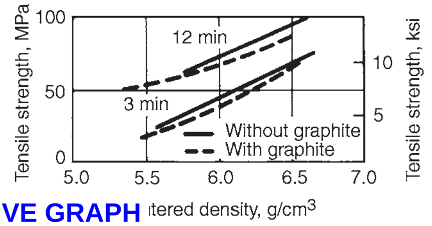


Fig. 4 Effect of density on the strength of copper-tin and copper-tin-graphite compacts. Source: Ref 3

coils, nose cones, and electrical twist-type plugs. Copper powders also are used in copper-graphite compositions that have low contact resistance, high current-carrying capacity, and high thermal conductivity. Typical applications include brushes for motors and generators and moving parts for rheostats, switches, and current-carrying washers.

Bronze P/M Parts

Powder metallurgy bronzes typically originate as premixes consisting of elemental copper and tin powders plus 0.5 to 0.75% dry organic lubricants such as stearic acid or zinc stearate. Some structural parts, however, requiring densities >7.0 g/cm^3 are fabricated from prealloyed powders. Prealloyed powders have higher yield strengths and work-hardening rates than premixed powders. Therefore, pressing loads required to achieve given green densities in prealloyed powders are higher than the pressures required for elemental powders. Differences in pressing characteristics of premixed and prealloyed powders are compared in Fig. 3.

Typical sintering furnace temperatures for bronze range from 815 to 870 °C (1500 to 1600 °F); total sintering time within the hot zone may range from 15 to 30 min, depending on the furnace temperature selected, required dimensional change, and most importantly, the presence of an optimal α bronze grain structure. Sintering atmospheres should be protective and reducing to facilitate sintering. Reduction of the copper oxides that may surround each copper powder particle and of tin oxide allow for increased diffusion rates. Typical strength/density data for 90Cu-10Sn sintered bronzes with and without graphite additions are shown in Fig. 4. Control of sintered dimensions in premix systems is achieved by manipulating sintering time and/or temperature.

Generally, copper-tin blends composed of relatively coarser powders sinter to higher growth values than a blend composed of finer powders. After powder blends have been tested and adjusted to provide an approximation of target dimensions, final adjustments are made during production sintering to obtain dimensional precision. Factors affecting the ultimate dimensional values include physical characteristics of the constituents and compacted density.

Bronze Self-Lubricating Bearings

Self-lubricating bearings are one of the oldest industrial applications of porous P/M parts, dating back to the mid-1920s. They remain the highest volume part produced by the P/M industry. The major advantage of porous bearings is that porosity in the bearing acts as an oil reservoir. The pores are filled with a lubricant that comprises about 25% of the material. Design considerations for self-lubricating bearings are outlined in Ref 4.

Mechanism of Lubrication. The function of a bearing is to guide a moving part with as little friction as possible. For sintered self-lubricating bearings this is accomplished by using the interconnected porosity of the bearing as an oil reservoir. Figure 5 shows schematically the mechanism of this type of lubrication for rotating shaft. As the shaft begins to rotate, metal-to-metal friction between the shaft and the bearing causes the temperature of the bearing assembly to rise. As a result, the oil contained in the pores of the bearing expands, and the oil wedge (that is, the space between the shaft and the bearing) is partially filled with oil.

Rotation of the shaft develops a so-called hydrodynamic pressure, *p*, within the oil film that with correct clearance, shaft velocity, and pore structure of the bearing is able to lift the shaft so that it rides on a liquid film of oil. This is known as hydrodynamic lubrication and is a condition of lowest friction. During operation, the oil that passes into the pores of the bearing is being recirculated to the unloaded region. With low shaft velocities and during startup, the hydrodynamic pressure is insufficient to separate shaft and bearing. This leads to so-called "mixed" or even to "boundary" lubrication with attendant friction increase, temperature rise, oil loss, wear, and reduced bearing life. When the

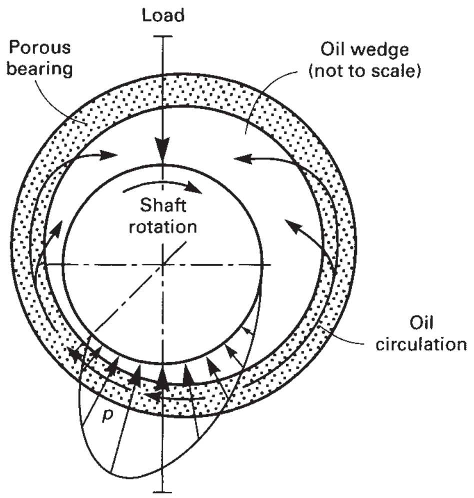


Fig. 5 Schematic of hydrodynamic pressure (*p*) and oil circulation in an oil-impregnated porous bearing

shaft ceases to rotate, the temperature of the assembly decreases and the oil within the oil wedge is drawn back into the porous bearing by capillary forces. Thus, the oil can be reused many times.

Uses. Every component that requires rotary motion relies on a bearing of some type. P/M self-lubricating bearings can be found in almost every part requiring rotary motion. Examples of the wide usage of P/M bearings include:

- *Automotive:* Heater motors, window lift motors, air conditioners, windshield wiper motors, power antenna motors, trunk-closing motors, seat adjuster motors, and tape deck motors
- *Portable power tools:* Drills, reciprocating saws, jigsaws, and sanders
- *Home appliances:* Washers, dryers, refrigerators, blenders, mixers, food processors, fans, and clocks
- *Consumer electronics:* Phonographs, high-fidelity equipment, stereo equipment, tape players, and video recorders
- *Business machines:* Typewriters, computers, and copiers
- *Farm and lawn equipment:* Tractors, combines, cotton pickers, lawn mowers, string cutters, and chain saws
- *Marine equipment:* Outboard motors

The most common shapes of self-lubricating bearings are shown in Fig. 6.

Bearing Compositions. The most widely used bearing material is 90Cu-10Sn with or without the addition of graphite. Sintered bronze bearings are covered in ASTM Standard B 438, "Standard Specification for Sintered Bronze Bearings (Oil Impregnated)" and in MPIF Standard 35, "Materials Standards for Structural Parts." Properties and compositions of sintered bronze bearings are given in Table 4.

So-called "diluted bronze" bearings contain various amounts of iron. Dilution with iron reduces the cost of the bearing at the expense of some loss in performance. Diluted bronze bearings are covered in ASTM Standard B 612, "Standard Specification for Iron Bronze Sintered Bearings (Oil Impregnated)" and MPIF Standard 35. Properties and compositions of sintered diluted bronze bearings are listed in Table 5.

Fig. 6 Typical bronze self-lubricating bearings. The most common shapes are simple or flanged bushings, but some have spherical external surfaces. Sizes range from about 0.8 to 75 mm ($\frac{1}{32}$ to 3 in.).

Copper is also a constituent is some iron-base bearing compositions. Copper contents range from 1.5 to 22%. Iron-copper-carbon bearings are covered in ASTM B 439, "Standard Specification for Iron-Base Sintered Bearings (Oil Impregnated) and MPIF Standard 35.

Mixing or blending of fine elemental powders normally is done in a double-cone blender. For bronze bearings, mixtures of electrolytic, reduced, or atomized copper powders, atomized tin powders, and natural graphite powders are used. The particle size distribution of the copper powder is 100% –100 mesh and between 40 to 70% –325 mesh. The tin powder is 95% –325 mesh. Both reduced and atomized iron powders are used for iron-base bearings. The powders are combined with a fine lubricant such as stearic acid, zinc stearate, or Acrawax (Glyco, Inc., Norwalk, CT). The lubricant, which burns off during sintering, acts as a die release.

Blending of elemental and/or prealloyed powders is done for a predetermined time to produce a homogeneous mixture of all components and to supply a mix that has a specific density, which is necessary for fixed-fill die cavities. Thorough mixing is required to achieve uniform strength, density, and dimensional control during sintering. The idea is to obtain uniform melting and diffusion of low melting constituents such as tin in bronzes or copper in iron-base alloys.

Compacting. The mix or preblend of raw materials is then transferred to a hopper, which is attached to a mechanical or hydraulic press. Loose powder flows by gravity (some vibration may be required) to the die cavity, where it is compacted to the desired shape and density. Compacting pressure for typical bearing compositions varies from 138 to 413 MPa (10 to 30 tsi). Depending on final dimensional accuracy, the green compact, or bearing, is molded 1 to 5% oversize to allow for material movement during sizing.

Sintering transforms the green bearing into a metallurgically bonded alloy. The green bearing, an elemental mixture of copper and tin, is transformed into a true α bronze alloy at a temperature that is below the melting point of copper but above the melting point of tin. Under these liquid-phase conditions, sintering occurs without an appreciable change in the size of the bearing.

Sintering temperature for bronze may vary from 830 to 900 °C (1525 to 1650 °F), depending on the time at temperature (normally 3 to 8 min) and the desired sintered size. Suitable bronze bearings have microstructures that are essentially α bronze as shown in Fig. 7. Diluted bronze bearings require sintering temperature of

870 to 980 °C (1600 to 1800 °F). The microstructure of a sintered diluted bronze P/M alloy is shown in Fig. 8.

Sizing. Most precision bearings require a sizing operation after sintering. Sizing is done in highly polished, dimensionally accurate tools. Sizing pressures range from 206 to 551 MPa (15 to 40 tsi), depending on the amount of sizing required and the composition of the sintered part. Sizing is done primarily to improve dimensions; however, it cannot be done effectively without increasing density.

Typical-sized inside diameter tolerances range from 0.0076 mm (0.0003 in.) for spherical bearings up o 16 mm (0.63 in.), with an overall length of up to 19 mm (0.8 in.). Straight-wall bearing inside diameter tolerances normally are 0.03 mm (0.001 in.) per 25 mm (1 in.) of diameter for lengths up to 38 mm (1.5 in.).

Impregnation. Powder metal bearings appear solid, but are actually 20 to 25% porous. This characteristic—porosity—makes parts made by P/M processing ideal bearing materials. Porosity consists of thousands of small capillaries that are interconnected throughout the structure of the bearing and act as a built-in reservoir for the lubricant. These pores can be filled with a lubricant that is sufficient for the life of the unit for most applications. However, for longer bearing life, oil-saturated felt or wicking can surround the bearing.

The pores are impregnated with oil normally under vacuum. Bearings are placed in the tank or autoclave, the lid is closed, and the vacuum pump is turned on. Pressure is reduced to at least 709 torr (28 in. Hg) before oil is permitted to flow over the bearings. Oil is introduced into the tank without shutting off the vacuum pump, and the tank, now filled with bearings and oil, is evacuated for another few minutes or until the pressure is again reduced to 709 torr (28 in. Hg).

After obtaining the desired vacuum, the vacuum pump is shut off, a valve is opened, and the oil is forced out of the impregnating tank to the storage reservoir. A properly impregnated bearing contains sufficient oil to fill 90% of the available interconnecting porosity or approximately 20 vol% oil (standard density 6.4 to 6.8 g/cm^3 bearing) and $2\frac{1}{2}$ to 3 wt% oil.

Table 4 MPIF specification for sintered bronze bearings

Material	Material description code	Strength constant (*K*), ksi	Oil content (P_0)(b), vol%	Minimum values(a)				
				Density (O_{wet}) (c), g/cm^3		Chemical composition, wt%		
				min	max	Element	min	max
Bronze (low graphite)	CT-1000-K19	19	24(d)	6.0	6.4	Copper	87.2	90.5
						Tin	9.5	10.5
						Graphite	0	0.3
						Other(e)	…	2.0
	CT-1000-K26	26	19	6.4	6.8	Copper	87.2	90.5
						Tin	9.5	10.5
						Graphite	0	0.3
						Other(e)	…	2.0
	CT-1000-K37	37	12	6.8	7.2	Copper	87.2	90.5
						Tin	9.5	10.5
						Graphite	0	0.3
						Other(e)	…	2.0
	CT-1000-K40	40	9	7.2	7.6	Copper	87.2	90.5
						Tin	9.5	10.5
						Graphite	0	0.3
						Other(e)	0	2.0
Bronze (medium graphite)	CTG-1001-K17	17	22(f)	6.0	6.4	Copper	85.7	90.0
						Tin	9.5	10.5
						Graphite	0.5	1.8
						Other(e)	…	2.0
	CTG-1001-K23	23	17	6.4	6.8	Copper	85.7	90.0
						Tin	9.5	10.5
						Graphite	0.5	1.8
						Other(e)	…	2.0
	CTG-1001-K33	33	9	6.8	7.2	Copper	85.7	90.0
						Tin	9.5	10.5
						Graphite	0.5	1.8
						Other(e)	…	2.0
	CTG-1001-K34	34	7	7.2	7.6	Copper	85.7	90.0
						Tin	9.5	10.5
						Graphite	0.5	1.8
						Other(e)	0	2.0
Bronze (high graphite)	CTG-1004-K10	10	11	5.8	6.2	Copper	82.5	87.5
						Tin	9.5	10.5
						Graphite	3.0	5.0
						Other(e)	…	2.0
	CTG-1004-K15	15	(g)	6.2	6.6	Copper	82.5	87.5
						Tin	9.5	10.5
						Graphite	3.0	5.0
						Other(e)	…	2.0

MPIF, Metal Powder Industries Federation. (a) These data are based on material in the finished condition. (b) Minimum oil content will decrease with increasing density. Those shown are valid at the upper limit of the density given. (c) Oil-impregnated. Assumes an oil density of 0.875 g/cm^3. (d) For oil content of 27% min, density range will be 5.8–6.2 g/cm^3, and *K* constant will be 105 MPa (15 ksi). (e) Iron 1 wt% max. (f) For oil content of 25% min, density range will be 5.8–6.2 g/cm^3 and *K* constant will be 90 MPa (13 ksi). (g) At maximum graphite (5%) and density (6.6 g/cm^3), this material will contain only a trace of oil. At 3% graphite and 6.2–6.6 g/cm^3 density, it may contain 3-10 vol% oil. Source: MPIF Standard 35

Porous Bronze Filters

Porous P/M parts are made from various types of metal powders depending on the particular application. The most commonly used powders include bronze, stainless steel, nickel and nickel-base alloys, titanium, and aluminum. Materials used less frequently include the refractory metals (tungsten, molybdenum, and tantalum) and the noble metals (silver, gold, and platinum).

Filters constitute one of the major applications of porous metals. The ability to achieve close control of porosity and pore size is the main reason metal powders are used in filter applications. Most producers of nonferrous filters prefer atomized spherical powder of closely controlled particle size to allow production of filters within the desired pore range. The effective pore size of filters generally ranges from 5 to 125 μm.

Tin bronze is the most widely used P/M filter material, but nickel silver, stainless steel, copper-tin-nickel alloys, and nickel-base alloys also are used. The major advantage of P/M bronze materials over other porous metals is cost. Figure 9 shows assorted product forms of bronze P/M filters.

Fabrication. Bronze filters usually are made by gravity sintering of spherical bronze powders, which are generally made from the atomization of molten prealloyed bronze (Fig. 10). These powders typically contain 90 to 92% Cu and 8 to 10% Sn. Filters made from atomized bronze have sintered densities ranging from 5.0 to 5.2 g/cm^3. To produce filters with the highest permeability for a given maximum pore size, powder particles of a uniform particle size must be used.

Although not widely used, coarser powders for bronze filters can be obtained by chopping copper wire and tumbling the choppings. Filters made from tin-coated cut copper wire with tin contents ranging from 2.5 to 8% are also used to a lesser extent (Fig. 11). Filters made from these materials have sintered densities ranging from 4.6 to 5.0 g/cm^3.

During sintering the filters shrink slightly—as much as 8%. To avoid excessive shrinkage, filters from powders with fine particle size require lower sintering temperatures in the neighborhood of 815 °C (1500 °F). Because of the shrinkage during sintering. Filters must be designed with a slight draft, so they can be removed from the mold.

Properties. Mechanical properties such as ductility, tensile strength, shear strength, collapse strength, burst strength, and fatigue life of porous materials are highly dependent on the porosity and the processing method (Ref 5). Table 6 illustrates typical values for tensile strength, elongation, and shear strength of 90% Cu/10% tin bronze discs as a function of density and filter grade as rated by the bubble-point method (Ref 6–8). Mechanical properties increase significantly as the pore size and the percentage of porosity decreases. Alternatively, permeability decreases as the pore size and the percentage of porosity decreases. Therefore, an optimal balance of

Table 5 MPIF specifications for diluted bronze sintered bearings

		Minimum values(a)							
		Strength constant (K), ksi			Density (D_{wet}) (b), g/cm^3		Chemical composition, wt%		
Material	Material description code	min	max	Oil content (P_0), vol%	min	max	Element	min	max
Iron/bronze 60/40, diluted bronze	FCTG-3604-K16	16	…	36	22	6.0	Iron	54.2	62.0
							Copper	34.0	38.0
							Tin	3.5	4.5
							Total carbon(c)	0.5	1.3
							Other	…	2.0
	FCTG-3604-K22	22	50	17	6.0	6.4	Iron	54.2	62.0
							Copper	34.0	38.0
							Tin	3.5	4.5
							Total carbon(c)	0.5	1.3
							Other	…	2.0
Iron/bronze 40/60, diluted bronze	CFTG-3806-K14	14	35	22	5.6	6.0	Iron	50.2	58.0
							Copper	36.0	40.0
							Tin	5.5	6.5
							Total carbon(c)	0.5	1.3
							Other	…	2.0
	CFTG-3806-K22	22	50	17	6.0	6.4	Iron	50.2	58.0
							Copper	36.0	40.0
							Tin	5.5	6.5
							Total carbon(c)	0.5	1.3
							Other	…	2.0

MPIF, Metal Powder Industries Federation. (a) These data are based on material in the finished condition. (b) Oil-impregnated. Assumes an oil density of 0.875 g/cm^3. (c) Metallurgical combined carbon, 0.5 wt% max. Source: MPIF Standard 35

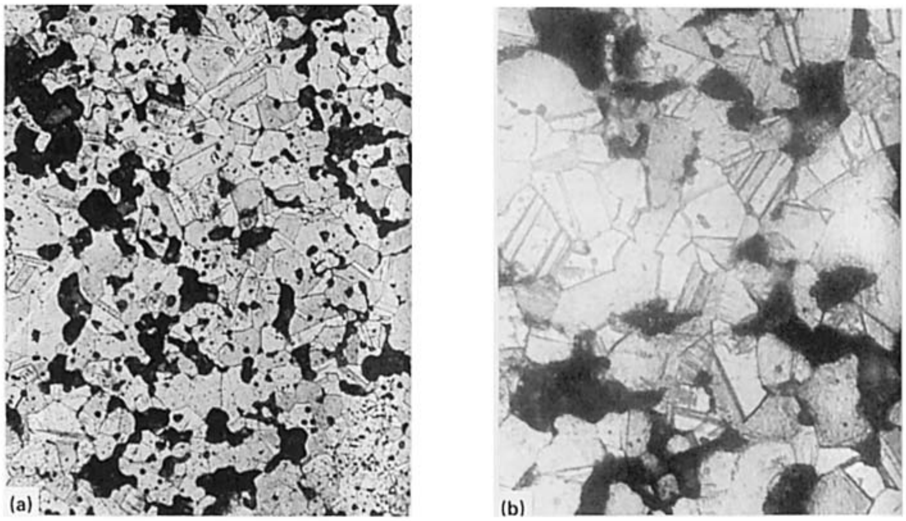


Fig. 7 Alpha bronze microstructure in 90%Cu-10%Sn P/M bearing alloy. (a) 150× (b) 300×

mechanical properties and permeability must be achieved to meet the application. Processing methods and materials can usually be selected to create a porous P/M material that meets the minimum mechanical properties and provides the maximum permeability. In some more severe applications involving high-pressure differentials, corrosive environments, and/or high-temperature service, mechanical properties are maximized at the expense of permeability in order to maximize service life. Enhanced mechanical properties also extend the number of cleaning and reuse cycles in some applications.

Other material properties such as thermal conductivity, thermal expansion, fatigue, electrical conductivity, and magnetic properties are also highly dependent on porosity and generally decrease as porosity increases (Ref 5).

Applications. Powder metallurgy bronze filters are used to filter gases, oils, refrigerants, and chemical solutions. They have been used in fluid systems of space vehicles to remove particles as small as 1 μm. Bronze diaphragms can be used to separate air from liquids or mixtures of liquids that are not emulsified. Only liquids capable of wetting the pore surface can pass through the porous metal part.

Bronze filter materials can be used as flame arrestors on electrical equipment operating in flammable atmospheres, where the high thermal conductivity of the bronze prevents ignition. They can also be used as vent pipes on tanks containing flammable liquids. In these applications, heat is conducted away rapidly so that the ignition temperature is not reached. Additional information on the manufacture, properties, performance characteristics, and applications of P/M bronze filters can be found in Ref 5.

Bronze Structural Parts

Powder metallurgy bronze parts for structural applications frequently are selected because of corrosion and wear resistance of bronze. They are generally produced by methods similar to those used for self-lubricating bearings. Typical compositions of bronze structural parts (CT-1000) are included in Table 7, and the typical properties are shown in Table 8.

Figure 12 shows an assortment of P/M bronze structural parts. These parts are generally used in automobile clutches, copiers, outboard motors, and paint-spraying equipment.

Brass and Nickel Silver P/M Parts

In contrast to bronze structural parts, parts made from brass, leaded brass, and nickel silver are produced from prealloyed atomized powder. Compositions of some common brass and nickel silver alloys used in structural parts are shown in Table 7. The leaded compositions are used whenever secondary machining operations are required.

The alloy powders are usually blended with lubricants in amounts from 0.5 to 1.0 wt%. Lithium stearate is the preferred lubricant because of its cleansing and scavenging action during sintering. However, bilubricant systems are common, such as lithium stearate and zinc stearate, which minimize the surface staining attributed to excessive lithium stearate. Lubricated powders are typically compacted to

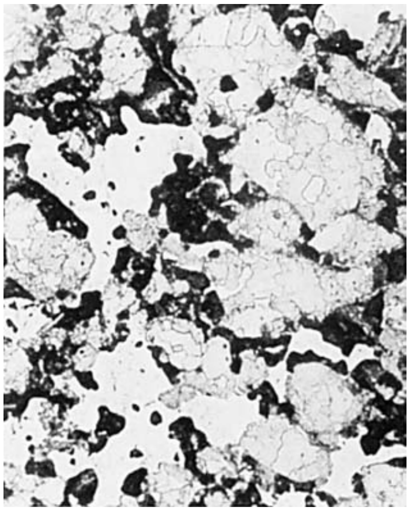


Fig. 8 Microstructure of diluted bronze P/M bearing material. This bearing grade has the unique feature of being bronze in appearance but lower in material cost. 150×

75% of theoretical density at 207 MPa (30 ksi) and to 85% of theoretical density at 415 MPa (60 ksi).

Sintering of brass and nickel silver compacts is normally performed in protective atmospheres. Dissociated ammonia, endothermic gas, and nitrogen-base atmospheres are most common. Temperatures range from 815 to 925 °C (1500 to 1700 °F) depending on alloy composition. To avoid distortion and/or blistering of the compacts, sintering temperatures should not exceed the solidus temperature of the alloy. Through multiple pressing and sintering operations, yield strength and hardness approaching those of the wrought alloy counterparts can be achieved. To minimize zinc losses during sintering, yet allow for adequate lubricant removal, protective-sintering-tray arrangements are used. Table 8 shows the typical properties of common brass and nickel silver P/M parts.

Next to bronze bearings, brasses and nickel silvers are the most widely used materials for structural P/M parts. Typical applications include hardware for latch bolts and cylinders for locks; shutter components for cameras; gears, cams, and actuator bars in timing assemblies and in small generator drive assemblies; and decorative trim and medallions. In many of these applications, corrosion resistance, wear resistance, and aesthetic appearance play important roles. Figure 13 shows some typical P/M brass components.

Copper-Nickel P/M Parts

Copper-nickel P/M alloys containing 75 Cu-25Ni and 90Cu-10Ni have been developed for coinage and corrosion-resistance applications. The 75Cu-25Ni alloy powder pressed at 772 MPa (112 ksi) has a green density 89% of its theoretical density. After sintering at 1090 °C (2000 °F) in dissociated ammonia, elongation is 14%, and apparent hardness is 20 HRB. Repressing at 772 MPa (112 ksi) increases density to 95%. This alloy has the color of stainless steel and can be burnished to a high luster. The 90Cu-10Ni alloy has a final density of 99.4% under similar pressing-and-sintering conditions. It has a bright bronze color and also can be burnished to a high luster.

Table 6 **Typical mechanical properties of bronze filters**

			Minimum ultimate tensile strength			Shear strength(c)	
Material(a)	Filter grade(b), μm	Density, %	MPa	ksi	Elongation, %	MPa	ksi
Bronze	10	75	48	7	8	130	18.8
	20	68	41	6	6	110	15.9
	40	62	35	5	4	100	14.5
	90	57	28	4	3	75	10.9
	150	54	21	3	2	40	5.8
	250	52	14	2	2	30	4.3

(a) For comparison purposes, wrought bronze (90% Cu/10% Sn) has a theoretical mean density of 8.8 g/cm^3 with a minimum UTS of 300 MPa (43 ksi) and 20% elongation. Data are for commercial bronze filter disks. (b) Filter grades in micrometers as estimated by bubble-point test method. See Ref 6–8. (c) Shear strength is the punching force divided by the sheared edge area per DIN standard V 30910 "Sintered Metal Materials, Part 2: Materials for Filters."

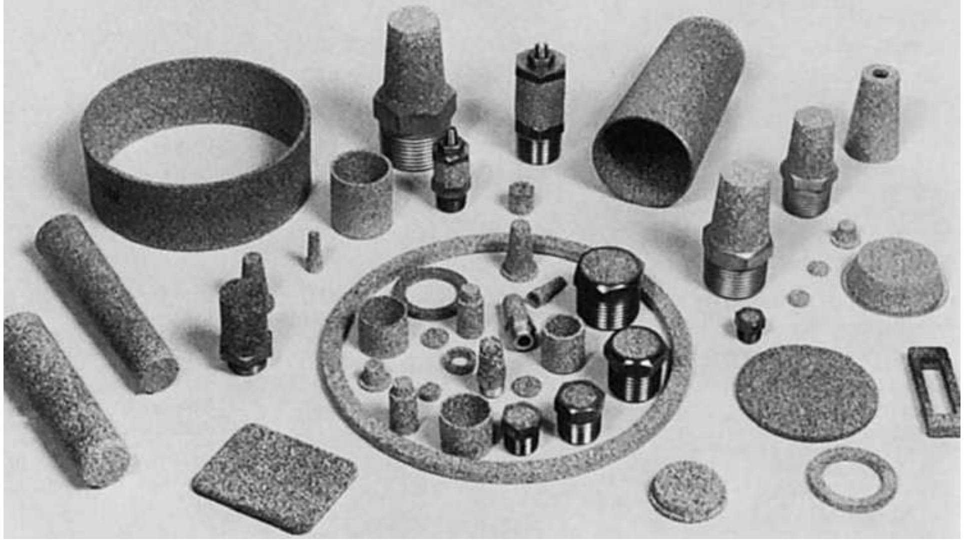


Fig. 9 Assorted filters made from P/M bronze

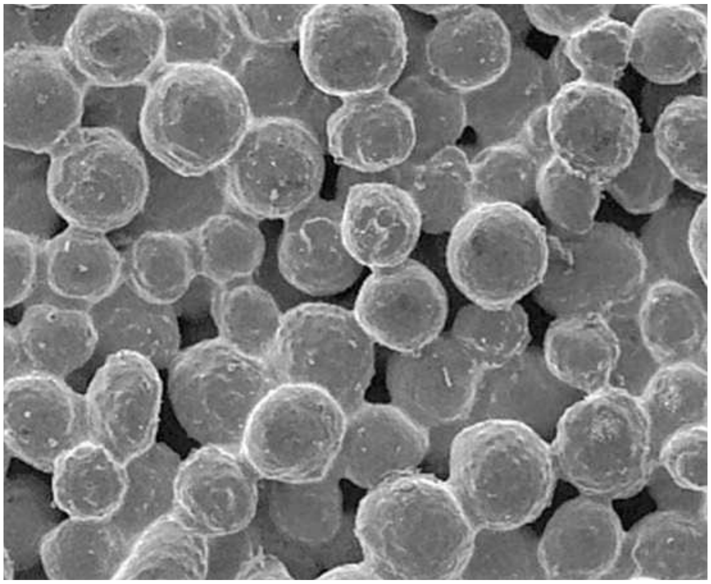


Fig. 10 Atomized 90/10 prealloyed bronze powder particles with a size range of 45 to 100 μm that are gravity sintered to 64% density in order to yield a 10 μm filter grade disk. 100×

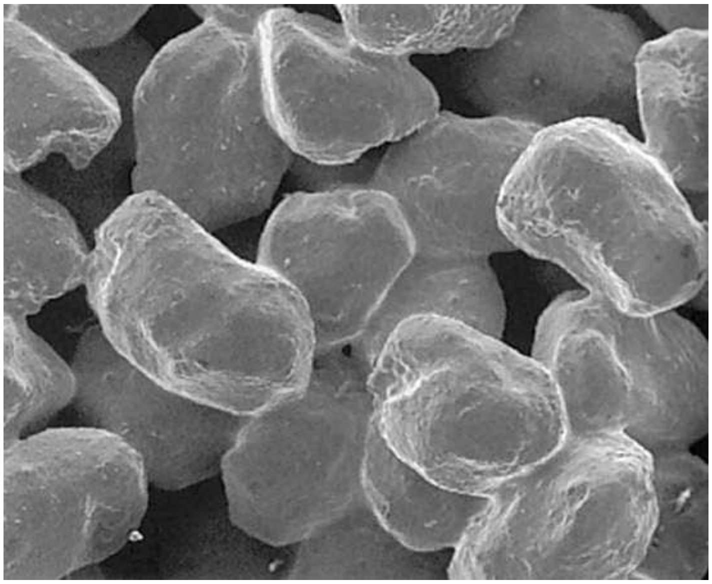


Fig. 11 95/5 bronze particles made from tin-coated, cut copper wire with a size range of 250 to 425 μm that are gravity sintered to 55% density in order to yield a 40 μm filter grade disk. 100×

In one method of producing coins, medals, and medallions, a mixture containing 75% Cu and 25% Ni powders is blended with zinc stearate lubricant and compressed, sintered, coined, and resintered to produce blanks suitable for striking. These blanks are softer than rolled blanks because they are produced from high-purity materials. Therefore, they can be coined at relatively low pressures, and it is possible to achieve greater relief depth with reduced die wear.

In another procedure, an organic binder is mixed with copper or copper-nickel powders and rolled into "green" sheets. Individual copper and copper-nickel sheets are pressed together to form a laminate, and blanks are punched from it. Blanks are heated in hydrogen to remove the organic binder and sinter the material. The density of the "green" blanks is low (45% of theoretical), but coining increases density to 97%. After pressing, the blanks are annealed to improve ductility and coinability.

Table 7 Compositions of copper-base P/M structural materials (brass, bronze, and nickel silver)

Material designation	Chemical composition, % Cu	Zn	Pb	Sn	Ni	Element
Brass						
CZ-1000	88.0	bal	…	…	…	min
	91.0	bal	…	…	…	max
CAP-1002	88.0	bal	1.0	…	…	min
	91.0	bal	2.0	…	…	max
CAP-2002	77.0	bal	1.0	…	…	min
	80.0	bal	2.0	…	…	max
CZ-3000	68.5	bal	…	…	…	min
	71.5	bal	…	…	…	max
CZP-3002	68.5	bal	1.0	…	…	min
	71.5	bal	2.0	…	…	max
Nickel silver						
CNZ-1818	62.5	bal	…	…	16.5	min
	65.5	bal	…	…	19.5	max
CNZP-1816	62.5	bal	1.0	…	16.5	min
	65.5	bal	2.0	…	19.5	max
Bronze						
CT-1000	87.5	bal	…	9.5	…	min
	90.5	bal	…	10.5	…	max

Note: Total by difference equals 2.0% max, which may include other minor elements added for specific purposes. Source: MPIF Standard 35

Copper-Lead P/M Parts

Copper and lead, which have limited solubilities in each other, are difficult to alloy by conventional ingot metallurgy. Copper-lead powder mixtures have excellent cold pressing properties; they can be compacted at pressures as low as 76 MPa (11 ksi) to densities as high as 80% of theoretical density. After sintering, they can be re-pressed at pressures as low as 152 MPa (22 ksi) to produce essentially nonporous bearings.

Steel-backed copper or Cu-Pb-Sn P/M materials are sometimes used to replace solid bronze bearings. They are produced by spreading the powder in a predetermined thickness on a steel strip, sintering, rolling to theoretical density, resintering, and annealing. The end product has a residual porosity of about 0.25%. Blanks of suitable size are cut from the bimetallic strip, formed, and drilled with oil holes or machined to form suitable grooves. These materials include Cu-25Pb-0.5Sn, Cu-25Pb-3.5Sn, Cu-10Pb-10Sn, and Cu-50Pb-1.5Sn alloys.

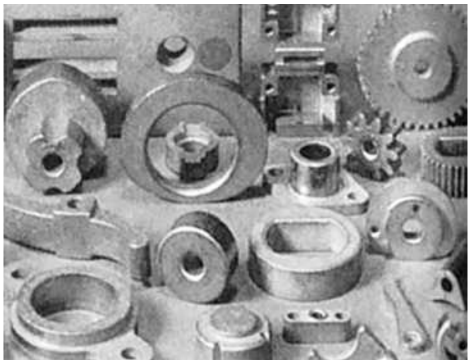


Fig. 12 Assorted P/M bronze parts

Copper-Base Friction Materials

Sintered-metal-base friction materials are used in applications involving the transmission of motion through fiction (clutches) and for deceleration and stopping (brakes). In these applications, mechanical energy is converted into frictional heat, which is absorbed and dissipated by the friction material. Copper-base materials are preferred because of their high thermal conductivity; however, lower cost iron-base materials have been developed for moderate to severe duty dry applications.

Compositions. Most friction materials contain copper powders blended with other metal powders, solid lubricants, oxides, and other compounds. These constituents are immiscible in each other and therefore can only be made by powder metallurgy. Compositions of some common copper-base friction materials are shown in Table 9.

Manufacturing. Mixtures of the appropriate powders are carefully blended to minimize segregation of the constituents. Fine metal powders with high surface area are necessary to provide a strong and thermally conductive matrix. The blended powders are compacted at pressures ranging from 165 to 275 MPa (24 to 40 ksi).

Bell-type sintering furnaces are used where the friction facing is bonded to a supporting steel backing plate such as in clutch disks. The green disks are placed on the copper-plated steel plates and stacked. Pressure is applied on the vertical stack of disks. Sintering temperatures range from 550 to 950 °C (1020 to 1740 °F) in a protective atmosphere. Typical sintering times are 30 to 60 min. The sintered parts are typically machined for dimensional accuracy and surface parallelism. Figure 14 shows the structure of a copper-base friction material, copper-plated layer, and steel backing plate after sintering at 650 °C (1200 °F) for 2 h.

The friction elements are usually brazed, welded, riveted, or mechanically fastened to the supporting steel members. They may also be pressure bonded directly to the assembly.

Table 8 Properties of copper-base P/M structural materials (brass, bronze, and nickel silver)

Mechanical property data derived from laboratory-prepared test specimens sintered under commercial manufacturing conditions

Material designation code(a)	Minimum yield strength		Typical values													
			Ultimate tensile strength		0.2% yield strength		Elongation in 25 mm (1 in.), %	Young's modulus		Transverse rupture strength		Unnotched Charpy impact strength		Density g/cm^3	Compressive yield strength		Apparent hardness, HRH
	MPa	ksi	MPa	ksi	MPa	ksi		GPa	10^6 psi	MPa	ksi	J	ft · lbf		MPa	ksi	
CZ-1000-9	62	9	124	18.0	65	9.5	9.0	52	7.5	270	39	(b)	(b)	7.60	(b)	(b)	65
CA-1000-10	70	10	138	20.0	76	11.0	10.5	69	10.0	315	46	(b)	(b)	7.90	(b)	(b)	72
CZ-1000-11	75	11	159	23.0	83	12.0	12.0	(b)	(b)	360	52	(b)	(b)	8.10	(b)	(b)	80
CZP-1002	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)
CZP-2002-11	75	11	159	23.0	93	13.5	12.0	69	10.0	345	50	38	28.0	7.60	103	15.0	75
CZP-2002-12	83	12	207	30.0	110	16.0	14.5	83	12.0	480	70	76	56.0	8.00	110	16.0	84
CZ-3000-14	97	14	193	28.0	110	16.0	14.0	62	9.0	425	62	31	23.0	7.60	83	12.0	84
CZ-3000-16	110	16	234	34.0	131	19.0	17.0	69	10.0	590	86	51.5	38.0	8.00	90	13.0	92
CZP-3002-13	90	13	186	27.0	103	15.0	14.0	62	9.0	395	57	(b)	(b)	7.60	(b)	(b)	80
CZP-3002-14	97	14	217	31.5	115	16.5	16.0	69	10.0	490	71	(b)	(b)	8.00	(b)	(b)	88
CNZ-1818-17	117	17	234	34.0	140	20.0	11.0	75	11.0	500	73	32.5	24.0	7.90	172	25.0	90
CNZP-1816	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)
CT-1000-13 (re-pressed)	90	13	152	22.0	110	16.0	4.0	38	5.5	310	45	5.4	4.0	7.20	186	27.0	82

(a) Suffix numbers represent minimum yield strength values in ksi. (b) Additional data in preparation will appear in subsequent editions of MPIF standard 35.

The operating conditions encountered by metal-base friction materials can be classified as dry/wet and mild/moderate/severe. Figure 15 shows some typical applications and the corresponding operating conditions. Some examples of copper-base friction elements are shown in Fig. 16.

Copper-Base Contact Materials

Electrical contacts are metal devices that make and break electrical circuits. Arcing, except in applications with low potential or current levels, is a major problem, particularly during opening of the contacts in a live circuit. The arc causes erosion of the contacts by blowing away the molten metal or by vaporizing the material. Welding can occur during closing of the contacts when small areas on the contact surfaces that are molten during arcing fuse together during closure (Ref 10).

Applications involving severe arcing and welding employ contacts made from refractory metals, such as tungsten and molybdenum, which have high melting and boiling points, and excellent resistance to arc erosion. Oxides are often used to prevent welding of the contacts. In both cases, a high conductivity metal such as silver or copper is used in conjunction with the refractory metal or oxide to provide the necessary current-carrying capability. Composites such as these are made by P/M techniques because the individual constituents are immiscible and cannot be made by conventional melt-cast process. Applications where arcing and welding are not severe utilize contacts made of pure metals or alloys. These are generally made by melting and casting followed by suitable metalworking processes.

Copper-base materials are used in electrical contacts because of their high electrical and thermal conductivities, low cost, and ease of fabrication. Their main drawbacks are poor resistance to oxidation and corrosion. Therefore, copper-base contacts are used in applications where the voltage drop resulting from the oxide film is acceptable or where it is possible to protect the contact, such as by immersion in oil or by enclosing the contact in a protective gas or vacuum.

Common copper alloys used in contacts include yellow brass (C27000), phosphor bronze (C51000), and copper beryllium alloys (C17200 and C71500). These are made by the melt-cast process and are limited to lower current applications where arcing and welding are not severe.

Composites of copper with refractory metals of their carbides are used in applications in which limited oxidation of the copper is acceptable or where oxidation is prevented by one of the methods mentioned above. Table 10 presents the compositions, properties, and typical applications for some P/M composite contact materials. The properties of the contacts depend on the manufacturing method used, and therefore the common methods used are also shown in the table. The specific method used depends on the composition of the composite. Generally, materials with 40% or less tungsten or its carbide are manufactured by the conventional pressing, sintering (generally below the melting point of copper), and re-pressing (PSR) technique. Materials containing more than 40% W are generally made by infiltrating (INF) the copper into either loose tungsten powder or pressed-and-sintered tungsten compacts. Their counterparts using tungsten carbide are made by infiltrating the copper into loose powder because the tungsten carbide power cannot be pressed into compacts.

Copper-Base Brush Materials

Brushes are components that transfer electrical current between the stationary and rotating elements in electric motors and generators. Most common brushes are made from composites of graphite and a conductive metal. The graphite provides the required lubrication, and the metal provides the current-carrying capability; copper and silver are preferred metals because of their high electrical conductivity.

Compositions. Table 11 shows the compositions of some typical copper-graphite brush materials. The copper content varies from about 20 to 75%, the balance being graphite. Powder metallurgy is the only way to produce these materials because of the immiscibility of the two components. Copper powder used in the brushes could be made by oxide reduction, electrodeposition, atomization, or flaking.

The manufacture of brushes involves blending the copper and graphite powders. These are molded into brushes or large blocks, typically at pressures ranging from 100 to 200 MPa (15 to 30 ksi), providing green densities of 2 to 4 g/cm^3. The molded parts are sintered at 500 to 800 °C (950 to 1500 °F) in a protective atmosphere. Machining is performed if necessary to achieve the final dimensional tolerances.

Operating Conditions and Applications. All metal-graphite brush applications must operate at lower voltages than nonmetallic brush materials. Typical voltages range from near 0 to 30 V and can be emanating from a direct current power source such as a battery, a rectifier, or a sensing device such as a thermocouple.

Copper-graphite brushes are widely used in battery-powdered tools that require high power outputs in small, lightweight packages. Typically, input voltage influences the metal

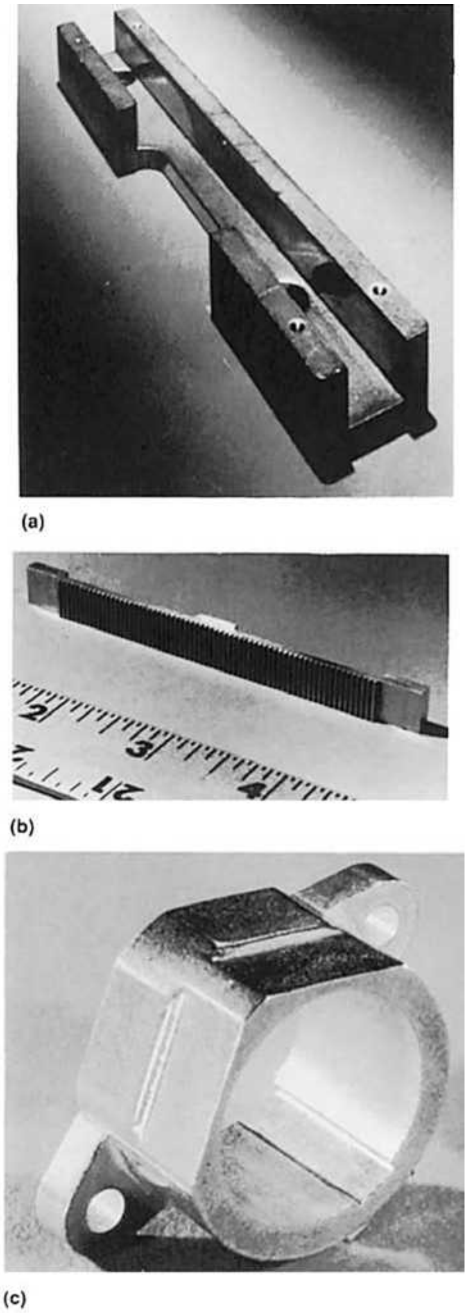


Fig. 13 P/M brass components. (a) Rack guide for rack-and-pinion steering column. (b) Leaded brass guide for stereomicroscope. (c) Leaded brass guide for microscope

Table 9 Compositions of copper-base friction materials for wet and dry applications

Composition, wt%							
Cu	Sn	Fe	Pb	Graphite	MoS_2	Other	Use(a)
60–75	4–10	5–10	…	3–10	3–12	2-7 SiO_2	D
52.5	…	…	7.5	…	…	5 SiO_2; 15 Bi	W
72	4.7	3.3	3.5	8.7	1.4	1.9 SiO_2; 0.2 Al_2O_3	W, D
72	7	3	6	6	…	3 SiO_2; 4 MoO_3	D
62	7	8	12	7	…	4 sand	D
74	3.5	…	…	16	…	2 Sb; 4.5 SiO_2	D

(a) W, wet; D, dry

content required. High voltages require a low metal content, whereas low voltages require a high metal content. Below 9 V, the metal content is usually higher than 80% while above 18 V, the metal content is generally below 50%.

Copper-graphite brushes are also used extensively in automotive applications including starter motors, blower motors, doorlocks, and windshield-wiper motors. The starter motors generally use high copper content grades to enable them to handle extremely high-current densities for short periods of time. Blower motors use lower copper content grades to extend service life to several thousand hours. The doorlocks and windshield-wiper motors use grades that are between the blower and starter motor grades.

Copper-Infiltrated Steels

Iron-base P/M parts can be infiltrated with copper or a copper alloy by placing a slug of the infiltrant on the part and then sintering above the melting point of the infiltrant. The molten infiltrant is completely absorbed in the pores by capillary action and a composite structure is created. The amount of infiltrant used is limited by the pore volume in the starting iron part and typically ranges between 15 and 25%. Table 12 lists the composition ranges of infiltrated steels.

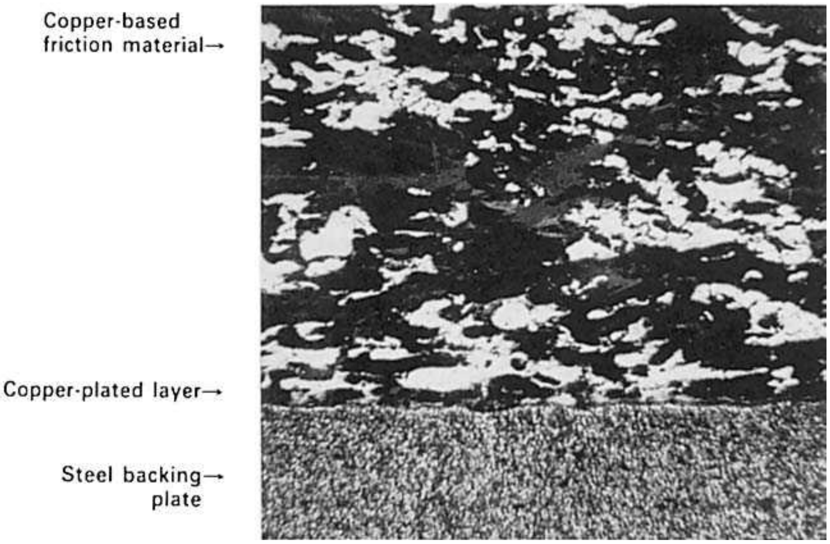


Fig. 14 Structure of a sintered copper-base friction material

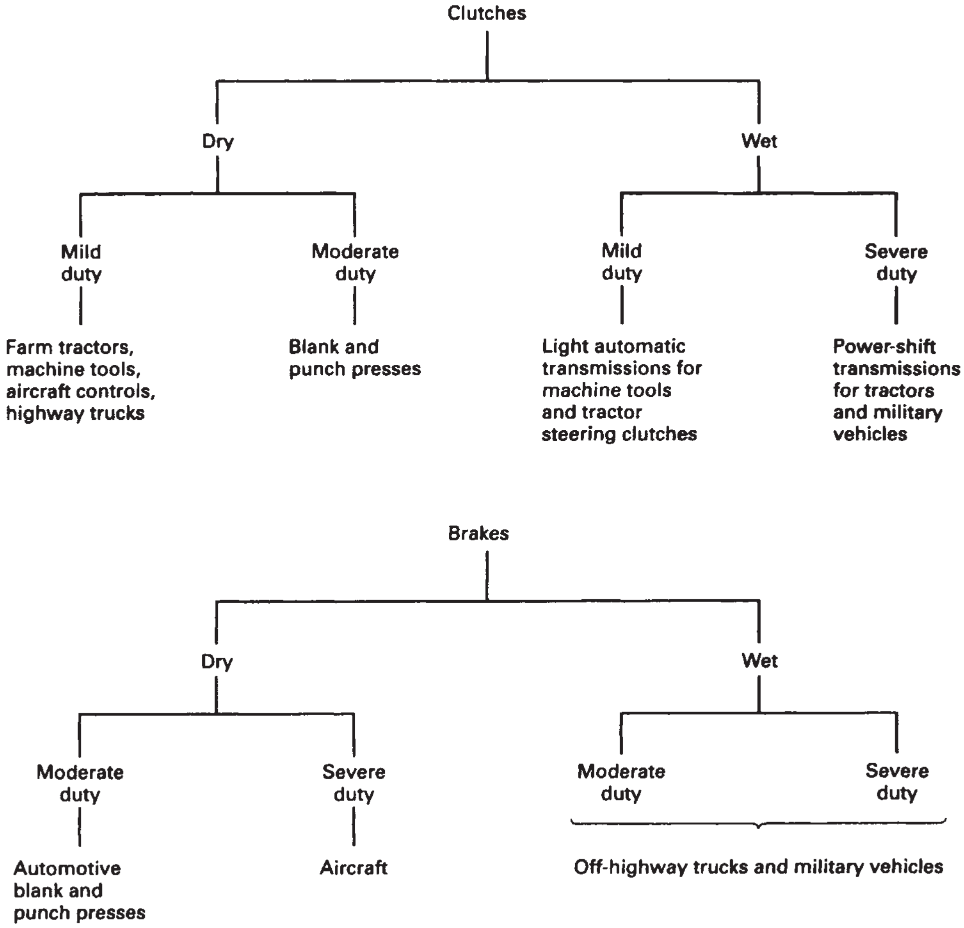


Fig. 15 Applications of sintered metal friction materials. Source: Ref 9

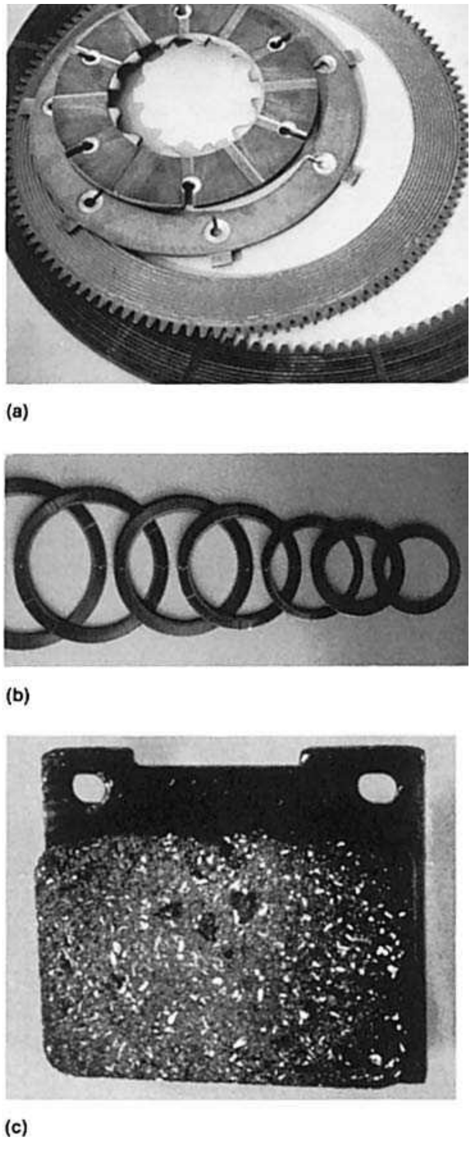


Fig. 16 Copper-base P/M friction elements. (a) Grooved P/M friction elements for wet applications. (b) Copper-base P/M clutch plates (280 to 400 mm OD) used in power-shift transmissions for tractors. (c) Copper-base P/M friction pad

Table 10 Compositions, properties, and applications of copper–containing electrical contacts

Nominal composition, %	Manufacturing method(a)	Density, g/cm^3		Electrical conductivity, %	Hardness	Tensile strength		Modulus of rupture		Data source(b)	Application examples
		Calculated	Typical	IACS		MPa	ksi	MPa	ksi		
Tungsten carbide-copper											
50Cu	INF	11.39	11.00–11.27	42–47	90–100 HRF	…	…	1103	160	C, A	(c)
44Cu	INF	11.77	11.64	43	99 HRF	…	…	1241	180	C	(c)
30Cu	INF	12.78	12.65	30	38 HRC	…	…	…	…	…	(c)
Tungsten-copper											
75Cu-25W	PSR	10.37	9.45–10.00	50–79	35–60 HRB	…	…	414	60	C, A	(d)
70Cu-30W	…	10.70	10.45	76	59–66 HRB	…	…	…	…	A	(c)
65Cu-35W	…	11.06	11.40	72	63–69 HRB	…	…	…	…	A	(e)
60Cu-40W	…	11.45	11.76	68	69–75 HRB	…	…	…	…	A	(f)
50Cu-50W	INF	12.30	11.90–11.96	45–63	60–81 HRB	…	…	…	…	A	(f)
44Cu-56W	INF	12.87	12.76	55	79 HRB	434	63	827	120	C	(f)
40Cu-60W	INF	13.29	12.80–12.95	42–57	75–86 HRB	…	…	…	…	A	(g)
35Cu-65W	INF	13.85	13.35	54	83–93 HRB	…	…	…	…	A	(g)
32Cu-68W	INF	14.20	13.95	50	90 HRB	…	…	896	130	C	(g)
30Cu-70W	INF	14.45	13.85–14.18	36–51	86–96 HRB	…	…	1000	145	C, A	(h)
26Cu-74W	INF	14.97	14.70	46	98 HRB	621	90	1034	150	…	(h)
25Cu-75W	INF	15.11	14.50	33–48	90–100 HRB	…	…	…	…	A	(i)
20Cu-80W	INF	15.84	15.20	30–40	95–105 HRB	758	110	…	…	C	(i)
15Cu-85W	PSR	16.45	16.0	20	190 HV(j), 260 HV(k)	…	…	…	…	M	(i)
13.4Cu-86.6W	INF	16.71	16.71	33	20 HRC	621	90	1034	150	C	(i)
10.4Cu-89.6W	INF	17.22	17.22	30	30 HRC	765	111	1138	165	C	(i)

(a) PSR, press-sinter-re-press; INF, press-sinter-infiltrate. (b) A: Advance Metallurgy, Inc., McKeesport, PA. C: Contacts, Materials, Welds, Inc., Indianapolis, IN. M: Metz Degussa, South Plainville, NJ. (c) Arcing contacts in oil switches, wiping shoes in power transformers. (d) Current-carrying contacts. (e) Vacuum interrupter. (f) Oil-cuircuit breakers, arcing tips. (g) Oil-circuit breakers, reclosing devices, arcing tips, tap change arcing tips, contractors. (h) Circuit breaker runners, arcing tips, tap change arcing tips. (i) Vacuum switches, arcing tips, oil-circuit breakers. (j) Annealed. (k) Cold worked. Source: Ref 10

Table 11 Characteristics of typical graphite-copper brush materials

Nominal composition	Density, g/cm^3	Specific resistance		Maximum current density		Typical voltage, V	Scleroscope hardness
		Ω · m	Ω · in.	A/m^2	A/in.^{2}		
21Cu-79C	2.2	0.024	0.0006	125,000	80	<72	28
35Cu-65C	2.5	0.016	0.0004	125,000	80	<72	28
50Cu-50C	2.75	0.006	0.00015	130,000	85	<36	28
65Cu-35C	3.5	0.0016	0.00004	190,000	125	<18	20
75Cu-25C	4.0	0.0008	0.0002	235,000	150	<15	18
94metal-6C	6.0	0.0003	0.0000065	235,000	150	<6	6
97metal-3C	6.5	0.0001	0.0000025	235,000	150	<6	5

Source: Ref 11

Table 12 Composition ranges of copper-infiltrated steels

Material designation	Chemical composition, %			
	Fe	Cu	C(a)	Element
FX-1000	82.8	8.0	0.0	Minimum
	92.0	14.9	0.3	Maximum
FX-1005	82.5	8.0	0.3	Minimum
	91.7	14.9	0.6	Maximum
FX-1008	82.2	8.0	0.6	Minimum
	91.4	14.9	0.9	Maximum
FX-2000	72.7	15.0	0.0	Minimum
	85.0	25.0	0.3	Maximum
FX-2005	72.4	15.0	0.3	Minimum
	84.7	25.0	0.6	Maximum
FX-2008	72.1	15.0	0.6	Minimum
	84.4	25.0	0.9	Maximum

(a) Carbon on the basis of iron only, may be a metallographic estimate

Infiltration increases the density of the part, resulting in improved mechanical properties (Fig. 17), corrosion resistance, electrical and thermal conductivities, machinability, and brazeability. Tensile strengths ranging from 480 to 620 MPa (70 to 90 ksi) can be achieved in iron-base parts infiltrated with 15 to 25% Cu. An overview of typical mechanical properties of these materials is given in Table 13.

Infiltration is used for iron-base structural parts that must have densities greater than 7.4 g/cm^3. Typical examples include gears, automatic transmission components, valve seat inserts, automobile door hinges, and so forth. More detailed information on copper-infiltrated steels can be found in Ref 12.

Copper-Base Dispersion-Strengthened Materials

Copper is widely used in industry because of its high electrical and thermal conductivities, but it has low strength, particularly when heated to high temperatures. It can be strengthened by using finely dispersed particles of stable oxides such as alumina, titania, beryllia, thoria, or yttria in the matrix. Because these oxides are immiscible in liquid copper, dispersion-strengthened copper cannot be made by conventional ingot metallurgy; P/M techniques must be used.

Manufacture

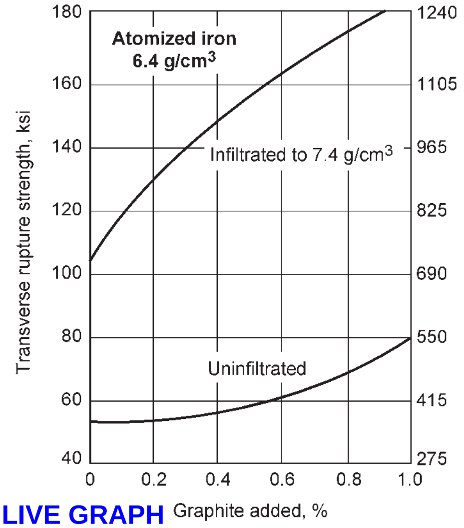
Oxide dispersion strengthened (ODS) copper can be made by simple mechanical mixing of the copper and oxide powders (Ref 13), by coprecipitation from salt solutions (Ref 14), by mechanical alloying (Ref 15), or by selective or internal oxidation (Ref 16). Dispersion quality and cost vary substantially among these methods; internal oxidation produces the finest and most uniform dispersion. Aluminum oxide is a common dispersoid used in the manufacture of ODS copper.

In internal oxidation, a copper-aluminum solid-solution alloy is internally oxidized at elevated temperature. This process converts the aluminum into aluminum oxide. For effective internal oxidation, oxygen must diffuse into the matrix (copper) several orders of magnitude faster than the solute element (aluminum). Because internal oxidation depends on diffusion of oxygen into the matrix, the reaction time is proportional to the square of the distance through which the oxygen must diffuse to complete the reaction. To hold reaction times within practical limits, diffusion distance must be small. In wrought form, internal oxidation can only be practical in thin wire or strip, which would severely limit the use of ODS materials. Powder metallurgy offers a unique solution to this problem because powder particles can be internally oxidized rapidly and then consolidated into almost any shape.

The process involves melting a dilute solid-solution alloy of the aluminum in copper and atomizing the melt by use of a high-pressure gas such as nitrogen. The resulting powder is blended with an oxidant that consists primarily of fine copper oxide powder. The blend is heated to a high temperature; the copper oxide dissociates, and the oxygen produced diffuses into the particles of solid-solution copper-aluminum alloy. Because aluminum forms oxide more readily than copper, the aluminum in the alloy is preferentially oxidized to aluminum oxide. After complete oxidation of all the aluminum, excess oxygen in the powder is reduced by heating the powder in hydrogen or a dissociated ammonia atmosphere.

Consolidation. Full theoretical density is essential to realize the best potential properties of ODS copper. The powder is fabricated into fully dense shapes by various techniques. Mill forms, such as rod and bar, are made by canning the powder in a suitable metal container (generally copper) and hot extruding it to the desired size. Wire is made by cold drawing coils of rod. Strip is made either by rolling coils of extruded rectangular bar or by directly rolling powder with or without a metal container. Large shapes that cannot be made by hot extrusion are made by hot isostatic pressing (HIP) of canned powder; alternatively, such shapes can be made by hot forging canned powder or partially dense compacted preforms.

Properties of the consolidated material depend on the amount of deformation introduced into the powder particles. Consequently, low-deformation processes such as HIP and, to a lesser extent, hot forging develop materials with lower strengths and ductilities than those produced by extrusion.



LIVE GRAPH
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Fig. 17 Increase in transverse rupture strength of sintered steel due to infiltration as a function of amount of graphite added

Secondary Operations. Finished parts can be made from consolidated shapes by machining, brazing, and soldering. Fusion welding is not recommended because it causes the aluminum oxide to segregate from the liquid copper matrix, resulting in loss of dispersion strengthening. However, flash welding, in which the liquid metal is squeezed out of the weld joint, and electron beam welding, in which a small heat-affected zone is created, have been used successfully. Solid-state welding (with multiple cold upsets in a closed die) has also been used with success to join smaller coils into a large coil for wire drawing.

Properties

Oxide dispersion strengthened copper offers a unique combination of high strength and high electrical and thermal conductivities. More importantly, it retains a larger portion of these properties during and after exposure to elevated temperatures than any other copper alloy.

The properties of ODS copper can be modified to meet a wide range of design requirements by varying its aluminum oxide content and/or the amount of cold work. Figure 18 shows the ranges in tensile strength, elongation, hardness, and electrical conductivity obtained as a function of aluminum/aluminum oxide contents. These properties are typical for rod stock in the hot extruded condition. Cold work can be used to broaden the ranges in tensile strength, elongation, and hardness; its effect on electrical conductivity is minimal.

Three grades of ODS copper are commercially available. They are designated as C15715, C15725, and C15760 by the Copper Development Association. The nominal compositions of these three grades are:

	Copper		Aluminum oxide	
Grade	wt%	vol%	wt%	vol%
C15715	99.7	99.3	0.3	0.7
C15725	99.5	98.8	0.5	1.2
C15760	98.9	97.3	1.1	2.7

The free or reducible oxygen content of the three ODS coppers, generally about 0.02 to 0.05 wt%, is present in the form of dissolved oxygen and cuprous oxide. Alloys in this state are prone to hydrogen embrittlement at high temperatures. Low-oxygen (LOX) compositions are available in all of these grades, in which the reducible oxygen is converted to nonreducible oxide by adding up to 0.020 wt% B as the oxygen getter. These grades are then immune to hydrogen embrittlement and must be specified for applications in which the components are likely to be subjected to reducing atmospheres during manufacture or use.

Physical Properties. Because ODS copper contains small amounts of aluminum oxide as discrete particles in an essentially pure copper matrix, its physical properties closely resemble those of pure copper. Table 14 shows physical properties of the three commercial ODS coppers comparing them with oxygen-free (OF) copper. The melting point is essentially the same as for copper because the matrix melts and the aluminum oxide separates from the melt. Density, modulus of elasticity, and coefficient of thermal expansion are similar to those of pure copper.

High electrical and thermal conductivities are particularly interesting to design engineers in the electrical and electronics industries. At room temperature, these range from 78 to 92% of those for pure copper. Coupled with the high strengths of these materials, they enhance the current-carrying or heat-dissipating capabilities for a given section size and structural strength. Alternatively, they enable reduction of section sizes for component miniaturization without sacrificing structural strength or current and heat-carrying capabilities. At elevated temperatures, the decrease in electrical and thermal conductivities of ODS coppers closely parallel those of pure copper.

Room-Temperature Mechanical Properties. Table 15 shows the room-temperature mechanical properties of the three ODS coppers in available mill forms. These cover a wide range of sizes, typified by various amounts of cold work by drawing and rolling, for example. Oxide dispersion strengthened copper has strength comparable to many steels and conductivity comparable to copper.

Table 13 Mechanical properties of copper-infiltrated iron and steel

					Typical properties(b)																		
	Minimum strength				Tensile properties					Elastic constant			Unnotched Charpy impact energy		Transverse rupture strength		0.1% compressive yield strength		Rockwell hardness		Fatigue limit 90% survival		
Material designation	Yield		Ultimate		Ultimate strength		0.2% yield strength		Elongation,	Young's modulus		Poisson's							Macro	Micro			Density,
code(a)	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	%	GPa	10^6 psi	ratio	J	ft · lbf	MPa	ksi	MPa	ksi	(apparent)	(converted)	MPa	ksi	g/m^3
FX-1000-25	170	25	…	…	350	51	220	32	7.0	160	23.5	0.28	34	25.0	910	132	225	33	65 HRB	N/A	130	19	7.3
FX-1005-40	280	40	…	…	530	77	340	50	4.0	160	23.5	0.28	18	13.0	1090	158	365	53	82 HRB	N/A	200	29	7.3
FX-1005-110HT(c)	…	…	760	110	830	120	(d)	(d)	<0.5	160	23.5	0.28	9	7.0	1445	210	760	110	38 HRC	55 HRC	230	33	7.3
FX-1008-50	340	50	…	…	600	87	415	60	3.0	160	23.5	0.28	14	10.0	1140	166	490	71	89 HRB	N/A	230	33	7.3
FX-1008-110HT(c)	…	…	760	110	830	120	(d)	(d)	<0.5	160	23.5	0.28	9	6.5	1300	189	790	115	43 HRC	58 HRC	280	41	7.3
FX-2000-25	170	25	…	…	320	46	260	37	3.0	145	21.0	0.24	20	15.0	990	144	280	41	66 HRB	N/A	120	17	7.3
FX-2005-45	310	45	…	…	520	75	410	60	1.5	145	21.0	0.24	11	8.0	1020	148	415	60	85 HRB	N/A	140	20	7.3
FX-2005-90HT(c)	…	…	620	90	690	100	(d)	(d)	<0.5	145	21.0	0.24	9	7.0	1180	171	490	71	36 HRC	55 HRC	160	23	7.3
FX-2008-60	410	60	…	…	550	80	480	70	1.0	145	21.0	0.24	9	7.0	1080	156	480	70	90 HRB	N/A	160	23	7.3
FX-2008-90HT(c)	…	…	620	90	690	100	(d)	(d)	<0.5	145	21.0	0.24	7	5.0	1100	159	510	74	36 HRC	58 HRC	190	27	7.3

Note: All data based on single-pass infiltration. (a) Suffix numbers represent minimum strength values in ksi; yield in the as-sintered condition and ultimate in the heat treated condition. (b) Mechanical property data derived from laboratory prepared test specimens sintered under commercial manufacturing conditions. (c) Tempering temperature for heat treated (HT) materials: 177 °C (350 °F). (d) Yield and ultimate tensile strength are approximately the same for heat treated materials. Source: MPIF Standard 35

Table 14 Physical properties of three ODS coppers and OF copper

	Material			
Property	C15715	C15725	C15760	OF Copper
Melting point, °C (°F)	1083 (1981)	1083 (1981)	1083 (1981)	1083 (1981)
Density, g/cm^3 (lb/in.^{3})	8.90 (0.321)	8.86 (0.320)	8.81 (0.318)	8.94 (0.323)
Electrical resistivity at 20 °C (68 °F), Ω · mm^2/m (Ω · circular mil/ft)	0.0186 (11.19)	0.0198 (11.91)	0.0221 (13.29)	0.017 (10.20)
Electrical conductivity at 20 °C (68 °F), 10^6 S/m (%IACS)	54 (92)	50 (87)	45 (78)	58 (101)
Thermal conductivity at 20 °C (68 °F), W/m · K (Btu/ft · h · °F)	365 (211)	344 (199)	322 (186)	391 (226)
Linear coefficient of thermal expansion for 20 to 1000 °C (68 to 1830 °F), ppm/°C (ppm/°F)	16.6 (9.2)	16.6 (9.2)	16.6 (9.2)	17.7 (9.8)
Modulus of elasticity, GPa (10^6 psi)	130 (19)	130 (19)	130 (19)	115 (17)

ODS, oxide dispersion strengthened. OF, oxygen free. Source Ref 18

Table 15 Typical room-temperature mechanical properties of three ODS coppers

	Thickness or diameter			Tensile strength		Yield strength			
Shapes	mm	in.	Temper or conditions(a)	MPa	ksi	MPa	ksi	Elongation, %	Hardness, HRB
C15715									
Flat products	10	0.400	AC	413	60	331	48	20	62
	1.3	0.050	CW 88%	579	84	537	78	7	…
	0.6	0.025	CW 94%	620	90	579	84	7	…
	0.15	0.006	CW 98%	661	96	613	89	6	…
Plate	Up to 130	Up to 5.0	AC	365	53	255	37	26	62
	25	1.0	CW 60%	476	69	427	62	10	…
	16	0.625	CW 75%	483	70	455	66	10	…
Rod	29	1.125	AC	393	57	324	47	27	62
	19	0.75	CW 55%	427	62	407	59	18	68
	7	0.275	CW 94%	496	72	469	68	9	72
Wire	1.3	0.050	CW 99%	524	76	496	72	2	…
	1.3	0.050	HT 650 °C	400	58	351	51	10	…
	0.4	0.015	CW 99.9%	606	88	579	84	1	…
Rounds	Up to 760	Up to 30	AC	365	53	255	37	26	…
C15725									
Flat products	10	0.400	AC	434	63	345	50	21	72
	2.3	0.090	CW 78%	586	85	544	79	8	83
	0.15	0.006	CW 98%	675	98	613	89	6	…
Plate	Up to 130	Up to 5.0	AC	413	60	296	43	19	68
	25	1.0	CW 60%	496	72	441	64	9	…
	16	0.625	CW 75%	524	76	467	68	9	…
Rod	38	1.5	AC	441	64	358	52	24	73
	64	2.5	As drawn	551	80	531	77	14	76
Rounds	Up to 760	Up to 30	AC	413	60	296	43	19	68
C15760									
Flat products	1.0	0.400	AC	517	75	413	60	13	81
	2.5	0.100	CW 75%	627	91	572	83	8	85
	0.15	0.006	CW 98%	737	107	655	95	6	…
Rod	14	0.54	AC	551	80	517	75	22	80
	13	0.5	CW 14%	572	83	544	79	16	83
	7	0.275	CW 74%	620	90	599	87	14	86
	7	0.275	HT 650 °C	579	84	544	79	18	80
	64	2.5	AC	496	72	475	69	4	80
Rounds	Up to 760	Up to 30	AC	469	68	331	48	4	76

(a) AC, as consolidated; CW, cold work % reduction in area; HT, heat treatment for 1 h. Source: Ref 19

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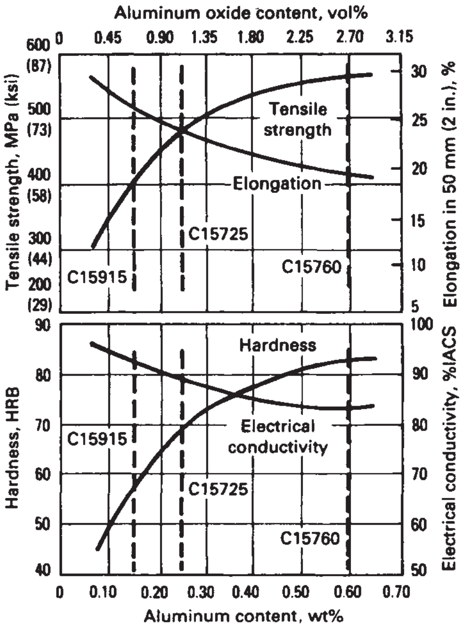

Fig. 18 Properties of three ODS coppers. Source: Ref 17

Oxide dispersion strengthened copper has excellent resistance to softening even after exposure to temperatures close to the melting point of copper because the aluminum oxide particles are stable at these temperatures and retain their original size and spacing. These particles block dislocation and grain-boundary motion and thus prevent recrystallization, which is normally associated with softening. Figure 19 compares the softening behavior of C15715 and C15760 strip with OF copper (C10200) and copper-zirconium (C15000) alloy. At common brazing and glass-to-metal sealing temperatures (above 600 °C, 1100 °F) encountered in practice, ODS coppers retain much of their strength while OF copper and copper-zirconium lose most of their strength. Therefore, ODS copper is used in applications in which the component manufacture involves high-temperature operations such as brazing, glass-to-metal sealing, HIP diffusion bonding, and so forth.

Elevated-Temperature Mechanical Properties. ODS copper has excellent strength at elevated temperatures. Figure 20 shows the 100 h stress rupture strengths of C15760 and C15715 at temperatures up to 870 °C (1600 °F). Other high-conductivity copper-base materials are shown for comparison. Ranging from pure copper on the low end to precipitation-hardened alloys on the high end, there is a sharp drop in stress rupture strength in the 200 to 450 °C (400 to 850 °F) temperature range. Above 400 °C (750 °F), the ODS coppers are superior to any of the other alloys. Above 600 °C (1100 °F), the ODS coppers have rupture strengths comparable or superior to some stainless steels. Oxide dispersion strengthened copper has excellent thermal stability at high temperatures because the aluminum oxide particles retain their original particle size and spacing even after prolonged heating and do not allow recrystallization of the matrix. Cold work significantly enhances the stress rupture properties of ODS copper; the higher the temperature, the more noticeable the enhancement.

Applications

Oxide dispersion strengthened copper has gained wide market acceptance in several applications, and design engineers are continually developing new applications. The major applications are described in the following sections.

Resistance Welding Electrodes. Oxide dispersion strengthened copper electrodes are widely used for resistance welding in automotive, appliance, and other sheet metal industries. Sticking of the electrodes to the workpiece is a major problem when welding galvanized and other coated steels. This usually results in electrodes pulling off their holders and having to stop the assembly line to change the electrodes. Such interruptions are extremely costly. Oxide dispersion strengthened copper electrodes do not stick to galvanized and other coated steels and thus eliminate the costly downtime. Increasing use of coated steels in the automotive industry has prompted wide usage of ODS copper electrodes throughout the world. When used under optimal conditions, including heavy duty welding, these electrodes consistently outperform the conventional copper-chromium electrodes in weld life. Table 16 lists some typical applications of ODS copper C15760 electrodes and also compares typical life multiples obtained over copper-chromium electrodes.

Metal-Inert-Gas Welding Contact Tips. Oxide dispersion strengthened copper is used in metal-inert-gas (MIG) welding contact tips. Its resistance to abrasive wear from the steel wire allows the tips to maintain the bore diameter and minimizes the wandering of the arc. This is very important in automated welding lines. The non-sticking property of ODS copper also minimizes the material buildup on the tip from the weld splatter.

Lead Wires. Oxide dispersion strengthened copper wire is used in leads for incandescent lamps. Its high-temperature strength retention capability enables glass-to-metal seals to be made without undue softening of the leads. This in turn eliminates the need for expensive molybdenum support wires without sacrificing lead stiffness. Superior strength of the leads allows reduction in lead diameter to conserve materials. Thinner lead wires also minimize heat loss from the filament, which enables the lamp to provide higher light output at lower wattage and results in a more energy efficient lamp.

Oxide dispersion strengthened copper wire also can be used in leads for discrete electronic components such as diodes. Advantages of ODS copper wire include its high-temperature strength retention during brazing as well as hermetic sealing. The lead stiffness also enables multiple insertions in circuit boards.

X-Ray and Microwave Tube Components. Oxide dispersion strengthened copper rod and tube are used in x-ray and microwave tube components. An example is the stems for the rotating anodes in x-ray tubes where high strength retention after brazing and glass-to-metal sealing are important. The high thermal conductivity of ODS copper also allows more efficient heat removal, this lowering the operating temperature and providing longer tube life and quieter tube operation.

Relay Blades and Contact Supports. These are current-carrying arms that move between the fixed contact points to "make" or "break" an electrical circuit. In a limit switch, the force that moves the contact arm (or contact support) to the "make" position is provided by mechanical means, such as a moving object. In a relay, the contact arm (relay blade) is moved by electromagnetic action. In most cases, the spring force of the arm itself moves the contact back to the "break" position.

Generally, the relay blades and contact supports have silver contacts brazed or riveted to them at the point where they touch the fixed contacts. The strength retention capability of ODS copper after exposure to elevated temperatures allows brazing of contacts to the blade without appreciable strength loss. Because of its higher electrical conductivity, ODS copper has replaced conventional copper alloys, such as phosphor bronze and beryllium copper, in some relays. Such relays can carry a higher current than was possible with the prior relays.

Sliding Electrical Contacts. Oxide dispersion strengthened copper bars are used in overhead sliding electrical contacts for high-speed electric trains. Its excellent resistance to abrasive wear against the electrical cable provides up to 10 times longer contact life and reduces the maintenance costs significantly. The higher the train speed, the greater the advantage ODS copper has over other copper-base materials.

Particle Accelerator Components. Particle accelerators are used for physics and materials research, medical diagnostics, and so forth. The high-energy particle beams are shaped and focused by using mirrors, lenses, and prisms in large doughnut-shaped hollow rings. The stray beams are absorbed by special x-ray absorbers. Oxide dispersion strengthened copper plates and bars are used in mirrors and x-ray absorbers because of their high thermal conductivity, high strength, creep resistance, and vacuum integrity.

Hybrid Circuit Package Components. Oxide dispersion strengthened copper strip is used as the base plate for hybrid circuit package cases. Manufacture of these cases involves brazing of the base plates to stainless steel and/or kovar components. The ability of ODS copper to retain its strength after such brazing operation makes it the material of choice when the package is used in high-stress environments. Oxide dispersion strengthened copper wire is also used in the leads for such packages because of its ability to retain its stiffness after the high-temperature ceramic sealing of the leads into the case.

Other Applications. Some other diverse applications of ODS copper include high field magnet coils, anode stems in chlorine cells, electrodischarge machining electrodes, high-speed motor and generator components, commutators, and so forth.

Nonstructural Applications of Copper and Copper Alloy Powders

Although the major applications of copper and copper alloy powders are in structural components, significant quantities of the powders are employed in nonstructural applications. These range from the strictly utilitarian to the purely ornamental. Several important nonstructural end uses are discussed in the following section. Table 1 lists both structural and nonstructural applications for copper and copper alloy powders.

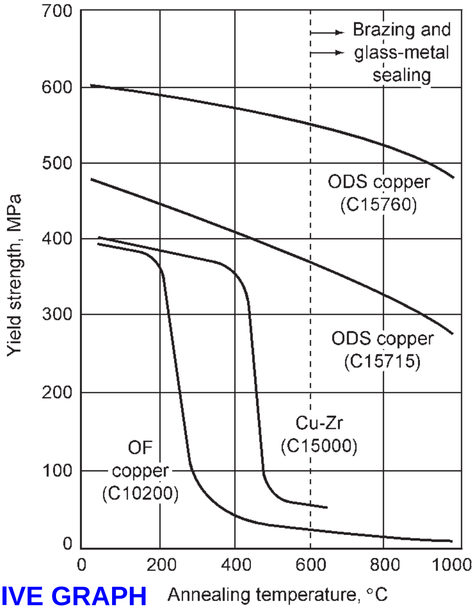

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Fig. 19 Softening behavior of ODS copper compared to OF copper and copper-zirconium alloy. Source: Ref 20

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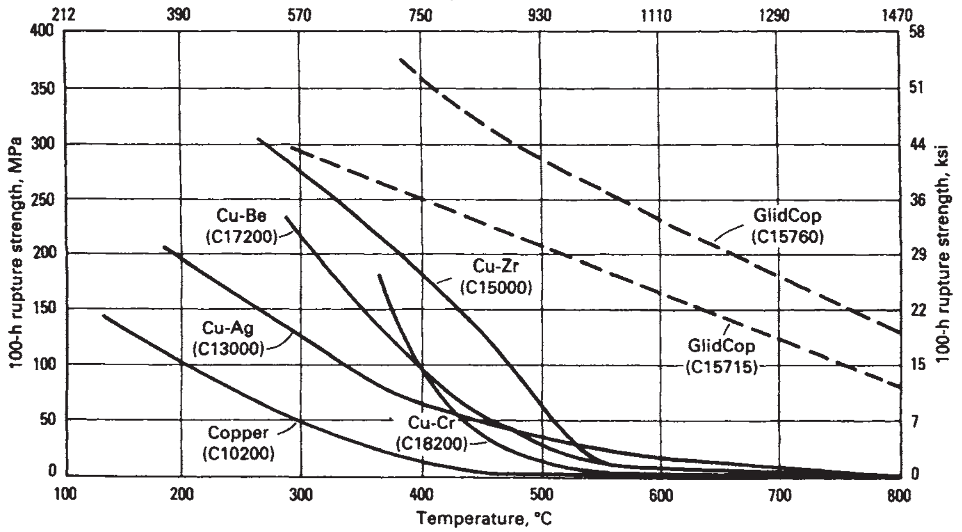

Fig. 20 Elevated-temperature stress-rupture properties of ODS copper compared to several high-conductivity copper alloys. Source: Ref 21

Table 16 Typical applications of dispersion-strengthened copper electrodes

Application	Thickness welded, mm (in.)	Material	Force		Current, A	Weld time, cycles	Welding rate, welds/h	Life comparison with copper-chromium electrodes
			N	lb				
Rocker panel	0.79–0.79 (0.031–0.031)	Galvanized steel	2,670	600	15,000	15	3,024	10 to 1
	1.37–1.73 (0.054–0.068)	Galvanized steel	4,805	1,080	15,500		2,600	5 to 1
Pillar assembly	1.09–0.37 (0.043–0.054)	Galvanized steel	3,115	700	14,000	13	228	6 to 1
Light truck box	1.09–1.37 (0.043–0.054)	Galvanized steel-cold rolled steel	3,560	800	16,000	18	160	65 to 1
Cowl side to rocker	1.35–1.27 (0.53–0.050)	Galvanized steel	4,360	980	15,500	13	1,750	5 to 1
Rocker panel to body	1.73–1.37 (0.068–0.054)	Galvanized steel-cold rolled steel	4,360	980	15,000	13	1,720	6 to 1
Floor panel extension	0.79–0.79 (0.031–0.031)	Galvanized steel-cold rolled steel	2,450	550	13,500	12	645	4.5 to 1
Windshield header	0.91–1.73 (0.036–0.068)	Cold rolled steel	3,785	850	14,000	13	645	6 to 1
Dash extensions	0.79–0.79 (0.031–0.031)	Cold rolled steel	2,450	550	13,500	12	1,144	5.5 to 1
Station wagon assembly	1.37–0.79 (0.054–0.031)	Cold rolled steel	2,940	660	12,000	9	3,120	4 to 1
Van assembly	1.09–1.42–0.91 (0.043–0.056-0.036)	Cold rolled steel	3,450	775	13,500	18	180	6 to 1
Wheelhouse assembly	0.79–0.84 (0.031–0.033)	Zincrometal	3,425	770	12,500	11	3,300	4 to 1
	0.79–0.79 (0.31–0.031)	Zincrometal-cold rolled steel	2,805	630	12,265	10	546	8 to 1
Dash panel	0.79–1.73 (0.031–0.068)	Zincrometal-galvanized steel	2,450	550	13,500	12	1,806	6 to 1

Metallic Flake Pigments. The so-called "gold bronze" pigments are brass alloy flake powders ranging in composition from 70Cu-30Zn to 90Cu-10Zn. Copper and gold-bronze flake pigments are made by ball milling atomized powders. They are used for decorative applications (e.g., cigarette packages, cigar boxes, wrapping paper, greeting cards, and picture frames), in paints, and in printing inks.

Antifouling Paints. Copper powder and cuprous oxide (Cu_2O) are used in the formulation of organic-base paints for use in marine applications to prevent or delay fouling of the submerged portions of ships and structures by marine organisms. These coatings are applied by brush, roller, spray, or dipping. In North America, copper-containing paints have been replaced by organo-tin compounds due to environmental regulations.

Plastic-Metal Combinations. Copper or copper alloy powders are used as filler in various polymeric materials. For example, prealloyed bronze powder is added to Teflon (Dupont, Wilmington, DE) and other plastics to provide strength and wear resistance. Copper powder is also added in other applications where the physical properties, for example, electrical and/or thermal conductivity, are modified for a specific end use.

Brazing Pastes. Copper and copper alloy powders in paste form are used as filler metals for brazing steel and copper alloy parts. A brazing alloy paste consists of copper or copper alloy powder (55 to 90%) and a neutral binder (10 to 35%). It may or may not contain a flux (up to 10%). The most common use for copper brazing pastes is for the furnace brazing of carbon and alloy steel parts.

Chemical Applications. Copper powder is used as a catalyst in various chemical operations. In one process, the addition of activated copper powder to solutions containing cyanides and tartrates causes the precipitation of lead, bismuth, tin, cadmium, and silver but zinc, cobalt, nickel, copper, and aluminum remain in solution.

Powder Coatings. Copper powder coatings are deposited by thermal spraying, weld surfacing, or mechanical (peen) plating. These are described in the article "Copper and Copper Alloy Coatings" in this Handbook.

ACKNOWLEDGMENTS

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Shape Memory Alloys and Composite Materials

COPPER ALLOYS exhibiting shape memory characteristics and copper-containing composites specially processed to enhance physical and/or mechanical properties are discussed in this article. Shape memory alloys are based on the Cu-Zn-Al and Cu-Al-Ni ternary systems. Composites include copper reinforced with tungsten or graphite fibers, tungsten-copper and molybdenum-copper composites made by powder metallurgy (P/M) processing, multifilament composite wires used for superconducting applications, and copper-clad brazing sheet laminates.

Shape Memory Alloys

The term shape memory alloys (SMA) is applied to that group of metallic materials that demonstrate the ability to return to some previously defined shape or size when subjected to the appropriate thermal procedure. Generally, these materials can be plastically deformed at some relatively low temperature, and upon exposure to some higher temperature will return to their shape prior to the deformation. Materials that exhibit shape memory only upon heating are referred to as having a one-way shape memory. Some materials also undergo a change in shape upon recooling. These materials have a two-way shape memory.

Although a relatively wide variety of alloys are known to exhibit the shape memory effect, only those that can recover substantial amounts of strain or that generate significant force upon changing shape are of commercial interest. To date this has been the copper-base alloys such as Cu-Zn-Al and Cu-A1-Ni, and the equiatomic NiTi alloys.

A shape memory alloy is further defined as an alloy that yields a thermoelastic martensite. In this case, the alloy undergoes a martensitic transformation of a type that allows the alloy to be deformed by a twinning mechanism below the transformation temperature. The deformation is then reversed when the twinned structure reverts upon heating to the parent phase.

General Characteristics. The martensitic transformation that occurs in the shape memory alloys yields a thermoelastic martensite and develops from a high-temperature austenite phase with long-range order. The martensite typically occurs as alternately sheared platelets, which are seen as a herringbone structure when viewed metallographically (Fig. 1b). The transformation, although a first-order phase change, does not occur at a single temperature but over a range of temperatures that varies with each alloy system. The typical method of characterizing the transformation and naming each point in the cycle is shown in Fig. 1(a). Most of the transformation occurs over a relatively narrow temperature range, although the beginning and end of the transformation during heating or cooling actually extends over a much larger temperature range. The transformation also exhibits hysteresis in that the transformation on heating and on cooling does not overlap (Fig. 1a). This transformation hysteresis (shown as *T* in Fig. 1a) varies with the alloy system.

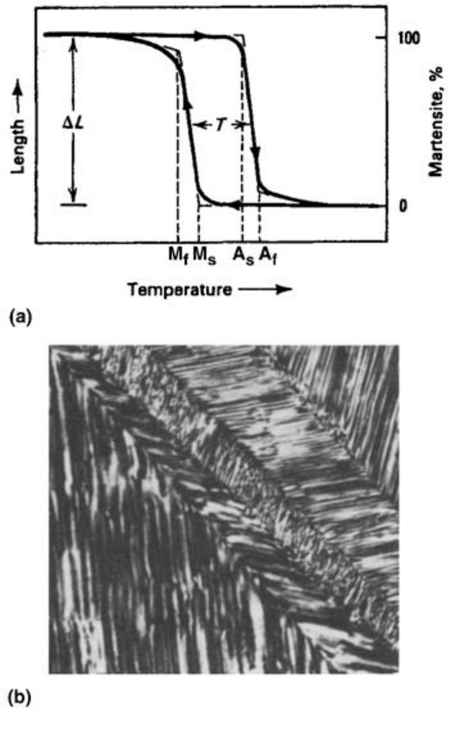

Fig. 1 Characteristics of shape memory alloys. (a) Typical transformation versus temperature curve for a specimen under constant load (stress) as it is cooled and heated. *T*, transformation hysteresis. M_s, martensite start; M_f, martensite finish; A_s, austenite start; A_f, austenite finish, Source: Ref 1 (b) Martensitic structure typical of those in copper-aluminum, copper-tin, and copper-zinc alloys.

Compositions and Properties. Commercial copper-base shape memory alloys are available in ternary Cu-Zn-Al and Cu-Al-Ni alloys or in their quaternary modifications containing manganese. Manganese depresses transformation temperatures of both Cu-Zn-Al and Cu-Al-Ni alloys and shifts the eutectoid to higher aluminum content. It often replaces aluminum for better ductility. Elements such as boron, cerium, cobalt, iron, titanium, vanadium, and zirconium are also added for grain refinement. Compositions of the Cu-Zn-Al alloys usually fall in the range of 10 to 30 wt% Zn and 5 to 10 wt% Al; Cu-Al-Ni alloys contain 11 to 14.5 wt% Al and 3 to 5 wt% Ni. The martensitic transformation temperatures can be adjusted by varying chemical composition. Table 1 lists the major properties of copper-base SMAs.

Processing. The melting of copper-base shape memory alloys is similar to that of alu-

Table 1 Properties of copper-base shape memory alloys

Property	Property value	
	Cu-Zn-Al	Cu-Al-Ni
Thermal properties		
Melting temperature, °C (°F)	950–1020 (1740–1870)	1000–1050 (1830–1920)
Density, g/cm^3 (lb/in.^{3})	7.64 (0.276)	7.12 (0.257)
Resistivity, μΩ · cm	8.5–9.7	11–13
Thermal conductivity, W/m · °C (Btu/ft · h · °F)	120 (69)	30–43 (17–25)
Heat capacity, J/kg · °C (Btu/lb · °F)	400 (0.96)	373–574 (0.089–0.138)
Mechanical properties		
Young's modulus(a), GPa (10^6 psi)		
β phase	72 (10.4)(a)	85 (12.3)(a)
Martensite	70 (10.2)(a)	80 (11.6)(a)
Yield strength, MPa (ksi)		
β phase	350 (51)	400 (58)
Martensite	80 (11.5)	130 (19)
Ultimate tensile strength, MPa (ksi)	600 (87)	500–800 (73–116)
Shape memory properties		
Transformation temperatures, °C (°F)	<120 (250)	<200 (390)
Recoverable strain, %	4	4
Hysteresis, Δ°C (Δ°F)	15–25 (30–45)	15–20 (30–35)

(a) The Young's modulus of shape memory alloys becomes difficult to define between the M_s and the A_s transformation temperatures. At these temperatures, the alloys exhibit nonlinear elasticity, and the modulus is both temperature and strain dependent.

minum bronzes. Most commercial alloys are induction melted. Protective flux on the melt and the use of nitrogen or inert-gas shielding during pouring are necessary to prevent zinc evaporation and aluminum oxidation. Powder metallurgy and rapid solidification processing are also used to produce fine-grain alloys without grain-refining additives.

Copper-base alloys can be readily hot worked in air. With low aluminum content (<6 wt%), Cu-Zn-Al alloys can be cold finished with interpass annealing. Alloys with higher aluminum content are not as easily cold workable. Cu-Al-Ni alloys, conversely, are quite brittle at low temperatures and can only be hot finished.

Because copper-base shape memory alloys are metastable in nature, solution heat treatment in the parent β-phase region and subsequent controlled cooling are necessary to retain β-phase for shape memory effects. Prolonged solution heat treatment causes zinc evaporation and grain growth and should be avoided. Water quench is widely used as a quenching process, but air cooling can be sufficient for some high-cooling aluminum content Cu-Zn-Al alloys and Cu-Al-Ni alloys. The as-quenched transformation temperature is usually unstable. Postquench aging at temperatures above nominal A_f temperature is generally needed to establish stable transformation temperatures.

Cu-Zn-Al alloys, when quenched rapidly and directly into the martensitic phase, are susceptible to the martensite stabilization effect (Ref 2). This effect causes the reverse transformation to shift toward higher temperatures. It therefore delays and can completely inhibit the shape recovery. For alloys with M_s temperatures above the ambient, slow cooling or step quenching with intermediate aging in the parent β-phase state should be adopted.

The thermal stability of copper-base alloys is ultimately limited by the decomposition kinetics. For this reason, prolonged exposure of Cu-Zn-Al and Cu-Al-Ni alloys at temperatures above 150 °C (300 °F) and 200 °C (390 °F), respectively, should be avoided. For high-temperatures stability, Cu-Al-Ni is generally a better alloy system than Cu-Zn-Al. However, even for moderate temperature applications, which demand tight control of transformation temperatures, these effects need to be evaluated.

Applications. A Cu-Zn-Al coupling for copper and aluminum tubing has been developed. In this application, the Cu-Zn-Al shape memory cylinder shrinks on heating and acts as a driver to squeeze a tubular liner onto the tubes being joined. The joint strength is enhanced by a sealant coating on the liner.

The Cu-Zn-Al shape memory alloys have also found several applications in the force actuation device area. One such example is a fire safety valve that incorporates a Cu-Zn-Al actuator designed to shut off toxic or flammable gas flow when fire occurs.

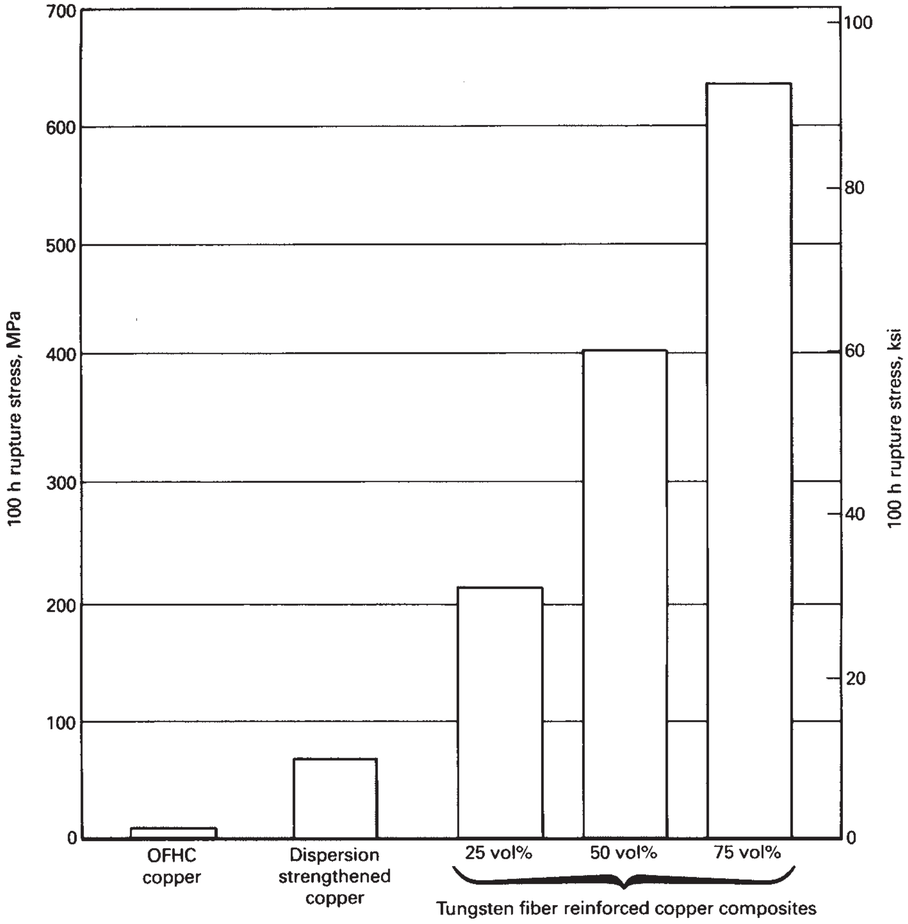

Fig. 2 Comparison of 100 h rupture stress of several copper-based materials at 815 °C (1500 °F). Source: Ref 5

Table 2 Thermal properties of unreinforced and reinforced copper and aluminum

Material	Reinforcement content, vol %	Density		Axial thermal conductivity		Axial coefficient of thermal expansion	
		g/cm^3	lb/ft^3	W/m · °C	Btu/ft · h · °F	10^{-6}/°C	10^{-6}/°F
Aluminum	0	2.71	169	221	128	23.6	13.1
Copper	0	8.94	558	391	226	17.6	9.7
SiC_p/Al	40	2.91	182	128	74	12.6	7
P120 Gr/Al	60	2.41	150	419	242	–0.32	–0.17
P120 Gr/Cu	60	4.90	306	522	302	–0.07	–0.04

Copper-Matrix Composites

Copper-matrix composites have been produced with continuous tungsten, silicon carbide, and graphite fiber reinforcements. Of these three metal-matrix composites (MMCs), continuous graphite-copper composites have been studied the most. Discontinuous MMCs based on niobium-copper have also been developed.

Continuous tungsten fiber reinforced copper composites were first fabricated in the late 1950s as research models for studying stress-strain behavior, stress-rupture and creep phenomena, and impact strength and conductivity in MMCs (Ref 3). The composites were made by liquid-phase infiltration. On the basis of their high strength at temperatures up to 925 °C (1700 °F), copper-tungsten MMCs have been considered for use as liner materials for the combustion chamber walls of advanced rocket engines (Ref 4). Tungsten fiber reinforcement of the copper increases the liner wall strength, while retaining sufficiently high thermal conductivity. Figure 2 shows the effect of tungsten fiber reinforcement on the stress-rupture strength of copper-tungsten composites.

Continuous Graphite Fiber-Reinforced Copper Composites. Interest in continuous copper-graphite MMCs gained impetus from the development of advanced graphite fibers. Copper has good thermal conductivity, but it is heavy and has poor elevated-temperature mechanical properties. Pitch-base graphite fibers have been developed that have room-temperature axial thermal conductivity properties better than those of copper (Ref 6). The addition of these fibers to copper reduces density, increases stiffness, raises the service temperature, and provides a mechanism for tailoring the coefficient of thermal expansion. One approach to the fabrication of copper-graphite MMCs uses a plating process to envelop each graphite fiber with a pure copper coating, yielding MMC fibers flexible enough to be woven into fabric

(Ref 7). The copper-coated fibers must be hot pressed to produce a consolidated component. Table 2 compares the thermal properties of aluminum and copper MMCs with those of unreinforced aluminum and copper. Copper-graphite MMCs have the potential to be used for thermal management of electronic components (Ref 7), satellite radiator panels (Ref 8), and advanced airplane structures (Ref 9).

In Situ Composites. Discontinuous MMCs formed by the working of mixtures of individual metal phases exhibit strengths as much as 50% higher than those predicted in theory from the strength of the individual constituents (Ref 10). These materials are called in situ composites because the elongated ribbon morphology of the reinforcing phase is developed in place by heavy mechanical working, which can consist of extrusion, drawing, or rolling. This approach has been applied to the fabrication of discontinuous copper-refractory metal composites, with copper-niobium serving as the prototype. Copper-niobium maintains high strength at temperatures up to 400 °C (750 °F), and it remains stronger than high-temperature copper alloys and dispersion-hardened copper up to 600 °C (1100 °F) (Ref 11). These composites are candidates for applications such as electrical contacts that require good strength plus conductivity at moderate temperatures.

Tungsten-Copper P/M Composites

Tungsten-copper composites containing between 25 and 65% Cu are used for resistance welding electrodes and electrical contacts (electrical contacts are discussed in the article "Powder Metallurgy Copper and Copper Alloys" in this Handbook). These composites are produced by infiltrating a sintered refractory metal (tungsten) skeleton with liquid copper or a copper alloy (e.g., a precipitation-hardenable copper alloy). A typical microstructure of a tungsten-copper composite is shown in Fig. 3.

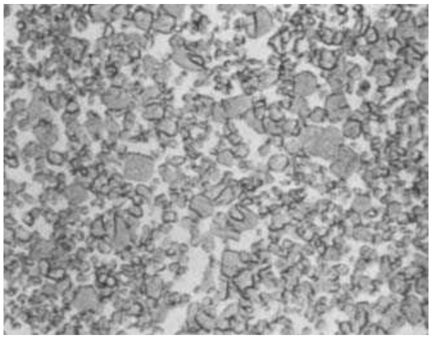

Fig. 3 Micrograph of a tungsten-copper composite electrode material. Magnification: 700×

Refractory metal resistance welding electrodes are divided into classes 10 through 14 by the Resistance Welder Manufacturers Association (RWMA). Classes 10, 11, and 12 represent composites of tungsten and copper. Class 13 is tungsten rod or bar, and class 14 is molybdenum rod or bar. Properties for the five RWMA standard classes or refractory metal group B electrode materials are compared in Table 3. Figures 4 and 5 compare the hardnesses of various tungsten-copper composites used for resistance welding electrodes. Refractory metal compositions, including the tungsten-copper composites, are used in specialty applications, in which the high heat, long weld time, inadequate cooling, and high pressure involved may cause rapid deterioration of dispersion-strengthened copper-base alloys (Group A RWMA electrode materials). The RWMA Bulletins 16, "Resistance Welding Equipment Standards," and 34, "Manufacturer's Cross Reference of Standard Resistance Welding Electrode Numbers and Alloys," list suppliers and trade names for all classes of resistance welding electrodes.

Molybdenum-Copper P/M Composites

Molybdenum-copper composites containing between 15 and 40% Cu are used for electronic thermal management applications. These composites are produced by roll compaction of molybdenum and copper powders. Physical properties of various compositions are given in Table 4. The excellent thermal conductivity and low thermal expansion of these composites make them suitable for:

- Chip mounting
- Heat sinks
- Circuit board cores
- Lids or covers
- Thermal spreaders

Molybdenum-copper composite materials are available as finished parts with the following maximum dimensions depending on overall size:

- Width: 150 mm (6 in.)
- Thickness: 6.4 mm (0.250 in.)
- Length: 610 mm (24 in.)

These materials can also be machined into shapes readily plated if required.

Table 3 Properties of RWMA group B refractory metal electrodes

Electrode	Hardness	Conductivity, %IACS	Ultimate compression strength, MPa	Ultimate compression strength, ksi
Class 10	72 HRB	35	930	135
Class 11	94 HRB	28	1100	160
Class 12	98 HRB	27	1170	170
Class 13	69 HRA	30	1380	200
Class 14	85 HRB	30	…	…

Table 4 Compositions and properties of molybdenum-copper P/M composites

Composition, wt%	Density, g/cm^3	Density, $lb/in.^3$	Thermal conductivity, W/m · K	Thermal conductivity, Btu/h · ft · °F	Thermal expansion in./in. × 10^{-6}/°C, 30–150 °C	30–400 °C	30–800 °C
60Mo-40Cu	9.68	0.349	215	125	9.5	10.2	10.5
65Mo-35Cu	9.74	0.352	205	119	9.0	9.4	9.8
75Mo-25Cu	9.87	0.356	185	108	7.8	8.0	8.4
80Mo-20Cu	9.94	0.359	175	102	7.2	7.5	7.9
85Mo-15Cu	10.01	0.361	165	96	6.8	7.0	7.4

Source: Ametek Specialty Metal Products, Wallingford, CT

Multifilament Composite Wires

Niobium-titanium superconductors are actually composite wires that consist of niobium-titanium filaments (<10 μm in diameter) embedded in a ductile matrix (stabilizer) that must provide:

- High electrical and thermal conductivity
- High heat capacity
- Good mechanical strength at cryogenic temperature

LIVE GRAPH
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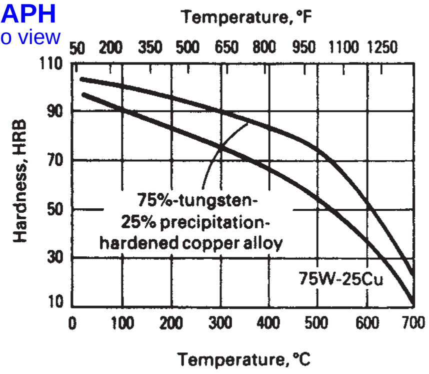

Fig. 4 Effect of infiltration with a precipitation-hardened copper alloy on the hardness of tungsten-copper electrodes

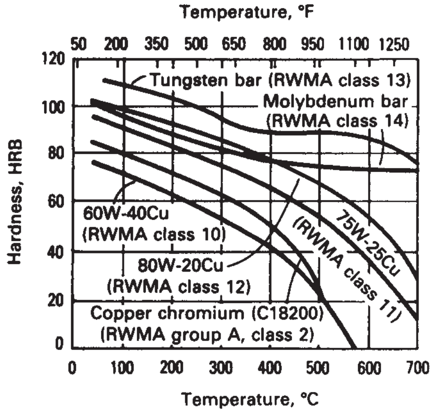

Fig. 5 Hardness at elevated temperatures for RWMA group B refractory metal electrode materials

LIVE GRAPH
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- Good adherence to the superconductor
- Good ductility for forming and winding

High-purity oxygen-free copper (C10100) satisfies all of these requirements to a high degree and is, therefore, the most frequently used stabilizing matrix material. Commercially pure aluminum (alloy 1100, 99.0% Al) and copper-nickel alloy (typically in concentrations of 90 to 10 or 70 to 30) matrices have also been used. The filament alloy most widely used is Nb-46.5Ti. Composite conductors containing as few as one to as many as 25,000 filaments have been processed by advanced extrusion and wire-drawing techniques (Fig. 6 and 7). Important applications for niobium-titanium superconductors include magnets for use in magnetic resonance imaging (MRI) devices used in hospitals, high-energy physics pulsed accelerator magnet applications (particle accelerators), and devices for magnetically confining high-energy plasma for thermonuclear fusion.

Niobium-Tin Intermetallic Superconductors. Like niobium-titanium superconductors, the intermetallic compound Nb_3Sn is also assembled into multifilamentary wires embedded by various techniques into a copper stabilizing matrix (Fig. 8). Diffusion barriers (niobium, tantalum, or vanadium) are also used to prevent reaction between the matrix and filaments during elevated-temperature processing. Applications for Nb_3Sn-based superconductors include large commercial solenoid magnets, alternating current (ac) motors, and generators for power generation, power transmission cables, and high-energy physics and fusion technology applications.

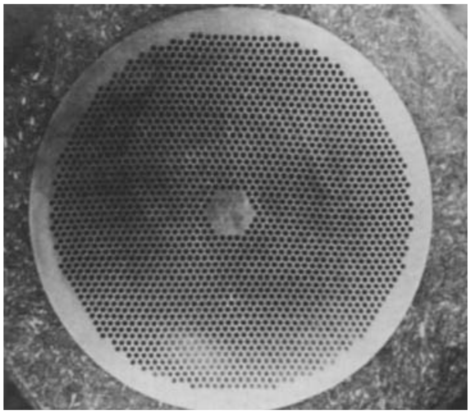

Fig. 6 Cross section of a composite superconducting wire containing 2070 niobium-titanium filaments surrounded by a copper matrix.

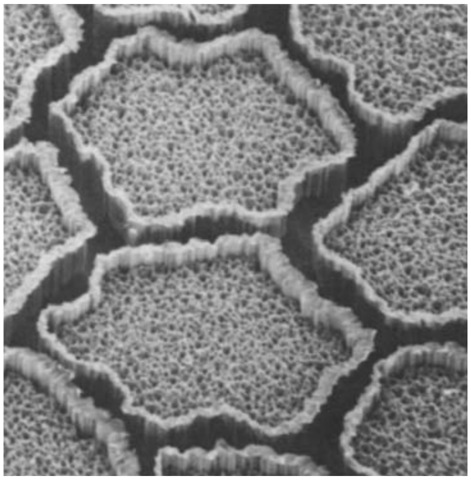

Fig. 7 Partial cross section of a multifilamentary NbTi composite with a niobium diffusion barrier (in high relief) around each filament. The copper interfilamentary matrix is deeply etched. Courtesy of Supercon, Inc.

Copper-Clad Brazing Sheet

This section focuses on clad brazing material, which is defined as any base material or alloy that is clad with an appropriate lower-melting-point brazing filler metal. A common example of such a laminated composite structure is copper-clad stainless steel sheet, which is used in the fabrication of heat exchangers. The copper layer acts as the brazing filler metal. Table 5 lists the typical brazing strip products that are used in the fabrication of compact heat exchangers for the automotive, truck, and aircraft industries.

General Characteristics. Clad brazing materials are produced as strips, using the roll bonding technique. The strips comprise a base metal that is clad with a brazing filler metal on either one or both sides. These products are used primarily in high-volume manufacturing operations, such as the production of heat exchangers, brazed bellows, and honeycomb structures. The use of a self-brazing sheet reduces the total part count, simplifies the assembly operation (because the brazing filler metal is always present on the core material), and reduces assembly time and, therefore, cost. In addition, there is no need for the application of flux, nor for its subsequent removal. This saves not only the initial purchase cost of the flux, but also the waste-management cost that is associated with the disposal of the spent material.

The thickness of the brazing filler metal used in a clad brazing material can range from 0.050 to 2.54 mm (0.002 to 0.100 in.) and will represent 5 to 20% of the total strip thickness. This range of strip thickness covers the majority of applications in the heat-exchanger industry. Figure 9 shows a typical clad brazing strip of copper-clad stainless steel.

Figure 10 depicts an automotive transmission fluid cooler that was assembled using clad brazing materials. A turbulator is brazed to a copper-clad stainless steel base and cover. The base and cover are formed from a stainless steel strip containing copper braze on one side. After brazing, the dimensional changes in this part are minimal, which is important when making a hermetically sealed heat exchanger.

Stamping, Cleaning, and Assembly. Clad metals should be considered to have the same forming characteristics as the core material. For example, a copper-clad 304L stainless steel system will have approximately the same ductility as the unclad 304L stainless steel. In some instances, the formability of the clad is better than that of the monolithic metal core because the copper on the surface of the stainless steel acts as a lubricant in the forming tool.

The tooling that is used for stamping parts from clad metals can be the same as that used to make the monolithic metal core. Because the brazing filler metal is an integral part of the core material, additional stamping and forming operations associated with the production of the shim material are eliminated.

The parts must be cleaned after stamping, prior to assembly. The procedure for the clad metal

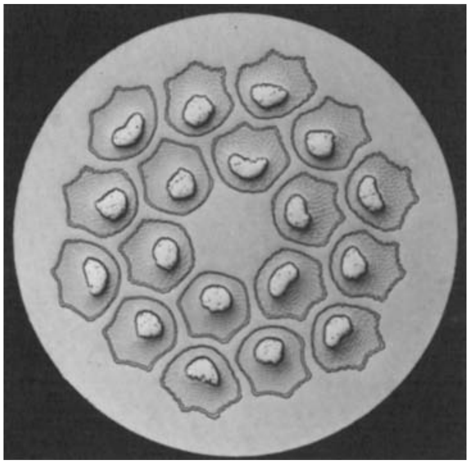

Fig. 8 Cross section of a multifilamentary Nb_3Sn superconductor wire (20 mm, or 0.78 in. diam). The 18 filaments in the wire each have individual bimetal diffusion barriers composed of concentric rings of niobium around vanadium. The matrix surrounding the filaments is copper. 75×

Table 5 Typical clad brazing strip products

Material	Clad layer ratios	Thickness		Temper	Tensile strength		0.2% yield strength		Elongation, %
		mm	in.		MPa	ksi	MPa	ksi	
C12200 copper clad to 409 stainless steel	10/80/10 5/80/15	0.51–0.76	0.020–0.030	Annealed	400	58	230	33	37
C12200 copper clad to 304L stainless steel	13.5/86.5	0.51–0.30	0.020–0.012	Annealed	635	92	290	42	56
	10/80/10	0.51–0.30	0.020–0.012	Annealed	620	90	275	40	55
C12200 copper clad to 1008 steel	10/80/10	0.38	0.015	No. 4 temper	380	55	290	42	35
C52400 phosphor bronze clad to C10200 copper	10/80/10	0.51	0.020	Annealed	275	40	97	14	48

parts should be similar to that used for cleaning the brazing filler metal shims or preforms. Copper-clad materials should be cleaned by a procedure that is appropriate for copper parts. Because the copper cladding is metallurgically bonded to the stainless steel core, wetting by the copper is ensured, as shown in Fig. 11, and the cleaning of any stainless steel parts is eliminated.

As with any copper part, care must be taken to prevent oxidation during assembly prior to brazing. Because the copper brazing filler metal is bonded to the stainless steel, the number of parts to be assembled is significantly reduced, and any handling of the thin, delicate brazing shim stock is eliminated. Unlike preform shims, which are usually used as flat, two-dimensional inserts, the brazing filler metal on the clad brazing material follows the complex surface topography that was stamped into the base material. Two examples are shown in Fig. 12 and 13. The former depicts a typical plate-type heat exchanger made from a clad brazing material, whereas the latter shows typical contoured joints that can be made easily with clad brazing materials.

One design benefit of using clad brazing materials is a reduction of the clearance between the parts, because no allowance needs to be made for the insertion of thick shims, wires, or preforms.

Another benefit is that less copper brazing filler metal can be used, because the concerns associated with the handling of shim material have been eliminated. The thinner copper coating thickness, which typically ranges from 0.025 to 0.075 mm (0.001 to 0.003 in.), results in less shrinkage during brazing and is less likely to cause large brazing fillets. Consequently, the possibility that excess brazing filler metal will clog small passageways is greatly reduced. The typical joint shown in Fig. 14 illustrates the small-geometry passages that can be achieved and the capillary action of the brazing filler metal as it forms the fillets at the joints.

Yet another benefit of using clad metals is that once the parts are assembled and fixtured, the brazing filler metal will not shift, move, or fall out as a result of the movement of fixtured assemblies prior to or during the brazing cycle.

ACKNOWLEDGMENTS

Portions of this article were adapted from:

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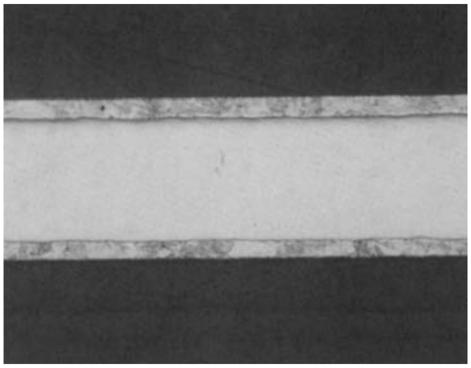

Fig. 9 Micrograph of typical clad brazing material: C12200 copper clad to type 304L stainless steel

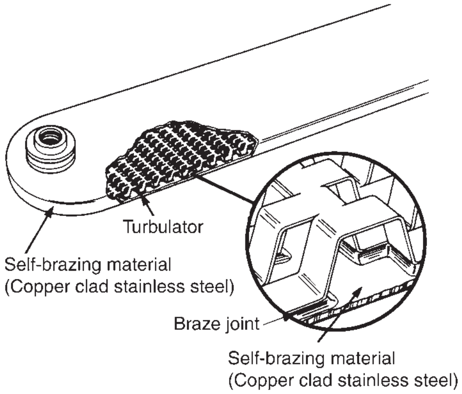

Fig. 10 Heat exchanger fabricated using clad brazing ("self-brazing") materials

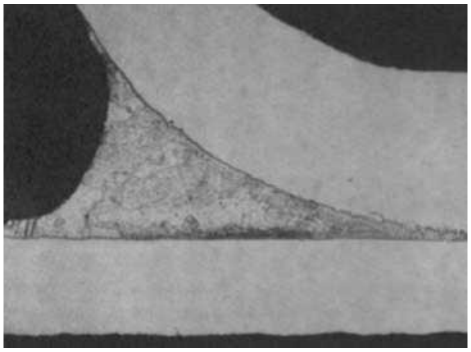

Fig. 11 Micrograph of a typical brazed joint that was formed using a clad brazing material

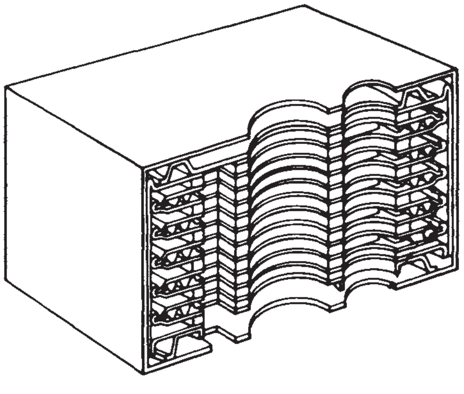

Fig. 12 Cutaway view of a typical plate-type heat exchanger

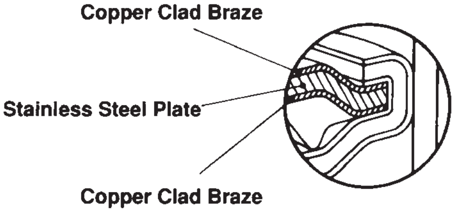

Fig. 13 Contoured joints that can be made easily with clad brazing materials

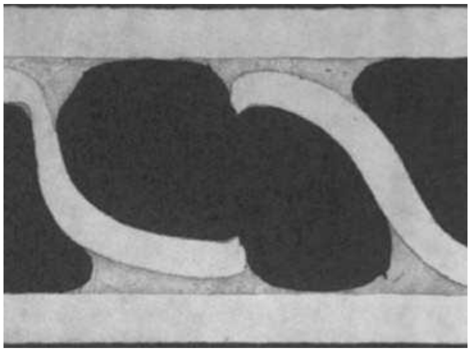

Fig. 14 Micrograph of a passageway in a heat exchanger fabricated using copper-clad stainless steel clad brazing material

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Copper and Copper Alloy Coatings

COPPER AND COPPER ALLOY COATINGS for both decorative and engineering applications are most commonly deposited by electroplating or electroless plating. Wear- and corrosion-resistant copper alloy coatings can also be applied by thermal spraying, weld surfacing, and solid-state cladding techniques (e.g., roll bonding). Each of these processes is discussed in this article with emphasis on electro- and electroless plating, which are the most commercially important processes.

For specialized applications, copper and copper alloys can be deposited by selective plating and chemical vapor deposition (CVD). Selective plating, also known as brush plating, is a variation of the conventional tank or bath electroplating process. Chemical vapor deposition, which is used in semiconductor manufacture, involves the deposition of thin copper films from a gas-phase precursor. More detailed information on these alternative copper coating processes can be found in *Surface Engineering*, Volume 5 of *ASM Handbook*.

Copper Plating

Copper plating deposits are used for both functional and decorative applications. They are used widely as underplates in multiplate systems, as barrier coatings, as stopoffs in heat treatment, and for heat transfer (e.g., as heat sinks). They also find use in electroforming, in electromagnetic interference (EMI) shielding, and in plating of electronic circuitry. The smoothness and brightness of copper deposits can be improved through buffing techniques because copper is a relatively soft metal. Copper deposits also act as thermal expansion barriers, especially in multiplate systems, due to their ability to absorb the stress produced when metals with different thermal expansion properties undergo temperature changes or if the deposit is thermally shocked. Similarly, corrosion failures from cracking caused by physical deformation of a part can be reduced by incorporation of a soft metal such as copper in the composite plate. Copper plating is also used as a final finish in some decorative applications and is sometimes used alone in applications where a durable and attractive surface is required. However, copper tarnishes and stains rapidly when exposed to the atmosphere and must be protected against this by an overcoating of clear lacquer or another suitable type of corrosion-resistant finish.

Copper can be deposited from both electrolytic and autocatalytic (electroless) electrolytes that are alkaline or acid. Cyanide and noncyanide pyrophosphate alkalines plus sulfate and fluoborate acid baths are the electrolytes used in the electrolytic deposition of copper deposits. Bath chemistries for autocatalytic deposition are described in the section "Electroless Copper Plating" in this article.

Alkaline Plating Baths

Alkaline cyanide copper solutions are used to plate the initial deposits (as a strike) on a variety of substrates. These baths can be easily controlled to produce thin deposits of relatively uniform thicknesses on all surfaces. They have the best macro throwing power, which describes the relative plating thickness distribution over all current densities. They also have traditionally been the most widely used strike and plating baths. However, with a greater emphasis on hazards and waste management, more recently developed alkaline, noncyanide systems are being examined and used as replacements for the copper cyanide systems in many applications. The deposits from the noncyanide copper processes compare favorably with those from the cyanide processes. These noncyanide processes require more precise control and more thorough cleaning and surface preparation compared to cyanide systems; however, their use does allow the elimination of cyanide in many plating facilities. Pyrophosphate alkaline copper solutions are seldom used because they are difficult to control and have limited operating ranges. They are used primarily to produce thick deposits because they exhibit good plating rates. They also find some use in through-hole printed wiring board applications.

Dilute cyanide and Rochelle cyanide baths are primarily used to deposit a strike coating of 1.0 to 3.0 μm (0.05 to 0.1 mil) of copper prior to further copper plating or electrodeposition of other metals. Often the coverage during this step is the most important in the overall performance and appearance of the final plated part. The high-concentration Rochelle cyanide bath can be used efficiently for plating up to approximately 8 μm (0.3 mil) thickness. With a modification in composition, the Rochelle electrolyte may be used for barrel plating. The Rochelle cyanide bath can be used for still-tank plating, with mechanical agitation, or more efficiently with air agitation. These baths can also be used with pulsed-current or periodic-reverse plating.

The cyanide copper plating baths listed in Table 1 are characterized by low-copper metal and high free-cyanide contents. This type of chemistry helps to clean the surface of parts during the plating operation. This results because of the tendency to produce gassing at the work due to the low cathode efficiencies. Although plating baths should not be used intentionally for cleaning purposes, the cleaning action of these cyanide baths can be an advantage, because difficult-to-clean parts can be given a copper strike in one of these baths with a high degree of success. Plating in other baths without the use of an alkaline cyanide copper strike could result in poor adhesion and incomplete coverage.

High-Efficiency Sodium and Potassium Cyanide Baths. With proprietary additives, the high-concentration baths are used to produce deposits of various degrees of brightness and leveling, in thicknesses ranging from 8 to 50 μm (0.3 to 2.0 mils). Thick deposits that are ductile and bright can be produced in routine operations. Under most plating conditions, the high throwing power of the electrolyte produces adequate coverage of sufficient thickness in recessed areas. Antipitting additives are generally used in these baths to promote pore-free (nonpitted) deposits.

Before being plated in the high-efficiency baths, parts must first receive a strike coating of copper approximately 1.3 μm (0.05 mil) thick from a dilute cyanide copper electrolyte.

The high-efficiency baths are characterized by relatively high operating temperature, high copper content, and rapid operation. Deposition rates are three to five times faster than the rates for the dilute cyanide and Rochelle cyanide baths. Parts to be plated in the high-efficiency electrolytes must be cleaned thoroughly, or the plate will be of inferior quality and the bath will require frequent purification for the removal of organic contaminants.

The potassium complexes formed by the combination of potassium cyanide and copper cyanide are more soluble than those formed when sodium cyanide is used; therefore, a higher metal content and higher rates of deposition are possible than with the sodium cyanide high-concentration bath. The potassium bath has more operating flexibility than the sodium bath and is favored because it raises the resistance to

Table 1 Compositions and operating conditions of cyanide copper plating baths

		Rochelle cyanide			High-efficiency	
Constituent or condition	Dilute cyanide (strike)	Standard barrel	Low concentration(a)	High concentration(a)	Sodium cyanide(b)	Potassium cyanide(b)
Bath composition, g/L (oz/gal)						
Copper cyanide	22 (3)	45 (6)	26 (4)	60 (8)	80 (11)	80 (11)
Sodium cyanide	33 (4)	68 (9)	35 (5)	80 (11)	105 (14)	105 (14)
Sodium carbonate	15 (2)	…	30 (4)	30 (4)	…	…
Sodium hydroxide	To pH	…	To pH	To pH	30 (4)	…
Rochelle salt	15 (2)(c)	45–75 (6–10)	45 (6)	90 (12)	…	…
Potassium hydroxide	…	8–15 (1–2)	…	…	…	35 (5)
Bath analysis, g/L (oz/gal)						
Copper	16 (2)	32 (4)	18 (2)	43 (6)	56 (7)	56 (7)
Free cyanide	9 (1)	27 (3.6)	7 (0.8)	15 (2)	18 (2)	18 (2)
Operating conditions						
Temperature, °C (°F)	30–50 (86–120)	55–70 (130–160)	55–70 (130–160)(d)	60–75 (140–170)	60–75 (140–170)	60–75 (140–170)
Cathode current density, A/dm^2 (A/ft^2)	1.0–1.5 (10–15)	…	1.0–4.0 (10–40)	2.0–5.0 (20–50)	2.0–6.0 (20–60)	2.0–6.0 (20–60)
Cathode efficiency, %	30–50	…	40–60	60–90	70–100	70–100
Voltage, V	6	6(e)	6	6	6	6
pH	12.0–12.6	…	12.0–12.6(d)	13	>13	>13
Anodes	Copper, steel	Copper	Copper	Copper	Copper	Copper

(a) Low concentration typical for strike; high concentration typical for plating. (b) Used with addition agents, as proprietary or patented processes. (c) Optional. (d) For zinc-base die castings, maintain temperature at 60–71 °C (140–160 °F) and a pH between 11.6 and 12.3. (e) At 6 V, the bath draws approximately 0.3 A/L (2 A/gal) through the solution. At 12 V, the bath draws 0.4 A/L (3 A/gal)

Table 3 Concentration limits and operating conditions of copper pyrophosphate plating baths

Constituent or condition	Strike	Typical
Concentration limits, g/L (oz/gal)		
Copper metal	9–11 (1.2–1.5)	19–30 (2.5–4.0)
Potassium pyrophosphate	112–205 (15–27)	235–405 (31–54)
Copper pyrophosphate	25–30 (3.3–4.0)	52–84 (7.0–11.0)
Ammonium hydroxide (conc. mL/L)	0.5–1.0	3.75–11.0
Potassium nitrate	1.5–3.0 (0.2–0.4)	3.0–12.0 (0.4–1.6)
Weight ratio (pyrophosphate:copper)	7.0–8.0:1	7.0–7.5:1
Operating conditions		
Temperature, °C (°F)	22–30 (72–86)	43–60 (110–140)
Current density, A/dm^2 (A/ft^2)	1.0–3.0 (10–30)	1.0–7.0 (10–70)
Cathode efficiency	…	95–100%
Voltage at tank, V	2–5	2–6
pH, electrometric(a)	8.0–8.5	8.0–8.7
Anodes(b)	Copper	Copper
Anode:cathode ratio	2:1	2:1

(a) May be maintained with pyrophosphoric acid and potassium hydroxide. (b) OFHC anodes

deposit burning and accordingly permits the use of higher current densities (faster plating rates).

Pulsed-current techniques are used frequently for operating high-efficiency electrolytes to produce greater leveling and uniform distribution of copper on complex shapes and to reduce plating time and the amount of metal required for plating complex shapes to a specified minimum thickness. Periodic reversal may be used to provide even higher leveling and better metal distribution that can be obtained with current interruption. Periodic reversal also improves the pore-filling characteristics of the high-efficiency electrolytes. Compositions and operating conditions of high-efficiency cyanide copper plating baths are given in Table 1.

The operation of high-efficiency electrolytes can be improved by the use of proprietary additives, which improve anodic and cathodic bath efficiency and anode corrosion. These additives produce matte to full-bright, fine-grain deposits. Proprietary additives are also used to control the effects of organic and inorganic contaminants.

Alkaline noncyanide copper plating is the subject of recent interest due primarily to environmental pressures on the use and disposal of cyanide-containing processes. These systems are being used in many of the same applications where cyanide systems have traditionally found success. In applications where copper is plated as a heat-treat masking barrier prior to carburizing, nitriding, or through hardening, the noncyanide processes have been shown to perform equally well or better than cyanide systems (Ref 1). These systems produce fine-grain, smooth, dense deposits that are nonporous and exhibit good bonding properties that can be deposited in rack, barrel, and continuous operations. These systems have also found use as strikes prior to the additional plating of metals and in EMI shielding applications. Their proprietary formulations are based on a variety of chelating ligands, most commonly carboxylic acids, amines, and phosphonates (Ref 2). Metallurgical analysis of these deposits shows a crystalline structure and surface morphology comparable to that produced by copper cyanide plating baths, except that the cyanide-free deposit is more compact (Ref 3). Concentration limits and operating conditions of these baths are given in Table 2.

Table 2 Concentration limits and operating conditions of alkaline noncyanide copper plating baths

Constituent or condition	Typical
Copper metal (from copper sulfate) concentration limit, g/L (oz/gal)	6–13.5 (0.8–1.8)
pH, electrometric	9.0–10.5
Temperature, °C (°F)	38–65 (100–150)
Cathode current density, A/dm^2 (A/ft^2)	0.5–3.0 (5–30)
Tank voltage	2–12
Anode:cathode ratio	1.5:1
Copper anodes	OFHC or EPT C11000 copper

Note: The systems currently commercially available are proprietary but typically contain an organic complexing agent, buffer salts, anode depolarizer, and proprietary addition agents.

Alkaline copper pyrophosphate baths are used for decorative multiplate applications including plating on plastic, plating through-holes of printed circuit boards, and as a stopoff in selective case hardening of steels. Concentration limits and operating conditions are given in Table 3.

Copper pyrophosphate bath characteristics are intermediate between those of cyanide and acid baths and are very similar to those of the high-efficiency cyanide bath. Electrode efficiencies are 100%; throwing power and plating rates are good. The bath also operates at an almost neutral pH. Deposits from pyrophosphate baths are fine-grain and semibright. For pyrophosphate plating on steel, zinc die castings, magnesium, or aluminum, a preliminary strike should be used. For striking, a dilute cyanide or pyrophosphate copper, nickel, or other solution may be used.

Acid Plating Baths

Electrodeposition of copper from acid baths is used extensively for electroforming, electrorefining, and decorative electroplating. Acid copper plating baths contain copper in the bivalent form and are more tolerant of ionic impurities than alkaline baths. They also have less macro throwing power and poorer metal distribution. Acid baths have excellent micro throwing power, resulting in the ability to fill or level scratches, grooves, or other substrate conditions, and additionally they are effective in sealing porous substrates. In most instances the smooth deposits produced by these solutions reduce or eliminate the need for mechanical smoothing for various substrates. A cyanide, noncyanide copper, or nickel strike must be applied to steel or zinc-alloy die castings before they are plated in acid copper solutions. Acid copper solutions cannot be used directly over substrates that are attacked by the high acidity or those where the copper forms an immersion deposit. Immersion deposits usually have poor adhesion to the substrate. Concentration limits and operating conditions of acid copper plating baths are given in Table 4.

The copper sulfate bath is the most frequently used of the acid copper electrolytes and has its primary use in electroforming. In this application, the advantages of acid copper lie in its strength and ductility. Acid copper sulfate is used to plate thick deposits over 150 μm (6 mils) on large nickel-plated rolls; it is then engraved to electroform textile printing screens. It is also used extensively for the application of copper as an undercoating for bright nickel-chromium plating, especially for automotive components. Plates and rolls have been plated with acid copper sulfate for graphic arts and rotogravure printing where thicknesses of 500 μm (20 mils) or more are not uncommon. Bright acid copper sulfate baths are used extensively as an underlayer in decorative plating of the plastic trim found on automobiles, appliances, and various housewares. By altering the composition of the copper sulfate bath, it can be used in through-hole plating of printed circuit boards where a deposit ratio of 1 to 1 in the hole-to-board surface is desired. In some applications, acid copper sulfate solutions are used to plate over electroless deposited copper or nickel. With additives, the bath produces a bright deposit with good leveling characteristics or a semibright deposit that is easily buffed. Where copper is used as an undercoating, deposit thicknesses will generally range up to about 50 μm (2 mils).

Typical mechanical properties of electroformed deposits from copper sulfate acid electrolytes are as follows:

Tensile strength, MPa (ksi)	205–380 (30–55)
Elongation, %	15–25
Hardness, HV	45–70
Internal tensile stress, MPa (ksi)	0–10 (0–1.45)

Table 5 shows how changes in operating variables and electrolyte composition can affect these properties.

The copper fluoborate bath produces high-speed plating and dense deposits up to any required thickness, usually 500 μm (20 mils). This bath is simple to prepare, stable, and easy to control. Operating efficiency approaches 100%. Deposits are smooth and attractive. Deposits from the low-copper bath operated at 49 °C (120 °F) are soft and are easily buffed to a high luster. The addition of molasses to either the high copper or the low copper bath operated at 49 °C (120 °F) results in deposits that are harder and stronger. Good smoothness of coatings up to 500 μm (20 mils) thick can be obtained without addition agents. For greater thicknesses, addition agents must be used to avoid excessive porosity.

Table 4 Compositions and operating conditions of acid copper plating baths

Constituent or condition	Copper sulfate bath		Copper fluoborate bath	
	General	Printed circuit through-hole	Low copper	High copper
Bath composition, g/L (oz/gal)				
Copper sulfate, $CuSO_4{\cdot}5H_2O$	200–240 (27–32)	60–110 (8–15)	…	…
Sulfuric acid, H_2SO_4	45–75 (6–10)	180–260 (24–35)	…	…
Copper fluoborate, $Cu(BF_4)_2$	…	…	225 (30)	450 (60)
Fluoboric acid, HBF_4	…	…	To pH	40 (5)
Bath analysis, g/L (oz/gal)				
Copper	50–60 (7–8)	15–28 (2–4)	8 (1)	16 (2)
Sulfuric acid	45–75 (6–10)	180–260 (24–35)	…	…
Specific gravity at 25 °C (77 °F)	…	…	1.17–1.18	1.35–1.37
Operating conditions				
Temperature, °C (°F)	20–50 (68–120)	20–40 (68–105)	20–70 (68–160)	20–70 (68–160)
Current density, A/dm^2 (A/ft^2)	2.0–10.0 (20–100)	0.1–6.0 (1–6)	7.0–13.0 (70–130)	12–35 (120–350)
Cathode efficiency, %	95–100	95–100	95–100	95–100
Voltage, V	6	6	6	6–12
pH	…	…	0.8–1.7	<0.6
Anodes	Copper(a)	Copper(a)	Copper(b)	Copper(b)

(a) Phosphorized copper (0.02–0.08% P) is recommended. (b) High-purity, oxygen-free, nonphosphorized copper is recommended.

Table 5 Variables affecting mechanical properties of electroformed deposits from acid copper sulfate electrolytes

Property	Operational effects	Solution composition effects
Tensile strength	Decreases slightly with increasing solution temperature. Increases significantly with increase in cathode current density	Relatively independent of changes in copper sulfate concentration within the range suggested. Relatively independent of changes in sulfuric acid concentration within the range suggested
Elongation	Decreases with increasing solution temperature. Increases slightly with increasing cathode current density	High acid concentrations, particularly with low copper sulfate concentration, tend to reduce elongation slightly
Hardness	Decreases slightly with increasing solution temperature. Relatively independent of change in cathode current density	Relatively independent of copper sulfate concentration. Increases slightly with increasing acid concentration
Internal stress	Increases with increasing solution temperature. Increases with increasing cathode current density	Relatively independent of copper sulfate concentration. Decreases very slightly with increasing acid concentration

Surface Preparation Considerations

Careful cleaning and preparation of the substrate material being plated is required for the effective electrodeposition of copper. Surface oils and greases, buffing compounds, rust, scale, and oxides, especially around weld or solder areas, must be thoroughly removed before copper plating to ensure adhesion and to minimize contamination of the plating bath. However, before considering any preparation, it is important to know the type of substrate being used as well as any substrate surface conditions that may be present. This information is important because the preparation cycles used prior to copper plating can vary considerably, depending on the alloy or type of substrate. Also, substrate heat treatment variations can contribute to complications in surface preparation. Because there are also variations in organic and inorganic soil conditions on the work to be plated, preparation cycles should include adequate cleaning, rinsing, and activation steps to ensure quality deposits. Some of the cleaning methods used to prepare substrate surfaces prior to copper plating include soak or electrolytic alkaline cleaning, alkaline derusting, vapor degreasing, and solvent cleaning.

Good rinsing between preparation steps is a very important and often-overlooked step in the preparation cycle. Time, temperature, and concentration considerations should be applied to rinsing techniques as well as to the cleaning processing solutions. Often, rinse times are too short, immersion temperatures are too cold, and the water flow rate is too low to adequately rinse cleaner films from the surfaces.

The activation step is usually carried out with the use of an acid to remove inorganic soils, oxides, or cleaner films from the surfaces. The acid used depends on the type of substrate to be plated. The most commonly used acids in preplate processes are hydrochloric acid and sulfuric acid. More information about the techniques used in these surface preparation processes can be found in *Surface Engineering*, Volume 5 of *ASM Handbook*. Specifications and practices for surface preparation and copper electroplating are given in Table 6.

Cyanide Baths. Although the dilute cyanide and Rochelle cyanide baths exert a significant cleaning action on the surface of the parts during the plating operation, thorough cleaning of parts to be plated in these baths is still necessary.

The high-efficiency sodium cyanide and potassium cyanide electrolytes have virtually no surface-cleaning ability during plating because of the absence of hydrogen evolution. Parts to be plated in these electrolytes must be thoroughly cleaned. Parts also must receive first a dilute cyanide copper strike approximately 1.3 μm (0.05 mil) thick.

Noncyanide Alkaline Baths. Unlike cyanide baths, noncyanide alkaline baths do not offer any cleaning, and parts plated in these electrolytes must first be thoroughly cleaned, rinsed, and activated. If being used as a strike prior to acid copper or other similar deposit, a minimum thickness of 5.2 μm (0.2 mil) is desired. These systems can be plated directly on properly prepared steel, brass, stainless steel, zincated aluminum, lead-tin, and most high-quality, properly prepared zinc-base die castings (Ref 4, 5). One advantage of the noncyanide electrolyte is the fact that accidental drag-in of acids poses no hazard of the evolution of poisonous cyanide gas, which could occur with cyanide copper electrolytes.

Pyrophosphate Baths. If pyrophosphate electrolytes are to be used, conventional cleaning cycles are generally satisfactory. A preliminary strike should be applied to steel, zinc-base die castings, magnesium, and aluminum. The strike solution may be a dilute cyanide copper, dilute pyrophosphate copper, or nickel. If a cyanide copper strike is used, adequate rinsing or, preferably, a mild acid dip following the strike is recommended before final pyrophosphate copper plating.

Acid Baths. When sulfate or fluoborate copper is to be deposited, steel or zinc must first receive a cyanide or noncyanide alkaline copper or nickel strike. With complete coverage, the strike may be as thin as 2 μm (0.08 mil). After the strike, the parts should be dipped in a dilute solution of sulfuric acid to neutralize solution retained from the alkaline strike bath. The parts should be rinsed thoroughly before acid copper plating. Nickel or nickel alloy parts, when surface activated by reverse-current etching in sulfuric acid, can be plated directly, provided contact is made to the work with the current or power on before immersion into the acid copper solution.

Bath Composition and Operating Variables

The compositions and analyses given in Tables 1 to 4 for cyanide, noncyanide alkaline, pyrophosphate, and acid copper plating baths may be varied within the control limits to satisfy requirements for specific applications.

Current density can be altered to effect more efficient control and to increase the deposition rate of copper. The data in Table 7 can be used as a guide to the selection of current density.

Impurities. The degree of control required to protect copper plating baths from impurities varies with the type of bath and the method of processing used. Known causes of roughness in copper deposits are:

- Dragover from cleaners, which results in the formation of insoluble silicates in the electrolyte
- Poor anode corrosion
- Insoluble metallic sulfides because of sulfide impurities
- Organic matter in the water used for composition, especially in rinse tanks
- Insoluble carbonates because of calcium and magnesium in hard water
- Oil from overhead conveyors
- Airborne dust or particles

If the level of impurities reaches a critical point, causing poor results, a batch carbon treatment or circulation through a carbon-packed filter may be required. For the noncyanide processes, a sulfur-free carbon pack must be maintained on the bath and changed weekly. Lead and cyanide are contaminants to these systems and tend to cause a black smutted deposit. When converting a plating line from a cyanide system to a noncyanide electrolyte, all associated equipment must be cleaned and thoroughly washed to ensure no cyanide contamination. *Caution: Cyanide remains in the system. Acids can be used only after all traces of cyanide have been eliminated.*

Purity of Water Used in Composition. The purity of the water used in the composition of the baths is important for all plating operations. Iron in the water causes roughness in the deposit if the pH of the electrolyte is above 3.5, where iron can be precipitated. Chlorides in concentrations greater than about 0.44 g/L (0.05 oz/gal) promote the formation

Table 6 Specifications and standards for copper electroplating

Specification	Uses
Copper plating	
AMS 2418	Copper plating
MIL-C-14550 (Ord)	Copper plating
ASTM B 503	Recommended practice for use of copper and nickel electroplating solution for electroforming
Copper plating in multiplate systems	
ASTM B 456	Specification for electrodeposited coatings of copper plus nickel plus chromium and nickel plus chromium
ASTM B 200	Specification for electrodeposited coatings of lead and lead-tin alloys on steel and ferrous alloys
AMS 2412	Plating silver, copper strike, low bake
AMS 2413	Silver and rhodium plating
AMS 2420	Plating, aluminum for solderability, zincate process
AMS 2421	Plating, magnesium for solderability, zincate process
QQ-N-290	Nickel plating (electrodeposited)
Surface preparation	
ASTM A 380	Practice for cleaning and descaling stainless steel parts, equipment, and systems
ASTM B 183	Practice for preparation of low-carbon steel for electroplating
ASTM B 242	Practice for preparation of high-carbon steel for electroplating
ASTM B 252	Recommended practice for preparation of zinc alloy die castings for electroplating
ASTM B 253	Practice for preparation of aluminum alloys for electroplating
ASTM B 254	Practice for preparation of and electroplating on stainless steel
ASTM B 281	Practice for preparation of copper and copper-base alloys for electroplating and conversion coatings
ASTM B 319	Guide for preparation of lead and lead alloys for electroplating
ASTM B 322	Practice for cleaning metals prior to electroplating
ASTM B 480	Practice for preparation of magnesium and magnesium alloys for electroplating
ASTM B 481	Practice for preparation of titanium and titanium alloys for electroplating
MIL-HDBK-132 (Ord)	Military handbook, protective finishes

Table 7 Estimated time required for plating copper (valence 1) to a given thickness at 100% cathode efficiency

Cyanide baths contain copper with a valence of 1. For baths containing copper with a valence of 2, such as noncyanide alkaline, sulfate, pyrophosphate, and fluoborate baths, double the time values given in this table. Values must be corrected for losses in cathode efficiency by adding the difference between the actual cathode efficiency and 100%; for example, for 70% cathode efficiency, add 30% to values in table to determine estimated time.

Thickness of plate		Plating time, min(a) at current density, A/dm^2 (A/ft^2)							
μm	mils	1.0 (10)	1.5 (15)	2.0 (20)	2.5 (25)	3.0 (30)	3.5 (35)	4.0 (40)	4.5 (45)
2	0.08	4	3	2	2	2	1	1	1
5	0.2	11	8	6	5	4	3	3	2
10	0.4	23	15	11	9	8	6	6	5
20	0.8	45	30	23	18	15	13	11	9
30	1.2	68	45	34	27	23	19	17	14
40	1.6	90	60	45	36	30	26	23	18
50	2.0	113	75	57	45	38	32	28	23
60	2.4	136	90	68	54	45	39	34	27
70	2.8	158	106	79	63	53	45	40	32
80	3.1	181	120	90	72	60	52	45	36

(a) To nearest whole value

of nodular deposits. Calcium, magnesium, and iron precipitate in the bath. Organic matter may cause pitting of deposits.

When plating in sodium or potassium, high-efficiency electrolytes and distilled, deionized, softened, or good quality tap water may be used for solution composition and for replenishment. Tap water with high contents of calcium and/or iron should not be used because it may cause roughness of the deposit. Softened water should be used with care, especially in plating baths where chloride contents are critical such as bright copper sulfate baths.

Agitation during plating permits the use of higher current densities, which create rapid deposition of copper. The amount of increase permissible in current density varies for different baths. Preferred methods of agitation for the types of baths are:

Cyanide baths	Cathode movement, air agitation, or both
Pyrophosphate baths	Air agitation
Acid baths	Cathode movement, air agitation, or both
Noncyanide baths	Vigorous air agitation

When air agitation is used, all airline pipes should be made of inert material or coated with an inert material to prevent attack by the electrolytes. The air used for agitation must be clean to avoid bath contamination. Filtered air from a low-pressure blower is required.

Ultrasonic vibration also has been used for the agitation of copper plating baths. This method does not largely improve the properties or appearance of electroplates, but it can improve plating speed by permitting an increase in the current density without the hazard of burning the parts. Increased plating speed does not necessarily justify the increased cost and complexity of ultrasonic operation, because the high-speed baths can usually be operated with a fairly high current density at nearly 100% efficiency.

Plating in Dilute Cyanide Baths

In the dilute cyanide bath, corrosion of the anodes increases with increasing concentration of free cyanide. Low free-cyanide content may cause rough deposits due to anode polarization; however, excessive free cyanide lowers cathode efficiency, resulting in thinner deposits per unit of time. Modifications of the pH, or alkalinity, of the strike compositions are used for striking various substrates. For use on steel, additional sodium hydroxide (NaOH) or potassium hydroxide (KOH) improves the conductivity of the solution and aids in protecting steel anode baskets, tanks, and other steel fixtures from corrosion. For use on zinc-base die castings, the hydroxide concentration is kept in the range of 1.3 to 3.8 g/L (0.2 to 0.5 oz/gal). For use on zincated aluminum alloys, the pH should be reduced to approximately 9.7 to 10.0 with sodium bicarbonate. The operator should keep adding tartaric acid or sodium bicarbonate to the solution to maintain the desired pH range (e.g., 10.0 to 10.5 for plating on aluminum alloys).

The dilute copper cyanide bath can be operated at room temperature, but the general practice is to operate the bath between 32 and 49 °C (90 and 120 °F) to increase the rate of deposition and to improve anode dissolution. This electrolyte is usually operated with a cathode current density of 1 to 1.5 A/dm^2 (10 to 15 A/ft^2). The tank voltage is normally between 4 and 6 V.

Agitation of the bath produces more uniform composition throughout the electrolyte, more uniform anode corrosion, and an increase in current densities where the brightest deposits are obtained. Current densities in excess of 5 A/dm^2 (50 A/ft^2) have been applied successfully by using air agitation of the solution and agitating the work.

Continuous filtration is preferred for dilute cyanide baths. Organic contamination or suspended matter in the strike is frequently responsible for roughness of copper plate subsequently deposited in the cyanide copper plating bath. Hexavalent chromium in the strike causes blistering of the deposit. Proprietary additives can be used to improve the bath operation, as well as aid in the control of organic and inorganic contaminants. These proprietary additives consist of organic complexing agents, such as tartrate salts. Organic reducing agents are used to control impurities such as hexavalent chromium. Wetting agents (surfactants) are used to control organic contaminants and to lower the surface tension of the plating solution, to allow better throwing power of copper over substrate irregularities, and to aid drainage and rinsing.

Plating in Rochelle Cyanide Baths

Rochelle electrolytes with lower metal concentrations can be used both for striking applications and, with higher metal concentrations, for plating applications. Rochelle salts produce some grain refinement, reduce the effects of some metallic contaminants, and aid in anode corrosion by increasing the anode current density range before anode polarization occurs. The Rochelle electrolyte can also be used for periodic-reverse plating with good results. Barrel plating with a Rochelle bath requires a variation in the chemistry. When plating parts that tend to nest or stick together during the barrel rotation, increasing the free cyanide to 25 to 30 g/L (3 to 4 oz/gal) or slightly higher to obtain adequate coverage on the nested parts is necessary.

Rochelle baths usually are operated at a current density between 2 and 5 A/dm^2 (20 and 50 A/ft^2). Substituting potassium salts for sodium salts in the baths with higher metal concentration, up to 38 g/L (5 oz/gal) copper, can increase the allowable current density to 6 A/dm^2 (60 A/ft^2), with the penalty of lowering the cathode efficiency. The Rochelle baths are usually operated at between 54 and 71 °C (130 and 160 °F) for best efficiency. The rate of deposition is higher at the higher temperatures. A high-efficiency electrolyte having a higher metal concentration can be operated at up to 77 °C (170 °F). For copper plating zinc-base die castings, the electrolyte is best operated at 60 to 71 °C (140 to 160 °F), provided the pH of the bath is maintained between 11.6 and 12.3. An increase in the operating temperature of Rochelle cyanide baths increases the efficiency of the anode and cathode; however, free cyanide decomposes more rapidly, which increases carbonate formation. An increase in agitation causes an increase in anode efficiency, but this also increases carbonate formation. Carbonates are always present in cyanide copper solutions from oxidation of the cyanide and, also, from adsorption of carbon dioxide from the air that reacts with the alkali in solution. Carbonates from a sodium copper cyanide plating solution can be removed by cooling the solution, which precipitates the less soluble sodium carbonate. High carbonate concentrations lower the anode efficiency, which accelerates additional carbonate formation in addition to producing rough or porous plated deposits (Ref 6).

Rochelle copper baths should be maintained at a pH between 12.2 and 13.0. Anode efficiency may be prohibitively low if the pH is too high. Raising the pH also decreases the voltage drop across the anode film. Figure 1 shows a buffer curve for adjusting the pH of Rochelle electrolytes.

Conductivity of the bath is improved by raising the free alkali cyanide and the concentration of

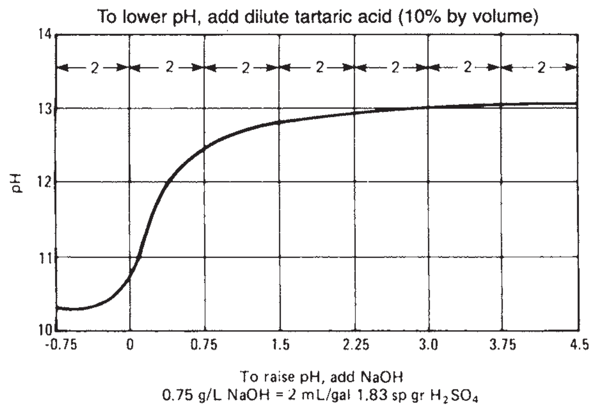

Fig. 1 Buffer curve for adjusting the pH of Rochelle electrolytes. sp gr, specific gravity. Source: Ref 7

LIVE GRAPH
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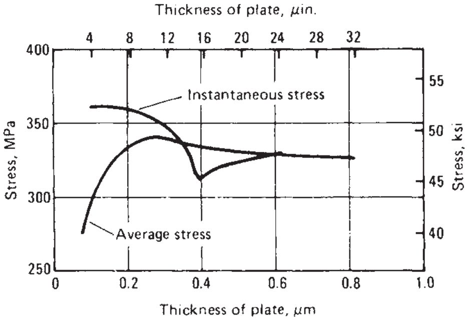

Fig. 2 Stress in thin copper plate deposited on stainless steel spirals. Stainless steel spirals are 0.127 mm (0.005 in.) thick. Source: Ref 8

the copper complexes. When depositing copper directly on steel, brass, or copper, conductivity can be improved by the addition of 2 to 15 g/L ($\frac{1}{4}$ to 2 oz/gal) of sodium hydroxide. Sodium hydroxide concentrations should be reduced if the electrolyte is used to deposit copper onto zinc-base die castings, aluminum, or magnesium.

Rochelle baths can become contaminated during plating of zinc-base die castings. Zinc contamination can be removed by electrolysis of the bath at room temperature, at the current density that produces the most brassy or off-color deposit, usually 0.2 to 0.3 A/dm^2 (2 to 3 A/ft^2). Iron, which forms complexes with cyanide, cannot be removed readily from the bath and causes a reduction in current efficiency. Drag-in of chloride ion from acid dips must be kept very low to prevent iron buildup due to dissolution of steel equipment. Bipolarity of steel tanks or heat exchangers should be avoided.

The Rochelle bath is susceptible to organic contamination, which can be controlled by the use of wetting agents. Organic contaminants should be removed by periodic batch treatment of the electrolyte with activated carbon, followed by filtration. Organic contamination is especially high in barrel plating. A low-foaming, free-rinsing surfactant or a dispersion agent must be used in barrel plating baths to prevent organic contamination from adversely affecting the quality of the plated deposit. Organic contamination can be controlled with carbon treatment methods. Continuous filtration of cyanide electrolytes is recommended to eliminate particulate matter or salts, which can result in rough deposits.

Increase in the current density or the presence of lead in the Rochelle cyanide bath causes an increase in the stresses of copper plate. These stresses can be reduced by increasing the concentration of copper in Rochelle baths. The addition of 15 g/L (2 oz/gal) of potassium thiocyanate produces an expansion stress instead of the usual contraction stress. Figure 2 shows stress in thin copper electrodeposits plated from a cyanide solution onto stainless steel.

Plating in High-Efficiency Sodium and Potassium Cyanide Baths

High-efficiency sodium and potassium cyanide baths allow the use of higher current densities. Cyanide plating baths typically decrease in cathode efficiency, or speed of deposition, with increasing current, which accounts for the good plate distribution (throwing power). The cathode efficiency approaches 100% only at low current densities, often 10 A/dm^2 or less. With more practical current densities of 2.0 to 3.0 A/dm^2, the cathode efficiency may drop 20%, especially with lower agitation rates. The sodium or potassium constituent improves the conductivity of the bath.

Operation of the sodium cyanide and potassium cyanide electrolytes at 66 to 74 °C (150 to 165 °F) produces quality deposits. Temperatures in excess of 74 °C (165 °F) allow the use of higher current densities, but breakdown of the cyanide becomes excessive at elevated temperatures. The anode current densities are limited by polarization, resulting in poor anode efficiency and higher voltage requirements. The cathode current densities are limited by burning of the deposit, resulting in reduced efficiency, loss of brightness, and roughness. These limits are higher in the potassium cyanide electrolyte.

Agitation of sodium cyanide and potassium cyanide high-efficiency baths is important for achieving maximum plating speed. Agitation can be accomplished by solution movement, cathode-rod movement, or use of air. Each type of agitation improves the maximum allowable current densities, with air agitation providing the greatest improvement. However, it should be noted that carbonate levels in air-agitated baths tend to increase at a greater rate than in baths using mechanical agitation. All three types of agitation may be used within a single bath. Solution movement can be accomplished by mixing or by the flow of solution through filtration equipment. Cathode-rod movement of about 1 to 2 m/min (3 to 7 ft/min) allows increased plating rates. Gentle air agitation should be supplied by the use of a low-pressure blower that has a clean, filtered air source. Care must be taken to use clean, oil-free air for agitation to avoid contamination of the plating solution.

Filtration is also essential when operating high-efficiency cyanide copper electrolytes, especially for plating deposits thicker than 13 µm (0.5 mil). Filtration equipment should have the capability of one to two complete turnovers of the solution each hour while removing particulate matter from the electrolyte. Roughness of the copper deposits from particulate matter is often caused by faulty cleaning or by the formation of metallic copper or cuprous oxide particles at the anodes. Suspended dirt or solid matter in the cyanide copper electrolyte also causes surface roughness. Anode bags of proper size, material, weight, and weave are beneficial in retaining particulate matter formed at the anode. Other foreign particles introduced into the cyanide copper electrolyte are removed by the filtration equipment.

Carbonate buildup in high-efficiency copper cyanide baths can adversely affect the bath operation. High concentrations of carbonate reduce plating efficiency and speed. Excessive carbonates also affect the smoothness of the deposits. Carbonate contents of 120 to 150 g/L (16 to 20 oz/gal) or more may result in lower plating efficiency and plating speed. Excessive carbonates can also lower and reduce the acceptable plating range. These effects are more pronounced in a sodium cyanide bath than in a potassium cyanide bath.

The primary source of carbonate formation is the breakdown of cyanide as a result of poor anode efficiency. Operating cyanide electrolytes at temperatures above the recommended levels can also result in carbonate formation. Operating temperatures above approximately 74 °C (165 °F) cause decomposition of the cyanide ion. Air containing high levels of carbon dioxide should not be used in air-agitated systems, because the carbon dioxide is dissolved by the alkaline plating solution, also forming carbonate. The air source for air-agitated systems should be placed where it provides a clean, fresh supply.

Excessive carbonates can be removed by freezing or precipitation with lime or proprietary additives. Sodium cyanide baths can be treated either by precipitation or freezing. Potassium cyanide baths can only be treated by precipitation. Freezing is not effective for potassium cyanide baths because of the high solubility of the carbonate salts.

Current interruption cycles frequently improve the operating range of high-efficiency sodium or potassium copper cyanide plating solutions. Current interruption cycles generally allow the use of higher current densities while maintaining bath efficiency. Current interruption cycles also improve the brightness of the copper deposits, and in some cases they give excellent deposit brightness from bright plating baths that are so contaminated that acceptable deposits cannot be produced when using continuous direct current.

Current interruption cycles in the range of 8 to 15 s plating time followed by 1 to 3 s current interruption are generally used. Plating times of less than 8 s and current interruptions of more than 3 s lower the net plating rate. Plating times of more than 15 s and current interruption of less than 1 s reduce the benefits obtained by using a current interruption cycle.

The use of periodic current reversal can also be used to great advantage in high-efficiency copper cyanide plating solutions. This technique involves plating parts in the conventional manner for a selected time and then deplating for a shorter period by reversing the current. Shorter periodic reversal cycles, such as 2 to 40 s of plating followed by 1 to 10 s of deplating (reversal), result in improved deposit brightness similar to that obtained with current interruption. A major advantage in using periodic reversal is the degree of leveling that can be achieved, particularly when relatively long reversal cycles are used. These longer cycles, in excess of 45 s direct with reverse cycles in excess of 10 s, can provide leveling characteristics in excess of 50%. The use of periodic reversal permits the use of higher plating and deplating current densities.

LIVE GRAPH
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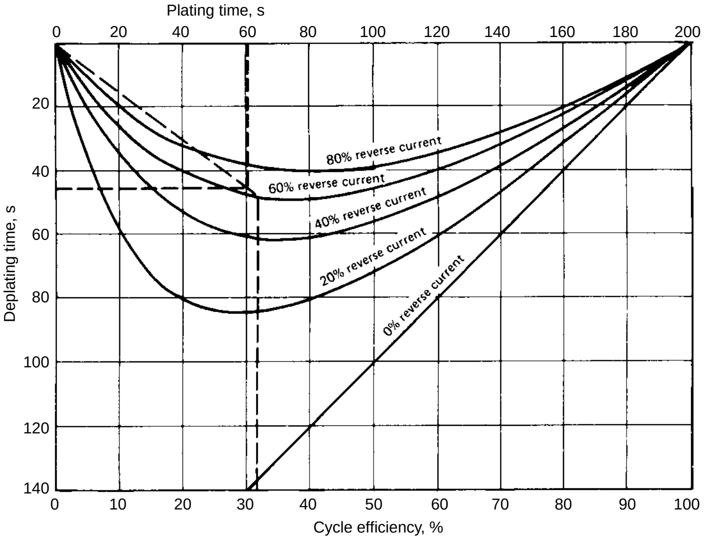

Fig. 3 Cycle efficiency during copper plating with periodic current reversal. Source: Ref 9

LIVE GRAPH
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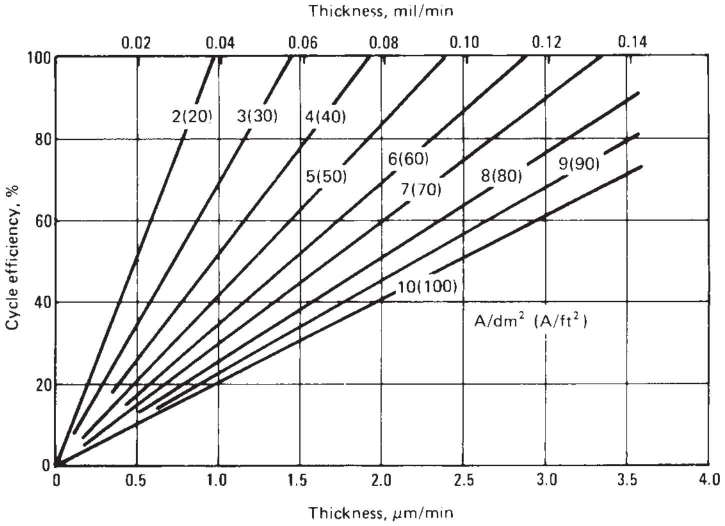

Fig. 4 Thickness of copper deposits as a function of cycle efficiency and current density during plating with periodic current reversal. Source: Ref 9

The leveling characteristics of the deposit are improved by increasing the reversal current, whereas cycle efficiency is increased by lowering the reversal current. Figure 3 shows cycle efficiency for periodic-reverse plating. Figure 4 indicates thickness of deposit as a function of cycle efficiency.

Another current-interrupting scheme being used for this and other copper plating systems is pulse plating. This normally involves a pulse power source (rectifier) that produces square-wave current pulses. *Square wave* conventionally suggests a pulse with a rise-and-fall time of approximately 10 to 85 μs and a standard frequency of 150 and 10,000 cycles. The periodic interruption of the current with proper time sequences allows much faster plating without surface burning, produces finer grain deposits, and increases throwing power and distribution.

Proprietary additives are used in high-efficiency copper cyanide baths to improve anode corrosion, increase both anode and cathode efficiencies, and control contamination. Organic and metallic additives are also used to improve deposit characteristics and brightness. These additives produce deposits ranging from matte to full-bright.

Plating in Noncyanide Copper Baths

The development and refinement of proprietary noncyanide copper baths continues today. The copper deposit from these systems is a fine-grain, dense deposit (Ref 3). The noncyanide copper systems exhibit excellent throwing and covering power, even in deeply recessed areas. In addition to eliminating the cyanide, these processes operate at much lower copper metal concentrations of 7.5 to 13.5 g/L (1 to 2 oz/gal). As a result, they offer additional savings in lowering waste treatment costs. Copper sulfate is the source of copper ions for these systems. The plating electrolytes producing these deposits are very stable compared to those of cyanide copper processes, because there is no decomposition of cyanide resulting in carbonate buildup.

Over the typical current density range of 0.5 to 3.5 A/dm^2 (5 to 35 A/ft^2), the cathode efficiency of noncyanide systems approaches 100%. The good efficiency tends to offset the lower deposition rate of divalent copper electrolysis compared to that of monovalent copper systems. Agitation has a dramatic effect on deposit appearance and cathode efficiency. To obtain a uniform, fine-grain deposit over a wide current density range, air agitation is required for these systems. Lack of agitation produces dull, burned deposits at average current densities of 1.5 to 2.0 A/dm^2 (15 to 20 A/ft^2).

Of the commercially available systems, one process is affected by the buildup of cuprous ions in the cupric phosphonate system, which results in rough, nonadherent copper deposits (Ref 10). To overcome this effect, the process uses continuous electrolysis carried out in an auxiliary tank with special ceramic or platinized anodes to oxidize the cuprous to cupric.

Because the operating pH of these systems is in the range of 9 to 10, these baths can be used as both strikes and plates. There are no special adjustments required for processing zinc diecast and zincated aluminum, as there are in cyanide copper plating. At pH values below 9, the deposits are brighter but adhesion is adversely affected. Values greater than 10 cause high-current-density dullness and can reduce the limiting current density.

These systems, unlike the cyanide systems, are more susceptible to metallic and organic contaminants. Iron, lead, and silver are critical impurities that should be removed by low-current-density electrolytic treatments. Organic impurities are treated using hydrogen peroxide and carbon treatments on a regular basis. Continuous filtration through a 10 μm retention-size cartridge is beneficial for the noncyanide systems. Occasional carbon filtration using a sulfur-free carbon can be used to control organic contamination. Noncyanide systems have very little tolerance to cyanide contamination. When converting cyanide plating lines to noncyanide processes, it is essential to clean and leach out all the cyanide from the tank linings, racks, filters, heaters, plating barrels, and any associated equipment.

Plating in Pyrophosphate Baths

Copper pyrophosphate plating baths offer a number of desirable features. Copper pyrophosphate forms a highly soluble and conductive complex when dissolved in potassium pyrophosphate solution. Potassium salts are preferred because of their higher solubilities. Copper pyrophosphate plating baths operate at nearly 100% cathode efficiency and provide good throwing power. They are noncorrosive because the operating pH is near neutral. Concentration limits and operating conditions for copper pyrophosphate baths are given in Table 3.

Pyrophosphate forms a highly soluble complex with copper. Excess pyrophosphate is necessary to increase the conductivity of the bath and to effect proper corrosion of the anodes. Ammonia assists anode corrosion, helps enhance the luster of the deposit, and aids pH control. Nitrate allows the use of higher operating current densities by inhibiting the reduction of hydrogen at the upper end of the current density range. The pH of the pyrophosphate bath is maintained between 8.0 and 8.8. A high pH reduces anode efficiency, and a low pH reduces the throwing power of the solution and the stability of the complex compound in solution with the formation of orthophosphate. The pH of the bath can be lowered with pyrophosphoric acid and raised with potassium hydroxide. Good agitation is also essential for consistent operation. Air agitation provides for good performance of the anodes and cathodes and is preferred to cathode agitation.

Pyrophosphate electrolytes can be operated at current densities up to 7.0 A/dm^2 (70 A/ft^2) or higher. The operating current density can be increased by agitation the solution or by increasing the temperature of the bath. The anode current density should be maintained between 2 and 4 A/dm^2 (20 and 40 A/ft^2).

High bath temperatures should be avoided, because excessive formation of orthophosphate occurs. Orthophosphate formed by the hydrolysis of pyrophosphate is beneficial up to about 90 g/L (12 oz/gal), because it promotes anode corrosion and acts as a buffer. Above this concentration, conductivity and bright plating range are decreased and banded deposits are obtained. Orthophosphate cannot be removed chemically from the solution. The concentration can be reduced only by discarding the bath or diluting and rebuilding the pyrophosphate plating solution.

Copper pyrophosphate plating baths are susceptible to organic contamination, including oil and excess or decomposed addition agents. These are removed by treatment with activated carbon and filtration. Cyanide and lead also contaminate the bath. Cyanide is removed by treatment with hydrogen peroxide and lead by electrolysis. Precautionary methods such as proper cleaning, adequate rinsing, and good solution control and maintenance prevent these contaminants from entering or building up in the bath, avoiding the need for frequent purification. Copper pyrophosphate solutions are tolerant of other metallic contamination.

Proprietary brighteners are available that refine the grain structure, impart leveling characteristics, and act as brighteners. However, decomposition products from an excessive additive concentration cause stress and brittle deposits. Thus, for quality deposits, additives should be added to the bath on an as-consumed basis.

Plating in Acid Sulfate Baths

The chemical composition of acid sulfate baths is simple. Copper sulfate pentahydrate and sulfuric acid are the primary constituents of the copper sulfate electrolyte. The metal ions are furnished by the copper sulfate. Sulfuric acid increases solution conductivity and helps prevent the formation of basic cuprous or cupric crystals on the anodes and the tank, which causes poor anode corrosion and roughness. Low sulfuric acid contents produce more high-current-density burn, poorer leveling, more low-current-density dullness, and more nodular deposits. High sulfuric acid has less effect on the deposit but increases the anode dissolution. With cathode efficiencies of 95 to 100%, the copper sulfate bath is easy to operate and control.

Many copper sulfate plating solutions require the use of additives to produce smooth, fine-grain, bright, leveled, and ductile deposits. Most of the addition agents used in copper sulfate plating solutions are proprietary formulations. These proprietary additives are capable of producing the desired characteristics in the copper deposit, and deposit hardness can be increased where necessary.

In copper sulfate systems that produce bright deposits, a catalyst must be added in addition to the primary constituents to avoid streaky deposits. This catalyst is chloride, which is maintained between 0.02 to 0.1 g/L (0.003 to 0.01 oz/gal), or 20 to 100 ppm. The chloride, usually added as hydrochloric acid, inhibits rough nodular plate from forming. Low chloride can cause dark deposits on the edges and high-current-density areas of the work, loss of leveling, loss of brightness, pitting, and poor anode corrosion. High chloride causes streaks, increased brightener usage, and loss of leveling and brightness in the bright bath formulations. High chloride can be reduced with zinc dust treatments or precipitation with silver.

If solution agitation or work movement is minimal, current densities should not exceed about 4.5 A/dm^2 (45 A/ft^2), because excessive anode polarization may occur and the deposits can be spongy. Where higher current densities are desired, such as electrotypes or wire plating, air agitation is used. Air agitation is necessary to accelerate ionic diffusion and produce high-quality, fine-grain deposits where current densities are in excess of 10 A/dm^2 (100 A/ft^2).

The effect of temperature changes on the grain structure and surface smoothness of deposits plated from the copper sulfate bath is less significant than the effect of changes in cathode current densities. An increase in temperature results in higher conductivity and reduced anode and cathode polarization. Increased temperature also reduces the tensile strength of deposits and increases grain size. Excessive temperatures should be avoided in copper sulfate baths where proprietary brightener formulations are used, because reduced plating ranges, excessive additive use, and solution contamination from additive breakdown result.

Care must be taken to avoid accelerated buildup of copper metal, as in cases where dragout rates are low or improper anode-to-cathode ratios are maintained. An increase in the concentration of the copper sulfate increases the solution resistivity and slightly reduces the anode and cathode polarization. Copper sulfate concentrations in excess of 248 g/L (33 oz/gal) may result in salt crystallization in the plating solution. Normal bath composition is restored by discarding a portion of the bath and adding water and sulfuric acid.

To improve the throwing power of some bright copper sulfate baths used for plating printed circuit boards, a low copper sulfate and high sulfuric acid electrolyte is used. The use of this electrolyte allows a nearly equal deposit distribution when plating the through-holes of the printed circuit board.

In sulfate electrolytes, impurities such as silver, gold, arsenic, and antimony can co-deposit with copper. Arsenic and antimony cause copper deposits to be brittle and rough, and silver may cause roughness. Nickel and iron impurities reduce the conductivity of the plating bath. Lead impurities do not codeposit with copper; however, they precipitate in the electrolyte. Soluble silicates may precipitate onto the work. Organic contamination from decomposition products of addition agents, tank linings, and anode bags can cause brittle or discolored deposits. These organics can be removed from the electrolyte by treating it with activated carbon.

Plating in Fluoborate Baths

Copper fluoborate and fluoboric acid are the primary constituents of the copper fluoborate electrolyte. The metal ions are furnished by the copper fluoborate, which is more soluble than copper sulfate used in the sulfate bath, and the anode current density is not critical. Therefore, the metal-ion concentration in the fluoborate bath can be more than twice that in the copper sulfate solution, and this permits higher cathode current densities. The cupric salts in the fluoborate bath are highly ionized, except for small amounts of less ionized complex salts formed with certain addition agents.

In the copper fluoborate bath, the anode current density can be as high as 40 A/dm^2 (400 A/ft^2) without excessive anode polarization. The effect of temperature changes on the grain structure and surface smoothness of deposits plated from the copper fluoborate bath is less significant than the effect of changes in cathode current density.

Agitation is preferred for the fluoborate bath, although acceptable deposits 25 μm (1 mil) thick have been produced in a high-concentration bath without agitation and with current density maintained at 35 A/dm^2 (350 A/ft^2). When agitation is used, a low-concentration bath operated at a current density of 4 to 5 A/dm^2 (40 to 50 A/ft^2) is preferred.

Although fluoborate baths containing no additives can produce dense and smooth deposits up to 500 μm (20 mils) thick, additives may be used to aid in the deposition of brighter or more uniform coatings or to assist in control of plating conditions. Although deposits from fluoborate baths are easily buffed to a high luster, brighteners of acetyl thiourea can be added to the electrolyte to produce bright coatings. The addition of free acid to the bath increases solution conductivity, reduces anode and cathode polarization, and prevents the precipitation of basic salts. Hard deposits and minimum edge effects result when molasses (1 mL/L, or 0.1 fluid oz/gal) is added to the electrolyte. If the pH of these baths exceeds 1.7, deposits become dull, dark, and brittle.

The resistivity of fluoborate electrolytes is reduced if the concentration of fluoboric acid exceeds 15 g/L (2 oz/gal) or if the concentration of copper fluoborate exceeds 220 g/L (29 oz/gal). In the fluoborate bath, the metal-ion concentration can be more than double that in a copper sulfate solution containing 50 to 75 g/L (6.7 to 10 oz/gal) of sulfuric acid.

In the fluoborate electrolytes, silver, gold, arsenic, and antimony may co-deposit with copper, but the effects of such impurities in this electrolyte have not been reported. Lead is the only metallic impurity known to interfere with the deposition of ductile copper deposits. Additions of sulfuric acid precipitate the lead. As with the sulfate electrolytes, organic impurities sometimes causes deposits to be brittle or discolored. They can be removed by treating the bath with activated carbon.

Wastewater Control and Treatment

Increasing regulations governing discharge water have led to improved techniques for reducing the quantities of wastes that must be treated. These techniques have not only reduced the quantity of wastewater to be treated but have also reduced the quantity of chemicals used and lowered water consumption. These methods can be applied to any plating operation. Many references are available, including Ref 11, that cover waste treatment technologies.

The use of counterflow rinses has reduced water consumption and wastewaters while maintaining adequate rinsing between plating operations. Reduced dragout of plating electrolytes can be accomplished by allowing processed parts leaving the plating solution to drain into the plating solution. Drip pans also reduce the amount of electrolyte dragout.

Closed-loop systems have dramatically reduced wastewater, lowered water consumption, and diminished chemical usage. Closed-loop systems allow recovery of rinse waters and chemicals by evaporative, reverse osmosis, or ion exchange recovery methods. Care must be exercised when using closed-loop systems, especially with copper plating, to keep impurities and contaminants from preplate operations out of the copper plating bath where they will be trapped by the closed-loop operation.

In any plating operation, wastewaters must be treated to reduce the hazardous materials to meet regulations. The general procedures for treating copper plating electrolytes and rinse waters resulting from copper plating systems are:

- Cyanide-bearing solutions require oxidation of the cyanide with an oxidizing agent such as chlorine or hypochlorite, followed by precipitation of the heavy metals.
- Noncyanide alkaline solutions are pH-adjusted and have calcium chloride added to precipitate the copper.
- Pyrophosphate wastes require low pH hydrolysis to orthophosphate, followed by precipitation of the heavy metals.
- Acid sulfate and fluoborate wastes are pH-adjusted to precipitate the copper.

Copper Plating Equipment

Construction materials for equipment are indicated in Table 8. Construction materials for racks and anodes are given in Table 9.

Tanks. For cyanide copper solutions, low-carbon steel tanks are suitable. Polypropylene tanks with adequate reinforcing may also be used, provided that the operating temperature is not excessive. Low-carbon steel tanks should be lined with rubber, polyvinylchloride, or another synthetic material that is not susceptible to attack by the cyanide plating solution. This will prevent bipolar effects, which may rob current from significant areas of the work. Tanks for alkaline noncyanide copper, copper pyrophosphate, acid copper sulfate, and copper fluoborate solutions should be of similar construction. Low-carbon steel tanks used for these solutions must be lined with the above materials to prevent the solutions from attacking the low-carbon steel, resulting in short tank life and immersion deposits. New tanks, as well as all other equipment coming in contact with the plating solution, should be leached before use to remove any materials that may leach into the plating solution and cause poor quality deposits. Leaching solutions should be similar to the plating solution to be used, such as a 15 to 30 g/L (2 to 4 oz/gal) caustic solution for copper cyanide or noncyanide copper equipment, or a 5 to 10% sulfuric acid solution for acid copper sulfate. When converting a tank or line that contained cyanide to a noncyanide electrolyte, it is essential to leach out all residual cyanide from the tank lining and any associated equipment.

Table 8 Materials of construction for equipment basic to copper plating

Tank linings are of rubber or plastic(a), or Koroseal.

Plating bath	Heating coils	Filters	Filter aids
Dilute cyanide	Low-carbon steel	Low-carbon or stainless steel; cast iron	Diatomite
	Teflon(b)	Low-carbon or stainless steel; cast iron	Cellulose
Rochelle cyanide	Low-carbon steel	Low-carbon or stainless steel; cast iron	Diatomite
	Teflon(b)	Low-carbon or stainless steel; cast iron	Cellulose
High-efficiency cyanide	Low-carbon steel	Low-carbon or stainless steel; cast iron	Diatomite
	Teflon(b)	Low-carbon or stainless steel; cast iron	Cellulose
Pyrophosphate	Stainless steel	Stainless steel	Diatomite
	Teflon(b)	Rubber- or vinyl-lined steel	Cellulose
Noncyanide alkaline(c)	Stainless steel	Stainless steel	Diatomite
	Titanium	Rubber- or vinyl-lined steel	Cellulose
Acid copper sulfate	Titanium(d)	Rubber- or vinyl-lined steel	Diatomite
	Teflon (b)	Rubber- or vinyl-lined steel	Cellulose
Fluoborate	Carbon(b)	Rubber- or vinyl-lined steel	Diatomite
	Teflon (b)	Rubber- or vinyl-lined steel	Cellulose

(a) Of approved compositions; in the absence of data on bath contamination and effects on deposites, compatibility tests are required. (b) Dupont trademark. (c) Polypropylene filter cartridges may be used. (d) Also for cooling coils, if bath is used below 32 °C (90 °F)

Barrels. High-speed copper plating solutions for barrel plating are being used in product operations. Polypropylene barrels have been used successfully for prolonged periods.

Anodes. The types of copper anodes used in each of the copper plating solutions are indicated in Table 9. High-purity copper anodes are recommended. Anodes with a lesser purity may form heavy sludges during electrolysis and contribute appreciably to roughness of the deposit. Anodes used for acid copper plating solutions should be phosphorized. These contain a small percentage of phosphorus, which helps to control chemical dissolution and limits the buildup rate of copper in the acid solution. These types should not be used in alkaline cyanide or noncyanide electrolytes, because anode polarization will develop and cause deposit roughness and more difficult copper metal control.

Copper anodes are available in many forms, such as bars, balls, or chips. Bars are suspended from the anode bar. Balls or chips are placed in titanium baskets.

The anode area in a copper plating solution should be controlled and maintained. If the anode area is not maintained, it decreases as the copper is dissolved and the anode current density rises, resulting in increased polarization and formation of undesirable films. These films can restrict current flow or sluff from the anode and cause roughness in the plating solution.

Anode Bags. Bags made of cotton, Dynel, or polypropylene are used in copper plating solutions. Cotton bags are preferred for cyanide copper solutions, and Dynel or polypropylene is used in the acid copper solutions. Bags are used to keep the fine particles formed at the anode from migrating to the cathode, resulting in roughness. The weave and weight of the anode bag are most important. The bag material must be capable of retaining the particles formed at the anode and at the same time allow the plating solution to flow freely around the anode. Anode bags are not generally used in pyrophosphate baths, because they interfere with dissolution of the anode by decreasing the circulation of the solution around the anode.

Characteristics of Copper Plate

Variations in processing during surface preparation or during plating have significant effects

Table 9 Materials for anodes and racks for use in copper plating

Racks are made of copper(a).

Plating bath	Anodes
Dilute cyanide	Copper; steel
Rochelle cyanide	Copper(b)(c)(d)
High-efficiency cyanide	Copper(b)(c)(d)
Noncyanide alkaline	Copper(d)
Pyrophosphate	Copper(b)(c)(d)
Acid copper sulfate	Copper(e)
Fluoborate	Copper(d)

(a) Racks are generally coated with an enert plastic coating to prevent plating. (b) Cast copper, high purity. (c) Rolled copper, high purity. (d) Oxygen-free high-purity copper. (e) Phosphorized copper on the quality of the copper electrodeposit. Certain variations can adversely affect the adhesion of copper to the substrate metal. Variations also can affect brightness, porosity, blistering, roughness, hardness, solderability, and leveling.

Brightness. Bright copper coatings are generally obtained by the addition of brighteners to the electrolyte, although buffing of the electrodeposited coating provides a higher luster. Plating from high-concentration cyanide baths with current interruption or periodic reversal of current also improves the luster of the copper coating.

Buffing or electropolishing the work before plating it in an electrolyte not containing a brightener results in deposition of a smooth and sometimes semibright coating. If an electrolyte containing a brightener is used, the luster of the coating is enhanced. The high cost of labor is a primary concern when buffing is considered as the method of brightening the coatings. Plating from high-efficiency cyanide baths with current interruption or periodic reversal of current also improves the luster of the deposits. Improved casting techniques and mechanical finishing before plating can improve the quality of the copper deposit.

Adhesion. Careful selection of substrate surface and proper preparation of the surface before plating are important for good adhesion. In general, cast and other porous surfaces are less receptive to good-quality electrodeposited coatings than wrought surfaces.

The kind of material to be electroplated with copper is another important consideration. For magnesium-base or aluminum-base die castings, the zincate layer between the substrate and the copper deposit is a critical control factor. For a properly activated stainless steel surface, a controlling factor for ensured adhesion of copper is the speed with which the workpiece is immersed in the bath. Some brighteners, especially organic brighteners, may adversely affect adhesion of subsequent electrodeposited coatings. Adhesion of copper electrodeposits from acid baths can be ensured only if a strike from a cyanide copper bath precedes copper plating.

Porosity. The degree of porosity in a copper coating can be controlled by the kind of copper plating bath selected, the composition and control of the electrolyte, the basis material to be plated, and the condition of the surface to be plated. The degree of porosity on the surface of the metal to be plated also dictates the techniques needed to minimize porosity in the coating. A porous surface has high surface area and requires high current density for efficient plating.

Blistering of copper plate, particularly when the plated work is subjected to heat, occurs mostly on zinc-base die castings. Blistering can also occur on parts made of magnesium or aluminum in any form, as a result of poor quality of castings, poor surface preparation, or both. Blistering of copper plate on zinc-base die castings plated in a cyanide strike electrolyte and then subjected to heat can be reduced by lowering the pH of the cyanide strike bath from the range of 12.0 to 12.6 to about 10. Caution must be used because operation at a pH value this low may result in the release of poisonous hydrogen cyanide gas. It is imperative that the plating bath be thoroughly vented.

Blistering of copper-plated magnesium and aluminum, especially during subsequent soldering or heating in service, is caused by poor adhesion at the zincate-copper interface. Unfortunately, blistering often does not become evident until subsequent electrodeposits have been applied and the coating has been subjected to heat. Exposing all copper-plated magnesium and aluminum parts to controlled heat representative of that to be subsequently encountered is good practice. This causes blistering before deposition of subsequent metal coatings if there is poor adhesion at the interface.

Roughness in copper deposits is often caused by foreign particles present in the bath as the result of faulty cleaning or by the migration to the cathode of metallic copper or cuprous oxide particles that form at the anode. Such roughness is especially likely to occur with the sodium cyanide high-concentration electrolytes and can be prevented by using anode bags.

Solderability of the coating is good when the copper surface is free of oxide, the coating is thick enough, and the adhesion of the copper plate is superior. Direct soldering of electrodeposited copper is not unusual for parts that are subsequently contained in hermetically sealed units.

Soldering is a routine operation for aluminum and magnesium electronic parts used in aerospace applications. A copper strike and copper plate frequently comprise the initial metal coating over the zincated surfaces of these parts, after which electrodeposits of other metals are applied before soldering. A top coat of tin, or of cadmium plate that has been chromate conversion coated, is a particularly effective means of producing a good combination of solderability and corrosion resistance for parts exposed to the atmosphere.

Hardness. Without the use of addition agents, cyanide electrolytes produce harder coatings than acid baths. With the use of addition agents, the hardness of copper deposits from any electrolyte can be increased. Hardness of the electrodeposit is generally associated with fine grain, but hardness can be increased by introducing preferred crystal orientation in the absence of grain refinement. Changes in the copper sulfate or sulfuric acid concentration of acid baths have little effect on the hardness of copper plate.

Leveling has a significant effect on the appearance of the copper coating, as well as on the appearance of the final product when other metals are subsequently plated over the copper. Often, the substrate metal does not have the degree of smoothness that is desired of the plated surface. Metal substrate surfaces can be mechanically or chemically worked to reduce surface roughness before electroplating; however, some copper electrolytes can produce substantial leveling in the deposited coating, thus reducing cost related to elaborate prepolishing or other means of smoothing the surface. The high-concentration potassium cyanide electrolytes produce excellent leveling when certain addition agents are added and interrupted current or periodic reversal is used during plating. Although somewhat less effective, high-concentration sodium cyanide baths, mixed sodium and potassium electrolytes, and Rochelle cyanide electrolytes also have good leveling characteristics with interrupted or periodically reversed current. Acid copper sulfate electrolytes also provide very good leveling characteristics.

Copper in Multiplate Systems

Electrodeposited copper is widely used as a basis for subsequent plated coatings in multiplate systems. The use of copper plate in copper-nickel-chromium systems is discussed in the article "Decorative Chromium Plating" in *Surface Engineering*, Volume 5 of *ASM Handbook*.

Cost

The cost of copper plating is influenced largely by the type of installation. In a modern, automated, multiple-phase shop, brighteners and wetting agents probably are the greatest cost factor. In a still-tank operation, the cost of labor is of major importance. An increase in current density reduces cost because of the reduction in time required to deposit a given thickness of coating.

For a routine plating operation, the cost of the copper deposited can be estimated with the aid of Fig. 5. For example, Fig. 5 shows that 120 g (4 oz) of copper is required for plating an area of 0.7 m^2 (7 ft^2) with a coating 20 μm (0.8 mil) thick. The cost of the copper coating is obtained by multiplying the weight of copper required by the cost of copper anodes. For areas larger than 2.4 m^2 (10 ft^2), multiply by the proper factor.

Copper Alloy Plating

Copper alloys are widely used as electroplated coatings, and they can be used with practically any substrate material that is suitable for electroplating. While alloys such as copper-gold and copper-gold-nickel are commonly electroplated, these are usually considered as part of gold plating technology. The most frequently electroplated copper alloys are brass (principally alloys of copper and zinc) and bronze (principally alloys of copper and tin).

The history of brass and bronze plating dates back at least as far as the 1840s. Early work that was commercially exploited occurred in Russia, France, and England. All of the early copper alloy plating solutions were cyanide based and used batteries for power. Progress was slow, with much of the work being of an academic nature. A major advance was made in 1938 when patents on a high-speed copper plating process by DuPont were extended to a high-speed process for plating of both yellow and

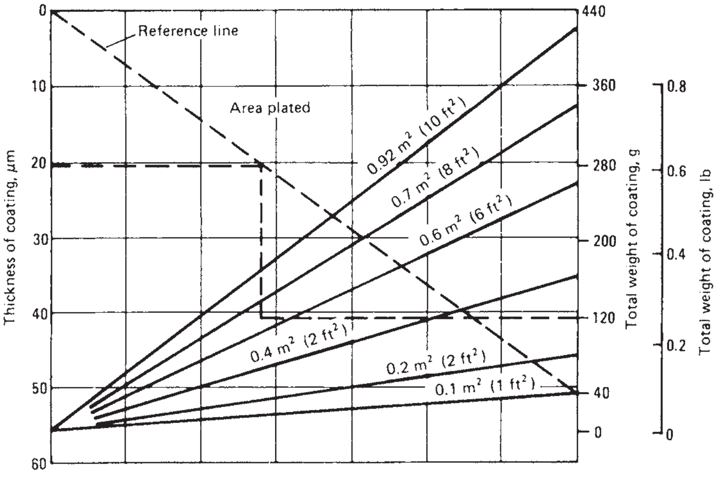

Fig. 5 Copper required for covering an area with a specific thickness

white brass (alloys containing about 70 to 80% Cu). The solution was cyanide based with a relatively high hydroxide content.

Brass Plating

The brass plating alloys considered in this section are binary copper-zinc alloys with zinc contents ranging from 10 to 40 wt%. As described in the section "Decorative Applications," the color of brass alloys varies according to their respective copper and zinc contents.

Applications

Decorative Applications. The largest use of brass plating is for decorative applications. Copper-zinc alloys that contain more than 60% Cu have distinct colors, depending on the composition. The 60Cu-40Zn alloys are pale yellow, sometimes with a brown cast. Alloys with compositions from 70Cu-30Zn to 80Cu-20Zn are yellow, with only slight color variations over this range. The 85Cu-15Zn alloys are darker and resemble gold. The 90Cu-10Zn alloys are darker still, with a reddish, bronze-like cast. With proper control of plating parameters, the variation of the alloy composition of brass plate can be kept within 1%, and consistency in color can be achieved. Plated alloys have the same color as wrought alloys of the same composition and surface treatment. Brass darkens with age due to the formation of copper oxide on the surface, so the appearance of old samples will not match that of newly plated items.

Yellow brass plate (nominally a 75Cu-25Zn alloy) is frequently flash plated over bright nickel plating to maintain its bright appearance; the surface is subsequently lacquered to preserve the finish. (*Flash plating* is the electrodeposition of a thin layer of material; plating times are usually under 1 min.) This type of flash plating is accomplished in both rack plating and barrel plating operations. Heavy brass plate can be buffed to a bright finish or oxidized to a dark finish; dark finished can be *relieved* (selectively buffed) for an antique appearance. Brass plated items can also be burnished in tumbling barrels to give a uniform bright finish. Cosmetic cases are frequently plated with an 85Cu-15Zn alloy to impart a golden appearance; the alloy can be applied as a flash plate or as a heavier plate that is subsequently burnished. Builders hardware plated with a 90Cu-10Zn alloy called *architectural bronze* uses these same techniques.

Engineering applications for brass plating are also important. Brass plate on sheet steel and wire performs a lubricating function in deep drawing and wire drawing operations. Brass plating is used to promote adhesion of rubber bonded to steel. For example, the wire in steel-belted radial tires is plated with a brass alloy containing between 63 and 70% Cu (to secure the best adhesion, it is important that composition limits of the alloy be kept within 1%). After plating, the wire is drawn from 1.2 mm (0.049 in.) to approximately 0.15 mm (0.006 in.) without a break in the coating. The wire bonds to rubber so that blistering of the tires does not occur. Brass is also plated on sheet steel from which parts are stamped.

Equipment

Brass plating can be done in all the standard plating equipment, including barrel, rack, and continuous wire and strip machines. Steel is a suitable material for tanks, coils, and filters. However, rubber- or plastic-lined tanks with stainless or titanium coils are preferred because the iron in the steel can form ferrocyanides that precipitate as zinc ferrocyanide, resulting in the formation of a gray-colored sludge.

Surface Preparation

Brass can be plated on most metallic surfaces (e.g., zinc castings, steel, nickel, and aluminum) after only standard preplating procedures. Direct brass plating of zinc castings requires the use of relatively heavy coatings to prevent diffusion of the brass into the zinc and a resulting loss of color; an intermediate layer of plate is often used for this purpose. One method of brass plating uses this diffusion interaction to produce brass by plating separate layers of copper and zinc of appropriate thickness and then heating the plate to create the alloy by diffusion.

Table 10 **Low-pH brass plating conditions**

Constituent or condition	Standard brass solution	High-copper brass solution
Makeup		
Sodium cyanide, g/L (oz/gal)	50 (6.7)	75 (10.0)
Copper cyanide, g/L (oz/gal)	35 (4.7)	45 (6.0)
Zinc cyanide, g/L (oz/gal)	10 (1.3)	7.5 (1.0)
Sodium carbonate, g/L (oz/gal)	10 (1.3)	10 (1.3)
Sodium bicarbonate, g/L (oz/gal)	7.5 (1.0)	7.5 (1.0)
Ammonia (aqua), %	0.5	0.1
Analysis		
"Total" sodium cyanide, g/L (oz/gal)	22 (2.9)	33 (4.4)
Copper (as metal), g/L (oz/gal)	23 (3.1)	22 (2.9)
Zinc (as metal), g/L (oz/gal)	6 (0.8)	4.2 (0.6)
pH	9.8–10.2	9.8–10.5
Operating conditions		
Temperature, °C (°F)	24–35 (75–95)	27–45 (80–113)
Current density, (A/ft^2) A/dm^2	≤3 (≤28)	≤2.5 (≤23)
Sodium cyanide to zinc		
Ratio	3.5:1	7.0:1
Range	3-5:1	6-9:1

Plate Thickness

Plate thickness can be varied as required from very thin flash deposits for decorative purposes to deposits over 0.02 mm (0.001 in.) thick. The heavier plates are needed to withstand buffing, bright dipping, antiquing, and other post-treatments that require heavier plate to maintain coverage.

Solution Composition and Operating Conditions

The majority of currently used brass plating solutions are based on cyanide complexes. No other material brings the deposition potential of copper and zinc so close together. Solutions using a pyrophosphate base have been used commercially with limited success. Brass solutions using polyhydroxy aliphatic chemicals have also been used commercially with limited success. Formulas for low-pH brass plating solutions are given in Table 10.

The formulas for standard brass plating solution can be varied to suit various uses while maintaining the ratios of components. The solution listed in Table 10 is well suited for barrel plating, where high efficiency is needed and good conductivity enables the use of maximum current. (Barrel plating is carried out at a voltage

Table 11 High-alkalinity brass plating solutions

Constituent or condition	Original (potassium)	High-speed strip plating	Modern
Makeup, g/L (oz/gal)			
Sodium cyanide	…	120 (16.1)	125 (16.8)
Potassium cyanide	125 (16.8)	…	…
Copper cyanide	44 (5.9)	100 (13.4)	75 (10.1)
Zinc cyanide	17.3 (2.3)	…	5 (0.7)
Sodium hydroxide	…	11 (1.5)	45 (6.0)
Potassium hydroxide	30 (4.0)	…	…
Analysis, g/L (oz/gal)			
Copper (as metal)	31 (4.2)	70 (9.4)	50 (6.7)
Zinc (as metal)	9.6 (1.3)	7 (0.9)	3 (0.4)
"Total" cyanide	80 (10.7)	50 (6.7)	53 (7.1)
Sodium hydroxide	…	11 (1.5)	45 (6.0)
Potassium hydroxide	30 (4.0)	…	…
Operating conditions			
Temperature, °C (°F)	45 (113)	80 (176)	70 (158)
Current density, A/dm^2 (A/ft^2)	1–4 (9–37)	3–16 (28–149)	1–8 (9–74)

of 6 to 14 V.) Where flash plating is used, the solution should be operated with the cyanide constituents at approximately half the amounts shown in Table 10. This reduced cyanide concentration allows the use of a wider range of current densities and results in excellent covering power. The plating efficiency at the reduced cyanide concentration is lower, but this is not a significant factor in flash plating. For rack plating, the optimum cyanide concentration is about two-thirds of that shown in Table 10; this level provides improved efficiency (compared to flash plating) while still allowing use of a wide range of current densities.

Formulas for high-alkalinity brass plating solutions are given in Table 11. The solutions listed in Table 11 may be varied to meet specific applications. The functions of the solution constituents are somewhat different than in the low-pH solutions. In the high-alkalinity solutions, the hydroxide and cyanide can work together so that a higher hydroxide content increases the zinc content of the deposit; thus, the ratio of cyanide to zinc is not applicable. The high-alkalinity solutions have high efficiencies and can be used at high current densities; the use of additives is needed to secure uniform color at low current densities. Thus they are difficult to use in barrel plating operations.

The copper cyanide content of the plating solution serves as a source of copper for the plating deposit but also is a major factor in plating efficiency. Cyanide is necessary to form the complexes that enable the copper and zinc to plate together to form brass. The ratio of cyanide to zinc in a conventional brass solution is the major determinant of the resulting composition of the plated alloy. The zinc can form a complex with either cyanide or hydroxide, depending on the hydroxide content of the solution. Cyanide is also necessary for solubility of the anodes. While zinc is usually added as cyanide, a very pure grade of zinc oxide can also be used.

The carbonate content of a brass solution is usually regarded as an impurity. It is formed by breakdown of the cyanide. Small amounts (15–20 g/L) are necessary in low-pH solutions to buffer the solution. Without carbonate, the solution is unstable and will give inconsistent plating. Hydroxide acts as a stabilizer in the solutions in which it is present, and thus carbonate is not essential in these solutions. The carbonate in the low-pH solutions exists as an equilibrium between carbonate and bicarbonate, making the use of both necessary to secure the proper pH. Carbonates in sodium baths can be frozen out; potassium baths can be treated with barium cyanide or barium hydroxide to precipitate the carbonate. It should be noted, however, that the use of barium cyanide or barium hydroxide creates insoluble sludges that are poisonous and cannot be destroyed, so that a hazardous waste is created. The use of calcium salts is recommended.

Hydroxide is used in the high-speed solutions to complex the zinc and increase efficiency. Increasing the hydroxide content increases the zinc content in the plated alloy.

Ammonia is a very important constituent in the low-pH brass plating solutions. Ammonia serves as a brightener and improves the appearance of plating accomplished at both high- and low-current densities. Ammonia is formed during plating by the decomposition of cyanide and is usually stable at temperatures up to 30 °C (86 °F). Higher temperatures (and the high hydroxide content of high-speed solutions) drive off ammonia faster than it is formed, making regular additions necessary to maintain color. Amines may be used to secure the benefit of ammonia at higher temperatures. An excess of ammonia causes the alloy to become richer in zinc; large excesses may result in white plate. Additions of ammonia do not change the pH level of the solution.

The temperature of the plating solution should be controlled to give constant alloy composition. A rise in temperature increases the copper content of the plate and also increases the plating efficiency.

Impurities in the solution affect the quality of the plating. Soluble oils and soaps will cause a brown smutty plate; they can be removed by carbon filtration. Tin is not usually troublesome but can cause dullness and white plate in recesses. Treatment is by dummy plating. Iron is not troublesome because it forms ferrocyanides, which precipitate out of the solution (but, as noted previously, may result in the formation of sludge). Lead is by far the most troublesome impurity. As little as 10 ppm Pb will result in red recesses in the plate, especially in barrel-plated parts. Higher amounts of lead will cause dullness, black areas, and blistering. The source of lead is usually the anodes, although lead pipe and other lead-containing objects in the solution can cause contamination.

Anodes for brass plating may be forged, cast, extruded, or rolled, and differences in performance are minimal. Balls or nuggets (chopped rod) are frequently used with steel or titanium baskets; these furnish a uniform high-current area, which is especially good for barrel plating where a relatively high current is used. Brass anodes should be used at low-current densities because high-current densities cause polarization. The anodes should be of high purity and contain less than 0.02% Pb and less than 0.1% Fe or other metals. The optimum composition of yellow brass anodes is 70% Cu and 30% Zn. Use of anodes with higher copper contents will necessitate frequent additions of zinc to the solution. Deposition of brass with higher copper content requires the use of 85Cu-15Zn or 90Cu-10Zn anodes; the composition of the anodes should approximate that of the alloy being plated. Anodes of the composition types mentioned previously are readily available. Steel anodes can be used in place of some of the brass anodes in order to lower the metal concentration in the solution.

Solution Analysis

Analysis and close control of the plating solution are essential for maintaining control of the alloy composition and color of the plated deposit. Analysis of copper and zinc content can be done by several methods, ranging from simple titrations to x-ray fluorescence. The results of these methods are generally accurate and reproducible.

Analysis of cyanide content is not so simple. Many methods analyze the "free" cyanide content, which is applicable to copper cyanide solutions but of dubious value when zinc is present, as in brass plating solutions. A simple and reproducible method is that used to determine the total cyanide content in zinc cyanide plating solutions: the cyanide is titrated with silver nitrate using a small amount of hydroxide in the sample being analyzed. This makes all of the cyanide in the brass solution available except that which is combined with the copper. A meaningful number is the ratio of this "total" cyanide to the zinc content of the solution. Another method for analyzing cyanide content involves distilling the cyanide from an acidified sample. This method is used to determine the cyanide content of waste solutions. Its results include cyanide present in the solution as ferrocyanide, so this method may indicate relatively high cyanide contents.

The pH level can be determined by meters, pH papers, or colorimetric comparison with suitable indicators. Hydroxide content can be determined by titration with acid using a high pH indicator. Carbonate content is easily determined by standard methods involving precipitation of the carbonate, separation, and titration.

Ammonia content can be determined by using a specific ion electrode but is more commonly determined by using a plating cell and checking the effects of ammonia additions. For the standard Hull cell, a total current of 1 A for 10 min can be used. The plating cell panel will also indicate the effect of impurities and additions determined by analysis. For high-speed solutions, a current of 2 A for 10 min is recommended. Effects at various current densities can also be determined by reading the panels. For flash plating, a Hull cell preplated with bright nickel and a total current of 1 A for 1 min is preferred.

Bronze Plating

The bronze plating alloys considered in this section are binary copper-tin alloys with tin contents ranging from 10 to 45 wt%. Ternary alloys of copper and tin with other metals can be plated, but control of the plating process is so difficult that the ternary alloys have found limited use.

Applications

Applications of bronze plating are varied. Alloys containing from 10 to 15% Sn are attractive and are used for decorative wares. These alloys have a gold color that is browner than true gold; equivalent copper-zinc alloys are pinker in color.

Bronze plating is used on builders hardware, locks, and hinges to provide an attractive appearance and excellent corrosion resistance. Bronze-plated steel or cast iron bushings replace solid bronze bushings for many uses. Bronze plating is used where improved lubricity and wear resistance against steel are desired. Its good corrosion resistance makes it desirable as an undercoat on steel for bright nickel and chromium plate. Speculum alloys (45Sn-65Cu) are similar in appearance to silver and are used almost entirely for decorative purposes.

Equipment

Equipment requirements for bronze plating are similar to those for brass plating; however, the tanks should be built to withstand the higher temperatures that are generally used for bronze plating.

Solution Composition and Operating Conditions

Copper-tin alloys are plated from a simple system containing copper as a cyanide complex and tin as a stannate complex. A typical formula is given in Table 12. Because there are no interrelated complexes in the bronze plating solution, the alloy composition is controlled by the relative amounts of copper and tin in the solution (i.e., raising the tin content of the solution produces a higher tin content in the bronze plate). Alloys with very high tin contents, such as speculum, can be produced by simply increasing the tin content of the solution. Additives can be used to produce a bright plate. These additives usually contain lead, which acts as a brightener in bronze plating solutions.

The temperature of the solution is an important plating variable. Temperatures below 40 °C (105 °F) generally produce poor deposits that are almost always higher in copper content. Higher temperatures create higher efficiencies and allow the use of a wide range of current densities. Normal temperatures are from 60 to 80 °C (140 to 175 °F). Barrel plating solutions usually use lower temperatures.

Anodes. The choice of anodes for bronze plating is complicated by a number of factors. The tin in bronze plating solutions is present as stannate, and when bronze alloy anodes are used, the tin dissolves as stannite. Bronze anodes, thus, are not suitable for use. Dual anodes of copper and tin, where each type of anode has a separate current source, have been used. To eliminate the need for separate current sources, it is customary to use oxygen-free copper anodes and to add stannate tin as stannic oxide, potassium stannate, or a slurry of stannite oxide to replace the tin being plated. The presence of stannite is indicated by a dark color in the solution. The stannite is oxidized to stannite by the use of hydrogen peroxide, which must be added slowly and with constant stirring to prevent reaction with cyanide. Other impurities are not of major concern in bronze plating solutions.

Table 12 Composition and operating conditions for a typical bronze plating solution

Composition of plated deposit, 88Cu-12Sn

Constituent or condition	Amount
Makeup, g/L (oz/gal)	
Potassium cyanide	64 (8.6)
Copper cyanide	29 (3.9)
Potassium stannate	35 (4.7)
Potassium hydroxide	10 (1.3)
Rochelle salt	4.5 (6.0)
Analysis, g/L (oz/gal)	
"Free cyanide"	22 (2.9)
Copper (as metal)	20 (2.7)
Tin (as metal)	14 (1.9)
Hydroxide	10 (1.3)
Operating conditions	
Temperature, °C (°F)	65 (149)

Waste Water Treatment

The treatment of waste water from brass and bronze plating operations is relatively simple. Normal procedures for eliminating cyanide (i.e., treating the waste water with chlorine and adjusting pH to precipitate the metals) are all that is required. The metallic limits and allowance for chemicals in the final discharge are fixed by federal, state, and local regulations. Waste water treatment systems are usually designed by engineers who are conversant with local regulations and can make sure the equipment meets the necessary requirements.

Electroless Copper Plating

Electroless, or autocatalytic, metal plating is a nonelectrolytic method of deposition from solution. The minimum necessary components of an electroless plating solution are a metal salt and an appropriate reducing agent. An additional requirement is that the solution, although thermodynamically unstable, is stable in practice until a suitable catalyzed surface is introduced. Plating is then initiated on the catalyzed surface, and the plating reaction is sustained by the catalytic nature of the plated metal surface itself. This definition of electroless plating thus eliminates both those solutions that spontaneously plate on all surfaces (homogeneous chemical reduction), such as silver mirroring solutions, and immersion plating solutions, which deposit by displacement a very thin film of a relatively noble metal onto the surface of a sacrificial, less noble metal.

The history of electroless plating began with the serendipitous discovery by Brenner and Riddell of electroless nickel-phosphorus during a series of nickel electroplating experiments in 1946 (Ref 12). Electroless copper chemistry was first reported in the following year by Narcus (Ref 13). The first commercial applicability of electroless copper was reported in the mid-1950s with the development of plating solutions for plated-through-hole (PTH) printed wiring boards. Electroless copper solutions resembling today's technology were first reported in 1957 by Cahill (Ref 14) with the report of alkaline copper tartrate baths using formaldehyde as the reducing agent. Copper baths of the 1950s were difficult to control and very susceptible to spontaneous decomposition. Over the years, continual advances in control and capabilities have taken place and continue to be recorded in a variety of reviews (Ref 15, 16). At present, not only are formulations extremely stable and predictable in behavior over long periods and under a wide variety of operating conditions, but they also provide copper deposits having excellent physical and metallurgical properties comparable with those of electrolytic deposits.

Electroless copper plates much more slowly and is a much more expensive process than electrolytic copper plating. However, electroless copper plating offers advantages over electrolytic plating that make it the method of choice in certain cases. Electroless copper plates uniformly over all surfaces, regardless of size and shape, demonstrating 100% throwing power. It may be plated onto nonconductors or onto conductive surfaces that do not share electrical continuity. The ability to plate large racks of substrates simultaneously is also an advantage in certain instances. These advantages have contributed to the choice of electroless copper in the applications to be discussed herein.

Bath Chemistry and Reactions

The theoretical basis of the electroless copper deposition process has been studied on numerous occasions and has recently been reviewed (Ref 17). As stated above, the minimum necessary components of an electroless plating solution are the metalzeen suggested (Ref 18) for use in electroless copper baths: formaldehyde, dimethylamine borane, borohydride, hypophosphite (Ref 19), hydrazine, sugars (sucrose, glucose, etc.), and dithionite. In practice, however, virtually all commercial electroless copper solutions have used formaldehyde (HCHO) as the reducing agent despite health concerns regarding formaldehyde exposure. This is due to the combination of cost, effectiveness, and ease of control of formaldehyde systems. Because of its overwhelming commercial importance, the discussion in this section is confined to formaldehyde-based systems.

For Cu(II), the relevant half-cell reaction for electroless deposition is:

$$Cu^{2+} + 2e^- \leftrightarrow Cu^0 \quad E^0 = +0.340\ V$$

For formaldehyde, the standard electrode potential, E^0, depends on the pH of the solution:

$$HCOOH + 2H^+ + 2e^- \leftrightarrow HCHO + H_2O$$
$$pH = 0 \quad E^0 = +0.056$$

$$HCOO^- + 2H_{2+}\ 2e^- \leftrightarrow HCHO + 3OH^-$$
$$pH = 14 \quad E = -1.070$$

Therefore, electroless copper solutions using formaldehyde as reducing agent employ high pH, above pH 12 (typical sodium hydroxide, NaOH, concentration is $>0.1\ N$; theoretically $0.1\ N$ = pH 13).

Complexing Agents. Because simple copper salts are insoluble at pH above approximately 4, the use of alkaline plating media necessitates use of a complexing, or chelating, component. Historically, complexing agents for electroless copper baths have almost always fallen into one of the following groups of compounds:

- Tartrate salts
- Alkanol amines, such as quadrol (N,N,N′, N′ tetrakis(2-hydroxypropyl)ethylenediamine) or related compounds
- EDTA (ethylenediamine tetraacetic acid) or related compounds.

Glycolic acids and other amines have also been reported (Ref 18).

Tartrates were used in the earliest baths and continue to be used, particularly for low-plating-rate (0.5 μm/20 min), low-temperature (near ambient) applications. Tartrates are more easily waste-treatable than the other two classes of chelates, but they have not readily lent themselves to formulation of faster plating systems.

Alkanol amines came into wide use in electroless copper baths in the late 1960s, with the advent of faster plating systems. This type of chelate made it possible to achieve "high-build" (≥2 μm/20 min) electroless copper solutions, and it continues to have wide use even today. Because quadrol and its analogs are liquids and totally miscible with water, they are not easily removed from the waste solution, and hence they are resistant to many conventional waste treatment procedures.

Ethylenediamine tetraacetic acid (EDTA) salts are also widely used for complexing electroless copper solutions; EDTA has certain desirable characteristics versus those of quadrol, based on waste treatability. Specifically, EDTA can be more easily separated (precipitated) from waste solutions by pH adjustment. Starting in the late 1970s, bath additives for EDTA systems (see subsequent paragraphs) were developed that allowed excellent control of plating rate, grain structure, and other important factors. Because of the very high affinity of EDTA for any metal ions, even small residual amounts of dissolved EDTA can draw potentially toxic metals into the waste streams. This has led to increased legislative efforts (notably in Germany and Japan) against use of this chelate and its derivatives. However, at present, the most commonly used plating baths are based on EDTA.

Additives. Besides the copper salt, the reducing agent, the source of alkalinity (i.e., NaOH), and the chelate, other important components are present in commercial electroless copper solutions. These components are generally considered the proprietary portion of the formulation. They control such parameters as initiation and plating rate, stability (versus dragged-in catalyst; versus excessively high bath activity; versus long shutdown periods; versus Cu(I) oxide), deposit stress, color, ductility, and so on. Prior to development of well-characterized and controlled trace additives, electroless copper baths were prone to "triggering" (spontaneous decomposition of the bath), "plateout" (decomposition over a prolonged standing period), "second day startup" (inability to induce a controlled plating reaction when first stored after makeup), dark deposit color, rough deposit, coarse grain structure, and so on. Literally hundreds of papers and patents have been published relating to these additives. Useful summaries of this data are available (Ref 20, 21).

Additives that stabilize the bath against various manifestations of undesired plateout are referred to as *stabilizers*. Understanding their composition, mechanism, and optimal replenishment rate is key to successful operation of a bath. They are usually employed at low concentrations, typically 1 to 100 ppm. Principal among the materials reported are compounds such as mercaptobenzothiazole, thiourea, other sulfur compounds, cyanide or ferrocyanide salts, mercury compounds, molybdenum and tungsten, heterocyclic nitrogen compounds, methyl butynol, propionitrile, and so on. Pressure from environmental and regulatory groups over the years has led to near-elimination of cyanide- and mercury-type additives. It is noteworthy that perhaps the most common stabilizer for electroless copper baths is a steady stream of air (i.e., oxygen) bubbled through the solution.

Additives that increase the plating rate of the solution are variously referred to as *rate promoters, rate enhancers, exhaltants*, or *accelerators*. This last term is particularly unfortunate and confusing in view of the use of the term *accelerator* to describe a key process step in electroless copper processes (see the section "Pretreatment and Post-Treatment Processes" in this article). Materials that have been reported to function as rate promoters include ammonium salts, nitrates, chlorides, chlorates, perchlorates, molybdates, and tungstates. Rate promoters may be present in the electroless formulation at concentrations of 0.1 *M* or higher.

Other additives may also be incorporated in certain cases. For example, surfactants may be used to improve deposit characteristics (Ref 22), and incorporation of excess halide ion into the formulation permits elimination of the normal accelerator step (Ref 23).

Typical examples of freshly made-up electroless copper baths are given in Table 13.

Plating Bath Reactions. The overall electroless copper plating reaction is theoretically given as:

$$Cu^{2+} + 2HCHO + 4OH^- \leftrightarrow Cu^0 + H^2 + 2\ H_2O + 2\ HCO_2^-$$

This equation calls for the consumption of four hydroxide ions and two molecules of formaldehyde for each atom of copper deposited. However, certain side reactions may also take place, the most common being the Cannizzaro reaction, which consumes additional caustic and formaldehyde:

$$2HCHO + OH– \leftrightarrow CH_3OH + HCOO–$$

In addition, other side reactions also occur, consuming formaldehyde and producing unwanted byproducts such as cuprous oxide, which can lead to bath decomposition unless suitable stabilizers are present.

Once the bath begins to be used, copper, caustic, and formaldehyde are consumed and must be replenished. This is typically carried out by routine analysis, either manually or electronically, with back addition of appropriate replenishment chemistries. Ordinarily, some bailout of the plating solution must be done at this point, to allow for the volume of new chemistry to be added. Because the anion of the copper salt (usually sulfate or chloride) and the cation of the caustic component (usually sodium) are not consumed, a buildup of sodium sulfate or chloride occurs. This can cause deleterious effects such as "voiding" or high deposit stress over prolonged bath life, particularly when bailout volumes are very low. In addition, formate ion builds up as a byproduct of the plating reaction itself. The extent to which the Cannizzaro reaction takes place also contributes to the quantity of byproduct buildup. Byproduct buildup can cause deterioration of bath and deposit properties (Ref 24, 25), and it is now typically accounted for during the bath formulation. Steady-state performance is achieved after a specified number of bath turnovers (or "cycles"), depending on the recommended bailout volume, and is typically controlled through specific gravity.

Deposit Properties

Electroless coatings are characterized by their thickness, purity, density, electrical properties, grain structure, and tensile properties. Other deposit properties, such as hydrogen inclusion, are also of interest.

Table 13 Examples of electroless copper formulations

	Low build (tartrate)	High build (quadrol)	High build (EDTA)	Full build (EDTA)
Copper salt, as Cu(II)	1.8 g/L 0.028 *M*	2.2 g/L 0.035 *M*	2.0 g/L 0.031 *M*	3.0 g/L 0.047 *M*
Chelate	Rochelle salt 25 g/L 0.089 *M*	Quadrol 13 g/L 0.044 *M*	Disodium EDTA dihydrate 30 g/L 0.080 *M*	Disodium EDTA dihydrate 42 g/L 0.11 *M*
Formaldehyde, as HCHO	10 g/L	3 g/L	3 g/L	1.5 g/L
Alkalinity, as NaOH	5 g/L	8 g/L	7 g/L	3 g/L
Additives(a)	<2 g/L	<2 g/L	<2 g/L	<2 g/L
Temperature, °C (°F)	20 (70)	43 (110)	45 (115)	70 (160)
Plating rate, µm/20 min	0.2	2.5	2	1

Note: The terms low build, high build, and full build are defined in the section "Deposit Properties" in this article. (a) Examples of additives: 2-mercaptobenzothiazole, diethyldithiocarbarmate, 2,2′-dipyridyl, potassium ferrocyanide, vanadium pentoxide, nickel chloride, polyethylene glycol

Plating Rate and Deposit Thickness

Not strictly a deposit property, plating rate is a key characteristic of an electroless copper plating bath. Plating rate and useful range of deposit thickness dictate the specific applicability of a formulation. As described subsequently, plating baths are typically categorized as *low build, high (heavy) build*, or *full build.*

Low build deposits about 0.5 µm (or less) in about 20 min and typically operates at ambient temperature. This was typical of the earliest stable bath formulations developed in the 1960s. These baths are traditionally tartrate-based; in fact, it has proven difficult to formulate stable, faster plating baths using a tartrate chelate system. These deposits are typically fine-grain and exhibit good deposit integrity. They are suitable for applications such as subtractive printed wiring boards, where an electrolytic plateup process follows immediately after copper deposition.

High (heavy) build deposits 2 to 3 µm in approximately 20 min and typically operates at elevated temperature (35 to 55 °C, or 95 to 130 °F), but room-temperature formulations are also available. These baths are usually based on EDTA or quadrol chemistry. Acceptable formulations of this type were first developed in the early 1970s. Earlier baths tended to give coarse-grain deposits and produced somewhat highly stressed deposits, especially at higher limits of deposit thickness. However, these formulations have been refined to a high degree and are readily controlled to give excellent deposit properties. Major applications for this type of bath are those where intervening process steps may occur prior to subsequent plateup, such as in pattern plate printed wiring boards.

Full build deposits are typically 25 µm or more and are deposited over a more prolonged plating cycle of up to 15 h. (By comparison, a typical electroplating process would deposit 25 µm of copper in 35 to 50 min.) The typical temperature of operation is 55 to 80 °C (130 to 175 °F). A fundamental requirement in developing this type of bath has been the achievement and maintenance of deposit characteristics such as high ductility and tensile strength, fine grain structure, low intrinsic stress, and so on throughout the thick deposit. This type of bath was first reported in 1964 (Ref 26) and has been employed primarily for additive-type printed wiring board applications. The main chelate used has been EDTA. This deposit typically represents the full metal thickness required for the applications and hence eliminates the need for electroplating altogether (Fig. 6). The very high expense of building a thick copper deposit using an electroless versus electroplating process is warranted (or required) for certain applications, such as when absolutely uniform thickness is needed, when electrically discontinuous surfaces are to be plated, or when very high aspect ratio holes are to be plated. For example, processes for fabricating multichip modules require use of a full-build electroless copper. In this application the copper thickness requirement may be substantially less than 25 µm. A number of advances in the area of full-build copper plating have occurred since 1990 (Ref 26–28). The most critical deposit characteristics are ductility and tensile strength, particularly at the elevated temperatures (260 to 288 °C or 500 to 550 °F) employed in the printed wiring board assembly processes. Current development activities in this area are aimed toward achievement of substantially higher plating rates without loss of deposit properties.

Intermediate thicknesses of copper are achievable by appropriate manipulation of the bath operating parameters. *Very slow* and *medium build* formulations are also applicable to some of the applications to be discussed.

Purity, Density, and Electrical Properties

Deposit purity of electroless copper films is somewhat lower than that of electrolytic films, due to codeposition of traces of electroless bath components. This affects several physical properties, including percent purity, density, and resistivity. Typical acid-copper electrolytic baths produce films of 99.9% purity, 8.92 g/cm^3 density, and 1.72 µΩ · cm volume resistivity (at 20 °C) (Ref 29), whereas the printed wiring board industry standard (Ref 30) for full-build electroless copper is 99.2% purity (min), 8.8 ± 0.1 g/cm^3 density, and 1.90 µΩ · cm (at 20 °C) resistivity (max).

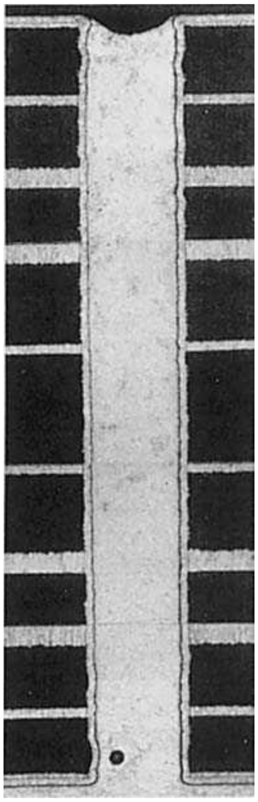

Fig. 6 Through-hole plated using full-build electroless copper

Grain Structure

Because electroless copper deposition is initiated on the randomly distributed catalyst particles on the substrate, initial grain structure is largely determined by that surface morphology. Bath formulation is of course a strongly determining factor as well, and it will control the grain structure as the deposit thickness increases. It is thought that fine-grain deposits, initiating at close proximity on the catalytic sites and coalescing to form a film early in the deposition process, offer superior copper quality in the early stages of film growth. Recently, full-build electroless copper grain structure was studied, correlated with etching rate in a variety of common copper foil etching solutions, and compared with typical electrolytic copper grain structure (Ref 28).

Tensile Strength and Ductility

Advances in electroless copper formulations, particularly for full-build applications in printed wiring board applications, have centered on achieving deposit mechanical properties, specifically tensile strength and ductility, that ensure the needed film reliability (Ref 31). Tensile strength of up to 490 MPa (70 ksi) and elongation of up to 15% can now be achieved (Ref 26), although these properties are not achieved from the same formulation. Improvement in the as-plated elongation values may be achieved with heat aging, at the expense of tensile strength. It has also been reported that ductility at thermal shock temperature (e.g., 260 to 288 °C, or 500 to 550 °F) may be significantly higher than as measured at ambient temperature. References 26 and 32 discuss the relative importance of these two properties in defining an ideal plated deposit.

Applications

Printed Wiring Boards (PWBs)

By far the most important commercial application of electroless copper plating has been the PTH process for fabricating printed wiring boards (PWBs). Prior to the mid-1950s, mounting components onto PWBs relied on mechanical interlocking using inserted eyelets. The through-holes could not be electroplated directly because the base material of the circuit board (paper-phenolic, epoxy-glass, or other dielectric) did not provide the needed electrical conductivity. Development of electroless copper plating solutions (Ref 33), made practical by concurrent development of suitable selectively adsorbing catalytic materials, led to a dramatic improvement in the reliability of printed circuit boards and prompted the rapid growth of the PWB market during the 1960s through 1980s.

Subtractive Processing. The vast majority of PWBs are made by a subtractive process using base material, typically epoxy-glass laminate, clad with electrolytic copper foil. The substrate is drilled, after which electroless copper is plated through the holes (and incidentally over the foil surface). Then electrolytic copper buildup and surface copper imaging (using dry film) take place; the order of these processes defines the fabrication process as either panel plating or pattern plating. In pattern plating, the plated areas are next overplated with a dissimilar metal (typically Sn/Pb), the dry film is removed, and all exposed copper is etched. In panel plating, no dissimilar metal plating is required; etching takes place immediately after imaging. The term “subtractive processing” arises from the fact that the circuitry is ultimately formed by removing base copper from the circuit board.

Although the basic overall process flow for fabricating a PWB has remained essentially constant for decades, the technology associated with every subprocess has undergone great improvement over that time period, and the electroless copper process is no exception. Improvements in electroless copper formulations, as discussed earlier, have greatly improved control of PWB processing and end product reliability. However, developments in PTH pretreatment have probably contributed even more greatly to end board reliability over that period. New hole preparation methods for multilayer boards provided such substantial benefits in terms of key criteria like copper coverage, adhesion (to laminate), and solderability (Ref 34) that two-sided boards are now also frequently processed through these additional steps.

Careful integration of the steps immediately preceding catalyzation has also ensured that the optimal uniform, yet minimal, catalyst film is deposited in preparation for plating. This has provided the key to achieving interconnect bonds sufficiently strong (Ref 35) to withstand multiple thermal shocks, thus assuring very high end-product reliability (see the section “Performance Criteria”). At present, the PWB market is under considerable environmental and cost pressure to replace electroless copper with a direct metallization process. Recent quality improvements such as those described present a formidable target for replacement technologies.

Additive processes for PWBs rely, as the name implies, on the buildup of the circuit copper over bare laminate. Variations on the fully additive process include semiadditive and partly additive processes. Description of these is documented in many published reports, which have been recently reviewed (Ref 36). Fully additive processes have been in use since 1964 and offer a number of advantages over conventional subtractive processing. Despite this, growth in the additive market has been slow; worldwide production has been estimated at 2 to 5% of the world PWB production (Ref 37, 38). This slow growth is due partly to the more difficult adhesion and selectivity requirements and partly to the lack of adequate physical properties in the full-build electroless copper that is an integral component of the process. However, in recent years the quality of full-build electroless has become satisfactory, and this, coupled with improved process control and new automatic bath controller, provides support for future growth of the additive PWB market.

Decorative Plating-on-Plastic (POP) (Ref 39)

Since the 1950s, plastics have been substituted for metals in a multitude of applications and for a variety of reasons, including weight advantages, cost advantages, and the relative ease of creating complexly shaped substrates through molding. These factors prompted the development of suitable decorative finishing processes, specifically plating processes, starting in the early 1960s. Electroless metal deposition as a base for a thicker, decorative electrolytic deposit has proven extremely reliable and commercially successful. For lower-performance applications, electroless nickel is a suitable choice. However, ever since the demonstration in the 1970s that electroless copper provides better resistance to environmental exposure (Ref 40, 41), it has become the material of choice in the majority of higher-performance applications, especially automotive. The molded substrate is chemically treated to improve adhesion of the copper film; then, about 0.5 to 0.75 μm of electroless copper is applied. Typically an electrolytic copper or Watts nickel strike follows, and then a thicker (12 to 25 μm) electrolytic bright acid copper deposit is applied. Finishing coats of electrolytic nickel and/or chromium plating are then applied.

Substrate materials (Ref 39) for decorative plating-on-plastic include acrylonitrile-butadiene-styrene (ABS), ABS/polycarbonate, polyphenylene oxide, polycarbonate, polysulfone, polyester, nylon, and so on. There are many grades for any given plastic, and these may differ considerably in plateability. Certain grades of foamed plastics may also be used. For decorative POP, ABS is by far the most commonly used plastic. Acrylonitrile-butadiene-styrene is a thermoplastic alloy with an acrylonitrile-styrene matrix that has butadiene rubber dispersed throughout. The butadiene is selectively etched by the pretreatment chemistry, creating a uniformly roughened surface suitable for plating.

In all POP applications, control of the molding process is critical. Care must be taken to avoid introducing stresses or strains, to avoid troublesome mold-release agents, to limit use of “regrind” resin, to ensure a resin-rich surface (in cases where fillers are used), and so on. The use of complexly shaped parts necessitates close attention to such details as mold design and maintenance, melt and mold temperatures, fill speed, and many other parameters. In designing or troubleshooting a plating-on-plastic process, it is critical to use molded parts of the exact grade and design to be used, as there is high interdependence between molding and plating processes.

Functional POP (Electromagnetic Interference Shielding)

Another commercially important application for electroless copper is electromagnetic interference (EMI) shielding of electronic components. The need to reduce (attenuate) electromagnetic signals (Ref 42) generated either internally or externally to a packaged component leads to the need to provide EMI shielding to the component. Electromagnetic interference shielding capability is directly related to the conductivity of the component; hence, metal cases are highly effective in attenuating EMI. However, the same factors (cost and weight) that led to the use of plastics as base materials for decorative applications have also led to their implementation in electronic cabinetry. Because plastic enclosures are poor at attenuating EMI signals, a variety of coating methods have been developed to address this need. Methods that address the requirements of EMI shielding of plastic enclosures include electroless copper plating, as well as various types of metal-filled paints, zinc arc/flame spray, sputtered or evaporated metals, and conductive foils/tapes. Table 14 summarizes and updates published data (Ref 43, 44) on the most common methods of shielding. Key in choosing a method is the attenuation (measured in decibels) over a desired frequency range (Ref 45). Note that decibels of shielding is

Table 14 Methods of electromagnetic interference shielding

Material/method	Shielding capability(a)	Process cost(b)	Advantages	Disadvantages
Zinc arc spray	H	H	Good conductivity; hard, dense coat; very effective	Special equipment needed; prone to flaking; may distort housing
Conductive paints				
Silver	VH	VH	Good conductivity; conventional equipment; resists flaking; easy to apply	Expensive
Nickel	L	M	Conventional equipment	Multiple coats needed; effectiveness not high; thickness causes problems
Copper	M-H	M	Conventional equipment	Multiple coats needed; thickness causes problems
Evaporated metal	M	H	Familiar technology	Size limited by vacuum chamber; expensive equipment
Sputtered metal	M	M	Good conductivity	Expensive equipment; may distort housing
Conductive foils/tapes	H	VH	Good conductivity; good for experimentation	Complex parts are difficult; labor intensive
Conductive plastics	L	L	No secondary process	Material expensive; poor attenuation
Electroless plating				
Copper (two-sided)	VH	M	Uniform thickness; good for all shape parts; resists chipping; good conductivity	Limited to certain plastics; two-sided process usually requires paint finish; prone to oxidation
Nickel (two-sided)	M	H	Same as above, except conductivity	High thickness required for effective shielding
Copper/nickel (two-sided)	VH	M	Same as copper only, plus corrosion resistant	Same as copper only, except no oxidation
Copper/nickel (one-sided)	H	M	Same as Cu/Ni two-sided; fewer chemical steps; allows molded-in color	Same as Cu/Ni two-sided, except no finish coat

(a) Attenuation: VH (very high), 90 to 120 dB + ; H (high), 60 to 90 dB: M (moderate), 30 to 60 dB; L (low), 10 to 30 dB; VL (very low), 0 to 10 dB (b) Cost: VH (very high), > \$3.25/ft^2; H (high), \$2.50 to \$3.25/ft^2; M (moderate), \$1.50 to \$2.50/ft^2; L (low), \$0.35 to \$1.50/ft^2; VL (very low), < \$0.35/ft^2. Source: Updated from Ref 43, 44

a logarithmic term, so a difference of 20 dB equals 100 times the shielding effectiveness.

Clearly, electroless copper is a very effective method of EMI shielding over a wide range of radio frequencies, having been first suggested in 1966 (Ref 46) and subsequently developed in the early 1980s (Ref 47). Considerable commercial activity has taken place, as several large computer manufacturers anticipated that higher "clock speeds" of electronic devices would require rapid conversion to the most effective methods of EMI shielding, such as electroless copper. However commercial activity using electroless copper for EMI shielding applications has lagged versus the rate previously anticipated. Sustained growth in the use of electroless copper for EMI shielding is probable in the future, because the increased clock speeds of the devices emitting the signals accentuate the need for more effective shielding.

When electroless copper is employed for EMI shielding, the conductive film used typically consists of electroless copper plating to a thickness of about 0.7 to 2 μm, overplated with a thin film (0.25 to 0.5 μm) of electroless nickel. The parameter used to specify copper thickness is resistivity (Ref 48); normally less than 0.05 Ω/point-to-point over a set distance is readily achievable using electroless copper. The nickel contributes virtually nil to the shielding effectiveness (Ref 49), but it provides durability and corrosion resistance.

Specific substrate resins used in electronic enclosures include solid and/or foamed forms of ABS, polycarbonate, ABS/polycarbonate alloys, polyphenylene oxide, polystyrene, and polysulfone. A newly emerging, and potentially very large, market involves electroless copper for shielding fabric used in cable, military, and wall covering applications.

Electroless copper plating for EMI shielding may employ either a two-sided or single-sided process. In the two-sided process the entire cabinet is treated and plated; this approach generally requires a finish coat of paint. The single-sided process involves plating of the interior surface only; thus the molded plastic surface represents the final surface finish. These two processes involve totally different pretreatments, as discussed in the section "Pretreatment and Post-Treatment Processes."

Hybrid and Advanced Applications

Molded Interconnect Devices. Following advances in control and capability of imaging and plating technologies, and commercialization of high-performance injection molded plastics, a natural development was the molded circuit board, or molded interconnect device (MID). Adhesion promotion principles developed for the decorative POP industry have been applied to devising adhesion promotion processes for a variety of engineering thermoplastics (Ref 50), permitting deposition of adherent electroless copper deposits that could be built up in thickness and imaged similarly to conventional PWBs.

In certain cases, conventional plastics such as ABS have been used as MID substrates. However, in order to survive board assembly temperatures, more advanced plastics are often required. These include polyetherimide, polyethersulfone, polyarylsulfone, liquid crystal polymers, and so on. Molding requirements are even more critical than those for decorative POP, due to the need for higher levels of adhesion (typically $\geq$ 1.1 kN/m, or 6 lb/in., peel strength, versus $\sim$ 0.7 kN/m, or 4 lb/in., for decorative POP) and due to the stresses induced by plateup, imaging, and assembly processes. Certain of the plastics mentioned have proven more amenable than others to development of suitable adhesion promotion processes. Polyetherimide, in particular, has proven to be compatible with surface chemistry-altering pretreatments that produce very strongly adherent electroless copper (Ref 51), while not roughening the substrate surface excessively. The latter characteristic is particularly important when fine-line imaging processes are to be employed later in the process.

Depending on the MID design and process chosen, plateup of the initial electroless copper strike plate may employ either electrolytic copper or full-build additive copper (20 to 35 μm). Imaging of three-dimensional substrates has necessitated development of inventive materials and processes (Ref 52). Electrodeposited photoresists, as well as novel methods of exposure and related equipment, have proven key in this effort.

The MID market has proven to be feasible and has achieved commercial success in several dedicated facilities. Many ingenious and cost-saving devices have been designed and are in production (Ref 50, 53). Figure 7 demonstrates a number of commercially produced MIDs. However, this market has not achieved the level of acceptance predicted in the late 1980s, due to the need for high volumes of a given design to amortize mold costs, the failure of materials costs to come down to required levels, and the tendency of electronic designers to employ more familiar methods, such as conventional PWBs, whenever possible.

Composite Connectors. The composite connector application is a hybrid of two-sided EMI shielding with molded interconnects. These parts are currently made of aluminum, and for all the usual reasons, considerable interest lies in replacing the aluminum with a lighter material such as plastic. The physical requirements of the connector are such that only advanced engineering plastics, such as those used in the MID market, are suitable. The parts must be plated, not to form circuitry but to provide EMI shielding. Fabrication of these devices employs the same plastics and pretreatments for electroless plating that are employed for molded interconnects. Due to the durability, lubricity, and hardness requirements of the finished parts, the electroless nickel overcoat is built up to a rather higher thickness ($\sim$5 μm) than that for EMI shielding of electronic cabinetry. Examples of some plastic composite connectors, processed through electroless copper and nickel, are show in Fig. 8.

Multichip Modules. Progress in semiconductor technology continues to place increasing demands on interconnection and assembly technology. In the 1980s, the response to this demand on the PWB side was increasing numbers of layers and finer circuitry. However, this trend cannot be sustained at the needed rate (Ref 54), leading to the requirement for an intermediate level of interconnection onto which bare chips may be mounted (Ref 55). These devices, known as multichip modules (MCMs), may be fabricated using several approaches (Ref 56-58). However, a common feature is the use of full-build electroless copper (Ref 59) to build up the conductive traces.

An example of a fabrication process for a multichip module (MCM) is given in Fig. 9. The electroless copper process generally follows along the lines of the PTH and POP processes. Adhesion promotion for the metallization layer to the unique dielectric materials employed in MCMs can be a challenge in itself. Conventional "swell and etch" approaches are normally used; other approaches are also in development.

Silicon Devices. Recently some interest has arisen in employing electroless copper for integrated circuit manufacture (Ref 60-62). It is felt that aluminum, which is used in providing the conductive path on chips, may not be sufficiently conductive at the very high resolutions required in future devices. Very thin films of electroless copper (~0.1 to 0.2 μm), deposited additively in channels between a photodefined temporary film, have been used.

Pretreatment and Post-Treatment Processes

Properties of the electroless copper bath and deposit are highly dependent on the pretreatment (and, to a lesser degree, the post-treatment) system used. Although the plating bath is the most visible and complex-to-operate solution in the process line, a mistake commonly made is to blame any process problem on the plating chemistry itself. In a majority of cases, this is not the case. Lack of correct attention to the details of the preplate chemistry is more likely to have caused the problem.

This section concentrates on the main commercial processes for electroless copper, namely PTH, decorative POP, and EMI. Other applications employ similar processes, some of which are shown in the overall process flow summary given in Fig. 10. Note that rinse steps are not shown; unless stated otherwise it should be assumed that one or more rinse steps intervene between every two process steps. This is not to minimize the importance of adequate rinsing; the adage of "it's the water" has been proven true in many troubleshooting situations. Specific requirements of water quality for PWB plating processes have been published (Ref 63).

Other than single-sided EMI, which is discussed separately, electroless copper processes are similar in terms of functionality of pretreatment steps. As described subsequently, pretreatment for PWBs and POP EMI shielding can be categorized as either *gross surface preparation* or *immediate preparation for plating*.

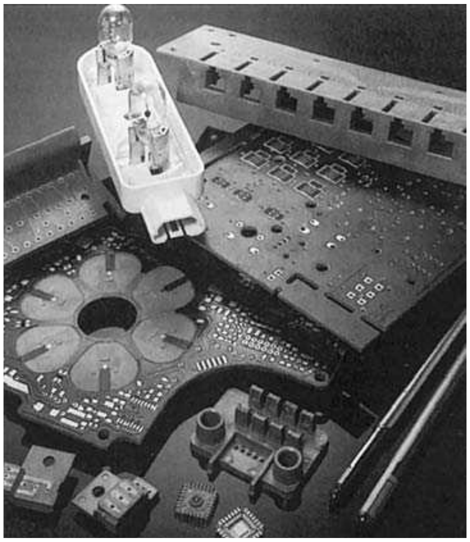

Fig. 7 Examples of commercially produced molded interconnect devices

Fig. 8 Examples of plastic composite connectors plated with electroless copper and nickel

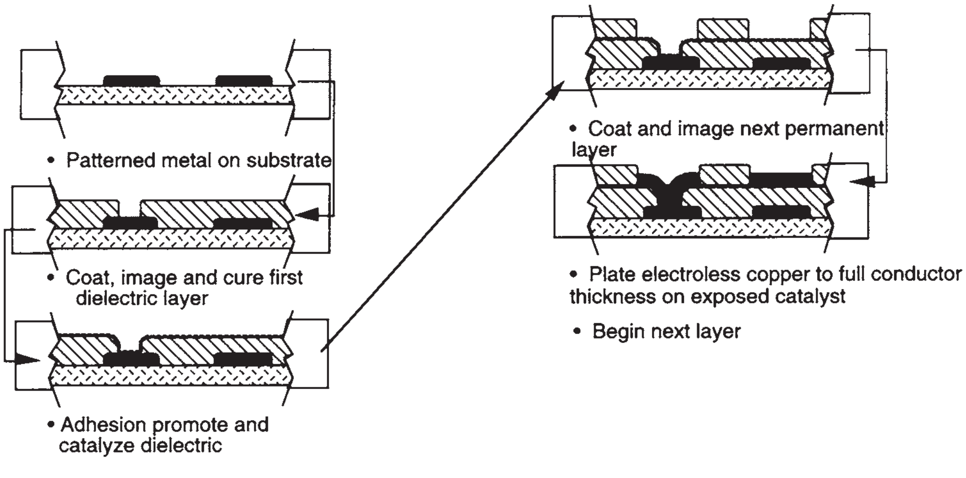

Fig. 9 A process flow chart for deposition of a multichip module on a conventional printed wiring board

Pretreatment: Gross Surface Preparation

The first steps of pretreatment for either multilayer PWBs or bare plastic employ fairly aggressive chemicals to remove debris and foreign matter from the substrate and etch the surface. These steps may change the topography and/or surface chemistry of the substrate significantly. The main objectives of this sequence of steps are to ensure good adhesion and eliminate the visible (gross) voiding that can result from a poorly prepared surface.

Printed Wiring Boards. This sequence of steps encompasses the desmear process for drilled holes in multilayer boards (MLBs). Drilling of the through-holes causes the laminate material (usually epoxy) to be smeared across hole wall surfaces. Reliable fabrication of multilayer boards requires that this drill smear be removed from the copper inner layers to ensure an effective copper-copper bond. The most common type of desmear process is based on a permanganate (Ref 64–66) oxidizing solution and involves three steps:

- *The MLB conditioner or pre-etch:* an aqueous-alkaline-oxygenated solvent solution that is operated at elevated temperatures (60 to 70 °C, or 140 to 160 °F) and penetrates slightly into the epoxy laminate so as to prepare it for optimal effect in the subsequent permanganate solution. Although analogous to the swell and etch system used in POP, this PWB analog does not penetrate deeply into the plastic; only surface layers (<5 μm) are thought to be affected. (Note that the term *conditioner* as used in this context must be differentiated from the PTH conditioner, or catalyst promoter, to be discussed below.)
- *The MLB etch or promoter:* a strongly alkaline permanganate solution that is operated hot (75 to 85 °C, or 165 to 185 °F) and actually dissolves a minute amount of epoxy, in particular removing any epoxy smeared on the copper inner layers. A microporous surface structure is also nor-

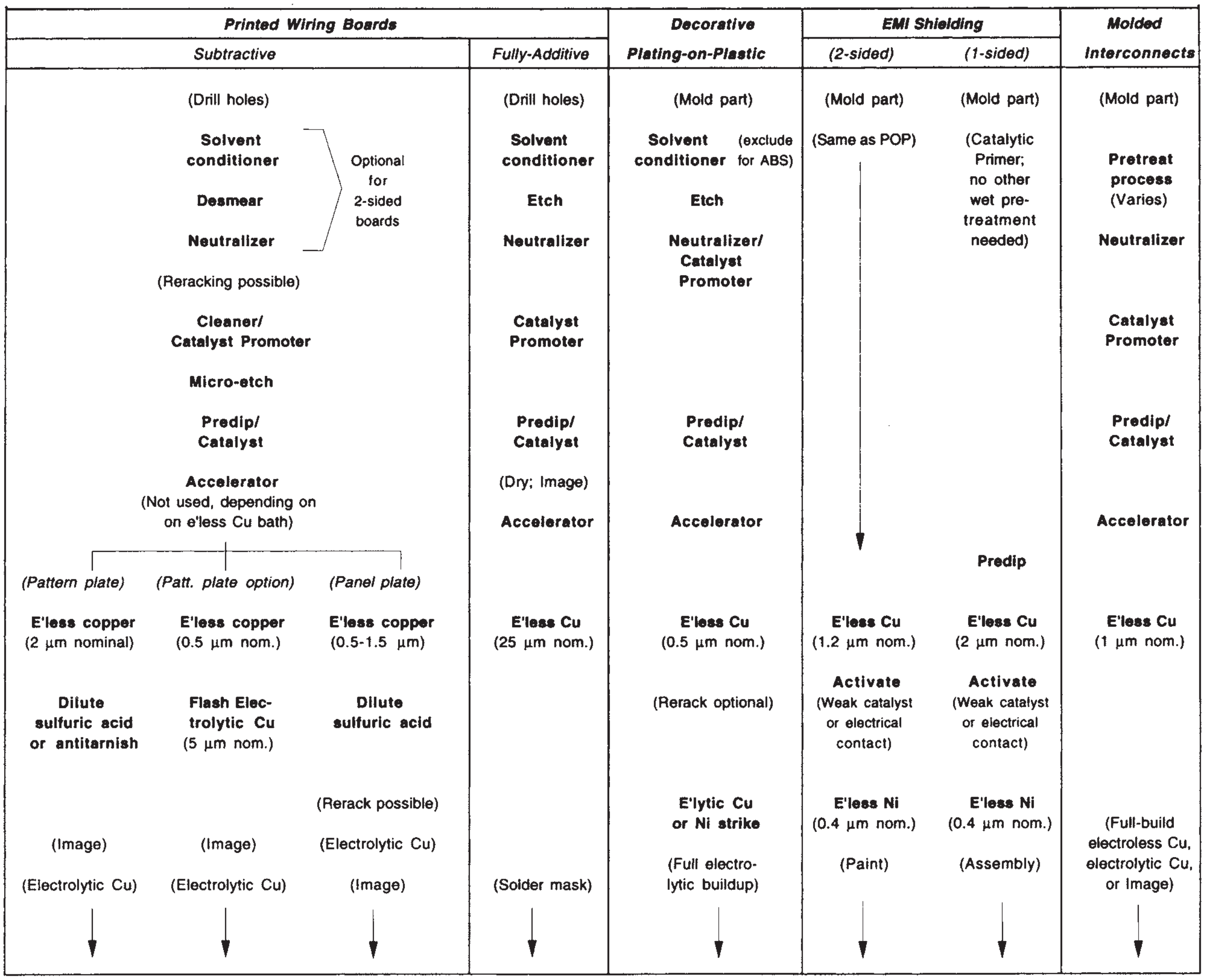

Fig. 10 Comparison of electroless copper processes. Unless otherwise stated, it should be assumed that one or more rinse steps intervene between each two process steps.

mally imparted to the resin. This results in an excellent surface on which catalysis and plating can take place.

- *The neutralizer:* an acidic, mildly reducing solution that removes manganese (MnO_2) residues from all board surfaces. Typical chemistries include dilute sulfuric-peroxide solutions or acid solutions of hydroxylamine salts. It is noteworthy that, in contrast with the use of chromium-containing etchants, special care need not be taken to ensure total removal of all manganese residues, as manganese does not have a harmful effect on subsequent processing.

Figure 11 compares a typical multilayer board through-hole, after drilling, with a permanganate-desmeared through-hole that exhibits a clean hole wall and microroughened resin surface.

Chemistries alternative to permanganate that have been used for desmearing PWBs include chromic acid or concentrated sulfuric acid (each with appropriate pre- and/or post-treatment) or plasma treatment. These methods exhibit numerous shortcomings relative to permanganate in terms of safety, toxicity, reliability, cost, and/or control.

Following the desmear process, depending on the configuration of the plating equipment, it may be necessary to unrack the parts, and then rerack for treatment in the balance of the electroless process.

Plating-on-Plastic (Decorative and Two-Sided EMI Shielding). The corresponding process steps for POP applications also typically include three steps:

- *The conditioner or pre-etch:* an aqueous-organic solvent mixture. The specific solvent used will differ qualitatively depending on which plastic is being treated. In the case of ABS, this step is not needed.
- *The etch:* typically based on aqueous chromic acid (a sulfuric acid admixture is also commonly used).
- *The neutralizer:* a reducing solution that may be either acid or alkaline and that removes all hexavalent chromium residues. In comparison with the permanganate neutralizer used in PWB desmear, it is essential that every trace of hexavalent chromium be removed from the surface, as Cr(VI) is a poison for the subsequent catalyst step. The neutralizer chemistry may be modified to include in one step the catalyst promoter discussed below.

Pretreatment: Immediate Preparation for Plating

Immediate preparation for plating ensures the final cleanliness of the part (if necessary), ensures that the surface will be receptive to catalyst, deposits the catalytic film, and converts the catalyst to its active form, in preparation for electroless plating.

Cleaning (Optional). For substrates such as two-sided PWBs that do not require the gross surface preparation sequence above, a conventional cleaning step is needed. Also, in cases where equipment configuration forces a split between the gross surface preparation steps and the balance of the process, a cleaning step may be needed to remove any soils that were thereby introduced. It is common practice to incorporate this cleaning step together with the subsequent catalyst promotion step. A hot solution is typi-

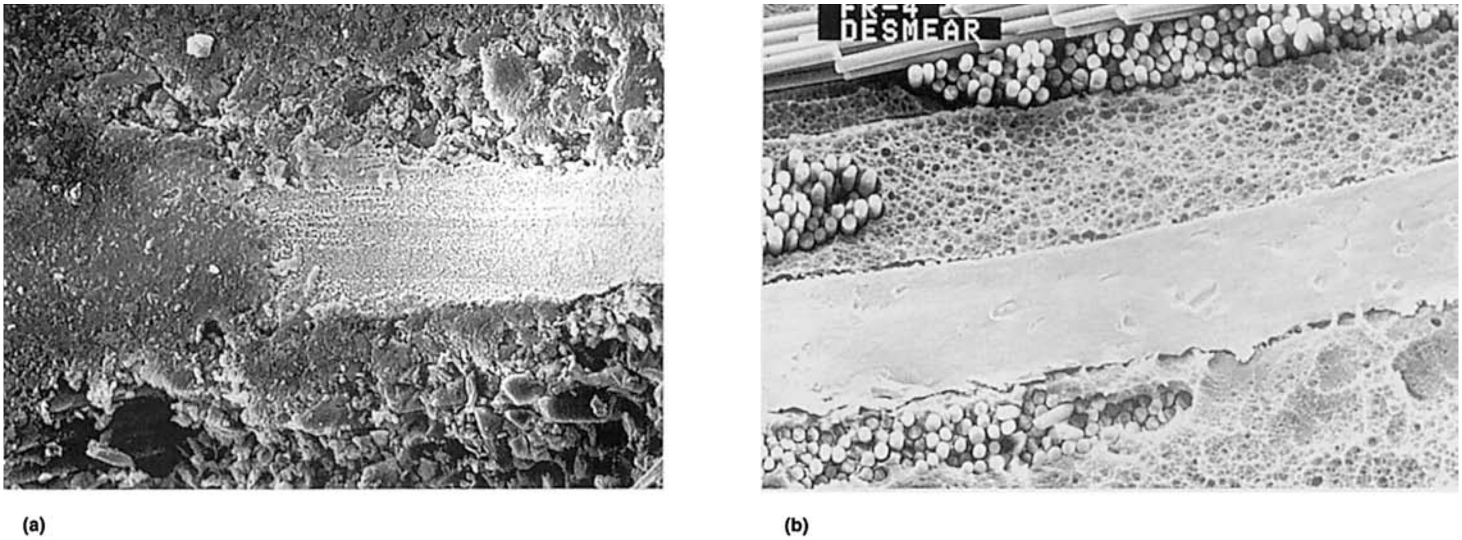

Fig. 11 Multilayer board through-holes. (a) After drilling. Note resin smear over copper inner layer surface and loosely adherent debris covering surface. (b) After permanganate desmear. Note clean overall appearance and uniformly microroughened epoxy surface.

cally used, ~55 to 70 °C (130 to 160 °F). The main constraints on the chemistry are that it be easily rinsable and that it be compatible with the rest of the process line. Waste treatment concerns are shifting cleaning chemistries away from the use of amine chelates and strongly acid or alkaline solutions.

Catalyst promotion (conditioning) imparts a uniform surface film to the substrate, which ensures uniform adsorption by the subsequent catalyst step and therefore promotes better plating. Because the most commonly used catalyst, the palladium-tin colloidal catalyst, is negatively charged, conditioning agents tend to bear a positive charge. The conditioning step may be combined with either the preceding cleaning step (two-sided PWBs) or the neutralizer (POP). The main issue is compatibility with subsequent steps. Specifically, in the case of PWBs, this means the ability to effectively remove any residual film from the copper during the intervening rinse and microetch steps. In the case of decorative POP, the need to achieve selectivity in the plating (i.e., no rack plating) favors the use of marginally effective catalyst promoters, whereas for PWB applications, the general difficulty of plating glass fibers in the laminate material leads to use of more effective conditioning chemistries, despite the resultant rack plating.

Microetching is required for PWBs only. It etches a thin film (0.75 to 2 μm) of the foil and inner-layer copper, thus ensuring cleanliness in preparation for plating. Any conditioning agent from the previous step is ideally removed from copper surfaces, as it could lead to a poor copper-copper bond if left in place. Normally either a mildly acidic sodium or potassium persulfate solution or a sulfuric acid-peroxide solution is used. If a persulfate solution is used, it may be followed by a dilute sulfuric acid dip.

A catalyst predip is normally employed just prior to the catalyst solution (no intervening rinses). This predip contains all components of the catalyst solution minus the catalyst itself. The purposes of the predip are to protect the expensive catalyst bath from contaminants and normalize the substrate surface chemistry prior to exposure to the catalytic species.

Catalyzation (Sensitization). Good catalyzation is the key to the entire electroless copper process. All the preceding steps are employed so as to optimize this step and ensure the uniformity and selectivity of the catalyst deposit. In theory, any of a wide range of metals, including copper, nickel, gold, silver, and all the other precious metals (Group VIIIB), may be used. In practice, because of a tradeoff between cost and selectivity (preferential adsorption of the catalyst to certain surfaces rather than others), only a few metals and physical/chemical forms of these have found acceptance in the electroless copper industry. These are discussed roughly in chronological order of their development:

- *Binary precious metal salt:* Acidic solutions of simple precious metal salts, including $PdCl_2$, $PtCl_2$, and so on, may be used as catalyst for electroless plating in some instances. Because these salts are not tightly bound to the substrate surface, they may be removed by excessive rinsing. These solutions generally promote plating only on the most active surfaces, thus providing a good method of selectivity in certain applications.
- *Sequential tin, then palladium (so-called "two-step"):* An acidic Sn(II) solution, typically $SnCl_2$, dissolved in dilute hydrochloric acid, is first used to provide a uniform film of Sn^{2+} ions over the entire substrate surface. Because Sn(II) is inherently a strong adherent material, the resultant film is tenaciously retained during rinsing. Then immersion in a dilute hydrochloric acid solution of $PdCl^2$ causes the more noble palladium ion to be reduced onto the substrate at the expense of the adsorbed Sn(II), which is oxidized to Sn(IV). This catalyst system was reported in 1955 (Ref 67) and has proven reliable and effective in metallizing nonconductive materials. However, a major disadvantage is the marked lack of selectivity; all exposed surfaces are heavily catalyzed. In the case of PWBs, use of the two-step catalyst often produces such a heavy catalyst film on the copper substrate that the resultant electroless copper deposit exhibits poor adhesion.
- *Palladium-tin colloid:* This type of catalyst system (Ref 68, 69) is by far the most prevalent type in commercial use. It is a stable reaction product of palladium and tin chlorides in acidic solution. The colloid is about 1 to 5 nm (10 to 50 Å) in size, consisting of a palladium-rich inner core and bearing hydrous Sn(IV) chlorides in the outer sphere. The overall colloid is negatively charged. Excess Sn(II) plays a key role in the stabilization of the catalyst solution. A high salt content is also present in modern versions of the colloidal catalyst. This system offers a number of advantages over earlier catalysts: it is more stable, it is more active per unit of palladium, and it allows good selectivity. The catalyst as-deposited bears a high-tin-containing "sheath" surrounding the active catalytic species, and it is not optimally activated until the subsequent acceleration step.
- *Copper catalyst:* Because palladium is more expensive than the less noble metals (such as copper and nickel) that are known to be autocatalytic, there have been numerous attempts to develop a viable catalyst based on one of these metals. A copper-tin colloidal catalyst was first reported in 1976 (Ref 70) and has proven commercially successful in a number of installations. A major disadvantage is that because the catalyst is much less active catalytically, the accompanying electroless copper bath must be formulated as a much less stable solution than copper baths employed with the more active palladium-tin catalysts. This can result in process control problems.

- *Ionic (alkaline) complexed palladium:* In the mid-1970s, an alkaline, ionic palladium catalyst system was developed (Ref 71) that demonstrated improved selectivity versus prior ionic palladium systems. This catalyst requires a subsequent activation step, namely immersion in a solution of a strong reducing agent such as dimethylamine borane, in order to become catalytically active. This catalyst system continues to have applicability (Ref 72) and is currently second in popularity to the colloidal palladium-tin catalyst system.

Acceleration (Activation). Discussion of this step will focus on the palladium-tin colloidal system, as it is the most commonly used catalyst. The tin-containing sheath surrounding the active palladium-rich catalytic core must be removed in order to initiate a strong plating reaction. Accelerating solutions typically are based on chemistries that dissolve and/or complex Sn(II) and Sn(IV) compounds. Commonly used formulations include dilute fluoboric acid or hydrochloric acid (or mixtures thereof), or other acidic or alkaline solutions. The catalyzation/acceleration process has been characterized in a number of studies (Ref 73). Proper control of accelerator parameters is needed to avoid an "overacceleration" condition wherein catalyst may actually be stripped, thus leading to voids in the electroless plating process. In recent years, particularly for PTH, the acceleration step has been eliminated altogether by incorporating excess chloride into the copper bath, thus causing it to be "self-accelerating" (Ref 23) without loss of stability.

Post-Treatment

As Fig. 10 shows, post-treatments for electroless copper vary considerably, depending on the application.

Printed Wiring Boards. For conventional subtractive pattern plated boards, the panels may be treated in an antitarnish solution immediately after electroless copper. Afterward they are rinsed and dried, prior to unracking and going on to the imaging process. Antitarnish solutions are usually mildly acidic solutions, optionally containing a weakly chelating acid salt such as citrate or tartrate. Alternatively, a dilute solution of a specific antitarnish component such as benzotriazole may be used.

An optional pattern plate sequence, which employs very thin (≤ 0.5 μm) electroless copper, uses a post-treatment step of thin (flash) electrolytic copper, ~5 μm thick, prior to unracking.

For subtractive panel plating processes, electrolytic copper plating is carried out immediately after the electroless copper process. The electroplating may be either in-line (thus necessitating use of a single flight-bar throughout the entire electroless process) or in separate equipment (allowing more flexibility in electroless equipment and racking, but involving additional handling steps).

Decorative Plating-on-Plastic. After electroless copper deposition, the parts are usually treated with an electrolytic copper or nickel strike about 2.5 μm thick. The purpose of this step is to build up the initial thin electroless film so as to facilitate the subsequent buildup. Following the strike, bright acid copper plating is usually carried out to a thickness of 12 to 25 μm. Next, depending on the final finish and physical characteristics desired, one to three different electrolytic nickel treatments may be employed, totaling up to ~33 μm thickness. The final finish is usually electrolytic chromium, 0.12 to 0.25 μm thick; however, the final finish may also be brass, gold, silver, or other finishes.

Single-Sided EMI Process

In order to plate electroless copper on the inside (only) of a cabinet so that the molded plastic substrate needs no other finish, special pretreatment methods have been developed and commercialized. These take the form of catalytic spray paints (Ref 74) that can be applied selectively onto the plastic surface and, following a defined bake or cure step, allow direct deposition of electroless copper. In theory, any of the metals that catalyze electroless deposition may be used; in practice, the choice of metal is a tradeoff of catalytic activity versus cost. Typically, the single-sided EMI process requires no chemical pretreatment other than the paint. Other mechanical steps required include masking of the surfaces not to be plated, drying/baking of the paint, and racking for the plating process.

Controls

Electroless Copper Solution. The electroless copper solution requires a variety of controls, all aimed toward maintaining steady-state performance in terms of plating rate, deposit physical properties, and bath stability (both during operation and on storage). First and foremost, the principal chemical parameters (copper, formaldehyde, and caustic content) must be kept within specification. Normally, by following replenishment and bailout instructions with respect to these primary components, all other bath chemical components will remain within the recommended ranges. However, occasionally chelate and stabilizer levels will also need independent control. Other than the chemistry, operating temperature is the most critical operating parameter. Too low a temperature will shut the plating off; too high may cause excessive plating rate and instability. Other key operating parameters include specific gravity (a measure of byproduct buildup), air agitation, filtration, circulation, panel loading, and others. Specific methods for maintaining bath stability during periods of shutdown are also specified: plating down to 70 to 80% copper content in the case of room-temperature operating baths, or simply reducing the temperature for storage in the case of heated baths. Air agitation is usually employed to improve storage stability.

In general, baths providing higher film thicknesses have tighter requirements in terms of equipment parameters such as heaters, air agitation, circulation, filtration, replenishment mode, and so on. Full-build baths in particular have stringent requirements for agitation, circulation, and filtration, and they require close control over plating rate consistency. The needed controls are well characterized for all current electroless formulations, and most plating facilities can readily maintain the required controls on a regular basis.

Other Process Solutions. General controls for other process solutions include the temperature and concentration of critical components, as specified by the supplier. Immersion time may also be critical in certain cases (e.g., PTH microetch), but not so long as a specified minimum immersion is attained (e.g., catalyst promoter). Supplier recommendations should be followed. Due to interaction between various pretreatment chemistries, as well as with the electroless chemistry, it is strongly recommended that a single supplier be used for the entire process. This practice also facilitates prompt resolution in troubleshooting situations.

In the gross pretreatment sequence, certain general controls must be considered. For PWB desmear, the permanganate (Mn^{7+}) to manganate (Mn^{6+}) ratio must be maintained at a specified level. Similarly, for POP adhesion promotion, the (Cr^{3+}) level must be controlled as specified. In POP it is strongly recommended that the temperature of the neutralizing solution be higher than that of the etch, to ensure that all hexavalent chromium residues are leached from any porous surfaces.

Adherence to specified chemistry controls is also necessary in the direct pretreatment sequence. In the PTH microetch, deviation from the prescribed parameters can lead to over- or underetching. In the catalyst solution, important parameters include specific gravity (to control salt content, which helps maintain colloid stability), Sn(II) level (which protects the colloid from oxidation and sedimentation), and colloid content (to control catalytic activity). In addition, certain metallic contaminants that can poison the catalytic activity (such as iron and chromium) must be monitored and controlled. Attention must be paid to the temperature and immersion time of the accelerator solution, to avoid under- or overacceleration. In addition, especially in chloride-containing accelerators, the dissolved copper content must be controlled to avoid formation of a rough deposit (believed to be CuCl) on the panel surface.

Miscellaneous. The importance of adequate rinsing using good-quality water can hardly be overemphasized. Heated rinses may be recommended after the catalyst promotion step to aid in removal of excess surfactant film. Rinsing after catalyzation requires maintenance of slightly acidic water containing no multiple charged cations, in order to prevent agglomeration of the negative colloid and surface roughness on the panel. Thorough rinsing in clean water is a general requirement in electroless copper processes, to prevent both panel surface defects and shortened bath life due to contaminated solutions.

Performance Criteria

The critical performance criteria for electroless copper processes vary somewhat, depending on the application. Two primary criteria that relate to all applications are coverage and adhesion. Other criteria have become increasingly important over the past decade or so, especially for PTH.

Coverage relates to the uniform and complete deposition of copper over the substrate. Coverage defects may be referred to as *voiding* (PWBs) or *skip plating* (POP). Gross coverage defects that are easily discerned by the naked eye are typically caused by an improperly prepared surface or major abnormality in the overall plating process parameters. Pinpoint defects, which may also be detectable to the eye, have long been a recognized problem in the POP industry, due to the importance of the appearance of the final product. Since approximately the late 1970s, microscopy has been widely used to detect minute defects in PTH, due to increasing demands on circuit integrity. Typically a panel is sliced so that half the plated hole is visible for microscopic examination. Rather than incident light, backlighting is often used (Ref 75), which provides a very sensitive measure of assessing coverage. Figure 12 demonstrates levels of coverage that can be discriminated. (Both these through-holes would appear totally covered when viewed using incident light.) Some debate has taken place regarding whether "total" backlight coverage is necessary or even advisable. The critical importance of deposit adhesion, for instance, requires that any mechanism employed to promote coverage, such as use of strong catalyst promoters, be carefully controlled so as not to introduce weak boundary layers in the plated composite.

Adhesion of the copper deposit to the substrate is typically controlled by proper surface preparation. Typically the first two or three steps in the plating process prepare the surface in a gross manner. The subsequent steps of conditioning, microetch (for PWBs), catalyzation, and acceleration ensure that a complete yet minimal catalyst film is present so as to maximize adhesion. Adhesion requirements vary, depending on the application. For POP the adhesion requirement is ~0.7 kN/m (4 lb/in.) peel strength, as measured by the Jacquet test (Ref 76), with good integrity to be maintained under a variety of environmental test conditions. The important factor is maintenance of a durable, cosmetic film over the lifetime of the part. The primary failure mode is blistering of the deposit. For conventional PWBs, peel strength per se is not usually measured. Adhesion is typically ascertained by cross-sectioning the board after electroplating, optionally subjecting the sample to high thermal stress that simulates or exceeds the expected stress to be induced during assembly, and then mounting and polishing prior to microscopic examination for failure between the electroless film and any of the other surfaces. Adhesion failure to the epoxy surface is commonly referred to as *hole wall pullaway*; adhesion failure to a copper inner layer is referred to as an *interconnect defect* (ICD). Detection and elimination of ICDs by improved electroless copper plating processes has led to significant improvement in PWB reliability over the past several years. Industry standard electroless copper processes stand up to significantly more severe test conditions than those defined in the industry specification (Ref 77) as shown in Fig. 13. In EMI shielding, the standard adhesion test involves scratching a cross-hatch pattern into the metallized film and then applying a tape test under prescribed conditions (Ref 78). This test is often used following a variety of environmental storage conditions.

Deposit quality has become increasingly important over the past ten years. Controlled grain size, low intrinsic stress, and low electrical resistivity are some of the most important qualities sought. A method of PWB reliability testing using elevated-temperature fluid bed media has been employed to rapidly assess the long-term reliability of the copper deposit in through-holes (Ref 27).

Control of the copper bath is now routinely achieved, in contrast with the unstable and unpredictable formulations of the 1960s and 1970s. Plating rate, rate of depletion, deposit characteristics, and so on are all maintained consistently throughout the lifetime of the bath, allowing statistical control procedures to be readily implemented.

Solderability. The effect of the through-hole copper plating bath and process on solderability has been the subject of several studies (Ref 79), because outgassing or "blow holes" (Fig. 14) occurring during the assembly process can significantly affect PWB end-product reliability. It has been shown that outgassing is dramatically reduced by a permanganate-based surface preparation treatment used for desmearing multilayer boards in combination with a fine-grain, low-stressed copper deposit (Ref 35).

Equipment

Processing Equipment

Printed Wiring Boards. Electroless copper process equipment consists essentially of a juxtaposed series of tanks, typically 380 to 1135 L (100 to 300 gal) in size (or as high as

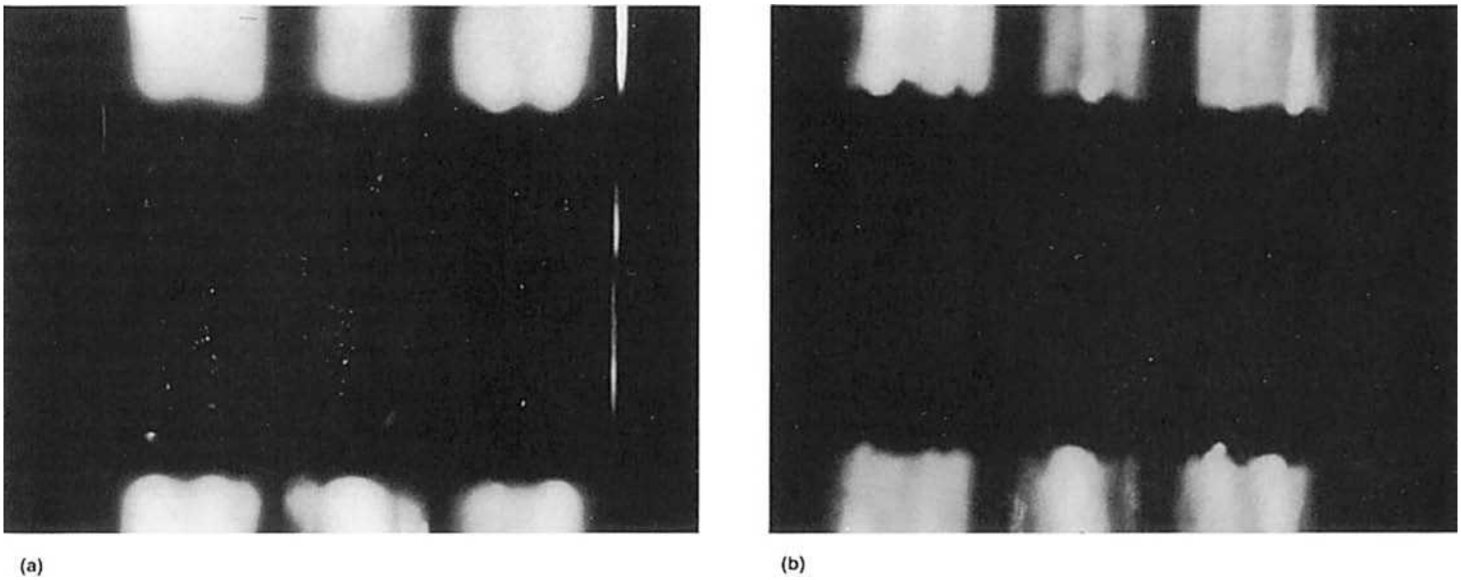

Fig. 12 Backlight test coupons. (a) Showing pinpoints voids. (b) Showing total electroless copper coverage

3800 L, or 1000 gal), including process chemistry tanks, rinse tanks, and load/unload stations, with all associated heaters, chillers, air spargers, and so on. The panels are transported vertically through the system in a rack that typically holds panels representing a surface area of 25 to 735 cm^2/L (0.1 to 3 ft^2/gal) of copper bath. (Other process tanks may be sized appropriately to most efficiently hold the rack.) An automatic hoist system is used, except in the smallest installations.

In the past, electroless lines were designed for two-sided boards only. The multilayer desmear process was entirely separate, thus requiring additional unracking and reracking between segments. Most electroless copper plating lines now being built include tanks for the desmear process as well.

Considerable interest has developed in applying conveyorized horizontal processing to part or all of the electroless copper process, as there are a number of technical and operational benefits to this approach. Horizontal desmear is being used in select facilities worldwide, and several facilities are also successfully operating in production using horizontal equipment for electroless copper itself (Ref 80).

Plating-on-Plastic. Plating equipment for POP typically involves tank volumes of about 3800 L (1000 gal), but tanks of up to 26,500 L (7000 gal) have been used. The plating process in decorative POP is carried out in one of two modes: designated straight-through or semibulk. Straight-through processing is carried out in a continuous system where the preplate, electroless, and electroplating steps are carried out with no interruption for reracking. In semibulk processing, two separate fixtures are used, one for the pretreatment/electroless steps and the other for electroplating. There are numerous advantages for each type of system (Ref 39). Advantages of straight-through processing are evident: only one piece of equipment, fewer processing steps, less handling, and so on. Semibulk processing, however, offers a number of advantages, including much higher capacity, more degrees of freedom in choosing racking systems and chemicals, and flexibility in processing sequences.

Control Equipment

Due to rapid changes in the chemistry of an operating electroless plating bath, frequent analysis and replenishment are required. Hence, automatic control equipment has been of interest (Ref 81) almost since the baths were first commercially employed. A benchmark controller developed in about 1980 measured and controlled copper, hydroxide, and formaldehyde contents. Copper content was determined by an optical absorbance method, hydroxide and formaldehyde contents were determined by a titration method. Over the years, the simplicity and reliability of such equipment have undergone great improvement, but the basic techniques of analysis have remained essentially the same (Ref 82). Today these control systems are commonplace in all but the very smallest installations and are used to automatically replenish all bath components, as well as for bailout. To address the added control requirements of full-build electroless copper baths, a more accurate method of copper analysis and control has been devel-

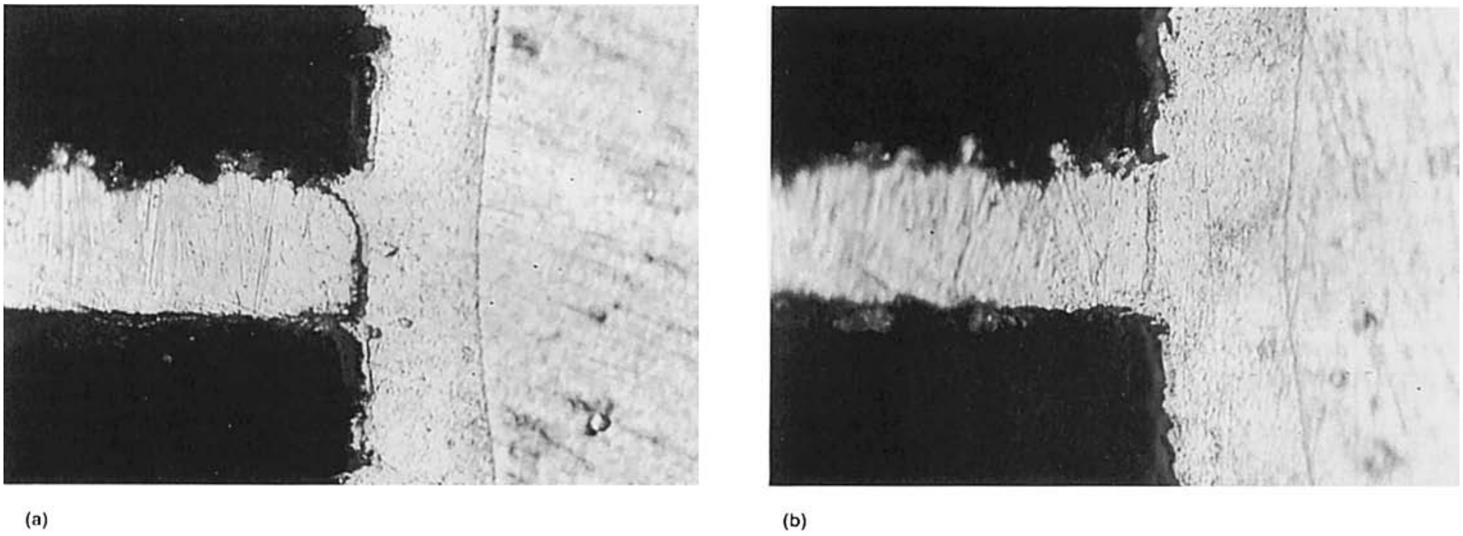
(a) (b)

Fig. 13 Solder shock test coupons. (a) Showing interconnect defect. (b) Showing strong interconnect bond after multiple solder shock exposure

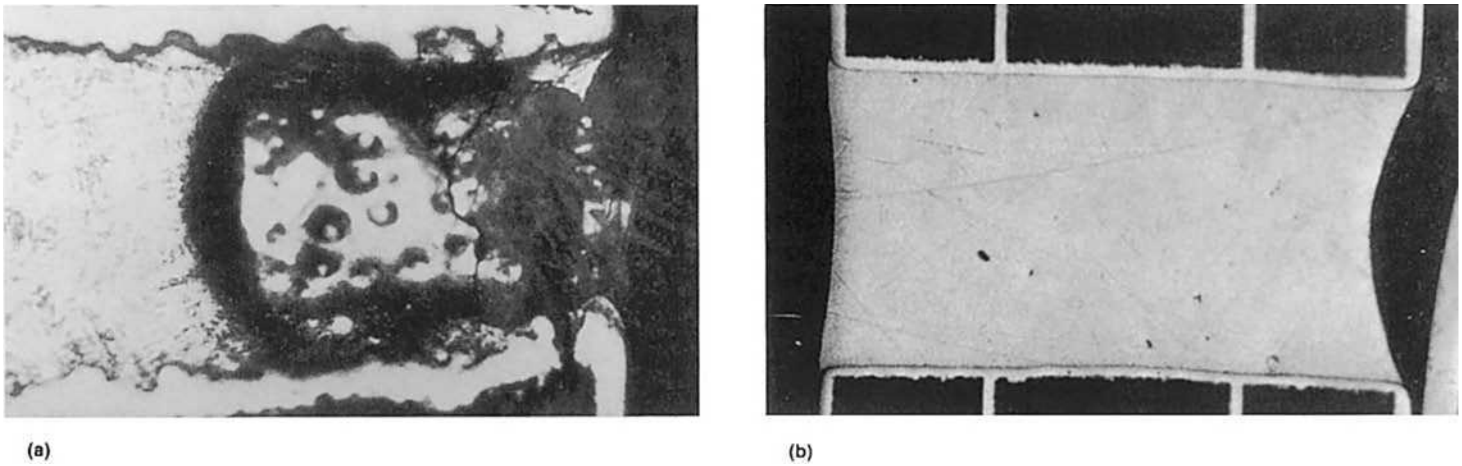
(a) (b)

Fig. 14 (a) Solder blow hole induced during solder shock testing. (b) Through-hole showing good solder fill after solder shock testing oped and commercialized. This method is based on vibration of a quartz crystal that acts as a microbalance (Ref 83), thus measuring the mass of copper plated on its surface and providing real-time measurement and control of thickness.

Environmental and Safety Issues

The electroless copper plating industry has come under increasing legislative control in recent years due to a variety of environmental and safety concerns relative to the chemistry and processes. The main issues are quality of waste water discharged, volatile components discharged, and health and safety concerns about handling of the various chemicals.

Waste Water. Regulations regarding effluent vary dramatically, both globally and within single countries. This factor has probably contributed significantly to the relocation of numerous plating facilities to areas having less stringent regulations. Copper itself is probably the main concern; waste treatment equipment designed to plate residual copper from discarded plating solutions will normally reduce Cu^{2+} below the legal limit (typically 1 ppm). Strong chelates have become a concern recently due to their tendency to dissolve any metallic surfaces encountered, either before or after discharge. Certain plating bath additives used in the past, including mercury and cyanide compounds, have been virtually eliminated from use due to waste water restrictions. Adjustment of waste water pH to a neutral range is also usually required. Chromium, used in POP pretreatment, is particularly toxic to the environment, but virtually all current users recycle their chromic acid etchants internally, thus avoiding any discharge. Discharge of strong oxidizing or reducing agents is also typically regulated closely. The issue of waste water treatment is so key to operating a successful plating operation that considerable literature on designing and implementing waste treatment systems is available (Ref 84).

Handling of individual chemicals in the plating process presents a number of concerns. A significant concern is the use of formaldehyde, which has been shown to be a carcinogen for certain laboratory animals, although no direct link with cancer in humans has been demonstrated at this time. Limits by the Occupational Health and Safety Administration on airborne formaldehyde have recently been reduced from 1 to 0.075 ppm (8 h time-weighed average permissible exposure in air). Concerns about formaldehyde, as well as concerns about waste treatment of electroless copper, have contributed to ongoing development of direct electroplating (Ref 37, 80, 85, 86), which could eliminate the need for electroless copper, particularly in portions of the PWB market.

Wear-Resistant and Corrosion-Resistant Copper Alloy Coatings

Thicker, more durable copper alloy coatings are used for engineering applications that require wear and/or corrosion resistance in aggressive environments. Important examples include aluminum bronze and copper-nickel alloy coatings.

Wear-Resistant Coatings

Copper-base alloy coatings used for wear-resistant applications are referred to as *hardfacing alloys*. They are deposited by either arc welding processes (e.g., shielded-metal arc or gas-metal arc welding) or thermal spray methods. More detailed information on welding and thermal spray processes can be found in *Welding, Brazing, and Soldering*, Volume 6 of *ASM Handbook*.

Weld Surfacing. The two bronze compositions given in Table 15 fall in the aluminum bronze category. Silicon and phosphor bronzes are also available in welding consumable form for hardfacing.

Aluminum-bronze hardfacing alloys are used for applications where resistance to corrosion, cavitation, and metal-to-metal wear is desired. Components typically protected using the aluminum bronzes include bearings, gears, cams, and cold-drawing/forming dies. Copper-base hardfacing alloys have poor resistance to corrosion by sulfur compounds and very low resistance to abrasive wear. In addition, they are not recommended for elevated-temperature use because their mechanical properties decrease considerably at temperatures greater than 200 °C (400 °F).

Thermal Spraying. Hardfacing alloys deposited by thermal spraying include aluminum bronzes and copper-zinc-tin alloys (e.g., Tobin bronze). They are used to prevent adhesive wear, fretting wear, and cavitation wear. Applicable thermal spray processes include oxyfuel wire spray, electric arc spray, oxyfuel powder spray, plasma arc powder spray, and high-velocity oxyfuel powder spray methods.

Table 15 Compositions of aluminum bronze hardfacing alloys

		Composition, wt%					
AWS designation	UNS No.	Al	Fe	Pb	Si	Zn	Cu
ECuAl-B	W60619	8.0–10.0	2.5–5.0	0.02 max	1.0 max	…	bal
ERCuAl-A2	C61800	8.5–11.0	0.5–1.5	0.02 max	0.10 max	0.02 max	bal(a)

(a) Cu + Ag; Cu + sum of named elements = 99.5 min

Corrosion-Resistant Coatings

Copper-nickel alloys are frequently used to clad less noble metals such as carbon steels for use in marine environments. They are deposited onto the steel surface by weld cladding, solid-state bonding techniques, or by sheathing.

Weld Cladding. The term *weld cladding* usually denotes application of a relatively thick layer ($\geq$ 3 mm, or $\frac{1}{8}$ in.) of weld metal for the purpose of providing a corrosion-resistant surface. Hardfacing produces a thinner surface coating than a weld cladding and is applied for dimensional restoration or wear resistance. For weld cladding, covered electrodes are designed as ECuNi, and bare electrode wire and rods are designated as ERCuNi. The nominal compositions are 70% Cu and 30% Ni. These filler metals are sometimes deposited over a first layer of nickel. Shielded-metal arc and gas-metal arc welding are commonly employed. In addition, the automatic gas-tungsten arc welding process with hot wire addition of filler metal is also used.

Solid-state cladding methods include hot-roll bonding, explosive bonding, and extrusion bonding. These processes differ from welding in that none of the metals to be joined is molten when a metal-to-metal bond is achieved. Steel plate or tube are frequently roll-clad with 90Cu-10Ni (C70600) or 70Cu-30Ni (C71500) alloys. The resistance of these alloys to marine environments is discussed in the article "Corrosion Behavior" in this Handbook.

Sheathing refers to the attachment of relatively thin copper-nickel sheet to ship hulls by peripheral welding and/or the use of adhesives. Sheathing, with or without an insulating layer between the copper-nickel and the steel, is also applicable to offshore oil and gas structures as well as a wide variety of bridge, dock structures, and power or chemical plant seawater intake systems for corrosion protection and prevention of biofouling. The sheathing alloy most commonly used is 90Cu-10Ni (C70600), but copper-nickel-chromium alloy C72200 has also been used.

ACKNOWLEDGMENTS

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Applications

MAJOR MARKET CATEGORIES for copper and copper alloys, as identified by the Copper Development Association Inc., include the following:

Market	Total,%
Building construction	43
Electrical and electronic products	24
Industrial machinery and equipment	12
Transportation	12
Consumer and general products	9

Selected applications from each of these market categories are described in this article.

About 90% of the total tonnage of wrought products sold by U.S. manufacturers is represented by the 16 applications listed in Table 1. End-use markets for cast copper alloys are show in Fig. 1. Typical applications for castings are plumbing hardware, pump parts, valves, and fittings; bearings and bushings; marine castings, such as propellers, propeller shafts, propeller hubs, hull gear, impellers, and turbines; electrical components, such as substation, transformer, and pole hardware for power transmission; and architectural and ornamental applications, such as door handles, church bells, and statuary. Additional information pertaining to applications for copper and copper alloy products can be found throughout this Handbook (see, in particular, the articles "Wrought Copper and Copper Alloys," "Cast Copper and Copper Alloys," and "Powder Metallurgy Copper and Copper Alloys"). Reference 1 also provides an extensive review of applications for copper and copper alloys.

Building Construction

The two most prominent building construction applications are plumbing goods (tubing, taps, valves, tanks, connectors, and fittings) and building wire. Both of these application areas are discussed subsequently. Other important uses of copper and copper alloys in building construction include:

- Heating and ventilation systems (Ref 2)
- Air conditioning and refrigeration systems (Ref 3)
- Solar energy systems (Ref 1)
- Gas distribution systems (Ref 1, 4)
- Fire sprinklers (Ref 1, 5, 6)
- Roofing, guttering, and flashing (Ref 1, 7)
- Architectural and builders' hardware (door and cabinet hardware, such as entrance handles, doorknobs, and locks) (Ref 7)

Plumbing Goods

Copper tube is the standard plumbing material for potable water and heating systems in North America and parts of Europe. As listed in Table 2, plumbing tube is sold in several wall thicknesses: Types K (heaviest), L (standard), and M (lightest) represent wall thickness gages used in plumbing systems. Type DWV (drain, waste, and ventilation) is used for drainage application. All four types are available in 20 ft (6.1 m) lengths in the drawn (hard) temper. Annealed (soft) temper tube in available in 60 ft (18.3 m) and 100 ft (30.5 m) coils, and straight lengths of types K and L are also available. Coils are frequently used as the underground service line between the water main in the street and the water meter in the home for the purpose of avoiding an intermediate joint. While straight lengths are generally used in the home in the United States, coils are frequently used in the United Kingdom and Europe. All copper tube produced to commodity or commercial tube classifications has a minimum chemical composition of 99.9% copper (including silver). Fittings for copper tube (water and drainage) are made to the American National Standards Institute (ANSI)/ASME standards. Wrought and cast copper and copper-alloy pressure fittings are available in all standard tube sizes and in a wide variety of types to meet needs for plumbing, heating, air conditioning, and fire sprinkler systems. Table 3 shows the allowable pressure ratings for copper tube as a function of temperature. These ratings are only a small fraction of the ultimate tensile, or burst, strength of copper. However, in practical systems, allowance must be made for joint strength.

Table 1 Major end-use applications for copper and copper alloys in the United States

Application	Mill products	Principal reason(s) for using copper(a)
Telecommunications	Copper wire	Electrical properties
Automotive: automobiles, trucks, and buses	Brass and copper strip, copper wire	Corrosion resistance, heat transfer, electrical properties
Plumbing and heating	Copper tube, brass rod, castings	Corrosion resistance, machinability
Building wiring	Copper wire	Electrical properties
Heavy industrial equipment	All	Corrosion resistance, wear resistance, electrical properties, heat transfer, machinability
Air conditioning and commercial refrigeration	Copper tube	Heat transfer, formability
Industrial valves and fittings	Brass rod, castings	Corrosion resistance, machinability
Power utilities	Copper wire and bar	Electrical properties
Appliances	Copper wire and tube	Electrical properties, heat transfer
Lighting and wiring devices	Alloy strip, copper wire	Electrical properties
Electronics	Alloy strip, copper wire	Electrical properties
Fasteners	Brass wire	Machinability, corrosion resistance
Military and commercial ordnance	Brass strip and tube	Ease of fabrication
Coinage	Alloy and copper strip	Ease of fabrications, corrosion resistance, electrical properties, aesthetics
Builders' hardware	Brass rod and strip	Corrosion resistance, formability, aesthetics
Heat exchangers	Alloy tube and plate	Heat transfer, corrosion resistance

(a) Although not specifically listed as a principal reason in all applications, ease of fabrication is a factor in all application categories.

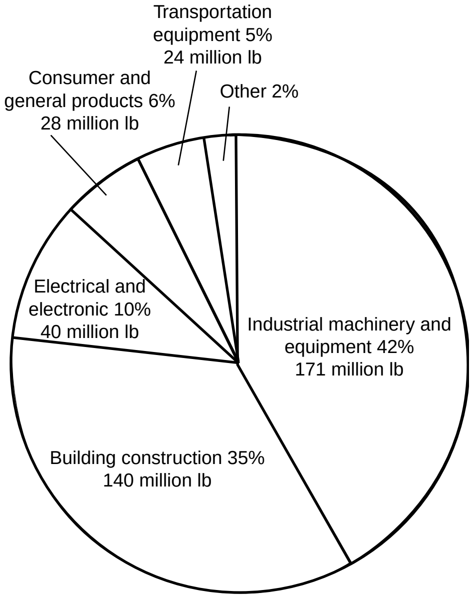

Fig. 1 End-use markets for copper casting alloys. Source: Copper Development Association Inc.

Applicable Grades. In the United States, the most commonly used copper grade for plumbing tube is alloy C12200 (phosphorus-deoxidized high-residual phosphorus, DHP). Deoxidation is required because the tube is commonly joined by soldering. Table 4 lists specifications, grades, and uses for copper plumbing tube products.

Table 2 Dimensions of copper tube types K, L, M, and DWV

	Nominal dimensions, in.			Calculated values, based on nominal dimensions			
Size	Outside diam	Inside diam	Wall thickness	Cross sectional area of bore, in.^{2}	External surface, ft^2/linear ft	Internal surface, ft^2/linear ft	Weight, lb/linear ft
Type K							
1/4	0.375	0.305	0.035	0.073	0.098	0.080	0.145
3/8	0.500	0.402	0.049	0.127	0.131	0.105	0.269
1/2	0.625	0.527	0.049	0.218	0.164	0.138	0.344
5/8	0.750	0.652	0.049	0.334	0.196	0.171	0.418
3/4	0.875	0.745	0.065	0.436	0.229	0.195	0.641
1	1.125	0.995	0.065	0.778	0.294	0.261	0.839
1 1/4	1.375	1.245	0.065	1.22	0.360	0.326	1.04
1 1/2	1.625	1.481	0.072	1.72	0.425	0.388	1.36
2	2.125	1.959	0.083	3.01	0.556	0.513	2.06
2 1/2	2.625	2.435	0.095	4.66	0.687	0.638	2.93
3	3.125	2.907	0.109	6.64	0.818	0.761	4.00
3 1/2	3.625	3.385	0.120	9.00	0.949	0.886	5.12
4	4.125	3.857	0.134	11.7	1.08	1.01	6.51
5	5.125	4.805	0.160	18.1	1.34	1.26	9.67
6	6.125	5.741	0.192	25.9	1.60	1.50	13.9
8	8.125	7.583	0.271	45.2	2.13	1.98	25.9
10	10.125	9.449	0.338	70.2	2.65	2.47	40.3
12	12.125	11.315	0.405	101.0	3.17	2.96	57.8
Type L							
1/4	0.375	0.315	0.030	0.078	0.098	0.082	0.126
3/8	0.500	0.430	0.035	0.145	0.131	0.113	0.198
1/2	0.625	0.545	0.040	0.233	0.164	0.143	0.285
5/8	0.750	0.666	0.042	0.348	0.196	0.174	0.362
3/4	0.875	0.785	0.045	0.484	0.229	0.206	0.455
1	1.125	1.025	0.050	0.825	0.294	0.268	0.655
1 1/4	1.375	1.265	0.055	1.26	0.360	0.331	0.884
1 1/2	1.625	1.505	0.060	1.78	0.425	0.394	1.14
2	2.125	1.985	0.070	3.09	0.556	0.520	1.75
2 1/2	2.625	2.465	0.080	4.77	0.687	0.645	2.48
3	3.125	2.945	0.090	6.81	0.818	0.771	3.33
3 1/2	3.625	3.425	0.100	9.21	0.949	0.897	4.29
4	4.125	3.905	0.110	12.0	1.08	1.02	5.38
5	5.125	4.875	0.125	18.7	1.34	1.28	7.61
6	6.125	5.845	0.140	26.8	1.60	1.53	10.2
8	8.125	7.725	0.200	46.9	2.13	2.02	19.3
10	10.125	9.625	0.250	72.8	2.65	2.53	30.1
12	12.125	11.565	0.280	105.0	3.17	3.03	40.4
Type M							
3/8	0.500	0.450	0.025	0.159	0.131	0.118	0.145
1/2	0.625	0.569	0.028	0.254	0.164	0.149	0.204
3/4	0.875	0.811	0.032	0.517	0.229	0.212	0.328
1	1.125	1.055	0.035	0.874	0.294	0.276	0.465
1 1/4	1.375	1.291	0.042	1.31	0.360	0.338	0.682
1 1/2	1.625	1.527	0.049	1.83	0.425	0.400	0.940
2	2.125	2.009	0.058	3.17	0.556	0.526	1.46
2 1/2	2.625	2.495	0.065	4.89	0.687	0.653	2.03
3	3.125	2.981	0.072	6.98	0.818	0.780	2.68
3 1/2	3.625	3.459	0.083	9.40	0.949	0.906	3.58
4	4.125	3.935	0.095	12.2	1.08	1.03	4.66
5	5.125	4.907	0.109	18.9	1.34	1.28	6.66
6	6.125	5.881	0.122	27.2	1.60	1.54	8.94
8	8.125	7.785	0.170	47.6	2.13	2.04	16.5
10	10.125	9.701	0.212	73.9	2.65	2.54	25.6
12	12.125	11.617	0.254	106.0	3.17	3.04	36.7
Type DWV							
1 1/4	1.375	1.295	0.040	1.32	0.360	0.339	0.65
1 1/2	1.625	1.541	0.042	1.87	0.425	0.403	0.81
2	2.125	2.041	0.042	3.27	0.556	0.534	1.07
3	3.125	3.030	0.045	7.21	0.818	0.793	1.69
4	4.125	4.009	0.058	12.6	1.08	1.05	2.87
5	5.125	4.981	0.072	19.5	1.34	1.30	4.43
6	6.125	5.959	0.083	27.9	1.60	1.56	6.10
8	8.125	7.907	0.109	49.1	2.13	2.07	10.6

Source: Ref 8

Corrosion. Certain water conditions, including those listed in Table 5, can lead to corrosive attack of copper water tube. In most cases, waters that are aggressive to metals are treatable, and water utilities are encouraged to provide such treatment. Five particularly aggressive conditions include (Ref 1, 9–12):

- *Hard well waters:* Cause pitting. Aggressive, hard well waters characteristically contain high total dissolved solids (tds), including sulfates and chlorides. They typically have a pH between 7.3 and 7.8, a carbon dioxide content (CO_2) greater than 10 ppm, and some dissolved oxygen. They can be identified by chemical analysis and can be treated to raise the pH and combine or eliminate dissolved CO_2. Sometimes simple aeration by spraying or sparging is sufficient to render them harmless.
- *Soft, acidic waters:* Inhibit formation of the protective film that normally forms inside the copper tube. Soft, acidic waters cause staining of fixtures, a form of so-called "blue water." Raising the pH to 7 or higher usually solves the problem. Simple treatments include flowing the water through a bed of marble chips or injecting sodium carbonate (Na_2CO_3).
- *Excessive water flow velocity or turbulence:* Produces erosion-corrosion or impingement attack in the tube. Velocity effects can be aggravated if the water is also chemically aggressive or if it contains entrained solids (silt). To avoid this problem, flow rate should not exceed 1.5 m/s (4.9 ft/s).
- *Shoddy workmanship:* For example, solder and flux residue left inside the tube. Dribbles of solidified flux left in the tube lead to pitting due to the continuing corrosive action of the flux, and erosion-corrosion, caused by disturbance of the smooth water flow around the obstruction.
- *An aggressive soil composition:* Deteriorates buried tube. Most natural soils do not attack copper, but any buried metal pipe laid in cinders is subject to attack by the acid generated when sulfur compounds in the cinders combine with water. The presence of chlorides and an acidic pH aggravates the situation. Under such circumstances, the tube should be isolated from the environment with a wrapping of insulating tape, a plastic coating, or an asphaltic paint.

Copper drainage tube rarely corrodes, except when misused or improperly installed. Insufficient slope can permit corrosive solutions to lie in the tube and attack it. Hydrogen sulfide gas that vents back into the drainage system can also attack the tube.

Additional information regarding corrosion of copper in water can be found in the article "Corrosion Behavior" in this Handbook.

Building Wire

Building wire is used to distribute electric power inside residential, commercial, or industrial buildings; mobile homes; recreational vehicles; boats; and substations at potentials of 600 V or less. Building wire is the largest market for copper in the United States, and continued growth is expected due to the increased use of computers and other electronic equipment (Ref 13).

For distribution mains inside buildings, the National Electric Code (NEC) requires conductors to contain insulated wires for neutral and

Table 3 Pressure ratings for copper tube joints

Maximum service temperature		Tube size		Pressure rating	
°F	°C	in.	mm	psi	kPa
Joints made with 50Sn-50Pb solder(a)					
100	38	1¼–2	32–51	95	655
		3–4	76–102	80	552
		5–8	127–203	70	482
150	66	1¼–2	32–51	70	482
		3–4	76–102	55	379
		5–8	127–203	45	310
200	93	1¼–2	32–51	50	345
		3–4	76–102	40	276
		5–8	127–203	35	241
Joints made with 95Sn-5Sb solder(a)					
100	38	1¼–2	32–51	220	1,517
		3–4	76–102	165	1,138
		5–8	127–203	120	827
150	66	1¼–2	32–51	195	1,344
		3–4	76–102	150	10,348
		5–8	127–203	100	690
200	93	1¼–2	32–51	140	965
		3–4	76–102	110	758
		5–8	127–203	80	552

(a) Solder alloys are described in ASTM B 32. Note: Metric numbers are conversions of U.S. customary units and are not necessarily standards expressed in SI units. Source: Ref 5

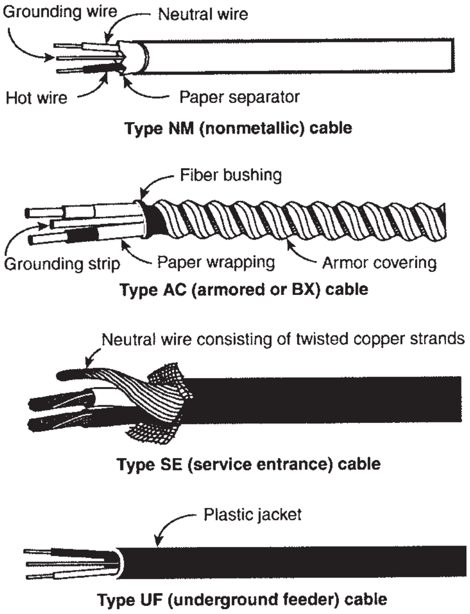

Fig. 2 Insulated conductor configurations. Source: Ref 1

hot phases, plus a bare wire for grounding (Fig. 2). Wires frequently incorporate color coding systems for ready identification: Grounding conductors are normally green or natural gray (or bare); "hot" phases are red and black; and neutral conductors may be white or gray. A general description of specific types of building wire can be found in Ref 1.

Copper versus Aluminum. Copper has almost always been the material of choice for building wire. Attempts to replace copper with aluminum were curtailed in most countries when it was found that aluminum connections gradually loosened due to a slow relaxation process known as *creep.* Insulating aluminum oxide, formed on loose connections, produced enough resistive heat to initiate electrical fires. Because copper oxides are semiconductors, this problem does not occur even in the presence of a loose connection. While improved spring-loaded contacts have largely alleviated this problem, aluminum building wire has never regained the market share it once enjoyed. While in 1974 aluminum had 31% of the building wire market, by 1991 it had only 8%. The present market for aluminum building wire is essentially confined to the larger gage sizes used in supply circuits.

Table 4 Overview of standard copper plumbing tube

ASTM specification	Designation	Application	Standard mill sizes, in.	UNS alloy							
				C10100	C10200	C10300	C10800	C12000	C12200	C21000	C23000
Seamless tube											
B 42	Copper pipe	Plumbing and feed lines	⅛–12		X	X	X	X	X		
B 43	Red brass pipe	Plumbing and feed lines	⅛–12								X
B 88	K, L, M	General plumbing water tube	¼–12		X	X	X	X	X		
B 302	TP	Threadless pipe for plumbing feed lines	¼–12			X	X	X	X		
B 306	DWV	Drainage, waste, vent	¼–8			X	X	X	X		
B 641	D	Distribution	¼–3	X	X	X	X	X	X		
Welded tube											
B 641	D	Distribution	¼–3	X	X	X	X	X	X		
B 642	Welded alloy water tube	General plumbing	¼–3							X	

Table 5 Effect of water conditions on copper corrosion

Water conditions	Corrosive effect
pH	
When pH is raised to give the water a slightly positive calcium carbonate saturation index, corrosion problems with copper are unlikely.	General attack on copper as a function of pH
CO_2 content and water mineral hardness	
Soft water, for example, water with less than 25 ppm mineral content, with 15 ppm or more, under stagnant conditions	Green staining and metallic taste due to dissolution of copper. Treatments include aeration to reduce CO_2 concentration, elevation of pH to neutralize CO_2 and blending in hard water to lay down a protective film.
Bicarbonate:sulfate ratio < 1	Pitting attack
Well water at pH 7.5 plus > 5 ppm $CO_2 + O_2$ and intermittent use	Pitting attack
pH < 7.8 plus > 25 ppm free CO_2 > 17 ppm sulfate and sulfate:chloride ratio 3:1	Pitting attack
pH between 7.1 and 7.8 plus > 100 ppm magnesium sulfate	Pitting attack
< 4.2 ppm potassium	Pitting attack
> 25 ppm silicate	Pitting attack
< 25 ppm nitrate	Pitting attack
Soft water at pH < 6.5 with 10 to 50 ppm CO_2, low in chloride, sulfate and nitrate ions, in hot water systems	Pitting attack
Hard water	No dezincification of duplex brass fittings

Source: Ref 1

Fig. 3 Typical copper cables as used in building construction applications

For branch-circuit sizes, virtually no aluminum is used today (Ref 1).

Building wire sizes generally range from No. 14 AWG (American Wire Gage) through 750 kcmil (kcmil is 1000 circular mils; 750 kcmil denotes wire having a cross-sectional area of approximately 0.59 in.^{2}, or 380 mm^2). Table 6 lists cross-sectional areas corresponding to some commonly encountered AWG round wire sizes. Wire sizes as small as No. 22 AWG are currently used for signal and communications functions (although there is a trend toward smaller gage numbers); larger gages are used for power transmission. Solid wire is used from No. 14 AWG through No. 10 AWG; larger sizes are stranded to provide flexibility.

Cable, whether standard or of proprietary design, denotes wire used for special and/or multiple purposes. For example, a single multifunctional cable for a residential system may carry power, telephone, video, and control/communications signals. Like electrical wire, cable is normally insulated with a rubber or polymeric compound, as shown in Fig. 3.

Electrical Applications

Roughly one-half of all copper mined is used in the form of electrical wire and cable (Ref 13). This large area of application includes conductors for power generation, transmission, and distribution (i.e., power cables as shown in Fig. 4 to 6), and for telecommunications, electronic circuitry, data processing, instrumentation, appliances, generators, motors, transformer windings, welding equipment, and other electrical equipment. Such applications are discussed in Ref 1 and 14 and in various publications available from the NEC, the American National Standards Institute (ANSI), the National Electrical Manufacturers' Association (NEMA), the Underwriters Laboratory (UL), and the Insulated Cable Engineers' Association (ICEA).

Fig. 5 Armored power cable as used in mines and industrial applications. EPR, ethylene propylene rubber. Source: Ref 14

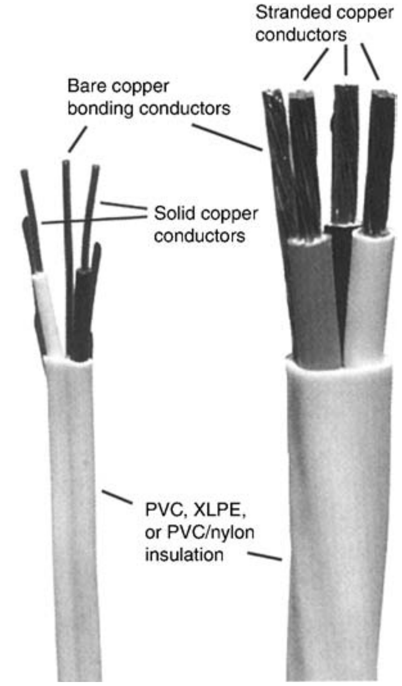

Fig. 4 Power conductor with insulation and exterior coating. PVC, polyvinyl chloride; XLPE, cross-linked polyethylene. Source: Ref 14

Other important electrical applications for copper and copper alloys include electrical contacts and resistors. Both of these are described subsequently.

Table 6 American wire gage (AWG) sizes

AWG No.	Area, mm^2	Area, in.^{2}
16	1.31	0.00203
14	2.08	0.00322
12	3.31	0.00513
10	5.26	0.00815
8	8.37	0.00130
6	13.3	0.0206
4	21.2	0.0328
3	26.7	0.0413
2	33.6	0.0520
1	42.4	0.0657
1/0	53.5	0.0829
2/0	67.4	0.104
3/0	85.0	0.132
4/0	107.2	0.166
Size, kcmil	**Area, mm^2**	**Area, in.^{2}**
250	126.7	0.196
300	152.0	0.235
350	177.3	0.275
400	202.7	0.314
500	253.0	0.392
600	304.0	0.471
7500	380.0	0.589
1000	506.7	0.785

Source: Ref 1

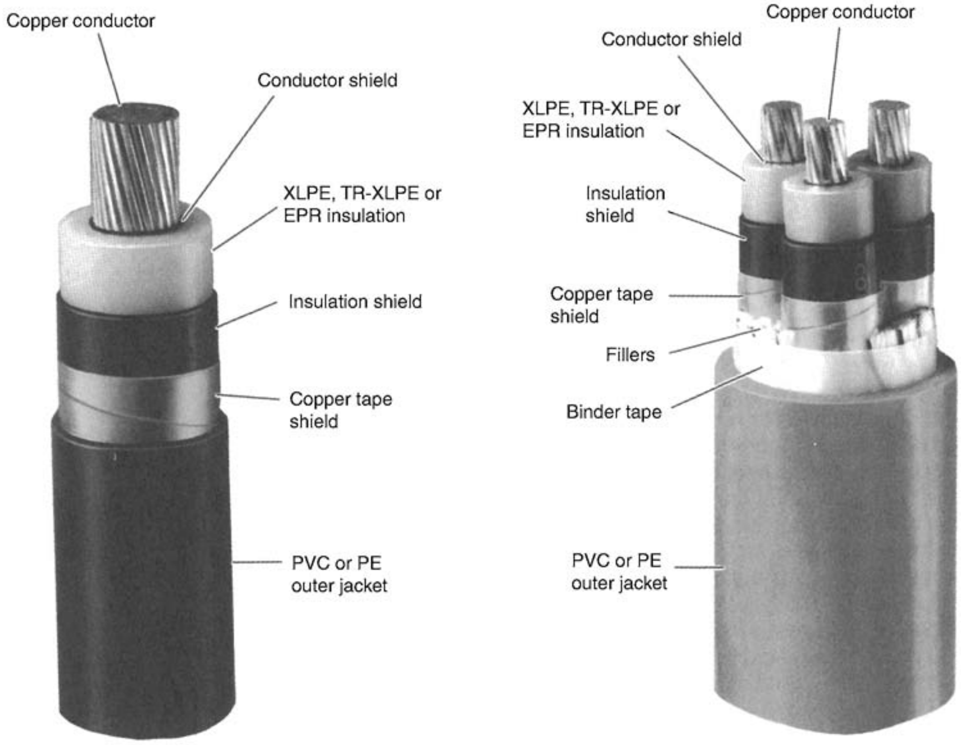

Fig. 6 Typical shielded conductor and shielded power cable. PE, polyethylene. Source: Ref 14

Electrical Contacts

Electrical contacts are metal devices that make and break electrical circuits. If an ideal electrical contact material could be found, it would have high electrical conductivity to minimize the heat generated during passage of current; high thermal conductivity to dissipate both the resistive and arc heat developed; high reaction resistance to all environments in which it was to be used to avoid formation of insulating oxides, sulfides, and other compounds; and immunity to arcing damage on the making and breaking of electrical contact.

Because no metal has all the desired properties, a wide variety of contact materials is required to accomplish the objectives of different contact applications. The economic choice of materials is usually a compromise between the various processing variables and the application requirements. Load conditions, service requirements, and ambient conditions present during the life of the unit must be considered in the selection of contact materials.

Copper Contact Alloys. High electrical and thermal conductivities, low cost, and ease of fabrication account for the wide use of copper alloys in electrical contacts. The main disadvantage of copper contacts is low resistance to oxidation and corrosion. In many applications, the voltage drop resulting from the film developed by normal oxidation and corrosion is acceptable. In some circuit breaker applications, the contacts are immersed in oil to prevent oxidation. In other applications, such as in drum controllers, sufficient wiping occurs to maintain fairly clean surfaces, thus providing a circuit of low resistance. In some applications, such as knife switches, plugs, and bolted connectors, contact surfaces are protected with grease or coatings of silver, nickel, or tin. In power circuits, where oxidation of copper is troublesome, contacts frequently are coated with silver. Vacuum-sealed circuit breakers use oxygen-free copper contacts (wrought or powder metal) for optimal electrical properties.

Pure copper is relatively soft, anneals at low temperatures, and lacks the spring properties sometimes desired. Some copper alloys, harder than pure copper and having much better spring properties, are listed in Table 7. The annealing temperature and the elevated-temperature properties of copper can be increased by additions of 0.25% Zr, 0.5% Cr, 0.03 to 0.06% Ag (10 to 20 oz per ton), or small amounts of finely dispersed metal oxides, such as Al_2O_3, with little loss of conductivity. On the other hand, improved mechanical properties are obtained only at the expense of electrical conductivity. Precipitation-hardened alloys, dispersion-hardened alloys, and powder metal mixtures can provide a wide range of mechanical and electrical properties. For example, powder metallurgy (P/M) copper-tungsten or copper-graphite mixtures are used when resistance to arcing, welding, and sticking is required. Table 8 lists properties and applications of copper-graphite brush contact materials. Additional information on copper-graphite and copper-tungsten P/M products can be found in the article "Powder Metallurgy Copper and Copper Alloys" in this Handbook.

Applications. Copper-base metals are commonly used in plugs, jacks, sockets, connectors, and sliding contacts. Because of tarnish films, the contact force and amount of slide must be kept high to avoid excessive contact resistance and high levels of electrical noise. Yellow brass (C27000) is preferred for plugs and terminals because of its machinability. Phosphor bronze (C50500 or C51000) is preferred for thin socket and connector springs and for wiper-switch blades because of its strength and wear resistance. Nickel silver is sometimes preferred over yellow brass for relay and jack springs because of its high modulus of elasticity and strength, resistance to tarnishing, and better appearance. Sometimes, copper alloy parts are nickel plated to improve surface hardness, reduce corrosion, and improve appearance. However, nickel carries a thin but hard oxide film that has high contact resistance; very high contact force and long slide are necessary to rupture the film. To maintain low levels of resistance and noise, copper metals should be plated or clad with a precious metal, most commonly, silver.

Resistors for Electrical and Electronic Devices

Copper alloys are used widely for wirewound precision resistors used in instruments and control equipment to regulate electrical characteristics. The primary requirements for such alloys, commonly referred to as resistance alloys, are uniform resistivity, stable resistance (no time-dependent aging effects), reproducible temperature coefficient of resistance, and low thermoelectric potential versus pure copper. Properties of secondary importance are coefficient of expansion, mechanical strength, ductility, corrosion resistance, and ability to be joined to other metals by soldering, brazing, or welding. Availability and cost are also factors.

Resistance alloys must be ductile enough that they can be drawn into wire as fine as 0.01 mm (0.0004 in.) in diameter or rolled into narrow ribbon from 0.4 to 50 mm ($^{1}/_{64}$ to 2 in.) wide and from 0.025 to 3.8 mm (0.001 to 0.15 in.) thick.

Alloys must be strong enough to withstand fabrication operations, and it must be easy to procure an alloy that has consistently reproducible properties. For instance, successive batches of wire must have closely similar electrical characteristics: If properties vary from lot to lot, resistors made of wire from different batches may cause a given model of instrument to exhibit widely varying performance under identically reproduced conditions, or they may cause large errors in a given instrument when a resistor from one batch is used as a replacement part for a resistor from another batch.

Coefficients of expansion of both the resistor and the insulator on which it is wound must be considered because stressed can be established that will cause changes in both resistance and temperature coefficient of resistance. It is equally important that consideration be given to the choice between single-layer and multiple-layer

Table 7 Properties of copper metals used for electrical contacts

	Solidus temperature		Electrical conductivity,	Hardness		Tensile strength			
						OS035 temper		H02 temper	
UNS No.	°C	°F	%IACS	OS035 temper	H02 temper	MPa	ksi	MPa	ksi
C11000	1065	1950	100	40 HRF	40 HRB	220	32	290	42
C16200	1030	1886	90	54 HRF	64 HRB(a)	240	35	415(a)	60(a)
C17200	865	1590	15–33(b)	60 HRB(c)	93 HRB(d)	495(c)	72(c)	655(d)	95(d)
C23000	990	1810	37	63 HRF	65 HRB	285	41	395	57
C24000	965	1770	32	66 HRF	70 HRB	315	46	420	61
C27000	905	1660	27	68 HRF	70 HRB	340	49	420	61
C50500	1035	1900	48	60 HRF	59 HRB	276	40	365	53
C51000	975	1785	20	28 HRB	78 HRB	340	49	470	68
C52100	880	1620	13	80 HRF	84 HRB	400	58	525	76

(a) H04 temper. (b) Depends ons heat treatment. (c) TB00 temper. (d) TD02 temper

Table 8 Properties of copper-graphite electrical contact materials

Composition, %		Approximate density, g/cm^3	Electrical conductivity, %IACS	Applications
Copper	Graphite			
30	70	2.60	0.11	Alternators; small auxiliary motors; low-metal, long-life brushes
30	70	2.50	2	Automotive auxiliary and appliance motors
36	64	2.75	3	Automotive heaters and blower motors
40	60	2.75	4	Automotive and other small auxiliary starting motors
40	60	2.75	2.5	Automotive heaters and ac motors
50	50	3.05	0.73	Automotive alternators
50	50	2.97	6	Automotive auxiliary and appliance motors
50	50	3.18	0.83	Industrial truck motors
62	38	3.65	3	Automotive starters. Excellent grade for low-humidity applications; excellent filming properties
65	35	3.15	3	Starters
75	25	3.25	0.51	ac wound motors and rotary converters
95	5	6.30	34	Collector roll brushes
92	8	7.30	41	High-current-carrying brush material for grounding applications
96	4	7.75	42	Automotive starters

wound resistors, because of the difference in rate of heat dissipation between the two styles.

In design of primary electrical standards of very high accuracy, cost of resistance material is not a consideration. For ordinary production components, however, cost may be the deciding factor in material selection.

Copper-nickel resistance alloys, generally referred to as *radio alloys,* have very low resistivities and moderate temperature coefficients of resistance (TCR), as shown in the first four listings in Table 9. Resistivity of radio alloys increases, and TCR decreases, as nickel content increases. Thermal electromotive force (emf) is negative with respect to copper, the magnitude being directly proportional to nickel content. All radio alloys can be readily soldered or brazed. Those with 12 and 22% nickel have high enough resistance to permit welding. Because of their high copper contents, radio alloys have low resistance to oxidation and thus are restricted to applications involving low operation temperatures. They are used chiefly for resistors that carry relatively high currents, and for this reason rapid dissipation of heat from the surface of the resistor is desirable. In this application, resistor temperature may vary over a wide range, but temperature changes are relatively unimportant.

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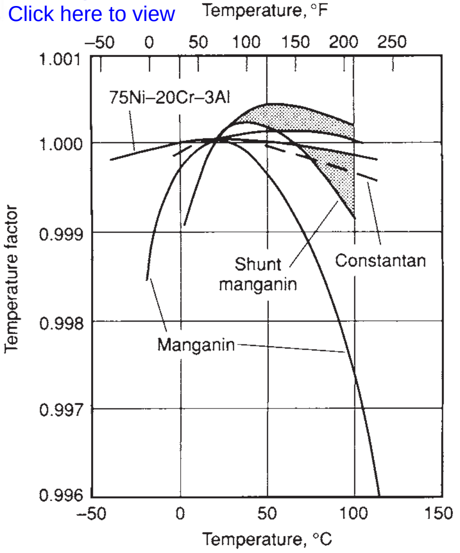

Fig. 7 Variation of resistance with temperature for four precision resistor alloys. To calculate resistance at temperature, multiply resistance at room temperature by the temperature factor.

Copper-manganese-nickel resistance alloys, generally referred to as manganins, have been adopted almost universally for precision resistors, slide wires, and other resistive components with values of 1 kΩ or less, and also are used for components with values up to 100 kΩ.

Originally, manganin was the name of a specific alloy, but the term is now generic and covers several different compositions (see Table 9). All manganins are moderate in resistivity (from 380 to 480 nΩ · m, or 230 to 290 Ω · circ mil/ft) and low in TCR (less than ±15 ppm/°C).

Manganins are stable solid-solution alloys. The electrical stability of these alloys, verified by several decades of experience, is such that their resistance values change no more than about 1 ppm per year when the material is properly heat treated and protected. Manganin-type alloys are characterized by rather steep, parabolic relations between resistance and temperature. This severely restricts the range of temperature over which resistance is stable, thus limiting the use of manganins to devices for which operating temperatures are both stable and predictable. For some applications, the maximum of the parabola (peak, or peak temperature) is kept near room temperature by controlling composition, minimizing the effects of small changes in ambient temperature. The temperature coefficient of commercial manganin is usually less than ±10 ppm/°C for an interval of 10 °C (18 °F) on either side of the peak.

When instruments are designed for operation above ambient temperature, the chemical composition of the manganin is chosen so that the peak will occur in the operating temperature range. So-called "shunt manganin," which carries high currents and consequently get hot in use, usually has a peak temperature from 45 to 65 °C (115 to 150 °F).

Manganins are susceptible to selective oxidation or preferential corrosive attack. This may occur during heat treatment, wire manufacture, or coil fabrication. Selective oxidation results in formation of a copper-rich (manganese-depleted) zone on the wire. This copper-rich sheath has the effect of greatly increasing the temperature coefficient of resistance and raising the peak temperature well beyond the range at which any precision resistor would ordinarily be used.

The resistivity of manganin—roughly 500 nΩ · m (300 Ω · circ mil/ft) at 25 °C (77 °F)—is adequate for most instrumentation purposes. The thermoelectric potential versus copper is very low, usually less than –2 μV/°C from 0 to 100 °C (32 to 212 °F).

Constantan, like manganin, has become a generic term for a series of alloys that have moderate resistivities and low temperature coefficients of resistance (see Table 9). Nominally, constantans are 55 Cu-45Ni alloys, but specific compositions vary from approximately 50 Cu-50Ni to approximately 65Cu-35Ni. The temperature coefficient of conventional constantan can be held within ±20 ppm/°C of ambient temperature. However, the difference in TCR between the low (–55 to 25 °C, or –67 to 77 °F) and high-temperature ranges (25 to 105 °C or 77 to 220 °F) is about 20 ppm. Thus, the specification is ±20 ppm/°C over one temperature range or ±40 ppm/°C over both ranges. A variation of constantan with 3% Mn improves the flatness of the resistance temperature curve and provides a TCR of ±20 ppm/°C from –55 to 105 °C (–67 to 220 °F). All constantans contain iron and cobalt in addition to manganese.

The temperature coefficient of resistance of constantan is very low and parabolic, like that of manganin, but remains flat over a much wider range (Fig. 7). Other properties are given in Table 9; specific property values vary somewhat with composition. Constantans are considerably more resistant to corrosion than manganins.

Use of constantans as electrical resistance alloys is restricted largely to ac circuits,

Table 9 Typical properties of copper-base electrical resistance alloys

Basic composition, %	Resistivity(a), nΩ · m(b)	TCR(c), ppm/°C	Thermoelectric potential versus Cu, μV/°C	Coefficient of thermal expansion(d), μm/m · °C	Tensile strength(a)		Density(a)	
					MPa	ksi	g/cm^3	lb/in.^{3}
Radio alloys								
98Cu-2Ni	50	1400 (25–105 °C)	–13 (25–105 °C)	16.5	205–410	30–60	8.9	0.32
94Cu-6Ni	100	700 (25–105 °C)	–13 (25–105 °C)	16.3	240–585	35–85	8.9	0.32
89Cu-11Ni	150	450 (25–105 °C)	–25 (25–105 °C)	16.1	340–515	35–75	8.9	0.32
78Cu-22Ni	300	180 (25–105 °C)	–36 (0–75 °C)	15.9	345–690	50–100	8.9	0.32
Manganins								
87Cu-13Mn	480	±15 (15–35 °C)	1 (0–50 °C)	18.7	275–620	40–90	8.2	0.30
83Cu-13Mn-4Ni	480	±15 (15–35 °C)	–1 (0–50 °C)	18.7	275–620	40–90	8.4	0.31
85Cu-10Mn-4Ni(e)	380	±10 (40–60 °C)	–1.5 (0–50 °C	18.7	345–690	50–100	8.4	0.31
Constantans								
57Cu-43Ni	500	±20 (25–105 °C)	–43 (25–105 °C)	14.9	410–930	60–135	8.9	0.32
55Cu-45Ni	500	±40 (–55–105 °C)	–42 (0–75 °C)	14.9	455–860	66–125	8.9	0.32
53Cu-44Ni-3Mn	525	±70 (–55–105 °C)	–38 (0–100 °C)	14.9	410–930	60–135	8.09	0.32

(a) At 20 °C (68 °F). (b) To convert to Ω · circ mil/ft, multiply by 0.6015. (c) Temperature coefficient of resistance is $(R - R_0)/R_0\ (t - t_0)$, where R is resistance at t °C and R_0 is resistance at the reference temperature t_0 °C. (d) At 25 to 105 °C. (e) Shunt manganin

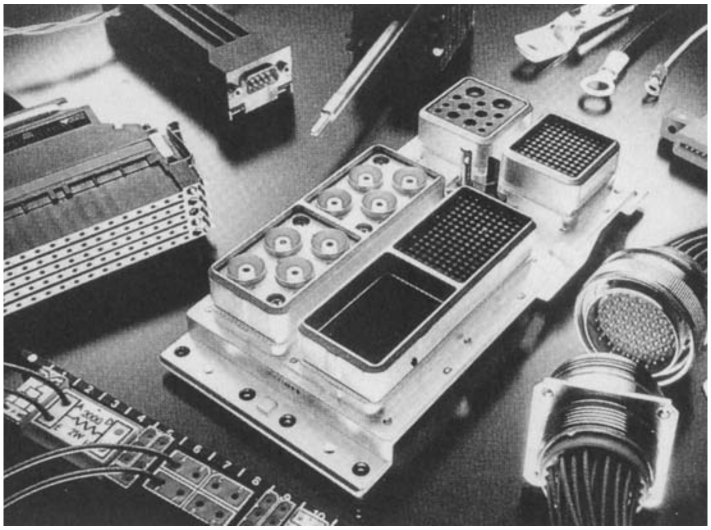

Fig. 8 Assortment of connectors using copper alloys as contacts. Source: Copper Development Association Inc.

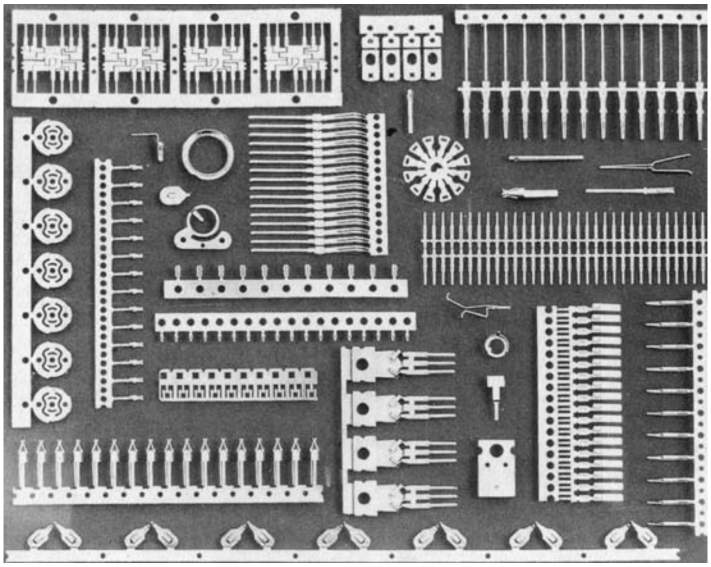

Fig. 9 Assortment of copper alloy lead frames and electrical contacts. Source: Copper Development Association Inc.

because thermoelectric potential versus copper is quite high for these materials (about 40 μV/°C at room temperature). However, if the circuit voltage is high enough to overshadow thermoelectric effects, constantans may be used in dc circuits as well.

Electronic Equipment

Electronic equipment constitutes a relatively small (in terms of tonnage consumed) but commercially and technically important application for copper. The stringent demands placed on modern electronic devices have increased the role of copper in this market. Examples of components used in electrical and electronic applications are shown in Fig. 8 and 9.

Printed Circuit Boards

Copper foil is the basic conductor in printed circuit boards (PCBs). Copper foil is available as either electrolytically deposited (ED) copper or rolled-annealed (RA) copper. Electrolytically deposited copper has a columnar grain structure, that is, the grain axes are perpendicular to the plane of the foil. This foil is formed by plating the copper from a solution so that the grains grow perpendicular to the plane of the foil. Rolled copper is formed by a mechanical process, taking ingots of pure copper and applying heat and rolling pressure to reduce the thickness and form a thin continuous web. This gives the foil a platelike grain structure that is parallel with the foil plane. This is why rolled foils tend to have better flex life endurance.

The main differences between copper foils are their mechanical properties. Rolled-annealed copper foil has lower tensile strength and greater elongation properties, is softer, and has greater ductility (Table 10). Electrodeposited foils have higher tensile strength, lower elongation, and tend to be stiffer and less ductile than RA copper.

One surface of both types of copper is usually treated by chemical oxidation to increase adhesion, to reduce resist undercutting by etchants, and to reduce bond degradation by plating chemicals. Electrolytically deposited copper is easily treated, but treating RA copper is difficult and expensive. A thin layer of zinc can be applied to the surface of the copper foil to increase bond strength and reduce corrosion. In addition, proprietary stain-proofing treatments are also used.

Copper foils are available in a variety of quality and property grades. If ED copper foil is used, it must be of the highest quality to avoid excessive foil defects. Both annealed and nonannealed ED copper foils are available. A special high-ductility grade of ED copper is available with increased elongation. Rolled copper is available as-rolled, annealed, or in a special low-temperature annealed (LTA) grade, which is easier to handle and harder than ordinary soft rolled copper. LTA foil is annealed after lamination to a dielectric substrate.

Copper foil is typically sold by weight, and flexible laminate manufacturers usually refer to the copper weight per unit of area. For example, 1 oz copper refers to foil that weighs 1 oz per square foot. This may also be referred to as 35 μm (1.36 mils) copper. Standard weights of copper used in flexible printed wiring (FPW) are 0.5, 0.75, 1, and 2 oz/ft^2. Foils less than 0.5 oz/ft^2 are being increasingly used in FPW to reduce copper usage in order to improve flexibility and to improve yields in narrow (<125 μm, or 5 mils) circuitry. Thinner foils reduce etching time and conductor undercutting. Ultrathin electrodeposited foils are available in weights of 0.375, 0.25, and 0.125 oz/ft^2. The last two gages are supplied on a disposable aluminum or copper carrier sheet, which is peeled or etched away after the foil is laminated to a substrate.

Table 10 Properties of electrodeposited and rolled-annealed copper foil

Property	Electrodeposited copper (high ductility)	Rolled-annealed copper
Purity, %	99.8	99.9
Resistivity (at 20 °C, or 68 °F), Ω · cm	1.7×10^{-6}	1.69×10^{-6}
Break elongation, %	10	10
Fatigue ductility, %	10–25	150
Surface quality (roughness), rms max, μm (μin.)	0.50 (20)	0.50 (20)
Standard weights, g (oz)	0.004–0.70 (1/8–20)	0.018–0.18 (1/2–5)
	2000 (80)	650 (25.5)
Maximum width, mm (in.)		

The costs of mechanical processes such as laminating, drilling, and deburring vary inversely with foil thickness for ultrathin gages. These added costs and the costs of the additional carrier sheets must be traded off against savings through increased circuit density and reduced etching time. All copper foils are treated with an oxidation inhibitor treatment. Although this treatment prevents premature oxidation, it can affect the adhesion of photoresist or imaging inks. Data on thickness requirements, mechanical properties, and applications for copper foil classes are available in Ref 15.

PCB Fabrication. Printed circuit boards are made by the so-called print and etch process. A copper-clad resin laminate is coated with the circuit pattern in a protective "resist" material. The unprotected copper areas are then chemically etched to remove the unwanted copper from the laminate. The resist is then removed, leaving a copper replica of the desired pattern on the laminate. For reverse prints, the uncovered copper areas are electroplated with a protective metal, usually tin, tin-lead solder, gold, or tin-nickel alloy. After plating, the organic resist is removed and the plated metal serves as the resist in the subsequent copper-etching operation. Copper foils can also be incorporated into the resin laminate to improve heat dissipation in boards with high-component densities. The foils add mechanical and thermal stability, thereby reducing the incidence of thermally or vibration-induced fatigue failures.

Connectors

About two-thirds of the copper-base products used in electronic components are found in connectors (Fig. 8). Copper is favored for this application because of its high conductivity, low-contact resistance, good spring properties, high-stress relaxation resistance, adequate strength, and excellent formability and plateability. The dominant electronic connector alloys are C26000, C50500, C51000, and C72500. Other connector materials include C11000, C15500, C17200, C17410, C17500, C19400, C19500, C68800, and C76200 (Ref 16).

Table 11 Nominal compositions of lead frame alloys

Alloy group	Designation	Nominal composition, net%
Cu-Fe	C19400	2.35Fe-0.03P-0.12Zn
	C19500	1.5Fe-0.8Co-0.05P-0.6Sn
	C19700	0.6Fe-0.2P-0.04Mg
	C19210	0.10Fe-0.034P
Cu-Cr	CCZ	0.55Cr-0.25Zr
	EFTEC 64T	0.3Cr-0.25Sn-).2Zn
Cu-Ni-Si	C70250	3.0Ni-65Si-0.15mg
	KLF-125	3.2Ni-0.7Si-1.25Sn-0.3Zn
	C19010	1.0Ni-0.2Si-0.03P
Cu-Sn	C50715	2Sn-0.1Fe-0.03P
	C50710	2Sn-0.2Ni-0.05P
Other	C15100	0.1Zr
	C15500	0.11Mg-0.06P
Fe-Ni	ASTM F 30 (Alloy 42)	42Ni-58Fe
Fe-Ni-Co	ASTM F 1 (Kovar)	29Ni-17Co-54Fe

Table 12 Electrical conductivities at 20 °C (68 °F) for lead frame materials

Alloy	Conductivity(a), %IACS	Resistivity, μΩ · cm
C15100	95	1.81
C15500	86	1.99
C19210	85	2.03
CCZ	85	2.03
C19700	80	2.16
K75	75	2.28
C19400	65	2.54
C19010	60	2.87
C19500	50	3.44
C70250	40	4.31
C50715	35	4.89
KLF-125	35	4.89
C50710	30	5.75
ASTM F 15	4	49
ASTM F 30	2.5	70

(a) % International Annealed Copper Standard (IACS) is 172.41/resistivity in μΩ · cm

Table 13 Thermal conductivities at 20 °C (68 °F) for lead frame materials

	Thermal conductivity	
Alloy	W/m · K	Btu · in./h · ft^2 · °F
C15100	380	2635
C15500	344	2385
C19210	340	2360
CCZ	340	2360
C19700	320	2220
C19400	260	1805
C19010	240	1665
C19500	200	1390
C70250	160	1110
C50715	140	970
KLF-125	140	970
C50710	120	830
ASTM F 15	40	275
ASTM F 30	12	85

Alloys with high-stress relaxation resistance are favored for contacts subjected to elevated temperatures, including the thermal spikes applied during burn-in. Highly stress-relaxation-resistant alloys include C17200 and other beryllium coppers, C70250, C51000, C52100, C72500, C15100, and a Cu-Ni-Sn spinodal alloy.

Connectors are normally stamped from strip, typically ranging from 0.25 to 0.6 mm (0.01 to 0.025 in.) thick. Heavy-duty, high-reliability products such as cylindrical military-type connectors are machined from rod or wire. Again, contact points are usually plated with oxidation-resistant metals. Tin and tin-lead contacts can be used in less-demanding applications, but noble metal contacts are more common. Gold-plated contacts require an underlying nickel barrier to prevent diffusion of gold into the copper substrate.

Beryllium coppers are used almost exclusively for the female sockets in cylindrical military connectors; male pins are made from brasses. Phosphor bronzes, alloy C72500, or other alloys are used in commercial products. Larger contacts can be stamped from strip, but screw-machined or cold-headed rod and wire dominate otherwise.

Insulation-displacement connectors were developed in the 1970s to permit efficient terminations in flat (ribbon) cable. Electrical contact is made by piercing the cable insulation with prongs on the connector. In female insulation-displacement connectors, springiness must be maintained at the piercing end to hold the (typically four) points in contact with the wire and at the socket end. The preferred materials are phosphor bronzes, beryllium coppers, and UNS alloys C68800 and C72500. The male halves are less critical and can be made from brasses or other copper alloys.

Lead Frames (Ref 17)

Lead frames are the mounting media for integrated circuits (ICs) and similar devices (Fig. 9). The ideal, all-purpose lead frame would have high electrical conductivity and thermal conductivity, good corrosion resistance, good solderability, and would be low in cost, like copper. It would also have the low coefficient of thermal expansion (CTE), high strength, good formability, and softening resistance of an Fe-42Ni alloy (alloy 42, or UNS K94100) covered in ASTM F 30 (for many years, lead frames were stamped from iron-nickel alloys). Because no such single alloy exists, there has been a conversion to copper alloys in nonhermetic packages, largely on the basis of thermal and cost considerations. Worldwide, copper alloys have become the predominant IC lead frame material in plastic dual-in-line packages (PDIPs), replacing iron-nickel alloys. ASTM F 30 alloys remains dominant in hermetic, glass-sealed ceramic packages because the CTE closely matches that of alumina and because it is compatible with the elevated-temperature manufacturing operations used for such packages.

Compositions. Copper alloys available throughout the world can be compiled into general compositional groupings. The most widely used alloys are shown in Table 11, where they are separated according to their dominant alloying element. The selection of any particular alloy will depend on the properties it can provide, the ability to be fabricated into high-quality strip having consistent properties, its availability, and its cost.

Electrical Conductivity. Minimum electrical conductivity for a selection of alloys is shown in Table 12. Lead frame materials can be ranked for electrical conductivity either as a percentage of pure copper conductivity as a unit standard, or by resistivity.

Thermal conductivity, shown in Table 13, is obtained by conversion from electrical conductivity using the Wiedemann-Franz relationship. This relationship is convenient to use because of the greater difficulty of measuring thermal conductivity. The conversion is more precise when comparing alloys of the same family.

Strength versus Formability. Metals are strengthened through alloying and processing. Alloying elements that remain in solid solution reduce conductivity, but processing can be adjusted with certain alloys to minimize conductivity loss through precipitation from solid solution, while still adding to final strength. Also, some elements in solid solution are less deleterious to conductivity than others. Alloy development involves maximizing the trade-off between strength and conductivity. Yield strength (0.2% offset) is used as the measure of strength because this property relates to the resistance of a lead to being plastically deformed or moved out of the specified position on a package.

Leads are typically formed around a radius that is about equal to the strip thickness as the lead exits the package. Therefore, any strength comparison among alloys must be normalized against this requirement, because generally, increasing the strength or temper of a given alloy reduces its ability to make a bend over a small radius.

The direction relative to the rolling direction of the strip can also be important. The smallest radius over which a bend can be made without fracture of the lead or strip, referred to as the minimum bend radius (MBR), is usually smaller when the axis of bending is normal to the rolling direction (longitudinal bend) than when the axis is parallel to the rolling direction (transverse bend). This difference becomes more pronounced as the strength (temper) of a given alloy is increased. The minimum bend radius for longitudinal bends controls formability of lead frame used for PDIPs while transverse bending limits will control formability of lead from for small-outline ICs (SOICs), four-

Table 14 Copper alloy maximum yield strengths for various plastic package configurations

	PDIP		PLCC/SOIC		Transistor outline	
Alloy	MPa	ksi	MPa	ksi	MPa	ksi
C15100	380	55	345	50	…	…
C19210	345	50	345	50	…	…
C19400	480	70	415	60	345	50
C50710	480	70	415	60	…	…
C19500	530	77	…	…	…	…
C19700	480	70	415	60	345	50
C70250	690	100	550	80	…	…

PDIP, plastic dual-in-line package; PLCC, plastic leaded chip carrier; SOIC, small-outline integrated circuit

Table 15 Solderabilities of lead frame alloys

Alloy group	Alloy	Solderability rating (type R flux)(a)
Cu-Fe	C19400	1–2
	C19500	1–2
	C19700	1–2
	C19210	1–2
Cu-Cr	CCZ	2
	EFTEC 64T	2
Cu-Ni-Si	C70250	1
	KLF-125	1
	C19010	1–2
Cu-Sn	C50715	2
	C50710	2
Other	C15100	1
	C15500	1
Fe-Ni	ASTM F 30	3–4

(a) Visual ratings: class 1, uniform smooth coating; class 2, 100% wetting, but not smooth; class 3, <50% dewetting, <10% pinholes; and class 4, >50% dewetting, >10% pinholes

Table 16 Coefficients of thermal expansion at 20 to 300 °C (68 to 570 °F) for lead frame materials

Alloy	Alloy group	Coefficient of thermal expansion, 10^{-6}/K
C15100	99.9% Cu	17.6
C18200	Cu-Cr	17.5
C19400	Cu-Fe	17.4
C70250	Cu-Ni-Si	17.2
C50710	Cu-Sn	17.8
ASTM F 30	Ni-Fe	4.0–4.7

Table 17 Lead bend fatigue comparison (longitudinal orientation)

	0.2% offset yield strength	
Alloy	MPa	ksi
C15100	380	55
C19210	380	55
CCZ	430	62
C19700	450	65
C50710	450	65
C19400	475	69
C50715	550	80
C19010	585	85
C70250	620	>90
ASTM F 30	620	>90 (>4–5 cycles)

sided packages, and ceramic dual-in-line packages (CERDIPs).

Another factor affecting the MBR is the ratio of lead width to thickness. The ability to make a sharper bend improves as the lead width decreases at constant thickness. The cause for this apparent "improvement" in bend formability is the mode of deformation that operates when the ratio of width to thickness decreases below about 8, and this deformation mode changes from one of plane strain to plane stress. More localized or necking strain is available to assist forming in the latter before fracture ensues. Thus, a given alloy temper may be capable of being formed successfully with narrow-leaded SOIC, plastic leaded chip carrier (PLCC), and quad flatpack packages (width-to-thickness ratios near 3 to 4) than for a PDIP package (ratio near 6). The preceding bend factors place a limit on the maximum strength that can be used for a given package configuration. Table 14 lists maximum strengths for selected lead frame alloys at which they can meet the formability requirements for the indicated package configuration. This table takes into account bend formability requirements for each. Accordingly, lower tempers are recommended for PLCC, SOIC, and transistor outline (TO)-type applications because of different lead thickness, width, lead orientation, and bending radius requirements.

Solderability. The inherent capability of a material to be soldered is usually determined by a dip test procedure covered under MIL-STD-202, method 208, and MIL-STD-883, method 2003.5. Visual ratings after successive immersions in flux (type R, inactivated, or type RMA, mildly activated), and 60Sn-40Pb solder are used to differentiate among alloys. The MIL-STD-883 requires 95% area coverage to pass this dip test. It is also common to compare alloys by using the same dip test procedures, but using agreed-upon standards for five classes of solder coverage. The ratings from class I to V are determined by degree of wetting, dewetting, and pores.

Wetting balance measurements promise to provide more quantitative comparisons, but universally accepted criteria have not been developed even though the procedure has been largely defined (MIL-STD-883C, method 2022.2). These specifications also include accelerated aging conditions.

Solderability ratings for selected lead frame alloys are summarized in Table 15. All results refer to type R flux immersion before soldering.

Coefficient of Thermal Expansion. All copper alloys have very nearly the same coefficient of thermal expansion. Values for selected alloys are summarized in Table 16. Most notable is that the CTE of copper alloys is much larger than that of Fe-Ni alloys. The low CTE of ASTM F 30 is attributed to magnetic ordering. As the temperature increase beyond 400 °C (750 °F), this alloy and ASTM F 15 alloy behave more like their component elements.

Lead Bend Fatigue. The lead bend fatigue test covered by MIL-STD-883 is applied to leads on packages, while SEMI G 10 refers to test samples sheared from strip before it is stamped into lead frame. The strengths of alloys capable of withstanding 4 to 5 cycles before failure in 0°-90°-0° cycles (which is above the three-cycles-to-failure minimum in MIL-STD-883) are listed in Table 17 for 0.25 mm (0.010 in.) thick strip that has been sheared to the 0.45 mm (0.017 in.) width of the lower lead section in PDIP packages. The samples used for this test comparison were cut parallel to the rolling direction of the strip (referred to as *longitudinal*), which is the same direction for leads in stamped, PDIP lead frames. About one-half to one less cycle to failure is typical for most alloys when tested in the transverse direction. For the strengths shown in Table 17, all alloys would pass the three-cycle minimum specified by MIL-STD-883. These data are appropriate, therefore, for PDIPs with leads in the longitudinal strip direction and SOIC packages with transverse orientation leads. ASTM F 30 alloy provides much higher resistance to lead bend fatigue than any of the available copper alloys. However, three to five cycles are adequate for all practical purposes.

Environmental Stability. Resistance to fracture while under stress is tested under accelerated conditions in Mattsson's solutions (ASTM G 30) with the pH adjusted for ranking in industrial-type environments. Moist ammonia can be used to stimulate severe industrial environments and dissociation of phenolic plastic components. Susceptibility to stress-corrosion cracking of new alloys can be referenced to commercial alloys whose resistance is known in practical terms. For instance, C15100, C19400, C19500, and C19700 are equivalent to unalloyed copper, C11000, which is considered immune to such failure, whereas C70250, C50710, and C50715 are equivalent to the phosphor bronze, C51000, which is known to be very highly resistant.

Softening Resistance. Thermal cycles, typically in plastic IC packaging, broadly include temperatures in the vicinity of 175 to 300 °C (350 to 570 °F) and various times, such as up to 1 min for wire bonding (200 to 300 °C, or 390 to 570 °F), 1 h for polyimide die attach (180 °C, or 355 °F), and up to 5 h at 175 °C (350 °F) for curing die attach adhesives. Burn-in testing is usually done at lower temperatures (150 °C, or 300 °F).

Figure 10 summarizes hardness change versus temperature as an indication of the relative stability of the various copper alloys. ASTM F 15 and F 30 alloys do not soften until temperatures in excess of 600 °C (1110 °F) are reached. Hence, they do not soften even during CERDIP glass sealing operations.

Industrial Machinery and Equipment

Copper and copper alloys are widely used in industrial equipment, generally because they offer a particularly beneficial combination of electrical and/or thermal conductivity, corrosion resistance, strength, and wear resistance.

Heat Exchangers and Condensers

Copper alloys have traditionally been the preferred materials for marine and fresh water condensers and heat exchangers. The most commonly used alloys are the copper-nickels, aluminum bronzes, aluminum brasses, and tin brasses. Alloys are chosen on the basis of their corrosion resistance (in the expected operation environment) and their ability to withstand high-velocity fluid flow (erosion-corrosion resistance). Equally important is the ability of copper alloys to inhibit the growth of marine organisms (biofouling), which, if unchecked, reduce flow rates, promote corrosion, degrade heat transfer, and necessitate costly maintenance.

Condenser tubes are one of a power plant's most critical elements, especially in plants that use saline or brackish water for cooling. Condenser tubes must not leak, because intrusion of oxygen and salt water to the boiler rapidly leads to corrosion and hydrogen embrittlement of boiler tubes and other components. Even fresh-water cooled plants are sensitive to this problem because the evaporative cooling towers often used in such installations can concentrate dilute salts by factors of from 2 to 8. Condenser tube failures generally result from stress-corrosion cracking (ammonia attack), pitting, parting corrosion, or erosion-corrosion due to entrapped foreign matter or faulty tube rolling.

Hydraulic shear forces in rapidly flowing media can damage protective oxide films, a process that eventually leads to erosion-corrosion. Condenser tube materials are rated by how well they withstand such hydraulic forces. Ratings are expressed in terms of shear stress or by the maximum or critical flow velocities the materials can tolerate without damage. The critical shear stress for aluminum brass is 19 Pa (2.8 ksi); for 90Cu-10Ni it is 43 Pa (6.2ksi), and for 70 Cu-30Ni it is 48 Pa, (7.0 ksi). Alloy C72200, a chromium-iron-manganese-modified 80Cu-15Ni, exhibits a critical sheer stress of 297 Pa (43 ksi), well above that encountered in normal condenser service. The critical coolant velocity for this alloy is 6 m/s (19.7 ft/s), almost twice that of alloy C70600. Alloy C71500 can be used at flow velocities between 3.5 and 4 m/s (11.5 and 13 ft/s).

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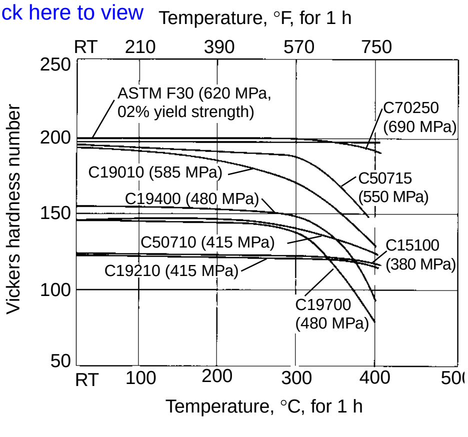

Fig. 10 Plot of hardness change versus temperature as an indication of stability of lead frame materials during assembly processes. Yield strength of each alloy before thermal exposure is shown in parentheses. RT, room temperature

Salt Water Cooling. The three most important copper alloys for salt water cooled condensers (in order of increasing corrosion resistance) are arsenical aluminum brass, C68700, 90 Cu-10Ni, C70600, and 70Cu-30Ni, C71500. Table 18 lists the performance of three copper alloys in polluted seawater; ratings are based on the percent of tubes failed per 10,000 service hours.

Fresh Water Cooling. Thin-walled condensers cooled with recirculated fresh water are often tubed with 90Cu-10Ni, C70600. This alloy withstands evaporatively concentrated corrosive species, aeration, low pH (required for scale control), and high biomass contents (bacteria, mussels, and slime). C70600 tolerates such waters at temperatures up to 90 °C (194° F) at velocities up to 3.9 m/s (12.8 ft/s).

Alloy Selection. The aqueous corrosion resistance of copper alloys is based on the formation of adherent and protective layers of insoluble corrosion products. Such layers cannot form on ordinary copper-zinc brasses in seawater; therefore, special brasses, copper-nickels, and aluminum bronzes are better suited for such service.

Special brasses include alloy C26130 modified with ~0.05% As to inhibit dezincification. An uninhibited 70-30 brass such as C26000 can be used in river water with salt contents as high as 2 g/L unless the pH is acidic, but tin brasses such as C44300 give better service. Better still is aluminum brass C68700, which was actually developed for seawater service. Handbook data indicate that this alloy should be limited to flow velocities between 0.8 and 2 m/s (2.6 and 6.6 ft/s), but the limit can be extended to 2.5 m/s (8.2 ft/s) in very clean water.

All brasses are susceptible to stress-corrosion cracking (SCC) in the presence of ammonia, amines, nitrites, and mercury and its compounds when the alloys are under residual or applied tensile stress. The organic amines morpholine and hydrazine used as oxygen scavengers in modern power plants break down in service to yield ammonia and, therefore, constitute a potential threat to copper condenser tubing. Experience suggests however, that the oxygen and ammonia contents in the main body of well-monitored condensers are quite low, and corrosion is not a serious problem. Corrosion can be more severe in the air removal section of the units, and in general, during shutdown and start-up. If ammonia contamination is high, it is better to specify SCC-resistant alloys such as copper-nickels.

Table 18 Comparative reliability of alloys C70600, C71500, and C68700 in polluted seawater

		Probability of reaching *X* years life with no more than *Y*% tube failures	
UNS No.	Median failure rate	*Y* = 30% *X* = 30	*X* = 20 *Y* = 10%
C70600 (Cu-10% Ni)	0.05	85	85
C71500 (Cu-30% Ni)	0.06	81	81
C68700 (Al brass, arsenical)	0.33	52	57

Source: Ref 1

Copper-nickel alloys (also called cupronickel) are single-phase binary alloys containing small amounts of additional alloying elements to enhance particular properties (iron improves erosion-corrosion resistance; niobium improves weldability). Uses for copper-nickels C70600, C71500, and C72200 are described previously. Other important alloys in this family include C70610, (Cu-10Ni-1.5Fe-1.0Mn), C71900, (Cu-30Ni+Mn, Cr, Zr, Ti), and C71640 (Cu-30Ni-2Fe-2Mn). Like other copper-nickels, these alloys are not susceptible to SCC, and unlike brasses, their corrosion behavior is not sensitive to changes in pH. Especially good resistance to high-velocity impingement attack has been demonstrated by alloy C71900 (Ref 1).

Alloy C71640 is intended for use in seawater. It has excellent corrosion resistance; however, high-flow velocities may induce pitting, even in this 30% Ni alloy. Very low seawater velocities (less than 1.5 m/s) and interrupted flow conditions can also be troublesome because stagnation may give rise to the formation of deposits, which invite crevice corrosion. The iron-bearing 10% copper-nickels are less affected by low-flow velocities and, therefore, present the best cost/benefits compromise for saline heat-exchanger applications.

Alloy C70600 has performed successfully in absorption-type air conditioning units charged with concentrated lithium-bromide solutions and in air, hydrogen, and oil coolers in which the cooling water was contaminated with ammonia. It also gives good service in dormitory shell- and tube-type heating plants; dishwashers and laundries; softened waters containing high concentrations of oxygen and CO_2; seawater-cooled compressor inter- and aftercoolers, and air ejector sections of power plant condensers. In the latter case, the copper alloy successfully replaced stainless steel that had failed by chloride-induced SCC.

Bearings

Copper-base alloys offer a wide range of properties for sleeve-type and other types of sliding bearings. The most commonly employed copper bearing alloys are commercial bronze, copper-lead alloys, and leaded and unleaded tin bronzes. They are used alone in single-metal bearings, as bearing backs with Babbitt surface layers, as bimetal layers bonded to steel backs, and as intermediate layers in steel-backed trimetal bearings (Ref 18). Table 19 lists characteristics and applications for copper-base sliding bearings. Table 20 gives specification numbers and nominal compositions of copper-base bearing alloys, as well as the forms in which the alloys are used.

The moderate strength and hardness of pure copper are readily increased by alloying, most commonly with tin (with which copper forms a solid solution). Lead is present in cast copper-base bearing alloys as a nearly pure, discrete phase, because its solid solubility in the matrix is practically nil. The lead phase, which is exposed on the running surface of a bearing, constitutes a site vulnerable to corrosive attack under certain operating conditions.

The antifriction behavior of copper-base bearing alloys improves as lead content increases, although at the same time strength is degraded because of increased interruption of the continuity of the copper alloy matrix by the soft, weak lead. Thus, through judicious control of tin content, lead content, and microstructure, a large family of bearing alloys has evolved to suit a wide variety of bearing applications. Some of the more common bearing alloy families are discussed below. Additional bearing alloys are listed in Table 19.

Commercial Bronze. Lead-free copper alloys are characterized by poor antifriction properties but fairly good load-carrying ability. Wrought commercial bronze strip (SAE 795) with 10% Zn can be readily press formed into cylindrical bushings and thrust washers. Strength can be increased by cold working this inexpensive material.

Unleaded Tin Bronze. The unleaded copper-tin alloys are know as phosphor bronzes because they are deoxidized with phosphorus. They are used principally in cast form as shapes for specific applications, or as rods or tubes from which solid bearings are machined. They have excellent strength and wear resistance, both of which improve with increasing tin content, but poor surface properties. They are used for bridge turntables and trunnions in contact with high-strength steel, and in other slow-moving applications.

Low-Lead Tin Bronzes. The inherently poor machinability of tin bronzes can be improved by adding small amounts of lead. Such additions do not significantly improve surface properties, however, and applications for these alloys are essentially the same as those for unleaded tin bronzes.

Medium-Lead Tin Bronzes. The only wrought strip material in this group of alloys is SAE 791, which is press formed into solid bushings and thrust washers. C83600 is used in cast form as bearing backs in bimetal bearings. SAE 793 is a low-tin, medium-lead alloy that is cast or sintered on a steel back and used as a surface layer for medium-load bimetal bushings. SAE 792 is higher in tin and slightly higher in lead; it is cast or sintered on a steel back and used for heavy-duty applications such as wrist pin bushings and heavy-duty thrust surfaces.

High-lead tin bronzes contain medium-to-high amounts of tin and relatively high lead contents to markedly improve antifriction characteristics. SAE 794, widely used in bushings for rotation loads, has the same bronze matrix composition as SAE 793 (4.5% Sn) but three times as much free lead. It is cast or sintered on a steel back and used for somewhat higher speeds and lower loads than alloy 793. The bronze matrix of SAE 794 is much stronger than that of a plain 75-25 copper-lead alloy. Alloy 794 can be used as the intermediate layer with a plated overlay in heavy-duty trimetal bearing applications such as main and connecting-rod bearings in diesel truck engines. This construction provides the highest load-carrying ability available in copper alloy trimetal bearings.

Copper-lead alloys are used extensively in automotive, aircraft, and general engineering applications. These alloys are cast or sintered to a steel backing strip from which parts are blanked and formed into full-round or half-round shapes, depending on final application. Copper-lead alloys continuously cast on steel strip typically consist of copper dendrites perpendicular and securely anchored to the steel back, with an interdendritic lead phase. In contrast, sintered copper-lead alloys of similar composition are composed of more equiaxed copper grains with an intergranular lead phase.

High-lead alloy SAE 48 can be used bare on steel or cast iron journals. Tin content in this alloy is restricted to a minimum value to maintain a soft copper matrix, which together with the high lead content improves the antifriction/antiseizure properties of the alloy. Bare bimetal copper-lead bearings are used infrequently today because the lead phase, present as nearly pure lead, is susceptible to attack by

Table 19 Characteristics and applications of copper-base bearing alloys

Alloy	Characteristics	Applications
Tin bronzes (C90300, C90500, C90700)	High strength for pounding resistance; high loads at slow-to-moderate speeds. High thermal conductivity promotes cool operation. Alloys have low frictional coefficients against steel, high wear resistance, good corrosion resistance, especially against seawater. Alloys work well with greases and can function under boundary lubrication, but should be used with adequate and reliable lubricant supply. Shafts should be hardened to 300–400 HB.	Piston pin bushings, valve guides, rolling mill bearings, and rocker shaft bearings for internal combustion engines.
Leaded tin bronzes (C92200, C92300, C92700)	Similar to those of tin bronzes. The lead provides high machinability	Similar to those of tin bronzes
High-leaded tin bronzes (C93200, C93400-C93800, C94100, C94300)	Slightly lower in strength and ductility than tin bronzes. Ideal for moderate loads and moderate-to-high speeds, but impact loads should be avoided. High thermal conductivity, wear resistance, and corrosion resistance. High lead content provides antiseizing protection in the event of lubricant failure. Lead also safely embeds dirt particles, tolerates dirty lubricants. Softer alloys accommodate some shaft misalignment; can be run against unhardened shafts.	Most commonly used bearing alloys. Best all-around choices for grease-lubricated and hydrodynamic bearings. Broadly used in automotive, off-highway, agricultural, railroad, mining, and industrial equipment. C93200 is considered the workhorse alloy. C93600 has improved pounding resistance, better corrosion resistance and machinabililty; C93700 has similar properties and resists acidic and mineral waters, paper-mill sulfite liquors.
High-strength brasses or manganese bronzes (C86300, C86400)	Strength greater than 790 MPa (115 ksi), but fatigue resistance rated as moderate. Require hardened shafts and reliable supply of clean lubricant; do not tolerate shaft misalignment. C86400 contains lead to improve machinability	Used under high loads at moderately high speeds. Have largely been replaced by aluminum bronzes in bearing applications.
Aluminum bronzes (C95300-C95500, C95520, C95800)	Higher strengths and fatigue strengths than all alloys except beryllium copper; compressive strength of C95400 at 260 °C (500 °F) equals that of tin bronze at room temperature. Alloys resist shock and repeated pounding loads well; have very high corrosion resistance but can be difficult to machine. Some alloys ("HT" suffix) can be heat treated. Require clean, reliable lubrication, fine shaft finishes, and shaft hardness >500 HB	Bushings for power shovels, off-highway equipment, roll-neck bearings, hydroelectric turbine wear rings, thrust bearings, machine tool slides, and boring-bar guide bearings
Silicon brass (C87500)	Moderately high strength for medium loads and high speeds. Good castability, relatively good machinability, but demands careful foundry practice. Requires hard shafts and clean, reliable lubrication.	Infrequently used, but can be economical in small motors, appliances.
Beryllium copper (C82500)	Ultrahigh strength and fatigue resistance, exceptional thermal conductivity. Requires hard, precisely aligned shafts and clean, reliable lubrication. Readily machined in the annealed condition, then heat-treated for highest strength.	Seldom used in cast form, although wrought Cu-Be alloys are commonly used in aircraft bearings and similar high-strength products.
Leaded coppers (C98200-C98840)	High conductivity, low to moderate strength, depending on composition,but somewhat better fatigue resistance than Babbitts (tin- or lead-base bearing alloys). Usually cast onto and supported by steel backing rings; may require electroplated Pb-Sn overlay for corrosion resistance.	Automotive main and connecting-rod bearings.

Table 20 Designations and nominal composition of copper-base bearing alloys

	Designation				Composition, %					
No.	UNS	SAE	ISO	Other	Cu	Sn	Pb	Zn	Product form	Applications
Commercial bronze										
1	C83420	Alloy 795	…	…	90	0.5	…	9.5	Wrought strip	Solid bronze bushings and washers
Unleaded tin bronzes										
2	C52100	…	CnSn8P	…	92(a)	8	…	…	Wrought strip	Solid bronze bushings and washers
3	C90300	…	…	…	88	8	…	4	Cast tubes	Solid bronze bearings
4	C90500	…	…	…	88	10	…	2	Cast tubes	Solid bronze bearings
5	C91100	…	…	…	84	16	…	…	Cast tubes	Solid bronze bearings
6	C91300	…	…	…	81	19	…	…	Cast tubes	Solid bronze bearings
Low-lead tin bronzes										
7	C92200	…	…	…	88.5	6	1.5	4	Cast tubes	Solid bronze bearings
8	C92300	…	…	…	87	8.5	0.5	4	Cast tubes	Solid bronze bearings
9	C92700	…	…	…	87.5	10	2	0.5	Cast tubes	Solid bronze bearings
Medium-lead tin bronzes										
10	C83520	Alloy 791	…	…	88	4	4	4	Wrought strip	Solid bronze bushings and washers
11	…	…	…	F32/F62	88	4	4	4	Cast on steel back	Bimetal bushings and washers
12	C83600	…	CuPb5SnZn5	…	85	5	5	5	Cast tubes	Solid bronze bearings, bronze bearing backs
13	C93200	…	CuSn7PbZn3	…	83	7	7	3	Cast tubes	Solid bronze bearings
14	…	Alloy 793	…	…	88	4	8	…	Cast on steel back	Bimetal surface layer
15	…	Alloy 793	…	…	88	4	8	…	Sintered on steel back	Bimetal surface layer
16	C93700	…	CuPb10Sn10	…	80	10	10	…	Cast tubes	Solid bronze bearings, bronze bearing backs
17	…	Alloy 792	CuPb10Sn10(G)	…	80	10	10	…	Cast on steel back	Bimetal surface layer, trimetal intermediate layer
18	…	Alloy 792	CuPb10Sn10(P)	…	80	10	10	…	Sintered on steel back	Bimetal surface layer
High-lead tin bronzes										
19	C93800	…	…	…	78	7	15	…	Cast tubes	Solid bronze bearings, bronze bearing backs
20	…	…	…	AMS 4825	74	10	16	…	Cast on steel back	Bimetal surface layer
21	…	Alloy 794	CuPb24Sn4(G)	…	73.5	3.5	23	…	Cast on steel back	Bimetal surface layer, trimetal intermediate layer
22	…	Alloy 794	CuPb24Sn4(P)	…	73.5	3.5	23	…	Sintered on steel back	Bimetal surface layer, trimetal intermediate layer
23	…	…	…	F112	72.5	2.5	25	…	Cast on steel back	Trimetal intermediate layer
24	C94300	…	…	…	70	5	25	…	Cast tubes	Solid bronze bearings
Copper-lead alloys										
25	…	Alloy 49	CuPb24Sn(G)	…	75	1	24	…	Cast on steel back	Trimetal intermediate layer
26	…	Alloy 49	CuPb24Sn(P)	…	75	1	24	…	Sintered on steel back	Trimetal intermediate layer
27	…	Alloy 48	CuPb30(P)	…	70	…	30	…	Sintered on steel back	Bimetal surface layer, trimetal intermediate layer
28	…	Alloy 485	…	…	48	1	51	…	Sintered on steel back, infiltrated with lead	Bimetal surface layer

Table 21 Typical room-temperature mechanical properties of copper-base bearing alloys

		Compressive yield strength(a)		Ultimate tensile strength		
Alloy family	Product form	MPa	ksi	MPa	ksi	Hardness, HB
Commercial bronze	Wrought strip	…	…	310–440	45–64	78–115
Unleaded tin bronzes	Wrought strip	…	…	400–580	58–84	80–160
	Cast tubes	90–125	13–18	240–310	35–45	70–170
Low-lead tin bronzes	Cast tubes	…	…	275–290	40–42	65–77
Medium-lead tin bronzes	Wrought strip	…	…	310–440	45–64	78–115
	Cast tubes	90–100	13–14	240–255	35–37	60–65
	Steel backed	…	…	…	…	50–130
High-lead tin bronzes	Cast tubes	75–85	11–12	185–210	27–30	48–55
	Steel backed	…	…	…	…	55–90
Copper-lead alloys	Steel backed	…	…	…	…	30–80

(a) 0.1% offset

corrosive products that can form in the crankcase lubricant during extended oil-change periods. Therefore, must copper-base alloys with lead contents >20%, including both SAE alloy 48 and alloy 49, are now used with plated overlays in trimetal bearings for automotive and diesel engines.

SAE 485 is a special sintered and infiltrated composite material, produced by P/M methods. By these methods, it is possible to combine a very strong continuous copper alloy matrix structure with a very high lead content, and to alloy the lead-rich constituent with sufficient tin to make it resistant to corrosion. SAE 485 is used principally for bushing and bearing applications that involve alignment, shaft surface finish, or unusual dir contamination problems.

Mechanical Properties of Copper-Base Bearing Alloys. Table 21 shows the ranges of mechanical strength properties that are exhibited by copper-base bearing alloys, according to alloy families and forms as listed in Table 20. Indentation hardness tests provide the most generally useful indications of behavior under compressive loads, and are the only standard strength tests that are applicable to all of the alloy forms. Conventional tensile and compression tests can be performed only on solid alloy bodies, which represent a relatively small fraction of total copper-base bearing alloy applications.

Test information of this kind is helpful in the material selection process as a supplement to information generated in dynamic rig tests and in actual service. Except in certain solid-alloy bearings and bushing applications, alloy strength and hardness values are rarely stated as absolute specification requirements.

Plastic Injection Molds

The primary function of an injection mold, besides defining the shape of a plastic part, is to remove heat from the plastic as quickly as possible. The injection mold may be thought of as a heat transfer device similar to a radiator. The faster the mold can transfer heat out of the molten plastic and solidify it, the faster the mold can be run. The higher thermal conductivity of copper alloys offers a maximum heat transfer effect and optimized productivity.

Copper alloys provide the best combination of high thermal conductivity and hardness for molds used in the plastics industry. As seen in Table 22, hardness and thermal conductivity vary over a range with each alloy system used for injection molding, including tool steels, aluminum alloys, and copper alloys. Copper alloys also are resistant to the acids associated with the molding of vinyl plastics and the chemical attack of acetals. Although oxidation of copper alloys can occur at temperatures above 200 °C (390 °F), this temperature is above the range used in the molding of most thermoplastics.

Transportation

Automobiles and trucks account for the largest share of copper usage in the transportation sector. Trains, ships, and aircraft, in that order, make up the balance. Copper is mostly used for electrical products, followed by heat transfer devices such as radiators and oil coolers, and bronze sleeve bearings.

Many fittings, fasteners, and other screw machine products make from leaded free-cutting brass, C36000, the most widely used of all copper alloys, are used in transport applications. In many cases, brass screw machine products can be made at lower finished cost than they can when made from leaded free-cutting steels, the principal competitor to brass in the screw machine product sector. This is possible for three largely unappreciated reasons:

- Production rates with brass are significantly higher than those attainable with leaded steel.
- Brass turnings, which are valuable, are recycled economically, whereas leaded steel turnings, which are virtually worthless, are difficult to dispose of.
- Unlike steel, brass ordinarily does not require protective electroplating to resist corrosion.

Motor Vehicles

The average 1990s-vintage North American-made automobile contains approximately 23 kg (50 lb) of copper. About 14 kg (30 lb) of copper can be found in the average foreign-made automobile sold in North America (Ref 1).

Traditionally, copper usage was distributed about equally among electrical systems (motors, generator/alternators, wiring harnesses), heat transfer systems (radiators, oil coolers, heater cores, and air-conditioning heat exchangers), and mechanical components such as bearings and shifter forks. Beginning in the late 1980s, electrical uses steadily increased, while heat transfer applications were gradually taken over by aluminum. By 1990, 79% of the total copper usage in an average North American automobile was in the electrical system, and less than 10% was in heat transfer systems. However, despite downsizing and a general reduction in the weight of automotive components, the large increase in the number and complexity of electrical systems has actually led to an increase in copper usage per vehicle.

Automotive Radiators and Heaters. For most of the twentieth century, copper and brass were the materials of choice for radiators and heaters. This trend began to change in 1978, the year Volkswagen introduced a car equipped with an aluminum radiator. Today the vast majority of automobile radiators for new cars are made from lighter-weight, lower-cost aluminum alloys, although truck bus, heavy vehicle, and aftermarket radiators continue to be made from copper and brass (Ref 1). The copper industry remains active in improving copper and brass radiator design, manufacturability, and corrosion resistance (Ref 19–21).

Automotive Wiring. Whereas cars once typically had only three electric motors (for the starter, windshield wiper, and heater/ventilator blower), modern vehicles contain up to 70 motors for various safety, comfort, and/or convenience features, many of which are now standard equipment. These motors, along with their wiring harnesses and connectors, add significantly to the modern vehicle's copper content.

New Automotive Applications. The trend toward so-called "smart" vehicles has increased copper consumption by 40% for devices such as antilock-brake systems (ABS), burglar alarms, gyroscopes, collision-avoidance systems, and navigation computers. The most significant nonelectrical development is the use of corrosion-resistant alloy C70600 brake line tube as standard equipment on several European and British cars (Ref 22). This alloy, which contains 10% Ni, with iron and manganese additions of 1.4% and 0.8%, respectively, has replaced furnace-brazed steels coated with zinc, terne metal, or epoxy/plastic coatings. As shown in Table 23, the copper-nickel alloy has almost the same resistance to burst pressure as steel. In corrosion testing, however, when exposed to salt spray for more than 180 days, steel's burst strength decreases dramatically (Fig. 11). The copper alloy remains consistently resistant. For tubes covered with a moist, salty mudpack for six months, brazed steel was severely corroded, resulting in perforation of the tubing wall, whereas only superficial general corrosion was found on the copper-nickel tubing.

Marine Applications

Copper alloys are widely used in marine heat exchangers and condensers, and in seawater piping, pumps, valves, fittings, waterboxes, propellers, and sleeve bearings. Table 24 lists the alloys commonly used in marine and marine-related service.

Industrial marine applications usually call for copper-nickels or aluminum bronzes. Manganese bronzes and silicon bronzes are also widely used, mainly in pipes, fittings, pump, and valve components and other high-strength mechanical products. Small pleasure and racing craft use propellers cast from manganese bronzes C86100

Table 22 Property comparison of injection mold alloys

		Nominal properties				
		Thermal conductivity			Tensile strength(a)	
Alloy UNS No.	Description	W/m · K at 293 K	Btu/ft^2/ft/h/°F at 68 °F	Rockwell hardness(a)	MPa	ksi
Steels						
S42000	Type 420 stainless steel	24.9	14.4	27–52 HRC	863–1725	125–250
T20813	H-13 tool steel	24.9	14.4	38–54 HRC	1421	206
T51620	P-20 tool steel	38.1	22.0	28–50 HRC	1007	146
Aluminum alloys						
A96061	Type 6061-T6	166.9	96.5	60 HRB	276	40
A97075	Type 7075-T6	129.8	75.0	88 HRB	462	67
Copper and copper alloys(b)						
C62400	Aluminum bronze	62.3	36.0	92 HRB	725	105
C17200	Beryllium copper (high hardness)	104.8	60.6	41 HRC	1311	190
C17200	Beryllium copper (moderate hardness)	131.0	75.7	30 HRC	1173	170
C17510	Beryllium copper (high conductivity)	233.6	135.0	96 HRB	759	110
C18200/18400	Chromium-hardened copper	325.5	187.0	60–80 HRB	352–483	51–70
C64700	Nickel-containing silicon bronze	162.6	94.0	94 HRB	725	105
C18000	Nickel-silicon-chromium-hardened copper	216.3	125.0	94 HRB	690	100

(a) For 25 mm (1 in.) rod; properties vary with product form and size. (b) The copper alloys are also available in cast versions with similar properties. Source: Copper Development Association Inc.

Table 23 Comparison of mechanical properties of materials used for hydraulic brake tubing

Material	Ultimate tensile strength		Yield strength 0.5% extension under load		Elongation in 50 mm (2 in.), %	Fatigue strength (10^7 cycles)		Burst pressure(a)	
	MPa	ksi	MPa	ksi		MPa	ksi	MPa	ksi
Copper-brazed steel	330–380	48–55	190–235	28–34	30–40	210	30	135	19.5
C12200-phosphorus deoxidized copper	220–265	32–38	70–100	10–14	45–60	70	10	83	12
C70600-copper-nickel 90-10	330–370	48–54	110–150	16–22	40–55	100	15	130	19

(a) For typical 4.7 mm (3/16 in.) outer diameter tubing and 0.7 mm (0.028 in.) wall thickness. Source: Ref 22

Table 24 Principal copper alloys used in substantial tonnages in marine and marine-related service

Copper alloy	Number	Principal uses
Wrought alloys		
DHP copper	C12200	Hull sheathing, piping
DPA copper	C14200	Hull sheathing, piping
Beryllium copper	C17000	Undersea telephone cable repeater housings
Cartridge or 70:30 brass	C26000	Hardware components
Muntz metal	C28000	Tubesheets
Admiralty, arsenical	C44300	Heat exchanger tubing
Naval brass, arsenical	C46500	Tubesheets
Phosphor bronze	C51000	Bolting, boat shafting, marine wire rope, naval ordnance
Phosphor bronze	C52400	Naval ordnance
Aluminum bronze	C61300, C61400	Power plant and offshore oil piping and waterboxes
NiAl bronze	C63000, C63200	Pump shafts, valve stems (Navy)
Silicon bronze	C65500	Bolting
Aluminum brass	C68700	Condenser and heat exchanger tubing
Copper-nickel	C70600	Condenser and heat exchanger tubing, piping and waterboxes–shipboard, power, industrial and desalination plants, waterflood and offshore oil
Copper-nickel	C71500	Condenser and heat exchanger tubing, piping and waterboxes–shipboard power, industrial and desalination plants, waterflood and offshore oil
Copper-nickel	C72200	Condenser and heat exchanger tubing
Cast alloys		
Ounce metal	C83600	Plumbing fittings
Manganese bronze	C86500	Ship propellers
G bronze	C90300	Pumps, valves, naval ordnance, tailshaft sleeves
M bronze	C92200	Pumps, valves
Al bronze	C95200	Waterflood and seawater pumps
NiAl bronze	C95500	Propellers
NiAlMn bronze	C95700	Propellers
NiAl bronze	C95800	Pump, valves and fittings, ship propellers
Copper-nickel (80:20)	C96300	Tailshaft sleeves for ships
Copper-nickel (70:30)	C96400	Pumps, valves, fittings

Source: Ref 23

or C86800. The manganese bronzes combine high-corrosion resistance with exceptional mechanical properties; some reach tensile strengths greater than 690 MPa (100 ksi). Small boat propellers are also available in cast silicon brass, C87500. Large propellers are cast in nickel-aluminum bronze, C95800.

Traditional antifouling paints are compounded with copper oxide, an effective biostatic agent. The insoluble paints are inhospitable to marine organisms. Copper-base systems are considered environmentally safer than, for example, tributyl tin-base coatings, which continuously release toxins into the surrounding water. Small boats that are infrequently used are more vulnerable to marine fouling than commercial vessels. For light craft, adhesively bonded copper-nickel foil and copper powder-filled epoxy resins offer permanent remedies to biofouling. The relatively high initial costs are offset by significantly reduced hull maintenance.

Castings for Ships and Offshore Platforms. The high corrosion resistance, strength, and low life-cycle cost of cast-copper alloys make them economical choices for pipes, flanges and fittings, pumps and valve components, bearings and other mechanical devices. In piping, the antifouling characteristics of the alloys reduce maintenance costs considerably compared with galvanized steel, fiberglass-reinforced plastic, or rubber-lined products, all of which may be cheaper initially. Also, because copper-alloy pipes need not be oversized to allow for biofouling, they can be smaller and lighter than those made from other materials.

Aluminum Bronzes. With their favorable combination of strength and corrosion resistance, cast aluminum bronzes have earned a reputation for reliable service in marine environments. Aluminum bronzes offer a broad range of mechanical properties; some can be heat treated to strengths higher than those of high-strength hull-plate steels. Aluminum bronzes are commonly used for shafts and mechanical components in pumps and valves for seawater cooling systems. Their antifouling properties are particularly valuable in safety-related systems such as fire-fighting equipment. Being non-sparking, aluminum-bronze hand tools can safely be used on tankers and oil and gas platforms. Because the aluminum bronzes are non-magnetic when properly processed, the alloys are also used for chains, slings, and other mechanical components in mine sweepers. Alloy C95800, a cast nickel-aluminum bronze containing small amounts of iron and manganese, has become the standard material for large propellers and the hubs and gearboxes used with them.

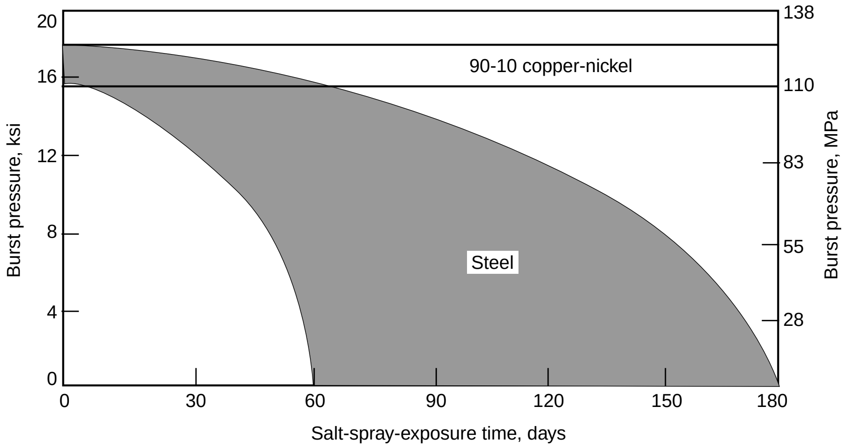

Fig. 11 Burst-pressure test results under salt-spray-exposure conditions for 90-10 copper-nickel and steel brake tubing. Source: Ref 22

Overlays for Ships and Offshore Structures. The copper industry has sponsored extensive research and development directed at the use of copper-nickel hull materials for commercial vessels and for offshore structures. Copper-nickel was chosen because it offers the best combination of erosion-corrosion resistance and antifouling properties. The idea of cladding boats with copper metals is hardly new; copper plates were commonly used in the 17th century to protect wooden hulls against wood-boring ship worms. Because early copper-clad craft were also free from the fronds of algae that formed on wooden hulls, they were significantly faster than unclad vessels. In the case of offshore structures the presence of fouling necessitates the use of a heavy structure to resist the wave action on the increased cross section presented by the fouled surface. The use of copper-nickel cladding enables the reduction in the amount of steel required in the submerged portion of the structure (Ref 1).

Copper-Nickel Hulls. Ship hulls can be fabricated from solid copper-nickel plates, from metallurgically bonded copper-nickel clad steel (cladded), or from steel hulls over which have been welded sheets of copper-nickel alloy (sheathed). Steel and light-gage copper-nickel plates can be metallurgically bonded by hot rolling or explosive bonding to produce a composite structure. Solid copper-nickel plate is slightly stronger than hot-rolled hull steel and is economically competitive in thicknesses up to 10 mm (0.4 in.); roll-bonded material, up to 35 mm (1.4 in.); and weld overlay at total hull thicknesses greater than 100 mm (4 in.). Cladding thickness is at least 1.5 mm (0.06 in.) and normally between 2 and 3 mm (0.8 and 1.2 in.). Clad plate is commercially available in thicknesses of 5 mm (0.196 in.) and heavier in lengths to 13 m (43 ft) and widths to 2.5 m (8.2 ft). Plate is guaranteed to exhibit a minimum shear strength of 137 MPa (20 ksi) between cladding and substrate (Ref 1).

Copper-Nickel-Clad Vessels. Among the first commercial copper-hulled vessels to be commissioned in recent years was the Copper Mariner, a 20 m (67 ft) shrimp boat operating in highly biofouling waters off Nicaragua (Ref 24). The ship's hull was fabricated from plates of alloy C70600. The boat did not require dry-docking for hull maintenance during its first 10 years of service. The Copper Mariner was followed by a small fleet of copper-clad shrimp boats, all of which were still in service in the mid-1990s. These vessels feature roll-bonded C70600-clad steel hull plates, which apparently perform as well as the earlier all-copper-nickel design. Several copper-nickel clad Italian fire boats, several Finnish ice breakers, and one large commercial vessel have been placed in service.

Copper-Nickel Sheathing. U.S. Maritime Administration studies have shown that for large cargo ships, tankers, and naval vessels, thin plates of copper-nickel fitted over conventional steel hulls offer the same advantages as solid or clad copper-alloy plate at significantly lower cost. The studies also demonstrated that hull sheathing is economically viable for new vessels and as retrofits on vessels less than 10 years old. Ships older than 10 years may not have enough remaining service life to amortize the investment required to retrofit the sheathing.

Consumer and General Products

The application of copper and copper alloys in consumer and general products covers an enormous variety of uses. Copper-base metals are favored because of their corrosion resistance, good formability, and bright colors. Highly malleable alloys such as cartridge brass (C26000), yellow brass (C27000), forging brass (C37700), and architectural bronze (C38500) are widely used as stampings and forgings for mechanical components and decorative products such as candlestick holders and lamps. The applications described subsequently demonstrate the diversity of this market category.

Coinage

It has been estimated that coinage accounts for about 1% of copper consumption in the United States. Despite growing use of electronic, credit card, and check transactions, coinage is becoming increasingly popular. Many countries have replaced low-denomination bank notes with coins, primarily because coins last longer (and therefore cost less) than paper notes. For example, Canada has withdrawn its one- and two-dollar paper currency bills, and substituted copper-base metal coins, commonly referred to as "Loonies" (so named for the symbol of the loon on the back of the one-dollar coin) and "Toonies" (two-dollar coin). In both the U.S. and Canada, 5-cent coins are composed of a 75Cu-25Ni (C71300) alloy. The U.S. 10-cent piece and 25-cent piece are composite structures consisting of a core of pure copper (C11000) that is clad with the 75Cu-25Ni alloy (Fig. 12). The U.S. dollar coin introduced in 2000 is also a clad metal. The gold-colored outer layer is composed of an alloy of 77Cu-12Zn-7Mn-4Ni that is roll bonded onto a pure copper core, which comprises 50% of the coin's thickness.

The recently introduced euro coins also contain copper (Ref 25). Metals and alloys used for these coins, which are minted in denominations of 1 and 2 euros and 1, 2, 5, 10, 20, and 50 euro cents, are:

- The 2 euro bimetallic coin consists of an outer ring of copper-nickel (75Cu-25Ni) surrounding an inner disk of pure nickel clad on both sides with nickel brass (Cu-20Zn-5Ni).
- The 1 euro bimetallic coin consists of an outer ring of nickel brass (Cu-20Zn-5Ni) surrounding an inner disk of pure nickel clad on both sides with copper-nickel (75Cu-25Ni).
- The 10, 20, and 50 euro cent pieces are made from the Nordic Gold alloy (89Cu-5Al-5Zn-1Sn).
- The 1, 2, and 5 cent pieces are made from copper-plated steel.

Containers for Nuclear Wastes

Bimetallic, centrifugally cast burial containers for high-level nuclear waste have been fabricated from copper-base materials (Ref 26). The double-wall container consists of an outer 50 mm (2 in.) thick layer of deoxidized copper (C81100) surroundings an inner 25 mm (1 in.) thick shell of nickel-aluminum bronze (C95800). The deoxidized copper provides resistance to corrosion while the nickel-aluminum bronze was chosen for its strength, toughness, and good elevated-temperature properties. The burial cylinders are 825 mm (32.5 in.) in diameter and 457 mm (18 in.) long with a 75 mm (3 in.) total wall thickness.

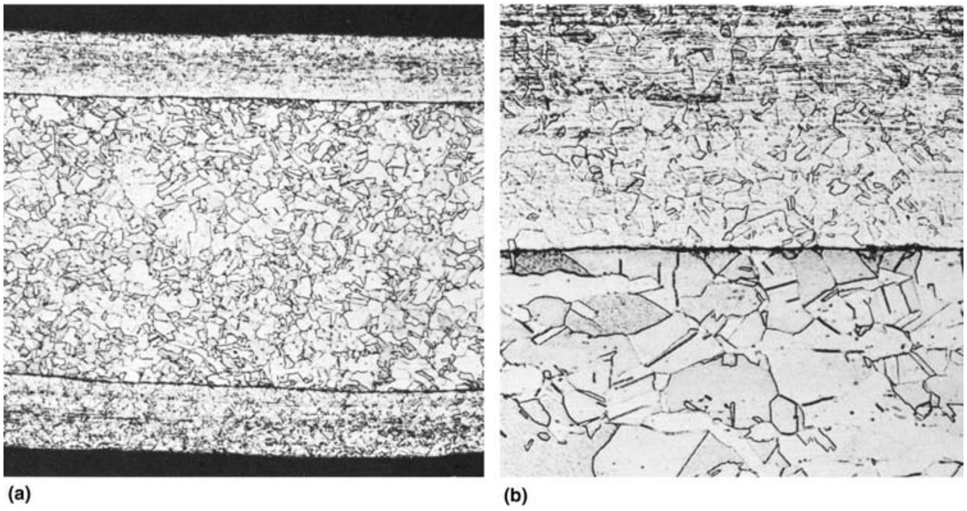

Fig. 12 The composite structure of the U.S. dime featuring a C71300 (copper-nickel, 25%) cladding on both sides of a copper C11000 (electrolytic tough pitch) core. (a) 50×. (b) Higher magnification (250×) showing the heavily cold-worked outer surface as a result of the coining operation. Both etched in $K_2Cr_2O_7$ plus H_2SO_4 plus HCl

Copper as an Alloying Element

Apart from its use in copper-base alloys, there are other base metals to which copper can be added. Of primary engineering importance are cast irons, structural steels, stainless steels, nickel alloys, and aluminum alloys.

Cast Irons. Copper increases the tensile strength of gray and ductile irons by promoting a pearlitic matrix. Its effect is most pronounced at lower addition levels (0.25 to 0.5%). In martensitic white irons, moderate copper additions (2.5% or less) are used to suppress pearlite formation.

Structural steels can be made resistant to atmospheric corrosion and heavy progressive rusting under many conditions by the addition of copper or copper plus small amounts of nickel, chromium, silicon, and phosphorus. These grades are known as *weathering steels* and contain 0.25 to 0.40% Cu.

Stainless Steels. The addition of copper (about 2 to 4%) in duplex stainless steels and high-nickel austenitic stainless steels enhances corrosion resistance in acid environments and can also confer greater resistance to certain forms of attack in seawater.

Nickel Alloys. Additions of copper provide improvement in the resistance of nickel to nonoxidizing acids. In particular, alloys containing 30 to 40% Cu (Monel alloys) offer useful resistance to nonaerated sulfuric acid.

Aluminum alloys containing about 4 to 6% Cu are age hardening and, by careful choice of composition and thermomechanical processing, very high levels of mechanical strength can be obtained, though at the expense of corrosion resistance.

Copper Compounds

Copper compounds are also used for a wide spectrum of industrial uses, including:

- Medical applications (e.g., dietary supplements in baby food and various vitamins and mineral preparations)
- Agriculture (e.g., fungicides and micronutrients for plants and animals)
- Preservatives for timber and fabrics
- Water treatment (e.g., copper salts are added to avoid algae growth in potable water and swimming pools and to treat drinking water to remove color and odor caused by algae)
- Catalysts (e.g., copper compounds are important catalysts in the synthesis of a variety of organic chemicals, including polymers

A more detailed account of the uses of copper compounds can be found in Ref 1 and 27.

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Fabrication and Finishing

Melting and Casting

SUCCESSFUL PRODUCTION of copper and copper alloy castings depends on three important factors:

- An understanding of casting and solidification characteristics of copper and its various alloys
- Adherence to proper foundry practices including melting practices (e.g., selection of melting furnace and molten metal treatments), pouring practices, and gating and risering techniques
- Proper selection of the casting process which, in turn, depends on the size, shape, and technical requirements of the product

This article addresses each of these factors. Additional information on the selection and application of copper castings can be found in the article "Cast Copper and Copper Alloys" in this Handbook.

Casting Characteristics

Copper is alloyed with other elements because pure copper is extremely difficult to cast as well as being prone to surface cracking, porosity problems, and to the formation of internal cavities. The casting characteristics of copper can be improved by the addition of small amounts of elements including beryllium, silicon, nickel, tin, zinc, chromium, and silver. Alloy coppers, for example, constituted to have improved strength properties over those of high-purity copper, while maintaining a minimum of 85% conductivity, are widely used for cast electrical conducting members.

In the liquid state, copper alloys behave much the same as ferrous alloys of similar density. Molten copper alloys are susceptible to contamination from refractories as well as from the atmosphere. Copper casting alloys are subject to fuming from the vaporization of zinc, which is a major alloying element in about three-fourths of the copper casting alloys. With a few exceptions, such as beryllium-coppers and 1% Cr copper, the copper casting alloys contain at least 10% alloying additions and sometimes these additions exceed 40%. Alloying additions have a marked effect on the temperature at which melting is completed (solidus and liquidus). Temperatures at the beginning and at the end of melting are discussed in this article in the section "Solidification Ranges."

When casting copper and its alloys, the lowest possible pouring temperature needed to suit the size and form of the solid metal should be adopted to encourage as small a grain size as possible as well as to create a minimum of turbulence of the metal during pouring.

Solidification Ranges

The copper-base casting alloy family can be subdivided into three groups according to solidification (freezing) range. Unlike pure metals, alloys solidify over a range of temperatures. Solidification begins when the temperature drops below the liquidus; it is completed when the temperature reaches the solidus. The liquidus is the temperature at which the metal begins to freeze, and solidus is the temperature at which the metal is completely frozen. The three groups are as follows.

Group I alloys are alloys that have a narrow freezing range, that is, a range of 50 °C (90 °F) between the liquidus and solidus. These are the yellow brasses, manganese and aluminum bronzes, nickel bronzes, (nickel silvers), manganese (white) brass alloys, chromium-copper, and copper. Nominal compositions and liquidus/solidus temperatures for these alloys are shown in Table 1.

Group II alloys are those that have an intermediate freezing range, that is, a freezing range

Table 1 Nominal chemical compositions and solidification ranges for group I alloys

	Composition, %											Liquidus temperature		Solidus temperature	
Alloy type	UNS No.	Cu	Sn	Pb	Zn	Ni	Fe	Al	Mn	Si	Other	°C	°F	°C	°F
Copper	C81100	100	…	…	…	…	…	…	…	…	…	1083	1981	1064	1948
Chrome copper	C81500	99	…	…	…	…	…	…	…	…	1.0 Cr	1085	1985	1075	1967
Yellow brass	C85200	72	1	3	24	…	…	…	…	…	…	941	1725	927	1700
	C85400	67	1	3	29	…	…	…	…	…	…	941	1725	927	1700
	C85700	61	1	1	37	…	…	…	…	…	…	941	1725	913	1675
	C85800	62	1	1	36	…	…	…	…	…	…	899	1650	871	1600
	C87900	65	…	…	34	…	…	…	…	1	…	926	1700	900	1650
Manganese bronze	C86200	63	…	…	27	…	3	4	3	…	…	941	1725	899	1650
	C86300	61	…	…	27	…	3	6	3	…	…	923	1693	885	1625
	C86400	58	1	1	38	…	1	5	5	…	…	880	1616	862	1583
	C86500	58	…	…	39	…	1	1	1	…	…	880	1616	862	1583
	C86700	58	1	1	34	…	2	2	2	…	…	880	1616	862	1583
	C86800	55	…	…	36	3	2	1	3	…	…	900	1652	880	1616
Aluminum bronze	C95200	88	…	…	…	…	3	9	…	…	…	1045	1913	1042	1907
	C95300	89	…	…	…	…	1	10	…	…	…	1045	1913	1040	1904
	C95400	86	…	…	…	…	4	10	…	…	…	1038	1900	1027	1880
	C95410	84	…	…	…	2	4	10	…	…	…	1038	1900	1027	1880
	C95500	81	…	…	…	4	4	11	…	…	…	1054	1930	1038	1900
	C95600	91	…	…	…	…	…	7	…	2	…	1004	1840	982	1800
	C95700	75	…	…	…	2	3	8	12	…	…	990	1814	950	1742
	C95800	81	…	…	…	4.5	4	9	1.5	…	…	1060	1940	1043	1910
Nickel bronze	C97300	57	2	9	20	12	…	…	…	…	…	1040	1904	1010	1850
	C97600	64	4	4	8	20	…	…	…	…	…	1143	2089	1108	2027
	C97800	66	5	2	2	25	…	…	…	…	…	1180	2156	1140	2084
White brass	C99700	58	…	2	22	5	…	1	12	…	…	902	1655	879	1615
	C99750	58	…	1	20	…	…	1	20	…	…	843	1550	818	1505

of 50 to 110 °C (90–200 °F) between the liquidus and solidus. These are the beryllium-coppers, silicon bronzes, silicon brass, and copper-nickel alloys. Nominal compositions and liquidus/solidus temperatures for these alloys are shown in Table 2.

Group III alloys have a wide freezing range, well over 110 °C (200 °F), even up to 170 °C (300 °F). These are the leaded red and semired brasses, tin and leaded tin bronzes, and high-leaded tin bronzes. Nominal compositions and liquidus/solidus temperatures for these alloys are shown in Table 3.

Melting Practice

Melting Furnaces

Furnaces for melting copper casting alloys are either fuel fired or electrically heated. They are broadly classified into three categories:

- Crucible furnaces (tilting or stationary)
- Open-flame (reverberatory) furnaces
- Induction furnaces (core or coreless)

Selection of a furnace depends on the quantity of metal to be melted, the degree of purity required, and the variety of alloys to be melted. Environmental restrictions also influence furnace selection.

Fuel-Fired Furnaces. Copper-base alloys are melted in oil- and gas-fired crucible and open-flame furnaces. Crucible furnaces, either tilting or stationary, incorporate a removable cover or lid for removal of the crucible, which is transported to the pouring area where the molds are poured. The contents of the tilting furnace are poured into a ladle, which is then used to pour the molds (Fig. 1 and 2).

These furnaces melt the raw materials by burning oil or gas with sufficient air to achieve complete combustion. The heat from the burner heats the crucible by conduction and convection; the charge melts and then is superheated to a particular temperature at which either the crucible is removed or the furnace is tilted to pour into a ladle. While the molten metal is in the crucible or ladle, it is skimmed, fluxed, and transferred to the pouring area, where the molds are poured.

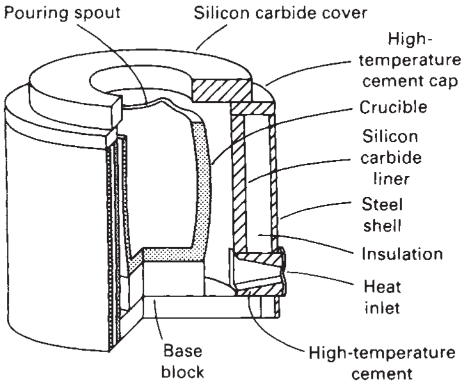

Fig. 1 Typical lift-out type of fuel-fired crucible furnace, especially well adapted to foundry melting of smaller quantities of copper alloys (usually less than 140 kg, or 300 lb)

Table 2 Nominal chemical compositions and solidification ranges for group II alloys

		Composition, %								Liquidus temperature		Solidus temperature	
Alloy type	UNS No.	Cu	Zn	Ni	Fe	Mn	Si	Nb	Other	°C	°F	°C	°F
Beryllium-copper	C81400	99.1	…	…	…	…	…	…	0.6 Be 0.8 Cr	1093	2000	1066	1950
	C82000	97	…	…	…	…	…	…	0.5 Be 2.5 Co	1088	1990	971	1780
	C82200	98	…	1.5	…	…	…	…	0.5 Be …	1116	2040	1038	1900
	C82400	97.8	…	…	…	…	…	…	1.7 Be 0.5 Co	996	1825	899	1650
	C82500	97.2	…	…	…	…	0.3	…	2.0 Be 0.5 Co	982	1800	857	1575
	C82600	96.8	…	…	…	…	0.3	…	2.4 Be 0.5 Co	954	1750	857	1575
	C82800	96.6	…	…	…	…	0.3	…	2.6 Be 0.5 Co	932	1710	885	1625
Silicon brass	C87500	82	14	…	…	…	4	…	…	916	1680	821	1510
Silicon bronze	C87300	9.5	…	…	…	1	4	…	…	916	1680	821	1510
	C87600	91	5	…	…	…	4	…	…	971	1780	860	1580
	C87610	92	4	…	…	…	4	…	…	971	1780	860	1580
	C87800	82	14	…	…	…	4	…	…	916	1680	821	1510
Copper-nickel	C96200	87	…	10	1.5	1	…	1	…	1149	2100	1099	2010
	C96400	66	…	30.5	0.5	1	…	1	…	1238	2260	1171	2140

Table 3 Nominal chemical compositions and solidification ranges for group III alloys

		Composition, %					Liquidus temperature		Solidus temperature	
Alloy type	UNS No.	Cu	Sn	Pb	Zn	Ni	°C	°F	°C	°F
Leaded red brass	C83450	88	2.5	2	6.5	1	1015	1860	860	1580
	C83600	85	5	5	5	…	1010	1850	854	1570
	C83800	83	4	6	7	…	1004	1840	843	1550
Leaded semired brass	C84400	81	3	7	9	…	1004	1840	843	1550
	C84800	76	2.5	6.5	15	…	954	1750	832	1530
Tin bronze	C90300	88	8	…	4	…	1000	1832	854	1570
	C90500	88	10	…	2	…	999	1830	854	1570
	C90700	89	11	…	…	…	999	1830	831	1528
	C91100	84	16	…	…	…	950	1742	818	1505
	C91300	81	19	…	…	…	889	1632	818	1505
Leaded tin bronze	C92200	86	6	1.5	4.5	…	988	1810	826	1518
	C92300	87	8	1	4	…	999	1830	854	1570
	C92600	87	10	1	2	…	982	1800	843	1550
	C92700	88	10	2	…	…	982	1800	843	1550
High-leaded tin bronze	C92900	84	10	2.5	…	3.5	1031	1887	857	1575
	C93200	83	7	7	3	…	977	1790	854	1570
	C93400	84	8	8	…	…	…	…	…	…
	C93500	85	5	9	1	…	999	1830	854	1570
	C93700	80	10	10	…	…	929	1705	762	1403
	C93800	78	7	15	…	…	943	1730	854	1570
	C94300	70	5	25	…	…	…	…	900	1650

The other type of fuel-fired furnace is the open-flame furnace, which is usually a large rotary-type furnace with a refractory-lined steel shell containing a burner at one end and a flue at the other. The furnace is rotated slowly around the horizontal axis, and the rotary movement helps to heat and melt the furnace charge. Melting is accomplished both by the action of the flame directly on the metal and by heat transfer from the hot lining as this shell rotates. These furnaces usually tilt so that they can be charged and poured from the flue opening. At the present time, these furnaces are not used often because of the requirement that a baghouse be installed to capture all the flue dust emitted during melting and superheating. While these furnaces are able to melt large amounts of metal quickly, there is a need for operator skill to control the melting atmosphere within the furnace. Also, the refractory walls become impregnated with the melting metal, causing a contamination problem when switching from one alloy family to another.

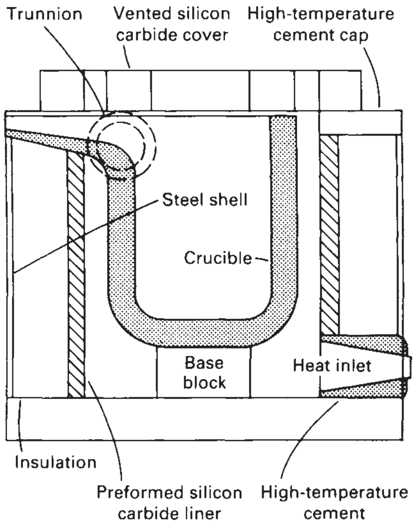

Fig. 2 Typical lip-axis tilting crucible furnace used for fuel-fired furnace melting of copper alloys. Similar furnaces are available that tilt on a central axis

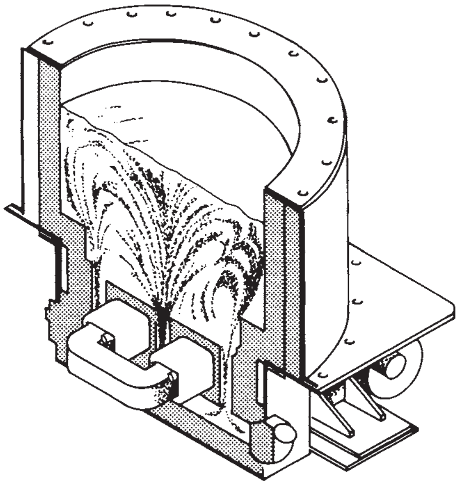

Fig. 3 Cutaway drawing of a twin-channel induction melting furnace

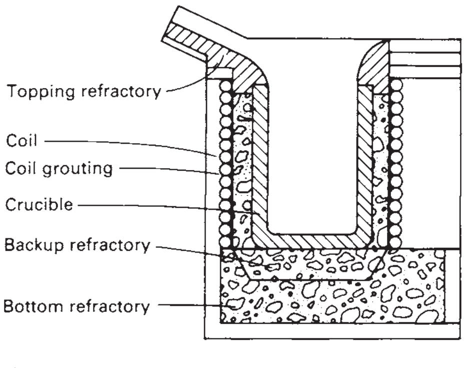

Fig. 4 Cross section of a tilt furnace for high-frequency induction melting of brass and bronze alloys. Crucible is of clay graphite composition.

Electric Induction Furnaces. In the past 30 years, there has been a marked changeover from fuel-fired melting to electric induction melting in the copper-base foundry industry. While this type of melting equipment has been available for more than 60 years, very few were actually used due to the large investment required for the capital equipment. Because of higher prices and the question of availability of fossil fuels and because of new regulations on health and safety imposed by the Occupational Safety and Health Administration (OSHA), many foundries have made the changeover to electric induction furnaces.

When melting alloys in group III, fumes of lead and zinc are given off during melting and superheating. The emission of these harmful oxides is much lower when the charge is melted in an induction furnace because the duration of the melting cycle is only about 25% as long when melting the same amount of metal in a fuel-fired furnace. By the use of electric induction melting, compliance with OSHA regulations can be met in many foundries without the need for expensive air pollution control equipment.

The two types of electric induction furnaces are the core type, better known as the channel furnace, and the coreless type.

Core Type. This furnace (Fig. 3) is a large furnace used in foundries for pouring large quantities of one alloy when a constant source of molten metal is required. This furnace has a primary coil, interfaced with a laminated iron core, surrounded by a secondary channel, which is embedded in a V- or U-shape refractory lining located at the bottom of a cylindrical hearth. Here the channel forms the secondary of a transformer circuit. This furnace stirs and circulates molten metal through the channel at all times, except when the furnace is emptied and shut down. When starting up, molten metal must be poured into the furnace to fill up the "heel" on the bottom of the bath. Because these furnaces are very efficient and simple to operate with lining life in the millions of pounds poured, they are best suited for continuous production runs in foundries making plumbing alloys of group III. They are not recommended for the dross-forming alloys of group I. The channel furnace is at its best when an inert, floating, cover flux is used and charges of ingot, clean remelt, and clean and dry turnings are added periodically.

Coreless Type. This furnace has become the most popular melting unit in the copper alloy foundry industry. In earlier years, the coreless furnace was powered by a motor generator unit, usually at 980 Hz. The present coreless induction furnaces draw 440V, 60 cycle power and, by means of solid-state electronic devices, convert the power to 440V and 1000 or 3000 Hz. These furnaces are either tilting furnaces (Fig. 4) or crucible lift-out units (Fig. 5, 6).

A coreless induction furnace comprises a water-cooled copper coil in a furnace box made

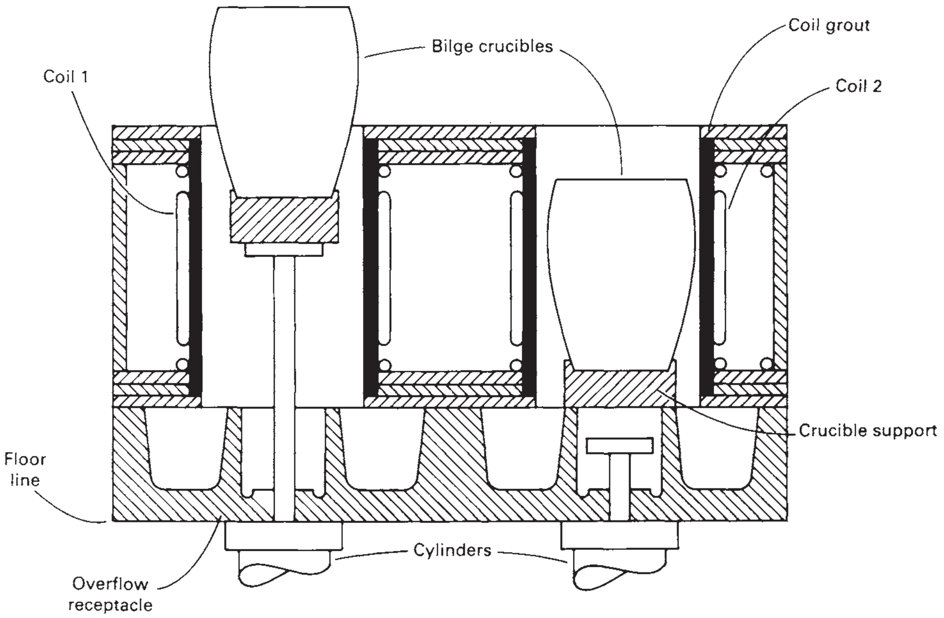

Fig. 5 Cross section of a double push-out furnace. Bilge crucibles are placed on refractory pedestals and raised and lowered into position within the coils by hydraulic cylinders.

of steel or Transite. The metal is contained in a crucible or in a refractory lining rammed up to the coil. Crucibles used in these furnaces are made of clay graphite; silicon carbide crucibles cannot be used because they become overheated when inserted in a magnetic field. Clay graphite crucibles do a good job of conducting the electromagnetic currents from the coil into the metal being melted.

Induction furnaces are characterized by electromagnetic stirring of the metal bath. Because the amount of stirring is affected by both power input and power frequency, the power unit size and frequency should be coordinated with the furnace size in order to obtain the optimal-size equipment for the specific operation. In general, the smaller the unit, the higher the frequency and the lower the power input.

Large tilting units are used in foundries requiring large amounts of metal at one time. These furnaces, if over 4.5 Mg (10,000 lb) capacity, operate at line frequency (60 Hz). They are very efficient and will melt large quantities of metal in a very short time if powered with the proper-size power unit.

Stationary lift-out furnaces are often designed as shown in Fig. 5. Here the crucible sits on a refractory pedestal, which can be raised or lowered by a hydraulic cylinder. This unit, also called a push-out furnace, operates by lowering the crucible into the coil for melting and then raising the crucible out of the coil for pickup and pouring. While one crucible is melting, the other crucible can be charged and ready to melt when the knife switch is pulled as the completed heat is being pushed up for skimming and pouring.

The other common type of coreless induction melting is the lift swing furnace (Fig. 6). Here the coil (and box) is cantilevered from a center post to move up or down vertically and swing horizontally about the post in a 90° arc. Because there are two crucible positions, one crucible can be poured, recharged, and placed into position to melt, while the other is melting. When the metal is ready to pour, the furnace box is lifted (by hydraulic or air cylinder), pivoted to the side, and lowered over the second crucible. The ready crucible is then standing free and can be picked up and poured, while melting is taking place in the second furnace.

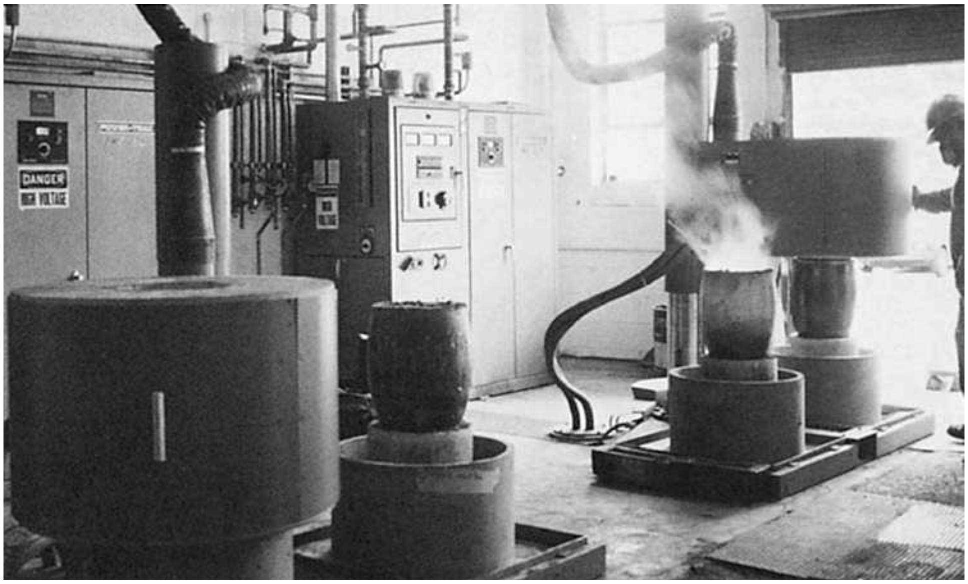

Fig. 6 Foundry installation of high-frequency induction lift swing furnaces

Melt Treatments

In the melting of copper alloys, various auxiliary molten metal processing steps are necessary other than melting and alloying to improve melt quality through the control of impurities. Melt treatments for copper castings include:

- Fluxing and metal refining
- Degassing
- Deoxidation
- Grain refining
- Filtration

Each of these is described in the sections that follow. It should be noted that some of these process methodologies pertain not only to foundry melting and casting, but also to smelting, refining, and in certain cases mill product operations.

Fluxing of Copper Alloys

The term fluxing is used in this article to represent all additives to, and treatments of, molten metal in which chemical compounds or mixtures of such compounds are employed. These compounds are usually inorganic. In some cases, metallic salts are used in powder, granulated, or solid tablet form and may often melt to form a liquid when used. They can be added manually or can be automatically injected, and they can perform single or, in combination, various functions, including degassing, cleaning, alloying, oxidation, deoxidation, or refining. The term fluxing also includes the treatment of nonferrous melts by inert or reactive gases to remove solid or gaseous impurities.

Fluxing practice in copper alloy melting and casting encompasses a variety of different fluxing materials and functions. Fluxes are specifically used to remove gas or prevent its absorption into the melt, to reduce metal loss, to remove specific impurities and nonmetallic inclusions, to refine metallic constituents, or to lubricate and control surface structure in the semicontinuous casting of mill alloys. The last item is included because even these fluxes fall under the definition of inorganic chemical compounds used to treat molten metal.

Types of Fluxes

Fluxes for copper alloys fall into five basic categories: oxidizing fluxes, neutral cover fluxes, reducing fluxes (usually graphite or charcoal), refining fluxes, and semicontinuous casting mold fluxes.

Oxidizing fluxes are used in the oxidation-deoxidation process; the principal function here is control of hydrogen gas content. This technique is still practiced in melting copper alloys in fuel-fired crucible furnaces, where the products of combustion are usually incompletely reacted and thus lead to hydrogen absorption and potential steam reaction (see the section "Degassing of Copper Alloys" in this article). The oxidizing fluxes usually include cupric oxide or manganese dioxide (MnO_2), which decompose at copper alloy melting temperatures to generate the oxygen required. Figure 7 illustrates the effectiveness of oxidizing fluxes in reducing porosity due to hydrogen and in improving mechanical properties for a tin bronze alloy.

Neutral cover fluxes are used to reduce metal loss by providing a fluid cover. Fluxes of this type are usually based on borax, boric acid, or glass, which melts at copper alloy melting temperatures to provide a fluid slag cover. Borax melts at approximately 740 °C (1365 °F). Such glassy fluxes are especially effective when used with zinc-containing alloys, preventing zinc flaring and reducing subsequent zinc loss by 3 to 10%. The glassy fluid cover fluxes also agglomerate and absorb nonmetallic impurities from the charge (oxides, molding sand, machining lubricants, and so on). As with aluminum alloys, fluxes containing reactive fluoride salts (CaF_2 and NaF) can strip oxide films in copper-base alloys, thus permitting entrained metallic droplets to return to the melt phase. Table 4 indicates the effectiveness of this type of flux in reducing melt loss in yellow and high-tensile brass. For red brasses, however, it may not be proper to use a glassy flux cover, because such a cover will prevent or limit beneficial oxidation of the melt (see the section "Degassing of Copper Alloys" in this article). Use of a glassy cover flux can sometimes result in reduced alloy properties (Ref 1).

Oxide films in aluminum and silicon bronzes also reduce fluidity and mechanical properties.

Fluxes containing fluorides, chlorides, silica, and borax provide both covering and cleaning, along with the ability to dissolve and collect these objectionable oxide skins. Chromium and beryllium-copper alloys oxidize readily when molten; therefore, glassy cover fluxes and fluoride salt components are useful here in controlling melt loss and achieving good separation of oxides from the melt.

Reducing fluxes containing carbonaceous materials such as charcoal or graphite are used on higher-copper lower-zinc alloys. Their principal advantage lies in reducing oxygen absorption of the copper and reducing melt loss. Low-sulfur, dry, carbonaceous flux materials should always be used with copper alloys to avoid gaseous reactions with sulfur or with hydrogen from contained moisture. However, carbonaceous materials will not agglomerate nonmetallic residues or provide any cleaning action when melting fine or dirty scrap. For this reason, a glassy cover must also be used in the latter case. Table 4 indicates the beneficial effects of a glassy cover when melting brass turnings.

Melt Refining Fluxes. It is possible to remove many metallic impurity constituents from copper alloys through the judicious use of fire refining (oxidation). According to standard free energy of reaction (Fig. 8), elements such as iron, tin, aluminum, silicon, zinc, and lead are preferentially oxidized before copper during fire refining (Ref 2), and there is an order of preference for their removal (Fig. 9). These metallic impurities are thus rendered removable if the oxide product formed can be adequately separated from the melt phase itself. A wet cover flux such as borax is useful with fire refining because it will agglomerate the impurity metal oxides formed and minimize the metal content of the dross.

The need to refine specific metallic impurities is highly dependent on and variable with the specific alloy system being refined. An alloying element in one family of copper alloys may be an impurity in another, and vice versa. In red brass (Cu-5Zn-5Pb-5Sn; alloy C83600), the elements lead, tin, and zinc are used for alloying, while aluminum, iron, and silicon are impurities. In aluminum bronzes, on the other hand, lead, tin, and zinc become contaminants, while aluminum and iron are alloying elements.

Foundries typically do little melt refining, leaving this assignment to the secondary smelter supplier of their foundry ingot. However, there may be certain instances when additional refining capability is necessary within the foundry or mill. Table 5 gives the results of fire refining a melt of C83600 with aluminum, silicon, and iron contaminants under a variety of flux covers.

Fire refining (oxidation) can be used to remove impurities from copper-base melts roughly in the following order: aluminum, manganese, silicon, phosphorus, iron, zinc, tin, and lead. Nickel, a deliberate alloying element in certain alloys but an impurity in others, is not readily removed by fire refining, but nickel oxide can be reduced at such operating temperatures. Mechanical mixing or agitation during fire refining improves the removal capability by increasing the reaction kinetics. Removal is limited, however, and in dilute amounts (<0.05–0.10%) many impurities cannot be removed economically.

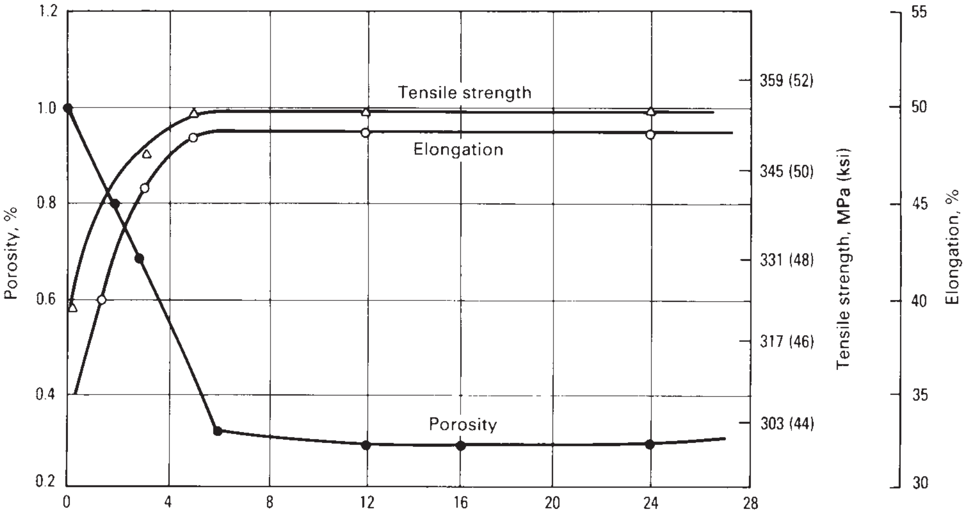

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Fig. 7 Effect of amount of flux used on the porosity and mechanical properties of cast tin bronze alloy. Source: Ref 1

Table 4 Effect of various slags and covers on losses in the melting of high-tensile and yellow brass

		Metal temperature				
Alloy	Melting conditions	°C	°F	Melting time, min	Gross loss, %	Net loss, %
Yellow brass	No lid or cover	1085	1985	50	2.8	1.8
	Charcoal	1087	1989	49	1.1	0.6
	Glassy cover flux	1100	2012	62	0.9	0.4
High-tensile brass	No lid or cover	1090	1994	65	2.5	1.2
	Charcoal	1095	2003	60	1.9	0.7
	Cleaning cover flux	1090	1994	54	0.6	0.3

Source: Ref 1

Oxygen-bearing fluxes can be effective in removing certain impurities, although they are less efficient than direct air or oxygen injection. Figure 10 demonstrates the effect of increasing the copper oxide content of a flux in removing iron and zinc from phosphor bronze.

Lead has been removed from copper alloy melts by the application of silicate fluxes or slags. The addition of phosphor copper or the use of a phosphate or borate slag flux cover and thorough stirring improves the rate of lead removal, as shown in Fig. 11 (Ref 4).

Sulfur, arsenic, selenium, antimony, bismuth, and tellurium can occur as impurities in copper alloy scrap, foundry ingot, and prime metal through incomplete refining of metal from the ore, electronic scrap, other scrap materials, or cutting lubricant. These impurities can largely be controlled by application and thorough contacting with fluxes containing sodium carbonate (Na_2CO_3) or other basic flux additives such as potassium carbonate (K_2CO_3). Figure 12 demonstrates the ability of Na_2CO_3 fluxes plus fire refining in eliminating arsenic, bismuth, and antimony from copper.

Sulfur is a harmful impurity in copper-nickel or nickel-silver alloys. It can be removed from these materials by an addition of manganese metal or magnesium.

Aluminum is often a contaminant in copper alloy systems, particularly the leaded tin bronzes and red brasses. Porosity and lack of pressure tightness result when the aluminum content is as little as 0.01%. Aluminum can be removed by a flux containing oxidizing agents to oxidize the aluminum, and fluoride salts to divert the Al_2O_3 from the melt and render it removable. Silicon can also be removed, but only after the aluminum has reacted. As much as 0.3% contaminant can be reduced to less than 0.01%, ensuring pressure tightness, by using a flux consisting of 30% NaF, 20% CaF_2, 20% Na_3AlF_6, 20% Na_2SO_4, and 10% Na_2CO_3 at an addition rate of 1 to 1.5% for 10 min at about 1100 °C (2010 °F) (Ref 6). As usual, the flux must be intimately mixed with the melt to ensure good reactivity. The melt should then be allowed to settle, and the flux residue or slag layer should be thoroughly skimmed.

Borax is useful as a flux constituent for refining to provide adequate fluidity and to agglomerate flux-reacted impurity oxides without excessive entrapment and loss of alloying elements. The borax mineral fluxes razorite and colemanite are commonly used in secondary smelting practice in converting copper alloy brass and bronze scrap to specified-composition foundry ingot.

Chlorine fluxing also has potential for refining impurities from copper-base melts, particularly magnesium, aluminum, manganese, zinc, iron, lead, and silicon. However, very little chlorine refining is practiced commercially; the process may be cost effective only when removing aluminum.

Mold Fluxes. Certain mold-lubricating fluxes have been used in the direct chill semicontinuous casting of brass and copper alloys into semifinished wrought shapes. These fluxes serve to protect the metal from oxidation during casting. They also act as lubricants so that the solidifying skin separates easily from the mold wall as the solidifying billet or slab moves downward from the mold during casting. Especially in brass alloys, zinc flaring and zinc oxide (ZnO) formation on the melt surface reduce lubricity, causing tearing and other undesirable skin defects during solidification that are detrimental to subsequent forming operations. Fluxing compounds are used on the melt surface feeding the mold to alleviate these problems. Fluxes used to alleviate this problem usually contain borax, fluoride salts, soda ash, and eutectic salt mixtures to ensure that the flux is molten as the cast continues. In the direct chill casting of higher-copper alloys, graphite may also be present in such fluxes. Because solid flux particles can cause inclusions in the solidifying skin, the flux must be free of coarse particles and must melt quickly.

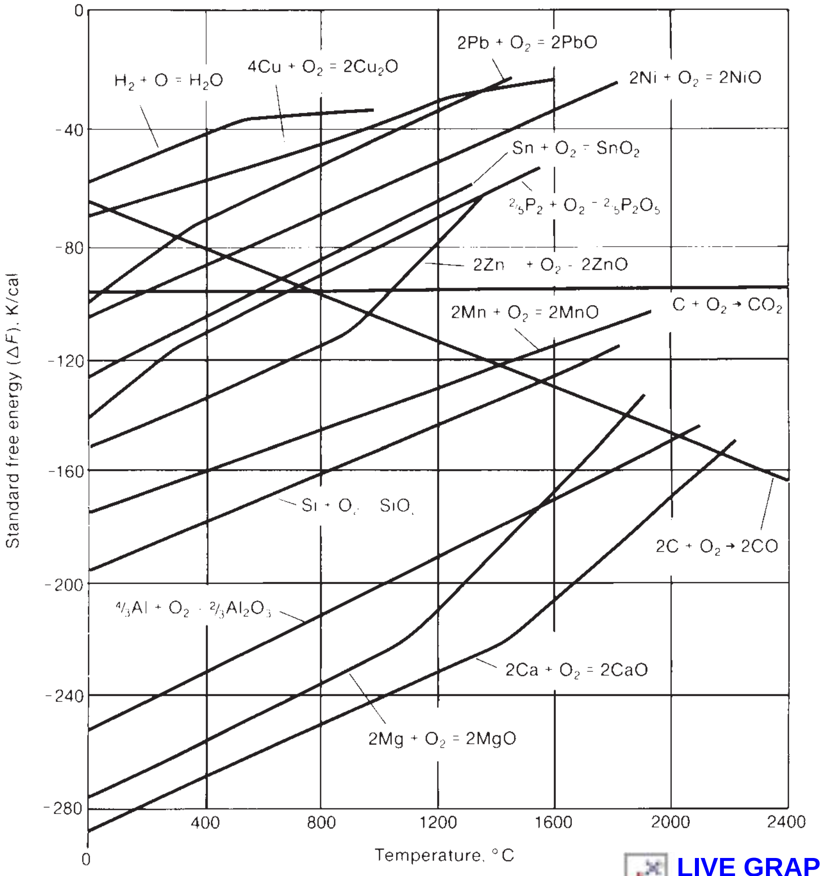

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Fig. 8 Free-energy changes for various metal oxidation reactions. Source: Ref 1

Table 5 Effect of fire refining under various fluxes on impurity levels in leaded red brass

50 kg (110 lb) heats were melted under 1 kg (2.2 lb) of flux at 1150 °C (2100 °F).

Melt No.	Flux	Refining time, min	Oxygen used, liters per kilogram of metal	Amount of zinc in refined metal, %	Impurities in refined metal, %		
					Al	Si	Fe
1	Borax	0	0	5.49	0.05	0.08	0.38
		10	1.5	5.66	0.015	0.05	0.38
		20	2.9	5.00	0.011	0.02	0.29
2	Borax-25% sand	0	0	6.30	0.14	0.13	0.37
		10	1.5	6.24	0.017	0.12	0.42
		20	2.9	6.45	0.007	0.12	0.41
3	Borax-20MnO	0	0	7.40	0.21	0.26	0.47
		10	1.5	7.35	0.05	0.19	0.52
		20	3.1	7.33	0.017	0.12	0.51
4	$70CaF_2$-$20Na_2SO_4$-$10Na_2CO_3$	0	0	7.47	0.10	0.08	0.62
		10	1.5	7.07	<0.005	0.02	0.55
		20	3.1	6.69	<0.005	<0.005	0.45
5	30NaF-$20CaF_2$-20KF-$20Na_2SO_4$-$10Na_2CO_3$	0	0	7.35	0.23	0.38	0.70
		10	1.8	6.74	0.005	0.17	0.83
		20	3.5	7.20	<0.005	0.08	0.88

Source: Ref 3

Degassing of Copper Alloys

In the melting and casting of many copper alloys, hydrogen gas absorption can occur because of the generous solubility of hydrogen in the liquid state of these alloys. The solid solubility of hydrogen is much lower; therefore, the gas must be rejected appropriately before or during the casting and solidification process to avoid the formation of gas porosity and related defects (excessive shrink, pinholing, blowholes, and blistering). These defects are almost always detrimental to mechanical and physical properties, performance, and appearance. Different copper alloys and alloy systems have varying tendencies toward gas absorption and subsequent problems. Other gases, particularly oxygen, can cause similar problems (see the section "Deoxidation of Copper Alloys" in this article).

Sources of Hydrogen

There are many potential sources of hydrogen in copper, including the furnace atmosphere, charge materials, fluxes, external components, and reactions between the molten metal and the mold.

Furnace Atmosphere. The fuel-fired furnaces sometimes used in melting can generate free hydrogen because of the incomplete combustion of fuel oil or natural gas.

Charge Materials. Ingot, scrap, and foundry returns may contain oxides, corrosion products, sand or other molding debris, and metalworking lubricants. All these contaminants are potential sources of hydrogen through the reduction of organic compounds or through the decomposition of water vapor from contained moisture.

Fluxes. Most salt fluxes used in copper melt treatment are hygroscopic. Damp fluxes can therefore result in hydrogen pickup in the melt from the decomposition of water.

External Components. Furnace tools such as rakes, puddlers, skimmers, and shovels can deliver hydrogen to the melt if they are not kept clean. Oxides and flux residues on such tools are particularly insidious sources of contamination because they will absorb moisture directly from the atmosphere. Furnace refractories, troughs and launders, mortars and cements, sampling ladles, hand ladles, and pouring ladles also are potential sources of hydrogen, especially if refractories are not fully cured.

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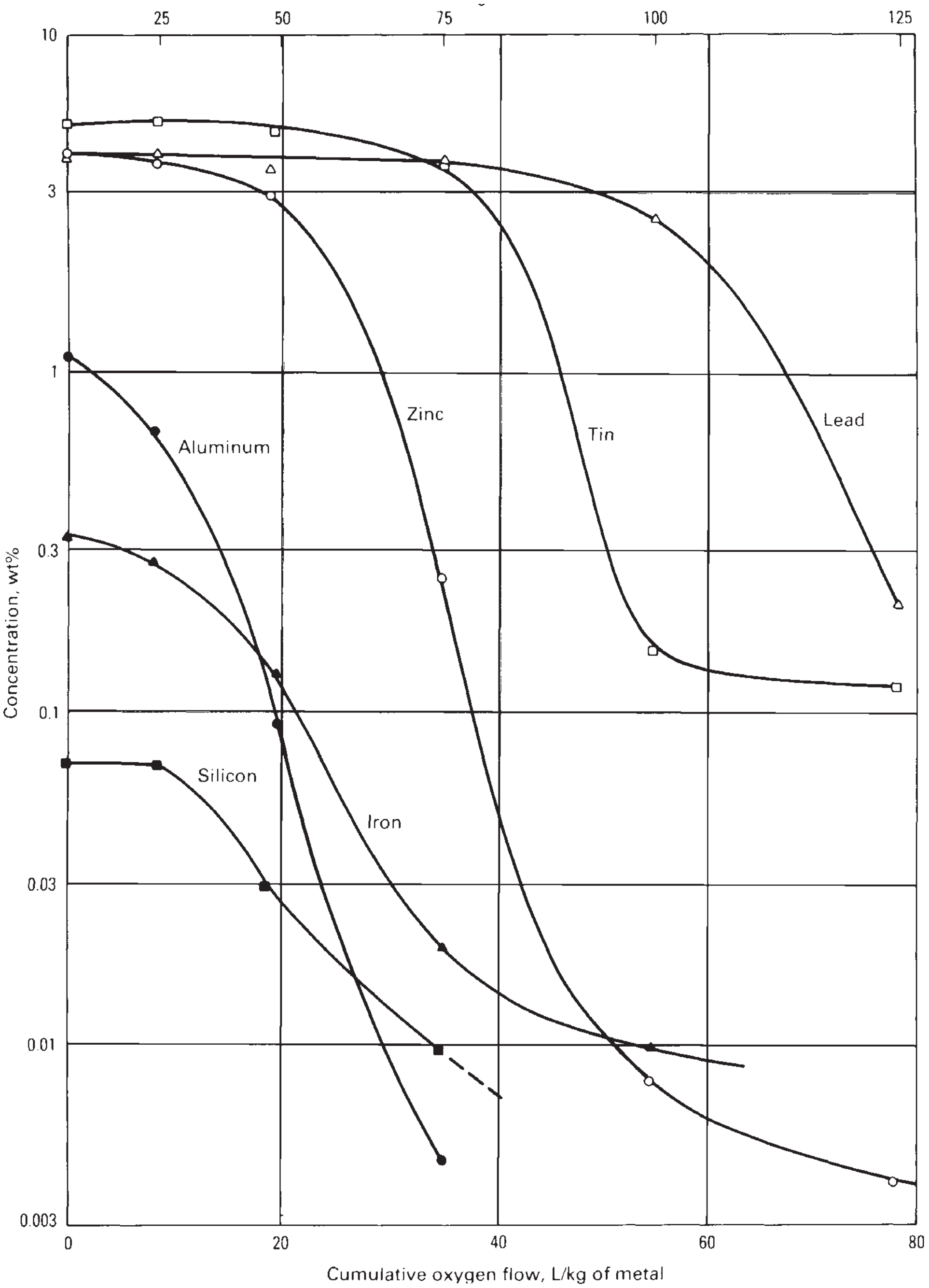

Fig. 9 Effect of fire refining (oxygen blowing) on the impurity content of molten copper. Source: Ref 3

Metal/Mold Reactions. If metal flow is excessively turbulent during the pouring process, air can be aspirated into the mold. If the air cannot be expelled before the start of solidification, hydrogen pickup can result. Improper gating can also cause turbulence and suctioning. Excessive moisture in green sand molds can provide a source of hydrogen as water turns to steam.

Gas Solubility

Hydrogen is the most obvious gas to be considered in copper alloys. Figure 13 shows the solubility of hydrogen in molten copper. As in aluminum and magnesium alloys, solubility is reduced in the solid state; therefore, the hydrogen must be removed prior to casting or rejected in a controlled manner during solidification. Alloying elements have varying effects on hydrogen solubility (Fig. 14).

Oxygen also presents a potential problem in most copper alloys. In the absence of hydrogen, oxygen alone may not cause problems, because it has limited solubility in the melt. However, it forms a completely miscible liquid phase with the copper in the form of cuprous oxide (Fig. 15). During solidification, the combination of cuprous oxide and hydrogen can give rise to casting porosity resulting from the steam reaction (discussed later).

Sulfur gases have significance in primary copper through the smelting of sulfide ores and in the remelting of mill product scrap containing sulfur-bearing lubricants. Sulfur dioxide is the most probable gaseous product. Foundry alloys and foundry processing usually do not experience sulfur-related problems unless high-sulfur fossil fuels are used for melting.

Carbon can be a problem, especially with the nickel-bearing alloys. The nickel alloys have extensive solubility for both carbon and hydrogen. Carbon can be deliberately added to the melt, along with an oxygen-bearing material such as nickel oxide. The two components will react to produce a carbon boil, that is, the formation of CO bubbles, which collect hydrogen as they rise through the melt (Ref 9). If not fully removed, however, the residual CO can create gas porosity during solidification.

Nitrogen does not appear to be detrimental or to have much solubility in most copper alloys. However, there is some evidence to suggest that nitrogen porosity can be a problem in cast copper-nickel alloys (Ref 10).

Water vapor can exist as a discrete gaseous entity in copper alloys (Ref 7, 11, 12). Water vapor is evolved from solidifying copper alloys, which always have some residual dissolved oxygen. When the oxygen becomes depleted, hydrogen is produced as a separate species.

The type and amount of gas absorbed by a copper alloy melt and retained in a casting depend on a number of conditions, such as melt temperature, raw materials, atmosphere, pouring conditions, and mold materials. Table 6 lists the gases that can be found in a number of copper alloy systems.

Testing for Gases

There are essentially three ways to determine the presence of gas in a copper alloy melt. The easiest and simplest is a chill test on a fracture specimen. In this method, a standard test bar is poured and allowed to solidify. The appearance of the fractured test bar is then related to metal quality standards (Ref 13).

The second method is a reduced-pressure test similar to the Straube-Pfeiffer test used for aluminum alloys. In recent years, considerable development and definition have been given to this test as adapted for copper alloys, because the different classes of copper alloys have different solidification characteristics that affect the response to the test (Ref 7, 14–16). The objective of the test is to use a reduced pressure only slightly less than the dissolved gas pressure so that the surface of the sample mushrooms but does not fracture (Fig. 16). The test apparatus is shown schematically in Fig. 17. The key to establishing controllable results, that is, unfractured but mushroomed test sample surfaces, is to provide wave front freezing. This is accomplished by proper selection of vessel materials to

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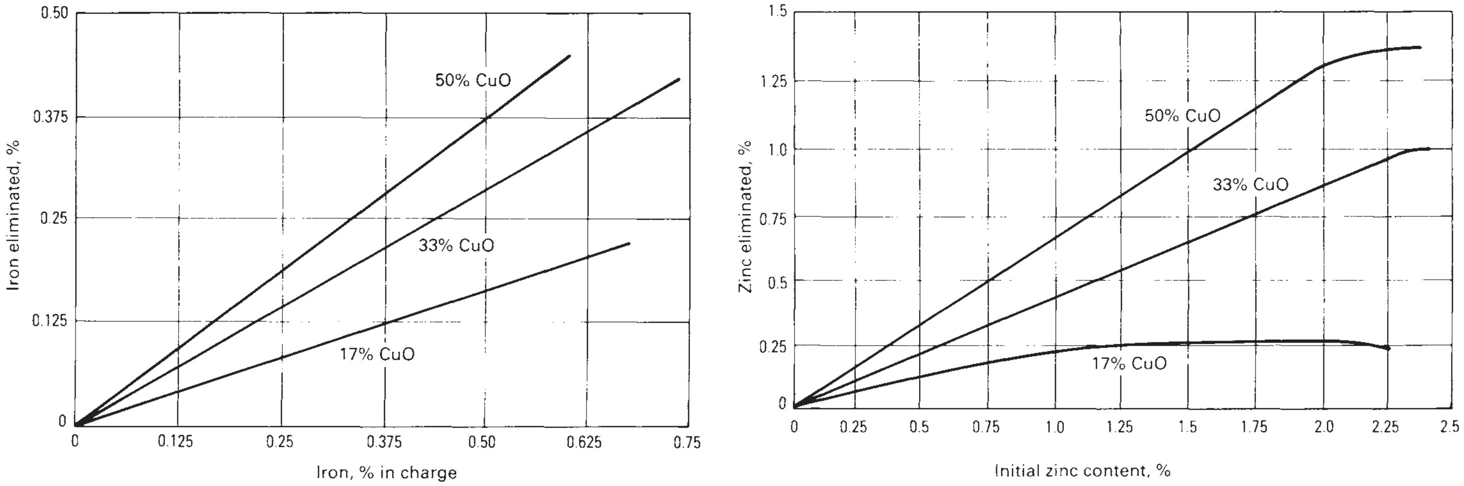

Fig. 10 Influence of oxygen content of flux in reducing iron (a) and zinc (b) impurities in phosphor bronze. Source: Ref 1

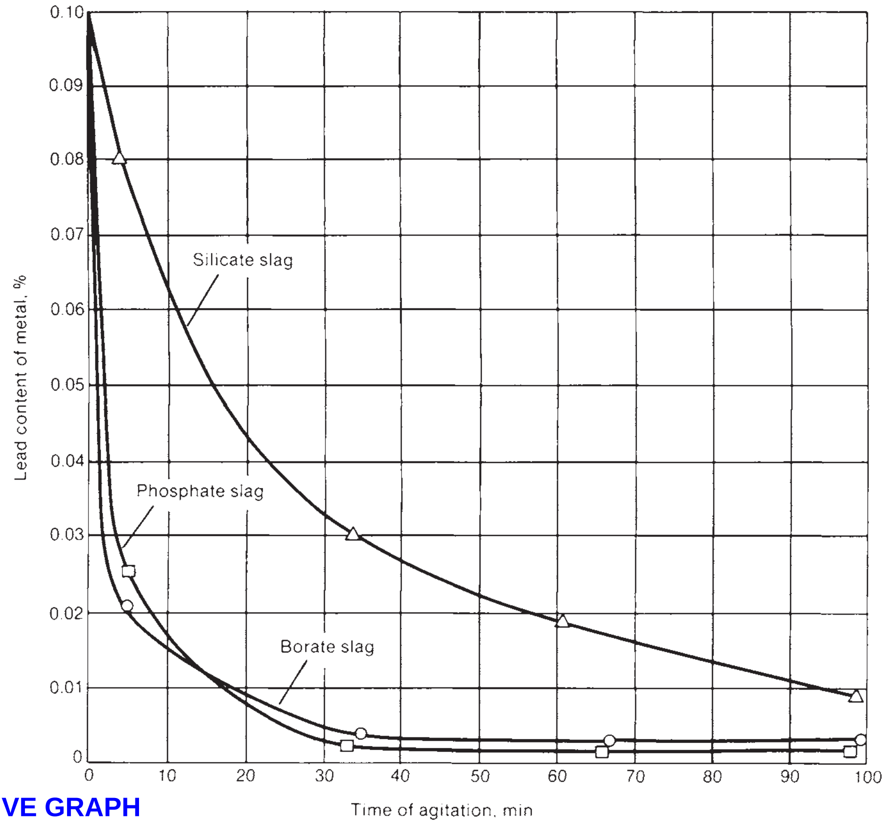

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Fig. 11 Removal of lead from oxidized Cu-0.1 Pb melts at 1150 °C (2100 °F) by different slags (fluxes) 2% of charge weight. Melt stirred with nitrogen at 2 L/min. Source: Ref 4

achieve the correct solidification characteristics. Because the freezing ranges of copper alloys vary from short to wide, different materials must be used. The various material combinations that have proved successful are described in Ref 7.

Degassing Methods

Oxidation-Deoxidation Practice. The steam reaction previously mentioned is a result of both hydrogen and cuprous oxide being present in the melt. These constituents react to form steam, resulting in blowholes during solidification as the copper cools:

$$2H + Cu_2O \rightarrow H_2O\ (\text{steam}) + 2Cu$$

The proper deoxidation of a copper alloy melt will generally prevent this steam reaction, although excessive hydrogen alone can still cause gas porosity if it is not expelled from the casting before the skin is completely solidified. Fortunately, there is a mutual relationship between hydrogen and oxygen solubility in molten copper (Fig. 18). Steam is formed above the line denoting equilibrium concentration, but not below. Consequently, as the oxygen content is raised, the capacity for hydrogen absorption decreases. Therefore, it is useful to provide excess oxygen during melting to preclude hydrogen entry and then to remove the oxygen by a deoxidation process to prevent further steam reaction during solidification.

This relationship gave rise to the Pell-Walpole oxidation-deoxidation practice for limiting hydrogen, especially when fossil-fuel-fired furnaces were used for melting. The melt was deliberately oxidized using oxygen-bearing granular fluxes or briquetted tablets to preclude hydrogen absorption during melting. The melt was subsequently deoxidized to eliminate any steam reaction with additional hydrogen absorbed during pouring and casting.

Zinc Flaring. The term zinc flare applies to those alloys containing at least 20% Zn. At this level or above, the boiling or vaporization point of copper-zinc alloys is close to the usual pouring temperature, as shown in Fig. 19 (Ref 8). Zinc has a very high vapor pressure, which precludes hydrogen entry into the melt. Zinc may also act as a vapor purge, removing hydrogen already in solution. Furthermore, the oxide of zinc is less dense than that of copper, thus providing a more tenacious, cohesive, and protective oxide skin on the melt surface and increasing resistance to hydrogen diffusion. In zinc flaring, the melt temperature is deliberately raised to permit greater zinc vapor formation. Because some zinc loss may occur, zinc may have to be replenished to maintain the correct composition.

Inert Gas Fluxing. With gas fluxing, an inert collector or sparger gas such as argon or nitrogen is injected into the melt with a graphite fluxing tube. The bubbling action collects the hydrogen gas that diffuses to the bubble surface, and the hydrogen is removed as the inert gas bubbles rise to the melt surface. The reaction efficiency depends on the gas volume, the depth to which the fluxing tube or lance is plunged, and the size of the collector gas bubble generated. Again, finer bubble sizes have higher surface-area-to-volume ratios and therefore provide better reaction efficiencies. Figure 20 depicts the amount of purge gas necessary to degas a 450 kg (1000 lb) copper melt. Figure 21 shows the response of an aluminum bronze alloy to nitrogen gas purging. The curve for oxygen purging is also shown.

Solid Degassing Fluxes. Other materials can be used to provide inert gas purging. A tabletted granular flux such as calcium carbonate ($CaCO_3$), which liberates CO_2 as the collector gas upon heating, has been successful in

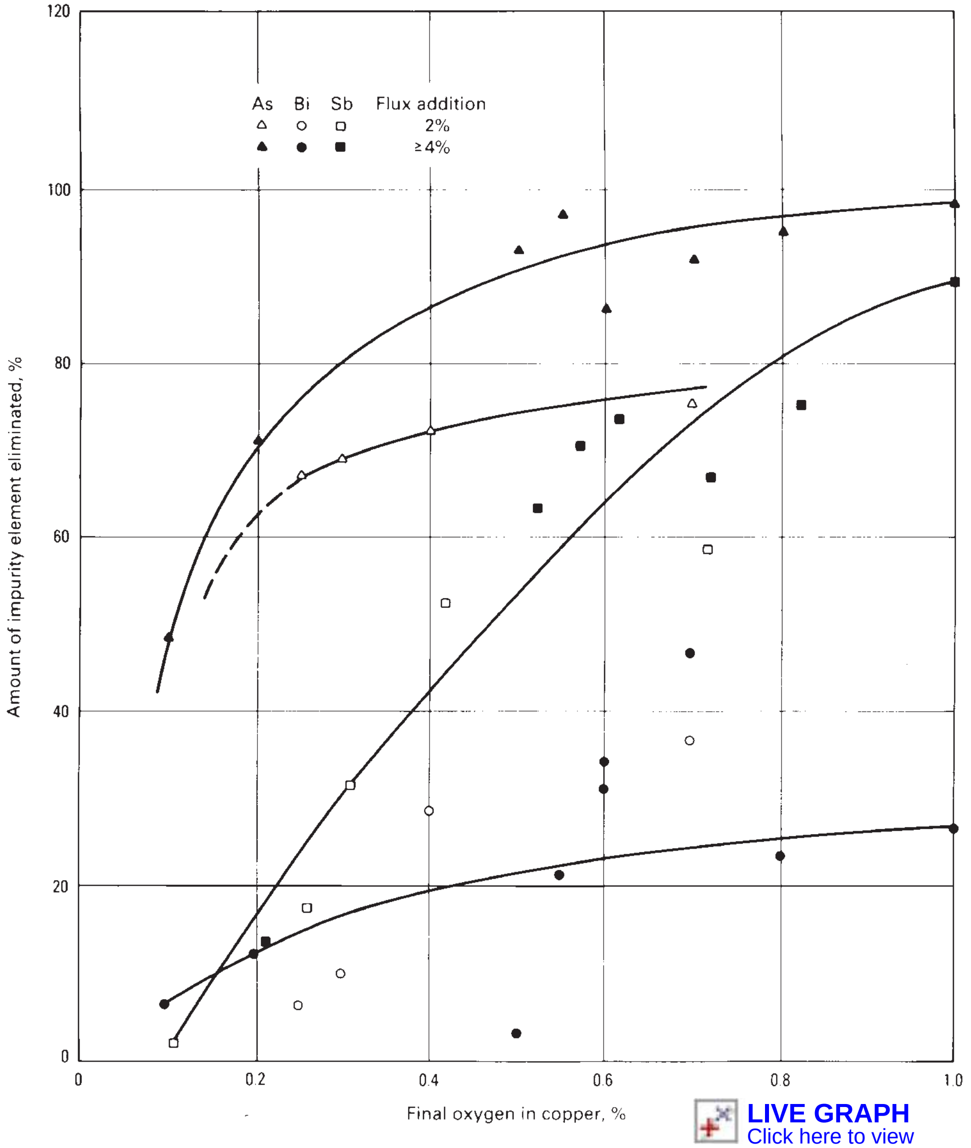

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Fig. 12 Effect of fire refining and use of Na_2CO_3 flux on removal of arsenic, bismuth, and antimony impurities from copper. Source: Ref 5

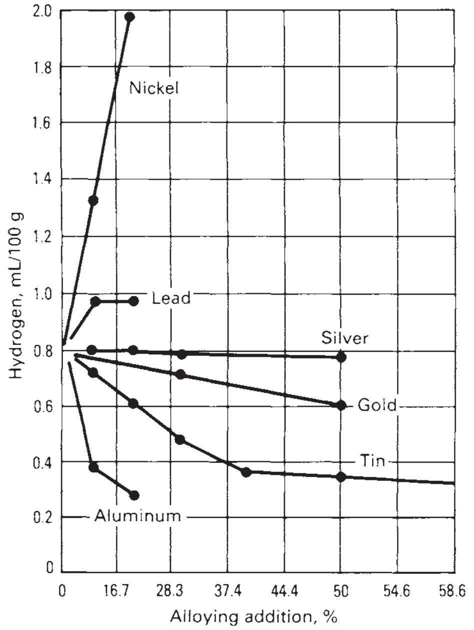

Fig. 14 Effect of alloying elements on the solubility of hydrogen in copper. Source: Ref 8

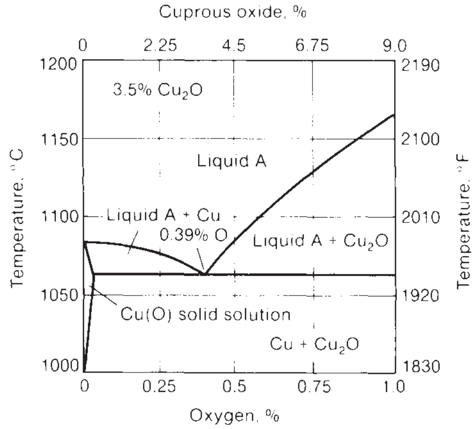

Fig. 15 Copper-oxygen phase diagram. Source: Ref 8

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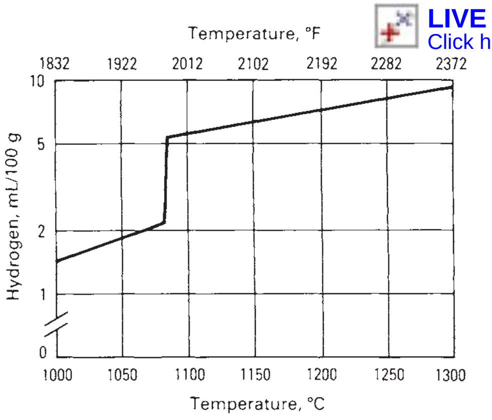

Fig. 13 Solubility of hydrogen in copper. Source: Ref 7

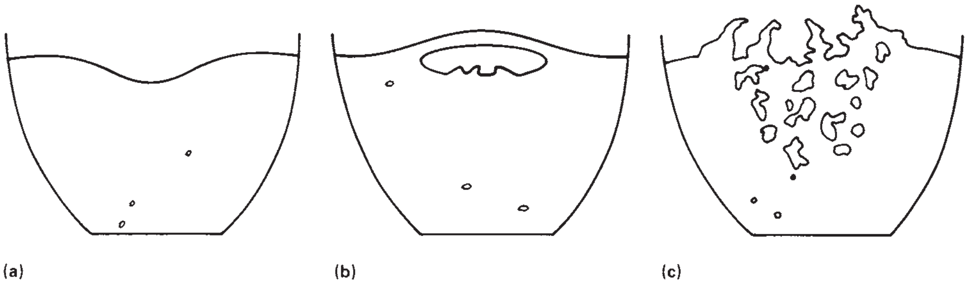

Fig. 16 Effect of pressure on the appearance of copper alloy reduced-pressure test samples containing the same amount of gas. (a) Pressure of 7 kPa (55 torr) results in surface shrinkage. (b) At 6.5 kPa (50 torr), a single bubble forms. (c) Boiling and porosity occur at 6 kPa (45 torr).

degassing a wide variety of copper alloys. This type of degassing is simpler than nitrogen, but must be kept dry and plunged as deep as possible into the melt with a clean, dry plunging rod, preferably made of graphite. This type of degasser may also have the advantage of forming the collector gas by chemical reaction in situ. This results in an inherently smaller initial bubble size than injected gas purging for better reaction efficiency. Such an advantage can be inferred from Fig. 22, although after 5 min of degassing the end results are the same.

Other solid degassers in the form of refractory metals or intermetallic compounds, such as Ca-Mn-Si, nickel-titanium, titanium, and lithium, are effective in eliminating porosity due to nitrogen or hydrogen by their ability to form stable nitrides and hydrides. Again, maintaining dry ingredients, deep plunging, and stirring or mixing will enhance their effectiveness. For best results and optimal reaction efficiency, such degassers should be wrapped or encapsulated in copper materials to provide controlled melting when plunged. Alternatively, copper master alloys containing these elements are available.

For both inert gas fluxing and solid degassing additions, the sparging gas reaction should not be so violent as to splash metal and create an opportunity for gas reabsorption. Furthermore, a melt can be overdegassed; an optimal amount of residual gas remaining in the melt helps to counter localized shrinkage in long freezing range alloys such as leaded tin bronzes.

Vacuum degassing is not generally applied to copper alloys, although it can be very effective. However, the cost of the equipment necessary is relatively high, and there may be a substantial loss of more volatile elements having a high vapor pressure such as zinc and lead. Furthermore, significant superheat (up to 150 °C, or 300 °F) may be required to accommodate the temperature drop during the degassing treatment, further aggravating the vapor losses.

Auxiliary Degassing Methods. There are other ways to degas a copper alloy melt than using a specific treatment. The technique of lowering the melt superheat temperature, if possible, and holding the melt (in a dry, minimal gas environment) provides outgassing simply by lower-

Table 6 Summary of gases found in copper alloys

Alloy family	Gases present	Remarks
Pure copper	Water vapor, hydrogen	Approximate hydrogen/water vapor ratio of 1. Higher purity increases the amount of water vapor and lowers hydrogen.
Cu-Sn-Pb-Zn alloys	Water vapor, hydrogen	Lead does not affect the gases present. Higher tin lowers total gas content. Increased zinc increases the amount of hydrogen, with a loss in water vapor.
Aluminum bronzes	Water vapor, hydrogen, CO	The presence of 5 wt% Ni in alloy C95800 causes CO to occur rather than water vapor. Lower aluminum leads to higher total gas contents.
Silicon brasses and bronzes	Water vapor, hydrogen	Approximate hydrogen/water vapor ratio of 0.5. Increased zinc decreases hydrogen and increases water vapor.
Copper-nickels	Water vapor, hydrogen, CO	All three gases are present up to 4 wt% Ni, after which only CO and hydrogen are present. Hydrogen increases with increasing nickel up to 10 wt% Ni, but is decreased at 30 wt% Ni.

Source: Ref 10

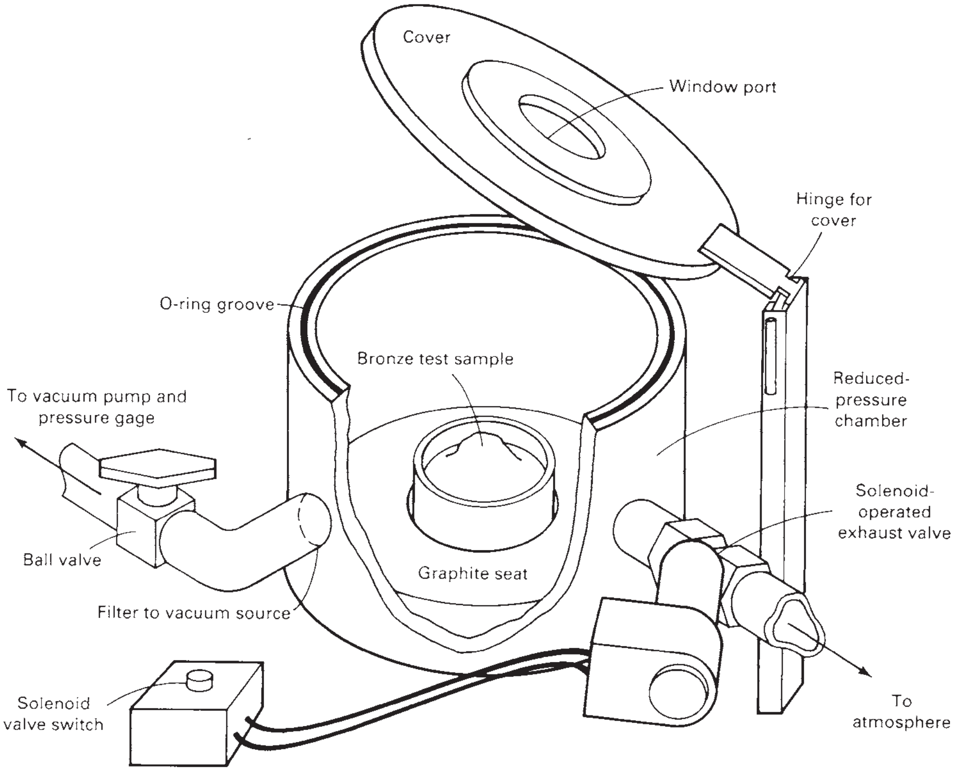

Fig. 17 Schematic of the reduced-pressure test apparatus used to assess amounts of dissolved gas in copper alloys

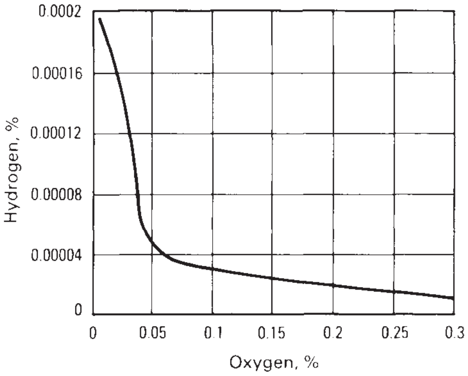

Fig. 18 Hydrogen/oxygen equilibrium in molten copper. Source: Ref 7

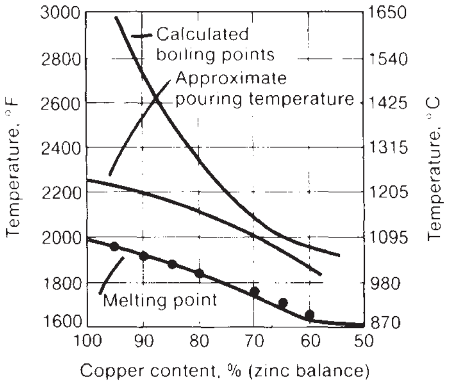

Fig. 19 Influence of zinc content on boiling point or vapor pressure in copper alloys. Source: Ref 8

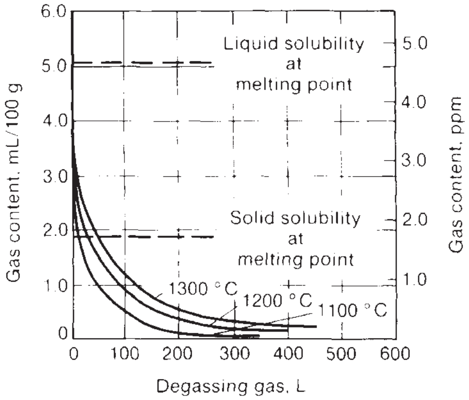

Fig. 20 Amount of purge gas required to degas a 450 kg (1000 lb) copper melt. Source: Ref 16

ing the equilibrium liquid state solubility of the gas. During casting, the use of chills to provide directional solidification, particularly for the long freezing range group III alloys such as the red brasses and tin bronzes, results in less tendency for gas porosity.

In the mold-metal reaction, previously degassed and deoxidized metal containing excess phosphorus or lithium deoxidants can react with green sand containing moisture. Hydrogen is liberated and absorbed as the metal comes into contact with the sand. This can be minimized by correct deoxidant additions (discussed in the following section in this article). In addition, finer facing sands or mold coatings (inert or reactive such as sodium silicate or magnesia) can be used; these confine any reaction to the mold/metal interface area and retard hydrogen penetration into the solidifying skin of the cast metal.

Deoxidation of Copper Alloys

All copper alloys are subject to oxidation during most melting operations. Oxygen reacts with copper to form cuprous oxide, which is completely miscible with the molten metal. A eutectic is formed at 1065 °C (1950 °F) and 3.5% Cu_2O, or 0.39% O, as shown in the copper-oxygen phase diagram in Fig. 15.

Therefore, cuprous oxide exists within the melt as a liquid phase and is not generally separated by gravity alone. If not removed, this liquid phase will cause discontinuous solidification during casting, resulting in considerable porosity and low mechanical strength. Thus, some type of deoxidation process is required. In addition, proper deoxidation of all melts enhances fluidity and therefore castability.

Of course, deliberate oxidation treatments (the oxidation-deoxidation process previously described) are still employed. These are designed to preclude hydrogen pickup in copper alloy melts.

Phosphorus Deoxidation. Most copper alloys are deoxidized by a phosphorus reduction of the cuprous oxide. Although several other oxygen scavengers are possible according to the free energy of oxide formation, phosphorus is usually the easiest, most economical, and least problematic deoxidant. The phosphorus is usually added in the form of 15% phosphor copper master alloy, either in granular shot or briquetted waffle form. Care must be taken to ensure that the deoxidant is dry. The deoxidant is often added to the bottom of the ladle before pouring so that during pouring the deoxidant reacts with the cuprous oxide contained in the melt. The turbulence created during pouring is sufficient to ensure adequate mixing. The phosphorus copper deoxidant should not be simply thrown onto the surface of the ladle after pouring, because little mixing will result. When the deoxidant is added directly to the furnace, however, it should be completely stirred into the melt using clean, dry tools, and pouring should begin as soon as possible so that the effect is not lost.

Use of phosphorus deoxidation results in the formation of a liquid slag of cuprous phosphate:

$$2P + 4Cu + 7O \rightarrow 2Cu_2O \cdot P_2O_5$$

This product easily separates from the rest of the melt; therefore, the phosphorus effectively scavenges the oxygen, delivering the product to the surface dross phase, where it can be easily skimmed.

Phosphorus is usually added at a rate of 57 g (2 oz) of 15% master alloy per 45 kg (100 lb) of melt. In cases where oxidation of the melt is deliberately employed to reduce hydrogen absorption, double this amount can be required for full deoxidation. This is usually sufficient to deoxidize completely a melt saturated with 0.39 wt% O. However, the recovery of phosphorus is less than 100% and may be as little as 30 to 60% (Ref 18). It is desirable to maintain a residual level of at least 0.01 to 0.015% P in the melt, especially during pouring, so that reoxidation and potential steam reaction problems are alleviated.

Each foundry must determine the proper addition rate for a given set of conditions. Furthermore, with foundry returns, a certain residual amount of phosphorus is usually already present. A routine addition of phosphor copper for deoxidation could then actually result in excessive phosphorus. If the phosphorus content is too high during melting or pouring, the lack of oxygen may invite hydrogen entry and result in the steam reaction during casting. Adding more phosphorus to control the steam reaction can therefore actually aggravate the condition. In addition, when the phosphorus content is 0.03% and beyond, excessive metal fluidity can result in penetration of the molding sand or burn-in during casting.

Phosphorus copper is an effective deoxidant for the red brasses, tin bronzes, and leaded bronzes. However, phosphorus should not be used for deoxidizing high-conductivity copper alloys, because of its deleterious effect on electrical conductivity (as is discussed in the next section), and it should not be used for copper-nickel alloys. In these materials, the presence of phosphorus results in a low-melting constituent that embrittles the grain boundaries. A silicon addition of 0.3% and a magnesium addition of 0.10% serve to deoxidize and desulfurize copper-nickel melts. For nickel silver alloys (Cu-Ni-Zn), the use of 142 g (5 oz)

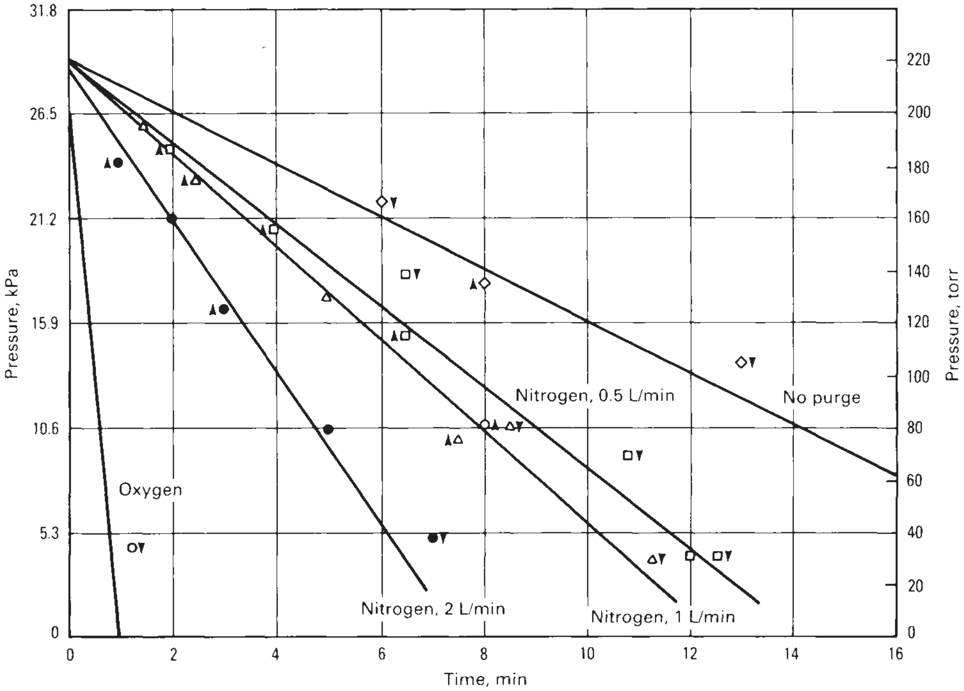

Fig. 21 Effect of nitrogen flow rate during purging on the residual gas pressure remaining in an aluminum bronze melt. The curve for oxygen purging is also shown. Source: Ref 15, 17

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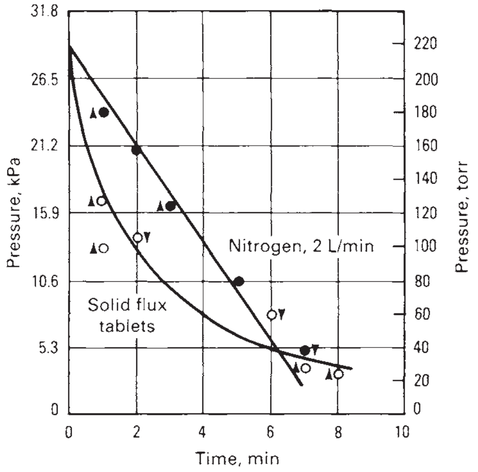

Fig. 22 Comparison of the effectiveness of solid degassing flux versus nitrogen purging. Source: Ref 17

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copper-manganese shot per 45 kg (100 lb) of melt, and 57 g (2 oz) manganese coupled with 85 g (3 oz) of 15% P-Cu, is a recommended deoxidation technique.

The yellow brasses, silicon bronzes, manganese bronzes, and aluminum bronzes usually do not require deoxidation per se, because of the oxygen-scavenging effects of their respective alloy constituents.

High-Conductivity Copper (Ref 18–21). Where the high-copper alloys (pure copper, silver-copper, cadmium-copper, tellurium-copper, beryllium-copper, chromium-copper) are employed and electrical conductivity is a desirable property, phosphorus-copper cannot be used as a deoxidant. Moreover, the strong oxide formers beryllium and chromium serve as their own deoxidants.

Figure 23 shows the effects of a variety of elements on the electrical conductivity of copper. Clearly, phosphorus even in small amounts significantly decreases conductivity; therefore, alternative deoxidants must be used. Fortunately, both boron and lithium are capable of deoxidizing high-conductivity copper without appreciably affecting electrical conductivity.

Boron Deoxidation. Boron is available either as a copper-boron master alloy or as calcium boride (CaB_6). The boron probably forms a copper-borate slag of the general form $2Cu_2O{\cdot}B_2O_3$ in much the same fashion as phosphorus produces a cuprous oxide phosphate slag (Ref 18). Theoretically, the boron combines with 60% more oxygen than the stoichiometric amount required to form B_2O_3 and therefore appears to be superefficient. However, practical experience has shown that this theoretical efficiency is not always achieved and that lithium is more effective, as shown in Fig. 24 (Ref 18). Therefore, lithium is often preferred, although there are greater precautions attendant upon its use.

Lithium Deoxidation (Ref 18, 19–22). Lithium has the advantage of serving as both a deoxidant and a degasser because it reacts readily with both oxygen and hydrogen. Lithium is soluble in molten copper but insoluble in the solid state. There is very little residual lithium contained in the casting or in scrap for remelt.

Because lithium metal is very reactive in air, bulk lithium metal must be stored in oil. For foundry applications, lithium is supplied in sealed copper cartridges. These cartridges must be stored in a safe, dry environment and must be preheated (to above 105 °C, or 225 °F) before use to drive off any surface moisture. These preheated cartridges should then be carefully yet firmly and quickly plunged to the bottom of the reacting vessel (furnace or ladle) to achieve full intimate contact and reactivity with the bulk of the melt. Only clean, dry, preheated plunging tools should be used for this task. Graphite rods are usually preferred.

Lithium-copper cartridges are generally available in various sizes ranging from 2.25 g (0.09 oz) for 23 kg (50 lb) melts to 108 g (4 oz). Thus, lithium additions can be made at maximum efficiency.

The specific chemical reactions that can occur with lithium include:

$$2Li + Cu_2O \rightarrow 2Cu + Li_2O \text{ (deoxidation)}$$

$$Li + H \rightarrow LiH \text{ (degassing)}$$

$$LiH + Cu_2O \rightarrow 2Cu + LiOH \text{ (recombination)}$$

$$2Li + H_2O \rightarrow Li_2O + H_2 \text{ (reaction during pouring)}$$

The lithium oxide (Li_2O) and lithium hydroxide (LiOH) products separate cleanly as a low-density fluid slag suitable for skimming (Ref 19). The lithium hydride that forms initially if hydrogen is present is unstable at normal copper melting temperatures and recombines with cuprous oxide (recombination).

When lithium is added in excess of the amount of cuprous oxide present, it will react with moisture in the air during pouring and can therefore generate sufficient hydrogen to regas the melt. This can result in unanticipated additional gas porosity and unsoundness during solidification.

Because lithium is such an effective deoxidant, it can also reduce residual impurity oxides (FeO, P_2O_5, and so on) in high-conductivity copper melts. This allows these elements to redissolve in the molten metal to the extent of their solubility limit and thus reduce electrical conductivity according to Fig 23. Furthermore, lithium can form intermetallic compounds with silver, lead, tin, and zinc when the residual lithium exceeds that required for deoxidation. These intermetallic compounds, while reducing solid solubility, may improve mechanical properties and electrical conductivity.

Occasionally, it may be desirable to practice a duplex deoxidation treatment using the less expensive phosphorus, followed by a lithium treatment (Ref 19, 21, 22). Care must be taken to do this quickly and not allow phosphorus reversion to occur by letting the copper phosphate deoxidation slag remain on the melt for an extended period of time.

Magnesium Deoxidation. Magnesium behaves similarly to lithium, but may be stored in air rather than oil. It is actually a stronger deoxidant in terms of its free energy of oxide formation (Ref 23), and it is used to deoxidize (and desulfurize) copper-nickel alloys. The

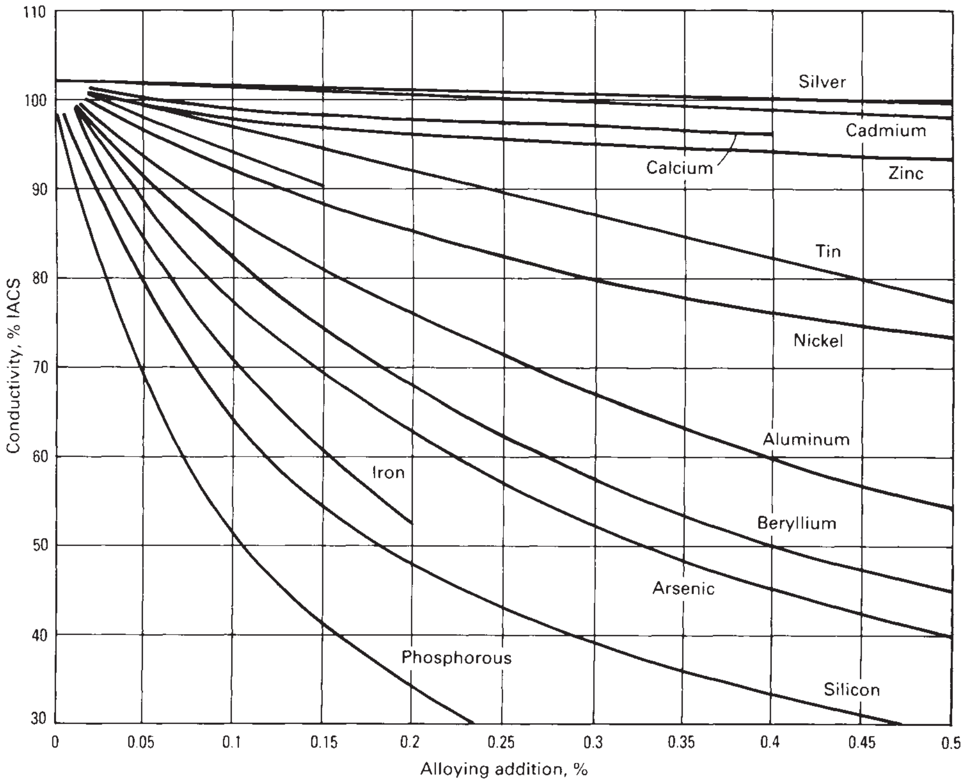

Fig. 23 Effect of alloying elements on the electrical conductivity of copper. Source: Ref 19

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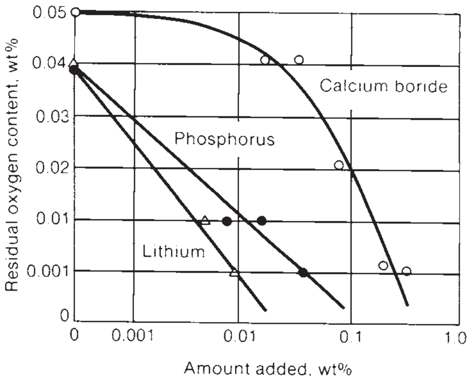

Fig. 24 Deoxidant efficiency in copper alloy melts. Source: Ref 18

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deoxidation product (magnesia) is a stable refractory, unlike lithium compounds, but it forms a tenacious oxide skin and can result in inclusions in copper casting alloys.

Testing for Proper Deoxidizer Addition. As stated previously, each foundry should assess its own casting practice for a given alloy and set of melting conditions and should determine the optimal addition of deoxidizer. However, there are two tests that can be used to determine whether a given amount of deoxidizer is adequate.

In the first test, a test plug or shrink bar of metal approximately 75 mm (3 in.) in diameter by 75 mm (3 in.) deep is poured. If a shrinkage cavity results, the metal is deoxidized and ready for pouring, which should then be done immediately. Shrinkage will not occur until about 0.01% residual phosphorus is present (Ref 23). A puffed-out or mushroomed cap on the test plug indicates that deoxidation is incomplete and that more should be added.

The second test involves a carbon or graphite rod immersed in the melt. When the rod surface reaches the molten metal temperature, if there is oxygen present, the rod will vibrate because of the reaction ($2C + O_2 \rightarrow 2CO$) occurring on the bar surface. The intensity of the vibration is a function of the oxygen content, and an experienced foundryman can readily determine the point at which the reaction becomes negligible, that is, when the melt is sufficiently deoxidized. The vibration decreases near the level of 0.01% residual phosphorus, as expected for a deoxidized melt (Ref 23).

Relative Effectiveness of Copper Deoxidizers. Various elements capable of scavenging oxygen from copper alloy melts have been described. The theoretical relative capabilities of several deoxidizers are:

		Amount of deoxidizer required to remove 0.01% oxygen	
Deoxidizer	Reaction products	g/100 kg	oz/100 lb
Carbon	CO	7.5	0.12
	CO_2	3.8	0.06
Phosphorus	P_2O_5	7.5	0.12
	$2Cu_2P_2O_5$	5.6	0.09
Cu-15P	P_2O_5	49.3	0.79
	$2Cu_2P_2O_5$	36.8	0.59
Boron	B_2O_3	4.4	0.07
Cu-2B	B_2O_3	224.5	3.60
Lithium	Li_2O	8.7	0.14
Magnesium	MgO	15.0	0.24

In practice, selection of the deoxidizer must be based on actual efficiency, economics, ease of use, and the specific metallurgical requirements of the alloy in question.

Grain Refining of Copper Alloys

In general, the grain refinement of copper alloys is not practiced as a specific molten metal processing step per se, because a certain degree of refinement can be achieved through normal casting processes. As with aluminum alloys, grain refinement in copper alloys can be achieved by rapid cooling, mechanical vibration, or the addition of nucleating or grain-growth-restricting agents. Further, many commercial copper alloys have sufficient solute (zinc, aluminum, iron, tin) to achieve constitutional supercooling during solidification. In this case, grain nucleation and growth are naturally retarded. Commercially pure copper can be grain refined by small additions (as little as 0.10%) of lithium, bismuth, lead, or iron, which provide constitutional supercooling effects (Ref 24, 25).

Copper-zinc single-phase alloys can be grain refined by additions of iron or by zirconium and boron (Ref 26). In the latter case, the probable mechanism is the formation of zirconium boride particle nuclei for grain formation. In one case, the vibration of a Cu-32Zn-2Pb-1Sn alloy improved yield and tensile strengths by about 15%, with a 10% reduction in grain size from the unvibrated state. In general, the α copper-zinc alloys (<35% Zn) exhibit grain size reduction and greater improvement in properties, while the α-β alloys do not.

Copper-aluminum alloys have been effectively grain refined with additions of 0.02 to 0.05% B; the effective nucleating agent is boron carbide (B_4C). Figure 25 illustrates the improvement in mechanical properties achieved by grain refining a Cu-10Al alloy.

Tin bronze alloys have been successfully grain refined by the addition of zirconium (0.02%) and boron master alloys (Ref 27). However, pressure tightness is reduced because in these long freezing range alloys, finer grain size concentrates porosity because of gas entrapment.

Filtration of Copper Alloys

The filtration process consists of passing the molten metal through a porous device (a filter) in which the inclusions contained in the flowing metal are trapped or captured. The filter material itself must have sufficient integrity (strength, refractoriness, thermal shock resistance, and corrosion resistance) so that it is not destroyed by the molten metal before its task is accomplished. Consequently, most filter media are ceramic materials in a variety of configurations. Although the bulk of filter technology has been directed toward aluminum alloys, the use of filtration is increasing for copper alloy melts.

Inclusions in Copper Alloys. In addition to the usual inclusions arising from oxides, fluxing salts, and intermetallics, copper oxide inclusions and phosphorus pentoxide (from deoxidation) may be present in copper alloys if the melt is not allowed to settle or if it is inadequately skimmed before pouring and casting.

Filter Applications. The filtration of copper casting alloys primarily involves the use of ceramic foam sections in the gating system. Oxide inclusions have been successfully removed from aluminum bronze alloys using such a filter deployment system (Ref 28). Investment castings can be successfully filtered using a filter section in the pouring cup or, in the case of larger castings, molded directly into the wax runner bars. Ceramic filters for copper alloys are usually alumina, mullite, or zirconia.

Melt Treatments for Group I to III Alloys

For group I to III alloys, the melting procedure, flux treatment, and pouring temperature (Table 7) vary considerably from one alloy family to another. It should also be noted that for any copper alloy, the temperature at which the metal is poured into the mold is higher than the liquidus temperature. Compare the liquidus temperatures in Tables 1 to 3 with those of the pouring temperatures in Table 7 for group I to III alloys. More detailed information on fluxing and

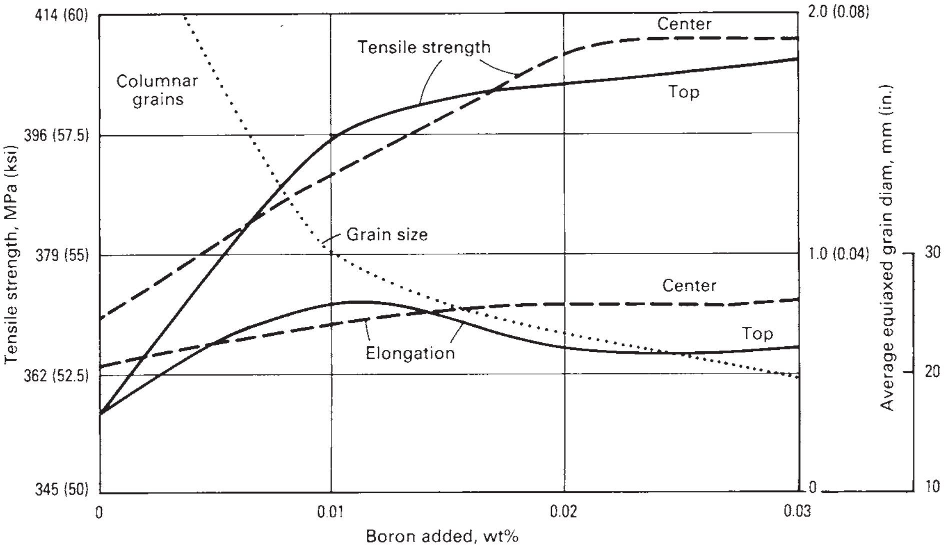

Fig. 25 Effect of boron-refined grain size on the mechanical properties of Cu-10Al alloy. Test specimens were removed from the center or the top of the ingot as indicated. Source: Ref 27

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other melt practices can be found in earlier sections of this article.

Group I Alloys

Pure Copper and Chromium-Copper. Commercially pure copper and high copper alloys are very difficult to melt and are very susceptible to gassing. In the case of chromium-copper, oxidation loss of chromium during melting is a problem. Copper and chromium-copper should be melted under a floating flux cover to prevent both oxidation and the pickup of hydrogen from moisture in the atmosphere. In the case of copper, crushed graphite should cover the melt. With chromium copper, the cover should be a proprietary flux made for this alloy. When the molten metal reaches 1260 °C (2300 °F), either calcium boride or lithium should be plunged into the molten bath to deoxidize the melt. The metal should then be poured without removing the floating cover.

Yellow Brasses. These alloys flare, or lose zinc, due to vaporization at temperatures relatively close to the melting point. For this reason, aluminum is added to increase fluidity and keep zinc vaporization to a minimum. The proper amount of aluminum to be retained in the brass is 0.15 to 0.35%. Above this amount, shrinkage takes place during freezing, and the use of risers becomes necessary. Other than the addition of aluminum, the melting of yellow brass is very simple, and no fluxing is necessary. Zinc should be added before pouring to compensate for the zinc lost in melting.

Manganese Bronzes. These alloys are carefully compounded yellow brasses with measured quantities of iron, manganese, and aluminum. The metal should be melted and heated to the flare temperature or to the point at which zinc oxide vapor can be detected. At this point, the metal should be removed from the furnace and poured. No fluxing is required with these alloys. The only addition required with these alloys is zinc. The amount required is that which is needed to bring the zinc content back to the original analysis. This varies from very little, if any, when an all-ingot heat is being poured, to several percent if the heat contains a high percentage of remelt.

Aluminum Bronzes. These alloys must be melted carefully under an oxidizing atmosphere and heated to the proper furnace temperature. If needed, degasifiers can be stirred into the melt as the furnace is being tapped. By pouring a blind sprue before tapping and examining the metal after freezing, it is possible to tell whether it shrank or exuded gas. If the sample purged or overflowed the blind sprue during solidification, degassing is necessary. As discussed earlier in this article, degasifiers remove hydrogen and oxygen. Also available are fluxes that convert the molten bath. These are in powder form and are usually fluorides. They aid in the elimination of oxides, which normally form on top of the melt during melting and superheating.

Nickel silvers, also known as nickel bronzes, are difficult alloys to melt. They gas readily if not melted properly because the presence of nickel increases the hydrogen solubility. Then, too, the higher pouring temperatures shown in Table 7 aggravate hydrogen pickup. These alloys must be melted under an oxidizing atmosphere and quickly superheated to the proper furnace temperature to allow for temperature losses during fluxing and handling. Proprietary fluxes are available and should be stirred into the melt after tapping the furnace. These fluxes contain manganese, calcium, silicon, magnesium, and phosphorus and do an excellent job in removing hydrogen and oxygen.

White Manganese Brass. There are two alloys in this family, both of which are copper-zinc alloys containing a large amount of manganese and, in one case, nickel. They are manganese bronze type alloys, are simple to melt, and can be poured at low temperatures because they are very fluid (Table 7). They should not be overheated, as this serves no purpose. If the alloys are unduly superheated, zinc is vaporized and the chemistry of the alloy is changed. Normally, no fluxes are used with these alloys.

Group II Alloys

Beryllium-Coppers. These alloys are very toxic and dangerous if beryllium fumes are not captured and exhausted by proper ventilating equipment. They should be melted quickly under a slightly oxidizing atmosphere to minimize beryllium losses. They can be melted and poured successfully at relatively low temperatures (Table 7). They are very fluid and pour well.

Silicon Bronzes and Brasses. The alloys known as silicon bronzes, UNS alloys C87300, C87600, and C87610, are relatively easy to melt and should be poured at the proper pouring temperatures (Table 7). If overheated, they can pick up hydrogen. While degassing is seldom required, if necessary, one of the proprietary degasifiers used with aluminum bronze can be successfully used. Normally no cover fluxes are used here. The silicon brasses (UNS alloys C87500 and C87800) have excellent fluidity and can be poured slightly above their freezing range. Nothing is gained by excessive heating, and in some cases, heats can be gassed if this occurs. Here again, no cover fluxes are required.

Copper-Nickel Alloys. These alloys—90Cu-10Ni (C96200) and 70Cu-30Ni (C96400)—must be melted carefully because the presence of nickel in high percentages raises not only the melting point but also the susceptibility to hydrogen pickup. In virtually all foundries, these alloys are melted in coreless electric induction furnaces, because the melting rate is much faster than it is with a fuel-fired furnace. When ingot is melted in this manner, the metal should be quickly heated to a temperature slightly above the pouring temperature (Table 7) and deoxidized either by the use of one of the proprietary degasifiers used with nickel bronzes or, better yet, by plunging 0.1% Mg stick to the bottom of the ladle. The purpose of this is to remove all the oxygen to prevent any possibility of steam-reaction porosity from occurring. Normally there is little need to use cover fluxes if the gates and risers are cleaned by shot blasting prior to melting.

Group III Alloys

These alloys, namely leaded red and semi-red brasses, tin and leaded tin bronzes, and high-leaded tin bronzes, are treated the same in regard to melting and fluxing and thus can be discussed together. Because of the long freezing ranges involved, it has been found that chilling, or the creation of a steep thermal gradient, is far better than using only feeders or risers. Chills and risers should be used in conjunction with each other for these alloys. For this reason, the best pouring temperature is the lowest one that will pour the molds without having misruns or cold shuts. In a well-operated foundry, each pattern should have a pouring temperature that is maintained by use of an immersion pyrometer.

Fluxing. In regard to fluxing, these alloys should be melted from charges comprising ingot and clean, sand-free gates and risers. The melting should be done quickly in a slightly oxidizing atmosphere. When at the proper furnace temperature to allow for handling and cooling to the proper pouring temperature, the crucible is removed or the metal is tapped into a ladle. At this point, a deoxidizer (15% phosphor copper) is added. The phosphorus is a reducing agent (deoxidizer). This product must be carefully measured so that enough oxygen is removed, yet a small amount remains to improve fluidity. This residual level of phosphorus must be closely controlled by chemical analysis to a range between 0.010 and 0.020% P. If more is present, internal porosity may occur and cause leakage if castings are machined and pressure tested.

In addition to phosphor copper, pure zinc should be added at the point at which skimming and temperature testing take place prior to pouring. This replaces the zinc lost by vaporization during melting and superheating. With these alloys, cover fluxes are seldom used. In some foundries in which combustion cannot be properly controlled, oxidizing fluxes are added during melting, followed by final deoxidation by phosphor copper.

Production of Copper Alloy Castings

Copper alloy castings are produced by sand, shell, plaster, investment, permanent mold, die, centrifugal, and continuous casting. Each of these casting/molding methods is briefly reviewed below in the section "Casting Process Selection." Additional information can be found in Volume 15 of the *ASM Handbook* and the *Metals Handbook Desk Edition,* second edition.

Pouring Temperature and Practice

Pouring Temperature. Temperature ranges for pouring the principal copper casting alloys are given in Table 7. It should not be inferred from the breadth of most of these ranges that pouring temperature is not critical; as noted in Table 7, the ranges are intended for pouring various section thicknesses. For castings with minimum section thickness, the metal should be poured at a temperature near the high side of the range. Conversely, for castings that have all heavy sections, pouring temperatures should be near the low side of the range. Under any conditions, identical castings should be poured at the same temperature, insofar as possible. It is generally advisable to allow a variation of no more than 55 °C (100 °F) during the pouring of a specific mold, or when pouring several molds from the same ladle. The casting process used also influences the pouring temperature for a specific alloy. In die casting, for instance, a temperature near the low side of a given range is used, in the interest of longer die life.

Pouring Practice. On the basis of the degree of care required when they are poured into molds, copper alloys can be classified into two groups:

- Alloys that form tight, adherent, nonfluid slags or oxides. Typical are group I aluminum bronze and manganese bronze alloys.
- Alloys that form fluid slags or oxides. These include most of the alloys in general use—those containing various combinations of copper, tin, lead, and zinc.

Copper alloys in the first group (those that form tight, adherent, nonfluid slags) require great care in pouring. Their general behavior can be compared to that of aluminum casting alloys, and similar pouring techniques are recommended.

Good pouring practice for this first group of alloys includes attention to:

- Molten alloys with tight oxide films should never be stirred. After the ladle is filled or the crucible is removed from the furnace, and before pouring, the metal should be carefully skimmed but not stirred or mixed—thus minimizing oxide entrapment.
- In addition to avoiding stirring of molten aluminum bronze and manganese bronze, other forms of agitation should also be avoided. If the metal is melted in a tilting furnace and must be transferred to a ladle for pouring, the distance the metal must drop should be minimized by holding the ladle close to the furnace lip.
- Pouring should be smooth and even to avoid splashing and separated metal streams. With careful pouring of aluminum bronze and manganese bronze, it is possible to form an aluminum oxide "glove" around the metal stream, which will protect the molten metal from further oxidation.

Alloys in this first group have a very narrow freezing range (see Table 1), so that they solidify in much the same way as does a pure metal. The total shrinkage is concentrated in the region of the casting that solidifies last. These alloys are thus prone to piping and gross shrinkage cavities. Risering is commonly used to prevent shrinkage from occurring in the casting. The metal is poured well above the liquidus so that the entire mold cavity is filled and so that solidification occurs from the bottom to the top, with feeding from a riser.

Copper alloys in the second group (those that form fluid slags) are generally less affected by turbulence in pouring than are those in the first group. Although turbulence in pouring can cause casting defects in any alloy, the fact that the oxides that are formed with this group of alloys separate readily from the molten metal means less likelihood of oxide entrapment in the casting and greater likelihood of the escape of entrained air bubbles.

Table 7 Pouring temperatures of copper alloys

		Light castings		Heavy castings	
Alloy type	UNS No.	°C	°F	°C	°F
Group I alloys					
Copper	C81100	1230–1290	2250–2350	1150–1230	2100–2250
Chromium-copper	C81500	1230–1260	2250–2300	1205–1230	2200–2250
Yellow brass	C85200	1095–1150	2000–2100	1010–1095	1850–2000
	C85400	1065–1150	1950–2100	1010–1065	1850–1950
	C85800	1150–1175	1950–2150	1010–1095	1850–2000
	C87900	1150–1175	1950–2150	1010–1095	1850–2000
Manganese bronze	C86200	1150–1175	1950–2150	980–1065	1800–1950
	C86300	1150–1175	1950–2150	980–1065	1800–1950
	C86400	1040–1120	1900–2050	950–1040	1750–1900
	C86500	1040–1120	1900–2050	950–1040	1750–1900
	C86700	1040–1095	1900–2000	950–1040	1750–1900
	C86800	1150–1175	1950–2150	980–1065	1800–1950
Aluminum bronze	C95200	1120–1205	2050–2200	1095–1150	2000–2100
	C95300	1120–1205	2050–2200	1095–1150	2000–2100
	C95400	1150–1230	2100–2250	1095–1175	2000–2150
	C95410	1150–1230	2100–2250	1095–1175	2000–2150
	C95500	1230–1290	2250–2350	1175–1230	2150–2250
	C95600	1120–1205	2050–2200	1095–1205	2000–2200
	C95700	1065–1150	1950–2100	1010–1205	1850–2200
	C95800	1230–1290	2250–2350	1175–1230	2150–2250
Nickel bronze	C97300	1205–1225	2200–2240	1095–1205	2000–2200
	C97600	1260–1425	2300–2600	1205–1315	2250–2400
	C97800	1315–1425	2400–2600	1260–1315	2300–2400
White brass	C99700	1040–1095	1900–2000	980–1040	1800–1900
	C99750	1040–1095	1900–2000	980–1040	1800–1900
Group II alloys					
Beryllium-copper	C81400	1175–1220	2150–2225	1220–1260	2225–2300
	C82000	1175–1230	2150–2250	1120–1175	2050–2150
	C82400	1080–1120	1975–2050	1040–1080	1900–1975
	C82500	1065–1120	1950–2050	1010–1065	1850–1950
	C82600	1050–1095	1925–2000	1010–1050	1850–1925
	C82800	995–1025	1825–1875	1025–1050	1875–1925
Silicon brass	C87500	1040–1095	1900–2000	980–1040	1800–1900
	C87800	1040–1095	1900–2000	980–1040	1800–1900
Silicon bronze	C87300	1095–1175	2000–2150	1010–1095	1850–2000
	C87600	1095–1175	2000–2150	1010–1095	1850–2000
	C87610	1095–1175	2000–2150	1010–1095	1850–2000
Copper nickel	C96200	1315–1370	2400–2500	1230–1315	2250–2400
	C96400	1370–1480	2500–2700	1290–1370	2350–2500
Group III alloys					
Leaded red brass	C83450	1175–1290	2150–2350	1095–1175	2000–2150
	C83600	1150–1290	2100–2350	1065–1175	1950–2150
	C83800	1150–1260	2100–2300	1065–1175	1950–2150
Leaded semired brass	C84400	1150–1260	2100–2300	1065–1175	1950–2150
	C84800	1150–1260	2100–2300	1065–1175	1950–2150
Tin bronze	C90300	1150–1260	2100–2300	1040–1150	1900–2100
	C90500	1150–1260	2100–2300	1040–1150	1900–2100
	C90700	1040–1095	1900–2000	980–1040	1800–1900
	C91100	1040–1095	1900–2000	980–1040	1800–1900
	C91300	1040–1095	1900–2000	980–1040	1800–1900
Leaded tin bronze	C92200	1150–1260	2100–2300	1040–1175	1900–2150
	C92300	1150–1260	2100–2300	1040–1150	1900–2100
	C92600	1150–1260	2100–2300	1050–1150	1920–2100
	C92700	1175–1260	2150–2300	1065–1175	1950–2150
High-leaded tin bronze	C92900	1095–1205	2000–2200	1040–1095	1900–2000
	C93200	1095–1230	2000–2250	1040–1121	1900–2050
	C93400	1095–1230	2000–2250	1010–1150	1850–2100
	C93500	1095–1205	2000–2200	1040–1150	1900–2100
	C93700	1095–1230	2000–2250	1010–1150	1850–2100
	C93800	1095–1230	2000–2250	1040–1150	1900–2100
	C94300	1095–1205	2000–2200	1010–1095	1850–2000

Casting Process Selection

Among the more important factors that influence the selection of a casting method are (Ref 29):

- The number of castings to be processed
- The size and/or weight of the casting
- The shape and intricacy of the product
- The amount and quality of finish machining needed
- The required surface finish
- The prescribed level of internal soundness (pressure tightness) and/or the type and level of inspection to be performed
- The permissible variation in dimensional accuracy for a single part and part-to-part consistency through the production run
- The casting characteristics of the copper alloy specified

Table 8 summarizes some of the technical factors that go into the choice of casting method for casting alloys. Additional information can be found in the descriptions of individual casting processes that follow.

Sand casting accounts for about 75% of U.S. copper alloy foundry production (Ref 29). The process is relatively inexpensive, reasonably precise, and highly versatile. It can be used for castings ranging in size from a few ounces to many tons. Further, it can be applied to simple shapes as well as castings of considerable complexity, and it can be used with all of the copper casting alloys.

There are a number of variations of the sand casting process. In green sand casting—the most widely used process—molds are formed in unbaked (green) sand, which is most often silica bonded with water and a small amount of clay to develop the required strength. The clay minerals absorb water and form a natural bonding system. Various sands and clays may be blended to suit particular casting situations. Other variations of sand casting include dry sand, cement-bonded sand, sodium silicate-bonded sand (the CO_2 process), and resin-bonded sand molding.

Sand casting imposes few restrictions on product shape. The only significant exceptions are the draft angles that are always needed on flat surfaces oriented perpendicular to the parting line. Dimensional control and consistency in sand castings ranges from about ±0.8 to 3.2 mm (±0.030–0.125 in.). Within this range, the more generous tolerances apply across the parting line. Surface finish ranges between approximately 7.7 and 12.9 μm (300 and 500 μin.) root mean square (rms).

Shell Molding. Resin-bonded sand systems are also used in the shell molding process, in which prepared sand is contacted with a heated metal pattern to form a thin, rigid shell. The shell molding process is capable of producing quite precise castings and nearly rivals metal-mold and investment casting in its ability to reproduce fine details and maintain dimensional consistency. Surface finish, at about 3.2 μm (125 μin.) rms, is considerably better than that from green sand casting.

Shell molding is best suited to small-to-intermediate size castings. Relatively high pattern costs (pattern halves must be made from metal) favor long production runs. On the other hand, the fine surface finishes and good dimensional reproducibility can, in many instances, reduce the need for costly machining. While still practiced extensively, shell molding has declined somewhat in popularity, mostly because of its high energy costs compared with no-bake resin-bonded sand methods; however, shell-molded cores are still very widely used.

Plaster Molding. Copper alloys can also be cast in plaster molds to produce precision products of near-net shape. Plaster-molded castings are characterized by surface finishes as smooth as 0.8 μm (32 μin.) rms and dimensional tolerances as close as ±0.13 mm (±0.005 in.) and typically require only minimal finish machining. Compared to other casting methods, plaster molding accounts for a very small fraction of the copper castings market.

Investment casting, also known as precision casting or the lost wax process, is capable of maintaining very high dimensional accuracy in small castings, although tolerances increase somewhat with casting size. Dimensional consistency ranks about average among the casting

Table 8 Technical factors in the choice of casting method for copper alloys

Casting method	Copper alloys	Size range	General tolerances	Surface finish	Minimum section thickness	Ordering quantities	Relative cost, (1 low, 5 high)
Sand	All	All sizes, depends on foundry capability	± 1/32 in up to 3 in.; ± 3/64 in.; 3-6 in.; add ± 0.003 in./in. above 6 in.; add ± 0.020 to ± 0.060 in. across parting line	150-500 μin. rms	1/8 − 1/4 in.	All	1–3
No-bake	All	All sizes, but usually > 10 lb	Same as sand casting	Same as sand casting	Same as sand casting	All	1–3
Shell	All	Typical maximum mold area = 550 in.^{2}, typical maximum thickness = 6 in.	± 0.005–0.010 in. up to 3 in.; add ± 0.002 in./in. above 3 in.; add ± 0.005 – 0.010 in. across parting line.	125–200 μin. rms	3/32 in.	≥100	2–3
Permanent mold	Coppers, high-copper alloys, yellow brasses, high-strength brasses, silicon bronze, high-zinc silicon brass, most tin bronzes, aluminum bronzes, some nickel silvers	Depends on foundry capability; best, ~ 50 lb Best max thickness, ~ 2 in.	Usually ±0.010 in.; optimum ± 0.005 in., ±0.002 in. part-to-part	150–200 μin. rms. best ~ 70 μin. rms	1/8 − 1/4 in.	100–1,000, depending on size.	2–3
Die	Limited to C85800, C86200, C86500, C87800, C87900, C99700, C99750, and some proprietary alloys	Best for small, thin parts; max area ≤3 ft^2	±0.002 in./in.; no less than 0.002 in. on any one dimension; add ±0.010 in. on dimensions affected by parting line	32–90 μin. rms	0.05–0.125 in.	>1,000	1
Plaster	Coppers, high-copper alloys, silicon bronze, manganese bronze, aluminum bronze, yellow brass	Up to 800 in.^{2}, but can be larger	One side of parting line, ±0.015 in. up to 3 in.; add ±0.002 in./in. above 3 in.; add 0.010 in. across parting line, and allow for parting line shift of 0.015 in.	63–125 μin. rms, best ~ 32 μin. rms	0.060 in.	All	4
Investment	Almost all	Fraction of an ounce to 150 lb, up to 48 in.	±0.003 in. less than 1/4 ; ±0.004 in. between 1/4 to 1/2 in.; ±0.005 in./in. between 1/2 –3 in.; add ±0.003 in./in. above 3 in.	63–125 μin. rms	0.030 in.	>100	5
Centrifugal	Almost all	Ounce to 25,000 lb. Depends on foundry capacity	Castings are usually rough machined by foundry.	Not applicable	1/4 in.	All	1–3

Source: Ref 29

methods; however, surface finishes can be as fine as 1.5 μm (60 μin.) rms, and the process is unsurpassed in its ability to reproduce intricate detail.

Investment casting is better suited to castings under 45 kg (100 lb) in weight. Because of its relatively high tooling costs and higher-than-average total costs, the process is normally reserved for relatively large production runs of precision products and is not often applied to copper alloys.

Permanent Mold Casting. As the name implies, permanent mold casting makes use of reusable metal molds, or dies, in place of the sand-base molds used in conventional foundries. The molds are “permanent” in the sense that they can be used thousands of times.

Permanent mold castings are characterized by good part-to-part dimensional consistency and very good surface finishes (about 1.8 μm, or 70 μin.). Any traces of metal flow lines on the casting surface are cosmetic rather than functional defects. Permanent mold castings exhibit good soundness. There may be some microshrinkage, but mechanical properties are favorably influenced by the characteristically fine grain size of the casting. The ability to reproduce intricate detail is only moderate, however, and for products in which very high dimensional accuracy is required, plaster mold or investment processes should be considered instead.

Permanent mold casting is more suitable for simple shapes in midsize castings than it is for very small or very large products. Die costs are relatively high, but the absence of molding costs make the overall cost of the process quite favorable for medium to large production volumes.

Die casting involves the injection of liquid metal into a multipart die under high pressure. Pneumatically actuated dies make the process almost completely automated. Die casting is best known for its ability to produce high-quality products at very low unit costs. Very high production rates offset the cost of the complex heat-resisting tooling required, and with low labor costs, overall casting costs are quite attractive.

The process can be used with several copper alloys, including yellow brass, C85800, manganese bronzes, C86200 and C86500, silicon brass, C87800, the special die-casting alloys C99700 and C99750, plus a few proprietary compositions. These alloys can be die cast because they exhibit narrow freezing ranges and high β phase contents. Rapid freezing is needed to complement the fast cycle times of the process. Rapid freezing also avoids the hot shortness associated with prolonged mushy solidification. Beta phase contributes the hot ductility needed to avoid hot cracking as the casting shrinks in the unyielding metal mold.

Highly intricate copper alloy products can be made by die casting (investment casting is even better in this regard). Dimensional accuracy and part-to-part consistency are unsurpassed in both small (<25 mm, or 1 in.) and large castings. The attainable surface finish, often as good as 0.76 mm (30 μin.) rms, is better than with any other casting process. Die casting is ideally suited to the mass production of small parts.

Extremely rapid cooling rates (dies are normally water cooled) results in very fine grain sizes and good mechanical properties. Leaded alloys C85800 and C99750 can yield castings that are pressure tight, although lead is incorporated in these alloys more for its favorable effect on machinability than for its ability to seal porosity.

Centrifugal castings are produced by pouring molten metal into a mold that is being rotated or revolved. Both centrifugal and semicentrifugal castings can be described as castings that are spun on their own axes during the castings operation.

The axis of rotation may be horizontal or inclined at any angle up to the vertical position. Molten metal is poured into the spinning mold cavity, and the metal is held against the wall of the mold by centrifugal force. The speed of rotation and metal pouring rate vary with the alloy and size and shape being cast.

The castings with larger diameter than the axial length are cast vertically, while pieces with smaller lengths are cast horizontally. A wide range of castings such as bearings, bushings, and gears of all types for applications in general machine production, road building equipment, farm machinery, and steel mill and marine applications are produced.

Centrifugal castings are made in sizes ranging from approximately 50 mm to 3.7 m (2 in. to 12 ft) in diameter and from a few inches to many yards in length. Size limitations, if any, are likely as not based on the melt shop capacity of the foundry. Simply shaped centrifugal castings are used for items such as pipe flanges and valve components, while complex shapes can be cast by using cores and shaped molds. Pressure-retaining centrifugal castings have been found to be mechanically equivalent to more costly forgings and extrusions.

Continuous casting is a process whereby molten copper alloy is fed through an open-ended graphite mold yielding a bar, tube, or shape of the required cross section. This process, which is performed on a continuous basis, can be accomplished either vertically or horizontally, with the molten metal drawn from the molten metal reservoir or “tundish” at a point below the surface of the bath. The solidified form is cooled and withdrawn at a controlled rate from the water-cooled mold by rollers, and the material is cut to length with a traveling saw.

Continuous casting is used to produce bearing blanks and other long castings with uniform cross sections. It is the principal method used for the large-tonnage production of semifinished products such as cast rods, tube rounds, gear and bearing blanks, slabs, and custom shapes.

The extremely high cooling and solidification rates attending continuous casting can, depending on the alloy, produce columnar grains. The continuous supply of molten metal at the solidification interface effectively eliminates microshrinkage and produces high quality, sound products with very good mechanical properties. With its simple die construction, relatively low equipment cost, high production rate, and low labor requirements, continuous casting is a very economical production method.

Gating (Ref 30)

The major function of a gating system is to deliver clean metal from the ladle into the mold cavity without adversely affecting the quality of the metal. Secondary considerations are the ease of molding, removal of gates, and high casting yield. However, these factors should not dictate a design that contributes to the production of castings of unacceptable quality.

The Pouring Basin. The production of high-quality castings requires not only proper melting and molding operations and properly designed pattern equipment, but also an understanding of the principles of gating so that clean metal can be delivered to the mold cavity with a minimum amount of turbulence. A pouring basin allows a sprue to be filled quickly and maintains a constant head throughout the pour (Fig. 26).

When the weight of poured metal in a mold exceeds 14 kg (30 lb), use of a pouring basin offers many advantages. The pourer can better direct the flow of metal from the ladle into the basin, with less chance of spillages; also, the sprue need not be located near the edge of the mold. The pouring ladle can be brought within 25 to 50 mm (1–2 in.) of the basin, and a continued flow rate may be more easily maintained through a larger pouring head. If there are any brief interruptions in pouring the metal into the basin, the surplus metal will take up the slack until pouring has resumed. The major disadvantage of the pouring basin is that the yield is lowered, thereby requiring more metal to be recycled.

Sprue. The correct sprue size is the single most important part of the gating system. If a wrong size is selected, or an improper taper is used, the damage done to the metal in the mold cavity is extensive and cannot be corrected regardless of the quality of the runner and gating systems.

Because most molds under about 14 kg (30 lb) of poured weight are made on a high production scale in flasks of 102 to 152 mm (4–6 in.) in cope height, a fairly standard sprue size may be used for all copper-base alloys. The top third of the sprue should be the pouring part, with about a 50 mm (2 in.) diam opening. The remaining portion of the sprue should taper down to 13 to 22 mm ($\frac{1}{2}$ to $\frac{7}{8}$ in.) in final diameter depending on the pouring rate to be used.

Figure 27 shows a sketch of a sprue that will do an excellent job of conveying brass or bronze into the gating system. There are many charts and formulas available to determine the entry diameter of a tapered sprue, but for the most part this diameter should be just sufficient to provide about a 10 to 20° slope on the side of the sprue. When the sprue height is over 305 mm (12 in.), the top diameter of the sprue is much more important and should be about 50% larger than the diameter at the base of the sprue. When designing a pouring system for sprues of 102 to 152 mm (4–6 in.) in height, it is best to select the desired pouring rate first in order to determine the proper sprue base to be used.

The Sprue Base. Because the velocity of the stream is at its maximum at the bottom of the sprue and is proportional to the square root of the height of the fall of the metal, it is mandatory that a sprue base or well be used as a cushion for the stream flowing down the sprue. The base also helps change the vertical flow of metal into a horizontal flow with the least amount of turbulence. Recommended sprue basin sizes are about twice as deep as the drag runner and two to three times as wide as the base of the sprue. In most cases a well 25 to 38 mm (1–1½in.) deep with a width of 38 to 50 mm (1½–2 in.) on each side is usually adequate for the majority of sprues being used for most normal pouring rates. Little damage is done if the sprue base is larger than necessary except that the overall casting yield will be lowered slightly.

Chokes should be used only when the proper pouring rate cannot be controlled by the correct sprue size. If clean metal is delivered into the sprue, a strainer core serves the sole function of retarding the metal flow rate. Conventional strainer cores, whether of tinned steel, mica, glass fiber, or ceramic, usually reduce the flow of metal by about 70%, depending on the size and number of holes that are open to the sprue area. The best strainer is one that has only one hole with a diameter of the correct sprue size. This avoids the turbulence caused by the metal being divided into many streams as it enters the runner. In no instance should a strainer be placed into the top of the sprue; if one must be used, the only suitable place is just above the sprue base at the parting line. Tinned steel strainers are the least acceptable because the remelted runners can introduce iron and hard spots to the copper-base alloys if they are not properly skimmed during melting. The mica and glass fiber strainers are popular because they can be laid on the parting line just above the sprue base before the mold is closed, thereby requiring no "prints" or recesses, as do the thicker ceramic or sand strainer cores, which are usually about 3.2 mm (⅛ in.) thick.

A choke in the runner pattern is often the only consistent way to achieve a proper pouring rate. In no instance should the choke be put in the gate area. When necessary, it should be placed in the drag runner as close to the sprue as possible (Fig. 27). The chokes should have a smooth rediused contour and be located at the bottom of the drag runner. Choke depth may vary from ¼ to ¾ of the total runner depth with a cross-sectional area not exceeding ¾ of the area of the sprue base. The chokes should be located within an inch of the sprue base to ensure rapid filling of the sprue and maintenance of full capacity throughout the pour. This also permits dissipation of the turbulence before the stream reaches the gates.

Pouring rate depends on many factors, such as weight of the casting, section size, height of the sprue, and alloy system. Most alloys in group III for small work weighing 14 kg (30 lb) or less are poured with a hand ladle at about 1.8 kg/s (4 lb/s). Light memorial plaque castings are being successfully poured at 4.5 kg/s (10 lb/s), while many automatic pouring units operate at mold pouring rates of 3.6 to 4.5 kg/s (8–10 lb/s). Alloys in group I, if the poured weight is under 14 kg (30 lb), should be poured at 0.9 to 1.8 kg/s (2–4 lb/s) in order to obtain a clean, nonturbulent metal flow in the mold. Sprue exit diameters required for specific flow rates and various sprue heights are shown in Fig. 28. Table 9 shows flow rates from the bottom of the sprue for a number of commonly used sprue heights and diameters. As an example, for a gross casting weight of 14 kg (30 lb) or less and a sprue height of 102 to 152 mm (4–6 in.), a sprue diameter of 13 to 19 mm (½ – ¾ in.) is adequate to obtain a flow rate of 0.9 to 1.8 kg/s (2–4 lb/s). It should not be necessary to use a 22 to 29 mm (⅞ – 1⅛ in.) diam sprue base unless pouring plaque work or using automatic pouring. A quite popular sprue for most production work is the 16 to 19 mm (⅝ – ¾ in.) diam size, which will deliver enough hot metal to fill most molds up to 14 kg (30 lb) weight in 8 to 10 s. The total pouring time in seconds may be calculated by dividing the total weight of the mold poured (castings plus gates and risers) by the flow rate at the base of the sprue, or:

$$\frac{\text{Total weight of castings including gates and risers (lb)}}{\text{Flow rate at base of sprue (lb/s)}}$$

$$= \text{Calculated pouring time in seconds}$$

Runners and Gates. For alloys in groups I and II, it is mandatory that all runners be placed in the drag and as much of the casting as possible be placed in the cope. In this way, all runners will be completely filled before any metal enters the gates, and the metal will drop the least amount or will rise to enter the mold cavity from the gates. Although this practice is also excellent for alloys in group III, experience has shown that quality castings may be obtained by using more traditional casting techniques because the alloys in group III are

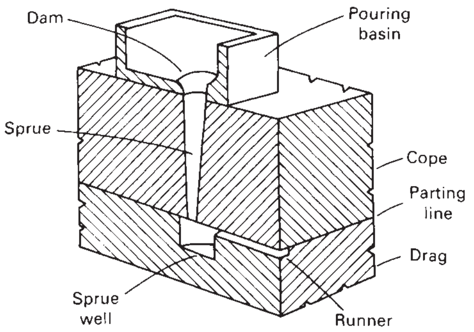

Fig. 26 Section of a typical sand mold with pouring basin

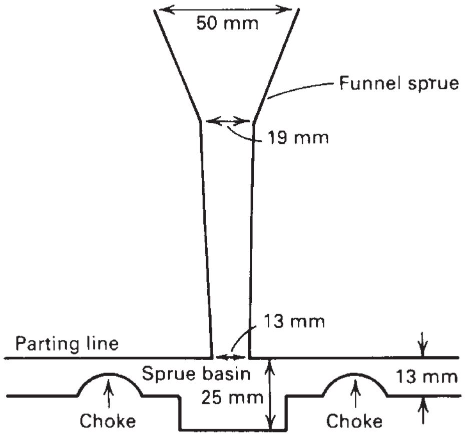

Fig. 27 Funnel sprue, sprue basin, and chokes (in drag runner) for reducing turbulence

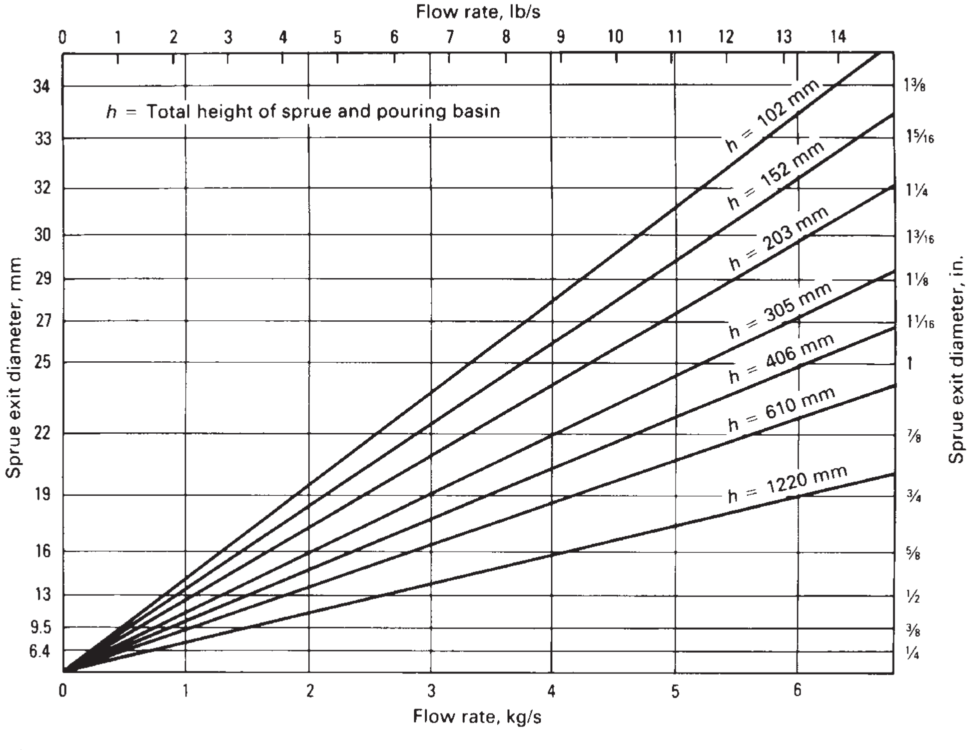

Fig. 28 Flow rates of copper-base alloys through tapered sprues of varying diameter and height

less sensitive to drossing and have a tendency to self-heal when dross is formed in the gating system. Runners should be as rectangular in shape as possible, and their total maximum cross-sectional area should be two to four times that of the tapered sprue or the choke, if chokes are used in the runner system. Care must be taken to ensure that the cross section of the runners is adequate in order to prevent premature chilling. Experience has shown that a rectangular runner with the wide side laying horizontal works best. The next best is a square runner, and the least desirable is a rectangular runner with the wide side being vertical, although sometimes space limitations necessitate use of this type of runner in order to obtain the proper ratios. The rectangular runner should be about twice as wide as it is deep.

The cross-sectional area of the runner must be reduced by that of each gate as it is passed, so that metal enters the mold cavity simultaneously from each gate (Fig. 29). Because back filling is seldom desired from the runner system, a well at the end of the runner can be used (Fig. 30), particularly if the runner does not have any taper. A good example of multiple-cavity gating may be seen in Fig. 30. X-ray movies of metal flow in sand molds show that relatively uniform gate discharge rates are achieved only when stepped or tapered runners are used.

Multiple gates are shown in Fig. 29 to 31. The preferred location is in the cope just above the runner at the parting line. A rectangular flat gate is more desirable than a square gate, and a gate that has its wide dimension in the vertical plane is the least desirable, just as is the case for runners. In order to avoid a pressurized gating system, it is important that the total gate area be at least as large as the total runner area. If a pattern has an excessive amount of small castings, it might be necessary to have the total gate area many times the runner area in order to obtain a sufficient gate to each casting. This deviation is acceptable because the gating system remains unpressurized. Figure 29 shows a good gating system that produces the minimum amount of turbulence. Gates should enter the casting cavity at the lowest possible level in order to avoid the erosion and turbulence associated with a falling stream of molten metal. To ensure nonturbulent filling of the casting nearest to the sprue, its gate should be at least 50 mm (2 in.) away from the base of the sprue.

Regardless of the excellence of a gating system design, castings of acceptable quality will not be produced if the ladle is not positioned as close as is practical to the pouring basin or sprue, and if the sprue is not filled quickly and kept at full capacity throughout the pour.

Knife and Kiss Gating Systems. Special applications of gating systems work in many cases for specific castings. Knife and kiss gating are popular when group III alloys are used but not recommended for groups I and II because these alloys form too much dross with this system and cannot be fed adequately to eliminate surface shrinkage. Advantages are a high casting yield, easy removal of runner systems, and minimum grinding of gates. The major disadvantage is that many small castings become detached during shakeout, necessitating their manual retrieval from mechanized systems. Figure 32 shows a graphic representation of the arrangement of knife and kiss gating. In kiss gating, the casting must be completely in the cope or the drag with the runner overlapping the casting by 0.8 to 2.4 mm ($\frac{1}{32}$ – $\frac{3}{32}$ in.). Actually there is no gate in this system because the metal goes directly from the runner into the casting.

Knife gating is used when the casting is in both the cope and the drag and there is a contact at the parting line of 0.8 to 2.4 mm ($\frac{1}{32}$ – $\frac{3}{32}$ in.) thickness just at the casting surface. Knife gating systems work well when the runner is in just the cope or just the drag or in both the cope and the drag.

Maximizing Casting Quality. Excellent, clean, high-quality castings may be obtained for the copper-base alloy groups of narrow, intermediate, and wide freezing range alloys if the basic principles discussed for the pouring basin, sprue, sprue base, chokes, pouring rates, runners, and gates are applied. By following these recommendations, the maximum ease in molding, casting yield, and ease of removal of gates and runners may be obtained.

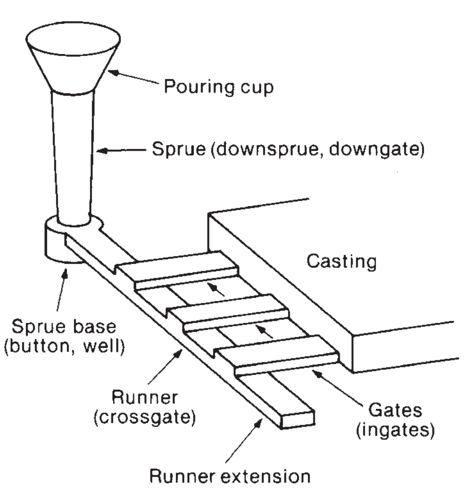

Fig. 29 Typical single-cavity gating system with tapered runner

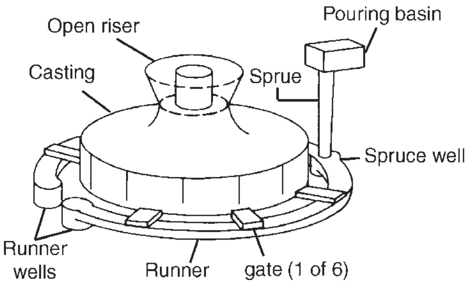

Fig. 30 Method of running a pump impeller with a well at the end of the runner

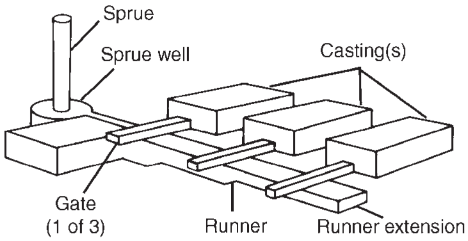

Fig. 31 Recommended multiple-cavity gating system with stepped runner

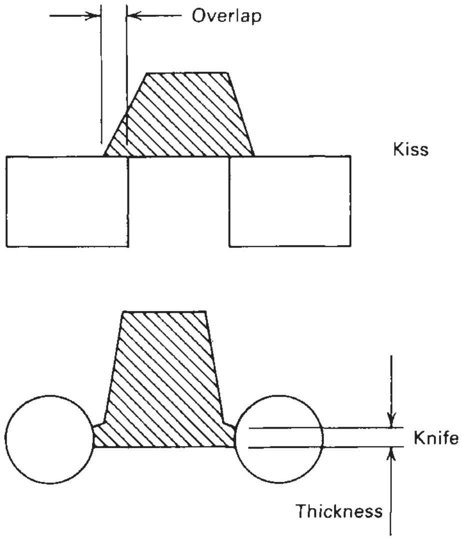

Fig. 32 Basic kiss and knife gates

Table 9 Flow rates of copper-base alloys through tapered sprues of varying diameter and height

Sprue				Flow rate for sprue height, mm (in.)									
Area		Diameter		102 (4)		152 (6)		305 (12)		610 (24)		1220 (48)	
mm²	in.²	mm	in.	kg/s	lb/s	kg/s	lb/s	kg/s	lb/s	kg/s	lb/s	kg/s	lb/s
129	0.2	13	½	0.82	1.8	0.91	2.0	1.36	3.0	1.81	4.0	2.72	6.0
194	0.3	16	⅝	1.27	2.8	1.50	3.3	2.04	4.5	2.72	6.0	4.08	9.0
284	0.44	19	¾	1.81	4.0	2.04	4.5	2.95	6.5	4.08	9.0	6.12	13.5
387	0.60	22	⅞	2.49	5.5	2.95	6.5	4.08	9.0	5.67	12.5	8.16	18.0
506	0.785	25	1	3.40	7.5	3.86	8.5	5.22	11.5	7.48	16.5	11.11	24.5
645	1.0	29	1⅛	4.30	9.5	4.76	10.5	7.71	17.0	9.30	20.5	13.61	30.0

Feeding

The objectives of feeding or risering are to eliminate surface sinks or draws and to reduce internal shrinkage porosity to acceptable levels (less than 1%).

To minimize porosity, the feeding system must establish:

- Directional solidification, as shown in Fig. 33, in which the solidification front is substantially V-shaped in a longitudinal cross section with the large end of the V directed toward the riser
- Steep temperature gradients along the casting toward the riser

The feeding techniques for group I (short freezing range) alloys and group II (medium freezing range) alloys can be discussed together. The basic principles of risering of group III (long freezing range) alloys will be described separately.

Group I and II Alloys

The feeding technique for these alloys is similar to that used in the manufacture of steel castings. Gates and risers are positioned such that directional solidification is ensured, with due consideration being given to the feeding range of the alloy in question. To avoid hot spots, local chills may be applied to bosses, ribs, and to other sections having sudden changes in thickness.

Solidification Contours. The first step in determining riser placement is to draw the solidification contours. This is illustrated by the hypothetical casting shown in Fig. 34, which consists essentially of a plate to which is attached a thinner section, C, and a boss, B. The thin end of the casting, C, would normally undergo rapid cooling after pouring as the result of edge-cooling effects. Thus, it is possible to place the riser at the heavy section, A, and gate through the riser to provide favorable temperature gradients. The dotted lines in Fig. 35 show successive positions of the solidification front. As shown, porosity will develop in the boss unless a chill is placed on the boss or the riser is relocated there. A chill is a block of metal or other material with a higher heat conductivity and heat capacity than sand.

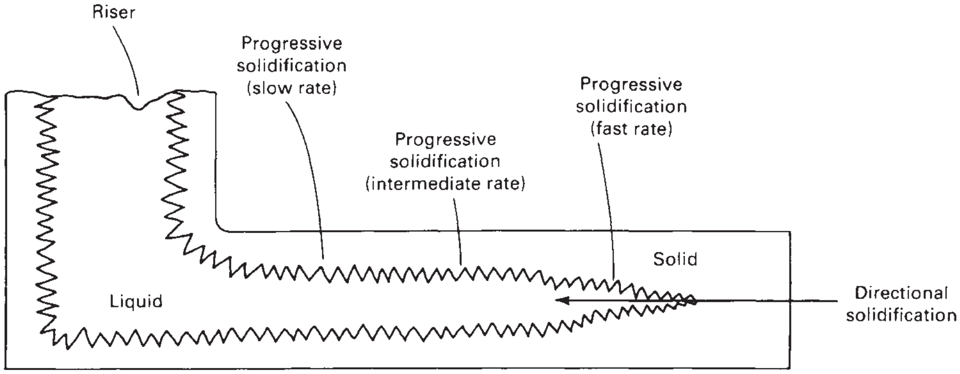

Fig. 33 Features of progressive and directional solidification. Source: Ref 31

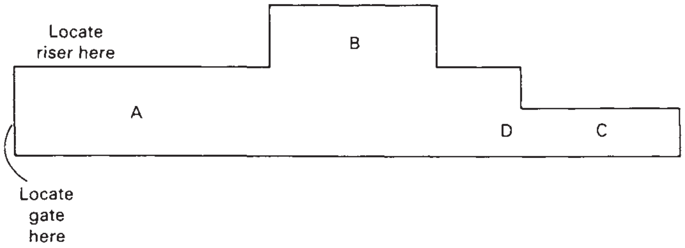

Fig. 34 Hypothetical casting used to illustrate the principles of feeding technique. Source: Ref 32

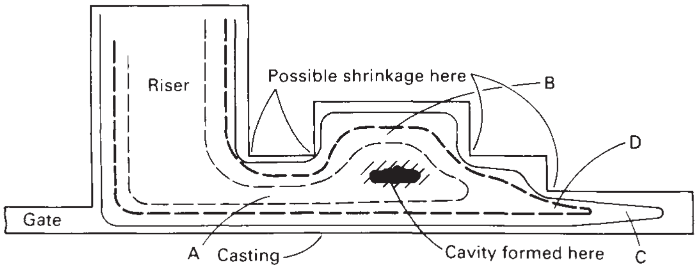

Fig. 35 Mode of freezing the casting in Fig. 34 without special precaution to avoid shrinkage. Source: Ref 32

Feeding Ranges. The number and location of the feeders to be used must be consistent with the feeding range of the alloy. The feeding range is the distance that can be fed by a feeder on a bar or plate. It is generally desirable to divide the casting into a number of sections to determine the number of risers to be used. Because all parts of a casting must be within the feeding range of at least one of the risers, it is important to have quantitative information regarding feeding ranges. The feeding range values for group I and II copper-base alloys have not been well documented. In the absence of specific data for particular alloys, satisfactory results can often be attained by applying values that have been developed for carbon steels. The following approximate values for feeding ranges have been quoted in the literature, but should be used with caution:

Alloy	Shape	Feeding distance, T
Manganese bronze	Square bars	4 T to 10 $\sqrt{T}$, depending on thickness
	Plates	5.5 to 8 T, depending on thickness
Aluminum bronze	Square bars	8 $\sqrt{T}$
Nickel-aluminum bronze	Square bars	<8 $\sqrt{T}$
Copper-nickel	Square bars	5.5 $\sqrt{T}$

Use of chills can further increase feeding range. Consequently, the spacing between risers may be increased to about ten times the section thickness if chills are located midway between each pair of risers (Fig. 36).

Riser Size. From time to time, various methods have been proposed for the calculation of the optimal riser size to be used to feed a particular casting or casting section. One of the earlier methods was developed for steel castings at the Naval Research Laboratories (NRL). In this technique, an empirical "shape factor" defined as the length (L) plus the width (W) of the casting divided by the thickness (T), that is, $(L + W)/T$, is first determined. The correct riser size is obtained from a plot of V_R/V_C versus $(L + W)/T$, where V_R and V_C are the riser and casting volume, respectively.

Work sponsored by the American Foundry men's Society has lead to the development of a series of curves for aluminum bronzes, copper-nickel, and manganese bronzes (Fig. 37–40).

Figures 37 to 40 indicate that the riser volumes necessary for sound castings can be reduced and the effectiveness of feeding improved by the use of exothermic sleeves. Insulating sleeves also can be used to increase the effectiveness of the risers. Exothermic sleeves, which were once popular, have now largely been discontinued in favor of insulating sleeves, which are more economical to use and cause fewer problems.

In recent years, greater attention has been given to what has become known as the modulus method for calculating riser size, which includes the development of pertinent data and computer programs to check that riser volume is adequate. This method is now, and no doubt will continue to be, the most widely used technique in the industry.

Chvorinov's rule states that the freezing time, *t,* of a cast shape is given by the relationship:

$$t = k \cdot (V/A)^2 \qquad \text{(Eq 1)}$$

where V and A are the volume and surface area, respectively, of the cast shape, and k is a constant proportionality whose value is dependent on the thermal properties of the metal and the mold.

For convenience, the term (V/A) in Chvorinov's equation is generally replaced by the symbol M, a value referred to as the modulus of the shape. Equation 1, above, can be rewritten more simply to read:

$$t = k \cdot M^2 \qquad \text{(Eq 2)}$$

Because Chvorinov's equation can be applied to any cast shape, it applies equally to that which is intended to be the casting itself and to the attached riser. With connected shapes, such as a riser and a casting, the surface area of each shape to be considered includes only those portions that contribute to the loss of heat during freezing.

For the riser to be effective in feeding, its solidification time, t_R, must be greater than the solidifiation time t_C, for the casting. This can be written:

$$\frac{t_R}{t_C} = \frac{k \cdot M_R^2}{k \cdot M_C^2} = F^2, \text{ or } M_R^2 = F^2 \cdot M_C^2 \qquad \text{(Eq 3)}$$

Further simplified, this becomes:

$$M_R = F \cdot M_C \qquad \text{(Eq 4)}$$

This means that the modulus for the riser, M_R, must be greater than the modulus for the casting, M_C, by some factor, F. Experience has shown that the proper value of F depends on the metal being cast. A value of about 1.3 is preferred for the short freezing range copper-base alloys.

As a practical working equation, therefore, one may say that with these alloys the modulus of the riser should be about 1.3 times that of casting (or casting section) to be fed, or:

$$M_R = 1.3\, M_C \qquad \text{(Eq 5)}$$

Equation 5 merely shows an empirical way of proportioning a riser so that it freezes more slowly than the casting. The other basic requirement of any riser is that it must have sufficient volume to provide the necessary amount of feed metal to the casting or casting section to which it is attached. These values can be calculated if necessary; however, it is much easier (though less precise) to use data of the type shown in Table 10. The numbers listed in the table indicate the minimum values for the ratio between riser volume and casting volume (as percentages) to ensure that the riser can, indeed, supply the necessary amount of feed metal to the casting. Five general classes of castings are shown, ranging from "very chunky" to "rangy." Notice that risers having a height-to-diameter ratio (H/D) of 1 to 1 are more efficient than when the H/D is 2 to 1. More important, it can be seen that insulated risers are far more efficient than those formed directly in the sand mold.

Feeder Shape. One of the requirements of the riser is to remain liquid longer than the casting; that is, from Chvorinov's rule:

$$(V/A)_R > (V/A)_C \qquad \text{(Eq 6)}$$

The shape with the highest possible V/A ratio is the sphere. However, spherical risers are rarely used in industry because of molding considerations.

The next best shape for a riser is the cylinder. The H/D for cylindrical risers is in the range of 0.5 to 1.0.

Riser Neck Dimensions. The ideal riser neck should be dimensioned such that it solidifies after the casting but slightly before the riser. With this arrangement, the shrinkage cavity is entirely within the riser, this being the last part of the casting-riser combination to solidify.

Specific recommendations for the dimensions of riser necks are contained in the literature for

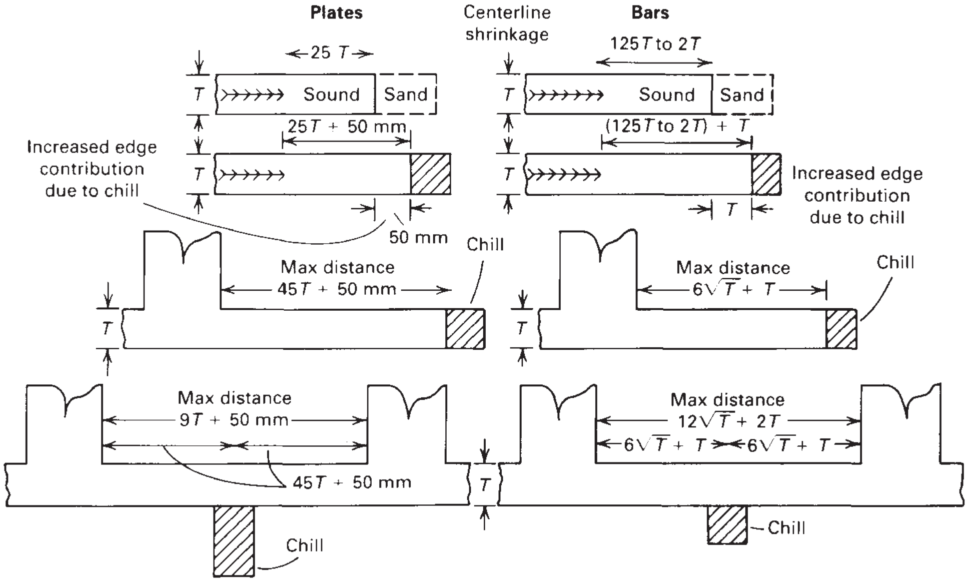

Fig. 36 Effect of chills in increasing feeding range of risers. Source: Ref 31

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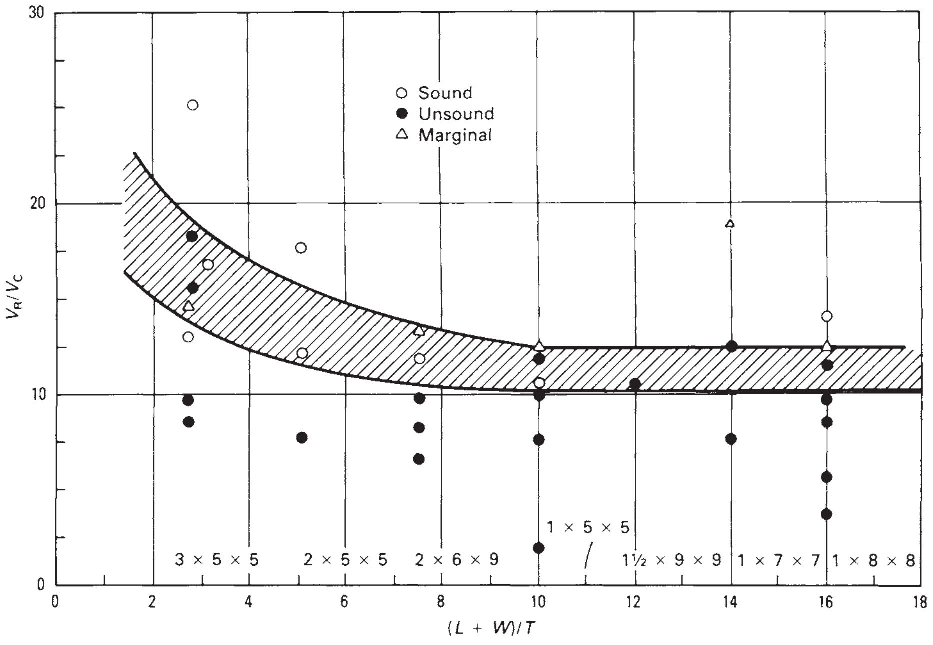

Fig. 37 Naval Research Laboratories (NRL)-type riser size curve for manganese bronze (alloy C86500). Source: Ref 33

ferrous alloys. These should apply to short freezing range copper alloys and are given in Table 11.

Hot Topping. About 25 to 50% of the total heat from a copper-base alloy riser is lost from the exposed surface by radiation. In order to minimize this radiation loss and thereby increase the efficiency of the riser, some sort of cover should be used on the top surface. Any cover, even dry sand, is better than nothing at all. A reliable exothermic hot topping is one form of usable cover.

Chills. The heat abstraction of the mold walls can be increased locally by the use of chills. Though expensive, metal chills are particularly effective because they reduce the solidification time by a factor of more than 55. As mentioned earlier, chills can be used to increase feeding distances and thereby reduce the number of feeders required. When it is impractical to attach feeders at certain locations, chills are particularly useful for initiating directional solidification, for example, at junctions, and so on, which would otherwise be porous.

Padding. The process of solidification can also be controlled by means of padding. Padding is the added section thickness (usually tapered) to promote directional solidification, and the bulk of it should be as close to the riser as possible.

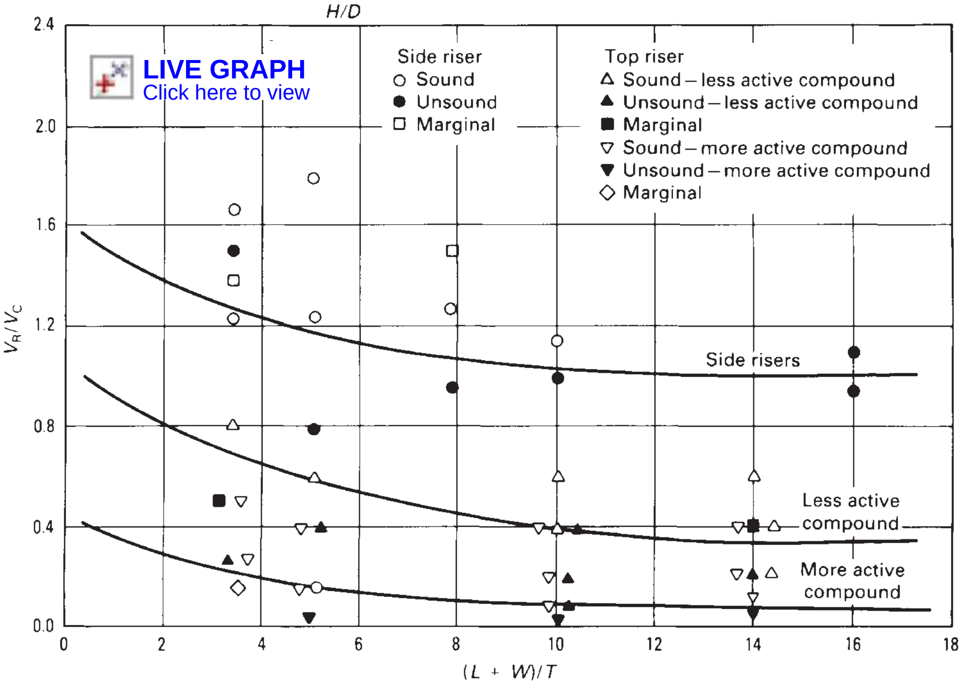

Fig. 38 NRL-type riser curve for manganese bronze (alloy C86500) using different types of exothermic hot topping and top risers. Source: Ref 34

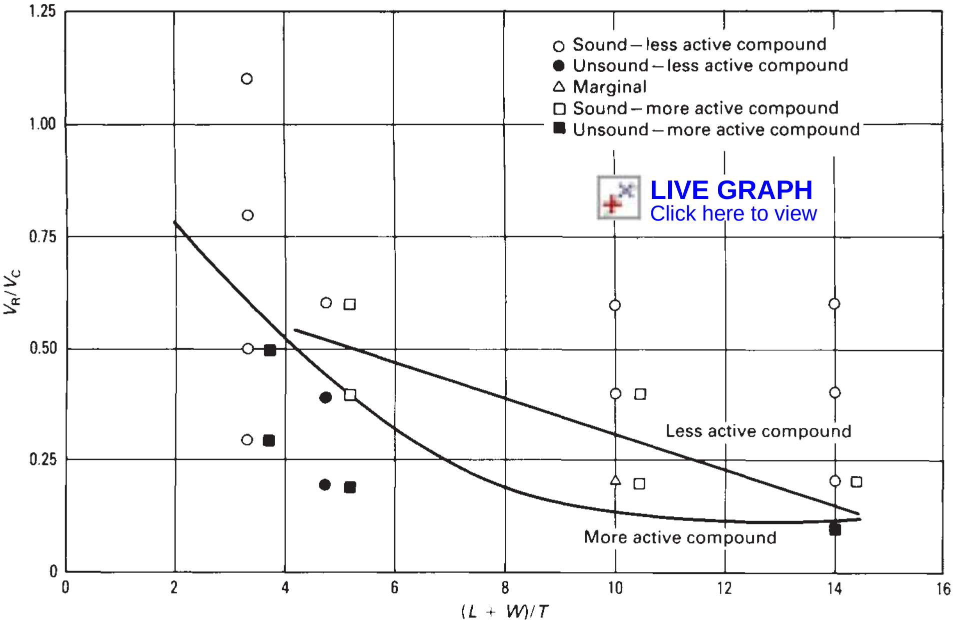

Fig. 39 NRL-type riser curve for aluminum bronze (alloy C95300) using different types of exothermic hot topping and top risers. Source: Ref 34

Interaction of Gates and Risers. The effectiveness of side risers can be increased considerably by using a gating system that enters the mold cavity through the riser. The advantages of this arrangement are:

- Cleaner molten metal enters the mold cavity.
- Because the metal in the riser remains liquid for a longer time, steep thermal gradients are established to improve the soundness of the casting.

Group III Wide Freezing Range Alloys

The "workhorse" alloys of the copper-base group are the leaded red brasses and tin bronzes, virtually all of which have wide freezing ranges. These alloys have practically no feeding range, and it is extremely difficult to get fully sound castings. The average run of castings in these alloys contains 1 to 2% porosity. Only small castings may exhibit porosity below 1%. Attempts to reduce it more by increasing the size of the risers are often disastrous and actually decrease the soundness of the casting rather than increase it.

Experience has shown that success in achieving internal soundness depends on avoiding slow cooling rates. The foundryman has three possible means for doing this, within the limitations of casting design and available molding processes:

- Minimize casting section thickness.
- Reduce and/or evenly distribute the heat of the metal entering the mold cavity.
- Use chills and mold materials of high chilling power.

In order to produce relatively sound castings, the following points should be considered.

Directional solidification, best used for relatively large, thick castings, can be promoted in various ways:

- Gate into hot spot.
- Riser into hot spot.
- Ensure that riser freezes last (consider riser size, insulation, and chills).
- Promote high thermal gradients by the use of chills, preferably tapered chills unless casting section is light (less than 12.5 mm, or $\frac{1}{2}$ in. thick).
- Make sure risers are not so large that they unduly extend the solidification time of the casting, which would generate porosity beneath or behind the riser.

Uniform solidification, best used for smaller, thin-wall castings, can be promoted in various ways:

- Gate into cold spots, using several gates for uniform temperature distribution.
- Use no risers, except perhaps on gate areas.
- Use chills on hot spots to ensure that they cool at the same rate as the rest of the casting.

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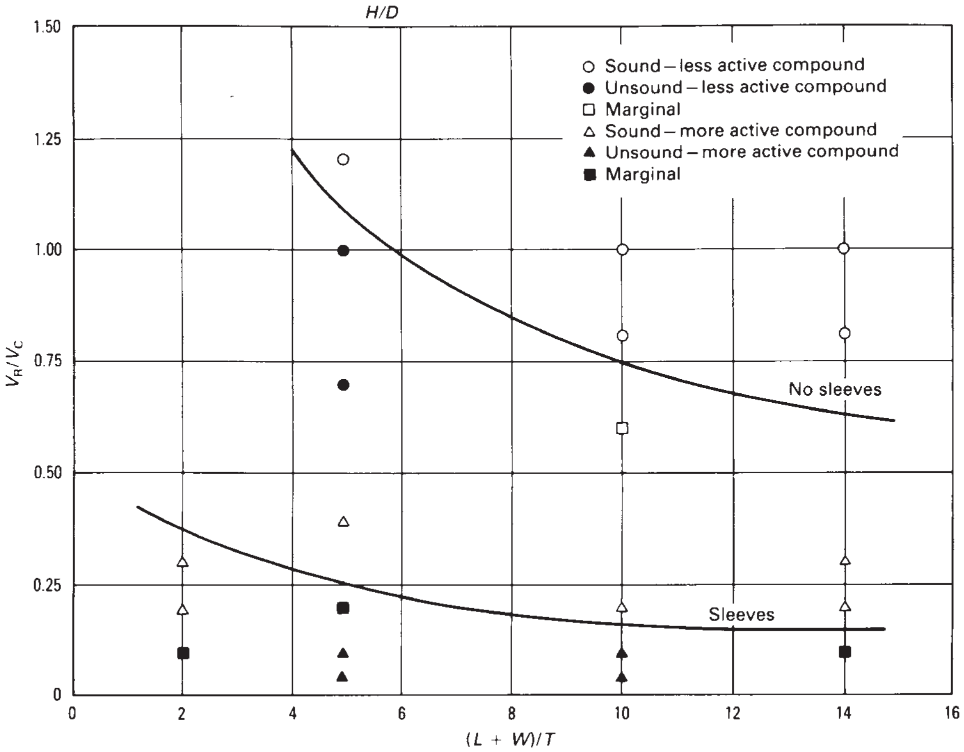

Fig. 40 NRL-type riser curve for Cu-30Ni (alloy C96400) using exothermic sleeves and hot topping versus hot topping alone. Source: Ref 34

Table 10 Minimum volume requirements of risers

	Minimum V_R/V_C, %			
	Insulated risers		Sand risers	
Type of casting	*H/D* = 1:1	*H/D* = 2:1	*H/D* = 1.1	*H/D* = 2.1
Very chunky; cubes, and so on; dimensions in ratio 1:1.33:2(a)	32	40	140	198
Chunky; dimensions in ratio 1:2:4(a)	26	32	106	140
Average; dimensions in ratio 1:3:9(a)	19	22	58	75
Fairly rangy; dimensions in ratio 1:10:10(a)	13	15	30	38
Rangy; dimensions in ratio 1:15:30 or larger(a)	8	9	12	14

(a) Ratio of thickness:width:length. Source: Ref 31

Table 11 Riser neck dimensions

Type of riser	Length, L_N	Cross section
General side	Short as feasible, not over *D*/2	Round, $D_N = 1.2\ L_N + 0.1D$
Plate side	Short as feasible, not over *D*/3	Rectangular, H_N = 0.6 to 0.8*T* as neck length increases. $W_N = 2.5\ L_N + 0.18D$
Top	Short as feasible, not over *D*/2	Round, $D_N = L_N + 0.2D$

L_N, D_N, H_N, W_N: length, diameter, height, and width of riser neck, respectively. *D*, diameter of riser. *T*, thickness of plate casting. Source: Ref 35

- Use chills on areas that must be machined, thereby moving porosity to areas where the cat skin will be left unmachined; that is, maintain pressure tightness.
- Gate into areas away from machined sections to maintain pressure tightness.
- Use low pouring temperature (care should be taken to avoid misruns).
- See whether increased gas content (no de gassing, reduced deoxidation) or induced metal mold reaction increases pressure tightness.
- Make castings as thin as possible to increase cooling rate and reduce machining.

ACKNOWLEDGMENTS

This article was adapted from:

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- D.V. Neff, Nonferrous Molten Metal Processes, *Casting,* Vol 15, *ASM Handbook*, ASM International, 1988, p 445–496

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Forming

COPPER AND MOST COPPER ALLOYS are readily formed at all sheet gages. The copper alloys commonly formed are characterized by strength and work-hardening rates between those of steel and aluminum alloys. This article will review the general characteristics of copper and copper alloys and how these characteristics affect the behavior of sheet and strip in different types of forming operations. Although emphasis is placed on the forming of flat products, the final sections of this article also address the forming of rod, bar, tube, shapes, and wire. Additional information on each of the forming processes discussed subsequently can be found in *Forming and Forging*, Volume 14 of the *ASM Handbook*.

General Considerations

The combination of moderate-to-high strength, high electrical and thermal conductivity, modest cost, good corrosion and stress-corrosion resistance, and ease of joining, coupled with good formability, accounts for the use of copper and copper alloys in a wide range of applications. The list of typical applications given subsequently reveals the diversity of forming operations used:

Application	Forming operations
Electrical terminals and connectors	Bending stretch forming, blanking, coining, drawing
Electronic leadframes	Bending, coining, blanking
Hollow ware, flatware	Roll forming, blanking
Builder's hardware	Shallow and deep drawing, and stretch forming operations
Heat exchangers	Roll forming, bending, sinking, blanking
Coinage	Blanking, coining, embossing
Bellows, flexible hose	Cupping, deep drawing, bending
Musical instruments	Blanking, drawing, coining, bending, spinning
Ammunition	Blanking, deep drawing

These applications are illustrated in Fig. 1 to 8.

Metallurgical Parameters Affecting Formability. All of the various major forming operations—blanking, bending, stretch forming, drawing, and coining—depend on some optimal combination of strength, ductility, and work-hardening behavior of the sheet metal to provide the most cost-effective part. Therefore, much of this article is devoted to understanding the trade-offs in strength, work hardening, and ductility available by selection of material and temper. Strain-rate sensitivity (m value) is also a factor in some forming operations. However, m is of practical significance only at elevated temperature.

Other metallurgical parameters used to rank copper alloy sheet forming characteristics are:

- The plastic-strain ratio (r value), which is a measure of sheet anisotropy
- The limiting draw ratio (LDR)
- Bulge height
- Minimum bend radius

These measurements are primarily used to assess drawing and stretching capacity specific to a given alloy composition, cold-work level, and texture development. A more comprehensive treatment of the relationships between these materials characteristics and formability is available in the article "Formability Testing of Sheet Metal" in Volume 14 of *ASM Handbook* and in various texts dealing with mechanical metallurgy (see, for example, the selected references listed at the conclusion of this article).

Effects of Composition, Cold Work, and Heat Treatment on Formability

Copper alloys are primarily strengthened by cold work or by alloying additions that solid solution strengthen and enhance strain hardening. A finely dispersed second phase is sometimes used as a grain refiner to maximize strength/ductility combinations and/or as a means of ensuring good surface finish after forming.

Precipitation hardening is important to a small but important class of alloys, most notably, the beryllium-copper alloys. Copper-nickel-aluminum and copper-nickel-silicon alloys are also commercially important precipitation-hardenable alloys. Spinodal and/or precipitation hardening is available in the copper-nickel-tin and copper-nickel-chromium systems. Hardening by martensitic transformation is available in the copper-aluminum system, but is rarely used commercially. A more detailed discussion of strengthening mechanisms for copper alloys can be found in the article "Wrought Copper and Copper Alloys" in this Handbook.

Copper alloys are classified using the Unified Numbering System (UNS). The designations of the Copper Development Association are also used and correspond closely to UNS designations. Wrought copper alloys are divided in the UNS system into the following groups:

Copper and high-copper alloys	C1*xxxx*
Zinc brasses	C2*xxxx*
Zinc-lead brasses	C3*xxxx*
Zinc-tin brasses	C4*xxxx*
Tin bronzes	C5*xxxx*
Aluminum, manganese, and silicon	C6*xxxx*
Copper-nickel and copper-nickel-zinc alloys	C7*xxxx*

Copper alloys are supplied in annealed (soft) and cold-worked (hard) tempers, as defined in

Table 1 ASTM B 601 temper designations for copper and copper alloys

Temper designation	Temper name or material condition
Annealed tempers	
O25	Hot rolled and annealed
O50	Light annealed
O60	Soft annealed
O61	Annealed
O65	Drawing annealed
O68	Deep-drawing annealed
O70	Dead soft annealed
O80	Annealed to temper 1/8 hard
O81	Annealed to temper 1/4 hard
O82	Annealed to temper 1/2 hard
OS005	Average grain size 0.005 mm
OS010	Average grain size 0.010 mm
OS015	Average grain size 0.015 mm
OS025	Average grain size 0.025 mm
OS035	Average grain size 0.035 mm
OS050	Average grain size 0.050 mm
OS070	Average grain size 0.070 mm
OS100	Average grain size 0.100 mm
OS120	Average grain size 0.120 mm
OS150	Average grain size 0.150 mm
OS200	Average grain size 0.200 mm
Cold-worked tempers	
H00	1/8 hard
H01	1/4 hard
H02	1/2 hard
H03	3/4 hard
H04	Hard
H06	Extra hard
H08	Spring
H10	Extra spring
H12	Special spring
H13	Ultra spring
H14	Super spring
Cold-worked and stress-relieved tempers	
HR01	H01 and stress relieved
HR02	H02 and stress relieved
HR04	H04 and stress relieved
HR06	H06 and stress relieved
HR08	H08 and stress relieved
HR10	H10 and stress relieved
HR50	Drawn and stress relieved
Cold-worked and order-strengthened tempers	
HT04	H04 and order heat treated
HT06	H06 and order heat treated
HT08	H08 and order heat treated

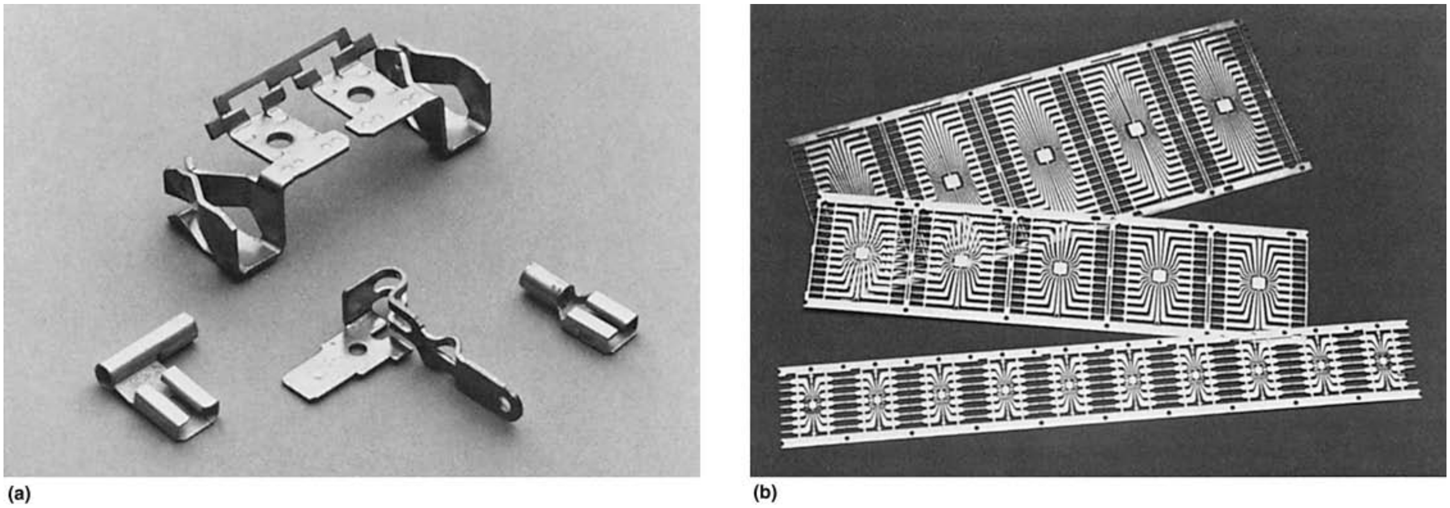


Fig. 1 Electrical and electronic applications for formed copper alloy parts. (a) Connectors used in home appliances and automotive electrical systems. (b) Copper alloy leadframe for a semiconductor device

Fig. 2 Typical household flatware utensils formed from copper alloys

Table 2 Mechanical properties of selected solid-solution copper alloys

Grain sizes of all materials listed ranged from 0.010 to 0.025 mm (0.0004 to 0.001 in.)

Alloy designation and common name	Nominal composition, %	0.2% offset yield strength		Tensile strength		Elongation, %
		MPa	ksi	MPa	ksi	
C11000 (Electrolytic tough-pitch)	99.90 min Cu	83	12	241	35	48
C21000 (Gilding, 95%)	Cu-5Zn	97	14	262	38	45
C23000 (Red brass, 85%)	Cu-15Zn	110	16	290	42	45
C26000 (Cartridge brass, 70%)	Cu-30Zn	179	26	379	55	48
C50500 (Phosphor bronze, 1.25% E)	Cu-1.4Sn	124	18	290	42	47
C51000 (Phosphor bronze, 5% A)	Cu-5Sn	165	24	345	50	50
C61000 (…)	Cu-8Al	207	30	483	70	65
C70600 (Copper nickel, 10%)	Cu-10Ni	124	18	317	46	38
C71500 (Copper nickel, 30%)	Cu-30Ni	172	25	400	58	32
C75200 (Nickel silver, 65–18)	Cu-18Ni-18Zn	179	26	414	60	37

(a) Available only as tube, but properties are illustrative of copper-aluminum alloy strip properties.

Table 1. These designations are only guidelines; the supplier should be consulted for specific property/temper characteristics. Temper designations for precipitation-hardened alloys are covered in the section "Precipitation Hardening and Cold Working" in this article.

Solid-Solution Strengthening and Cold Working. Solute elements provide a major means of strengthening copper, and the magnitude of strengthening depends on the type and level of addition. Table 2 lists mechanical properties resulting from various alloying additions to copper in the annealed condition. Neither tensile elongation (Table 2) nor reduction in area fully defines usable formability and should not be used to correlate formability; they can, however, offer some insight into formability. It is clear from Table 2 that strength higher than that of pure copper (Alloy C11000) can be acquired with limited or no loss of ductility by solid-solution alloying.

Figure 9 shows the work-hardening behavior of copper (C11000) and several copper alloys in terms of strength and ductility versus cold reduction. The relative work-hardening effects of various alloying elements are evident; the strong effect of aluminum is contrasted with the weak effect of nickel, with zinc and tin being intermediate. Ductility, as indicated by tensile elongation, decreases with cold reduction. Again, however the combinations of strength and ductility is enhanced by solid-solution additives even after cold working.

Precipitation Hardening and Cold Working. Precipitation-hardenable alloys offer the opportunity to form parts in the maximum-ductility (solution-annealed) condition and then harden the formed part to maximum strength with a precipitation heat treatment. However, fabrication requirements may preclude this option. Alloys containing 0.15 to 2.0% Be can be strengthened by solid-state precipitation. For alloys with high beryllium content (1.8 to 2.0%), combinations of cold work and elevated-temperature aging produce material with tensile strength above 1380 MPa (200 ksi). Lower beryllium contents are used to sacrifice some strength for better thermal and electrical conductivities. Forming can precede aging or follow it; the choice is based on property and formability requirements, as well as practicality.

In many cases, volume changes that accompany aging, or other fabricating constraints, preclude aging treatment of the formed part, and the precipitation-hardened alloys are therefore provided in mill-hardened tempers. Mill-hardened alloys are either solution annealed or cold rolled before being given an aging treatment at the mill to produce a specific set of final properties.

Mill-hardened tempers are designed to balance the requirements of strength and formability. They are of particular importance for intricate parts such as electronic connectors, where elimination of customer heat treatment and cleaning steps are important to the economics and/or fabrication of the part. Parts that require sharp bends or maximum formability should be formed from the annealed or rolled tempers before final aging to reach the desired peak strength.

Mill-hardened tempers are much stronger than unaged rolled tempers, but compromise some formability compared to the rolled tempers in favor of avoiding customer aging and

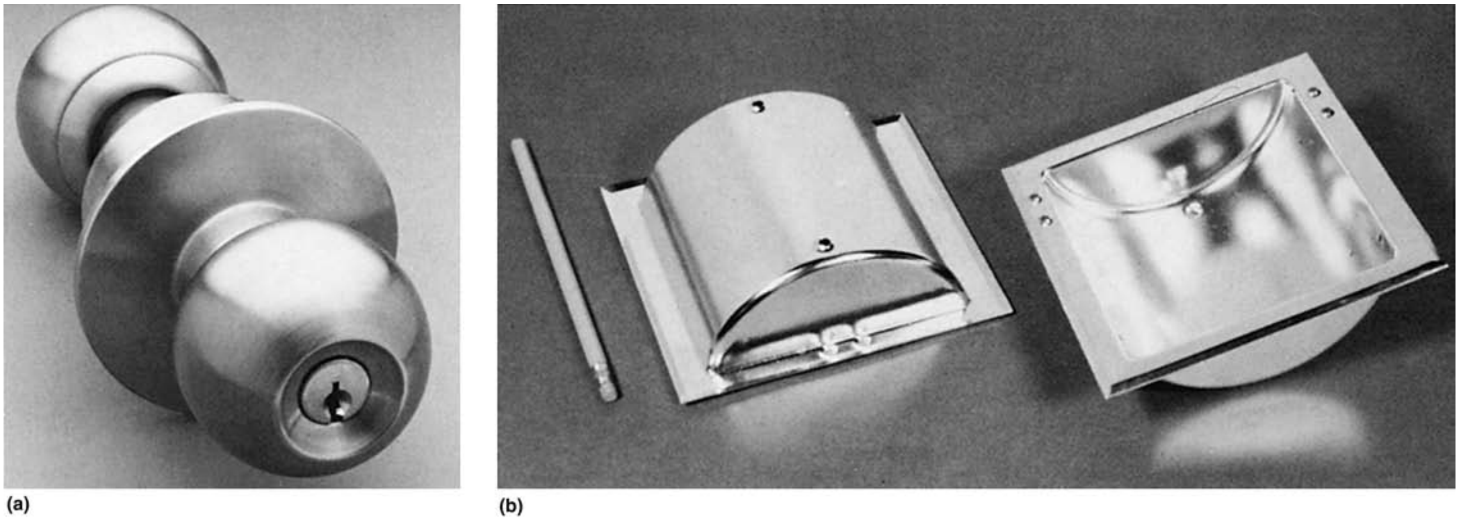


Fig. 3 Builder's hardware formed from copper alloys. (a) Doorknob fabricated by deep drawing. (b) Recessed fixture for kitchen and bathroom accessories

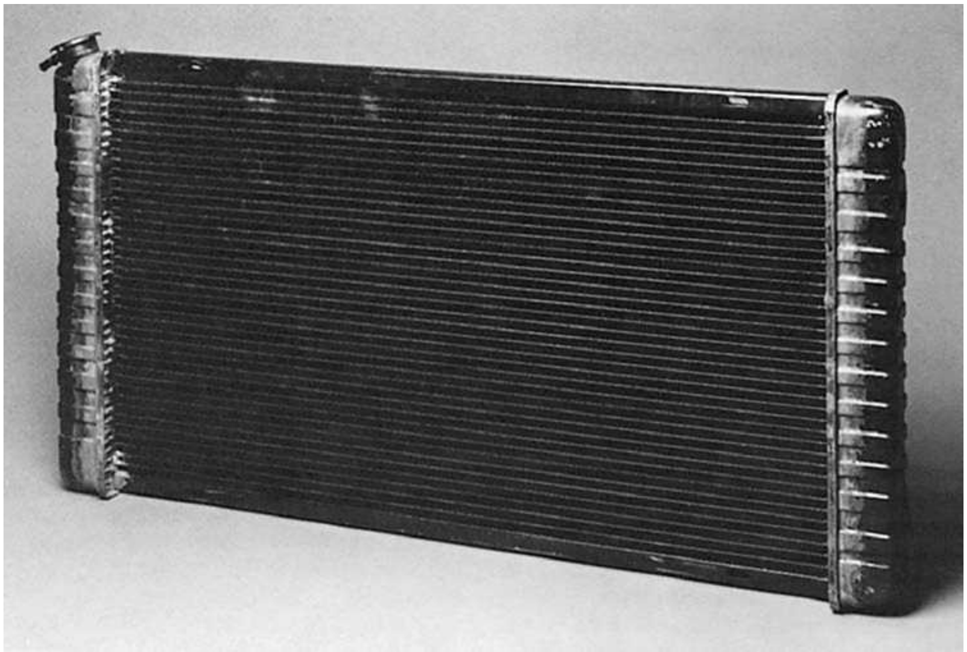


Fig. 4 Automotive radiator fabricated from several formed copper alloy components, including a deep-drawn water tank, roll-formed cooling tubes, and formed cooling fins

Fig. 5 Copper alloy U.S. currency with heavy coining and embossing

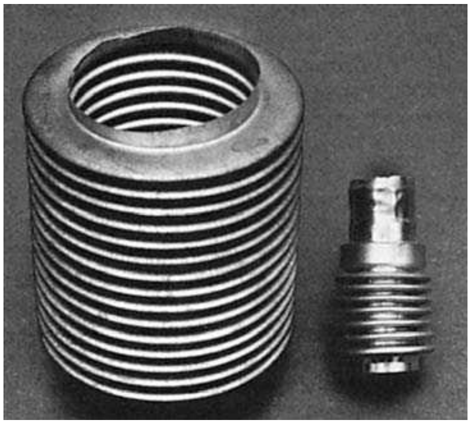


Fig. 6 Deep-drawn and corrugated copper alloy bellows

cleaning. The grain size of these alloys is less than 0.03 mm (0.001 in.) for gages from 0.1 to 1.27 mm (0.004 to 0.050 in.) thick. Temper designations for precipitation-hardening systems are given in Table 3; mill-hardened temper designations correspond to supplier designations.

The mechanical properties of four precipitation-hardenable alloys in the solution-annealed condition are given in Table 4. The work-hardening behavior of several precipitation-hardening systems in the solution-annealed condition is shown in Fig. 10. The strong effect of beryllium content on solid-solution strengthening and work hardening is evident in Fig. 10 for alloy C17200. Table 5 lists the mechanical properties of selected tempers of mill-hardened alloys.

Postforming Heat Treatment. Heat treatments, aside from those employed to precipitation harden, are used after forming to reduce susceptibility to stress corrosion (primarily the brasses) or to increase the stiffness or stress relaxation resistance of electrical or electronic springs (mainly the brasses, aluminum bronzes, and copper-silicon alloys). These postforming treatments are performed at low temperatures. See the article "Heat Treating" in this Handbook for details.

Formability of Copper Alloys versus Other Metals

In forming a given part, no single materials property completely defines formability. As previously noted, formability can best be rationalized in terms of the strength, work hardening, and ductility of a copper alloy, but these parameters do not allow direct correla-

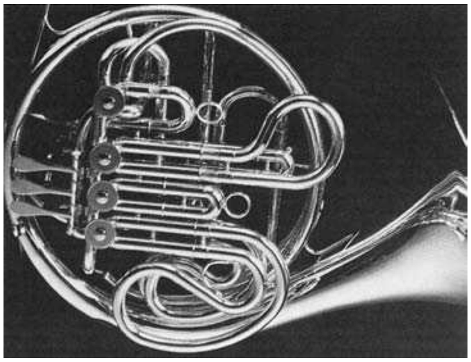


Fig. 7 French horn fabricated from copper alloys using complex bending and spinning operations

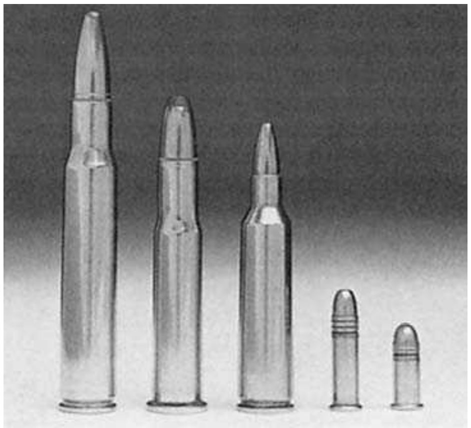


Fig. 8 Ammunition using a deep-drawn copper alloy cartridge case

Table 3 ASTM B 601 temper designations for precipitation-hardened copper alloys

Temper designation	Temper name or material condition
Solution-treated temper	
TB00	Solution heat treated
Solution-treated and cold-worked tempers	
TD00	TB00 cold worked to 1/8 hard
TD01	TB00 cold worked to 1/4 hard
TD02	TB00 cold worked to 1/2 hard
TD03	TB00 cold worked to 3/4 hard
TD04	TB00 cold worked to full hard
Precipitation-hardened temper	
TF00	TB00 and precipitation hardened
Cold-worked and precipitation-hardened tempers	
TH01	TD01 and precipitation hardened
TH02	TD02 and precipitation hardened
TH03	TD03 and precipitation hardened
TH04	TD04 and precipitation hardened
Precipitation-hardened and cold-worked tempers	
TL00	TF00 cold worked to 1/8 hard
TL01	TF00 cold worked to 1/4 hard
TL02	TF00 cold worked to 1/2 hard
TL04	TF00 cold worked to full hard
TL08	TF00 cold worked to spring
TL10	TF00 cold worked to extra spring
TR01	TL01 and stress relieved
TR02	TL02 and stress relieved
TR04	TL04 and stress relieved
Mill-hardened tempers	
TM00	AM
TM01	1/4 HM
TM02	1/2 HM
TM04	HM
TM06	XHM
TM08	XHMS

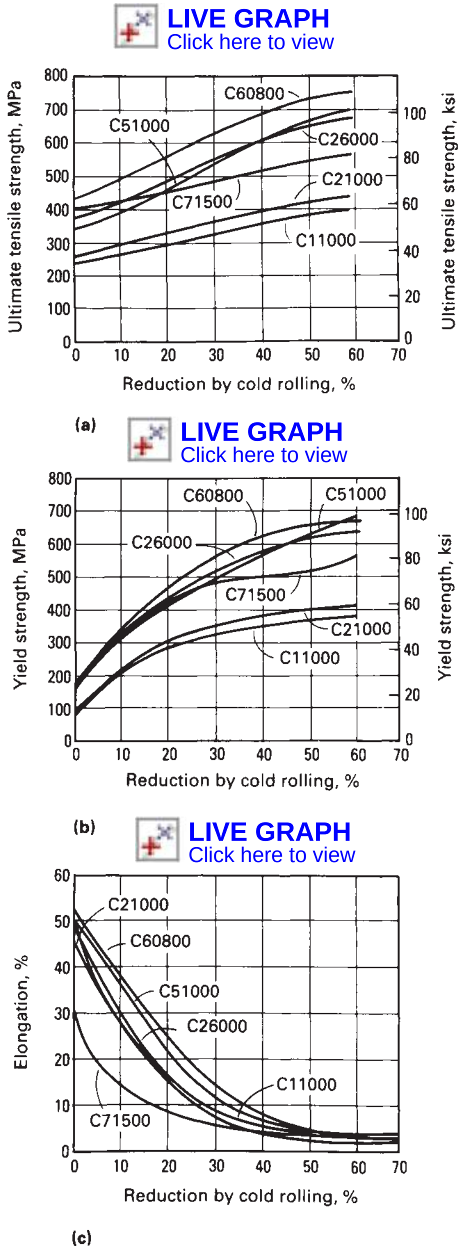


Fig. 9 Work-hardening behavior of copper and some solid-solution copper alloys. (a) Effect of cold work by rolling reduction on ultimate tensile strength. (b) Effect of cold work on yield strength. (c) Effect of cold work on elongation

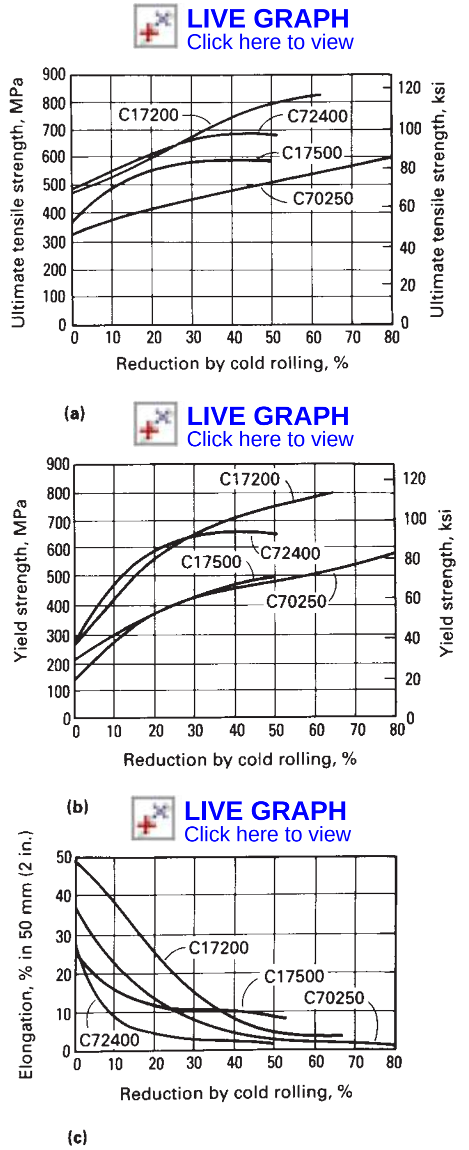


Fig. 10 Work-hardening behavior of four precipitation-hardening copper alloys in the solution-annealed condition. (a) Effect of cold work by rolling reduction on ultimate tensile strength. (b) Effect of cold work on yield strength. (c) Effect of cold work on elongation

Figure 11 shows the annealed ultimate tensile and yield strengths and response to cold rolling for American Iron and Steel Institute (AISI) type 304 stainless steel, 1045 steel, aluminum alloy 1100, copper alloy C11000, and some selected copper alloys. The high work-hardening rate and strength of the austenitic stainless steel are evident. The copper alloys range from above aluminum to above low-carbon steel in strength and work-hardening rate. A comparison of limiting draw ratio with the plastic-strain ratio *r* for ferrous and nonferrous alloys is shown in Fig. 12. Increasing values of *r* and LDR reflect increasing drawability (see the section "Drawing and Stretch Forming" in this article).

In general, copper alloys offer better strength/formability combinations than most other alloy systems. The choice of material system is usually based on economics, including material and other fabrication costs as well as properties.

Blanking and Piercing

Nature of the Operation. Blanking, piercing, and related cutting operations (trimming, notching, parting, and so on) are often used to provide parts that are subsequently formed to final shape by such operations as bending, drawing, coining, and spinning. Cutting operations are frequently conducted in the same press tooling used to form and shape the final part geometry. The principal objective of any cutting operation is to produce a workpiece that has the correct geometric shape, is free of distortion, and possesses sheared edges that are of sufficient quality to allow subsequent forming, finishing, and/or handling operations.

Materials Considerations. Copper and copper alloys can be readily blanked and pierced. The strip characteristics that directly affect the quality of the workpiece and/or final part produced by cutting operations are flatness, dimensional tolerances, (width, thickness, and so on), and shear-to-break ratio. The flatness and dimensional tolerances of copper alloy strip depend on the equipment and manufacturing expertise. The shear-to-break characteristics of strip depend on strip composition and temper.

Effects of Alloy Composition and Temper. The quality of blanked edges—shear-to-break, rollover, breakout angle, burr height, and so on—is determined by both die clearance and material characteristics. Burr-free and distortion-free parts can be cut from annealed copper alloy strip at die clearances to about 5% of strip thickness. Unalloyed coppers, such as C10100 and C10200, require smaller clearances (usually <5%) and less latitude in actual values to produce burr-free edges, even in rolled tempers. Copper alloys that contain second-phase particles (for example, C19400), that have high solute additions (such as C26000 or C51000), and/or that are cold rolled more than 50% generally exhibit high-quality of 3 to 12%. Low-lead additions to brass and other copper alloys will decrease burrs and the shear-to-break ratio in blanking operations, but at some cost to formability in almost all types of forming.

Table 4 Mechanical properties of precipitation-hardenable copper alloys in the annealed condition

UNS designation	0.2% offset yield strength		Tensile strength		Elongation, %
	MPa	ksi	MPa	ksi	
C17200	290	42	476	69	40
C17500	207	30	310	45	27
C70250	138	20	338	49	37
C72400	276	40	483	70	27

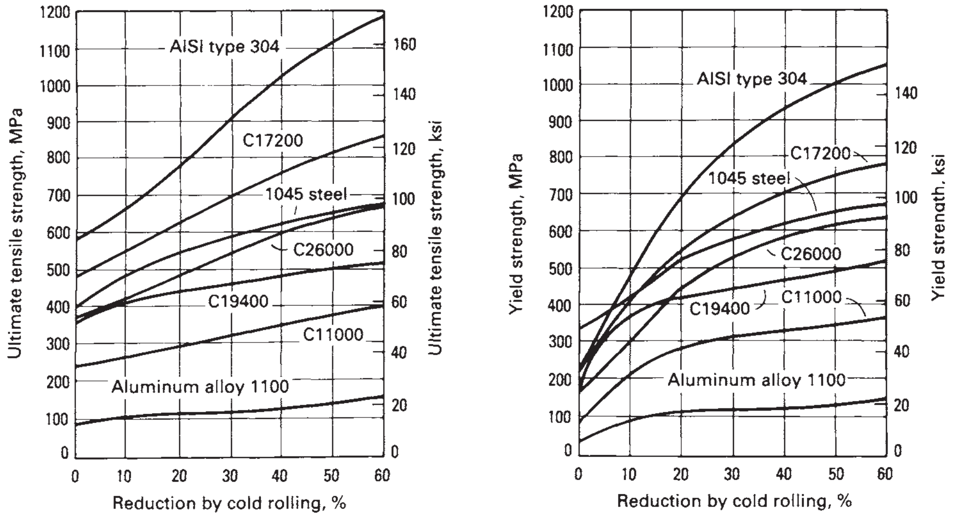
Bending

Nature of the Operation. Many connectors, terminals, and spring-like components are fabricated by simple bending operations. Bending is an operation in which a blanked coupon is wrapped, wiped, or formed over a die to specified radius and bend angle. Bend formability is usually expressed as minimum bend radius R in terms of strip thickness t (R/t). Minimum bend radius is defined as the smallest radius around which a specimen can be bend without cracks being observed on the outer fiber (tension) surface. Bend deformation is highly localized and is confined to the region of the workpiece in contact with the bending die. Workpiece thickness is not substantially reduced unless the bend radius is less than 1.0t or the part is coined during bending. More detailed information on bending ductility tests can be found in the article "Bend Testing" in *Mechanical Testing and Evaluation*, Volume 8 of *ASM Handbook*.

Table 5 Mechanical properties of mill-hardened copper alloys

UNS designation	Temper(a)	0.2% offset yield strength		Tensile strength		Elongation, %
		MPa	ksi	MPa	ksi	
C17410	TM04	655–862	95–125	758–896	110–130	4–15
C17500	HTR	758–965	110–140	827–1034	120–150	1–4
C70250	TM00	552 min	80 min	620 min	88 min	6 min
	TR04	690 min	100 min	731 min	106 min	2 min
C17200	TM02	690–862	100–125	827–931	120–135	12–18
	TM04	793–931	115–135	931–1034	135–150	9–15
C72400	TM02	690–827	100–120	876–1000	127–145	10–17
	TM04	827–965	120–140	938–1062	136–154	9–14

(a) See Table 3.



(a) LIVE GRAPH Click here to view

(b) LIVE GRAPH Click here to view

Fig. 11 Work-hardening behavior of copper alloys versus that of low-carbon steel, austenitic stainless steel, and aluminum. (a) Effect of cold work by rolling reduction on ultimate tensile strength. (b) Effect of cold work on yield strength

Materials Characteristics. Ductility is the principal materials factor that determines bend formability. The ductility factor of first order importance is the ability of a material to distribute strain in a highly localized region, that is, necking strain. The necking strain available depends on alloy composition and temper. As strength is increased by cold work, the ability of an alloy to distribute necking strain decreases. The extent to which bend formability is decreased with increasing strength is dependent on the alloy composition and the strengthening mechanism. Conventional tensile elongation cannot be used to predict bend formability because it does not adequately account for the contribution of necking strain. However, if the tensile specimen gage length were decreased to define an area of deformation equal to that deformed during bending, comparable ductility values would be obtained.

Effect of Alloy Composition, Temper, and Orientation. Bend data for a wide range of copper alloys are summarized in Table 6. Strength-to-bend formability characteristics are dependent on alloy composition, temper, and orientation. The principal strengthening mechanism is through solute additions to increase the work-hardening rate. For example, additions of 15 and 30% Zn to copper increase the tensile-strength-to-bend properties by 220 and 290 MPa (32 and 42 ksi), respectively, for 0.25 mm (0.010 in.) thick goodway bends at a bend radius of 0.4 mm ($\frac{1}{64}$ in.). Precipitation strengthening is also an important mechanism employed to improve the strength-to-bend performance of copper alloy strip, particularly if the part is bent in a softer temper and subsequently aged to a higher strength.

The practice of cold rolling to increase strip temper degrades bend formability. However, it is often used because most alloys still exhibit useful bend formability at modest cold-rolling reductions. Product applications that require both high strength and good bend performance are usually satisfied by selecting copper alloys that are precipitation and/or solute strengthened with additions that greatly increase the work-hardening rate and thus minimize cold-rolling requirements to achieve the desired strength.

Table 7 shows the relationship between temper and bend formability for precipitation-strengthened beryllium-copper alloys. As indicated by the data given in Table 7, formability is highest and most isotropic in the annealed (TB00) and $\frac{1}{4}$ hard (TD01) tempers. Slightly anisotropic but good formability is retained as cold work increases to the hard (TD04) temper;

these formability characteristics are also exhibited by the low-to-intermediate strength mill-hardened tempers (TM00 through TM04). Moderate-to-limited, more anisotropic formability is displayed by the high-strength mill-hardened tempers through TM08 and in mill-hardened C17410 TH04 strip.

Bend formability is typically dependent on bend direction with respect to strip-rolling direction (Fig. 13 and Table 6). All cold-rolled materials exhibit directionality. The extent of bend directionality varies from alloy to alloy, but always increases with increasing cold reduction. Bend directionality results from the development of strong textures during rolling. Copper alloys with low stacking fault energy, such as alloy C26000 (cartridge brass), develop strong {110} ⟨112⟩ textures during rolling and can exhibit bend directionality even at approximately 30% cold-rolling reduction. Dilute copper alloys and copper-nickel alloys do not develop well-defined rolling textures, and they show less bend directionality even at high (70%) cold-rolling reductions. In general, sharper bends can be made in the goodway than in the badway orientations for alloys that are cold rolled and/or solute strengthened. Bend anisotropy in precipitation-hardening systems is strongly process dependent.

Figure 14 shows the effects of bend directionality on part layout. This part includes both goodway and badway bends. If the part were fabricated from an alloy with strong bend directionality, for example, phosphor bronze (alloy C51000) in spring temper, the part layout would be restricted to avoid failure at badway bends. With alloys such as C68800 or C72500, which exhibit significantly less bend directionality, the part layout is not as restricted. It is not always possible to orient parts to minimize web scrap, regardless of the alloy selected, because tool design and part-handling and transfer costs may override the cost penalty of poor strip utilization.

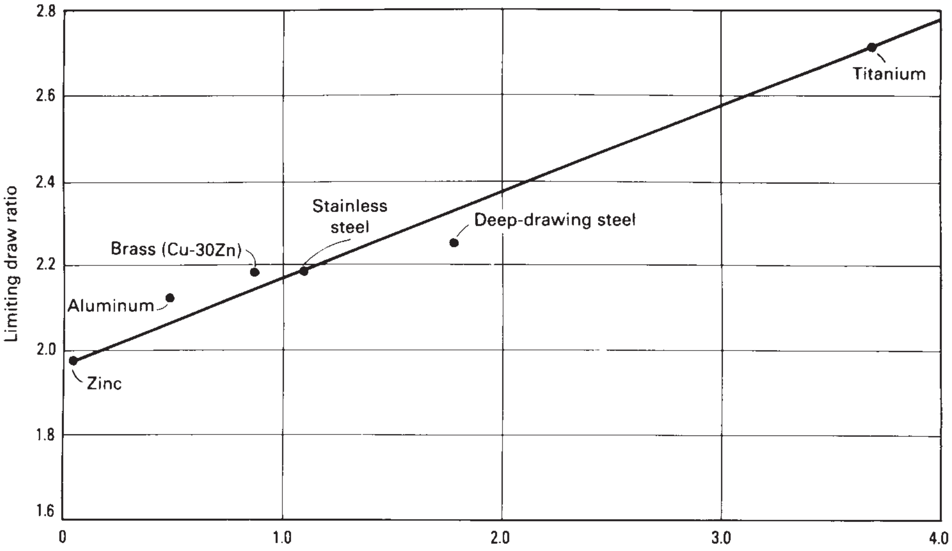


Fig. 12 Plastic-strain ratio *r* versus limiting draw ratio for different metals. Source: Ref 1

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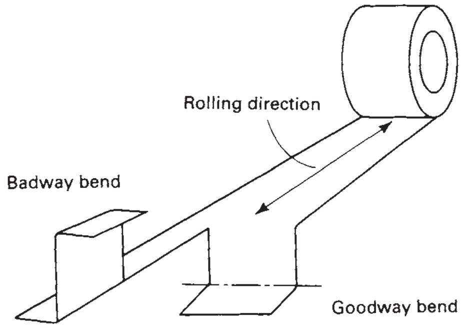

Fig. 13 Bend formability of copper alloys as a function of rolling direction. Bends with the axis transverse to the rolling direction are termed goodway bends; bends with the axis parallel to the rolling direction are badway bends. See also Table 6. Source: Ref 3

Table 6 Maximum strengths required to make the indicated bends in various copper alloys

	Maximum strength required to make bend of indicated radius, *r*, in material of indicated thickness, *t*, MPa (ksi)					
	Good-way bends			Bad-way bend		
UNS designation	0.25 mm (0.010 in.) *t* 0.4 mm (1/64 in.) *r*	0.50 mm (0.020 in.) *t* 0.8 mm (1/32 in.) *r*	0.76 mm (0.030 in.) *t* 1.2 mm (3/64 in.) *r*	0.25 mm (0.010 in.) *t* 0.4 mm (1/64 in.) *r*	0.50 mm (0.020 in.) *t* 0.8 mm (1/32 in.) *r*	0.76 mm (0.030 in.) *t* 1.2 mm (3/64 in.) *r*
C11000	372 (54)	352 (51)	352 (51)	365 (53)	331 (48)	345 (50)
C17200(a)	896 (130)	896 (130)	896 (130)	896 (130)	896 (130)	896 (130)
C17500(a)	…	…	724 (105)	…	…	724 (105)
C15100	428 (62)	400 (58)	400 (58)	407 (59)	400 (58)	400 (58)
C19400	538 (78)	510 (74)	496 (72)	517 (75)	496 (72)	490 (71)
C19500	614 (89)	572 (83)	572 (83)	592 (86)	572 (83)	558 (81)
C19700	538 (78)	510 (74)	496 (72)	517 (75)	496 (72)	490 (71)
C23000	593 (86)	593 (86)	593 (86)	572 (83)	552 (80)	538 (78)
C26000	662 (96)	662 (96)	662 (96)	627 (91)	524 (76)	524 (76)
C35300	641 (93)	572 (83)	572 (83)	496 (72)	483 (70)	469 (68)
C41100	517 (75)	496 (72)	496 (72)	468 (68)	448 (65)	434 (63)
C42500	621 (90)	621 (90)	621 (90)	552 (80)	475 (69)	462 (67)
C50500	490 (71)	469 (68)	469 (68)	490 (71)	468 (68)	469 (68)
C51000	710 (103)	662 (96)	648 (94)	621 (90)	572 (83)	538 (78)
C52100	765 (111)	745 (108)	731 (106)	614 (89)	558 (81)	552 (80)
C63800	827 (120)	807 (117)	793 (115)	724 (105)	696 (101)	696 (101)
C65400	745 (108)	731 (106	731 (106)	627 (91)	627 (91)	627 (91)
C66600	669 (97)	655 (95)	641 (93)	613 (89)	586 (85)	579 (84)
C68800	786 (114)	744 (108)	745 (108)	786 (114)	745 (108)	731 (106)
C70250(a)	690 (100)	655 (95)	…	552 (80)	517 (75)	…
C70600	524 (76)	496 (72)	496 (72)	489 (71)	483 (70)	483 (70)
C72400(a)	793 (115)	690 (100)	621 (90)	793 (115)	690 (100)	621 (90)
C72500	572 (83)	517 (75)	517 (75)	531 (77)	504 (73)	503 (73)
C73500	579 (84)	579 (84)	579 (84)	525 (76)	518 (75)	517 (75)
C74000	648 (94)	600 (87)	586 (85)	593 (86)	565 (82)	552 (80)
C75200	579 (84)	579 (84)	579 (84)	558 (81)	558 (81)	558 (81)
C77000	807 (117)	751 (109)	717 (104)	758 (110)	696 (101)	676 (98)

"Good-way" and "Bad-way" refer to the orientation of the bend with respect to the sheet or strip rolling direction (see Fig. 13). (a) Mill hardened to strength shown, then formed. Note: Tensile strengths of 965 and 1103 MPa (140 and 160 ksi) are available in 0.25 and 0.5 mm (0.010 and 0.020 in.) thicknesses with specially supplied mill tempers. Source: Ref 2

Special Considerations. The values listed in Tables 6 and 7 for the minimum bend radii of various alloys as a function of temper are approximate; actual results can deviate because of tool condition and shop practice. The bend performance required also depends on the part application. For example, "orange peel" (surface roughening) is unacceptable if the part is to be plated or subjected to other finishing operations and if appearance is important. Often, more than one alloy is available that will meet product requirements. In the absence of other limitations, bend formability may be the deciding factor in alloy selection.

The bend performance of copper alloy strip degrades as bend angle increases; that is, a 180° bend is more severe than a 90° bend angle. The effect of bend angle on bend formability is more severe as gage increases and/or bend radius decreases. Bend performance improves as the width-to-thickness ratio of the bend region is reduced to values of less than 8 to 1. Reducing the width-to-thickness ratio can enhance bend performance by as much as three times.

Drawing and Stretch-Forming

In drawing and stretch-forming, a suitably shaped blank of sheet metal is drawn or formed into a die cavity to produce a part. A clamping ring, draw beads, and/or other restraints are usually applied at the periphery of the blank to prevent wrinkling and/or tearing of the blank as it is drawn or formed into the die cavity. The complexity of the edge restraint required is usually directly proportional to the complexity of the final part.

A deep-drawn part is characterized by having a depth greater than the minimum part width. A deep-drawn part can be fabricated in a single drawing step or in multiple steps by redrawing preforms developed by deep-draw, shallow-draw, and/or stretch-forming methods. Ironing can be used during redrawing to control the wall thickness of the final part. Additional anneals may be required between redrawing steps.

A shallow-drawn part has a depth less than the minimum part width and is usually formed in one process step. It can be a final part or the preform for deep drawing.

A stretch-formed part is fabricated by pressing a punch into a blank that is fully or partially restrained at its periphery to develop positive biaxial strain on the part surface. A stretch-formed part can be a final part or the preform for drawing operations.

Materials Characteristics and Effects of Alloy Composition and Temper

Single-Step Drawing. Copper alloys that have high *r* values will provide the largest limiting draw ratio in a single deep-draw step. The *r* value is defined as the ratio of true width strain to true thickness strain in the region of uniform uniaxial elongation during a tensile test. It measures the resistance of material to thinning. The *r* value correlates with deep-drawing performance because it reflects the difference between the load-carrying capability of the cup sidewall and the compression load required to draw in the flange of the cup or blank during a deep-drawing operation.

The deepest single-step draws (highest LDR) can be made with alloy C52100, followed by the brasses (in order of decreasing zinc level) and by copper. The LDR of cartridge brass (alloy C26000) increases as its grain size increases.

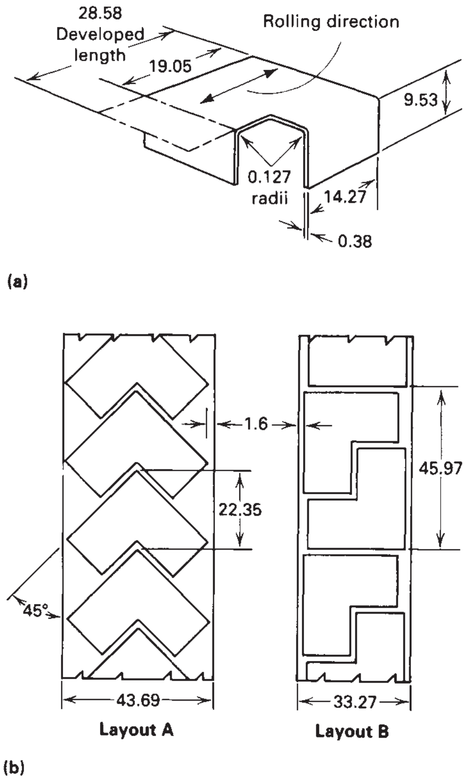

Fig. 14 Impact of bend anisotropy on part layout. (a) Hypothetical part, which has equal-radius bends at 90° orientations in the plane of the strip. Selection of the appropriate copper strip alloy for this application depends on the material strength and the bend properties in the relevant orientations. (b) Potential nesting of blanks for the part shown in (a). Layout A is required for directional alloys such as C51000 and results in 38% scrap; a nondirectional alloy such as C68800 would allow the more efficient layout B, with 23% scrap. Dimensions given in millimeters (1 in. = 25.4 mm). Source: Ref 3

Table 7 Relative formability of beryllium-copper strip

		Suitable alloy condition for specified formability rating and approximate formability ratio (*R*/*t*) for a 90° bend(a)								
		Alloy C17000			Alloy C17200			Alloys C17500 and C17510		
Formability rating	Specific formability	Alloy condition(b)	Transverse(c) (*R*/*t*) ratio	Longitudinal(d) (*R*/*t*) ratio	Alloy condition(b)	Transverse(c) (*R*/*t*) ratio	Longitudinal(d) (*R*/*t*) ratio	Alloy condition(b)	Transverse(c) (*R*/*t*) ratio	Longitudinal(d) (*R*/*t*) ratio
Excellent	Used for deep-drawn and severely cupped or formed parts	TB00	0.0	0.0	TB00	0.0	0.0	TB00	0.0	0.0
	As formable as the annealed (TB00) temper but easier to blank	TD01	0.0	0.0	TD01	0.0	0.0	…	…	…
					TM00(e)	0.0	0.0			
					TM02(e)	0.0	0.0			
Very good	Used for moderately drawn or cupped parts	TD02	1.0	0.5	TD02	1.0	0.5	TD04	0.6	0.5
		TM00	1.0	1.0	TM00	0.8	0.8	TF00	1.0	1.0
					TM01	1.0	1.0	HTC	1.0	1.0
					TM04(e)	1.0	1.0			
Good	Formable to a 90° bend around a radius <3 × stock thickness	TD04	2.9	1.0	TD04	2.9	1.0	TH04	2.0	2.0
		TM01	1.7	1.5	TM02	1.3	1.3			
		TM02	2.2	1.9	TM04	2.5	2.5			
					TM06(e)	2.0	2.5			
Moderate(f)	Suitable for light drawing; used for springs	…	…	…	TM05	3.2	2.8	HTR	3.5	2.8
					TM06	3.8	3.0			
					TM08(e)	3.0	3.5			
Limited	For essentially flat parts; forming requires very generous punch radii	TM04	5.1	3.8	TM08	6.0	4.1	…	…	…
		TM05	7.7	5.0						
		TM06	10.4	6.1						

(a) Formability ratios of punch radius (*R*) to stock thickness (*t*) are valid for strip up to 1.3 mm (0.050 in.) thick. Strip less than 0.25 mm (0.010 in.) thick will form somewhat better than shown. Values reflect the smallest punch radius that forms a strip sample into a 90° vee-shaped die without failure. (b) See Table 3 for descriptions of the alloy condition designations. (c) Transverse bend direction has a bend axis parallel to the rolling direction. (d) Longitudinal bend direction has a bend axis perpendicular to the rolling direction. (e) Special mill processing for high formability. (f) Moderately formable strip includes alloy C17410 in the TH04 condition with a longitudinal *R*/*t* ratio of 1.0 and a transverse *R*/*t* ratio of 6.0.

Multiple-Step Deep Drawing. The number of redrawing steps and the frequency of intermediate annealing treatments required depend on the initial preform geometry, the extent of ironing required, and the work-hardening rate of the particular alloy. Fewer redrawing steps are required if the preform geometry closely matches that of the final part. The trade-offs involved in selecting a fabrication procedure for the initial preform (for example, deep drawing, shallow drawing, or stretch forming) are complex.

In contrast to single-step deep drawing, in which alloys with high work-hardening rates give the highest LDR, copper alloys with lower work-hardening rates can be redrawn and ironed more times without intermediate annealing. The curves shown in Fig. 15 suggest that alloy C11000 (electrolytic tough-pitch, ETP, copper) will possess better redrawing and ironing characteristics and will require lower press forces than copper alloys with solute additions of zinc, tin, and/or silicon.

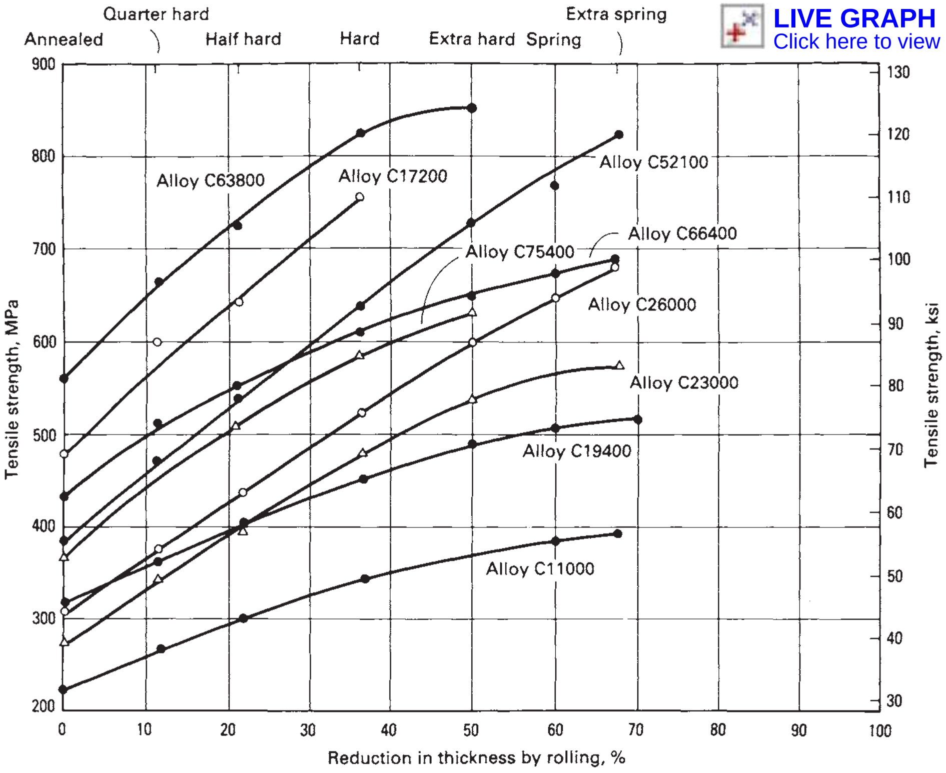

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Fig. 15 Redrawing characteristics of 1.0 mm (0.040 in.) thick sheets of several copper alloys. Curves of lower slope indicate a lower rate of work hardening and therefore a higher capacity for redrawing. Source: Ref 3

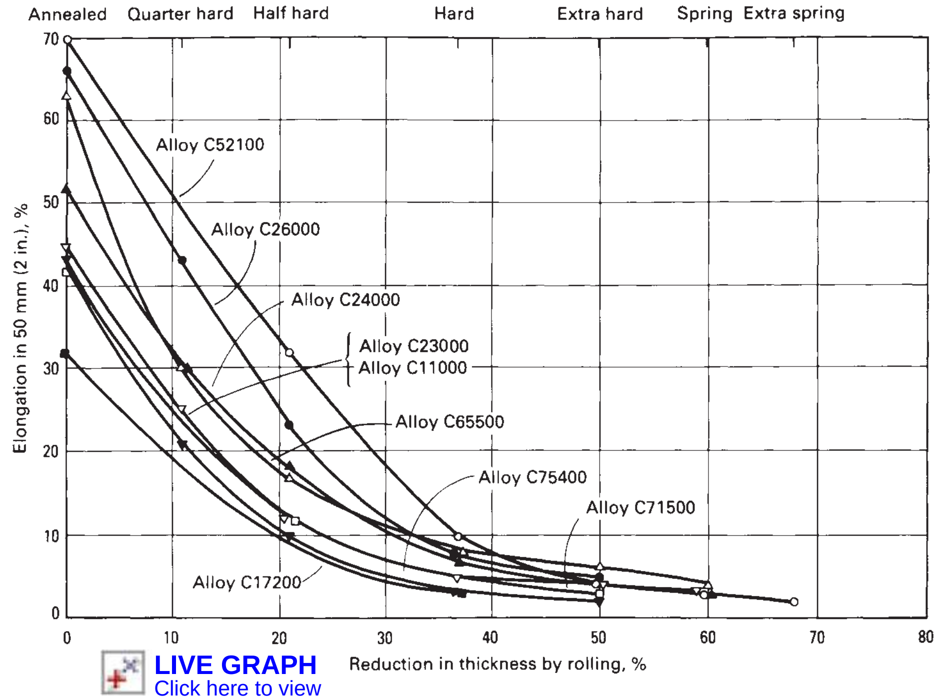

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Fig. 16 Stretch-forming characteristics of 1.0 mm (0.040 in.) thick copper alloys. Elongation values for a given percentage of cold reduction indicate the remaining capacity for stretch forming in a single operation. Source: Ref 3

In general, successively smaller reductions are selected at each redrawing step to ensure that the punch forces required to decrease the flange circumference do not exceed the load-carrying capability of the part sidewall. The magnitude of the incremental steps of redrawing is decreased if the part sidewall is to be ironed. Ironing increases the strength of the sidewall and flange proportionally to the distance from the cup bottom. In some applications, redrawing capacity can be improved by increasing the temper of the initial strip to enhance the load-carrying capability at the junction of the part sidewall and the cup bottom. The alternative is to use a stronger alloy.

Stretch Forming. The stretch formability of copper alloys correlates with the total elongation measured in a tension test. Annealed alloys that show high work-hardening rates offer the best stretch-forming characteristics. Improved combinations of strength and stretch formability are achieved by solute elements that greatly increase the work-hardening rate. Cold rolling to increase strip temper (strength) significantly reduces stretch formability.

The variation of tensile elongation with cold-rolling reduction for copper alloys is shown in Fig. 16. These data indicate that high-tin and high-zinc alloys offer the best combinations of strength and stretch formability.

Specific Characteristics of Copper Alloys. The higher-zinc brasses, such as alloy C24000 (low brass), alloy C26000 (cartridge brass), and alloy C26200 (high brass), have strengths comparable to those of low-carbon steels and high ductilities. They are outstanding materials for deep drawing and stretch forming.

Many other families of copper alloys also have good deep-drawing and stretch-forming properties. Phosphor bronze A (alloy C51000) has an excellent combination of high strength and high ductility and is used to form deep-drawn thin-wall shells that are then annealed and corrugated to produce bellows with high fatigue strength, corrosion resistance, and excellent flexibility.

The nickel silvers (copper-nickel-zinc) are white copper alloys that also have excellent deep-drawing characteristics similar to those of the high-zinc brasses. However, they have somewhat higher work-hardening rates and require more intermediate annealing for redrawing than cartridge brass. In the fully annealed condition, alloy C63800 (Cu-3Al-2Si-0.4Co) also exhibits good deep drawability (similar to that of the nickel silvers). Annealed high-zinc leaded brasses are suitable for shallow-drawn parts, such as garden-hose coupling nuts.

Copper-zinc-tin alloys such as C40500, C41100, C42200, and C42500 respond well to drawing and redrawing operations. With regard to deep-drawing properties, C40500 and C41100 are similar to the high-copper brasses, and C42200 and C42500 are similar to C24000.

Beryllium-coppers can be drawn in the solution-annealed temper and then age hardened. For example, annealed alloy C17200 has been deep drawn to 80% reduction before annealing. Parts drawn from beryllium-copper alloys can subsequently be heat treated to produce tensile strengths to 1275 to 1380 MPa (185 to 200 ksi).

There are many other special-purpose coppers and copper alloys. By examining their compositions and mechanical properties carefully and by comparing them with standard alloys, the user can estimate how they will respond in deep-drawing applications.

Grain Size Effects. For the coppers and single-phase alloys, grain size is the basic criterion by which deep drawability and stretch forming are measured. In general, for a given alloy and sheet thickness, ductility increases with grain size, and strength decreases. However, when grain size is so large that there are only a few grains through the thickness of the sheet or strip, both ductility and strength, as measured by tensile testing, decrease. Figure 17 illustrates how elongation changes with grain size for three different thicknesses of alloy C26000 (cartridge brass). General recommendations for the grain size of annealed strip for drawing and stretch-forming operations are provided in Table 8, along with the expected surface characteristics.

For optimal deep-drawing and stretch-forming properties, the grain size chosen should provide maximum elongation. With reference to Fig. 17, peak elongation for 0.15 mm (0.006 in.) thick strip occurs at an average grain size of 0.020 mm (0.008 in.). For 0.40 mm (0.0157 in.) thick brass, a range of 0.038 to 0.061 mm (0.0015 to 0.0024 in.) average grain size would provide maximum drawability. For 0.81 mm (0.032 in.) thick material, a range of 0.060 to 0.090 mm (0.0024 to 0.0035 in.) average grain size would give optimal performance.

The surface finish required on the final part is an important consideration when selecting the grain size to be used. When metal with a coarse grain size is drawn or stretch formed, the surface roughens and develops an appearance resembling orange peel. Such a surface is more difficult and costly to polish and buff. Therefore, when a part requiring a buffed surface is to be produced, much effort is expended in designing the tools and process to use brass with a fine grain size.

A classic example of this situation is the one-piece brass or bronze doorknob (Fig. 3a). Such useful and decorative articles are made by the millions, and these types of shapes are difficult to produce on draw presses. These parts are usually produced in transfer presses, and the process can include 15 to 20 operations with one intermediate anneal or partial anneal. The alloy C26000 or C22000 strip from which these parts are made is usually about 0.76 mm (0.030 in.) thick, and the grain size is usually 0.020 to 0.035 mm (0.008 to 0.0014 in.) or 0.015 to 0.030 mm (0.0006 to 0.0012 in.) to provide sufficient ductility for the part to be drawn without surface roughening.

Special Considerations (Ref 4). A common concern in all drawing operations is the formation of ears at the top of the cup sidewall (Fig. 18). Ears occur in preferred directions (usually 45 or 0 to 90°) relative to the strip-rolling direction. Earing reflects the crystallographic texture of the strip. In part manufacture, ears must be trimmed; therefore, nonearing grades of copper and copper alloy strip are preferred for drawn parts.

For copper alloys, the reduction in diameter in a single draw (cupping) usually ranges from 35 to 50%, with a 50% reduction corresponding to ideal conditions. Drawing procedures vary widely in commercial practice. Reductions for successive draws of the commonly formed brasses, under favorable operating conditions and without intermediate annealing, are usually 45% for cupping; 25% for the first redraw; and 20, 16, 13, and 10% for subsequent redraws. Greater reductions are usually obtained with blank thicknesses larger than about 1.62 mm (0.064 in.); for blank thicknesses less than about 0.38 mm (0.015 in.), reductions are usually about 80% of the percentages given previously. With an annealing operation before each redraw, a reduction of 35 to 45% in each successive redraw can be obtained under favorable operating conditions, assuming that the accompanying reduction in wall thickness is acceptable.

Die radius usually varies from about twenty times the metal thickness for material 0.127 mm (0.005 in.) thick to about five times the metal thickness for material 3.18 mm (0.125 in.) thick. Radii of this size prevent high stress concentrations at the die opening, which can lead to tearing in subsequent draws. Sharper radii are needed for flanged shells and for meeting special design requirements.

The punch radius, except for the final stages of drawing, is usually less than one-third of the punch diameter, or four to ten times the metal thickness. Clearance between punch and die is maintained at values that produce at least a slight amount of ironing of the sidewalls.

Coining

Nature of the Operation. Coining is a cold-forming process in which the work metal is compressed between two dies so as to fill the depression of both dies in relief or to reduce the strip thickness. The most familiar coining operation is the minting of coins. However, one of the most common uses of coining is in reducing

Table 8 Available grain size ranges and recommended applications

Average grain size		
mm	in.	Type of operation and surface characteristics
0.005–0.015	0.0002–0.0006	Shallow forming or stamping. Parts will have good strength and very smooth surface. Also used for very thin metal
0.010–0.025	0.0004–0.001	Stampings and shallow-drawn parts. Parts will have high strength and smooth surface. General use for metal thinner than 0.25 mm (0.010 in.)
0.015–0.030	0.0006–0.0012	Shallow-drawn parts, stampings, and deep-drawn parts that require buffable surfaces. General use for thicknesses under 0.3 mm (0.012 in.)
0.020-0.035	0.0008–0.0014	This grain size range includes the largest average grain that will produce parts essentially free of orange peel. Therefore, it is used for all types of drawn parts produced from brass up to 0.8 mm (0.032 in.) thick.
0.010–0.040	0.0004–0.0016	Begins to show some roughening of the surface when severely stretched. Good deep-drawing quality in 0.4–0.5 mm (0.015–0.020 in.) thickness range
0.030–0.050	0.0012–0.002	Drawn parts from 0.4–0.64 mm (0.015–0.025 in.) thick brass requiring relatively good surface, or stamped parts requiring no polishing or buffing
0.040–0.060	0.0016–0.0024	Commonly used for general applications for the deep and shallow drawing of parts from brass in 0.5–1.0 mm (0.020–0.040 in.) thicknesses. Moderate orange peel may develop on drawn surfaces.
0.050–0.119	0.002–0.0047	Large average grain sizes are used for the deep-drawing of difficult shapes or deep-drawing parts for gages 1.0 mm (0.040 in.) and thicker. Drawn parts will have rough surfaces with orange peel except where smoothed by ironing.

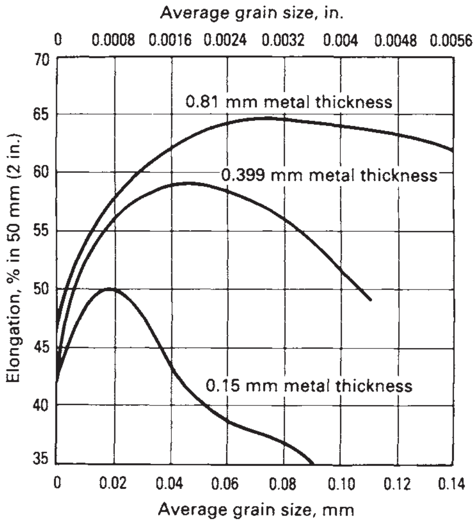

Fig. 17 Elongation versus grain size for alloy C26000 sheets of various thicknesses. Source: Ref 3

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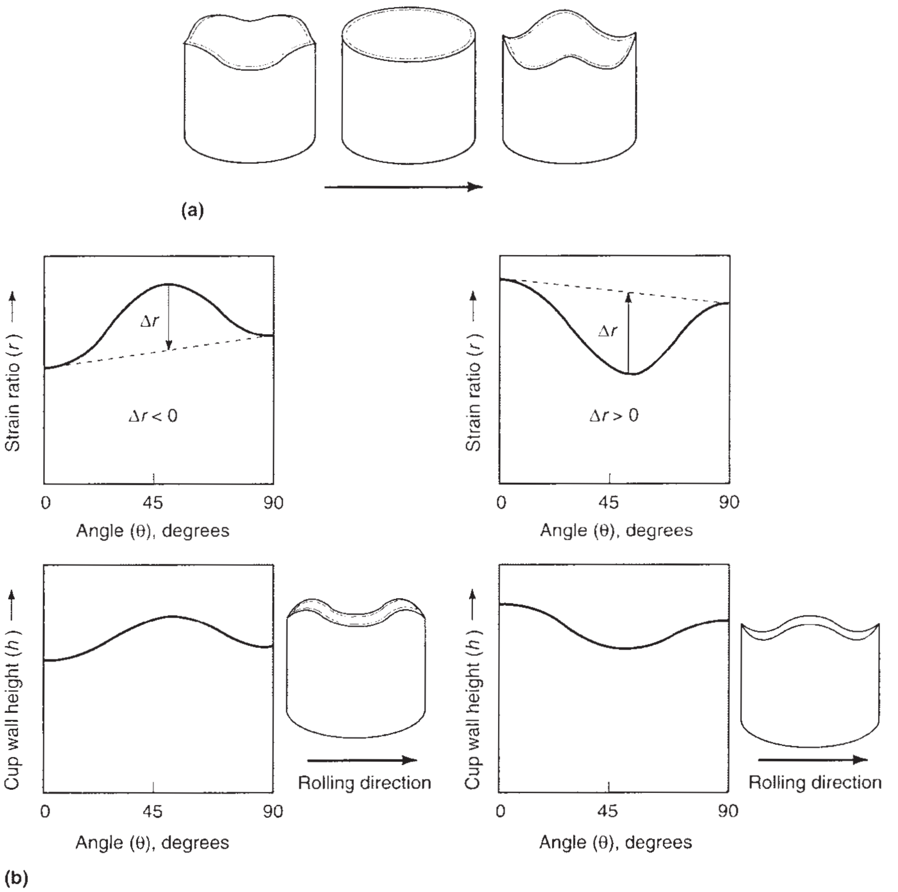

Fig. 18 Ear formation. (a) Drawn copper cups showing earing. The rolling direction is indicated by the arrow. Source: Ref 5. (b) The relation of ear formation to the direction of rolling. Source: Ref 6

the thickness or width of electrical and electronic connectors and leadframe leads.

Materials Characteristics. The ability of a material to be coined is determined by its strength and work-hardening rate. In general, copper, the lower-zinc brasses, the lower-alloy nickel silvers, and the copper nickels, which all exhibit low work-hardening rates, exhibit good coinability (Fig. 15).

Spinning

Nature of the Operation. Spinning is a method of forming sheet metal or tubing into seamless hollow cylinders, cones, hemispheres, or other circular shapes by a combination of rotation and force. Manual and power-automated equipment is used for spinning copper alloys.

Materials Characteristics. The principal materials factors that determine the spinnability of copper alloys are plastic-strain ratio *r*, total available elongation, and work-hardening rate. In general, alloys with high *r* values, high tensile elongation, and low work-hardening rates exhibit the highest spinnability.

Effects of Alloy Composition and Temper. Tough-pitch copper (alloy C11000) is the easiest copper material to spin and usually does not require intermediate annealing. Brasses, except for the multiphase alloy Muntz metal (C28000), are readily spun, although the higher-zinc brasses sometimes require intermediate annealing. Tin brasses containing at least 87% Cu require higher spinning pressure and more frequent annealing than brasses. Nickel silvers that contain at least 65% Cu, as well as the copper nickels, are also well suited for spinning. Phosphor bronzes, aluminum bronzes, and silicon bronzes are difficult to spin, but can be spun into shallow shapes under favorable conditions. Copper alloys that are difficult to spin include Muntz metal, nickel silvers containing 55% Cu or less, beryllium-coppers, alloys containing more than about 0.5% Pb, naval brass (C46400), and other multiphase alloys.

The single-phase high-strength copper alloys can be heated for spinning to reduce the force required to permit the spinning of thicker material or to permit more severe deformation, provided the increased cost for heating is justified. The forming characteristics of Muntz metal, extra-high-leaded brass, and naval brass are also improved at elevated temperature, but special precautions must be taken to avoid even the unintentional heating of the workpiece in spinning brasses that contain 0.5% Pb or more and more than 64% Cu.

Annealed tempers are almost always used in spinning copper alloys. Larger grain sizes (lower hardnesses) are easier to spin; finer grain sizes may be needed to meet surface finish requirements.

Although stock as thin as 0.1 mm (0.004 in.) can be manually spun under special conditions, manual spinning is usually restricted to thicknesses of 0.51 to 6.35 mm (0.020 to 0.250 in.). Powered equipment is used in the upper part of this range, and stock thicknesses in excess of 25.4 mm (1 in.) can be shaped by hot power spinning.

Applications. Typical products that are spun from copper alloys include bell-mouth shapes for musical instruments, lighting fixture components, vases, tumblers, decorative articles, pressure vessel parts, and other circular parts with bulged or recessed contours.

Contour Roll Forming

Nature of the Operation. Contour roll forming is an automated high-speed production process that is capable of producing tubular, box, angular, and folded parts of varied and complex shapes. Auxiliary operations such as notching, slotting, punching, and embossing can be combined with contour roll forming.

The materials characteristics that determine the roll-forming capability of copper alloy strip are the same as those that govern bend and stretch formability (see the sections "Bending" and "Drawing and Stretch Forming" in this article).

Alloy and Temper Effects. The bend properties given in Table 6 provide an indication of the relative suitability of copper alloys for contour roll forming. Annealed tempers are needed for complicated shapes and parts with extremely sharp bends or for severe stretch forming.

Applications. Contour roll forming is used less extensively with copper alloys than with steel and aluminum alloys because there are fewer copper alloy parts that are made in sufficient volume to be produced economically by this type of forming operation. Applications are primarily in the automotive and architectural industries.

Rubber-Pad Forming

Nature of the Operation. In this process, the rubber pad usually serves as the female die, in conjunction with an inexpensive male punch. The pad is practically incompressible, and it transmits pressure in all directions in the same manner as hydraulic fluid. Rubber-diaphragm forming uses hydraulic fluid behind the rubber pad. The most important reasons for using rubber-pad forming in preference to conventional press techniques or other production methods are improved formability, low tooling costs, and freedom from marking of workpiece surfaces. This is the most cost-effective method of fabricating one-piece doorknobs.

Deep drawing by rubber-diaphragm or Marforming techniques often permits a 65% reduction of diameter in a single draw, without producing wrinkles or surface defects that could require expensive finishing operations.

Materials Characteristics. The materials properties of greatest importance in rubber-pad

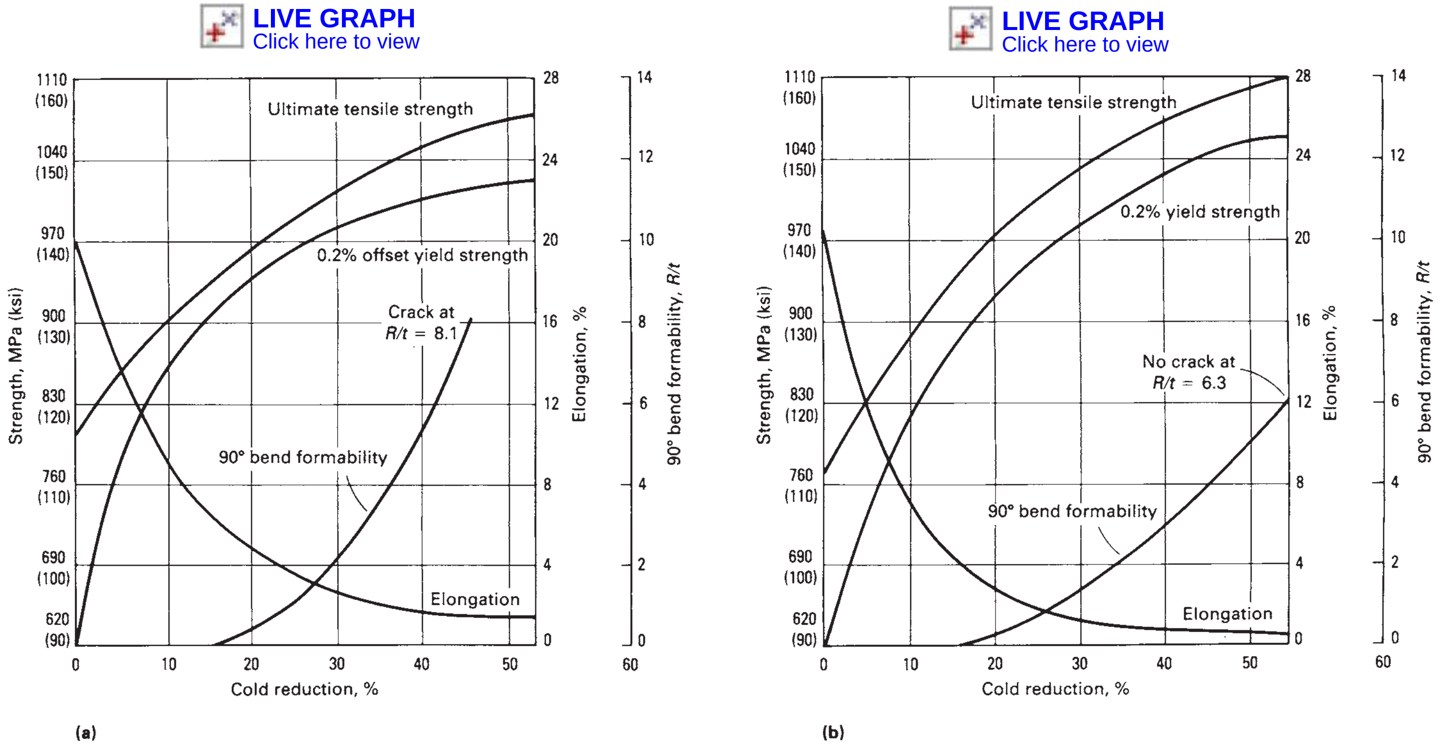

Fig. 19 Change in formability as a function of the coining of alloy C17200 in longitudinal (a) and transverse (b) directions. The effect of coining is simulated by cold reduction. Original strip thickness in both cases was 0.41 mm (0.016 in.). Bend formability is measured as the ratio of bend radius R to strip thickness t.

forming are the same as those that control strip performance in metal dies; that is, deep drawing is dependent on plastic-strain ratio r, stretch forming is dependent on tensile elongation, bending is determined by strip ductility, and so on.

Effects of Alloy Composition and Temper. The same principles can be used to select the appropriate alloy composition and temper for rubber-pad die forming that are used for parts formed with conventional metal dies.

Specialized Forming Operations

Hydraulic Forming. Copper alloys are sometimes formed by applying direct hydraulic pressure to the surface of the workpiece in order to shape the workpiece against a rigid die. This procedure can be used to form grooves on large, thin, flat sheets and to shape small parts to irregular contours. Tool cost is low, but the method is ordinarily applicable only to small-lot production because of comparatively low production rates.

Embossing and swaging, which are closely related to coining (being compressive or deformation operations), are also frequently used in the cold forming of copper alloys. The principles of alloy selection described for coining apply equally to embossing and swaging. However, embossing (impressing letters, numerals, or designs into a surface by displacing metal to either side) can be done on any copper alloy, with special attention to tooling and selection of temper on the less formable alloys. Swaging is often used for the production of complicated electrical contacts from copper or brass.

Electromagnetic forming, also known as magnetic pulse forming, is a process for forming metal by the direct application of an intense, transient magnetic field. The workpiece is formed without mechanical contact by the passage of a pulse of electric current through a forming coil.

Electromagnetic forming can be used on copper and some brasses because of their high electrical conductivity and excellent formability. Metals with a resistivity greater than about $16 \mu\Omega \cdot \mathrm{cm}$ are formed by the use of a copper or aluminum electromagnetic driver that is one to three times the thickness of the work metal. Thermally or electrically conductive joints and structural joints are produced in a single forming operation. Field shapers are frequently used to concentrate the forming force.

Electrical connections are made by electromagnetically swaging a copper band onto the end of stranded electrical conductor wire before insertion into a brass terminal. Optimal conductivity with 100% mechanical strength and long life under severe service conditions are obtained by using swaging forces great enough to compact the strands of the conductor so that a cross section of the joint appears to be essentially solid copper.

Special Forming Considerations for Conductive Spring Materials. Increasingly, contact designers are developing parts that rely on stepped or tapered beam thickness for optimal deflection or normal force characteristics. Some designs involve complex geometries requiring high formability in some regions (as for crimp connections) coupled with high strength in other regions (to resist permanent set in spring connections). Stepped or tapered contact beam thicknesses can be achieved by coining heavier-gage strip in progressive dies. This practice, however, rapidly work hardens copper alloys and reduces their formability. Die progressions that include the forming of contacts after a coining operation must incorporate more generous minimum bend radii than those suggested in the product literature of the supplier.

Figure 19 shows this change in formablility for a mill-hardened temper of alloy C17200 that was subjected to coining up to 50% reduction in area and simulated by cold rolling after mill hardening. To avoid this formability problem, strip can be purchased with variable gage across the slit width, which is produced by profile milling or skiving or by the longitudinal electron beam welding of dissimilar thicknesses of strip. The need for localized high formability can also be met by the longitudinal electron beam welding of dissimilar metals, combining, for example, ductile C19500 with high-strength mill-hardened C17200.

An emerging electron beam application is the localized thermal softening of mill-hardened copper alloy strip to provide increased formability with no sacrifice in strength in the remainder of a contact. Examples of these unique copper alloy strip forms are shown in Fig. 20.

Springback

Springback is the elastic recovery that occurs in a plastically deformed part when it is released from tooling. It causes the final part to have a geometry different from that of the press tooling. The springback that occurs in a bending operation is shown schematically in Fig. 21. Springback must be taken into account in design and materials selection.

Springback depends on alloy, temper, thickness, bend radius, and the angle of bend. For fixed tooling and press conditions, springback increases as the strength of the copper alloy strip increases. Therefore, springback is increased by cold rolling to increase strip temper and/or by alloy additions that increase strength. The springback behavior of three copper alloys (C21000, C26000, and C35300) is shown in Fig. 22. These data indicate that springback increases with increasing bend radius and decreasing strip gage. Springback values for tempers or bend radii not shown can be interpolated from Fig. 22. Some strip suppliers provide springback data upon request.

Three techniques are commonly used to compensate for springback: overbending, restriking, and the use of special dies. Overbending simply deforms the part to a larger bend angle so that it is at the desired value after springback. Restriking in original dies reduces springback in much the same manner as overbending, that is, by the introduction of additional plastic deformation. Special dies often use coining action at bend radii to deform the metal plastically in the bend area beyond the elastic limit. In other die modifications, the metal is pinched slightly at the bend region. When special dies are used, careful control must be exercised because excessive thinning can cause part failure during bending or can make the part susceptible to early failure in service.

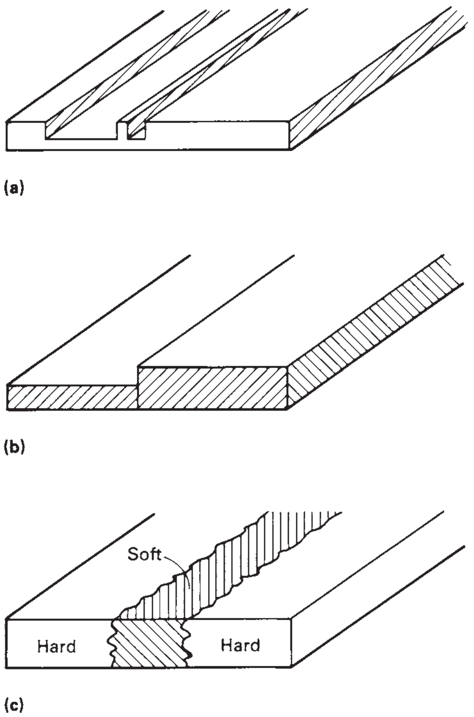

Fig. 20 Special treatment of copper alloy strip for optimized combinations of formability and spring characteristics. (a) Profile milled strip. (b) Dissimilar thicknesses longitudinally welded; this method can also be used to join dissimilar alloys. (c) Localized heat treatment (electron beam softening)

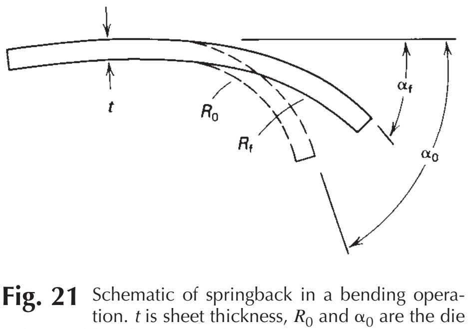

Fig. 21 Schematic of springback in a bending operation. t is sheet thickness, R_0 and α_0 are the die radius and bend angle, and R_f and α_f are the part radius and bend angle after springback.

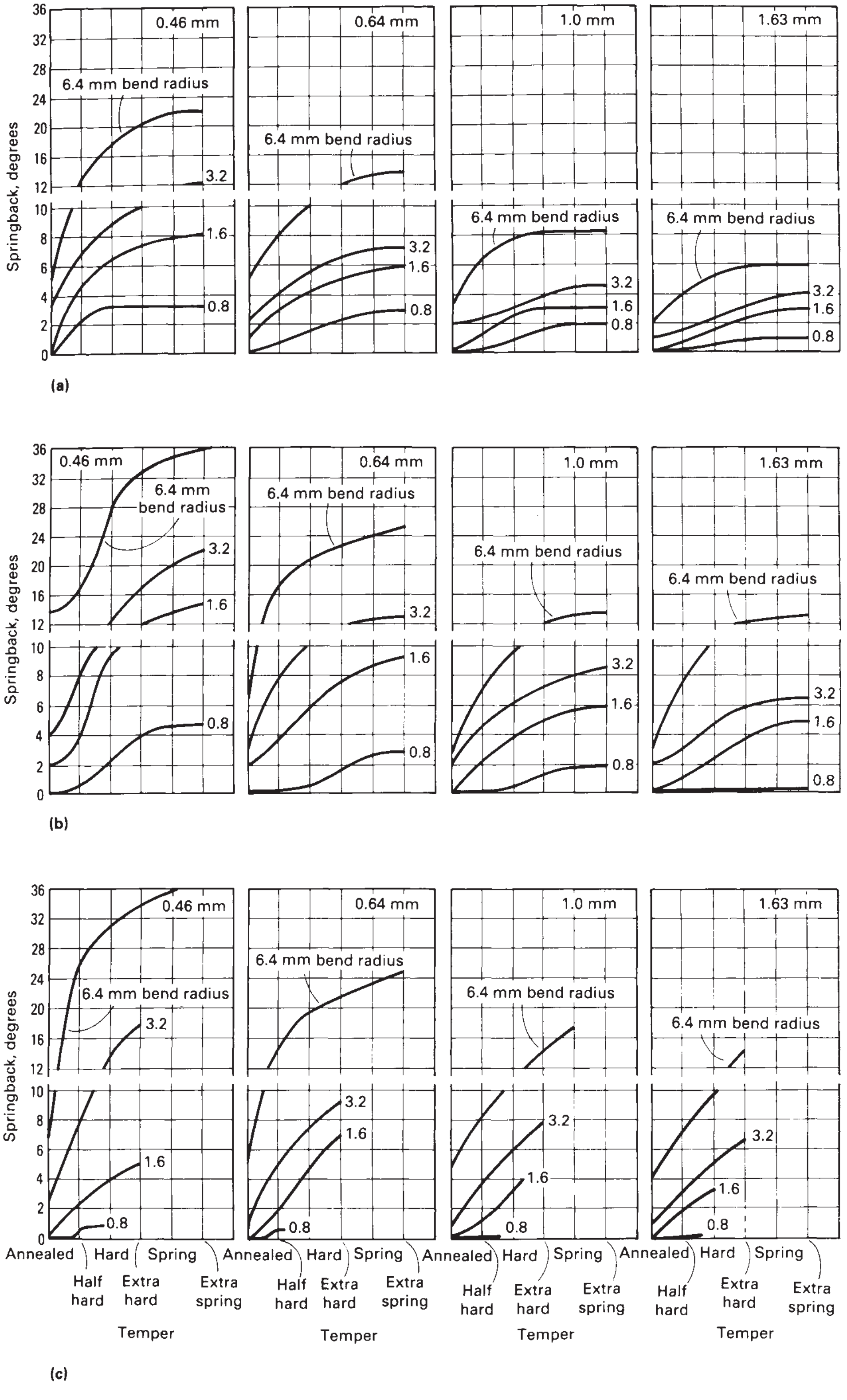

Fig. 22 Springback behavior of copper alloys as a function of temper, sheet thickness, and bend radius (90° bends). (a) Alloy C21000. (b) Alloy C26000. (c) Alloy C35300

Forming Limit Analysis

Forming limit analysis provides the means to assess sheet metal formability over a wide range of forming conditions, including drawing, bending, and stretching. The amount of deformation that occurs during sheet forming, that is, the strain state, is given in terms of, or related to, major and minor strains (e_1 and e_2, respectively) measured from fiducial markings printed or etched onto strip surfaces prior to fabrication. The analysis requires two curves:

- A forming limit curve (FLC), which indicates the ability of the material to distribute localized strain
- A limiting dome height (LDH) curve, which indicates the overall ductility for forming of the material

These empirically determined curves show the biaxial strain or deformation limits beyond which failure may occur in sheet metal forming.

Forming limit and limiting dome height curves for 13 copper alloys are shown in Fig. 23 and 24. Table 9 lists UNS designations, common names, alloy compositions, and tempers for the alloys tested. These data indicate that, in annealed tempers, high-copper and copper-zinc alloys exhibit the highest FLC values, followed closely by alloys C72500, C51000, and C74300; these materials in turn are slightly better than alloys C19400, C75200, and C70600. Increasing the temper by cold rolling decreases forming capability, as shown in Fig. 23. the LDH data essentially follow the trend shown in FLC behavior.

Solving Forming Problems. In addition to displaying the relative formability of one material versus that of another, forming limit and limiting dome height curves are valuable for identifying the cause of a sudden production problem that might arise from changes in tooling, lubrication, or material suppliers. This permits the forming process to be modified to maximize formability and productivity.

The most direct approach for determining if a sudden forming problem is materials related is to compare the LDH curve for the material with that of the control lot of known good material. If only one region of the part is subject to critical strains, it may be necessary only to test the blank width that will produce that critical value of minor strain. If the LDH curve of the new material is the same as that of the control lot, then tooling or lubrication are suspect. If the LDH curve of the new material is below that of the control lot, the material is the problem.

The best way to determine whether tooling or lubrication conditions have changed is to form a gridded sample under current tool conditions from a control lot held in inventory. Strain distribution and critical grid strains measured on this sample can be placed on the established forming limit curve and compared with those before the problem arose in order to establish their relationship to known, safe strain levels. If changes are detected, they can often be remedied by adjusting press conditions to change the magnitude of stretch or draw components.

This is illustrated in Fig. 25. Point A on this forming limit curve represents the strains in the critical region of a part when the part was being formed satisfactorily. Point B represents the critical strains when forming became a problem because the major and minor strains were too high. Draw bends, blank hold-down pressure, blank size, and/or lubrication can be modified to change the amount of major and

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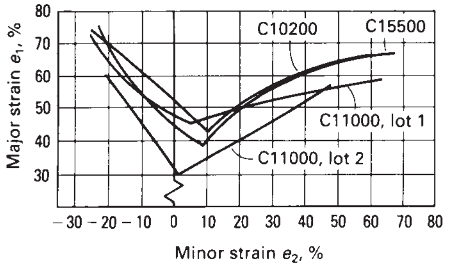

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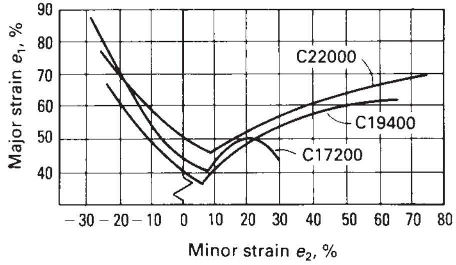

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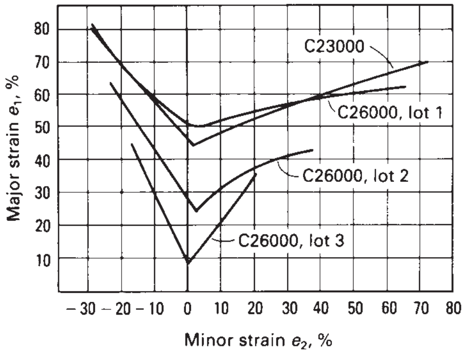

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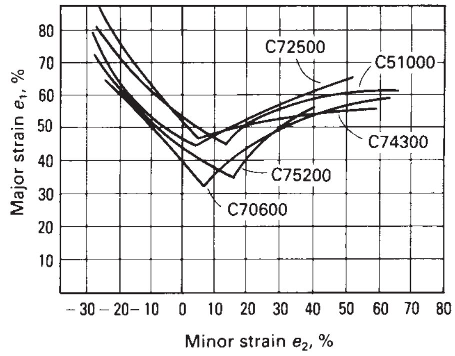

Fig. 23 Forming limit curves for selected copper alloys. FLCs reveal local ductility during forming. See Table 9 for material designations, thicknesses, and tempers. Source: Ref 7, 8

Table 9 Coppers and copper alloys evaluated using forming limit analysis

See Fig. 23 and 24 for results of analysis.

UNS designation	Common name	Material conditions applicable to FLCs and LDH curves
C10200	Oxygen-free copper	Annealed, 0.66 mm (0.026 in.) thick, 0.014 mm (0.0006 in.) grain, 234 MPa (34 ksi) UTS(a)
C11000, lot 1	ETP copper	Annealed, 0.74 mm (0.029 in.) thick, 0.016 mm (0.00063 in.) grain, 224 MPa (32.5 ksi) UTS(b)
C11000, lot 2	ETP copper	Half hard, 0.69 mm (0.027 in.) thick, 268 MPa (38.8 ksi) UTS, 20% tensile elongation(c)
C15500	Silver copper	Annealed, 0.71 mm (0.028 in.) thick, 0.009 mm (0.00035 in.) grain, 288 MPa (41.8 ksi) UTS
C17200	Beryllium-copper	Annealed, 0.25 mm (0.010 in.) thick, 0.019 mm (0.00075 in.) grain, 491 MPa (71.2 ksi) UTS
C19400	HSM copper	Annealed, 0.69 mm (0.027 in.) thick, 319 MPa (46.3 ksi) UTS, 29% tensile elongation(d)
C22000	Commercial bronze	Annealed, 0.69 mm (0.027 in.) thick, 0.017 mm (0.00067 in.) grain, 234 MPa (34 ksi) UTS(d)
C23000	Red brass	Annealed, 0.69 mm (0.027 in.) thick, 0.024 mm (0.00094 in.) grain, 293 MPa (42.5 ksi) UTS(e)
C26000, lot 1	Cartridge brass	Annealed, 0.64 mm (0.025 in.) thick, 0.025 mm (0.00098 in.) grain, 345 MPa (50 ksi) UTS(f)
C26000, lot 2	Cartridge brass	Half hard, 0.69 mm (0.027 in.) thick, 407 MPa (59 ksi) UTS, 28% tensile elongation(e)
C26000, lot 3	Cartridge brass	Full hard, 0.51 mm (0.020 in.) thick, 531 MPa (77 ksi) tensile strength
C51000	Phosphor bronze A	Annealed, 0.69 mm (0.027 in.) thick, 0.014 mm (0.0006 in.) grain, 374 MPa (54.3 ksi) UTS
C70600	Copper nickel, 10%	Annealed, 0.81 mm (0.032 in.) thick, 0.016 mm (0.00063 in.) grain, 361 MPa (52.4 ksi) UTS
C72500	Copper-nickel-tin alloy	Annealed, 0.69 mm (0.027 in.) thick, 0.023 mm (0.0009 in.) grain, 356 MPa (51.6 ksi) UTS
C74300	Nickel silver	Annealed, 0.69 mm (0.027 in.) thick, 0.035 mm (0.0014 in.) grain, 387 MPa (56.1 ksi) UTS
C75200	Nickel silver	Annealed, 0.69 mm (0.027 in.) thick, 0.020 mm (0.0008 in.) grain, 405 MPa (58.7 ksi) UTS

(a) UTS, ultimate tensile strength. (b) LDH curves are medians based on 0.69, 0.74, and 0.79 mm (0.027, 0.029, and 0.031 in.) thickness data. (c) LDH curves are medians based on 0.64, 0.69, and 0.79 mm (0.025, 0.027, and 0.031 in.) data. (d) LDH curves are medians based on 0.69 and 0.74 mm (0.027 and 0.029 in.) thickness data. (e) LDH curves are medians based on 0.69, 0.79, and 0.81 mm (0.027, 0.031, and 0.032 in.) data. (f) LDH curves are medians based on 0.66 and 0.69 mm (0.026 and 0.027 in.) data.

minor strains. The effects on critical strain can be compared on the forming limit curve to ensure that the adjustments will indeed enable the part to be formed.

A similar approach can be used to adjust the forming operation so that a less ductile material can be formed. Figure 26, for example, shows a forming limit curves for two materials (A and B) and the critical strain combination (point X) measured on a formed part. Material A forms successfully, but Material B fractures during forming, as indicated by the location of point X relative to the forming limit curve of each material.

Because of the shape of the forming limit curves, it is possible to maintain approximately the same e_1 value for point X but to fall in the safe region by changing e_2, as indicated by points X′ and X″. In this case, moving toward X′ requires that the draw component be increased during forming; moving toward X″ requires that the stretch component be increased. Either can be accomplished by altering lubrication, tooling, and/or blank hold-down pressure, thus enabling the part to be formed in Material B.

Bending of Rod, Bars, and Shapes

Among copper alloys, rod means round, hexagonal, or octagonal products supplied in

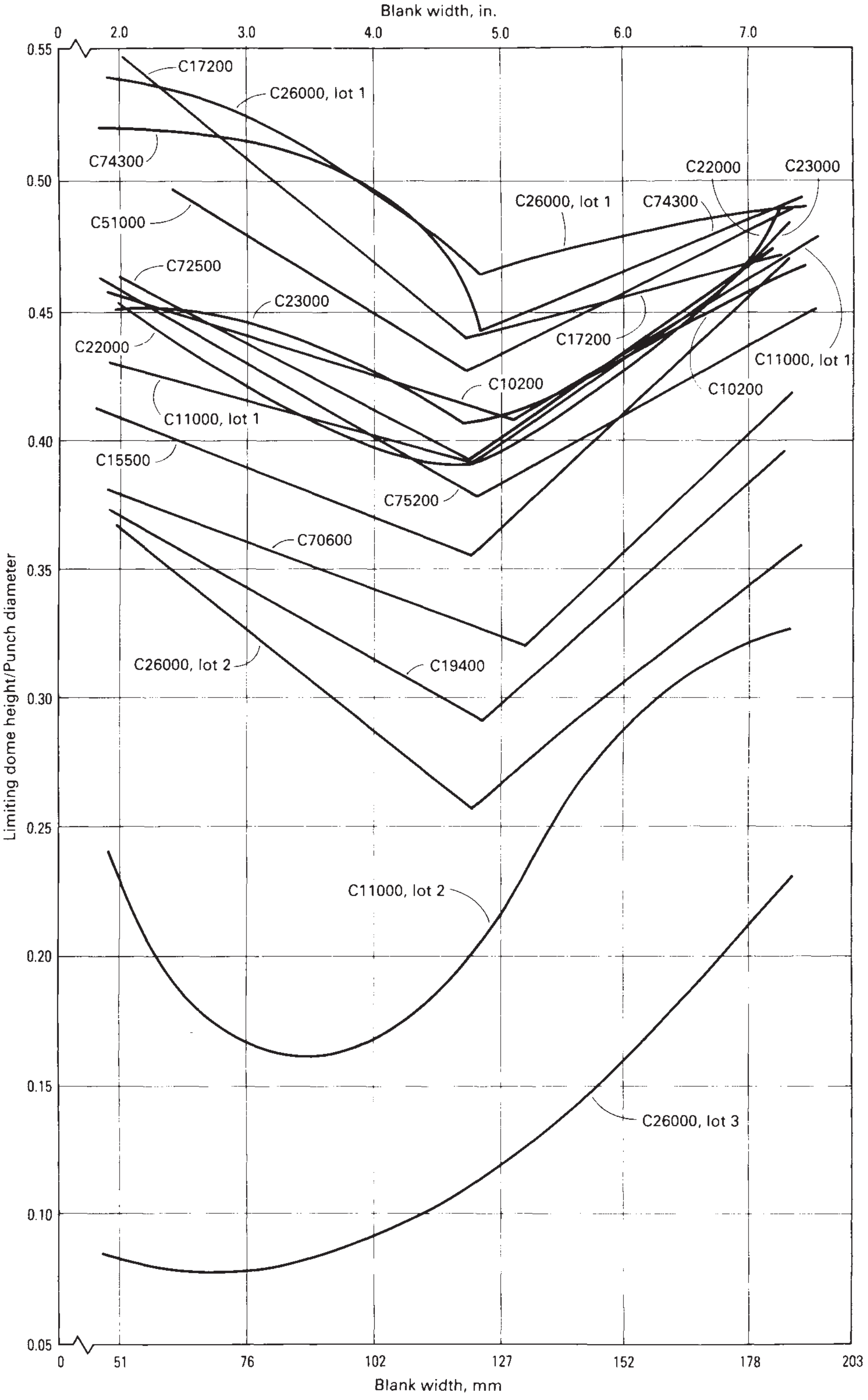

Fig. 24 Limiting dome height curves for copper and copper alloys. LDH curves illustrate the overall ductility of the coppers and copper alloys evaluated. See Table 9 for material designations, thicknesses, and tempers. Source: Ref 7, 8

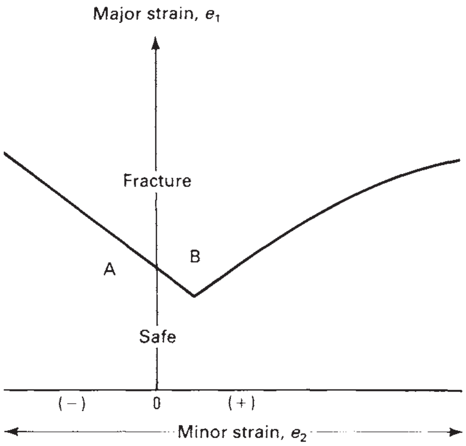

Fig. 25 Effect of tooling or lubrication on critical strain. Inadvertent changes in tooling or lubrication can shift strain from Point A to Point B, causing parts that previously were readily formed to fail during forming. Source: Ref 7, 8

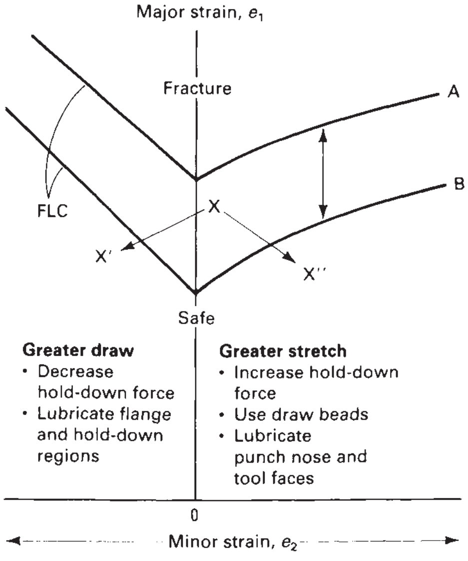

Fig. 26 Effect of changes in forming operation on critical strain. Shifting to strain from X to X′ by increasing draw or from X to X″ by increasing stretch permits Material B to be used in place of Material A despite its lower ductility. Source: Ref 7, 8

straight lengths, that is, not coiled (for steels, all such straight lengths would be called bars). Copper alloy bar products are square or rectangular cross sections when sold in straight lengths. Shapes are also supplied in straight lengths and can have oval, half-round, geometric, or custom ordered cross sections.

Bending Methods

Rod, bars, and shapes are bent by four basic methods: draw bending, compression bending, roll bending, and stretch bending.

In draw bending, the workpiece is clamped to a rotating form and drawn by the form against a pressure die (Fig. 27). The pressure die can be either fixed or movable along its longitudinal axis. A fixed pressure die must be able to withstand abrasion caused by the sliding of the work metal over its surface. A movable pressure die, because it moves forward with the workpiece as it is bent, is less subject to such abrasion. It provides better guidance and more uniform restraint of the work material. On power bending machines, draw bending is used more than any other bending method.

In compression bending, the workpiece is clamped to a fixed form, and a wiper shoe revolves around the form to bend the workpiece (Fig. 27). Compression bending is most useful in bending rolled and extruded shapes. A bend can be made close to another bend in the workpiece without the need for the compound dies required in draw bending. Although compression bending does not control the flow of metal as well as draw bending, it is widely used in bending presses and in rotary bending machines.

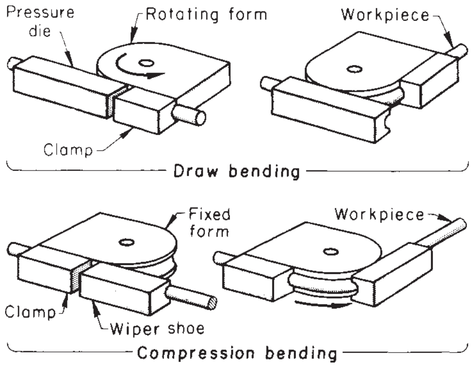

Fig. 27 Essential components and mechanics of draw bending and compression bending of bars and bar sections

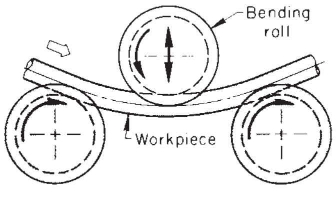

Fig. 28 Operating essentials in one method of three-roll bending

Roll bending uses three or more parallel rolls. In one arrangement using three rolls, the axes of the two bottom rolls are fixed in a horizontal plane. The top roll (bending roll) is lowered toward the plane of the bottom rolls to make the bend (Fig. 28). The three rolls are power driven; the top roll is moved up or down by a hydraulic cylinder.

A roll arrangement for four-roll bending is shown in Fig. 29. The workpiece enters between the two powered rolls on the left. The lower bending roll is then adjusted in two directions according to the thickness of the workpiece and the desired angle of bend.

Rings, arcs of any length, and helical coils are easily fabricated in a roll bender. The bend radius usually must be at least six times the bar diameter or the section thickness in the direction of the bend.

Roll bending is impractical for making more than one bend in a rod or bar. It is difficult to control springback in a roll bender, and it may take several passes through the rolls to make the needed bend. Therefore, this method of making bends is slower than other methods. Another disadvantage of roll binding is that a short section of each end of the workpiece is left straight. For three-roll bending, the ends can be preformed in a press before bending, or the straight parts can be trimmed off.

Stretch bending is used for bending large irregular curves. The workpiece is gripped at the end, stretched, and bent as it is stretched around a form. Usually, less springback occurs when the work is bent while it is stretched. The gripped ends are customarily trimmed off. This method can accomplish in one operation what would otherwise take several operations. The result is a possible savings in time and labor, even though stretch bending is a slow process. The tools, form blocks, or dies for stretch bending are simpler in design and less costly than conventional press tooling.

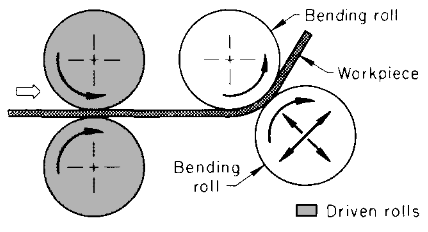

Fig. 29 Operating essentials in four-roll bending

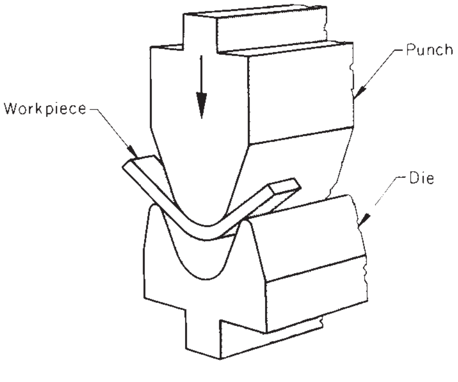

Fig. 30 Air bending of a bar in a press brake

Bending Machines

The machines used for the bending of rods, bars, and shapes include the following: devices and fixtures for manual bending, press brakes, conventional mechanical and hydraulic presses, horizontal bending machines, rotary benders, and bending presses.

Manual Bending. Hand-powered machines or fixtures are used in many shops for making bends that do not require much energy to form. This equipment is supplied with ratchets, levers, or gears to give the operator mechanical advantage. Different types of fixtures are used for manual draw bending, stretch bending, or compression bending. Roll bending is seldom done by hand. The tools used in manual bending are the same as those used on some power bending machines.

Press brakes are used for all types of bending, especially in small-lot production (25 to 500 pieces), when standard tooling or low-cost special tooling can be used. Often, the punch is not bottomed in the die; but the stroke is controlled, and the workpiece is bent "in air" (Fig. 30). With this technique, various bend angles can be made with the same die.

Mechanical presses are generally used only for mass production because only large production lots can justify the cost of tooling, which is more than that for most standard bending tools. Figure 31 shows a rod being bent into a U-bolt in a press. The rod is first cut to length and pointed at both ends (preliminary to a later threading operation). The rod is then loaded into the press and held in a grooved die that bends the rod into a U in one stroke. In the setup shown in Fig. 31, more than one workpiece can be bent at a time.

Hydraulic presses are often used to bend rod, bars, and shapes in much the same manner as mechanical presses. Although hydraulic presses

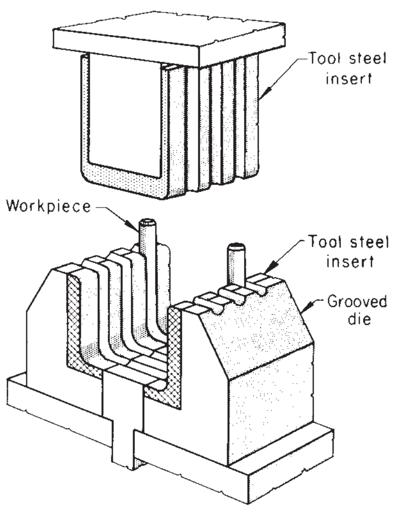

Fig. 31 Use of a grooved die in a mechanical press for bending a rod into a U-bolt in one stroke

are usually slower than mechanical presses, they have the advantage of exerting full force over a long stroke. Therefore, deep bends can often be made on a hydraulic press much smaller than the mechanical press that would be required.

Horizontal bending machines for bending rod, bars, and shapes consist of a horizontal bed with a powered crosshead that is driven along the bed through connecting rods, crankshaft, clutch, and gear train. Dies are mounted on the bed, and forward motion of the crosshead pushes the bar through the die. The long stroke and generous die space make this machine useful for a variety of cold- and hot-bending operations, although speeds are lower than those for mechanical presses of similar capacity.

Rotary benders, either vertical or horizontal, are used for the draw, compression, or stretch bending of rod, bars, and shapes. Such machines consist of a rotary table in either a horizontal or vertical position on which the form block or die is mounted (Fig. 27). Suitable hydraulic or mechanical clamping, tensioning, or compressing devices are provided to hold the workpiece while the die rotates to the required position, or while the workpiece is bent about the central forming die. Some machines can make bends by two, or all three, methods.

Bending presses are hydraulic machines that are made especially for bending rod, bars, and tubes, but most often for tubes. The ram of a bending press can be stopped at any point in the stroke. Wing dies and a cushioning device help to wrap the work around the ram die, as shown in Fig. 32. When the ram moves down, it causes the wing dies to pivot by a camming action and to wrap the workpiece around the ram die. The wing dies wipe the work to control the flow of metal; a compression bend is made on each side of the ram die, without wrinkles or distortion.

A bending press can usually make bends much faster than machines that are not made especially for bending. The open design of the press makes it possible the bending of complex shapes in one setup. Single bends can be made sequentially, or the press can make several bends simultaneously. Bends can be made to various angles and in various planes. The tube or rod/bar is usually passed through the press in one direction, and the press makes a sequence of bends automatically. The work is held against stops to locate each bend.

When several bends are made in one or more workpieces at each stroke of the press, all bends are in the same plane. Different angles and bend radii can also be made in the same workpiece, and the angles and spacing of bends can be adjusted. One disadvantage of the bending press is that it causes a slight reduction in the thickness of the workpiece at the bend.

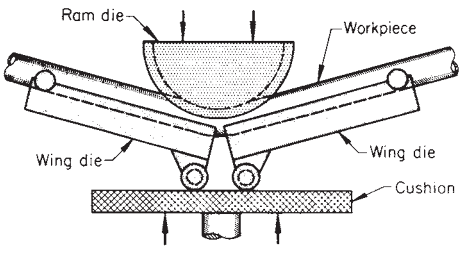

Fig. 32 Essential components and mechanics of a bending press

Bending and Forming of Tubing

Tube Bending

The principles for bending tubing are much the same as those for bending rod, bars, and shapes. Two important additional features in the bending of tubes are that internal support is often needed and that support is sometimes needed on the inner side of the tube bend.

The wall thickness of the tubing affects the distribution of tensile and compressive stresses in bending. A thick-wall tube will usually bend more readily to a small radius than a thin-wall tube. Table 10 lists the minimum practical inside radii for the cold draw bending of copper tubing, with and without various supports against flattening and wrinkling.

Selection of Bending Method. The four most common methods of bending tubing are basically the same as those used in the bending of rod, bars, and shapes: compression bending, stretch bending, draw bending, and roll bending. The method selected for a particular application depends on the equipment available, the number of parts required, the size and wall thickness of the tubing, the work metal, the bend radius, the number of bends in the workpiece, the accuracy required, and the amount of flattening that can be tolerated.

Bending Machines and Mandrels. Hand-powered machines used to bend copper tubes range up to 42 mm (1.65 in.) in capacity. They are small and light enough to be transported to the construction site. For larger diameters, ratchet action or geared machines should be used.

Copper tubes can usually be machine-bent without the need for internal support. Power benders equipped with mandrels support the sides of the tube to prevent it from distorting to an oval cross section. Light-gage tubes are easily bent, although some skills are needed. Hand bending of light-gage tubes is accomplished with the use of mandrels, usually in the form of flexible spiral springs.

Low-melting-point alloys can be used in place of bending mandrels. Tubes are simply warmed and filled with liquid metal, which is then allowed to freeze. After the tube is bent, the assembly is dipped into a tank of boiling water to remove the fusible alloy.

Metallurgical Considerations. Copper alloy tubing is usually extruded. It is easily bent in the annealed condition, and it has little springback. Copper and some brasses may not need to be annealed. Copper-nickel and beryllium-copper alloys, however, are more difficult to bend and have greater springback.

When copper alloys are annealed, as most of them are, oxides should be removed by pickling before the tube is bent to protect the tooling. Oxides increase friction and wear in bending.

Tube Forming

Tubular sections are converted into a variety of products. One or more forming processes can be used, including press forming, contour roll forming, tube spinning, electromagnetic forming, explosive forming, and electrohydraulic forming. Copper and copper alloy tubing can also be formed by bulk forming operations such as rotary swaging (see the section "Rotary Swaging of Rod, Bars, and Tubes" which immediately follows in this article).

Table 10 Minimum practical inside radii for the cold draw bending of annealed copper round tubing to 180°

Radii can be slightly less for a 90° bend, but must be slightly larger for 360°.

Tubing outside diameter		Minimum practical inside radius					
		Grooved bending tools				Cylindrical bending block without mandrel; ratio, <30(a) (poor conditions)	
		With mandrel; ratio, <15(a) (best conditions)		With mandrel or filler; ratio, <50(a) (normal conditions)			
mm	in.	mm	in.	mm	in.	mm	in.
3.2	1/8	1.6	1/16	6.4	1/4	13	1/2
6.4	1/4	3.2	1/8	7.9	5/16	25	1
9.5	3/8	4.8	3/16	9.5	3/8	50	2
12	1/2	6.4	1/4	11	7/16	75	3
16	5/8	7.9	5/16	14	9/16	102	4
19	3/4	11	7/16	17	11/16	152	6
22	7/8	13	1/2	19	3/4	203	8
25	1	14	9/16	22	7/8	254	10
32	1 1/4	17	11/16	25	1	381	15
38	1 1/2	21	13/16	29	1 1/8	508	20
44	1 3/4	24	15/16	32	1 1/4	686	27
50	2	27	1 1/16	35	1 3/8	889	35
64	2 1/2	35	1 3/8	41	1 5/8	…	…
75	3	41	1 5/8	48	1 7/8	…	…
89	3 1/2	48	1 7/8	54	2 1/8	…	…
102	4	54	2 1/8	60	2 3/8	…	…

(a) Ratio of outside diameter to wall thickness of tubing

Rotary Swaging of Rod, Bars, and Tubes

Rotary swaging is a process for reducing the cross-sectional area or otherwise changing the shape of copper and copper alloy rods, bars, tubes, or wires by repeated radial blows with two or more dies. The work is elongated as the cross-sectional area is reduced. The workpiece (starting blank) is usually round, square, or otherwise symmetrical in cross section, although other forms, such as rectangles, can be swaged.

Most swaged workpieces are round, the simplest being formed by reduction in diameter. However, swaging can also produce straight and compound tapers, can produce contours on the inside diameter of tubing, and can change round to square or other shapes.

Swaging Versus Alternative Processes

There are numerous applications for which swaging is the best method of producing a given shape and is therefore selected regardless of the quantity to be produced. Conversely, there are many workpiece shapes that can be successfully produced by swaging, but can be produced equally well by other processes, such as press forming, spinning, and machining. Applications comparing swaging with alternative processes are described in the following examples.

Example 1: Swaging Versus Press Forming. The ferrule illustrated in Fig. 33 was originally produced in a press by drawing disks into cups, redrawing to form the taper, and trimming the ends. With this procedure, 500 ferrules per hour were produced.

The improved method consisted of cutting the blanks from tubing, then swaging them in a 5 hp two-die rotary machine. Dies with an included taper angle of 9° 56' and 0.13 mm (0.005 in.) ovality were used. The production rate was increased to 750 pieces per hour.

Example 2: Swaging Versus Spinning. Blades for high-voltage switches were swaged from annealed copper tubes (Fig. 34) in three operations using a two-die rotary machine. Each die was 197 mm ($7\frac{3}{4}$ in.) long, 180 mm ($7\frac{1}{8}$ in.) wide, and 127 mm (5 in.) high. The tapered section in each die had a 15° included angle, and side clearance was used instead of ovality. Tubes were fed into the swager by a hydraulically actuated carriage on a long track. An intermediate steady rest moved along the track to help maintain tube alignment.

In the first operation, the tube was swaged through a 124.5 mm (4.900 in.) die up to the first step. In the second operation, a tube length of 1140 mm (45 in.) was swaged to a 99 mm (3.900 in.) outside diameter, and in the third operation, the end portion was swaged to a 73 mm (2.875 in.) outside diameter. In a final operation, the large end was trimmed to obtain an overall workpiece length of 4.2 m (167 in.).

Formerly, these blades had been produced by spinning 4.27 m (168 in.) lengths of annealed copper tubing 73.025 mm (2.875 in.) in outside diameter by 63.5 mm (2.5 in.) in inside diameter. By changing to swaging, production cost was reduced 10%. Swaging provided two additional benefits. First, the center of rotation was shifted toward the large diameter of the workpiece, thus reducing the number of counterweights required to balance the switch blade when operation, and second, the small end received the most cold work, thus strengthening this portion to the desired condition.

Example 3: Combining Drilling and Mandrel Swaging to Produce 0.9 mm (0.036 in.) Diameter Holes. The copper blank shown in Fig. 35 was produced by drilling six 3.2 mm (0.125 in.) diameter holes in bar sections 17.5 mm ($\frac{11}{16}$ in.) in outside diameter by 89 mm ($3\frac{1}{2}$ in.) long. After drilling six 0.9 mm (0.036 in.) diameter mandrels were inserted into the holes, and the blank was swaged to increase its length 102 mm (4 in.) to reduce its outside diameter to 15.8 mm ($\frac{5}{8}$ in.) and to reduce the holes to 0.09 mm (0.036 in.) in diameter. The mandrels were withdrawn after swaging.

The blank was drilled in a specially built horizontal machine and was swaged in a rotary swager using manual feed. The dies had 0.25 mm (0.010 in.) ovality and an included entrance angle of 8°. Overall length of the die was 75 mm (3 in.); blade length was 32 mm ($1\frac{1}{4}$ in.).

Forming of Wire

In the copper industry, wire can have any cross section; the term simply means that the product is sold in coils or on spools.

Bending. When production quantities are small or the size of the finished article is large, the wire may be straightened and cut to length as a preliminary operation before the individual pieces are fed into hand benders, kick presses, power presses equipped with appropriate dies, or coiling devices. For large quantities, the wire is straightened as it comes from the coil and is fed directly and continuously into power presses, automatic forming or spring-coiling machines, multiple-slide machines, or special machines actuated by cams, air, or hydraulic cylinders.

Other Fabrication Methods. Operations other than bending that are performed on copper wire include:

- *Threading* with single-head or multiple-head chasers, or with flat-die or rotary-die roll threaders. Roll dies can also be used for knurling, pointing, and chamfering
- *Heading* in open-die rod headers, to make a variety of heads such as flat, round, slotted, indented hexagon, tee, and ball
- *Swaging or extruding* of long points or reduced-diameter sections on rotary-die swagers or long-stroke headers
- *Welding* with resistance, arc, or gas

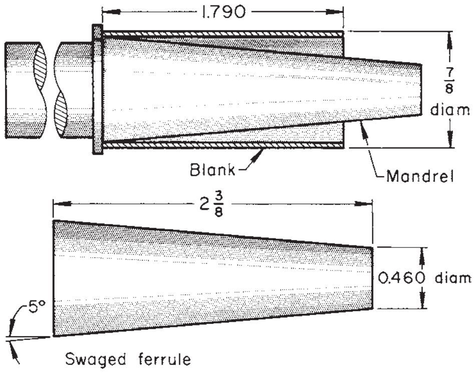

Fig. 33 Swaging a ferrule from tube stock (alloy C26000, cartridge brass, quarter hard, 0.032 in.) in preference to press forming. The change from press forming to swaging lowered tooling costs and resulted in a 50% increase in production. Dimensions given in inches

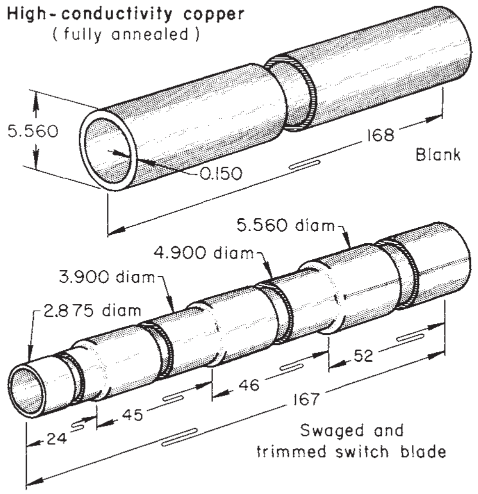

Fig. 34 High-voltage switch blade (bottom) that was swaged from tube stock (top) in three operations. Previously, the part was produced by spinning. Dimensions given in inches

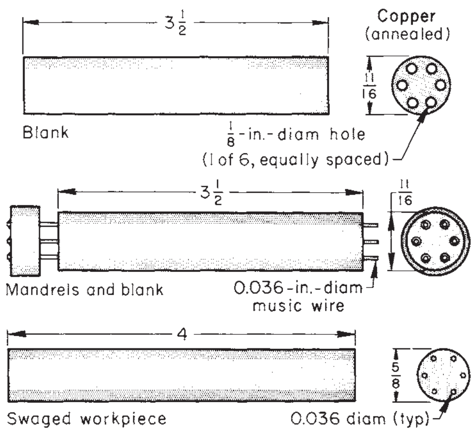

Fig. 35 Blank with drilled holes (top) that was swaged over music wire mandrels (center) to increase length and to reduce outside diameter and hole diameter (bottom). Dimensions given in inches

ACKNOWLEDGMENTS

The primary source for this article was:

- F. Mandigo and J. Crane, Forming of Copper and Copper Alloys, *Forming and Forging*, Vol 14, *ASM Handbook*, ASM International, 1988, p 809–824

Supplemental information originated from:

- Bending of Bars and Bar Sections, *Forming and Forging*, Vol 14, *ASM Handbook*, ASM International, 1988, p 661–664
- Bending and Forming of Tubing, *Forming and Forging*, Vol 14, *ASM Handbook*, ASM International, 1988, p 665–674
- Rotary Swaging of Bars and Tubes, *Forming and Forging*, Vol 14, *ASM Handbook*, ASM International, 1988, p 128–144
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Forging and Extrusion

COPPER AND COPPER ALLOYS undergo hot forging, cold forging, and hot extrusion operations. In hot forging, both the billet (workpiece) and forging dies are heated prior to deformation. In cold forging processes, which include cold extrusion, cold heading, and coining, deformation of the workpiece is carried out at room temperature. Hot extrusion involves pushing a heated billet of metal through a die. The extruded product may be hollow or solid, and the cross section may vary from a simple round to a complicated shape. All of the deformation processes listed previously are considered bulk, or massive, forming processes. In bulk forming, the input material is in billet, rod, or slab form, and the surface-to-volume ratio in the formed part increases considerably under the action of largely compressive loading. Bulk forming operations differ from sheet forming, in which a piece of sheet metal is plastically deformed by tensile loads into a three-dimensional shape, often without significant changes in sheet thickness or surface characteristics. Sheet forming operations are described in the article “Forming” in this Handbook.

Hot Forging

Copper and copper alloy forgings offer a number of advantages over parts produced by other processes, including high strength as a result of working, closer tolerances than competing processes such as sand casting, and modest overall cost. The most forgeable copper alloy, forging brass (alloy C37700), can be forged into a given shape with substantially less force than that required to forge the same shape from low-carbon steel. A less forgeable copper alloy, such as aluminum bronze, can be forged with approximately the same force as that required for low-carbon steel.

Copper and copper alloy forgings, particularly brass forgings, are used in valves, fittings, refrigeration components, and other high-pressure liquid and gas handling applications. High-strength bronze forgings find application as mechanical parts such as gears, bearings, and hydraulic pumps.

Selecting the Forging Process

The four most common types of hot forging processes for producing copper and copper alloy forged parts are open-die forging (also referred to as upset forging), closed-die forging, multistroke forging (also referred to as sub-press forging), and ring rolling (also referred to as ring forging). The process chosen is determined by the size, shape, and complexity of the product and by number of forgings produced. It should be noted that the metal flow that accompanies the forging process orients the grain structure of the metal. It is often possible to utilize this oriented structure to take maximum advantage of the mechanical properties of the metal in directions that match stresses the forging may be subjected to in service. More detailed information on forging processes can be found in *Forming and Forging*, Volume 14 of *ASM Handbook*.

Open-die forging is the simplest forging method. It involves compressing forging stock (called blanks or “slugs”) between die halves that are flat or have simple contours (Fig. 1). The process is primarily used for simple shapes and/or large forgings such as shafts, where the principal object is to impart deformation in order to improve mechanical properties. Open-die forging is also used as a means to upset or otherwise preform blanks into shapes suitable for subsequent closed-die forging operations.

Die costs are quite low and are often inconsequential. The open-die process can therefore be applied to single parts and small production quantities. The open-die process can, for example, be used to produce rough shapes from which prototypes can later be machined. This can provide an indication of the mechanical behavior of the forged product without incurring the expense of complex dies.

Closed-die forging, which is the most commonly used hot forging process, makes use of precisely machined dies that, when squeezed together, form a cavity in the shape of the finished forging (Fig. 2). Metal is supplied in the form of a billet sheared or sawed from rod or bar stock. The size and shape of the billet is carefully calculated to provide slightly more metal than is required to fill the die cavity. The extra metal appears as *flash* at the plane where the die halves meet. Forging frequently takes place in several stages: an initial *blocking* operation deforms the billet to the rough general shape of the product, after which the blocked billet is compressed between finishing dies to complete the forming process. The flash, which is trimmed by separate dies, is recycled to make new alloys or sold as scrap.

Die costs for closed-die forging are relatively high, and these costs must be amortized over large production quantities. Die-life depends on the alloy and the severity of the forging operation. With readily forged alloys such as C37700, forging dies can produce as many as 50,000 parts. Figure 3 illustrates copper alloy closed-die forgings in a variety of configurations.

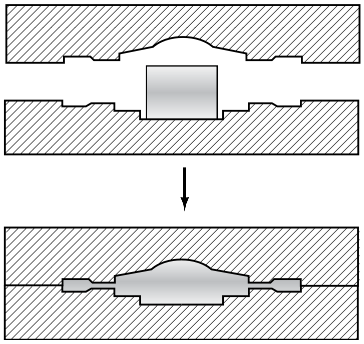


Fig. 1 Schematic of the open-die forging process, which involves compressing a billet between die halves that are flat or have simple contours. The process is primarily used for preforming a billet to achieve optimal metal distribution in a final forging operation.

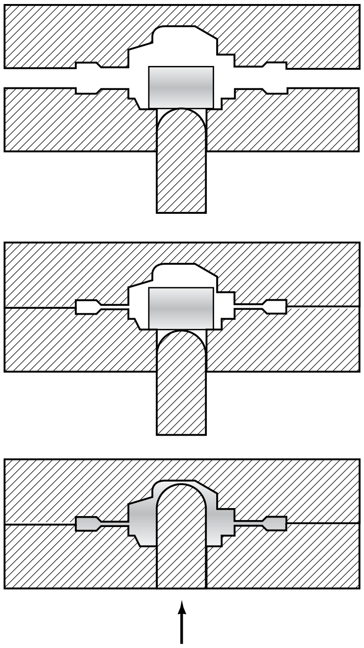


Fig. 2 Schematic of the closed-die forging process, which may be described as shaping of metal completely within the cavities of the dies that enclose the metal when they are brought together. The impression can be produced entirely in either the bottom die or upper die, or may be divided between the two dies.

Multistroke and Cored Forgings. Products with complex intersecting bores can be forged using multistroke or cored dies (Fig. 4). In this process, the billet (which may be blocked beforehand) is placed in a closed die set as described previously. The dies may or may not deform the billet, but most of the metal flow occurs when cores are introduced into the closed-die cavity through openings in or between the dies. The metal flows around the intruding cores, filling the cavity to the desired shape. The cores are withdrawn before the die halves are retracted.

The multistroke process can produce hollow, highly complex forgings containing multiple bores at any *x*-, *y*-, or *z*-axis orientation. Because the bores reduce the need for subsequent drilling operations, metal usage is very efficient and production rates are quite high. Dies are relatively expensive, however, and the process is most cost-effective when large quantities of forgings are to be produced.

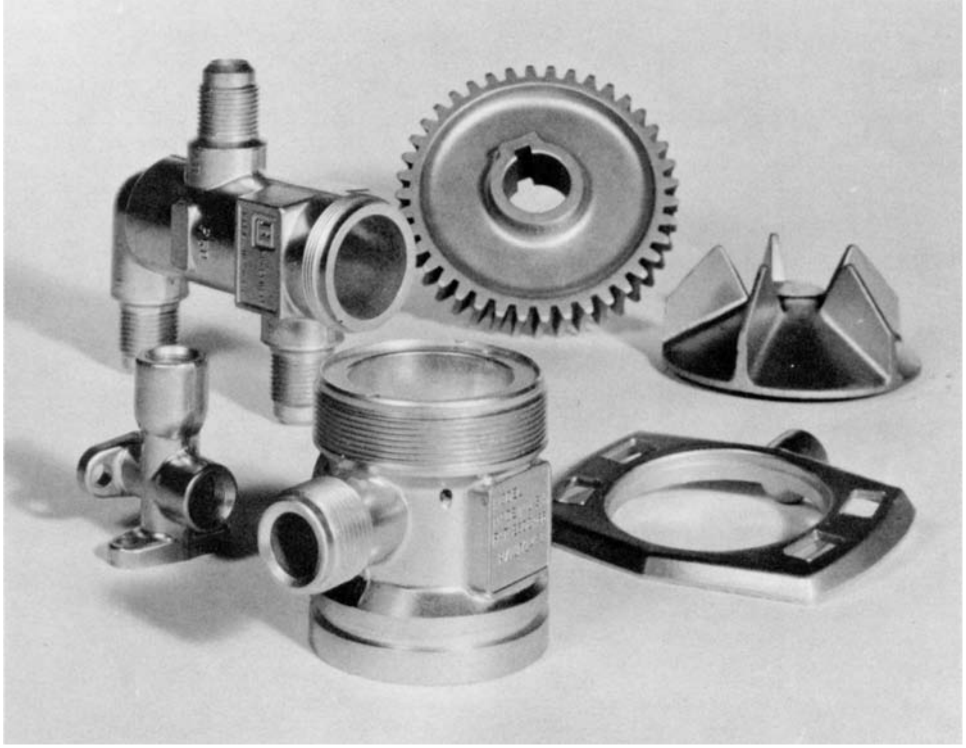


Fig. 3 Copper alloy parts made by closed-die forging

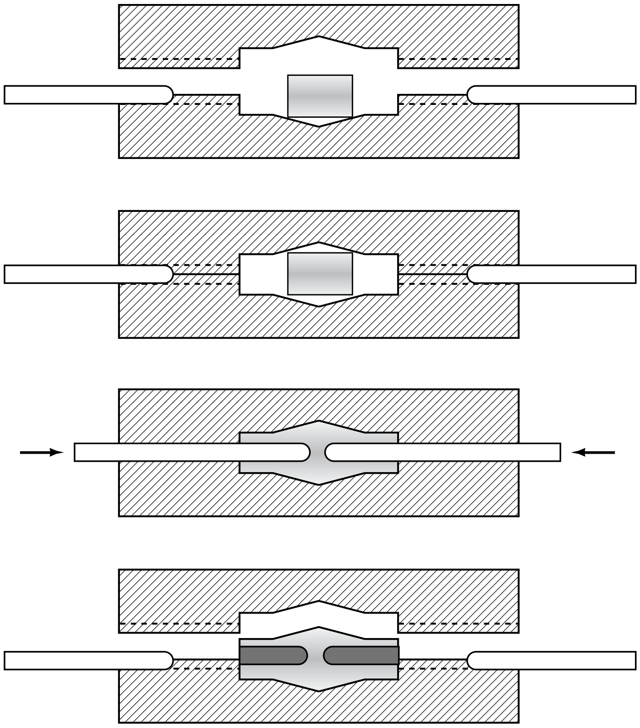


Fig. 4 Schematic of multistroke forging, which is a closed-die forging process in which horizontal punch action is introduced in combination with vertical action of the forging press. This makes possible the forming of cavities not possible with simple forging procedures. Multistroke forging is used in the manufacture of such items as complex valve bodies.

Ring rolling is a hot forging process for producing seamless annular rings that are accurately dimensioned and exhibit circumferential grain flow. Ring rolling produces less waste of material than alternative forging methods, and is applicable to production in any quantity.

Annular components can be ring rolled from any forgeable alloy. The configuration can range from very flat washer-shaped rings to long sleeve-type rings. Final product sizes typically range from 250 mm to 1 m (10 in. to 40 in.) in diameter to as large as about 7.5 m (25 ft) in diameter.

Forging Alloys

The choice of alloy to be used is dependent on the end use of the component. The selection is influenced by such factors as the required strength, corrosion resistance, and the need for machining. Different alloys will offer differing degrees of hot ductility, which in turn will affect the complexity of the component that can be produced and the die life of the hot forging tooling.

Brasses are by far the most popular alloys for hot forging because of their excellent hot working properties and good machinability, combined with high strength and corrosion resistance.

A number of different brasses are readily available for forging, covering a variety of properties suitable for particular applications. Forgings can also be successfully made in copper and other copper alloys including beryllium coppers, nickel silvers, aluminum bronzes, and copper-nickel alloys.

Table 1 lists the compositions and properties of copper and copper alloy forging alloys. The 16 alloys with forgeability ratings are the most commonly used in North America. Forging brass (alloy C37700), the least difficult alloy to forge, has been assigned an arbitrary forgeability rating of 100 (see footnote (b) in Table 1).

Some copper alloys cannot be forged to any significant degree because they will crack. Leaded copper-zinc alloys, such as architectural bronze, which may contain more than 2.5% Pb, are seldom recommended for hot forging. Although lead content improves metal flow, it promotes cracking in those areas of a forging, particularly deep-extruded areas, that are not completely supported by, or enclosed in, the dies. This does not mean that the lead-containing alloys cannot be forged, but rather that the design of the forging may have to be modified to avoid cracking.

The solubility of lead in β-brass at forging temperatures is about 2% maximum, but lead is insoluble in β-brass at all temperatures. Consequently, although a lead content of up to 2.5% is permissible in Cu-40Zn α-β brasses, lead in excess of 0.10% in a Cu30Zn α-brass will contribute to catastrophic cracking.

Other copper alloys, such as the copper-nickels, can be forged only with greater difficulty and at higher cost. The copper-nickels, primarily because of their higher forging temperatures, are sometimes heated in a controlled atmosphere, thus complicating the process. The silicon bronzes, because of their high forging temperatures and their compositions, cause more rapid die deterioration than the common forging alloys.

Forging Machines

Most copper alloy forgings are produced in crank-type mechanical presses. With these presses, the production rate is high, and less operator skill is needed and less draft is required than in forging copper alloys in hammers.

Press size is normally based on the projected (plan) area of the part, including flash. The rule of thumb is 0.5 kN of capacity per square millimeter of projected area (40 tonf/in.^{2}). Therefore, a forging with a projected area of 32.2 cm^2 (5 in.^{2}) will require a minimum of 1780 kN (200 tonf) capacity for forgings up to medium severity. If the part is complicated (for example, with deep, thin ribs), the capacity must be increased.

Speed of the press is not critical in forging copper alloys, but minimum duration of contact between the hot forging and the die is desirable to increase die life. Detailed information on hammers and presses is available in the article "Hammers and Presses for Forging", in *Forming and Forging*, Volume 14 of *ASM Handbook*.

Dies

Dies designed for forging copper or copper alloys usually differ from those designed for forging the same shapes from steel, as follows:

- The draft angle can be decreased for forging copper (3° max and often less than 3°).
- The die cavity is usually machined to dimensions that are 0.005 in./in. less than those for forging steels.
- The die cavity is usually polished to a better surface finish for forging copper and copper alloys.

Die materials and hardnesses selected for forging copper alloys depend on part configuration (forging severity) and number of parts to be produced. Figure 5 illustrates the forging severities of parts listed in Table 2.

Whether the dies are made entirely from a hot-work steel such as H11 or H12 or whether or not inserts are used depends largely on the size of the die. Common practice is to make the inserts from a hot-work steel and to press them into rings or holders made from a low-alloy die block steel (Table 2) or L6 tool steel. Hardness of the ring or holder is seldom critical; a range of 341 to 375 HB is typical.

Preparation of Stock

The two methods most often used for cutting stock into slugs for forging are shearing and sawing.

Shearing is faster than other methods of cutting stock. In addition, no material is wasted in kerf. However, the ends of the sheared stock are

Table 1 Compositions, mechanical properties, and forging/cold heading characteristics of copper and copper alloys

UNS number	Description or previous trade name	Nominal composition, wt%	Tensile strength(a)		Yield strength (a) (0.5% extension under load)		Elongation in 50 mm (2 in.), %	Hardness	Relative forgeability rating(b)	Cold heading(c)
			MPa	ksi	MPa	ksi				
C10200	Oxygen free	100 Cu	222	32	76	11	40	37 HRF	65	E
C10400	Oxygen free with Ag	99.95 Cu, 0.05 Ag	222	32	76	11	40	37 HRF	65	E
C11000	Electrolytic tough pitch	99.9 Cu min	221	32	76	11	40	37 HRF	65	E
C11300	Tough pitch with Ag	99.9 Cu min	221	32	76	11	40	37 HRF	65	E
C12200	Phosphorus deoxidized, high residual phosphorus	99.97 Cu, 0.03 P	221	32	76	11	40	37 HRF	65	E
C14500	Tellurium bearing	99.5 Cu, 0.5 Te	221	32	83	12	35	40 HRF	…	E
C14700	Sulfur bearing	99.6 Cu, 0.4 S	221	32	83	12	35	40 HRF	…	G
C15000	Zirconium copper	99.8 Cu, 0.15 Zr	200–483(d)	29–70(d)	41–448(d)	6–65(d)	11	72 HRB	…	G
C17000	Beryllium-copper	98.3 Cu, 1.7 Be	482–1138(d)	70–165(d)	221–1000(d)	32–145(d)	45–7(d)	60 HRB-35 HRC(d)	…	E
C18200	Chromium copper	99.1 Cu, 0.9 Cr	482(e)	70(e)	448(e)	65(e)	18	…	80	E
C36500	Leaded Muntz metal, uninhibited	60 Cu, 0.6 Pb, 39.4 Zn	400	58	159	23	40	45 HRB	…	F
C37700	Forging brass	60 Cu, 2 Pb, 38 Zn	359	52	138	20	40	45 HRB	100	P
C38500	Architectural bronze	57 Cu, 3 Pb, 40 Zn	414	60	138	20	30	65 HRB	…	P
C46400	Naval brass uninhibited	60 Cu, 0.8 Pb, 39.2 Zn	386	56	172	25	40	56 HRB	90	F
C48200	Naval brass, medium leaded	60.5 Cu, 0.7 Pb, 0.8 Sn, 38 Zn	441	64	179	26	40	55 HRB	90	P
C48500	Naval brass high leaded	60 Cu, 1.8 Pb, 0.7 Sn, 37.5 Zn	427	62	165	24	40	55 HRB	90	P
C62300	Aluminum bronze	87 Cu, 3 Fe, 10 Al	517	75	241	35	32	82 HRB	…	G
C62400	Aluminum bronze	86 Cu, 10.7 Al, 3.3 Fe	621	90	276	40	40	87 HRB	75	…
C63000	Aluminum bronze	82 Cu, 3 Fe, 10 Al, 5 Ni	345	50	…	…	15	90 HRB	75	P
C63200	Aluminum bronze	82 Cu, 9 Al, 4 Fe, 5 Ni	352	51	…	…	18	88 HRB	70	F
C64200	Aluminum bronze	91.2 Cu, 7 Al, 1.8 Si	241	35	…	…	35	77 HRB	80	P
C65500	High silicon bronze A	97 Cu, 3 Si	358	52	124	18	70	62 HRB	40	E
C67000	Manganese bronze B	65.5 Cu, 4.5 Al, 3.8 Mn, 3 Fe, 23.2 Zn	…	…	…	…	…	…	…	…
C67300	…	60.5 Cu, 1.7 Pb, 2.8 Mn, 35 Zn	517	75	379	55	15	81 HRB	…	…
C67400	…	58.5 Cu, 2.8 Mn, 1.3 Al, 2.7 Mn, 34.7 Zn	538	78	262	38	24	83 HRB	…	…
C67500	Manganese bronze A	58.5 Cu, 1.4 Fe, 1 Sn, 39 Zn, 0.1 Mn	448	65	207	30	33	69 HRB	80	P
C70600	Copper nickel, 10%	88.6 Cu, 1.4 Fe, 10 Ni	324	47	234	34	42	65 HRF or 15 HRB	…	G
C71500	Copper nickel, 30%	69.5 Cu, 0.5 Fe, 30 Ni	517	75	483	70	45	80 HRF or 45 HRB	…	G

(a) As-forged product.(b) Relative forgeability rating takes into consideration such variable factors as pressure, die wear, and plasticity (hot). Since it is impracticable to reduce these variables to common units, calibration in terms of a percentage of the most generally used alloy, C37700 forging brass (100), is considered the most practical basis for such ratings. The values shown represent the general opinion and are intended for information to enable the designer to better understand the forging characteristics of these various alloys.(c) Cold heading ratings: E, excellent (most easily cold headed); G, good; F, fair; P, poor (not recommended).(d) Value ranges from solutionized condition to the aged condition.(e) Value for aged condition. Source: Copper Development Association rougher than those of sawed sections. Rough or torn ends usually cannot be permitted because forging defects are likely to nucleate from the rough ends. If shearing is used, best practice is to condition the sheared ends—for example, with a radiusing machine.

Sawing with circular saws having carbide-tipped blades is widely used as a method of preparing stock because sawed ends are usually in much better condition than sheared ends. The principal disadvantage of sawing is the loss of metal because of the kerf. In addition, if the burrs left by sawing are not removed, defects are likely to develop in the forging. Deburring of the saw sections by grinding, radiusing, or barrel tumbling is always recommended.

Heating of Billets or Slugs

Optimal forging temperature ranges for ten alloys are given in Table 3. Atmosphere protection during billet heating is not required for most alloys, especially when forging temperatures are below 705 °C (1300 °F). For temperatures toward the top of the range in Table 3, a protective atmosphere is desirable and is sometimes required. An exothermic atmosphere is usually the least costly, and is satisfactory for heating copper alloys at temperatures above 705 °C (1300 °F).

Gas-fired furnaces are almost always used, and furnace design is seldom critical. Open-fired conveyor chain or belt types are those most commonly used.

Any type of pryometric control that can maintain temperature within ±5 °C (±10 °F) is suitable. As billets are discharged, a periodic check with a prod-type pyrometer should be made. This permits a quick comparison of billet temperature with furnace temperature.

Heating Time. The time at temperature is critical for all copper alloys, although to varying degrees among the different alloys. For forging brass (alloy C37700), the time is least critical, but for aluminum bronze, naval brass, and copper, it is most critical. Time in excess of that required to bring the billet uniformly to forging temperature is detrimental because it causes grain growth and increases the amount of scale.

Reheating Practice. When forging in hammers, all of the impressions are usually made in one pair of dies, and reheating is rarely required. In press forging, particularly in high-production applications, blocking is often done separately, followed by trimming before the forging is completed. The operations are likely to be performed in different presses; therefore the partially completed forging is reheated to the temperature originally used.

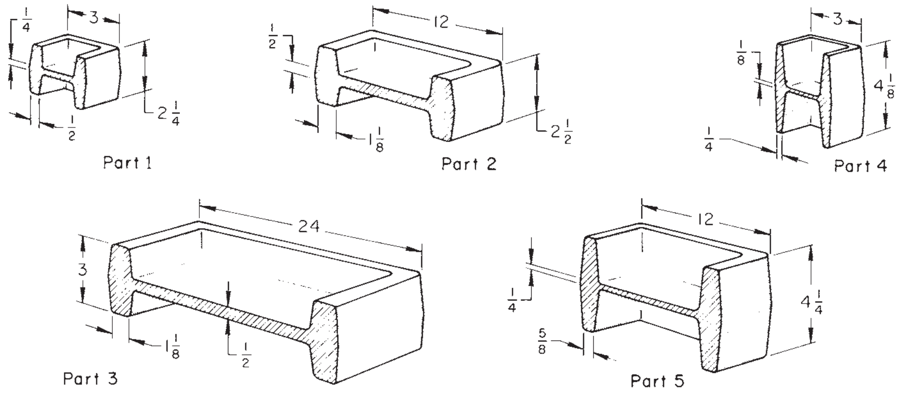


Fig. 5 Forged copper alloy parts of varying severity. Dimensions in inches. See Table 2 for recommended die materials.

Table 2 Recommended die materials for the forging of copper alloys

Part configurations of varying severity are shown in Fig. 5.

Maximum severity	Total quantity to be forged: 100–10,000 Die material	Hardness, HB	≥10,000 Die material	Hardness, HB
Hammer forging				
Part 1	H11 6G, 6F2	405–433 341–375	H12	405–448
Part 2	6G, 6F2	341–375	6G, 6F2 H12(a)	341–375 405–448
Part 3	6G, 6F2	269–293	6G, 6F2	302–331
Part 4	H11	405–433	H11	405–433
Part 5	6G, 6F2	302–331	6G, 6F2(b)	302–331
Press forging				
Part 1	H12 6G, 6F2	477–514 341–375	H12	477–514
Part 2	6G, 6F2	341–375	H12	477–514
Part 3	Part normally is not press forged from copper alloys			
Part 4	H11	405–433	6G, 6F2(c)	341–375
Part 5	6G, 6F2	341–375	H12	477–514

(a) Recommended for long runs—for example, 50,000 pieces. (b) With either steel, use H12 insert at 405–448 HB. (c) With either steel, use H12 insert at 429–448 HB.

Heating of Dies

Dies are always heated for forging copper and copper alloys, although because of the good forgeability of copper alloys, die temperature is generally less critical than for forging aluminum. Dies are seldom preheated in ovens. Heating is usually accomplished by ring burners. Optimal die temperatures vary from 150 to 315 °C (300 to 600 °F), depending on the forging temperature of the specific alloy. For alloys having low forging temperatures, a die temperature of 150 °C (300 °F) is sufficient. Die temperature is increased to as much as 315 °C (600 °F) for the alloys having the highest forging temperatures shown in Table 3.

Lubricants

Dies should be lubricated before each forging operation. A spray of colloidal graphite and water is usually adequate. Many installations include a spray that operates automatically, timed with the press stroke. However, the spray is often inadequate for deep cavities and is supplemented by swabbing with a conventional forging oil.

Trimming

Brass forgings are nearly always trimmed at room temperature. Because the forces imposed on the trimming tools are less than those for trimming steel forgings, the trimming of brass forgings seldom poses problems. Large forgings, especially in small quantities, are commonly trimmed by sawing off the flash and punching or machining the web sections. Trimming tools usually are used for trimming large quantities, especially of small forgings that are relatively intricate and require several punchouts.

Materials for trimming dies vary considerably among different plants. In some plants, it is common practice for normal trimming to make the punch from low-alloy die steel at a hardness of 46 to 50 HRC. One reason for using this steel

Table 3 Recommended forging temperature ranges for copper alloys

Alloy	Temperature range °C	°F
C12200	730–845	1350–1550
C18200	650–760	1200–1400
C37700	650–760	1200–1400
C46400	595–705	1100–1300
C62400	705–815	1300–1500
C64200	730–900	1350–1650
C67000	595–705	1100–1300
C67300	595–730	1100–1350
C67400	595–730	1100–1350
C67500	595–705	1100–1300

is economy; the punches are often made from pieces of worn or broken dies. Blades for normal trimming are sometimes made by hardfacing low-carbon steels such as 1020.

In other plants both punches and blades are made from L6 steel and are heat treated to 52 to 56 HRC. Worn tools of this material can be repaired by welding with an L6 rod, remachining, and heat treating; O1 tool steel heat treated to 58 to 60 HRC has also been used for punches and blades for cold trimming. When close trimming is required, blades and punches fabricated from a high-alloy tool steel such as D2, hardened to 58 to 60 HRC, will give better results and longer life.

Hot trimming is often used for one or both of the following reasons:

- For alloys such as aluminum bronzes that are brittle at room temperature
- When flash is heavy and sufficient power is not available for cold trimming

Hot trimming is usually done at 425 °C (800 °F).

Because of lower forces involved, tools for hot trimming are simpler than those for cold trimming. Although the tool materials discussed above can also be used for hot trimming, unhardened low-carbon steel will usually suffice as a punch material. The same grade of steel with a hardfacing is commonly used as blade material.

Cleaning and Finishing

Scale and excess lubricants are easily removed from copper and copper alloy forgings by chemical cleaning. Pickling in dilute sulfuric acid is the most common method for cleaning brass and most other copper alloy forgings, although hydrochloric acid can also be used. The compositions of sulfuric and hydrochloric acid solutions, the pickling procedures, and the typical uses are given in Table 4.

Aluminum bronzes form a tough, adherent aluminum oxide film during forging. An effective method of cleaning aluminum bronze forgings is first to immerse them in a 10% solution (by weight) of sodium hydroxide in water at 75 °C (170 °F) for 2 to 6 min. After rinsing in water, the forgings are pickled in acid solutions in the same way as brasses.

Alloys containing substantial amounts of silicon may form oxides of silicon removable only by hydrofluoric acid or a proprietary fluorine-bearing compound. Alloys containing appreciable quantities of nickel are difficult to pickle in solutions used for brasses because nickel oxide has a limited solubility in these solutions. For these alloys, billets should be heated in a controlled atmosphere, so that scale is kept to a minimum and can be removed by using the practice outlined previously and in Table 4 for brass.

Other methods of chemical cleaning can be used, depending largely on the desired finish. Additional information is available in the article "Surface Engineering" in this Handbook.

Appearance. When a bright, lustrous finish is desired, the metal can be pickled in the sulfuric or hydrochloric acid pickles listed in Table 4 and then given two additional dips. Pickling removes surface oxides, and the second dip, a "scale" dip, prepares the metal for the "bright" dip that follows. "Scale" dips and "bright" dips are mixtures of sulfuric and nitric acids in proportions that vary widely from plant to plant. Generally, nitric acid accelerates the action of the dip, while sulfuric acid slows it down. The solutions are used at room temperature. Parts are first dipped in the "scale" dip, rinsed in water, dipped in the "bright" solution, rinsed in cold running water, and then rinsed in hot water and dried. Compositions of "scale" and "bright" dips are listed in Table 4.

Surface Finish. In normal practice, the surface finish of cleaned forgings is expected to be 5 μm (200 min.) or better. By more precise control, a finish of 2.5 μm (100 μin.) or better can be obtained. Die finish is the major factor affecting the surface finish of forgings. The type of alloy forged and the amount of draft have a minor influence on surface finish.

Lacquer Coatings. The matte and mirror finishes preferred for decorative forged door hardware and architectural trim are readily maintained with protective lacquers. Simple lacquers suffice for indoor use, while grades containing benzotriazole or other inhibitors provide years of protection in outdoor use. Dark, nonreflective lacquers are used for optical instruments.

Electroplating. Copper forging alloys readily accept most electroplated coatings. Common plated coatings include chromium, which is ordinarily used for decoration, and copper, which is applied to brass electrical products to add corrosion protection and to minimize changes in contact resistance at elevated temperatures.

Minimum-Draft Forgings

Zero-draft forgings can be produced from copper alloys, but are usually impractical. However, the minimum-draft concept is a practical approach for producing locating and clamping surfaces for machining operations, mating surfaces in assemblies, or other functional shapes where dimensional tolerances on such surfaces are broad enough to include normal forging tolerances but too close for normal draft angles.

Forging Design. The most obvious consideration is that any shape that has a negative draft angle would be impossible to eject without damage to the die or workpiece. With zero draft, the smallest error of form or dimension can damage the die and the workpiece. Therefore, a draft angle of $\frac{1}{8}$° should be considered the absolute minimum for production forging. This very small amount of positive draft is sufficient to eliminate the possibility of negative draft while producing forgings that have essentially zero draft.

Tolerances on closed-die forgings are normally ±0.25 mm (±0.010 in.) or better for small-to-medium forgings. It can be seen from Table 5 that a small draft angle can easily be accommodated within these tolerance limits. For example, a draft of $\frac{1}{4}$° would produce a taper of only 0.083 mm (0.00327 in.) on each side of a cavity 19 mm ($\frac{3}{4}$ in.) deep. Because the total taper of 0.166 mm (0.00654 in.) (both sides of the cavity) would be less than the usual 0.51 mm (0.020 in.) total tolerance on the cavity diameter, the part would be within tolerance for a specification of parallel sides.

Die Design. Conventional forging practice calls for draft angles of 2° or more on press forgings and up to 5 to 7° for hammer forgings. Draft angles of 1° or less increase cost. In general, as the draft angle is decreased, more force is required to eject the forging from the die cavity or to withdraw the punch from a hole. Conventional forging can usually be ejected by a simple knockout pin. This method is not practical for minimum-draft forgings because pin pressure would be sufficient to damage the part.

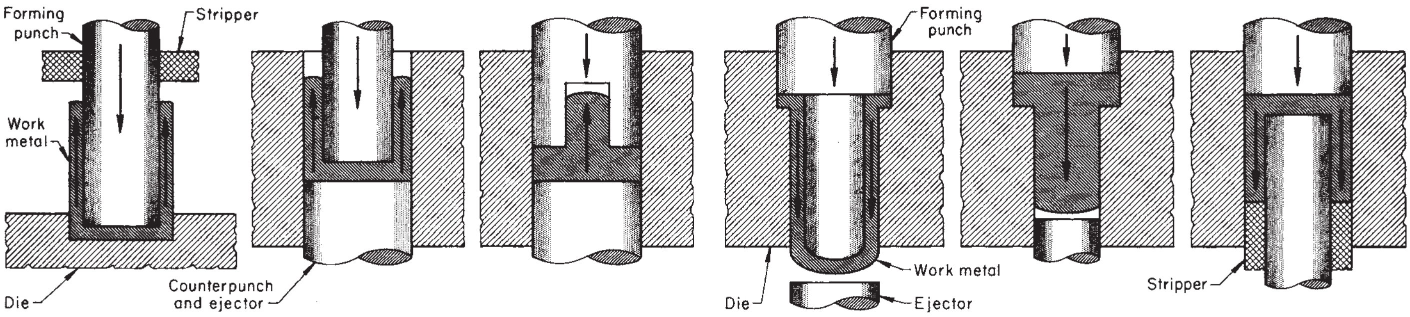
Ejection of minimum-draft forgings is nearly always accomplished through the use of inserted dies built on die cushions to provide a secondary action within the die. This provides a stripper action to the die so that ejection pressure is distributed over an entire surface rather than concentrated on a pin. Such double-action dies are more expensive to build and to maintain

Table 4 Cleaning solutions and conditions for copper and copper alloy forgings

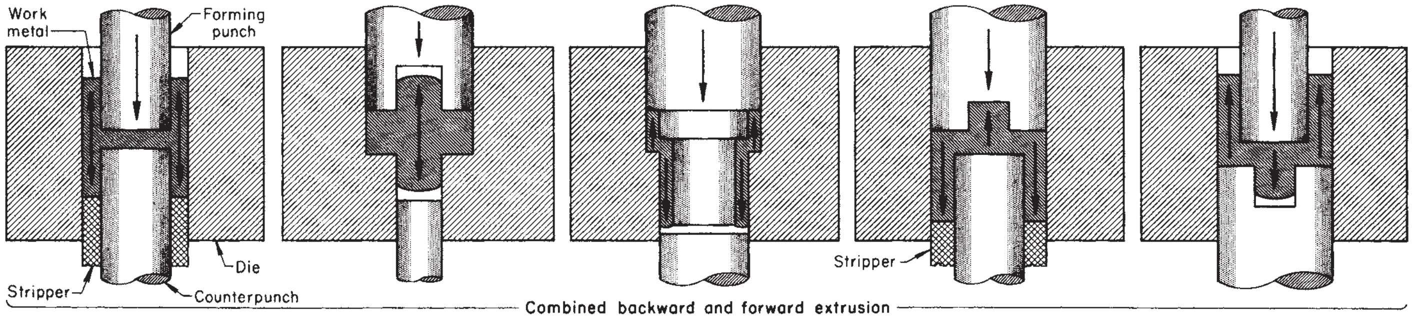
Solution	Composition	Use temperature, °C (°F)	Uses
Sulfuric acid	4–15 vol% H_2SO_4 (1.83 specific gravity); bal H_2O	Room–60 (140)	Removal of black copper oxide scale from brass forgings; removal of oxide from copper forgings
Hydrochloric acid	40–90 vol% HCl (35% conc); bal H_2O	Room	Removal of scale and tarnish from brass forgings; removal of oxide from copper forgings
"Scale" dip A	40% conc HNO_3; 30% conc H_2SO_4; 0.5% conc HCl; bal H_2O	Room	Used with pickle and "bright" dip to give a bright, lustrous finish to copper and copper alloy forgings
"Scale" dip B	50% conc HNO_3; bal H_2O	Room	Used with pickle and "bright" dip to give bright, lustrous finish to copper and copper alloy forgings
"Bright" dip	25 vol% conc HNO_3; 60 vol% conc H_2SO_4; 0.2% conc HCl; bal H_2O	Room	Used with pickle and "scale" dip to give bright,lustrous finish to copper and copper alloy forgings

Table 5 Relation of draft angle to draft for minimum-draft forgings

Draft angle, degrees	Draft, in./in.	Total taper on diameter, in./in.
$\frac{1}{8}$	0.00219	0.00438
$\frac{1}{4}$	0.00436	0.00872
$\frac{1}{2}$	0.00873	0.01746
1	0.01745	0.03490



(a) Backward extrusion (b) Forward extrusion



Combined backward and forward extrusion

Fig. 6 Displacement of metal during cold or hot extrusion

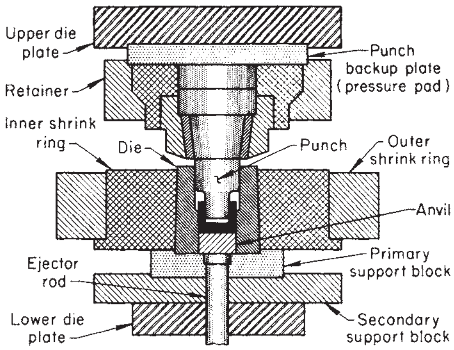


Fig. 7 Nomenclature of tools comprising a typical setup for backward extrusion

than solid dies, and their use slows the production rate.

Alloy Selection. Draft angles have no effect on the relative forgeability of copper-base alloys. Any alloy that can be forged by conventional means can be forged to minimum draft angles.

Cold Extrusion

Cold extrusion is so called because the slug or preform enters the extrusion die at room temperature. Any subsequent increase in temperature, which may amount to several hundred degrees, is caused by the conversion of deformation work into heat. Cold extrusion involves backward (indirect), forward (direct), or combined backward and forward (indirect-direct) displacement of metal by plastic flow under steady, though not uniform, pressure.

Backward displacement from a closed die is in the direction opposite to punch travel, as shown in Fig. 6(a). Workpieces are often cup-shaped and have wall thicknesses equal to the clearance between the punch and the die. In forward extrusion, the work metal is forced in the direction of the punch travel, as shown in Fig. 6(b). These two basic methods of extrusion are sometimes combined so that some of the work metal flows backward and some forward, as shown at the bottom of Fig. 6.

In cold extrusion, a punch applies pressure to the slug or preform, causing the work metal to flow in the required direction. The relative motion between punch and die is obtained by attaching either one (almost always the die) to the stationary bed and the other to the reciprocating ram. The axis of the machine can be vertical or horizontal. The pressure can be applied rapidly by a sharp blow, as in a crank press or header (impact extrusion), or more slowly by a squeezing action, as in a hydraulic press.

Alloy Extrudability

Oxygen-free copper (alloy C10200) is the most extrudable of the coppers and copper-base alloys. Other grades of copper and most of the copper-base alloys can be cold extruded, although there are wide differences in extrudability among the different compositions. For example, the harder copper alloys, such as aluminum-silicon bronze and nickel silver, are far more difficult to extrude than the softer, more ductile alloys, such as cartridge brass (alloy C26000), which can satisfactorily withstand cold reduction of up to 90% between anneals.

Alloys containing as much as 1.25% Pb can be successfully extruded if the amount of upset is mild and the workpiece is in compression at all times during metal flow. Copper alloys containing more than 1.25% Pb are likely to fracture when cold extruded.

The pressure required for extruding a given area for one of the more extrudable coppers or copper alloys (such as C10200 or C26000) is less than that required for extruding low-carbon steel. However, the pressure required for extruding copper alloys is generally two to three times that required for extruding aluminum alloys (depending on the copper or aluminum alloy being compared).

The length of a backward-extruded section is limited by the length-to-diameter ratio of the punch and varies with unit pressure. This ratio should be a maximum of 5 to 1 for copper. A ratio of 10 to 1 is common for the extrusion of aluminum, and ratios as high as 17 to 1 have been used. The total reduction of area for copper or copper alloys, under the best conditions, should not exceed 93%.

Equipment and Tooling

Equipment. Copper and copper alloys can be extruded in hydraulic or mechanical presses or in cold-heading machines. Of the three, mechanical presses are used most often because of their adaptability to other types of operations.

Tooling and Tool Materials. The components of a typical tool assembly used for backward extrusion of metal parts are identified in Fig. 7. Recommended materials for extrusion punches include M2 and M4 high-speed tool steels and tungsten carbide. Tool steel punches should be heat treated to a hardness of 62 to 66 HRC, and they must have a high compressive yield strength. Die inserts are usually fabricated from such alloy tool steels as D2, M2, and M4, and are heat treated to 58 to 64 HRC, depending on the steel.

Tungsten carbide is extensively used because it provides good die life, high production rates, and good dimensional control.

Tungsten carbide often finds application as a punch material in backward extrusion. Retainer rings or housings used for tungsten carbide dies should have sufficient strength and toughness to prevent splitting and failure of the working tools. Shrink rings should be fabricated from hot-work die steels such as H11 or H13 heat treated to 46 to 48 HRC. Outer housings are often made from H13 die steel or from 4340 alloy steel.

Preparation of Slugs

Sawing, shearing, and machining are the methods used to prepare copper and copper-alloy slugs. Each method has advantages and limitations. Sawing or shearing is generally used to produce solid slugs. Machining (as in a lathe) or cold forming in auxiliary equipment is seldom used unless a hole in the slug, or some other modification, is required.

Surface Preparation. In applications involving minimum-to-moderate severity, copper slugs are often extruded with no special surface preparation before the lubricant is applied. However, for the extrusion of harder alloys (aluminum bronze, for example) or for maximum severity or both, best practice includes the following surface preparation before lubricant is applied:

- Cleaning in an alkaline cleaner to remove oil, grease, and soil
- Rinsing in water
- Pickling in 10 vol% sulfuric acid at 20 to 65 °C (70 to 150 °F) to remove metal oxides
- Rinsing in cold water
- Rinsing in a well-buffered solution, such as carbonate or borate, to neutralize residual acid or acid salts

Lubrication. Zinc stearate is an excellent lubricant for extruding copper alloys. Common practice is to etch the slugs as described previously and then to coat them by dry tumbling in zinc stearate.

Examples of Practice

The following examples describe typical production practice for extruding parts from copper and brass. The part described in Example 2 could have been made by forging, casting, or machining; however, cold extrusion produced more accurate dimensions than forging or casting, consumed less material than machining, and was the lowest-cost method.

Example 1: Shearing, Heading, Piercing, Extruding, and Upsetting in a Header. The plumbing fitting shown in Fig. 8 was made of electrolytic tough pitch copper (alloy C11000) rod cold drawn (about 15% reduction of area) to a diameter of 26.9 mm (1.06 in.). The pipe-taper diameter and the 22.2 mm (0.875 in.) diameter of the tube socket were critical, being specified within 0.064 mm (0.0025 in.).

Manufacture of the fitting consisted of feeding the rod stock into the cold-heading machine, which cut the stock into slugs 20.3 mm (0.80 in.) long and transferred the slugs progressively to dies for heading, backward extruding, piercing, forward extruding, and upsetting (Fig. 8). Only trimming on each end and tapping were required for completion. The extrusion equipment consisted of a five-die cold-heading machine.

The final cross-sectional area of the thin end after extrusion was 16.4% of the 30.7 mm (1.21 in.) diameter headed preform from which the fitting was made. A reduction of this magnitude could have been made in one operation if a cylindrical rod were being extruded from the preform. The shape, however, was not suitable for production in one operation. Therefore, the fitting was made by backward and forward extrusion and mild upsetting. Production rate at 100% efficiency was 3600 pieces per hour, and minimum life of the D2 tool steel dies was 200,000 pieces.

Difficult Extrusions. The part described in the following example represents a difficult extrusion for two reasons. First, the metal (tellurium copper, alloy C14500) is one of the more difficult-to-extrude copper alloys, and second, the configuration (12 internal flutes and 12 external ribs) is difficult to extrude regardless of the metal used.

Example 2: Extrusion Versus Brazed Assembly for Lower Cost. The rotor shown in Fig. 9 was originally produced by brazing a machined section into a drawn ribbed and fluted tubular section. By an improved method, this rotor was extruded from a sawed, annealed slug in one hit in a 1.7 MN (190 tonf) mechanical press. A lanolin-zinc stearate-trichloroethylene lubricant was used to produce 1800 pieces per hour. The extruded rotor was produced at less cost and has better dimensional accuracy than the brazed assembly, and there were fewer rejects. Minimum tool life was 50,000 pieces.

Cold Heading

Cold heading is a cold-forged process in which the force developed by one or more strokes (blows) of a heading tool is used to upset (displace) the metal in a portion of a wire or rod blank in order to form a section of different contour or, more commonly, of larger cross section than the original. The process is widely used to produce a variety of small- and medium-sized hardware items, such as bolts and rivets. Cold heading, however, is not limited to the cold deformation of the ends of a workpiece nor to conventional upsetting; metal displacement may be imposed at any point, or at several points, along the length of the workpiece and may incorporate extrusion in addition to upsetting. In cold heading, the cross-sectional area of the initial material is increased as the height of the workpiece is decreased. Advantages of the process over machining of the same parts from suitable bar stock include:

- Almost no waste material (Fig. 10)
- Increased tensile strength from cold working
- Controlled grain flow

Although cold heading is principally used for the production of heads on rivets or on blanks for threaded fasteners, a variety of other shapes can also be successfully and economically formed by the process. Figure 11 illustrates the cold heading process.

Materials for Cold Heading. As listed in Table 1, a number of coppers and copper alloys exhibit good to excellent cold headability. It should be noted that hot forgeability and cold headability are not related. For example, forging brass alloy C37700, which exhibits the highest forgeability rating, has a poor cold heading rating.

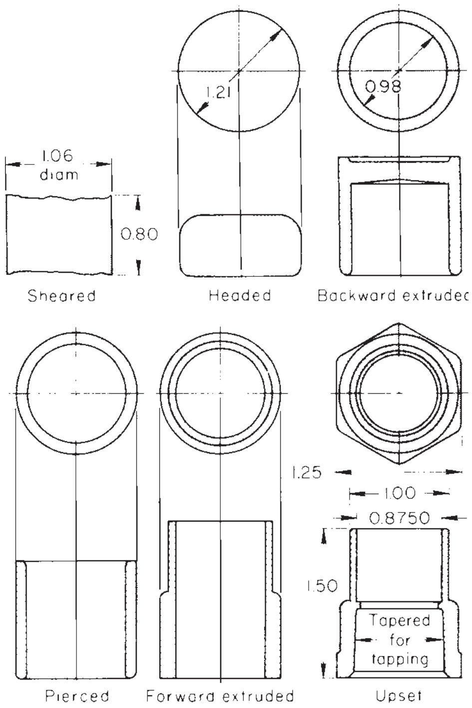


Fig. 8 Copper alloy C11000 plumbing fitting produced by the operation shown, including cold forward extrusion. Dimensions given in inches

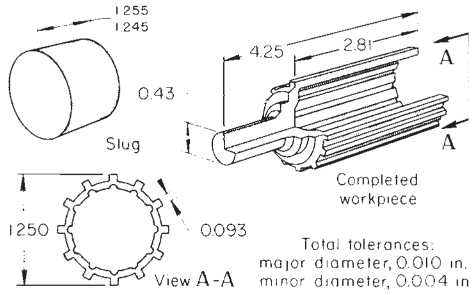


Fig. 9 Copper alloy C14500 rotor produced by combined backward and forward extrusion. Dimensions given in inches

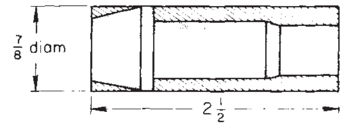


Fig. 10 Copper alloy C10200 nozzle component blank that was originally machined but was switched to cold heading to save the work metal indicated by the shaded regions. A materials savings of more than 50% was effected producing the component by cold heading rather than machining. Dimensions given in inches

Coining

Coining is a closed-die forging operation, usually preformed cold, in which all surfaces of the workpiece are confined or restrained, resulting in a well-defined imprint of the die on the workpiece. It is also a restriking operation (called, depending on the purpose, sizing or bottom or corner setting) used to sharpen or change a radius or profile.

The Coining Operation Sequence. Ordinarily, coining entails the following steps:

- *Preliminary Workpiece Preparation*: Full contact between the blank and die surfaces, which is necessary for coining, usually requires some preliminary metal redistribution by other processes, such as forging or extrusion, because only a small amount of metal redistribution can take place in the coining dies in single-station coining. In progressive-die operations, coining is done as in single-station dies, but it is preceded by other operations such as blanking, drawing, piercing, and bending. Coining is often the final operation in a progressive-die sequence, although blanking or trimming, or both, frequently follow coining.
- *Development of Detail in the Workpiece*: In coining dies, the prepared blank is loaded above the compressive yield strength and is held in this condition during coining. Dwell time under load is important for the development of dimensions in sizing and embossing; it is also necessary for the reproduction of fine detail, as in engraving.
- *Trimming*: Flash that develops during coining and any hangers used to carry the blank through coining, especially in progressive-die coining, must be trimmed from the piece.

Materials for Coining. Ease of coining is determined by the strength and work-hardening rate of the material. Copper, low-zinc brass, low-alloy nickel silvers, and copper-nickels, all of which exhibit low work-hardening rates, have good coinability.

Applications. The most familiar application of the coining process is the minting of coins, many of which are made from copper alloys. Electrical and electronic connectors and lead-frame leads are also often coined. Coining also makes possible the reproduction of ornate detail in tableware (Example 3) and allows close size control with a prescribed surface finish in small parts (Examples 4 and 5).

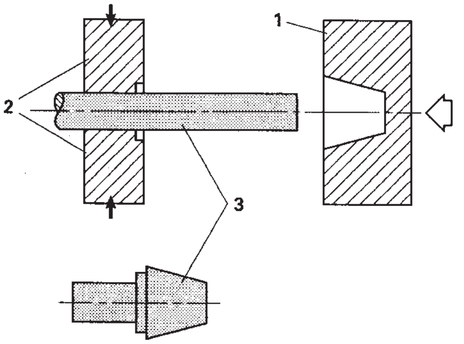


Fig. 11 Schematic of the cold heading process. 1, punch; 2, die; 3, forging

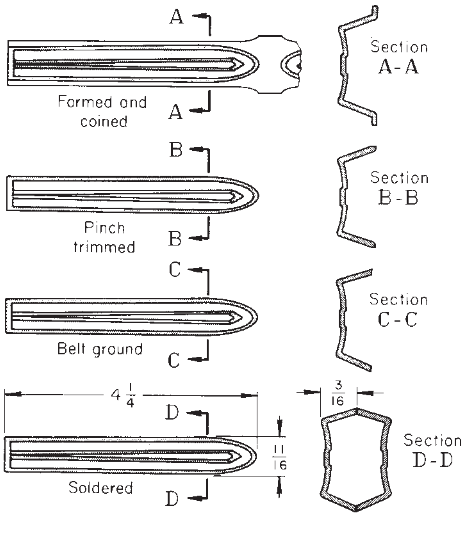


Fig. 12 Production of a hollow copper alloy C75700 knife handle by forming and coining. Dimensions given in inches

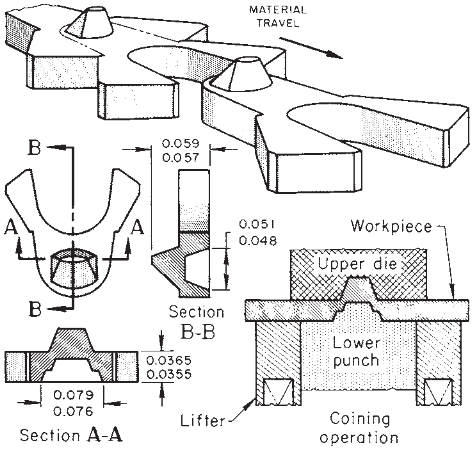


Fig. 13 Copper alloy C22600 interlocking-fastener element produced by coining and notching in a progressive die. Dimensions given in inches

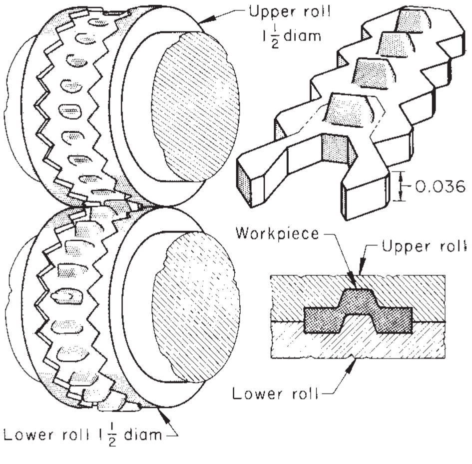


Fig. 14 Copper alloy C22600 interlocking-fastener element produced on coining rolls. Dimensions given in inches

Example 3: Production of a Nickel Silver Knife Handle by Forming and Coining in a Drop Hammer. Figure 12 shows the sequence of shapes in the production of a hollow handle for a table knife formed and coined in a 410 kg (900 lb) pneumatic drop hammer. The work metal was 0.81 mm (0.032 in.) thick copper alloy C75700 (nickel silver, 65-12) annealed to a hardness of 35 to 45 HRB; blank size was 25 by 230 mm (1 by 9 in.).

Two workpieces were formed and coined simultaneously from one blank, in two blows of the drop hammer. The two-cavity die permitted easy loading and unloading of parts and also provided symmetry to prevent shifting of the punch. A volatile, fatty oil-base lubricant was applied to the blank by rollers.

The formed and coined halves were separated by slitting with a rotating cutter made of T1 tool steel, and the flange was removed in a pinch-trim operation. After belt grinding to deburr and provide a smooth, flat surface, the half handles were fluxed along the edges and soldered together. The soldered handles were then pickled, washed, and finished by a light emery on the soldered seams, and then were silver plated. The handle and blade were assembled and finish buffed.

Example 4: Coining Interlocking-Fastener Elements in a Progressive Die. The interlocking-fastener element shown in Fig. 13 was manufactured from a precision-rolled, lubricated, flat strip of copper alloy C22600 (jewelry bronze; Cu-12.5Zn) 4.57 mm (0.180 in.) wide.

A special high-speed eccentric-shaft mechanical press with a 4.8 mm ($^3/_{16}$ in.) stroke was used. Tooling consisted of a D2 steel progressive die (59 to 61 HRC) that had edge-notching and coining stations. A ratchet-type roll feed was used. The coining portion of the die consisted of an upper die and a lower punch, with a spring-loaded stock lifter. The element was made at a production rate of 120,000 pieces per hour by notching, coining, and blanking, and then was attached to a tape.

Example 5: Roll Coining of Small Interlocking-Fastener Elements From Round Wire. Copper alloy C22600 (jewelry bronze; Cu-12.5Zn) wire was fed into coining rolls to form elements of an interlocking-fastener strip (Fig. 14).

The rolls illustrated in Fig. 14 were geared together so that the male and female forms hubbed into the roll peripheries were accurately matched. Roll peripheries were a whole-number multiple of the lengths of the article coined. Diameters were kept as small as possible to minimize the expense of replacement of the rolls if premature failure occurred. The rolls enclosed a coining space nominally equal in cross section to that of the wire fed into them. This wire was forged and coined to fill the section presented in the roll space, to give the configuration shown in Fig. 14.

Hot Extrusion

Hot extrusion involves pushing a heated billet of metal through a die. The extruded product may be hollow or solid, and the cross section may vary from a simple round to a complicated shape (Fig. 15). Direct (forward) extrusion, wherein the metal is forced under pressure through a die opening of the desired cross-sectional area and shape, is most widely employed. The die is located in the end of the cylinder opposite the ram. In the less-used indirect (backward) extrusion process, the die is mounted on a hollow ram and is pushed through the metal instead of the metal being pushed through the die. The principal differences between direct and indirect extrusion are illustrated in Fig. 6.

Hot extrusion is widely used in the production of wire, pipe, and tube, in which it is an intermediate process, and rod, bar, and shapes, for which it can be used to produce finished products. An example of the latter are architectural shapes such as banister rails, which are extruded from brass. Billet temperatures vary from about 595 to 995 °C (1100 to 1825 °F). Copper and brasses extrude readily, with ram speeds ranging from 50 to 400 mm/s (2 to 16 ft/s). Stiffer alloys require high pressures (>690 MPa, or 100 ksi).

Alloy Extrudability. Pure copper and beta brasses are the most easily extruded. Other copper alloys of this group comprise cadmium copper, silver-bearing copper, chromium copper, zirconium copper, aluminum bronzes up to 5% Al, tin bronzes with 2% Sn, and duplex ($\alpha + \beta$) brasses. High alloy aluminum bronzes (over 8% Al or complex bronzes) are considered very difficult to extrude because they require relatively high specific pressures. High tin bronzes and CuNiFe alloys belong in this group, as well. Alloys considered moderately difficult to extrude include leaded nickel silvers, which tend to show hot shortness; alpha brasses; $\alpha + \beta$ special brasses; aluminum bronzes containing from 5 to 8% Al; tin bronzes ranging from 4 to 8% Sn, and copper-nickels with 1 to 2% Si. Other difficult-to-extrude alloys are those that display hot shortness, such as silicon bronzes and leaded nickel silver. Unlike its action in forging, lead does not limit extrudability appreciably. Highly leaded alloys, such as free-cutting brass, are routinely extruded in large quantities.

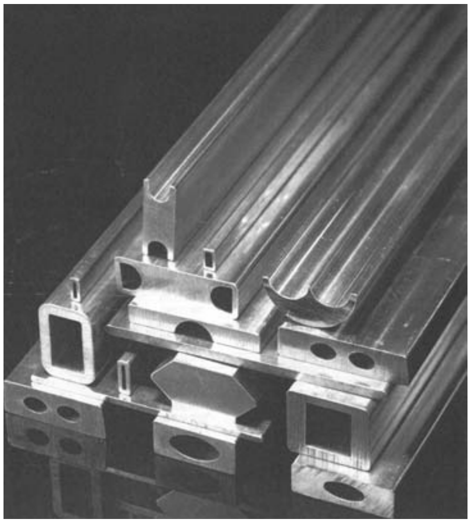


Fig. 15 Hollow copper sections produced by hot extrusion

Table 6 Typical materials and hardnesses for tools used in hot extrusion of copper and brass

Tooling application	Tool material	Hardness, HRC
Dies, for both shapes and tubing	H11, H12, H13, H14, H19, H21	42–44
Dummy blocks, backers, bolsters, and die rings	H11, H12, H13, H14, H19 Inconel 718	34–36
Mandrels	H11, H13	40–44
Mandrel tips and inserts	Inconel 718	40–42
Liners	A-286, V-57	46–50
Rams	H11, H12, H13	40–44
Containers	4140, 4150, 4340	35–40

Presses and Tooling. Horizontal and vertical presses are used for hot extrusion. Horizontal presses are the most common (Fig. 16). Most modern extrusion presses are driven hydraulically, but mechanical drives are used in some applications, such as the production of small tubes. Two basic types of hydraulic drives are available: direct and accumulator. In the past, accumulator presses were the most widely used type, but today direct-drive presses are used more extensively.

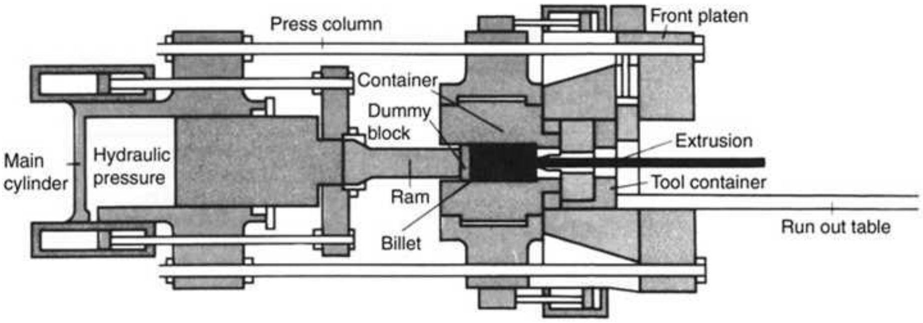


Fig. 16 Schematic of a horizontal extrusion press showing a hydraulically powered ram forcing the heated billet through the die

Table 6 lists typical materials and hardnesses for tools used in hot extrusion of copper and brass.

ACKNOWLEDGMENTS

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Powder Metallurgy Processing

POWDER METALLURGY (P/M) is a branch of metallurgy related to the manufacture of metal powders and articles fabricated from powders by the application of forming and sintering processes. Powder metallurgy processing offers the engineer a means of conserving materials, reducing machining, and securing a uniform product at a reasonable cost. It also permits the production of parts with close tolerances and a minimum of scrap and the development of products that cannot be produced by any other method. By proper selection of powders, the P/M specialist can control the density of the products over a wide range and secure a wide range of mechanical and physical properties.

Density can be controlled to produce parts with porosities as high as 60% or, conversely, those that are practically pore-free and have densities approaching the theoretical density of the material. It is even possible to vary the density in a single part. By producing parts with interconnected pores, the metallurgist can obtain a skeleton that can be impregnated with oils, plastics, or a metal having a lower melting point.

Copper and copper alloy powders have been used in industrial applications for many years. The self-lubricating bronze bearing, invented in the 1920s, and its subsequent development brought about the commercial production of copper powders. The first large-scale production powder processes were oxide reduction and electrolytic deposition. Electrolytic copper powders enabled the development of copper-graphite electrical brushes and copper-base friction materials in the 1930s. Copper powder made by the cementation process was also used in copper-base friction materials for a period of time, but ceased in the 1970s. Other hydrometallurgical processes for copper powder production were developed in the 1950s and 1960s. Some powders were commercially used for a number of years. Further growth of copper powder production took place with the development, during World War II, of the ferrous structural parts industry which uses copper additions for alloy strengthening. In the 1950s, production of copper and copper alloy powders by water atomization became commercially significant. By the early 1980s, competition from oxide-reduction and atomization processes caused commercial production of electrolytic copper powder to cease in the United States, but it is still commercially produced in Europe and Asia, where water atomization is the main competitive commercial process.

This article describes the four processes used for the production of copper and copper alloy powders, the physical and mechanical properties of the powders produced, and copper powder consolidation techniques, including compaction and production sintering practices. Additional information on the characteristics, properties, and applications of copper and copper alloy P/M materials can be found in the article "Powder Metallurgy Copper and Copper Alloys" in this Handbook.

Production of Copper Powder by the Reduction of Copper Oxide

Reduction of copper oxide is the oldest and (in the United States) still one of the main commercial processes for making copper powder, along with water atomization. In this process, particulate copper oxide is converted to copper at elevated temperature by reducing gases. The product, a sintered porous cake, is then milled to a powder. The starting material for reduction was originally copper millscale and cement copper. However, as demand for copper powder exceeded supply and higher purity was required, particulate copper of high purity (chopped scrap or atomized copper) was oxidized to form cuprous or cupric oxide or a mixture of both.

Melting of Copper

In recent years, the increasing emphasis on purity has supplanted both copper mill scale and cement copper as the starting materials for making oxide-reduced copper powders.

Copper melting is performed in both fuel-fired and induction-heated furnaces. Strong oxide formers, such as aluminum and silicon, are kept low; thus, the molten metal remains fluid and can be poured without difficulty. Aluminum and silicon oxides also make the powder less compressible and very abrasive. In addition, lead and tin cause problems in pouring the melt due to buildups and clogging in the furnaces and nozzles.

In some applications of copper powder (for example, metal-graphite brushes and friction parts), good electrical or thermal conductivity is important. For this reason, impurity levels must be kept low. The detrimental effect on electrical conductivity caused by some impurities that are present in solid solution is shown in Fig. 1.

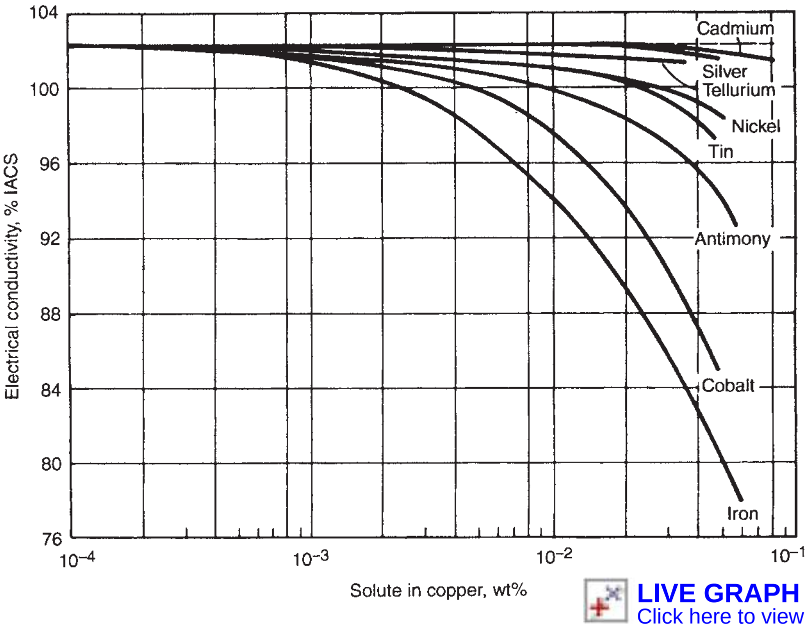

Fig. 1 Effect of impurities in solid solution on electrical conductivity of oxygen-free copper

Thermal conductivity is similarly dependent on the impurity content.

Atomization and Shotting of Copper

Large-scale atomization of copper usually is conducted in air as a continuous process. Liquid copper may be atomized directly from a tube in the side of the furnace wall or through a tundish. Both air and water may be used as atomizing media, and horizontal atomization with high-pressure air into a rotating drum eliminates the need for drying of the powder. For details of atomization, including nozzle configurations and pressure relationships, see the article "Atomization" in *Powder Metal Technologies and Applications*, Volume 7 of the *ASM Handbook*.

Scanning electron micrographs of air-atomized and water-atomized copper powders are shown in Fig. 2. The water-atomized powder has a more irregular particle shape, and its oxide content is somewhat lower. At this process stage, however, particle shape is not very important. The coarse shot-type powder that is produced by low-pressure air or water atomization (Fig. 3) is the typical starting material for the pure copper oxide process.

Oxidation of Copper Powder

Oxidation of air-atomized, water-atomized, or shotted copper is performed to radically change the shape of the powder and thus enhance control over the various engineering properties of parts made from the powder. Completely oxidized and reduced powders with a wholly spongy (porous) structure and entirely solid powders, as typified by a gas-atomized powder, constitute the extremes of available copper powders. Partial oxidation results in intermediate structures.

The oxidation of copper is a well-known process. There are two copper oxides, the red cuprous oxide, Cu_2O, and the black cupric oxide, CuO. At high temperatures and for the so-called thick film range, oxidation follows the parabolic rate law, in which film thickness (y) increases with the square root of time ($y = \sqrt{k_p t + c}$). At low temperatures, linear, logarithmic, and cubic oxidation rates have been observed, depending on the history of the oxide. Free energies, heats of reaction, and rates of copper oxide formation are shown in Table 1.

In commercial practice, oxidation or roasting of copper powder normally is done in air at temperatures above 650 °C (1200 °F). Oxidation in rotary kilns or fluidized beds provides faster oxidation rates by increasing the contact area between powder and oxidizing gas. However, due to the strongly exothermic nature of the oxidation reactions, these operations are more difficult to control than roasting in a belt conveyor furnace.

Grinding of Copper Oxide. Both oxides of copper are brittle and easy to grind to –100 mesh powder. The oxide particles themselves are porous. Figure 4 shows oxidized shot before and after grinding.

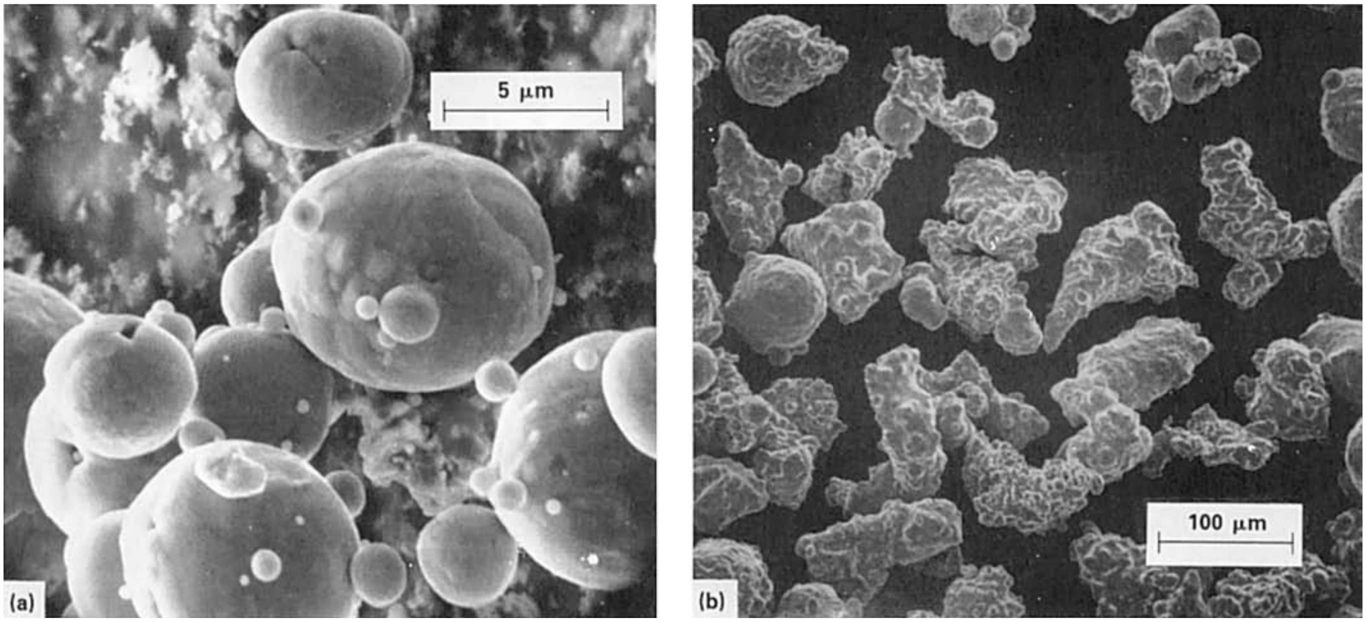

Fig. 2 Scanning electron micrographs of copper powder. (a) Air atomized. (b) Water atomized

Table 1 Free energies, heats, and rates of copper oxide formation

$2(Cu) + {}^1\!/_2(O_2) = <Cu_2O>$ exothermic
$\Delta G = -41{,}166 - 1.27 \times 10^{-3}\ T \ln T + 3.7 \times 10^{-3} T^2 - 1.80 \times 10^{-7} T^3 + 27.881\ T$
$k = 957\ e^{-37{,}700/RT}\ g^2cm^{-4}h^{-1}$

$<Cu> + {}^1\!/_2(O_2) = <CuO>$ exothermic
$\Delta G = -37{,}353 - 0.16\ T \ln T - 1.69 \times 10^{-3} T^2 - 9 \times 10^{-8} T^3 + 25.082\ T$
$\Delta H = -38{,}170 - 1.30\ T + 0.99 \times 10^{-3} T^2 + 0.57 \times 10^5\ T^{-1}$

$<Cu_2O> + {}^1\!/_2(O_2) = 2<CuO>$ exothermic
$\Delta G = -33{,}550 + 0.95\ T \ln T - 3.75 \times 10^{-3} T^2 + 22.340\ T$
$\Delta H = -35{,}710 + 3.28 \times T - 0.40 \times 10^{-3} T^2 - 0.20 \times -10^5\ T^{-1}$
$k = 0.0268\ e^{-20{,}140/RT}\ g^2cm^{-4}h^{-1}$

ΔG is free energy; ΔH is heat; values of ΔG and ΔH are given in calories per gram mole; k is a rate constant mathematically derived; T is the absolute temperature in kelvin; R is the absolute gas constant; ln is the natural logarithm (base e, where $e = 2.7182$).

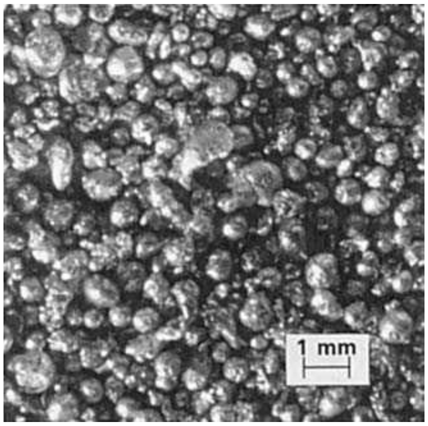

Fig. 3 Air-shotted copper

Reduction of Copper Oxide

Reduction of particulate copper oxide is generally accomplished on a stainless steel belt in a continuous belt furnace. The depth of the oxide bed is approximately 25 mm (1 in.). The typical reduction temperature ranges from 425 to 650 °C (800 to 1200 °F). Reduction occurs gradually from top to bottom of the bed. The reducing atmosphere in the furnace generally flows countercurrent to the motion of the conveyor belt.

Reducing atmospheres may include hydrogen, dissociated ammonia, water-reformed natural gas, or other endothermic or exothermic gas mixtures. Because reduction of copper oxides with hydrogen or carbon monoxide is exothermic, a careful balancing of oxide particle size, reducing gas species, and reduction temperature is necessary to optimize the reduction rate and to control the pore structure. Hydrogen diffuses readily through solid copper and is a more effective reducing agent than carbon monoxide, particularly at low temperatures. At higher temperatures, however, all reduction reactions involving either hydrogen or carbon monoxide proceed almost to completion. Free energies and heats of reaction for copper oxide reduction with hydrogen and carbon monoxide are shown in Table 2.

Control of Powder Properties. By manipulating the reduction process, the particle porosity, pore size, and particle size distribution of the finished powder can be controlled over a wide range. As with other metal oxides, low reduction temperatures generally produce particles having fine internal porosity and correspondingly high specific surface. High reduction temperatures produce particles containing large pores and low specific surface. High reduction temperatures generally result in more interparticle sintering and more complete reduction.

Post-Reduction Procedure. The reduced copper oxide emerges from the reduction furnace as a porous cake. It is broken into smaller pieces in a jaw crusher or similar equipment, followed by fine grinding in hammer mills. The amount of work hardening is moderate, and the resulting powders have good compressibility and green strength. A scanning electron micrograph of a typical copper powder is shown in Fig. 5.

Various combinations of the controlling parameters during melting, atomization, oxidation, reduction, and grinding permit the manufacture of powders with characteristics tailored to the requirements of all major applications.

The reduced and milled powder is screened and/or classified and, if necessary, blended and lubricated. These processing steps are carefully controlled to avoid losses or uncontrolled changes in characteristics such as apparent density, amount of fines, and powder flow. Some powder grades are treated with proprietary antioxidants to stabilize them against oxidation. Without this treatment, copper powders, particularly when exposed to moist air, generally tarnish, with attendant losses in green strength and other side effects. With increasing tarnish, the color of the powder changes from orange to purple to black. Simultaneously, oxygen content increases from a typical 0.1 or 0.2% to several tenths of a percent, and as much as approximately 1%.

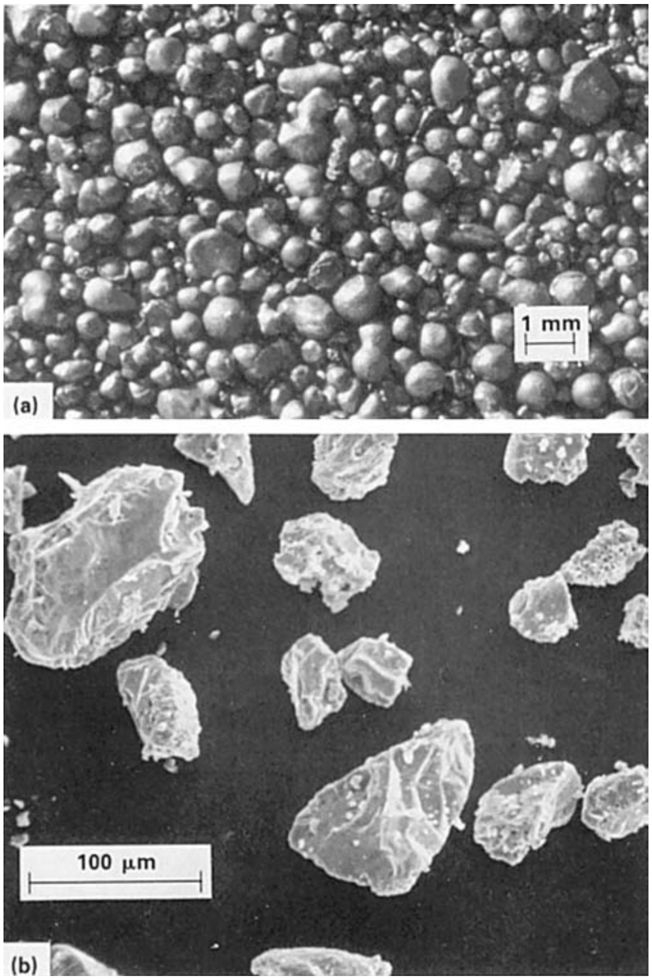

Fig. 4 Micrographs of copper oxide. (a) As-oxidized copper shot. (b) Scanning electron micrograph of copper shot after grinding

Table 2 Free energies, heats, and partial gas pressures for copper oxide reduction with hydrogen and carbon monoxide

$<Cu_2O> + (H_2) \leftrightarrow 2<Cu> + (H_2O)$ exothermic
$\Delta G = -16{,}260 + 2.21\ T \ln T + 1.28 \times 10^{-3}T^2 + 3.8 \times 10^{-7}T^3 - 24.768\ T$
$\Delta H_{298.1\ K} = -17{,}023$
Temperature, °C (°F): 450 (840), 900 (1650), 950 (1740), 1000 (1830), 1050 (1920)
P_{H2}, torr(a): 0.0104, 0.0150, 0.0207, 0.0283

$<Cu_2O> + (CO) \leftrightarrow 2<Cu> + (CO_2)$ exothermic
$\Delta G = -27{,}380 + 1.47\ T \ln T - 1.4 \times 10^{-3}T^2 + 0.5 \times 10^{-6}T^3 - 7.01\ T$
$\Delta H = -27{,}380 - 1.47\ T + 1.4 \times 10^{-3}T^2 - 1.1 -10^{-6}T^3$
Temperature, °C (°F): 25 (77), 900 (1650), 1050 (1920), 1083 (1980)
P_{CO}, torr(a): 0.021, 0.068 0.085

$2<CuO> + (H_2) \leftrightarrow <Cu_2O> + (H_2O)$ exothermic
$\Delta G = -24{,}000 - 0.01\ T \ln T + 5.4 \times 10^{-3}T^2 - 3.7 \times 10^{-7}T^3 + 22.896T$
$\Delta H_{298.1\ K} = -23{,}543$

$<CuO> + (H_2) = (H_2O) + <Cu>$ exothermic
$\Delta H_{290\ K} = -31{,}766$

$2<CuO> + (CO) \leftrightarrow (Cu_2O) + (CO_2)$ exothermic
$\Delta H = -33{,}300$

ΔG is free energy; ΔH is heat; values of ΔG and ΔH are given in calories per gram mole; P is pressure; T is the absolute temperature in kelvin; and ln is the natural logarithm (base e, where $e = 2.7182$). (a) Total pressure is 1 atm

Copper powders with large specific surface areas are more sensitive to tarnishing.

Finished Powders

Finished lots of powder are subjected to a series of tests designed to ensure performance in the various applications. The single most important application for copper powder is for self-lubricating bronze bearings. In the United States, these bearings are made predominantly from elemental blends of copper and tin. Since approximately 1960, preblended and lubricated mixtures of 90% Cu and 10% Sn that have graded dimensional change characteristics during sintering have increased in use.

Table 3 lists various grades of copper powders produced by the oxide reduction process; apart from bronze bearings, applications include copper-base friction materials, electrical contacts and brushes, diamond abrasive wheels, and copper additions to iron mixes for structural parts (Ref 1). Noncompacting applications include copper fillers in plastics, catalysts, and many chemical applications. The product brochures and data sheets of the powder producers generally provide details on the characteristics and performance properties of their powders (including sintered properties), as well as recommendations for specific uses.

Production of Copper Powder by Electrolysis

Production of electrolytic copper powder, as shown in Fig. 6, follows the same electrochemical principles that apply to the electrorefining of copper. The conditions of deposition, however, are changed to yield a powdery or spongy deposit, instead of the strongly adherent product desired in electrorefining. The formation of powdery deposits is favored by low copper ion concentration and high acid content in the electrolyte, as well as by high cathode current density.

Although these conditions yield spongy deposits, control of additional variables is necessary to produce powders that meet commercial requirements. Other factors are quantity and

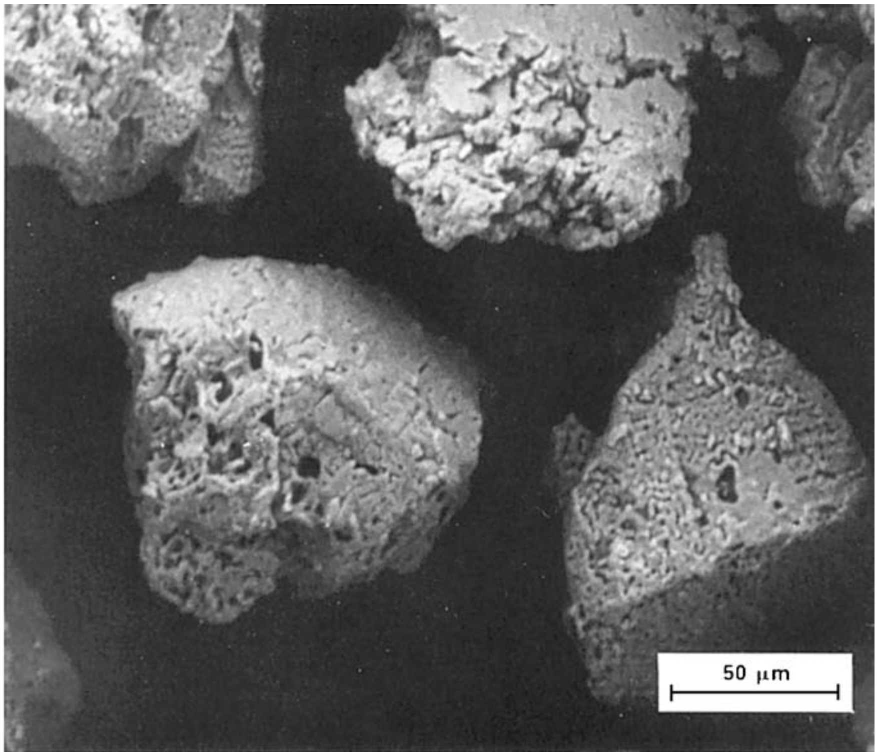

Fig. 5 Scanning electron micrograph of copper oxide reduced copper powder

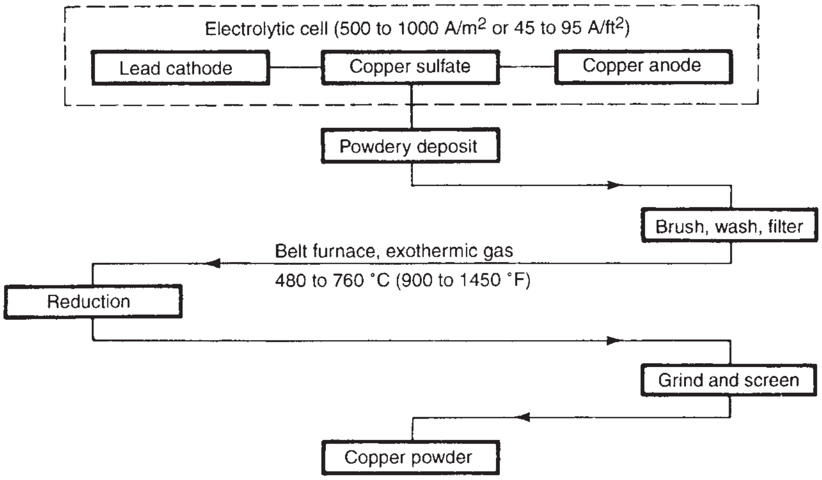

Fig. 6 Flowchart for production of electrolytic copper powder

Table 3 Typical properties of commercial grades of copper powders produced by oxide reduction

Chemical properties			Physical properties								Compacting properties at 165 MPa (12 tsi)(a)		
					Sieve analysis, % Tyler							Strength(b)	
Copper, %	Hydrogen loss, %	Acid insoluble, %	Apparent density, g/cm^3	Hall flow, s/50 g	+60	+100	+150	+200	+325	−325	Density, g/cm^3	MPa	psi
99.8	0.13	0.06	2.91	26	0.4	39.7	46.6	13.3	…	…	…	…	…
99.8(c)	0.13	0.03	3.00	22	…	0.1	0.6	15.5	42.8	41.1	6.15	8.6	1240
99.8(c)	0.13	0.04	2.83	23	…	…	0.1	9.5	33.4	57.0	6.12	9.7	1400
99.8(c)	0.16	0.04	2.75	24	…	…	0.1	7.3	29.0	63.6	6.03	10.4	1500
99.7	0.18	0.06	2.51	…	…	…	…	0.5	7.0	92.6	6.04	…	…
99.7	0.21	0.06	2.31	…	…	…	…	…	1.2	98.5	…	…	…
99.6(d)	0.28	0.10	1.61	…	…	…	0.1	2.8	10.3	86.7	6.0	20.0	2900
99.6(d)	0.26	0.10	1.36	…	…	…	0.1	1.5	7.9	90.5	5.97	22.8	3300
99.5(d)	0.26	0.10	0.94	…	…	…	0.1	0.2	1.4	98.6	5.90	29.0	4200

(a) Measured with die wall lubricant only. (b) Transverse rupture strength. (c) For bronze self-lubricating bearings. (d) For friction materials and electrical brushes type of addition agent, temperature and circulation rate of the electrolyte, size and type of anode and cathode, electrode spacing, and brush-down interval.

Effects of Electrolyte Composition

The composition of the electrolyte is a major factor in the production of powder. Copper concentration in the electrolyte must be sufficiently low to prevent adherent deposits. In the desired range, current efficiency rises with increasing copper ion concentration, as shown in Fig. 7, with a maximum of 92% in the range of 23 to 33 g/L (3 to 4.4 oz/gal) copper. Above approximately 3 g/L (4.4 oz/gal), current efficiency decreases, and a hard deposit is produced instead of powder. Apparent density and particle size also increase with a rise in copper ion concentration.

Acid Concentration. A high acid concentration favors the formation of powder. As shown in Fig. 8, current efficiency increases to a maximum at the concentration of 120 g/L (16 oz/gal) of sulfuric acid, then gradually falls as the acid concentration increases. Continued rise in acid concentration leads to passivity. Apparent density decreases with increasing acid concentration.

Table 4 Effect of addition agents on current efficiency and particle size

Test No.	Addition agent	Solution strength, %	Voltage, V	Current efficiency, %	Sieve analysis, % −200 mesh	Sieve analysis, % −300 mesh
1	…	…	1.0	95.9	74.6	55.0
2	Boric acid	0.5	1.0	95.2	…	100
3	Glucose	0.5	1.2	85.4	…	100
4	Glycerine	0.5	1.9	94.7	…	100
5	Glue	0.5	1.5	94.5	…	100

Source: Ref 1

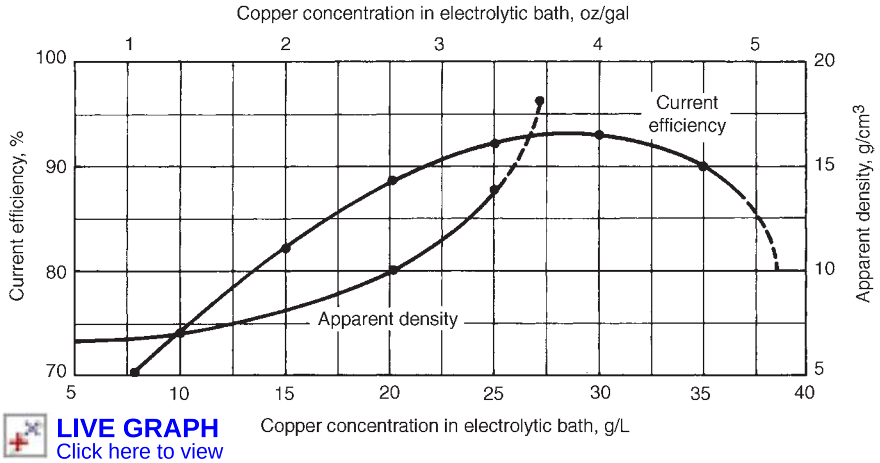

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Fig. 7 Effect of copper concentration on current efficiency and apparent density. Source: Ref 1

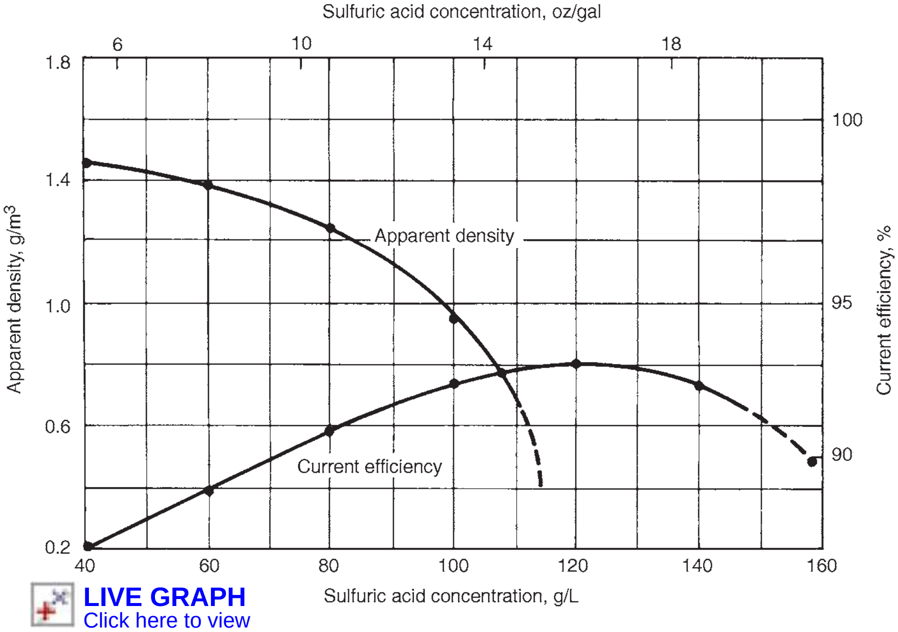

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Fig. 8 Effect of acid concentration on current efficiency and apparent density. Source: Ref 1

Addition Agents. The copper sulfate/sulfuric acid electrolyte occasionally is modified to alter powder characteristics. The addition of colloidal materials, such as glue or glucose, leads to the formation of fine powder deposits, possible because the colloid retards the evolution of hydrogen at the cathode. Table 4 indicates the effects of a number of additions to the electrolyte.

The addition of surfactants is reported to yield a powder with controllable particle size at a current density of 215 A/m^2 (20 A/ft^2), in contrast with the 700 to 1100 A/m^2 (64 to 100 A/ft^2) normally used, which results in considerable reduction in power cost (Ref 2). Small quantities of copper chloride have been added to the electrolyte to increase the dendritic character of the powder particles and to increase the yield of fine powder due to the polarizing effect of the chloride ions (Ref 3). The addition of sodium sulfate reportedly reduces the cathode current density, and as the sulfate content is increased, the powder becomes finer (Ref 4). By contrast, replacement of the normal sulfuric acid electrolyte by a sulfamate electrolyte favors the formation of a coarse copper powder (Ref 5).

Effects of Operating Conditions

Alteration of operating conditions can affect process variables such as current efficiency and the formation and size of particles.

Current Density. High current density favors the formation of powder, but has only a minor effect on current efficiency. A marked decrease in particle size occurs with rising current density. For example, in an electrolyte containing 25 g/L (3.3 oz/gal) copper and 120 g/L (16 oz/gal) free sulfuric acid, increasing the current density from 600 to 1000 A/m^2 (55 to 90 A/ft^2) raised the quantity of powder passing through a 300 mesh sieve from 20 to 96%.

Temperature. Raising the operating temperature of the cell increases the current efficiency and reduces the cell voltage. However, cell operation is difficult at temperatures higher than 60 °C (140 °F), and powders obtained at high temperatures are coarser than those produced at lower temperatures. Generally, electrolytic cells are operated at temperatures between 25 and 60 °C (77 and 140 °F).

Powder Removal. The method used to remove the powder from the cathode has a significant effect on powder characteristics. Usually the powder is removed mechanically by brushing. The brush-down interval aids in control of the particle size of the deposit and, as shown in Fig. 9, the powder becomes coarser as the interval is increased from 15 to 60 min. Figure 10 indicates that the apparent density increases as the brush-down interval is extended. Frequent brush-down also limits variations in cathode current density. In another approach to powder removal, an organic extract is used in combination with sodium lauryl sulfate to discharge the powder automatically from the cathode without brush-down (Ref 6).

Powder Production

The major producers of electrolytic copper powder generally follow the procedures used in electrolytic refining. However, as has been mentioned, changes in operating conditions are required to obtain a deposit of powder. Typical conditions for the production of copper powder are illustrated in Fig. 6 and can be summarized as:

Condition	Quantity
Copper	5–15 g/L (0.6–2 oz/gal)
Sulfuric acid	150–175 g/L (20–23 oz/gal)
Temperature	25–60 °C (77–140 °F)
Anode current density	430–550 A/m^2 (39–50 A/ft^2)
Cathode current density	700–1100 A/m^2 (64–100 A/ft^2)
Cell potential	1.0–1.5 V

Generally, the anodes are electrolytically refined copper, and the cathodes are lead alloy sheet. In a typical installation, the cathodes are 61 by 86 by 0.95 cm (24 by 34 by 0.37 in.) in dimension (Ref 7). Both anodes and cathodes are short to allow enough space at the bottom of the tank for the collection of the powder. The electrodes are arranged parallel to one another in lead-lined, rubber-lined, or plastic tanks, typically 3.4 m long by 1.1 m wide by 1.2 m high (11 ft long by 3.6 ft wide by 3.9 ft high). Each cell contains 18 cathodes spaced at 16 cm (6.4 in.) intervals and 19 anodes that are hung alternately. To ensure uniform current density and to eliminate short circuits in the cells, the electrodes are inspected frequently for prevention of excessive nodule buildup.

Typically, the electrolyte is pumped to an elevated storage tank, from which it flows by gravity into the tops of the cells and out through the bottoms. Thus, circulation is from top to bottom of the tanks, a type of circulation that yields a more homogeneous powder than that obtained by bottom-to-top circulation. The overflow returns to basement storage tanks to be recirculated.

The copper deposits on the cathode in the form of dendritic particles. To prevent short circuits between anode and cathode and heavy accumulation of powder on the cathode, both of which would decrease the cathode current density, the deposit is removed periodically by brushing.

After operating the cell for several days, the power is turned off. Most of the electrolyte is drained from the cell, leaving enough solution to cover the powder. The anodes and cathodes are washed down and removed, the remaining electrolyte is drained from the cell, and the powder is removed.

Thorough washing of the powder is essential. All traces of the electrolyte must be removed to prevent the powder from becoming oxidized. In addition, any remaining sulfate damages the heating elements if an electric furnace is used for subsequent drying and treatment of the powder. Various methods are employed to wash the powder. Although centrifuging to remove the electrolyte and wash the powder yields a clean product, the particles are compacted, and production of a low-density powder by this procedure is difficult.

In another method, the powder is transferred into a large tank, and water is added to produce a slurry that is pumped into a filter. In the filter, the powder is dewatered, washed several times, and again dewatered. Because the wet powder oxidizes readily due to its finely divided state and active surface, addition of a stabilizer is desirable. Treatment with an aqueous solution of gelatin protects the powder from oxidation in the intervals between successive operations (Ref 8). The addition of surface-active agents during washing or subsequent powder treatment also protects the powder from oxidation. Next, the powder must be subjected to a furnace operation to obtain an acceptable grade.

Furnace Operation

After thorough washing and filtering, the wet powder is ready for furnace processing. The furnace operation also alters certain properties, particularly particle size and shape, apparent density, and green strength. In a typical operation, the powder is transferred into the charge box of a mesh belt electric furnace (Ref 7). To prevent the powder from falling through the belt, a continuous sheet of high wet-strength paper is fed to the belt, and then the powder is transferred to the paper. A roller compresses the powder to improve heat transfer. As it enters the furnace, water is driven off and the paper burns, but not before the powder has sintered sufficiently to prevent it from falling through the belt.

The furnace atmosphere is produced in exothermic gas units in which natural gas and air are blended to yield an atmosphere containing 17% H_2, 12% CO, 4% CO_2, and the balance of nitrogen. The gas is refrigerated to lower the dew point to the range of –22 to –40 °C (–8 to –40 °F). The gas enters the furnace from the discharge end and, because it is refrigerated, aids in cooling the powder cake. The furnace operation dries the powder, alters the particle shape, reduces the oxides, and sinters the fines. The discharge temperature is sufficiently low to prevent reoxidation of the powder cake.

By varying the furnace temperature between 480 and 760 °C (900 and 1400 °F) and altering the time of exposure, considerable change can be made in the content of fines, apparent density, and dimensional characteristics. Upon completion of the furnace operation, the cake is broken and is ready for grinding.

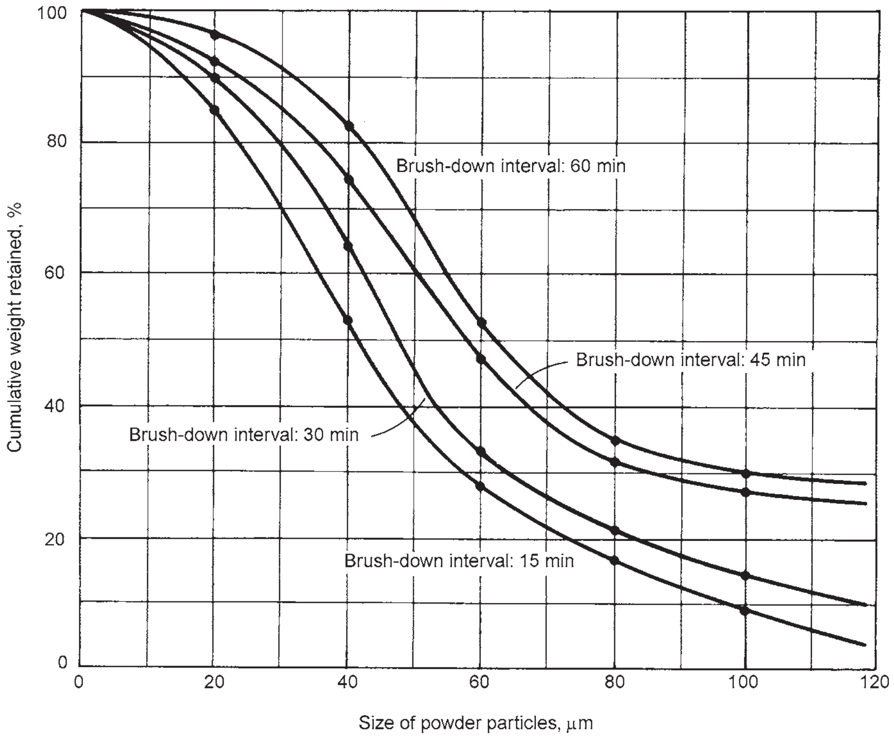

Fig. 9 Effect of brush-down interval on particle size. Source: Ref 1

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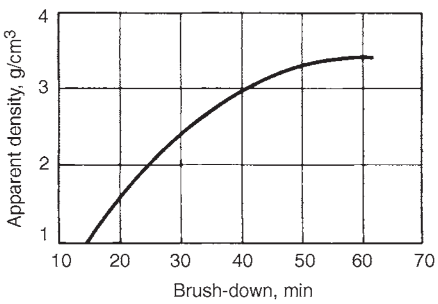

Fig. 10 Effect of brush-down interval on apparent density. Source: Ref 1

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Table 5 Properties of typical commercial grades of electrolytic copper powders

Chemical properties			Physical properties						
				Sieve analysis, % Tyler					
Copper, min, %	Hydrogen loss, max, %	Acid insoluble, max, %	Apparent density, g/cm^3	+60	+100	+150	+200	+325	−325
99.8	0.15	0.06	2.5–2.7	…	5 max	1–13	11–24	20–30	40–55
99.8	0.15	0.06	2.3–2.5	…	1 max	6 max	…	50–60	40–50
99.7	0.20	0.06	2.0–2.3	…	…	…	0.8	5–15	85–95
99.7	0.20	0.06	1.75–1.95	…	…	…	trace	5–15	85–95
99.7	0.20	0.06	1.25–1.45	…	…	…	trace	10 max	90 min
99.7	0.20	0.06	0.9–1.1	…	…	…	trace	10 max	90 min
99.7	0.20	0.06	0.65–0.75	…	…	…	trace	10 max	90 min

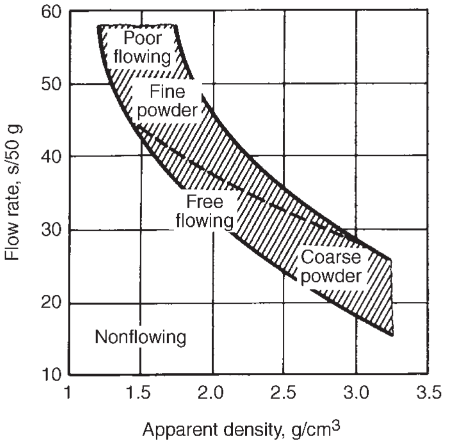

Fig. 11 Relationship between apparent density and flow rate. Source: Ref 11

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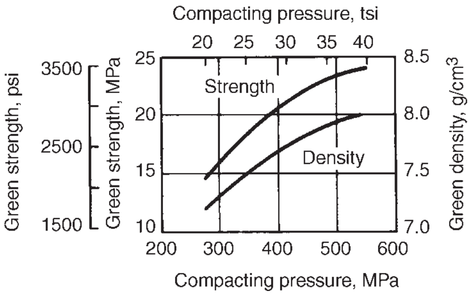

Fig. 12 Effect of compacting pressure on green strength and green density. Source: Ref 9

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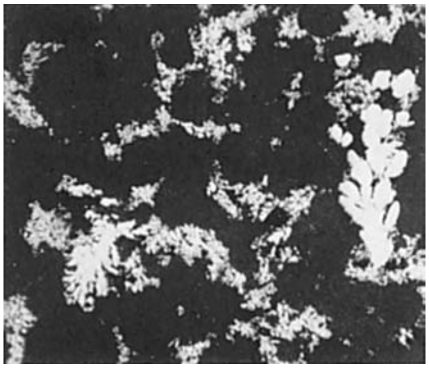

Fig. 13 Electrolytic copper powder showing dendritic structure. 85×. Source: Ref 9

Grinding and Finishing

Fine grinding is performed in high-speed, water-cooled hammer mills in which feed rate, mill speed, and screen openings under the mill can be varied to obtain the powder characteristics desired; thus, grinding is another operation in which powder properties can be changed. The powder leaving the hammer mills is fed to screens, where the oversize is separated and returned for additional grinding. The –100 mesh powder is classified in an air classifier, and the fines are transferred to the blending operation. Oversize material is returned for regrinding or is used as melting stock.

The products of the grinding and classifying operations range in apparent density from approximately 1 to 4 g/cm^3. They are stored in drums to which a drying agent such as silica gel or camphor is added to prevent further oxidation. To produce high volume finished powder that meets customer specifications, powder is selected from various batches in the proper proportions and mixed in a blender. The lot is sampled before being removed from the blender, and if required, adjustments of the particle size distribution are made before the powder is packed in shipping drums. Table 5 lists the physical characteristics of several representative blends.

Process Modifications

Although most electrolytic powder is produced as previously described, other methods have been used. To obtain a very low density product, one producer employs small-size cells and handles the powder lightly in both the cell and the finishing operations. The resulting powder shape is fern-like and has an apparent density of 0.9 to 1.3 g/cm^3.

Another process for the production of copper powder uses a vertical rotating titanium cathode that is partially immersed in a copper sulfate/sulfuric acid electrolyte (Ref 10). In the operation, the powder is collected continuously above the liquid level by scraping the cathode, followed by continuous dewatering, washing, and drying steps.

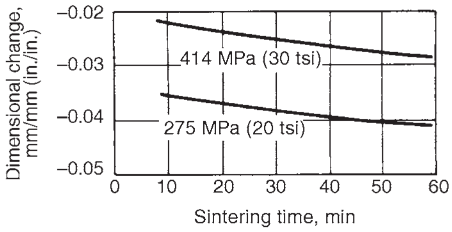

Fig. 14 Effect of sintering time on dimensional change. Source: Ref 9

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Properties of Electrolytic Copper Powder

The properties of electrolytic copper powder are dependent on various characteristics of the operation and, therefore, can often be controlled by altering certain process variables.

Purity of powder prepared by the electrolytic process is high, with a copper content that usually exceeds 99.5% (Table 5). A measure of the oxygen content is obtained by exposing a sample of powder to hydrogen at an elevated temperature as specified in ASTM Standard E 159 or Metal Powder Industries Federation Standard (MPIF) 02, and International Organization for Standardization (ISO) 4491/2. Generally, the hydrogen loss ranges from 0.1 to 0.5%, depending on the apparent density and particle size distribution of the powder. Nitric acid insolubles are determined by ASTM E 194 or MPIF 08 standard procedures and generally are less than 0.05%.

Particle size distribution for copper powder is selected to meet the requirements of the application and can be varied over a wide range. As noted in Table 5, several combinations are produced, and these are only representative. For example, the –325 mesh fraction can be varied from 5 to 90%.

Apparent densities of powders are available from 1.0 to 4.0 g/cm^3. Densities that are somewhat lower and higher can be produced depending on process and electrolyte conditions.

Flow rate is shown in relationship to apparent density in Fig. 11. Generally, powders with densities of less than about 1.3 g/cm^3 do not flow, powders with apparent densities of 1.3 to 2.3 g/cm^3 have poor flow rates, and powders with higher apparent densities flow freely. At approximately 2.2 g/cm^3, which is the transition range, flow depends on the content of fine particles of the powder, because relatively fine powders have poor flowability and relatively coarse powders flow freely. The flow rates of the usual blends of electrolytic copper powder range from 25 to 40 s/50 g.

Green density is a function of the compacting pressure. As shown is Fig. 12, the green density for the blend used rises from 7.2 to 8.0 g/cm^3 as the compacting pressure is increased from 275 to 550 MPa (920 to 40 tsi).

Green strength increases with the compacting pressure, as indicated in Fig. 12. In this example, the green strength rises from less than 15 to 24 MPa (2200 to 3500 psi) as the compacting pressure is increased from 275 to 550 MPa (20 to 40 tsi).

Particle shape of electrolytic copper generally is dendritic when deposited on the cathode (Fig. 13). During subsequent operations, however, the dendrites are rounded somewhat.

Compacting pressure is an important variable to consider, because the pressing and sintering conditions have a marked influence on the properties of sintered compacts. If sound compacts are to be obtained, gases from the atmosphere, from the products of reduction, or from the lubricant must escape during sintering. When the compacting pressure is too high, the flow through interconnected pores may be obstructed, and the gases cannot escape. Compacting pressures no higher than 275 MPa (20 tsi) should be used in the production of large, thick parts from electrolytic copper powder, although higher pressures can be used for thin-walled parts (Ref 12).

Dimensional changes in a typical powder blend lubricated with lithium stearate are shown in relationship to sintering time in Fig. 14. The lubricated powder blend was pressed as indicated and sintered at 1000 °C (1830 °F) in an atmosphere of dissociated ammonia atmosphere. Relatively stable dimensional changes are achieved at normal sintering times.

Tensile strength and elongation of a typical powder blend are shown in Fig. 15 in relationship to compacting pressure and sintering time. The powder was lubricated with lithium stearate, pressed as indicated, and sintered at 1000 °C (1830 °F) in an atmosphere of dissociated ammonia. The graph demonstrates that good tensile properties can be obtained with short sintering times.

Electrical conductivity that is high can be achieved. However, a high-purity powder, a characteristic of powder produced by the electrolytic process, must be used. Figure 16 shows the relationship between electrical conductivity and sintered density; high conductivity can be achieved only in high-density compacts. Electrical conductivity can be increased by coining and resintering (Fig. 17).

Applications

Presently, electrolytic copper powder is produced in Germany, Italy, Russia, Japan, India, and Brazil where it is used in most copper powder applications. However, in the United States, since the early 1980s when electrolytic copper powder production ceased, applications such as bronze bearings, copper-base friction materials and copper additions to iron mixes have, with a few exceptions, been converted to powders made by oxide reduction or water atomization. But electrolytic copper is still the powder of choice in many electrical and electronic applications, where high electrical and thermal conductivity is required. Using suitable fabricating procedures, parts can be produced with conductivities of 90% International Annealed Copper Standard (IACS) and higher. Complex parts such as armature bearing blocks, contacts for circuit breakers, shading coils for contactors, heavy-duty contacts for circuit breakers, switch gear components for use in switch boxes with capacities up to 600 A, and components for 150 and 250 A fuse blowouts are in regular production. Heat sinks for diodes used in silicon rectifiers for the alternating current system in automobiles and electrode tools for electrical discharge machining also are produced from electrolytic copper powder.

Although recently-developed oxide-reduced grades with higher purity, lower apparent density, higher green strength (see Table 3) and higher surface area (up to 0.8 m^2/g) have found increased usage in the manufacture of electrical brushes, electrolytic copper is still the preferred powder, having a combination of purity, high electrical conductivity, high surface area and particle morphology (dendritic shape) which allow a large volume of graphite to be accommodated while maintaining a copper matrix with high conductivity and high strength.

Electrolytic copper powder is used with various nonmetallic materials to produce friction parts, such as brake bands or clutch disks. Premixes of iron-copper or iron-copper-carbon are employed in various automotive applications—cams, sprockets, gears, piston rings for small-bore engines—and similar service.

Production of Copper Powder by Atomization

Water atomization of copper—that is, the disintegration of a molten stream of high-quality copper with high-pressure water jets—produces copper powders of compacting-grade quality. The resulting dried powder then may be subjected to an elevated-temperature treatment that further modifies its characteristics and engineering properties.

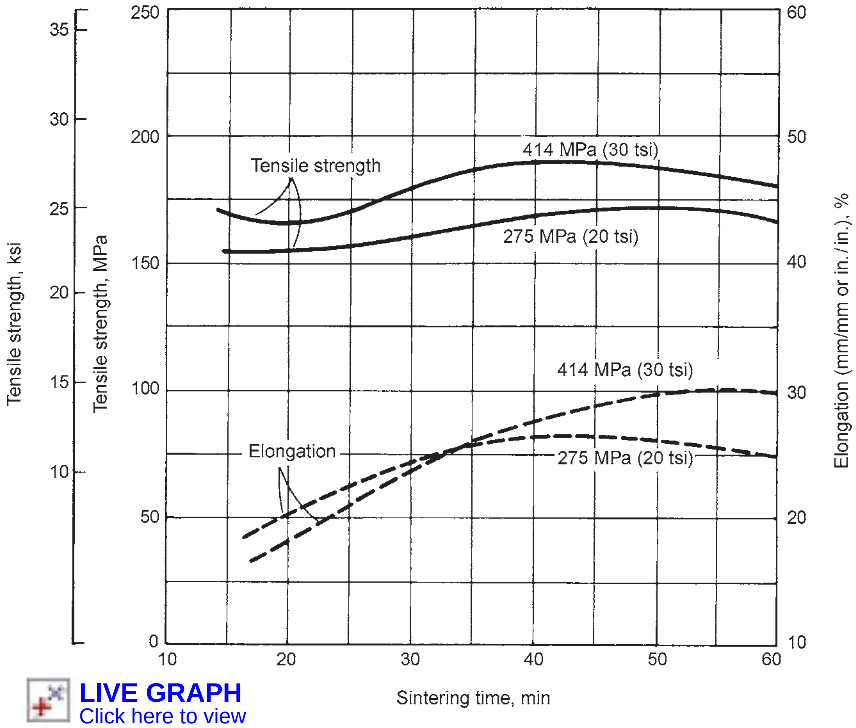

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Fig. 15 Effect of compacting and sintering conditions on tensile properties. Source: Ref 9

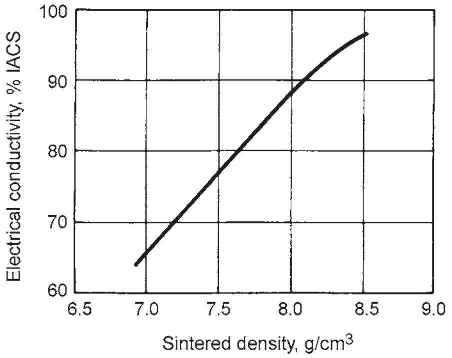

Fig. 16 Effect of sintered density on electrical conductivity. Source: Ref 9

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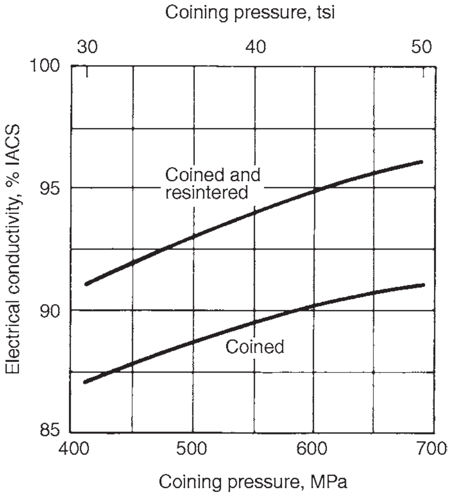

Fig. 17 Effect of coining and resintering on electrical conductivity. Source: Ref 9

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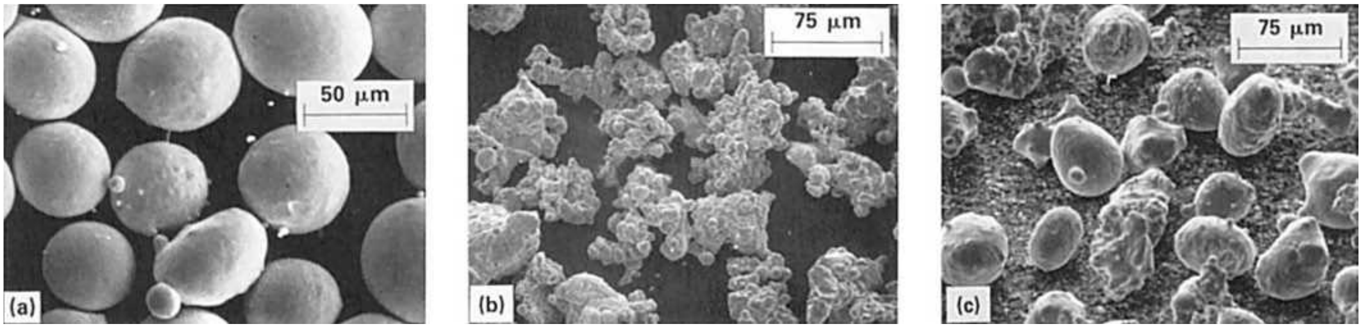

Fig. 18 Scanning electron micrographs of gas- and water-atomized copper powders. (a) Nitrogen atomized. (b) Water atomized, apparent density of 3.04 g/cm^3. (c) Water atomized, apparent density of 4.60 g/cm^3

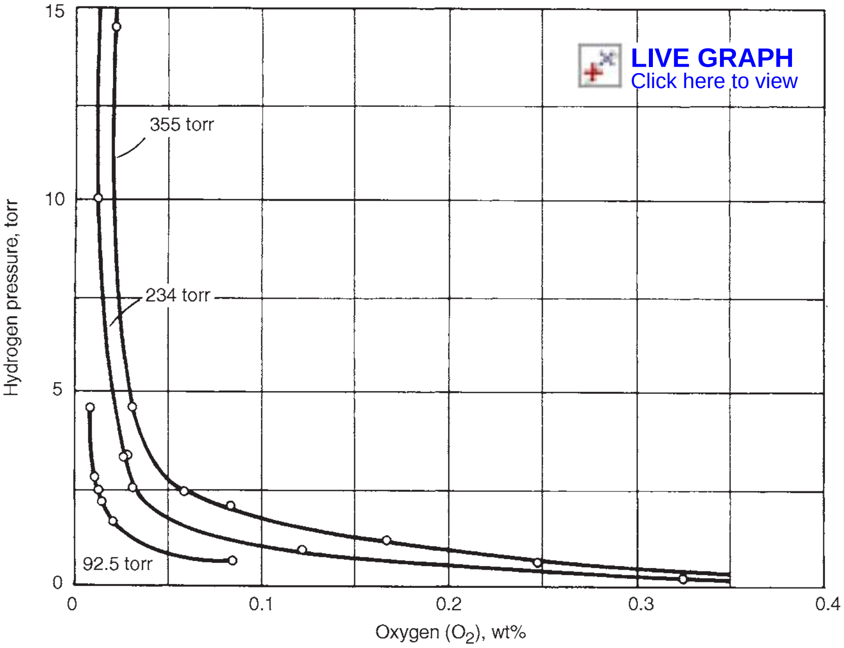

Fig. 19 Effect of partial pressures of hydrogen and steam on oxygen content of liquid copper at 1150 °C (2100 °F). $Cu + H_2 \leftrightarrow 2Cu + H_2O$ reaction at various water vapor pressures

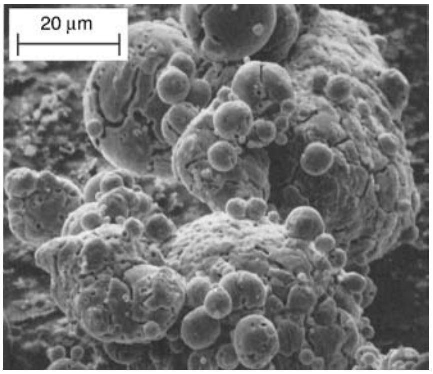

Fig. 20 Hydrogen-embrittled, air-atomized copper after reduction in hydrogen

Nearly spherical powders result from the atomization of liquid copper with inert gas or air. These powders are used in copper flake production and other specialty applications. Spherically shaped copper powders have insufficient green strength for use in conventional P/M. To render them compactible, their particle shape and morphology may be changed by deformation and/or oxidation and reduction, as described in the section "Production of Copper Powder by the Reduction of Copper Oxide" in this article. Particle shapes of gas- and water-atomized copper powder are shown in Fig. 18. Details specific to the water atomization of copper and subsequent processing are discussed subsequently in this article.

Commercial Practice

Liquid copper is superheated to approximately 1150 to 1200 °C (2100 to 2200 °F), utilizing flow rates of 27 kg/min (60 lb/min) or more. Generally, to produce a predominantly –100 mesh powder, water pressures of 10 to 14 MPa (1500 to 2000 psi) are used. Atomization may be conducted in an air or inert (nitrogen gas) atmosphere.

During melting of the copper, impurity content must be controlled to achieve good fluidity and high conductivity (Fig. 1). The need for oxygen control at this stage of the process depends on subsequent processing and end use of the powder. In conventional refining of copper, poling and steam-generated hydrogen keep copper oxidation under control in accordance with the equilibrium curves shown in Fig. 19. High oxygen content tends to produce a more irregular powder, and subsequent reduction of the atomized powder further improves compactibility through agglomeration and pore generation. If the powder is used in the as-atomized condition, lower oxygen contents are generally preferred, because of the detrimental effects of oxygen in many applications.

The apparent densities of –100 mesh gas-atomized copper powders, as a consequence of their spherical particle shape, range between 4 and 5 g/cm^3. Oxygen picked up during atomization is present partly as surface oxide and partly as copper oxide throughout the bulk of a copper particle. Removal of oxygen requires reduction temperatures of approximately 700 °C (1290 °F) or higher. At these temperatures, considerable sintering occurs, which in turn requires substantial milling of the sinter cake.

During reduction, hydrogen readily diffuses through solid copper to react with oxygen and form steam. The large steam molecules, unable to diffuse through solid copper, force their way outward through grain boundaries—phenomenon known as hydrogen embrittlement of copper that manifests itself in the formation of blisters or cracks. Figure 20 illustrates the grain boundary widening of air-atomized copper particles due to this phenomenon. These defects improve both compactibility and sintering rate during liquid phase sintering of copper mixed with tin.

Alloying Additions

Some applications of copper powders require apparent densities lower than those attainable with water atomization of pure copper. These powders can be produced by addition of small amounts, up to 0.2%, of certain elements (for example, magnesium, calcium, titanium, and lithium) to the liquid copper prior to atomization (Fig. 21 and 22). These metals are believed to decrease the surface tension of copper and/or to form thin oxide films on the particle surface during atomization. Magnesium additions are most frequently used to produce compaction-grade copper powders for applications such as bronze bearings, filters, structural parts, and additives for iron powders. These powders may have apparent densities as low as 2 g/cm^3.

The addition of small amounts (0.1 to 0.3%) of phosphorus to the liquid copper, prior to atomization, allows the production of a powder that is very spherical and very low in oxygen. During atomization, even with air, the phosphorus oxidizes preferentially and forms protective gaseous phosphorus pentoxide (P_2O_5). Such powders have apparent densities up to approximately 5.5 g/cm^3. Spherical copper powders with closely controlled particle size ranges are used in applications such as thermal spray coatings, metal impregnated plastics, and heat exchangers. Irregular copper powders are used in compacting applications such as bronze mixes for self-lubricating bearings, additions to iron mixes, friction materials, electrical brushes, diamond cutting wheels, and electrical parts requiring high strength and electrical/thermal conductivity. Irregular copper powders are also used in copper brazing pastes and various chemical applications such as catalysts and in the production of copper compounds. Table 6 lists the properties of typical commercial atomized copper powders. The specific surface areas of these powders are from 0.02 m^2/g for coarse spherical gas-atomized powder, to 0.2 m^2/g for fine water-atomized powder.

Production of Copper Powder by Hydrometallurgical Processing

Hydrometallurgical methods may be used to produce a number of metal powders, including copper, cobalt, and nickel. The basic processing steps consist of preparing pregnant liquor by leaching ore or another suitable raw material, followed by the precipitation of the metal from this solution. For copper, the most important precipitation methods are cementation, reduction with hydrogen or sulfur dioxide, and electrolysis. Use of several leach-precipitation steps or the inclusion of flotation, solvent extraction, or ion exchange improves the purity of the final material.

Despite several process development efforts in the 1950s and 1960s that led to radical improvements in purity and properties of hydrometallurgically produced copper powders, commercialization attempts in the United States have failed. Causes for this failure include the increasing cost of energy, coupled with the high energy requirements of some hydrometallurgical methods and the difficulty in economically producing powders with a wide range of properties suitable for various uses.

Cement copper, like other hydrometallurgically produced copper powders, has low apparent density and high specific surface area (1 m^2/g). The particles are spongy because they are agglomerates of very small primary particles (Fig. 23). Although cement copper often has higher green strength characteristics than most other copper powders, its sintering activity, when used alone or in 90/10 bronze, is inferior because of the presence of finely divided, unreducible aluminum and silicon oxides. The primary use of cement copper is in composite friction material applications.

Leaching

The leaching of copper oxide and copper sulfide ores entails partial dissolution to cupric sulfate ($CuSO_4$) with sulfuric acid (H_2SO_4) plus

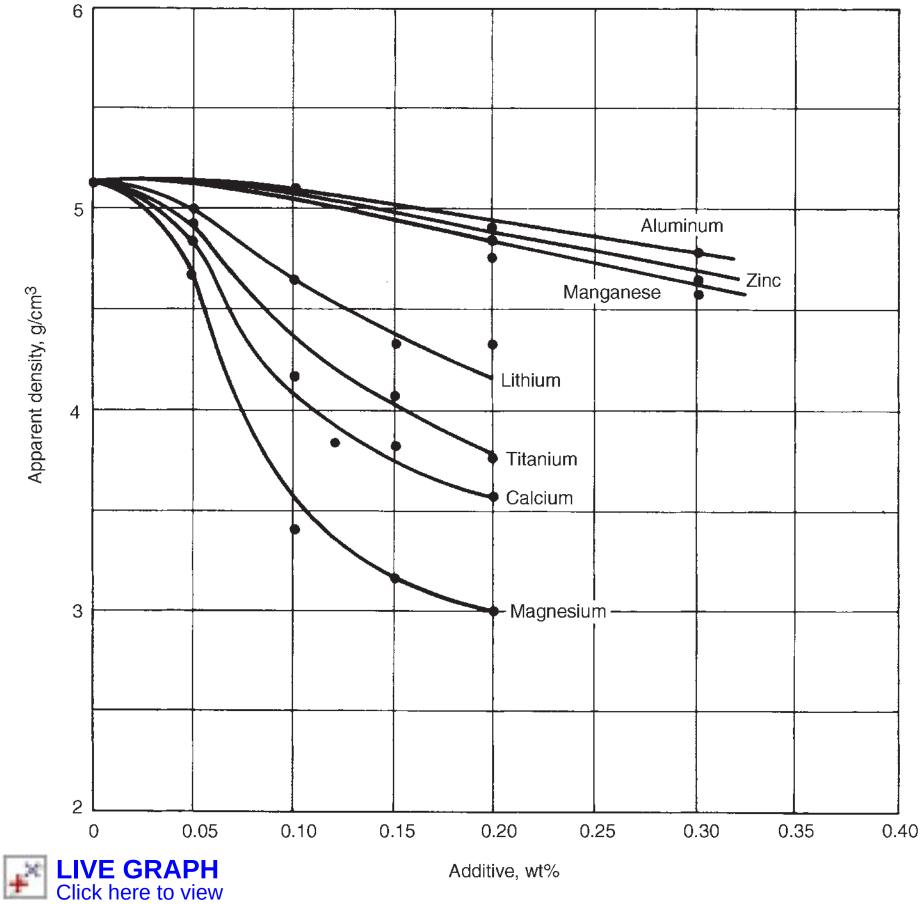

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Fig. 21 Effect of additions to the molten copper on apparent density of atomized copper powder

Table 6 Properties of typical commercial grades of water- and gas-atomized copper powders

Chemical properties			Physical properties							
Copper, min, %	Hydrogen loss, max %	Acid insoluble, max, %	Apparent density, g/cm^3	Sieve analysis, % Tyler						
				+60	+80	+100	+150	+200	+325	−325
99.0(a)	NA	NA	4.5–5.5	5 max	30–60	30–60	15 max	…	…	…
99.0(a)	NA	NA	4.5–5.5	…	2 max	20–50	50–75	10 max	trace	…
98.5(a)	0.7	NA	4.5–5.5	…	trace	0.2 max	5 max	2 max	bal	60–90
98.5(a)	0.7	NA	4.5–5.5	…	…	…	…	0.5 max	bal	95 min
99.3(b)	0.3	0.1	2.5–2.7	…	…	0.8 max	35 max	70 max	bal	5 max
99.3(b)	0.3	0.1	2.5–2.8	…	…	1 max	20 max	25 max	40 max	30–45
99.3(b)	0.3	0.1	2.5–2.8	…	…	0.5 max	10 max	20 max	bal	42–55
99.3(b)	0.3	0.1	2.8–3.0	…	…	trace	1 max	15 max	bal	55–65
99(c)	0.35	NA	2.1–2.4	…	…	5 max	15–25	10–20	15–35	20–40
99(c)	0.35	NA	2.3–2.6	…	…	1 max	10 max	5–20	15–30	60–70
99(b)	0.5	0.1	2.1–2.5	…	…	…	1 max	3 max	14 max	85 min

NA, not applicable. (a) Air atomized. (b) Water atomized/annealed. (c) Water atomized + Mg

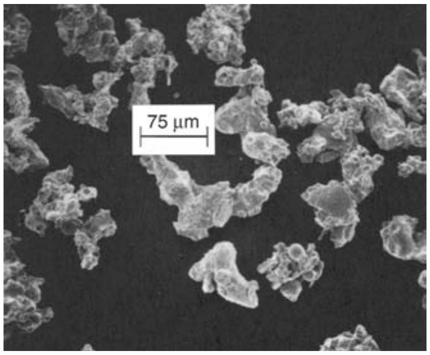

Fig. 22 Scanning electron micrograph of water-atomized copper containing 0.5% Li

iron sulfate ($FeSO_4$). The presence of pyrite (FeS_2) in many ore deposits, and its reaction with water and oxygen to form iron sulfate and sulfuric acid, represents an important source of acid. In dump leaching, the pH of the leach solution is maintained between 1.5 and 3.0, partly to protect bacteria that promote and accelerate the oxidation of pyrite and sulfidic copper minerals and also to avoid hydrolysis of iron salts.

The copper content of the pregnant solutions varies from less than 1 g/L (0.15 oz/gal) to several grams per liter (ounces per gallon); for vat leaching, it can be much higher. Other leaching methods include ammonia leaching, which is used for certain copper oxide ores, and the so-called leach-precipitation-flotation method, which is applied to mixed oxide sulfide ores.

Cementation

The precipitation of a metal from its solution by the addition of another less noble metal is known as cementation. The fundamental equation for copper recovery from copper-bearing pregnant liquors on iron is:

$$Fe + CuSO_4 = Cu + FeSO_4$$

In practice, the copper-bearing solution is passed over scrap iron, such as detinned and shredded cans. Subsequent separation, washing, reduction, and pulverizing produces a copper powder that contains considerable amounts of iron and acid insolubles, such as alumina and silica. Contamination with gangue varies and depends on the nature of the pregnant liquor.

Significant reduction in iron and alumina levels is possible through the use of V-trough or inverted precipitators that allow faster precipitation rates and more efficient iron utilization. Table 7 shows chemical analyses of cement copper from different sources. Copper and iron are present, partly as oxides.

Additional Reduction Processes

Electrowinning may be used to recover copper from leaching solutions containing more than approximately 25 g/L (3.4 oz/gal) of copper (Harlan process). The electrolytic cells are equipped with insoluble lead-antimony anodes and 99% Ni cathodes. The copper powder does not adhere, but falls to the bottom of the cells. Temperature of the electrolyte is 60 °C (140 °F); cathode current density varies from 1350 to 2700 A/m^2 (125 to 250 A/ft^2). When the copper concentration falls below 15 g/L (2 oz/gal), the electrolyte is drained and used for ore leaching. Particle size of the powder prior to furnace processing is 1 to 25 μm, with excellent purity (>99.9%). The power requirements for electrowinning of copper are approximately ten times as large as those for electrorefining of copper with soluble anodes.

Copper may be concentrated from low-content leach solutions by solvent extraction, followed by stripping with dilute sulfuric acid into an aqueous solution and electrowinning. Carboxylic acid and hydroxylamine-based compounds have been found to be selective solvents of low water solubility, to have good stability, and to be compatible with inexpensive diluents. Direct powder precipitation with hydrogen or ammonia is an alternative to stripping the metal from the organic solvent into an aqueous solution.

Metals can be precipitated from their acid or basic solutions by reduction with hydrogen. Sulfuric acid, ammoniacal ammonium carbonate, and ammoniacal ammonium sulfate solutions have been used to produce copper powder by this method. Sulfuric acid leaching of a cement copper and hydrogen reduction of the filtered solution in an autoclave at 120 to 140 °C (250 to 280 °F) and 3 MPa (425 psi) is reported to produce a precipitate with a purity of about 100% Cu. Drying and furnace processing in a reducing atmosphere at 540 to 790 °C (1000 to 1450 °F) increases particle size due to agglomeration of the very fine powder.

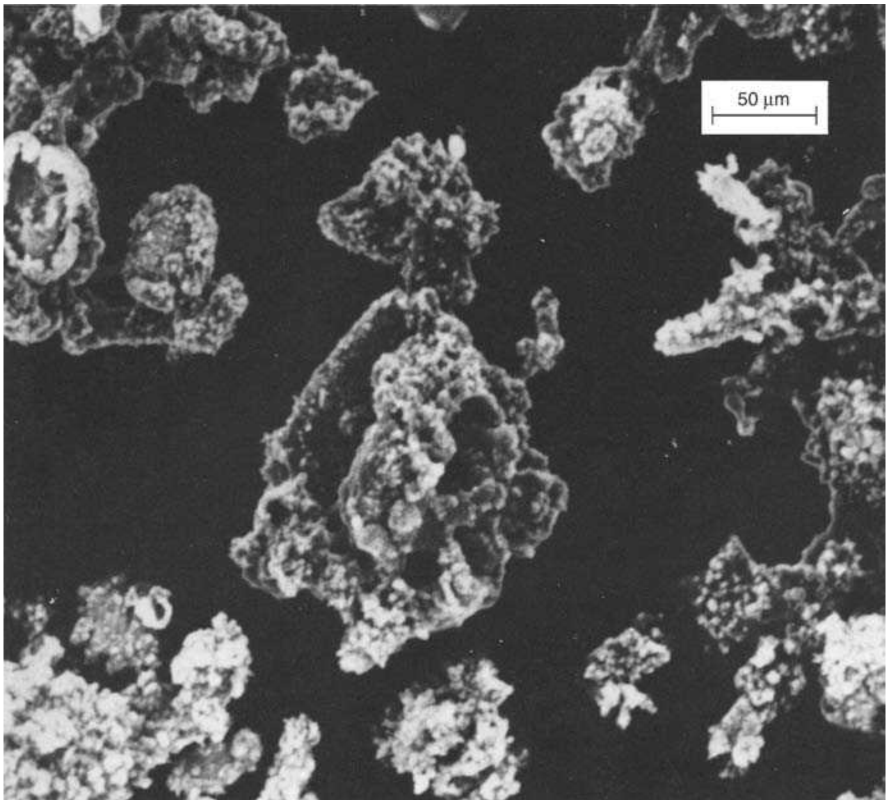

Fig. 23 Scanning electron micrograph of cement copper

Production of Copper Alloy Powders

Commercial copper alloy powders, including brasses, bronzes, and nickel silvers, are manufactured in a similar manner. Usually, the same integrated manufacturing facilities are used to complete the melting process, atomization, final screening, and blending of a lot or batch.

The powder-producing process is similar to a foundry operation in which high-purity virgin metals are charged to a melting furnace in preweighed batches to be processed at predetermined heating rates and times. High-purity raw materials are required because melting produces minimal refinement (only a partial transfer of contaminants from the melt to the formed slag occurs). To ensure continuity, homogeneity, and uninterrupted atomization, the molten batch of alloy is transferred to a second furnace with a greater holding capacity than the primary furnace melting rate. Induction heating is preferred for at least one furnace to ensure the constant induced metal movement required for alloy homogeneity and to ensure uniform lead dispersion in lead-bearing alloys.

Atomization is achieved by particulation of a controlled, constant-flowing, molten stream emitted from the secondary furnace by medium-pres-

Table 7 Chemical analyses of cement copper from various locations (dry basis)

	Composition, wt%, for location			
Component	A	B	C	D
Total copper	75	83.0	87.4	85.0
Iron	6	2.4	0.7	10.0
Sulfur	1	0.5	…	1.1
Nitric acid insolubles	2	…	0.7	1.9
Hydrogen loss	16	…	…	…
Calcium oxide	…	0.08	…	…
Aluminum oxide (alumina)	…	1.2	0.5	…
Silicon dioxide	…	0.4	…	…
Lead	…	…	0.2	…
Oxygen	…	…	9.5	…

sure dry air. A typical melting and atomizing sequence is show in Fig. 24. Subsequent reduction of oxides is not required for standard P/M grades.

Air-cooled, atomized powder is collected and passed over a primary control screen (sieve) to remove oversize particles. Usually, these are remelted concurrently during the processing of each alloy. Finally, the screened alloy powder may be blended with dry organic lubricants, such as lithium and zinc stearate, for use in the manufacture of P/M structural components.

Adjustment of powder properties (particle size distribution, apparent density, green strength, etc.) of each alloy is accomplished by controlled manipulation of the atomizing process conditions (e.g., atomizing air flow rate, molten metal temperature, nozzle configuration, etc.). Powder properties are maintained by periodically recording the atomizing parameters and by evaluating the properties of representative samples from the in-process atomized product.

A variety of copper-base alloys can be manufactured by the atomizing process; however, commercial P/M applications normally are confined to a rather narrow range of specific, single-phase (α) compositions.

Brass Powder Production

Brasses comprise the major portion of copper-base alloy powders used for parts fabrication, in comparison with prealloyed bronze and nickel silver materials. Typical copper-zinc brass powders contain zinc contents ranging from 10 to 30%. Lead may be added in small amounts (1 to 2%) to improve machinability of the sintered compact. A photomicrograph of an 80%Cu-18%Zn-2%Pb alloy powder is shown in Fig. 25. The melting temperatures of these alloys range from 1045 °C (1910 °F) for 90%Cu-10%Zn to 960 °C (1760 °F) for 70%Cu-30%Zn. As zinc content increases, melting temperature is lowered.

Additional superheat, or the temperature in excess of the alloy melting temperature, depends on heat losses within the manufacturing system and the physical property requirements of the atomized powders. Typical physical properties of brass alloy compositions are given in Table 8.

Bronze Powder Production

Air-Atomized Bronzes. Prealloyed atomized bronze compositions are not used extensively as base powders for compacted parts fabrication because of their nodular particle form and high apparent density, both of which contribute to poor compacted green strength. Common prealloyed compositions are 90%Cu-10%Sn and 85%Cu-15%Sn, prepared in the same manner as brass powder except that high-purity elemental copper and tin are used. A scanning electron micrograph of an 89%Cu-9%Sn-2%Zn alloy powder is shown in Fig. 26. Typical physical properties of a bronze alloy composition are given in Table 8.

Water-Atomized Bronzes. Prealloyed bronze powders are also made commercially by water atomizing. Application is more extensive in Europe, where 90/10 prealloyed bronze powders are incorporated in bronze premixes for bearing manufacture. Low green strength due to high apparent density (3.2 to 3.6 g/cm^3) is overcome by incorporating lower apparent density copper powders (see section on copper

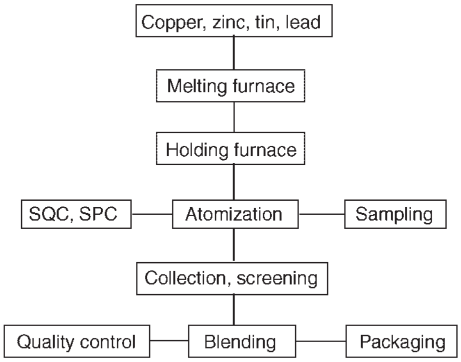

Fig. 24 Flowchart for copper alloy powder air atomization. SQC, statistical quality control; SPC, statistical process control

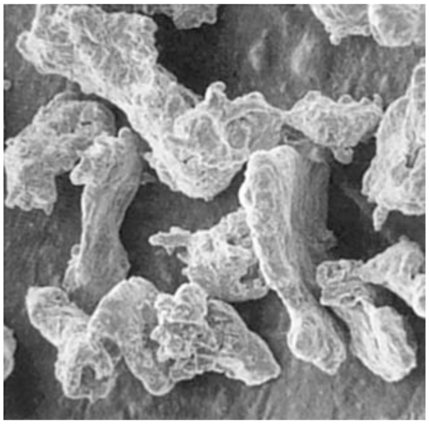

Fig. 25 Scanning electron micrograph of prealloyed, air-atomized brass (80%Cu-18%Zn-2%Pb). 165×

Table 8 Physical properties of typical brass, bronze, and nickel silver alloy powder compositions

Property	Brass(a)	Bronze(a)	Nickel silver(a)(b)
Sieve analysis, %			
+ 100 mesh	2.0 max	2.0 max	2.0 max
− 100 + 200	15–35	15–35	15–35
− 200 + 325	15–35	15–35	15–35
− 325	60 max	60 max	60 max
Physical properties			
Apparent density	3.0–3.2	3.3–3.5	3.0–3.2
Flow rate, s/50 g	24–26	…	…
Mechanical properties			
Compressibility(c) at 414 MPa (30 tsi), g/cm^3	7.6	7.4	7.6
Green strength(c) at 414 MPa (30 tsi), MPa (psi)	10–12 (1500–1700)	10–12 (1500–1700)	9.6–11 (1400–1600)

(a) Nominal mesh sizes; brass, −60 mesh; bronze, −60 mesh; nickel silver, −100 mesh. (b) Contains no lead. (c) Compressibility and green strength data of powders with 0.5% lithium stearate

Fig. 26 Scanning electron micrograph of prealloyed, air-atomized bronze (89%Cu-9%Sn-2%Zn). 165×

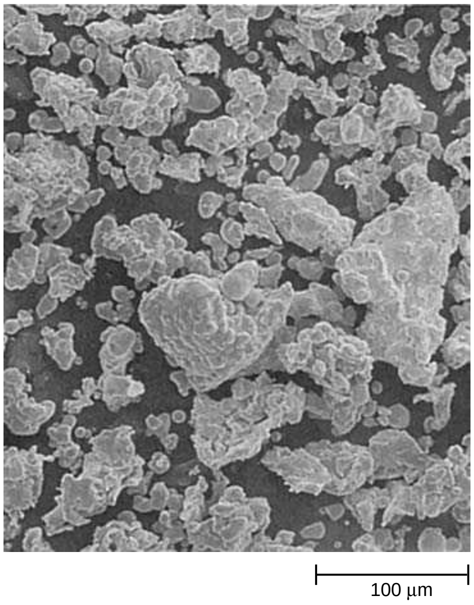

Fig. 27 Scanning electron micrograph of a typical prealloyed water-atomized bronze powder (90%Cu-10%Sn); apparent density 3.4 g/cm^3. 200×

powder manufacture) and choice of lubricants that have a less deleterious effect on green strength. Physical properties are similar to air-atomized powders, but particle morphology is different (Fig. 27). Powders contain 0.1 to 0.2% P to aid sintering.

Spherical 89/11 bronze powders are used to make filters. These are made by horizontal air atomizing and dry collection. The spherical shape is achieved by addition of small amounts of phosphorus, 0.2 to 0.45% (in the form of a Cu/15% P alloy), to the molten bronze prior to atomizing. During air atomizing, surface oxidation of atomized molten particles of bronze and brass, which case them to solidify in an irregular shape (see Fig. 26), is prevented. The oxygen in the air preferentially reacts with phosphorus to form phosphorus pentoxide (P_2O_5), which is volatile at atomizing temperatures. The spherical powders are screened to produce a number of grades, each with a narrow particle size range.

Microbearings. A more recent development has been prealloyed bronze powders for microbearings. These are very small bearings, often weighing less than 1 g, used in electronic equipment such as computers, audiocassette players, and videocassette recorders. Most powders used in this application are made by diffusion alloying tin into copper powder to produce a substantially alloyed powder with particles of uniform composition and a particle shape that gives high green strength (apparent density of 2.3 to 2.7 g/cm^3). As previously stated, water-atomized bronze powders have relatively high apparent density (3.2 to 3.6 g/cm^3) and are usually limited to application in high-density structural parts. Figure 28 shows the particle morphology of a typical diffusion-alloyed bronze powder.

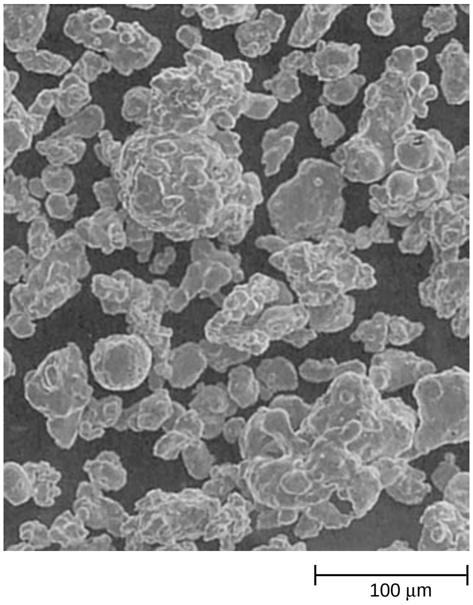

Fig. 28 Scanning electron micrograph of a typical diffusion-alloyed bronze powder (90%Cu-10%Sn); apparent density 2.6 g/cm^3. 200×

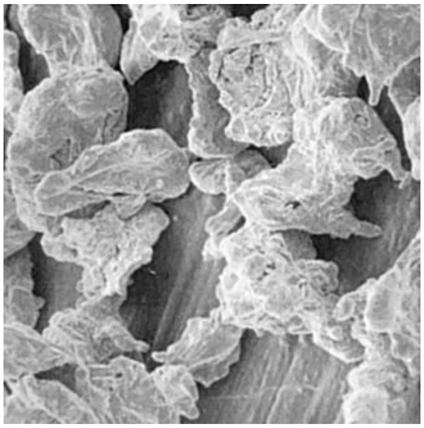

Fig. 29 Scanning electron micrograph of prealloyed, air-atomized nickel silver (63%Cu-18%Ni-17%Zn-2%Pb). 165×

Table 9 Properties of pressed-and-sintered compacts of various copper powder sizes

Particle size	Compacting pressure, MPa	Compacting pressure, tsi	Green density, g/cm^3	Sintered Density, g/cm^3	Sintered Hardness, HRH
Copper, 2 mm	69	5	4.95	7.72	29
	138	10	5.54	7.80	38
	275	20	6.29	7.95	51
	414	30	6.94	8.18	61
Copper, 44–74 mm	69	5	5.38	6.58	1
	138	10	6.07	7.04	12
	275	20	6.88	7.67	31
	414	30	7.65	7.98	42
Copper, 2 mm, tin, 44–74 mm	68	5	5.06	6.24	26
	138	10	5.75	6.24	…
	275	20	6.52	6.34	…
	414	30	7.01	6.40	33
Copper and tin, 44–74 mm	69	5	5.90	6.12	14
	138	10	6.45	6.18	…
	275	20	7.25	6.13	…
	414	30	7.65	6.04	17

Source: Ref 15

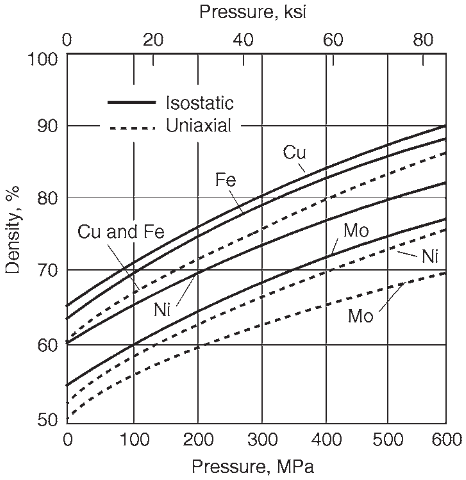

Fig. 30 Density as a function of pressure for isostatic and unidirectional pressing. Source: Ref 13

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Nickel Silver Powder Production

Only one nickel-silver-base alloy composition, 65%Cu-18%Ni-17%Zn, is commonly used in the P/M industry. This alloy can be modified by the addition of lead to improve machinability. Foundry practices are similar to those employed for brasses, except the melting temperature is in excess of 1093 °C (2000 °F). A micrograph of a 63%Cu-18%Ni-17%Zn-2%Pb alloy powder is shown in Fig. 29. Typical physical properties of a nickel silver alloy composition are given in Table 8.

Powder Pressing

Copper and copper alloy powders are generally cold compacted in closed dies with top and bottom punches used to apply the desired pressure. During cold compaction the powder particles mechanically interlock with each other. Typical compacted densities are 80 to 90% of the theoretical density of the material. When higher densities are required, consolidation methods such as hot pressing, extrusion, roll compaction, hot isostatic pressing (HIP), and hot forging are used. The amount of densification depends on several processing variables such as compaction pressure, powder characteristics, types and amounts of lubricants, and so forth.

Compressibility is a measure of the extent to which a mass of powder can be densified by the application of pressure. The pressure required to achieve a given green density depends on the powder particle size distribution, inherent hardness of the material, lubricants, and compaction method (e.g., isostatic or uniaxial). At a given compacting pressure, the density of a green compact generally is:

- Lower for fine particles than for coarse particle (Table 9)

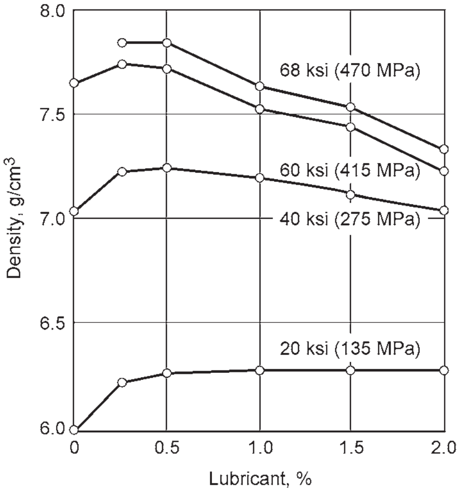

Fig. 31 Density of compact as a function of amount of lubricant (zinc stearate) in a copper-tin powder mix for various compacting pressures with 13 mm ($\frac{1}{2}$ in.) steel die (1.7 mm finish) and 6.4 mm ($\frac{1}{4}$ in.) compacts (double-end compression). Source: Ref 14

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Table 10 Typical compacting pressure and compression ratios of various copper P/M parts

P/M parts	Compacting pressure MPa	Compacting pressure tsi	Compression ratio
Brass parts	414–689	30–50	2.4–2.6 to 1
Bronze bearings	193–275	14–20	2.5–2.7 to 1
Copper-graphite brushes	345–414	25–30	2.0–3.0 to 1
Pure copper parts	206–248	15–18	2.4–2.8 to 1

Source: Ref 16

- Lower for hard powders than for soft powders (Fig. 30)
- Higher with lubricants, but there is an optimal lubricant level (Fig. 31)
- Higher for isostatic pressing than for uniaxial pressing (Fig. 30)

Copper powder is relatively soft compared to iron, nickel, and molybdenum powders and thus reaches a higher green density for a given compaction pressure (Fig. 30). Typical compacting pressures and compression ratios (green density of compact/apparent density of powder) for copper and copper alloy powders are summarized in Table 10. The ranges in Table 10 are only typical, as actual pressing requirements depend on the variables noted previously. Additional information pertaining to compaction pressures for specific copper and copper alloy P/M products can be found in the article “Powder Metallurgy Copper and Copper Alloys” in this Handbook.

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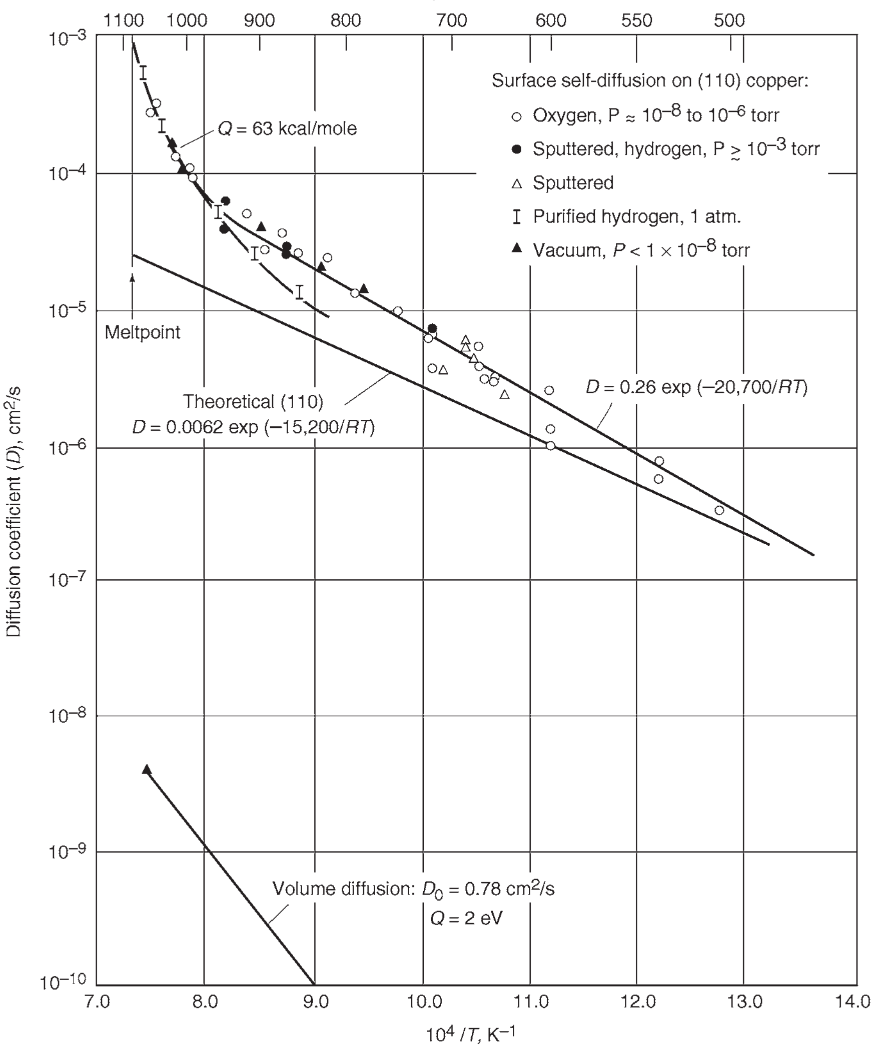

Fig. 32 Volume and surface diffusion coefficients of copper. Source: Ref 18

Table 11 Diffusion constants in copper

Diffusing element	Volume diffusion D_{v0}, cm²/s	Volume diffusion Qv, kcal/mole	Surface diffusion D_{s0}, cm²/s	Surface diffusion Qs, kcal/mole
Copper (self-diffusion)	0.6–0.78	50.5–50.9	1000	39
Nickel in copper	6.5×10^{-5}	30	…	…
Tin in copper	4.1×10^{-3}	31	…	…
Zinc in copper	2.4×10^{-3}	30	…	…
Bronze	6×10^{-6}	25	800	49

Sintering Principles

The compacted parts are sintered at elevated temperatures under protective conditions to avoid oxidation. During this process the powder particles are metallurgically bonded to each other. Sintering is generally understood as a three-phase process. Initially, neck growth between particles proceeds rapidly, but powder particles retain their identity. In the second phase, when most of the densification takes place, the pores become rounded and grain growth occurs, whereupon powder particles lose their separate identities and diffuse into each other. In the third phase, isolated round pores shrink, and densification proceeds at a slower rate.

The principal driving force for these changes is the decrease in free surface area (decrease in solid/gas interface) when particles grow together and voids shrink under the influence of surface tension or capillary forces. Material transport occurs during sintering by one or more mechanisms from among the following (Ref 17):

- Diffusional flow
- Evaporation/condensation
- Viscous flow
- Plastic flow

In most types of sintering, the most important mechanism is diffusion, which may occur through a lattice volume, along a free surface, or along a grain boundary. All three types of diffusion are governed by Fick’s law, which is expressed as:

$$D = D_0 \exp(-Q/RT)$$

where D is the diffusion coefficient, D_0 is a material constant known as the jump frequency, Q is the activation energy for the type of diffusion (volume, surface, or grain boundary), R is the gas constant, and T is the absolute temperature. The activation energy for volume diffusion is the highest, the one for grain-boundary diffusion is lower, and the one for surface diffusion is still lower.

Volume and surface diffusion coefficients for copper, as a function of temperature, are shown in Fig. 32. Values for jump frequencies and activation energies for self-diffusion in copper and for the common alloying elements in copper are given in Table 11. Coefficients for grain-boundary diffusion lie between those for volume and surface diffusion. Generally, diffusion in metals proceeds more rapidly along grain boundaries (i.e., planar defects that are structurally only several atoms thick), and the jump frequency of atoms diffusing along the grain boundaries can be a million times greater than the jump frequency of regular lattice atoms at $2T_m/3$ (where T_m is the melting temperature). Because of the very high atomic mobility at grain boundaries relative to that in the bulk, grain-boundary diffusion plays a crucial role in the kinetics of microstructural changes during metallurgical processing such as sintering and solid-state reactions.

Activated Sintering. This process involves techniques aimed at accelerating the sintering rate by decreasing the activation energy for diffusion. It allows lower sintering temperatures, shorter sintering times, or better properties such as strength, electrical conductivity, and so forth. The rate of sintering can be modified by either physical or chemical treatments of the powder or compact or by adding reactive gases in the sintering atmosphere.

Activated sintering has been observed in copper powders having thin films of copper oxide on the particle surfaces (Ref 19). Oxide layers of 40 to 60 nm show improved properties in sintered compacts as shown in Table 12. The copper oxide is partly soluble in the copper matrix, and the oxygen from the oxide film diffuses into the copper, leaving behind highly active copper surfaces that sinter more efficiently. Thicker layers inhibit sintering as the inferior oxide-to-oxide contacts overcompensate for the activation effects. Small additions of copper oxide to the copper powders also show a similar activation effect.

Liquid-Phase Sintering. In this process, a compact made from a mixture of two or more powders is sintered at a temperature below the melting point of the high-melting-point constituent, but above that of the low-melting-point constituent. The sequence of events in heating a mixed phase begins with a mixture of elemental powders, such as copper-tin or copper-iron premixes. When the liquid forms, it flows to wet the solid particles and begins acting on the solid phase. Melt penetration between the solid particles can cause swelling of the compact. Along with melt penetration, there is rearrangement of particles. The combination of wetting, liquid flow, and rearrangement contributes to a rapid change in the volume of the compact.

Table 12 Effect of copper powder oxide thickness on strength of press-and-sintered compacts

Thickness of oxide film on powder, nm	Tensile strength of sintered compact(a) MPa	ksi
Coarse copper powder		
0	29	4.2
40	51	7.4
80	38	5.5
120	21.5	3.1
160	15.7	2.2
200	7.8	1.1
Fine copper powder		
0	120	17.4
20	130	18.8
60	143	20.7
100	137	19.8
140	129	18.7
180	122	17.7
220	114	16.5

(a) Pressed at 414 MPa (30 tsi), sintered at 600 °C (1110 °F) for $1/2$ h in H_2. Source: Ref 13

In the copper-tin system, the tin melts and alloys with copper to form a bronze, with accompanying expansion of the compact. In the iron-copper system, the copper melts, becoming saturated with iron, and the copper-iron alloy diffuses into the iron skeleton, causing expansion of the skeleton. Pores remain at the sites vacated by the copper.

In both the copper-tin and iron-copper systems, growth or shrinkage of compacts can be altered by the addition of carbon in the form of graphite. Thus, graphite can be used to control dimensional changes in these systems. In the Cu-Sn-C system, sintering is inhibited by mechanical separation of the constituents; as a result, expansion increases. In the Fe-Cu-C system, the amount of the liquid phase is increased by the formation of a ternary Fe-Cu-C eutectic that restricts expansion. Sintering practices for various copper-base P/M materials are described later in this article.

Homogenization (Interdiffusion). When alloying involves blending of elemental powders, then the sintering step serves not only to increase the contact area between powder particles and promote densification, but also to partially or completely homogenize the alloy ingredients by interdiffusion between powder particles of the constituent elements. As in densification, homogenization is influenced by sintering time, sintering temperature, and particle size. Finer particles can greatly accelerate homogenization by reducing the diffusion distance.

Whether it is economical to produce an alloy by sintering compacts from elemental powders or from homogeneous alloy powders depends primarily on the coefficient for interdiffusion of the alloy ingredients. The difference in diffusion coefficients is a deciding parameter whether solid phase or transient liquid phase sintering can be used successfully. This influence of interdiffusion (homogenization) on densification depends on the difference between the diffusion coefficients of the single elements in a powder mixture. In a nickel-cobalt system ($D_{Co} \approx D_{Ni}$), for example, the interdiffusion exerts only a minor influence on densification. The shrinkage behavior of nickel-cobalt compacts lies between those of nickel and cobalt compacts. There is nearly linear correlation between shrinkage and concentration. Therefore, the densification process of the mixtures is dominated by the same defect-activated material transport mechanisms as in single-component systems.

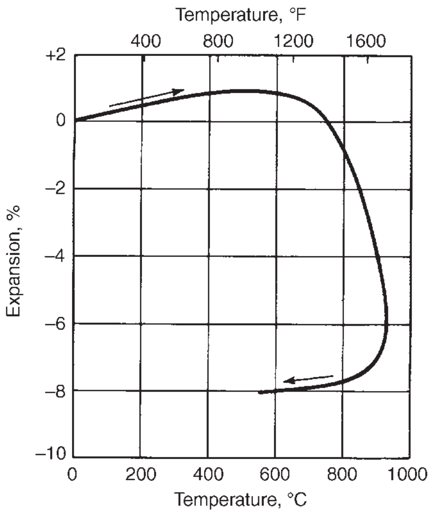

Fig. 33 Dimensional change during sintering of compacts from −74+43 μm copper powder. Pressed at 138 MPa (20 ksi) and heated at a rate of 3.9 °C/min (7 °F/min) to 925 °C (1700 °F) and then cooled at the same rate. MPa = 6.8947 ksi

However, in a copper-nickel system ($D_{Cu} > D_{Ni}$), the effect of interdiffusion is much stronger and depends on whether the component with the higher diffusivity (copper) is the minor or the major component. The faster diffusing species leaves porosity behind (Kirkendall porosity), causing expansion of the compact. An 80%Ni-20%Cu system shows more interdiffusion-induced porosity, while diffusion porosity is less pronounced in a 20%Ni-80%Cu system.

Densification. When compacts from a single metal powder are sintered, they undergo dimensional change as sintering proceeds. Figure 33 shows the dimensional changes that occur during sintering of copper powder compacts. In the initial stage, as the temperature increases, the compacts expand much like solid copper. The entrapped gases in the isolated pores and vaporized lubricant also contribute to this expansion, particularly in compacts pressed to high densities. When sintering begins, the compacts begin to shrink and reach a maximum at the peak sintering temperature. During cooling, the compacts contract like solid copper would. The total result of the three stages is generally a shrinkage and higher density.

Densification of P/M compacts during sintering depends on several variables, but principal factors are:

- Sintering temperature
- Sintering time
- Powder particle size
- Green density of the compact, which is primarily a function of compacting pressure

Typical sintering temperatures and times for various alloys are given in Table 13; copper alloys are generally sintered at much lower temperatures than iron- and nickel-base alloys. Typical shrinkage of a copper compact is shown in Fig. 34 for various sintering temperatures and times. The rate of shrinkage is initially high, but then decreases with increasing sintering time. Higher sintering temperatures promote a more rapid shrinkage than do longer sintering times.

Table 13 Typical sintering temperature and time of copper alloys and steels

Material	Temperature °C	°F	Time, min
Bronze	760–870	1400–1600	10–20
Copper	840–900	1550–1650	12–45
Brass	840–900	1550–1650	10–45
Iron, iron-graphite, etc.	1010–1150	1850–2100	30–45
Nickel	1010–1150	1850–2100	30–45
Stainless steel	1095–1285	2000–2350	30–60

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Another factor affecting densification is the particle size of the powder. In Fig. 35, the sintered density of copper powder compacts pressed at 276 MPa (40 ksi) from the two particle size fractions, $^{-}105+75$ and $^{-}44$ µm, and sintered at 865 °C (1590 °F) is plotted as a function of sintering time. Densification of compacts from the finer powder is faster than that of compacts from the coarser powder and, for sintering times above $\frac{1}{2}$ h, the final density is considerably higher for the compacts from the finer powder.

A final factor affecting the densification of compacts from a single metal powder is the green density of the compact or the pressure at which the compact is pressed, which determines green density. In Fig. 36, dimensional change is plotted versus sintering temperature for various compacting pressures. Higher compacting pressures result in higher green and sintered densities, but the sintering shrinkage, or the change from green to sintered density, is smaller. As previously noted, expansion may also occur when soft metal powders are compacted at higher pressures as shown in Fig. 36 for compaction pressures of 550 and 620 MPa (80 and 90 ksi). This effect is associated with expansion of the entrapped gases in the isolated pores.

Sintering Practices for Bronze

Sintered bronze can be produced either from mixtures of copper powder and tin powder or from a prealloyed tin bronze powder. The nominal composition of 90Cu-10Sn can be complemented with other constituents such as dry organic lubricants, graphite, lead, and iron, depending on the specified grade.

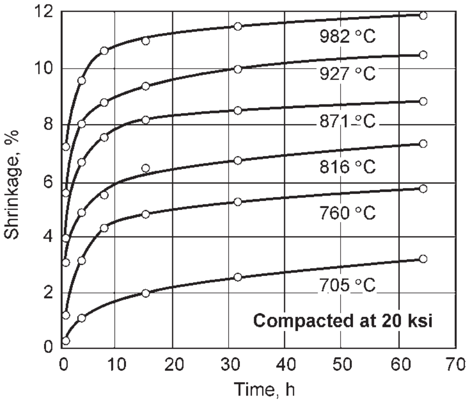

Fig. 34 Linear shrinkage of copper powder compacts from $^{-}75+44$ µm sieve fraction. Source: Ref 20

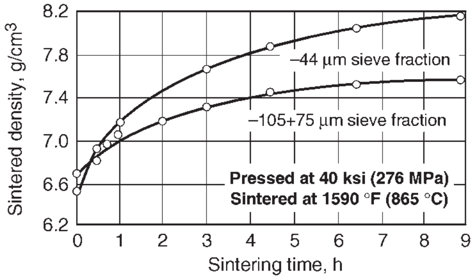

Fig. 35 Density of compacts from electrolytic copper powder. Source: Ref 21

Premix/Diffusion Alloyed Bronzes

Premix or partially diffused bronzes are used extensively in the manufacture of porous, self-lubricating bushings and bearings and for more complex structures requiring superior bearing and mechanical strength. Self-lubricating bushings and bearings are produced at nominal densities (oil impregnated) of 5.8 to 7.2 g/cm^3, with oil contents ranging from 24 to 11 vol%, respectively. Corresponding radial crush values (*K* strength constant) are approximately 69 MPa (10 ksi) of the lower density, increasing to 228 MPa (33 ksi) at the highest nominal density.

The basic manufacturing procedure consists of compacting the powder shapes to the appropriate green density and sintering to achieve a homogeneous metallurgical alpha bronze structure, followed by oil impregnation. A sizing operation completes the process to ensure dimensional precision and general surface integrity.

Dimensional Change. Several methods are used in the industry to produce bearings and structural parts from sintered 90Cu-10Sn bronze. For practical purposes, either pure copper and pure tin or prealloyed bronze and tin powder can be mixed. There are advantages and disadvantages to both methods. Mixed powders possess relatively good pressing properties, but there is always a risk of segregation. Premix powder containing prealloyed bronze (e.g., 94Cu/6Sn + 4Sn) have less liquid phase during sintering, which accounts for a comparatively lower sintered strength at similar green density. However, "partially prealloyed" bronze minimizes the risk of segregation and still maintains acceptable sintered strength.

Partially diffused bronze is possible when premix bronze is presintered at a temperature range from 400 to 750 °C (750 to 1380 °F), such that a metallurgical bond between tin and copper powder is created. The sintered cake is then crushed, ground, and screened. This treatment minimizes segregation and gives similar sintered properties to premix bronzes.

To include all dimensional patterns with related absolute dimensional change values for each commercially available premix system is prohibitive. A variety of premixed powders are available with specific sintered dimensional patterns to satisfy customer design and tooling needs. Despite the dimensional magnitude of the particular premix being sintered, compositions of this type exhibit a common sintered dimensional pattern. Absolute sintered dimensional characteristics typically are unique to a specific source of copper and tin powders. For example, sintered dimensional consistency can be obtained by blending two or more copper-base powders that exhibit different growth characteristics and/or by use of tin powders that also exhibit different growth characteristics.

Generally, copper-tin blends composed of relatively coarse powder sinter to higher growth values than a blend composed of finer powders. After powder blends have been tested and adjusted to provide an approximation of target dimensions, final adjustments are made during production sintering to obtain dimensional precision. For discussion purposes, Fig. 37 shows the relationship between dimensional change, sintering time, and green density of a premix bronze and a partially diffused bronze, using the

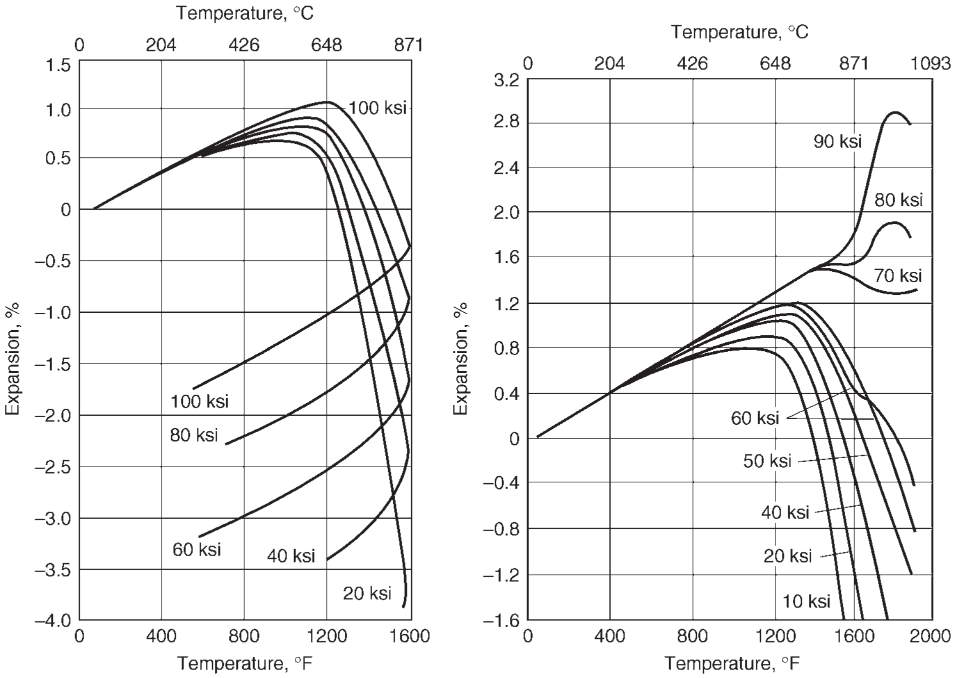

Fig. 36 Sintering curves for copper powder compacts at various compacting pressures. Source: Ref 22

same source of powders and a similar particle size distribution (see Ref 23).

Factors affecting the ultimate, or peak, dimensional values include physical characteristics of the constituents and compacted density. Control of sintered dimensions in premix systems is achieved by manipulating sintering time and/or temperature.

Sintering Time and Temperature. Typical sintering furnace temperatures for bronze range from 815 to 860 °C (1500 to 1580 °F); total sintering time within the hot zone ranges from 15 to 30 min, depending on the furnace temperature selected, required dimensional change, and most importantly, the presence of an optimal alpha grain structure. Figure 38 shows the typical microstructure of a sintered premix bronze part.

Sintering atmospheres should be protective and reducing to facilitate sintering. Reduction of the copper oxides that may surround each copper powder particle and reduction of tin oxide formation allow for increased diffusion rates. Consequently, faster sintering rates and more homogeneous structures can be obtained.

Prealloyed Bronzes

Sintered bronze alloys are rather uncommon in powdered metal usage. This is primarily due to their relatively high cost compared to low-alloy steels. However, sintered bronze properties can be advantageous for non-magnetic applications that require very good corrosion resistance, good mechanical strength, and excellent ductility.

Prealloyed 80Cu-9Sn-2Zn bronze powders with a select lubricant are intended for the fabrication of high-density P/M structural components. Unlike many elemental copper-tin premixes, the sintering of prealloyed bronze results in the attainment of high sintered densities (85 to 90% of theoretical) that provide correspondingly high strengths and hardnesses.

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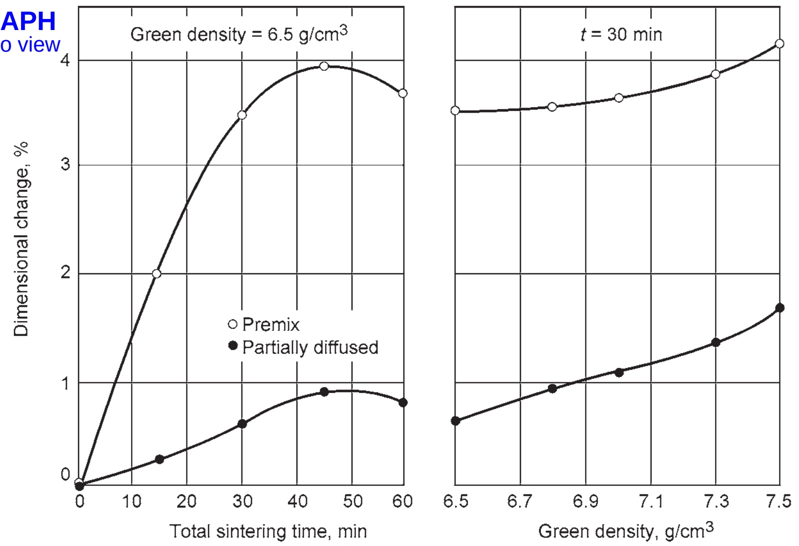

Fig. 37 Effect of sintering time and green density on dimensional change of bronze. Sintered at 820 °C (1500 °F), under dissociated ammonia atmosphere

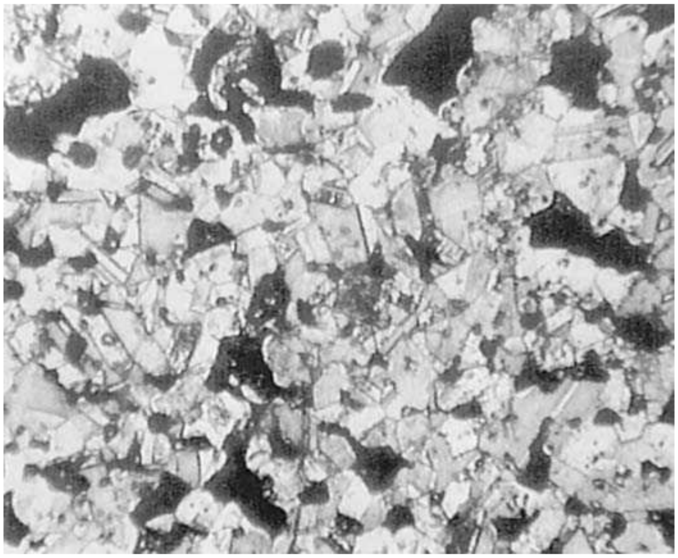

Fig. 38 Typical microstructure of sintered premix bronze. 90-10 bronze, etched in $K_2Cr_2O_7$ solution. 175×

Sintered Properties. Prealloyed bronze powders are relatively easy to work due to the excellent ductility obtained on sintering. For example, an 89Cu-9Sn-2Zn bronze pressed at 414 MPa (30 tsi) to 85% of theoretical density exhibits >30% elongation, thus allowing for a substantial degree of cold working. Compared with sintered brass, bronze powders reach higher yield strength and hardness levels when compacted under similar conditions. For example, pressing at 550 MPa (40 tsi) results in hardness of 45 HRB for an 89Cu-9Sn-2Zn-2Fe bronze and of 90 HR for a 70Cu-30Zn brass, respectively (after 30 min sintering at 840 °C (1550 °F) under dissociated ammonia).

The addition of 2% of a select-grade iron in the composition improves the sintered structure, which has a more uniform grain size and results in comparatively higher yield strength and hardness. Figure 39 shows the microstructure of a prealloyed bronze. Sintering temperature and atmospheres of prealloyed bronzes are similar to those of bronze premix. Figure 40 shows the dimensional change and transverse rupture strength of prealloyed bronzes as a function of green density.

Sintering Practices for Brass and Nickel Silvers

Powders of brasses and nickel silvers are prealloyed, single-phase (alpha) powders that, on sintering, yield moderate mechanical strength, excellent ductility, and good corrosion resistance. Parts can be subsequently burnished to improve surface finish. The various alloy compositions produced also provide suitable color, or shade, selection for applications that require a high degree of surface finish and appearance.

During alloy preparation, lead can be added to improve machinability of the sintered forms. Typical machining operations include drilling, tapping, turning, threading, and grinding. Excellent sintered ductility also facilitates secondary operations, such as sizing, cold densification, swaging, and staking. By using multiple pressing and sintering operations, the yield strength and hardness of the P/M structure may approach those of its wrought alloy counterpart (Ref 24).

Standard prealloyed brass and nickel silver powder compositions are controlled to conform to existing materials standards. This conformance precludes the additions of foreign metallic constituents, such as tin and iron, that affect sintered mechanical and dimensional characteristics. In spite of the various compositions comprising these standard alloy powders, most exhibit similar characteristics. After blending with lubricant, powders densify approximately 10% more than their as-atomized apparent density. For example, an as-atomized powder with an apparent density of 3.0 g/cm³ usually blends to a density of 3.3 g/cm³ minimum with the

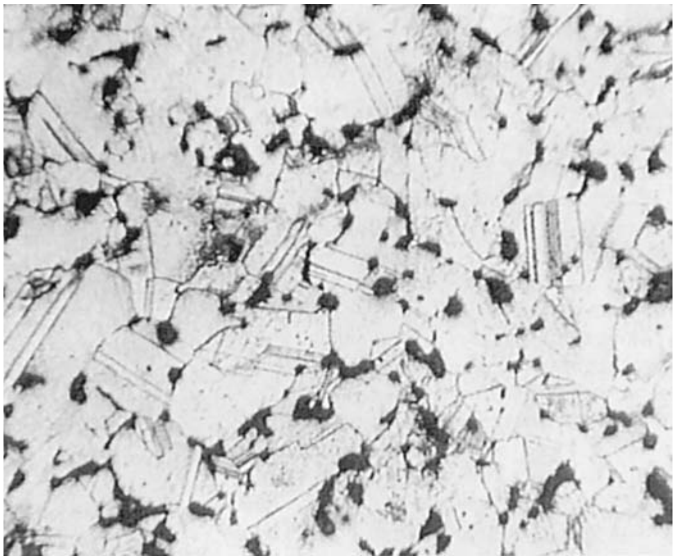

Fig. 39 Typical microstructure of sintered prealloyed 89Cu-9Sn-2Zn-2Fe bronze, etched in $K_2Cr_2O_7$ solution. 350×

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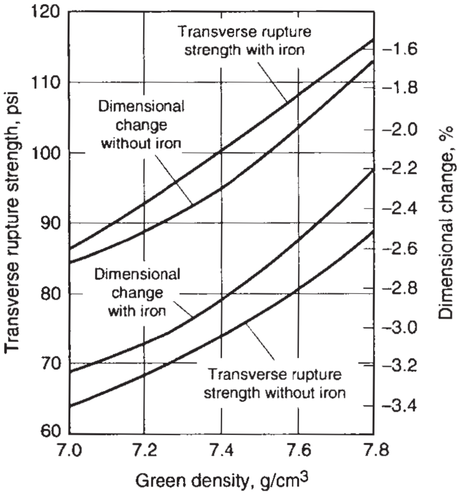

Fig. 40 Properties of prealloyed bronzes. Sintered 30 min at 840 °C (1550 °F), under dissociated ammonia (DA)

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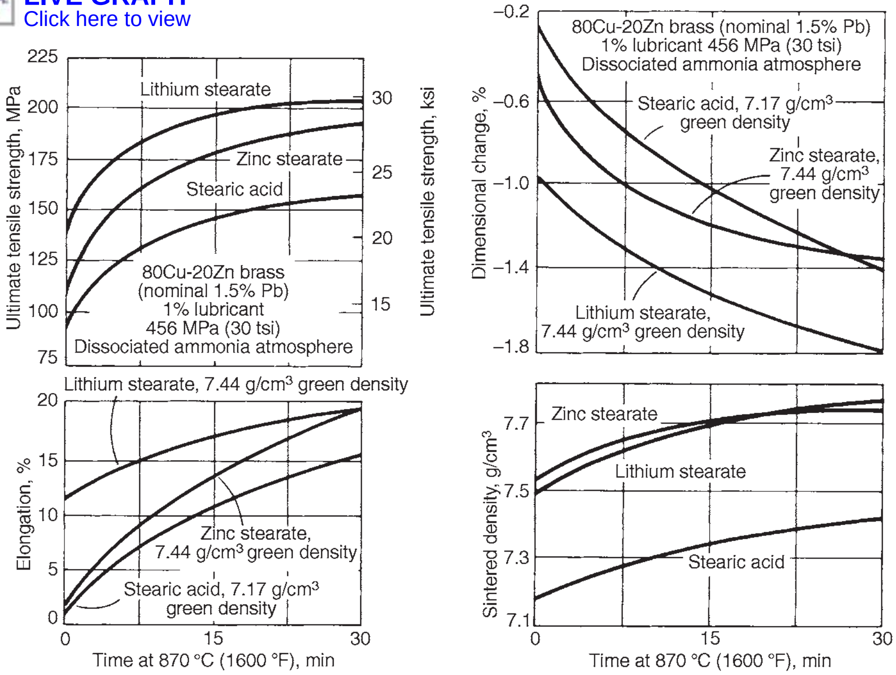

Fig. 41 Effects of lubricants and sintering time at temperature on tensile properties, sintered density, and dimensional change of brass compacts

addition of dry lubricant. Compressibilities are excellent, as lubricated powders compact to 85% of wrought counterpart densities at 414 MPa (60 ksi). Compression ratios of lubricated powders range from 2.0-to-1 to 2.2-to-1.

Effect of Lubricant. Blending of powders with dry organic lubricants is normally accomplished in a double cone-type blending unit. To minimize the inclusion of large lubricant agglomerates and other undesirable particles, the material is passed through a 40 mesh sieve, or screening is recommended prior to blending. The primary lubricant employed with brasses and nickel silvers is lithium stearate.

Lithium stearate provides an apparent scavenging or cleansing effect that enhances the sinterability of these powders. It may also result in spotty or speckled superficial stains on sintered surfaces. These phenomena affect the appearance of the components, but are not detrimental to mechanical properties. To minimize staining, lithium stearate additions of less than 0.5 wt% are recommended, and zinc stearate can be added to provide the additional required lubricity.

Different types of lubricant have a marked effect on the physical and mechanical properties of nonferrous prealloyed powder (Ref 24). To illustrate the effects on mechanical properties, Fig. 41 shows data for three frequently used lubricants in the P/M industry—lithium stearate, zinc stearate, and stearic acid. The beneficial effect of 1 wt% lithium stearate and the deleterious effect of 1 wt% stearic acid on mechanical properties are shown.

Compacting of lubricated powders is performed with standard types of compacting presses employing steel or carbide dies and punches. Excellent compressibility and good green strength permit compacting to 75% of theoretical density at pressures as low as 207 MPa (30 ksi).

Although powders are normally free of gangue and other inclusive, abrasive material that may cause tool wear, their relative softness does cause tooling difficulties. If powders are not adequately lubricated, fines within tool clearances gall the die wall and adjacent punch areas, thereby requiring tool removal and cleaning. The amount of lubricant added to the powder should be proportional to the total surface area of the die assembly requiring lubrication during forming and ejection. Low-profile, minimum die wall contact parts may only require 0.5 wt% added lubricant, whereas a high die wall contact part having core rods for holes or internal cavities may require 1.0 wt% lubricant.

Generally, there are no restrictions on the compacted configuration of these powders. In tool design, particularly with regard to die fill, consideration must be given to the relatively higher apparent densities of lubricated brass and nickel silver powder. Typical apparent densities for lubricated powders range from 3.3 to 3.6 g/cm^3.

Sintering of brasses and nickel silvers typically is not difficult; however, basic sintering practices do differ from those employed with other common alloy systems, such as elemental copper-tin blends and iron powder blends. These differences include sintering temperature, time at sintering temperature, and atmosphere protection.

Sintering temperatures for standard brasses range from 760 to 925 °C (1400 to 1700 °F). Temperature selection depends on the brass alloy being sintered and the mechanical properties desired after sintering. Lower brasses with higher zinc contents and lower melting points are sintered at the lower temperature. Generally, a starting temperature of 100 °C (180 °F) below the solidus temperature (as determined from any copper-zinc binary alloy constitutional diagram) is suitable.

Nickel silver can be sintered at 870 to 980 °C (1600 to 1800 °F). Currently, only one base alloy is used for the manufacture of P/M structural parts; it has nominal composition of 64Cu-18Ni-18Zn. The leaded alloy composition contains 1.5% Pb. Sintering characteristics are similar to those of the brasses; therefore, responses to sintering parameters that affect dimensional and mechanical properties of brass are equally applicable to nickel silver.

Sintered Properties. Dimensional and mechanical properties of brasses and nickel silvers are primarily affected by compact density and the amount of time at temperature, as well as the sintering temperature itself. As mentioned previously, other elements that affect dimensional and mechanical properties usually are not added to powders. However, sintered properties, especially dimensional change, can be effectively controlled by manipulation of sintering time at the appropriate temperature. Each alloy exhibits unique dimensional characteristics—a 90Cu-10Zn brass compacted at 414 MPa (30 tsi) and sintered for 30 min at 870 °C (1600 °F) may shrink 0.5%, while a 70Cu-30Zn brass similarly treated may shrink 2.5%.

Figures 42 and 43 show typical property relationships that can be controlled through manipulation of time at temperature. The leaded 80Cu-20Zn brass shown in Fig. 42 and 43 is commonly used for structural parts fabrication. The density of 7.6 g/cm^3 is "average" for compacting lubricated prealloyed powders containing 0.375% lithium stearate and 0.375% zinc stearate at 414 MPa (30 tsi). As shown, close dimensional control can be obtained with a minimum reduction in mechanical properties after 15 min at temperature. Ductility is increased for subsequent forming operations, such as sizing, cold repressing for densification, or coining, by increasing sintering time.

Non-leaded machinable brasses have been recently introduced on the market to reduce or eliminate lead. It has been shown (Ref 25) that by replacing lead with select alloy additions, brass parts still maintain similar mechanical and physical properties, while having improved machinability. Figure 42 illustrates the properties of non-leaded brass, leaded brass, and a non-leaded brass containing select alloy additions. Figure 44 also shows the machinability for those different types of 80Cu-20Zn brasses.

Atmosphere protection is required for sintering brasses and nickel silvers to prevent oxidation and to ensure effective sintering. Use of lithium stearate as the base lubricant allows the use of most common sintering atmospheres over a wide range of dew points. Although dry hydrogen or dissociated ammonia (DA) provides the best sintering atmosphere, comparable properties can be obtained with nitrogen-base or partially combusted hydrocarbon gas atmospheres.

When sintering, compacts should be protected from direct impingement of furnace flame curtains and atmosphere gases by partially or fully covering loaded trays to minimize zinc loss. Because it has a high vapor pressure at standard sintering temperature (boiling point of pure zinc 906 °C, or 1663 °F), zinc may be lost to the atmosphere as it diffuses through to the particle surfaces. Loss of excessive surface zinc results in a change in surface composition. In the case of brasses, pink copper or zinc-depleted areas are apparent. Although superficial zinc losses do not adversely affect sintered properties, surface finish is diminished; finished parts may be rejected because of color differences.

Furnace Design. A variety of protective sintering tray arrangements can be used, including graphite trays with full covers and graphite-base plates with steel covers, for example. Sintering of brasses on open belts is not common practice for several reasons; for example, overheating can melt brass parts that can fuse to the mesh belt. Also, excessive heat and direct impingement of flame curtain gas through the mesh can impair effective sintering due to oxidation and premature partial lubricant removal. Direct exposure to the sintering atmosphere can also cause objectionable surface dezincing.

Conversely, extremely gastight protective sintering setups should be avoided because lubricant decomposition products may not be completely volatilized. Excessive residual lubricant within the compact inhibits sintering; consequently, mechanical properties are adversely affected. Typically, compacts with excessive internal lubricant residuals cannot be salvaged by additional passes through a full sintering cycle. To avoid or minimize the deleterious effect of residual lubricants, covered tray setups should facilitate free venting of lubricant gases to the flowing furnace atmosphere.

ACKNOWLEDGMENTS

This article was adapted from:

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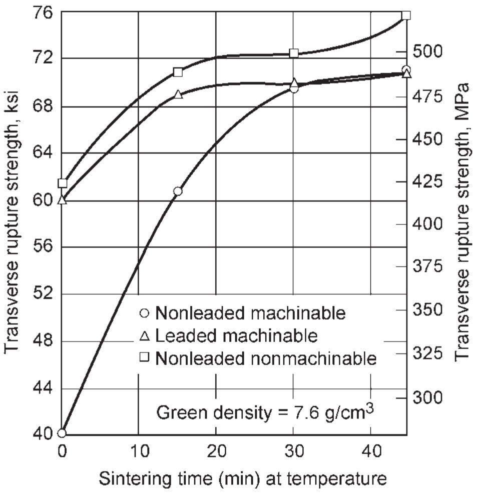

Fig. 42 Transverse strength of 80Cu-20Zn brasses. Sintered in hot zone at 870 °C (1600 °F) in dissociated ammonia (DA)

LIVE GRAPH
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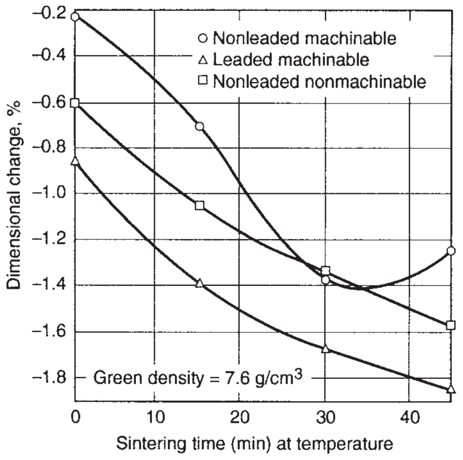

Fig. 43 Dimensional change of 80Cu-20Zn brasses. Sintered in hot zone at 870 °C (1600 °F) in dissociated ammonia (DA)

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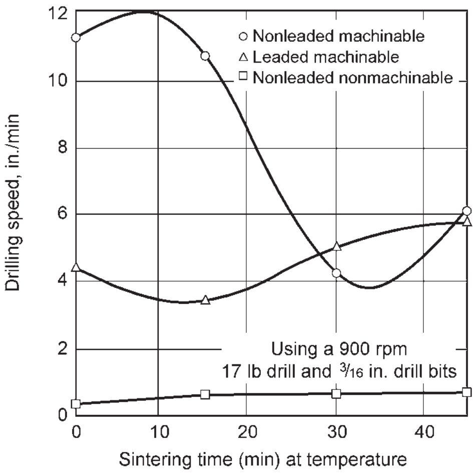

Fig. 44 Machinability of 80Cu-20Zn brasses. Sintered in hot zone at 870 °C (1600 °F) in dissociated ammonia (DA)

LIVE GRAPH
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Heat Treating

HEAT TREATING PROCESSES that are applied to copper and copper alloys include:

- Homogenizing
- Annealing
- Stress relieving
- Solution treating
- Precipitation (age) hardening
- Quench hardening and tempering

Each of these will be described below along with heat treating equipment and protective atmospheres and heat treating practices for specific copper alloys including beryllium coppers, copper-chromium alloys, copper-zirconium alloys, miscellaneous precipitation-hardening alloys, spinodal-hardening alloys, and aluminum bronzes. Additional information on heat treating principles can be found in the article "Physical Metallurgy: Heat Treatment, Structure, and Properties" in this Handbook.

Homogenizing

Homogenizing is a process in which prolonged high-temperature soaking is used to reduce chemical or metallurgical segregation commonly known as coring, which occurs as a natural result of solidification in some alloys. Homogenizing is applied to copper alloys to improve the hot and cold ductility of cast billets for mill processing, and occasionally is applied to castings to meet specified hardness, ductility, or toughness requirements.

Homogenization is required most frequently for alloys having wide freezing ranges, such as tin (phosphor) bronzes, copper nickels, and silicon bronzes. Although coring occurs to some extent in α brasses, α-aluminum bronzes, and copper-beryllium alloys, these alloys survive primary mill processing and become homogenized during normal process working and annealing. Rarely is it necessary to apply homogenization to finished or semifinished mill products.

A characteristic of high cooling rates is the uneven distribution of the alloy elements in the interior of the dendritic microstructure. These differences increase with higher cooling rates and greater differences in composition between melt and solid phase at the onset of crystallization. This difference may be equalized in some alloys by long-time homogenization as a result of diffusion processes taking place in the solid phase.

The time and temperature required for the homogenization process vary with the alloy, the cast grain size, and the desired degree of homogenization. Typical soak times vary from 3 to over 10 h. Temperatures normally are above the upper annealing range, to within 50 °C (90 °F) of the solidus temperature.

Homogenization changes the mechanical properties: ultimate tensile strength, hardness, and yield (proof) strength all slowly decrease, whereas elongation at fracture and necking increase by as much as twice the initial value. Figure 1 shows a typical example of these changes taking place at a homogenizing time of 4 h for alloy C52100, a wrought phosphor bronze alloy containing nominally 92% Cu, 8% Sn, a small amount of phosphorus, and trace amounts of several other elements.

The normal precautions that apply to annealing should be used for the homogenization of any particular alloy. The furnace atmosphere should be selected for the control of both surface and internal oxidation. Where there is appreciable danger of liquefying segregated phases, the materials, particularly castings, should be well supported and heated slowly through the final 100 °C (180 °F).

Typical applications of homogenization are:

- Alloy C71900 (copper-nickel-chromium) billets: 1040 to 1065 °C (1900 to 1950 °F) for 4 to 9 h, to prevent cracks, seams, and excessive wood fiber structure in extrusions

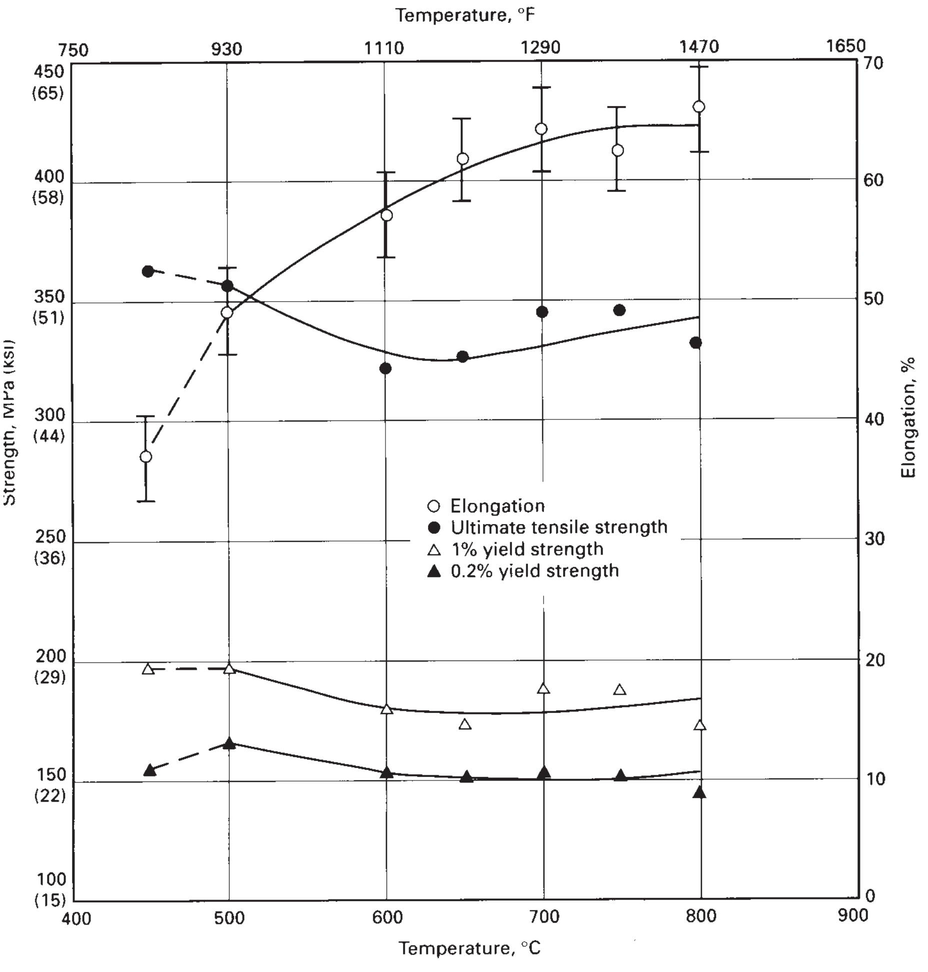


Fig. 1 Effect of annealing temperature on the mechanical properties of an alloy C52100 slab. Annealing time 4 h

- Alloy C52100 and C52400 (phosphor bronzes, 8 and 10% Sn): 775 °C (1425 °F) for 5 h, to reduce embrittlement in billets and slabs that are to be cold rolled
- Alloy C96400 (cast 70Cu-30Ni): 1000 °C (1830 °F) for 2 h under a protective atmosphere and then cooled to 400 °C (750 °F), followed by air cooling

For the precipitation-hardenable alloys, homogenization may involve a prolonged solution treatment.

Annealing

Annealing is a heat treatment intended to soften and to increase the ductility and/or toughness of metals and alloys. Annealing is applied to wrought products, during and after mill processing, and to castings. The process includes heating, holding, and cooling, and a proper process description should include heating rate, temperature, time at temperature, atmosphere, and cooling rate where each may affect results.

Understanding the Annealing Process

Work-hardened metal can be returned to a soft state by heating or annealing. During the annealing of simple single-phase alloys, deformed and highly stressed crystals are transformed into unstressed crystals by recovery, recrystallization, and grain growth (see subsequent discussion). In severely deformed metal, recrystallization occurs at lower temperatures than in lightly deformed metal. Also, the grains are smaller and more uniform in size when severely deformed metal is recrystallized.

Grain size can be controlled by proper selection of cold-working and annealing practices. Large amounts of prior cold work, fast heating to annealing temperature, and short annealing times favor fine grain sizes. Larger grain sizes are normally produced by a combination of limited deformation and long annealing times. In normal commercial practice, annealed grain sizes are controlled to about a median value in the range of 0.01 to 0.10 mm (0.0004 to 0.004 in.).

Variations in annealed grain size produce variations in hardness and other mechanical properties that are smaller than those that occur in cold-worked material, but these variations are by no means negligible. Fine grain sizes often are required to enhance end-product characteristics such as load-carrying capacity, fatigue resistance, resistance to stress-corrosion cracking (SCC), and surface quality for polishing and buffing of either annealed or cold-formed parts.

Recovery, Recrystallization, and Grain Growth. To illustrate the annealing process, consider an alloy of copper with 5% zinc (a single-phase solid solution) that has been rolled at 25 °C (75 °F). As the reduction in thickness increases, the hardness increases, and the microstructure develops a complex array of dislocations. In the optical (light) microscope, this manifests itself in a high density of deformation bands, bent annealing twins, and elongated grains (Fig. 2 and 3).

If the deformed alloy is held at 400 °C (750 °F), and the hardness periodically measured, the data give a curve such as that shown in Fig. 4. The annealing curve is divided into three regions, labeled *recovery, recrystallization*, and *grain growth*. In the recovery stage the hardness remains constant, or may increase slightly. This is followed by a drastic decrease in hardness during recrystallization. The hardness continues to decrease, but much more gradually, during grain growth.

Although hardness is not affected greatly during recovery, other properties (e.g., electrical resistivity) are, showing that significant structural changes occur during this stage, but they are changes to which the hardness is not very sensitive. The term *recovery* is used because recovery of some of the original properties occurs during this short time. During recrystallization, it is observed that relatively soft, strain-free (low dislocation density) crystals form (nucleate) and grow in the plastically deformed matrix (Fig. 5). (This is shown more clearly in Fig. 6, which shows small, isolated crystals having just formed in the deformed matrix.) Once the deformed matrix is consumed by these new crystals, further annealing only causes grain growth.

It is emphasized that more than one mechanism bringing about the structural changes may be operating simultaneously. For example, once a small strain-free crystal forms (the beginning of recrystallization), it then grows into the deformed matrix, which at the same time is continuing to undergo recovery. The particular annealing process is a consequence of all of the mechanisms operating, and this is dependent upon the material, the processing history, and the annealing procedure.

Annealing behavior is usually presented by plotting property against annealing temperature, for a fixed annealing time (Fig. 7). The same type of curve results, with the stages of recovery, recrystallization, and grain growth present. This type of curve is used to determine the *recrystallization temperature*, a term that can be defined several ways. It can be defined as the approximate minimum temperature at which complete recrystallization of a cold-worked metal occurs within a specified time. It can be defined also as the temperature at which recrystallization just begins, as the temperature at which recrystallization is half completed, or as the inflection point of the hardness-annealing temperature curve. This last definition gives the approximate recrystallization temperatures listed in Fig. 7.

The recrystallization temperature depends, of course, upon several variables. The time at the annealing temperature (Fig. 8), the chemical composition of the alloy (Fig. 7), and the amount and type of plastic deformation (Fig. 9) all must be specified. Any variable that increases the energy of the cold-worked material will make it more unstable relative to the annealed condition. This energy difference is the "driving force" for the return to the soft, strain-free condition, and usually the larger this energy difference is, the more rapidly the process occurs. Thus, even such variables as the original grain size and the temperature of deformation affect the recrystallization temperature. Table 1 summarizes these effects.

Annealing of Wrought Products

The annealing of cold-worked metal is accomplished by heating to a temperature that

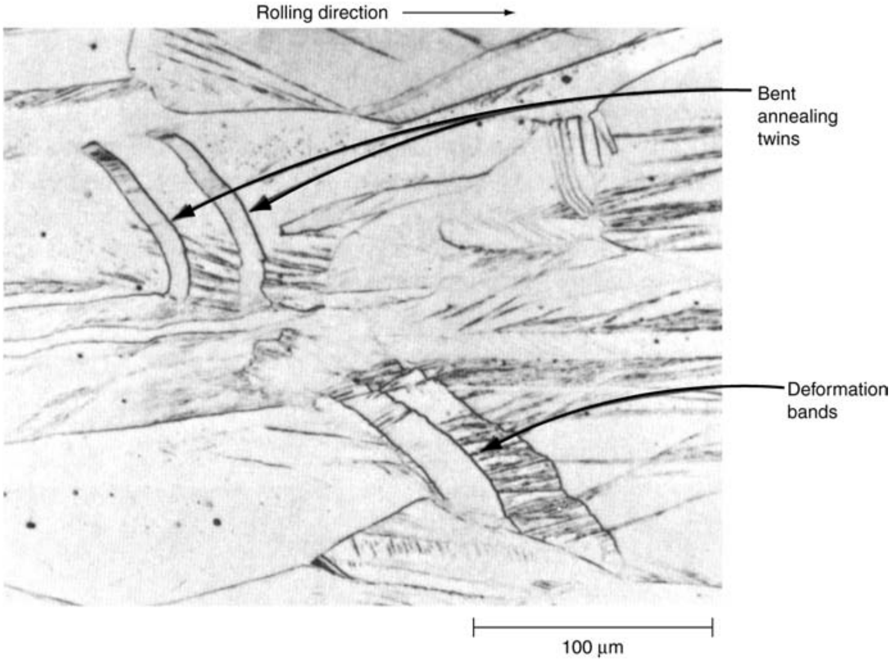


Fig. 2 Microstructure of a Cu-5Zn alloy cold rolled at 25 °C (75 °F) to a 40% reduction in thickness, showing deformation bands and bent annealing twins revealed by etching the polished surface.

produces recrystallization and, if desirable, by heating beyond the recrystallization temperature to initiate grain growth. Temperatures commonly used for annealing cold-worked coppers and copper alloys are given in Table 2.

Annealing is primarily a function of metal temperature and time at temperature. Except for multiphase alloys, including certain precipitation-hardening alloys, and alloys susceptible to fire cracking, rates of heating and cooling are relatively unimportant. On the other hand, the source and application of heat, furnace design, furnace atmosphere, and shape of the workpiece are important because they affect finish, cost of annealing, and uniformity of results obtained.

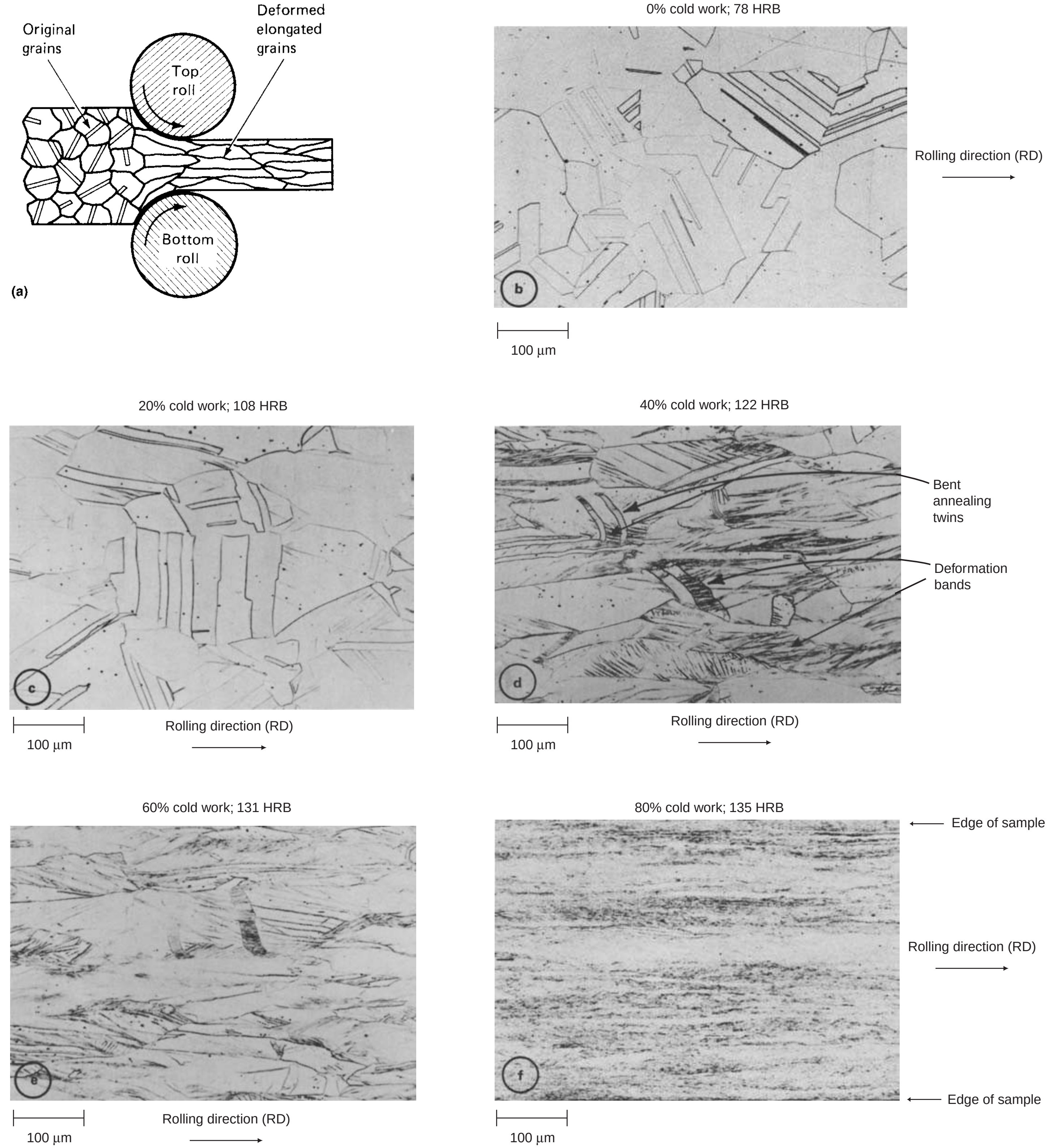


Fig. 3 Optical micrographs (all at same magnification) of a cold-worked Cu-5Zn solid solution alloy, showing Rockwell B hardness (HRB) at each stage. Percentages for cold work are based on reduction in thickness. Rolling direction is from left to right.

The multiplicity of influential variables (such as temperature, time, and furnace load) make it difficult to tabulate a definite annealing schedule that will result in completely recrystallized metal of a specific grain size. The effects of annealing temperature on the tensile strength, elongation, and grain size of hard-drawn (63%) C27000 (yellow brass) wire annealed for 1 h and the effect of annealing time on the grain size of C27000 strip are shown in Fig. 10.

The annealing response of alloy C26000 (cartridge brass) strip after a reduction of 40.6% by cold rolling is shown in Fig. 11. Time at temperature was 1 h. The actual increases in hardness and tensile properties shown at temperatures below the recrystallization range are typical of alloys such as brasses, nickel silvers, phosphor bronzes, and α-aluminum bronzes. Depending on the individual alloy, these increases are attributable to phenomena of the strain-aging and/or lattice-ordering type.

Methods of rapid recrystallization have gained importance in heat treatment technology. Softening time can be significantly reduced, compared to conventional annealing processes, by increased heating rates using higher temperatures. However, these heat treat parameters may affect the mechanical properties of the materials.

An increased amount of cold work prior to annealing lowers the recrystallization temperature. The lower the degree of prior deformation, the larger the grain size after annealing. For a fixed temperature and duration of annealing, the larger the original grain size before working, the larger the grain size after recrystallization.

In commercial mill practice, copper alloys are usually annealed at successively lower temperatures as the material approaches the final anneal, with intermediate cold reductions of at least 35% and as high as 50 to 60% in single or multiple passes wherever practicable. The higher initial temperatures accelerate homogenization, and the resulting large grains permit a more economical reduction during the early working operation.

During subsequent anneals, the grain size should be decreased gradually to approximate the final grain size required. This point is usually reached one or two anneals before the final anneal. With such a sequence and with sufficiently severe intermediate reductions, it is possible to produce a uniform final grain size within a lot and from lot to lot.

The grain size and mechanical properties required for further cold working vary considerably with the alloy and with the amount and kind of further cold work to be done. The goal of annealing for cold working is to obtain the optimal combination of ductility and strength. However, when press-drawn parts are to be finished by polishing and buffing, the grain size should be as fine as practicable to keep the surface texture smooth and thus to avoid the need for excessive buffing and the attendant costs. The anneal must be governed by definite specifications and coordinated with cold-working operations to yield the desired finished properties.

Because the annealing of closed strip in tightly wound coils of large weight causes uneven heating in the individual layers corresponding to the direction of heat flow, uneven deep-drawing properties and variations in size may result.

These difficulties led to the development of the continuous-strip furnace through which the

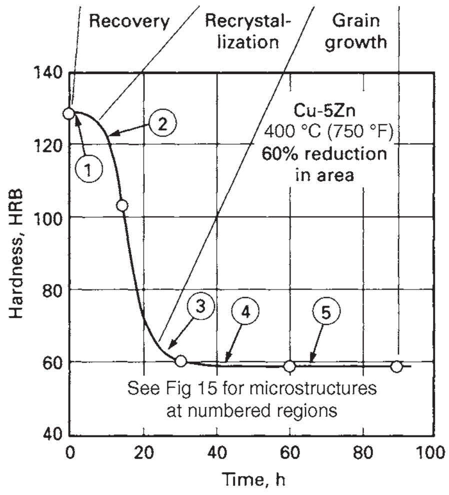
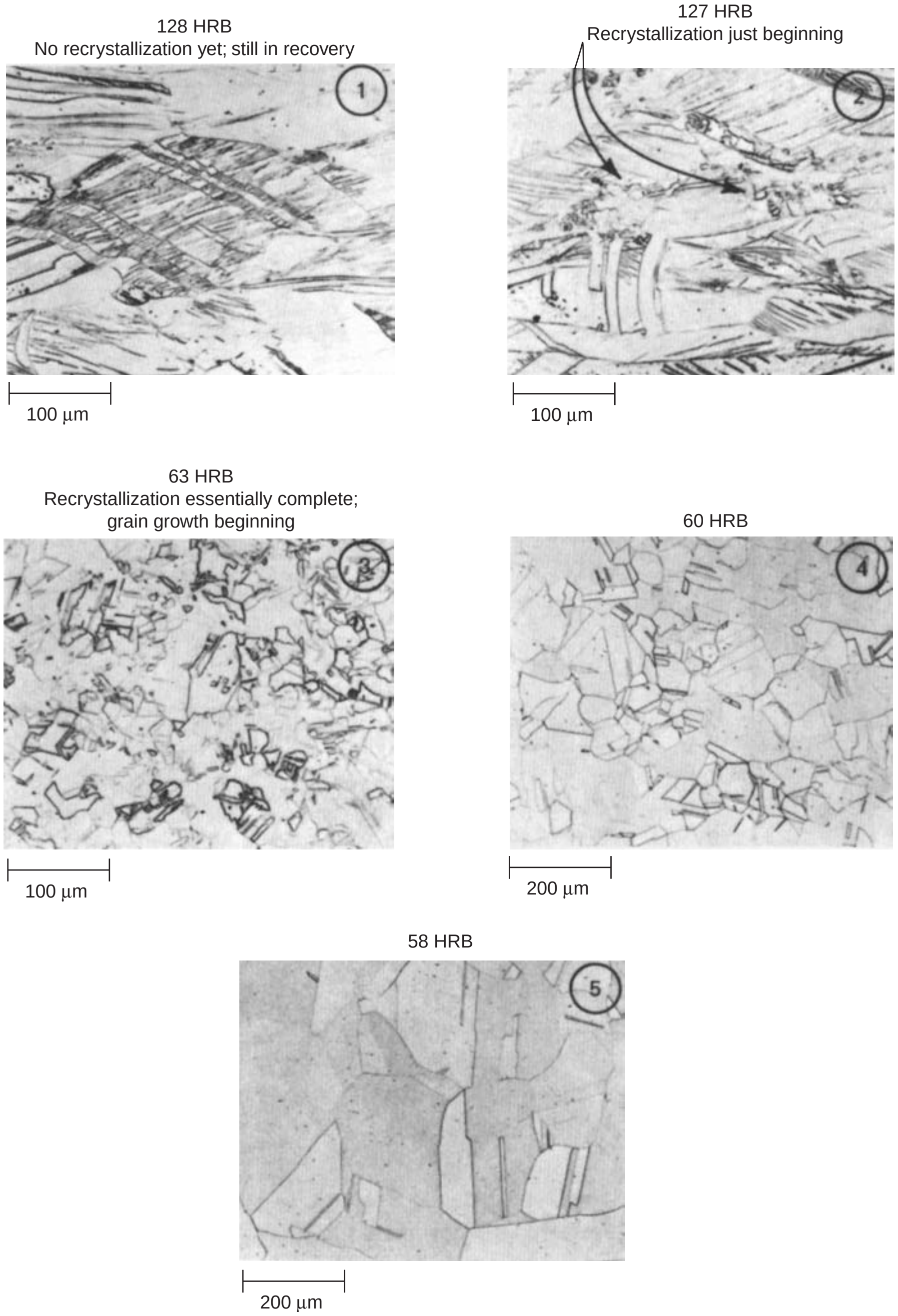


Fig. 4 Effect of annealing time at fixed temperature (400 °C, or 750 °F) on hardness of a Cu-5Zn solid-solution alloy cold worked 60%



128 HRB
No recrystallization yet; still in recovery

127 HRB
Recrystallization just beginning

63 HRB
Recrystallization essentially complete; grain growth beginning

60 HRB

58 HRB

Fig. 5 Microstructure of a Cu-5Zn alloy, cold rolled to 60%, then annealed for different times at 400 °C (750 °F). The numbers refer to the different annealing times shown in Fig. 4.

material to be annealed passes in a single strip. The annealing temperature for the entire length is dependent only on the furnace temperature and the speed of travel of the strip through the furnace.

The very large surface area with respect to weight permits extremely rapid heating of the metal strip in comparison to previous annealing methods. The annealing time can be measured accurately in seconds by controlling the speed of travel.

Annealing to Specific Properties

Although specific properties are most frequently produced by the controlled cold working of annealed material, there are occasions in which annealing to temper is necessary or advantageous. In the hot rolling of copper alloy plate—particularly plate of large pattern—the finishing temperature may not be consistent or controllable, and varying degrees of work hardening may occur. Also, small quantities and/or odd sizes of required drawn or roll-tempered materials may not be readily available, while appropriate stocks of harder material may be. Thin-gage strip (0.25 mm, or 0.010 in., thick) for radiator fabrication produced by annealing to temper is more closely controlled and more suitable for fabrication than strip in cold-worked tempers. In each case, an anneal is used to alter hardness and tensile properties to levels between those of the hard and fully annealed tempers, with reasonably predictable results. For most copper alloys, the rapid drops in tensile properties and hardness that occur with an increase in temperature in the annealing range necessitate the very close control of the annealing process to produce the desired results. Temperatures used are those in the lower annealing range, with special precautions taken to avoid any overheating. The resultant microstructures may indicate incomplete recrystallization for the harder tempers and grain sizes generally up to 0.025 mm (0.001 in.) for softer tempers. Tensile strengths and hardness levels similar to those of $\frac{1}{8}$, $\frac{1}{4}$, and $\frac{1}{2}$ hard cold-worked tempers can be produced by annealing hard-worked brasses, nickel silvers, and phosphor bronzes. While the yield strength for a given final hardness tends to be lower for alloys annealed to temper than for those cold worked to temper, the fatigue resistance of some phosphor bronze spring materials in annealed $\frac{1}{2}$ hard tempers appears to be superior to that of cold-worked material. Table 3 gives typical properties of annealed-to-temper mill materials. The successful use of annealing to provide specific tempers in mill products requires well-regulated working and annealing schedules designed to produce homogeneous material with controlled grain size, such that the final anneal can produce a uniform result throughout a given lot.

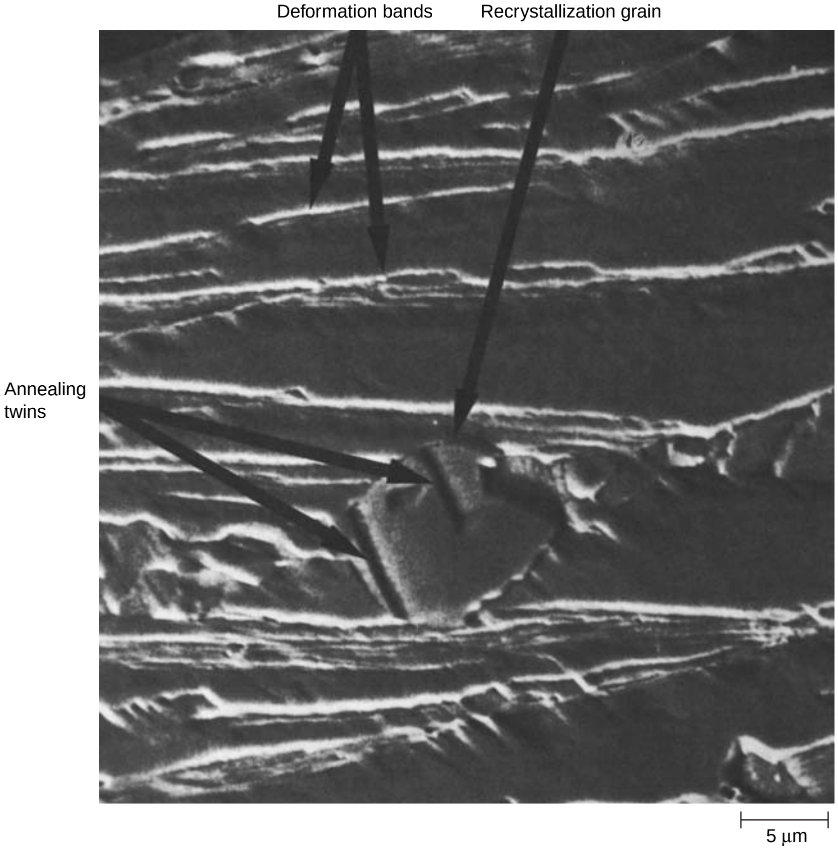


Fig. 6 High-magnification scanning electron micrograph (SEM) showing the beginning of recystallization in a Cu-5Zn alloy, cold worked by rolling 20 °C (68 °F) to reduction in thickness of 60%; annealed 60 min at 350 °C (660 °F). Note the annealing twins in the small isolated crystal newly formed in the deformed matrix.

General Precautions for Annealing

For best results in annealing copper and copper alloys, the precautions discussed subsequently should be observed.

Sampling and Testing. Test specimens must represent the extreme conditions of the furnace load. For copper alloys that do not contain grain-growth inhibitors, the best and most accurate test for the extent of annealing is the size of the average grain. Grain size is usually the basis for acceptance or rejection of the material. This determination requires special equipment not always available in the plants of consumers or fabricators. For convenience in testing, Rockwell-type hardness testers are used to approximate the grain size; ASTM specifications correlate Rockwell hardness with grain size values for many copper alloys.

Effect of Pretreatment. Because the amount of cold working and the anneal prior to cold working greatly affect the results of annealing after cold working, any schedule that is set up must take this pretreatment into account. Once a schedule has been established, both the anneal and the pretreatment must be adhered to for consistent results.

Effect of Time. In most furnaces, there is an appreciable difference between the temperature of the metal and that of the furnace. Consequently, time in the furnace greatly affects the final temperature of the metal. For a fixed anneal and furnace temperature, time must vary with the type of work load.

Oxidation should be held to a minimum to reduce the loss of metal and the cost of pickling and to improve surface finish. In some instances, specially prepared atmospheres are used to produce a bright annealed material. Usually the control of furnace atmosphere also results in better furnace economy.

Effect of Lubricants. Lubricants on metal to be annealed may cause staining that is difficult to remove. Regardless of the type of furnace or the article to be annealed, it is advisable to eliminate as much of the lubricant as possible before the metal is heated by degreasing or washing.

Hydrogen Embrittlement. When copper that contains oxygen (tough-pitch copper) is to be annealed, the hydrogen in the furnace atmosphere must be kept to a minimum. This reduces the embrittlement caused by the combination of the hydrogen in the atmosphere with the oxygen in the copper, forming water vapor under pressure and resulting in minute porosity in the metal. For temperatures lower than about 480 °C (900 °F), the hydrogen content of the atmosphere preferably should not exceed 1%, and as the temperature is increased, the hydrogen content should approach 0.

Impurities. Occasionally, it is difficult to obtain proper grain growth by annealing under standard conditions that previously have resulted in the desired grain size. This difficulty may sometimes be traced to impurities in the alloy.

Loading. It usually is inadvisable to anneal a variety of different sizes or kinds of material in the same charge because of the different rates of heating and the resulting final metal temperatures.

Fire cracking occurs when some alloys that contain residual stresses are heated too rapidly. Leaded alloys are particularly susceptible to fire cracking. The remedy is to heat slowly until the stresses are relieved. Special types of cold deformation, such as springing (flexing or reeling through a straightener), aid considerably in preventing fire cracking by inducing countervailing mechanical stresses.

Thermal shock or fatigue takes place when rapid and extreme changes in temperatures occur. Stresses that result in thermal shock are influenced by thermal expansion, thermal conductivity, strength, toughness, the rate of temperature change, and the condition of the material. Brasses containing lead, lead and tin, or lead and certain impurities including bismuth or tellurium may be hot short. If they are repeatedly subjected to extreme temperature changes, they may be subject to thermal shock, especially if highly stressed in tension on the surface.

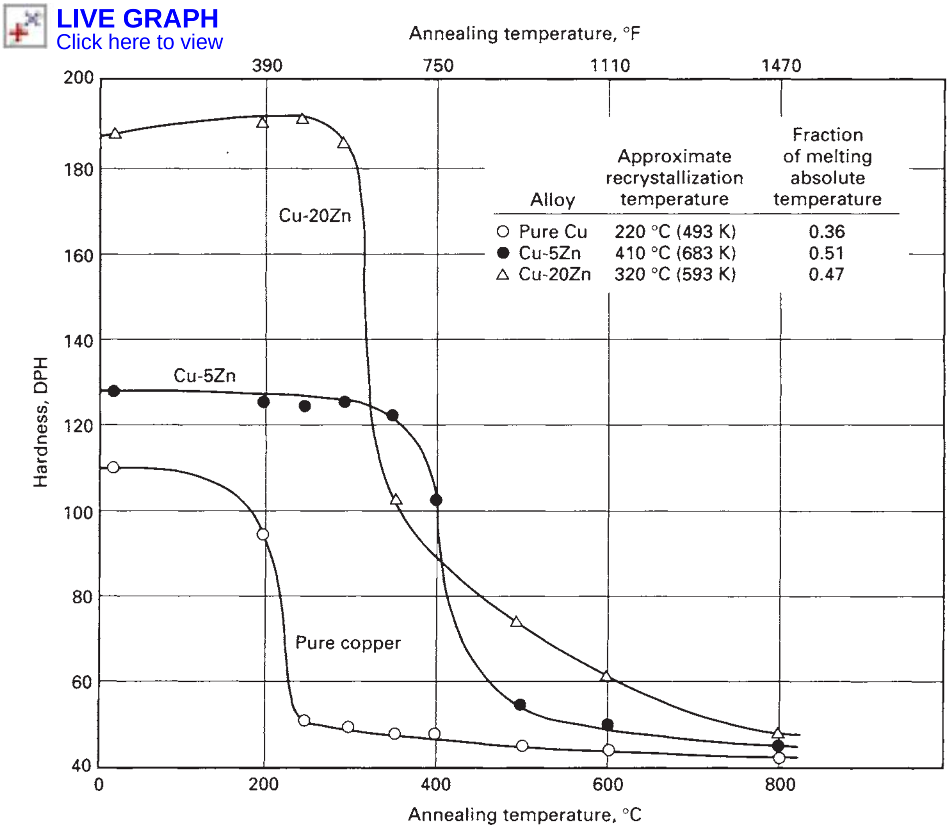


Fig. 7 Hardness as a function of annealing temperature for a 15 min annealing time. The alloys were originally cold rolled at 25 °C (77 °F) to 60% reduction in thickness. The recrystallization temperatures listed are based on the inflection point of each curve.

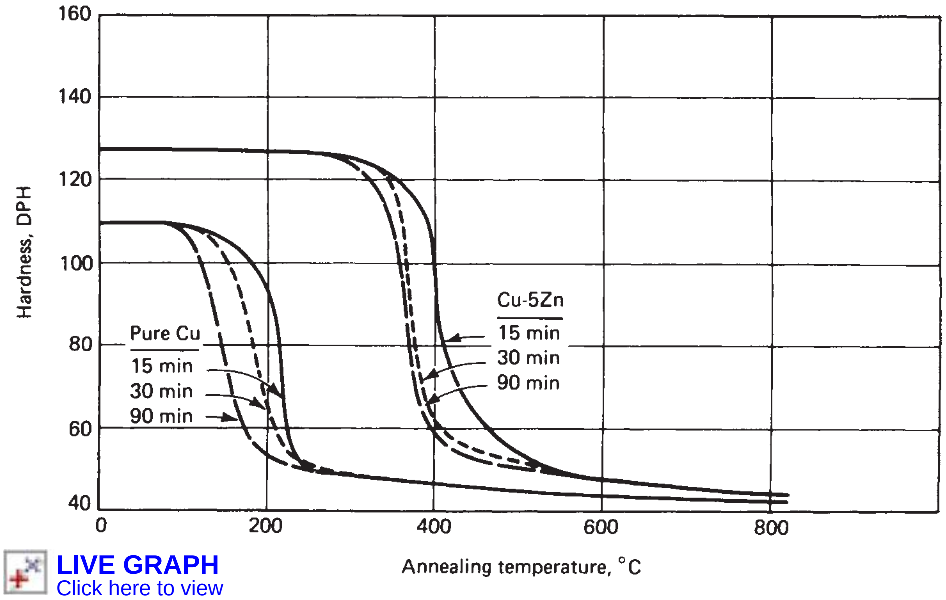


Fig. 8 Hardness as a function of annealing time and temperature for pure copper and a Cu-5Zn alloy. Both materials were originally cold rolled at 25 °C (77 °F) to 60% reduction in thickness.

Cooling. Alpha brasses containing less than 70% copper may contain some β phase that is formed during casting or during heat treatment above 600 °C (1110 °F), especially if the metal section is massive. Quenching rapidly will entrap the β phase in the brass. Slow cooling will permit the time and temperature to convert the β to the α phase.

Sulfur Stains. Excessive sulfur in the fuel or lubricant will cause discoloration of the metal; red stains appear on yellow brass, and black or reddish-brown stains on copper-rich alloys.

Annealing of Castings

Annealing is applied to castings of some duplex alloys, such as manganese bronzes and aluminum bronzes, in order to correct the effects of mold cooling. The extremely slow cooling of sand and plaster castings, or the rapid cooling of permanent mold or die castings, can produce microstructures resulting in hard hardness and/or low ductility and occasionally inferior corrosion resistance. Typical annealing treatments for castings are in the range of 580 to 700 °C (1075 to 1300 °F) for 1 h at temperature. For aluminum bronzes, rapid cooling by water quenching or high-velocity air is advisable.

Stress Relieving

Stress relieving is a process intended to relieve internal stress in materials or parts without appreciably affecting their properties. Stress-relieving heat treatments are applied to wrought or cast copper and copper alloys as one means of accomplishing this objective.

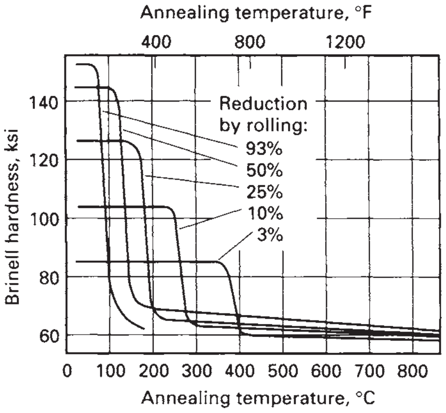


Fig. 9 Curves for copper showing the effect of the amount of the initial deformation on the annealing response.

During the processing or fabrication of copper or copper alloys by cold working, strength and hardness increase as a result of plastic strain. Because plastic strain is accompanied by elastic strain, residual stresses remain in the resultant product. If allowed to remain in sufficient magnitude, residual surface tensile stresses can result in stress-corrosion cracking of material in storage or service, unpredictable distortion of material during cutting or machining, and hot cracking of materials during processing, brazing, or welding. In brasses that contain more than 15% Zn, SCC can occur if sufficient amounts of residual tensile stress and trace amounts of atmospheric ammonia are present. Other copper alloys, such as cold-worked aluminum bronzes and silicon bronzes, may also suffer SCC under more severe environments.

Although mill practice for stress relief frequently involves mechanical means such as flexing, cross-roll straightening, or shot peening, stress-relief heat treatments are employed for some tubular products and odd shapes. Thermal stress relief is also used for formed parts and fabrications made by material users. It is important to recognize that thermal stress relief reduces residual stress by eliminating part of the residual elastic strain, whereas mechanical stress relief merely redistributes residual stress into a less detrimental pattern.

Stress-relief heat treatments are carried out at temperatures below those normally used for annealing. Typical process stress-relieving temperatures for selected coppers and copper alloys are given in Table 4 (wrought products) and Table 5 (cast products). Temperatures for the treatment of cold-formed or welded structures are generally 50 to 110 °C (90 to 200 °F) higher than the temperatures in Table 4. In the case of the weld repair of ship propellers, for example, care must be exercised to prevent the buildup of excessive residual stresses in the weld zone because such stresses may lead to accelerated corrosion attack. Current propeller repair specifications require postweld treatment for the aluminum and manganese bronze weldments. Heat treatment of the aluminum bronze at 565 or 650 °C (1050 to 1200 °F) imparts the best overall corrosion resistance to the heat-affected zone. Manganese bronze weldments are not susceptible to SCC when subjected to yield stress loading in flowing seawater. Heat treatment in the range of 200 to 540 °C (400 to 1000 °F) does not significantly change the tensile, corrosion-fatigue, or general corrosion properties of manganese bronze.

From a practical standpoint, higher-temperature/shorter-time treatments are preferable. However, to guarantee the preservation of mechanical properties, lower temperatures and longer times are sometimes necessary. The optimal cycle produces adequate stress relief without adversely affecting properties. As shown in Fig. 10, some alloys may undergo slight increases in property values during stress-relief heat treatment.

To detect the presence of significant residual stress and to evaluate the effectiveness of stress-relieving treatments, samples of material may be tested with mercurous nitrate solutions, as described in ASTM B 154. This test method is an accelerated test for detecting the presence of residual (internal) stresses, which might result in failure of individual parts in storage or in service due to SCC. It is not intended for testing assemblies of fabricated parts from mill products. Because of the hazards of mercurous salts, tests in high concentrations of moist ammonia have also been used. Warping of rod or tube during longitudinal saw slitting has also been used as a crude field test for residual stress.

Hardening

Copper alloys that are hardened by heat treatment are of two general types: those that are softened by high-temperature quenching and hardened by lower-temperature precipitation heat treatments, and those that are hardened by quenching from high temperatures through martensitic-type reactions. Alloys that harden during low-to-intermediate-temperature treatments following solution quenching include precipitation-hardening, spinodal-hardening, and order-hardening types. Quench-hardening alloys comprise aluminum bronzes, nickel-aluminum bronzes, and a few special copper-zinc alloys. Usually quench-hardened alloys are tempered to improve toughness and ductility and reduce hardness in a manner similar to that used for alloy steels.

Low-Temperature-Hardening Alloys

For purposes of comparison, Table 6 lists examples of the various types of low-temperature-hardening alloys, as well as typical heat treatments and attainable property levels for these alloys. Additional details are given in the three subsections below.

Precipitation-Hardening Alloys. Most copper alloys of the precipitation-hardening type find use in electrical and heat conduction applications. Therefore the heat treatment must be designed to develop the necessary mechanical strength and electrical conductivity. The resulting hardness and strength depend on the effectiveness of the solution quench and the control of the precipitation (aging) treatment. It should be noted that the terms age hardening and aging are used in heat-treating practice as substitutes for the term precipitation hardening or a spinodal hardening. Copper alloys harden by elevated-temperature treatment rather than ambient-temperature (natural) aging, as in the case of some aluminum alloys. As dissolved atoms proceed through the coagulation, coherency, and precipitation cycle in the quenched alloy lattice, hardness increases, reaches a peak, and then decreases with time. Electrical conductivity increases continuously with time until some maximum is reached, normally in the fully precipitated condition. The optimal condition generally preferred results from a precipitation treatment of temperature and duration just beyond those that correspond to the hardness aging peak. Cold working prior to precipitation aging tends to improve heat-treated hardness. In the case of lower-strength wrought alloys such as C18200 (copper-chromium) and C15000 (copper-zirconium), some heat-treated hardness may be sacrificed to attain increased conductivity, with final hardness and strength being enhanced by cold working. Two precipitation treatments are necessary in order to develop maximum electrical conductivity and hardness in alloy C18000 (copper-nickel-silicon-chromium) because of two distinct precipitation mechanisms.

Certain guidelines can be used to diagnose problems encountered in producing desired properties in precipitation-hardening alloys:

Problem	Diagnosis
Low hardness	Solution temperature too low; solution quench delayed or cooling rate too low; aging temperature too low and/or time too short (underaging) or temperature too high and/or time too long (overaging)
Low hardness; low conductivity	Inadequate solution treatment and/or underaging
Low hardness; high conductivity	Inadequate solution treatment and/or overaging
High hardness; low conductivity	Underaging; contaminated material

When precipitation hardening is performed at the mill, further treatment following the fabrication of parts is not required. However, it may be desirable to stress relieve parts in order to remove stresses induced during fabrication, particularly for highly formed cantilever-type springs and intricate, machined shapes that require maximum resistance to relaxation at moderately elevated temperatures.

Spinodal-Hardening Alloys. Alloys that harden by spinodal decomposition are hardened by a treatment similar to that used for precipitation-hardening alloys. The soft, ductile spinodal structure is generated by a high-temperature solution treatment followed by quenching. The material can be cold worked or formed in this

Table 1 Variables that affect the recrystallization temperature

Variable	Effect on recrystallization temperature
Time at annealing temperature	Increasing time decreases temperature
Amount of plastic deformation by cold working	Increasing amount of cold work decreases temperature
Solute concentration in solid solution	Generally increases temperature; depends upon effect on melting temperature
Presence of second phases	Second-phase particles decrease temperature
Original grain size before cold working	Decreasing grain size decreases temperature
Rate of plastic deformation	Increasing rate decreases temperature
Temperature of cold working	Decreasing temperature of cold working decreases recrystallization temperature

condition. A lower-temperature spinodal-decomposition treatment, commonly referred to as aging, is then used to increase the hardness and strength of the alloy. Spinodal-hardening alloys are basically copper-nickel alloys with chromium or tin additions. The hardening mechanism is related to a miscibility gap in the solid solution and does not result in precipitation. The spinodal-hardening mechanism does result in the chemical segregation of the α crystal matrix on a very fine (Ångström) scale and requires the use of the electron microscope to discern the metallographic effects (Fig. 12). Because no crystallographic changes take place, spinodal-hardening alloys retain excellent dimensional stability during hardening.

Order-Hardening Alloys. Certain alloys, generally those that are nearly saturated with an alloying element dissolved in the α phase, undergo an ordering reaction when highly cold-worked material is annealed at a relatively low temperature. Alloys C61500, C63800, C68800, and C69000 are examples of copper alloys that exhibit this behavior. Strengthening is attributed to the short-range ordering of the dissolved atoms within the copper matrix, an ordering which greatly impedes the motion of dislocations through the crystals.

The low-temperature order-annealing treatment also acts as a stress-relieving treatment, which raises yield strength by reducing stress concentrations in the lattice at the focuses of dislocation pileups. As a result, order-annealed alloys exhibit improved stress-relaxation characteristics.

Order annealing is done for relatively short times at relatively low temperatures, generally in the range from 150 to 400 °C (300 to 750 °F). Because of the low temperature, no special protective atmosphere is required. Order hardening is frequently done after the final fabrication step to take full advantage of the stress-relieving aspect of the treatment, especially where resistance to stress relaxation is desired.

Quench Hardening and Tempering

Quench hardening and tempering (also referred to as quench and temper hardening) is used primarily for aluminum bronze and nickel-aluminum bronze alloys, and occasionally for some cast manganese bronze alloys with zinc equivalents of 37 to 41%. Aluminum bronzes with 9 to 11.5% Al, as well as nickel-aluminum bronzes with 8.5 to 11.5% Al, respond in a practical way to quench hardening by a martensitic-type reaction. Generally alloys higher in aluminum content are too susceptible to quench cracking, whereas those with lower aluminum contents do not contain enough high-temperature β phase to respond to quench treatments.

Heat-Treating Equipment

Although basic furnace design is similar for all copper alloys, consideration must be given to the annealing temperature range and method of cooling. Solid-solution alloys that do not precipitation harden are usually annealed at temperatures below 760 °C (1400 °F) and may be cooled at any convenient rate. Precipitation- or spinodal-hardenable alloys are solution treated at temperatures up to 1040 °C (1900 °F) and require rapid quenching to ambient temperatures.

Batch-type atmosphere furnaces may be heated electrically or by oil or gas. When non-

Table 2 Annealing temperatures for widely used cold-worked copper and copper alloys

Alloy	Common name	Annealing temperature °C	Annealing temperature °F
Wrought coppers			
C10100–C10300	Oxygen-free copper	375–650	700–1200
C10400–C10700	Oxygen-free silver-bearing copper	475–750	900–1400
C10800	Oxygen-free low-phosphorus copper	375–650	700–1200
C11000	Electrolytic tough-pitch copper	250–650	500–1200
C11100	Electrolytic tough-pitch, anneal-resistant copper	475–750	900–1400
C11300, C11400, C11500, C11600	Silver-bearing tough pitch copper	400–475	750–900
C12000	Phosphorus-deoxidized copper, low residual phosphorus	375–650	700–1200
C12200	Phosphorus-deoxidized copper, high residual phosphorus	375–650	700–1200
C12500, C12700, C13000	Fire-refined, tough-pitch copper with silver	400–650	750–1200
C14500	Phosphorus-deoxidized, tellurium-bearing copper	425–650	800–1200
C14700	Sulfur copper	425–650	800–1200
C15500	…	475–525	900–1000
Wrought copper alloys			
C16200	Cadmium copper	425–750	800–1400
C17000, C17200, C17500	Beryllium copper	775–925(a)	1425–1700(a)
C19200	…	700–800	1300–1500
C19400	…	375–650	700–1200
C19500	…	375–600	750–1100
C21000	Gilding metal	425–800	800–1450
C22000	Commercial bronze	425–800	800–1450
C22600	Jewelry bronze	425–750	800–1400
C23000	Red brass	425–725	800–1350
C24000	Low brass	425–700	800–1300
C26000	Cartridge brass	425–750	800–1400
C26800, C27000, C27400	Yellow brass	425–700	800–1300
C28000	Muntz metal	425–600	800–1100
C31400, C31600	Leaded commercial bronzes	425–650	800–1200
C33000, C33500	Low-leaded brass	425–650	800–1200
C33200, C34200, C35300	High-leaded brass	425–650	800–1200
C34000, C35000	Medium-leaded brass	425–650	800–1200
C35600	Extra-high-leaded brass	425–650	800–1200
C36000	Free-cutting brass	425–600	800–1100
C36500, C36600, C36700, C36800	Leaded Muntz metal	425–600	800–1100
C37000	Free-cutting Muntz metal	425–650	800–1200
C37700	Forging brass	425–600	800–1100
C38500	Architectural bronze	425–600	800–1100
C41100	…	425–600	800–1100
C41300	…	425–750	800–1400
C42500	…	475–750	900–1400
C44300, C44400, C44500	Inhibited admiralty brasses	425–600	800–1100
C46200, C46400–C46700	Naval brass	425–600	800–1100
C48200, C48500	Leaded naval brass	425–600	800–1100
C50500	Phosphor bronze	475–650	900–1200
C51000, C52100, C52400	Phosphor bronze	475–675	900–1250
C53200, C53400, C54400	Free-cutting phosphor bronze	475–675	900–1250
C60600, C60800	Aluminum bronze	550–650	1000–1200
C61000	Aluminum bronze	615–900	1125–1650
C61300, C61400	Aluminum bronze	750–875	1400–1600
C61800, C62300–C62500	Aluminum bronze	600–650(b)	1100–1200(b)
C61900	…	550–800	1000–1450
C63000	Aluminum bronze	600–700(c)	1100–1300(c)
C63200	Aluminum bronze	625–700(c)	1150–1300(c)
C64200	Aluminum bronze	600–700	1100–1300
C63800	…	400–600	750–1100
C65100	Low-silicon bronze	475–675	900–1250
C65500	High-silicon bronze	475–700	900–1300
C66700	Manganese brass	500–700	930–1300
C67000, C67400, C67500	Manganese bronze	425–600	800–1100
C68700	Aluminum brass	425–600	800–1100
C68800	…	400–600	750–1100
C70600	Copper nickel, 10%	600–825	1100–1500
C71000, C71500	Copper nickel, 20%, Copper nickel, 30%	650–825	1200–1500
C72500	…	675–800	1250–1475
C74500, C75200	Nickel silver	600–750	1100–1400
C75400, C75700, C77000	Nickel silver	600–815	1100–1500
C78200	Leaded nickel silver	500–620	930–1150
Cast copper alloys			
C95300–C95800	Aluminum bronze castings	620–670	1150–1225

(a) Solution-treating temperature; see Table 7 for temperatures for specific alloys. (b) Cool rapidly (cooling method important in determining result of annealing). (c) Air cool (cooling method important in determining result of annealing) explosive atmospheres are used, electrically heated furnaces permit the atmosphere to be introduced directly into the work chamber.

Furnaces that are heated by gas or oil and that employ protective atmospheres sometimes have a muffle to contain the atmosphere and protect the work from the direct fire of the burners.

A properly constructed and safely operated muffle that prevents the infiltration of air by maintaining positive pressure is always required when explosive atmospheres, such as hydrogen, are used.

When protective atmospheres are used during annealing, the work must be cooled in the atmosphere almost to room temperature to prevent surface scale or discoloration. Metal temperatures above 65 °C (150 °F) in air may result in light tarnishing. If some degree of surface oxidation and discoloration can be tolerated, direct-natural-gas-fired furnaces may be used. The products of combustion from the gas-air burners are controlled to yield reducing combustion products similar in composition to manufactured protective atmospheres. Parts annealed in reducing atmospheres developed by the control of the furnace air-to-gas ratio require cleaning to restore luster.

Continuous atmosphere furnaces (Fig. 13) offer versatility for solution heat treating a wide variety of products. Usually, the furnace consists of a vestibule that provides a seal for the atmosphere and in some instances preheats the work, a heating chamber of sufficient length to ensure complete solution treating, and a cooling or quenching chamber that also serves as an atmosphere seal.

Because the work is usually conveyed at a fixed rate through the furnace, moderate temperature gradients are less harmful than in batch furnaces. When long heating chambers are required, the furnace may be divided into more than one temperature-controlled heating zone. It is practical to develop a high temperature in the entrance zone to facilitate the heating of the work to the desired temperature. The cooling chamber may be either a long tunnel through which cool, protective atmosphere is circulated or a water-quench zone supplied with a protective atmosphere.

Products such as stampings, machined shapes, castings, and small assemblies are conveyed through the furnace on an endless belt or conveyor chain. Long sections such as tubing, bar, and flat products, or heavy sections that permit stacking on trays, may be conveyed on a roller hearth. In rolling-mill operations, the product is uncoiled at the entrance of the furnace and pulled through the furnace by terminal equipment at the exit end; thus, there are no moving parts within the furnace. For wire products, either annealing is carried out in bell furnaces, with the wire reel wound, or in-line resistance annealing is performed upon exit of the product from the drawing machine prior to reel winding.

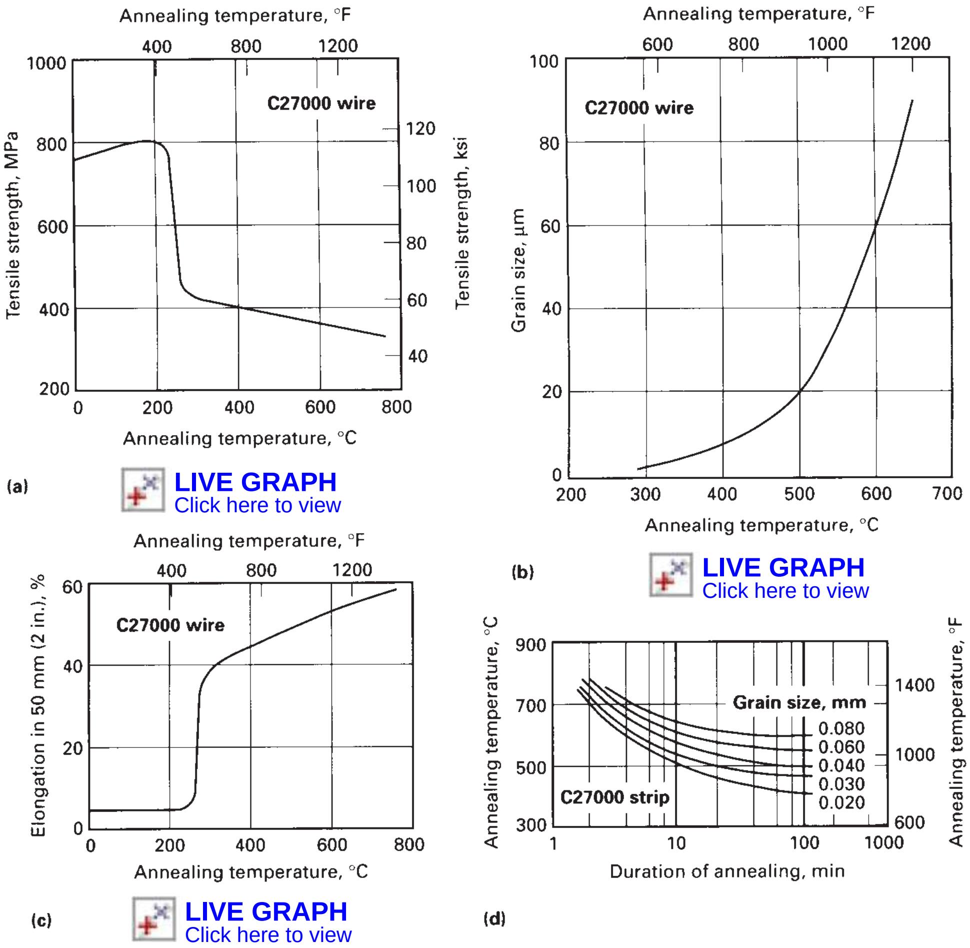


Fig. 10 Effects of annealing temperature and time on characteristics of C27000 wire and strip. Effects of annealing temperature (annealing time, 1 h) on (a) tensile strength, (b) grain size, and (c) elongation of C27000 wire hard drawn 63%. (d) Effect of annealing time on grain size of C27000 strip 1.3 mm (0.050 in.) thick

Salt Baths. Molten neutral salts may be used for the annealing, stress relieving, solution heat treating, or aging of copper alloys. The composition of the salt mixture depends on the temperature range required. For heating between 705 and 870 °C (1300 and 1600 °F), mixtures of sodium chloride and potassium chloride are commonly used. Various mixtures of barium chloride with sodium and potassium chlorides are used for a wider temperature range (595 to >1095 °C, or 1100 to >2000 °F). The latter mixtures are compatible with each other and are commonly used in multiple-furnace operations when it is advantageous to preheat the work in one mixture at a low temperature and then transfer the work to a high-temperature bath. The least common neutral salts are mixtures of calcium chloride, sodium chloride, and barium chloride. They have an operating temperature range of 540 to 870 °C (1000 to 1600 °F) but usually are operated between 540 and 650 °C (1100 and 1200 °F).

The sodium chloride-carbonate mixtures (not true neutral salts) are used between 595 and 925 °C (1100 and 1700 °F), primarily for annealing. For operating temperatures below 540 °C (1000 °F), the only practical mixtures are the nitrate-nitrite salts. Cyanide-base salts have limited application for heating copper alloys. Although copper is soluble in cyanide, these salts can be used, with caution, when a very bright finish is required.

None of the above salt mixtures can be used for the solution treating of standard beryllium-copper alloys because of intergranular attack, pitting, or discoloration.

Aging and stress-relieving operations require furnace equipment that can be controlled to within 3 °C (5 °F) throughout the work zone. Unless cleaning after heating is permissible, it may be necessary to use controlled-atmosphere or vacuum equipment.

Because of the necessity for close temperature control, forced-convection (recirculating-air) and salt bath furnaces are commonly used for aging and stress relieving. Forced-convection furnaces may be of the box, bell, or pit type. Each is equipped with a fan that recirculates the constant-temperature atmosphere over the work. When forced-convection furnaces are fired by gas or oil and protective atmosphere or vacuum is used, the work must be contained in a properly operating muffle chamber or retort to seal off all products of combustion and to prevent air infiltration. Temperature variations and heating and cooling times are compared in the subsequent example.

Example 1: Comparison of Atmosphere Furnaces and Salt Bath Treatment. A comparison was made of temperature variations in a bell furnace and in a pit retort furnace during the heat treating of small, flat springs made of beryllium copper (Fig. 14). Both furnaces were rated at

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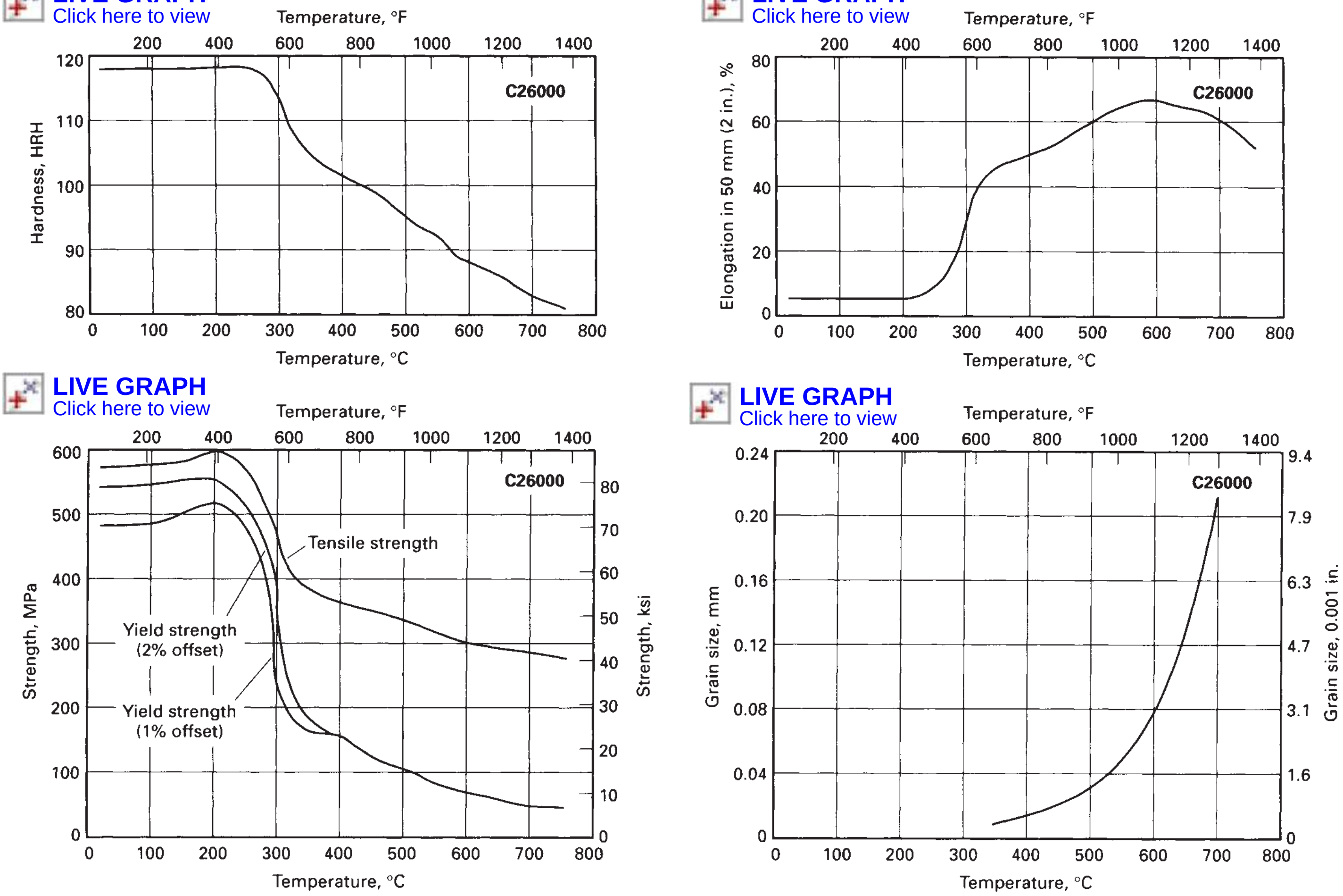

Fig. 11 Annealing data for alloy C26000. Finish rolling reduction 40.6%

Table 3 Typical properties of copper alloys annealed to temper

Alloy	Common name	Annealed temper: Standard designation	Annealed temper: Former designation	Tensile strength: MPa	Tensile strength: ksi	Approximate hardness, HR30T
C26000	Cartridge brass	O81	¼ hard	340–405	49–59	43–51
		O82	½ hard	395–460	57–67	56–66
C51100, C53200, C53400, C54400	Phosphor bronze	O82	½ hard	380–485	55–70	57–73
C75200	Nickel silver	O81	¼ hard	400–495	58–72	49–67
		O82	½ hard	455–550	66–80	62–72

30 kW. The load in each furnace weighed 90 kg (200 lb) and contained 55,000 to 60,000 springs. An exothermic gas, produced by a generator using an air-to-gas ratio of 6.75:1 (capacity, 10 m^3/h, or 350 ft^3/h), was used as the protective atmosphere. The composition of the atmosphere was 6.5% CO, 6% CO2, 10% H_2, bal N_2, dew point was 2 °C (35 °F) after refrigeration (18 to 21 °C, or 65 to 70 °F, as generated).

Salt baths can reduce total furnace time by up to 30%, compared to that required with atmosphere furnaces (Fig. 15). Salt baths are particularly valuable when the age-hardening time is of short duration and when the precise control of time at the aging temperature is required.

Commercially available nitrate-nitrite salt mixtures (40 to 50% sodium nitrate, remainder sodium or potassium nitrite) that melt at 143 °C (290 °F) are used for aging and stress relieving. All material to be heated in salt should be properly cleaned and dried before being immersed in the molten salt; any organic substance (such as oil or grease) will react violently with the nitrate-nitrite salt.

Protective Atmospheres

The selection of protective atmospheres for heat treating copper and copper alloys is influenced by the temperature used in the heat-treating process.

Heating above 705 °C (1300 °F). An exothermic atmosphere is the least expensive protective atmosphere for the heat treatment of copper alloys. The air-to-gas ratio is adjusted to produce a combusted gas that contains 2 to 7% H for use in muffle furnaces operating at 705 to 995 °C (1300 to 1825 °F). The atmosphere is used successfully for solution treating alloys such as beryllium coppers, chromium coppers, zirconium coppers, and copper-nickel-silicon alloys.

Usually, combusted gases are dried with a surface cooler, using tap water to keep the water-to-hydrogen ratio reducing throughout the heating and cooling cycle. It may be necessary to lower the dew point further by refrigerating the gas. If the furnace atmosphere is not sufficiently reducing, or if the muffle leaks air, a subscale, or internal oxidation of the hardening elements below the surface of the metal, results. Subscale formation can occur rapidly above 845 °C (1550 °F) if the atmosphere becomes oxidizing.

Dissociated ammonia is used primarily for annealing and brazing operations. The gas is very flammable and can explode if air enters the furnace while at an elevated temperature or if the furnace is improperly purged before reaching the elevated temperature.

Dissociated ammonia can be partly or completely burned with air to reduce cost and flammability. The hydrogen content can be controlled within a range of 1 to 24%, the remainder being nitrogen saturated with water vapor. Water must be removed to maintain a reducing atmosphere.

Table 4 Typical stress-relieving temperatures for wrought coppers and copper alloys

		Stress-relief temperature for						
		Sheet and strip		Rod and wire			Tube(d)	
Copper or copper alloy number	Name	Flat products(a), °C (°F)	Parts, °C (°F)	Rod(b), °C (°F)	Wire(c), °C (°F)	Parts, °C (°F)	Tube(e), °C (°F)	Parts, °C (°F)
Coppers								
C11000	Electrolytic tough-pitch	180 (355)	180 (355)	180 (355)	180 (355)	180 (355)	…	…
C12000	DLP	…	…	…	…	…	220 (430)	200 (390)
C12200	DHP	…	…	…	…	…	240 (465)	220 (430)
C14200	DPA	…	…	…	…	…	260 (500)	240 (465)
Copper alloys								
C21000	Gilding, 95%	275 (525)	275 (525)	…	…	…	…	…
C22000, C22600	Commercial bronze and jewelry bronze	275 (525)	275 (525)	300 (570)	260 (500)	275 (525)	…	…
C23000	Red brass, low brass	275 (525)	275 (525)	300 (570)	260 (500)	275 (525)	330 (625)	275 (525)
C26000	Cartridge brass	260 (500)	260 (500)	290 (555)	250 (480)	260 (500)	320 (610)	260 (500)
C27000	Yellow brass, 65%	260 (500)	260 (500)	290 (555)	250 (480)	260 (500)	290 (555)	260 (500)
C31400	Leaded commercial bronze	…	…	300 (570)	260 (500)	275 (525)	…	…
C33000, C33200	High- and low-leaded brasses	…	…	…	…	…	320 (610)	260 (500)
C33500	Low-leaded brasses	…	…	290 (555)	250 (480)	260 (500)	…	…
C34000, C35000	Medium-leaded brasses	260 (500)	260 (500)	…	…	…	…	…
C35300, C35600, C36000, C37700	Leaded, free-cutting and forging brasses	…	…	290 (555)	250 (480)	260 (500)	…	…
C43000	…	275 (525)	275 (525)	300 (570)	260 (500)	275 (525)	…	…
C43400	…	275 (525)	275 (525)	…	…	…	…	…
C44300–C44500	Admiralty brasses	…	…	…	…	…	320 (610)	260 (500)
C46200, C46400–C46700	Naval brasses	…	…	290 (555)	250 (480)	260 (500)	…	…
C51000	Phosphor bronze A	275 (525)	275 (525)	300 (570)	260 (500)	275 (525)	…	…
C52100	Phosphor bronze C	…	…	300 (570)	260 (500)	275 (525)	…	…
C54400	Phosphor bronze B-2	…	…	300 (570)	…	275 (525)	…	…
C65100, C65500	Silicon bronzes	…	…	300 (570)	275 (525)	275 (525)	…	…
C68700	Aluminum brass, arsenical	…	…	…	…	…	330 (625)	290 (555)
C69700	…	…	…	360 (680)	360 (680)	360 (680)	…	…
C70600	Copper nickel, 10%	420 (790)	420 (790)	…	…	…	480 (895)	420 (790)
C71500	Copper nickel, 30%	460 (860)	460 (860)	…	…	…	520 (970)	460 (860)
C73500	…	380 (715)	380 (715)	400 (750)	350 (660)	380 (715)	…	…
C74500	Nickel silver, 65–10	…	…	340 (645)	290 (555)	320 (610)	…	…
C75200	Nickel silver, 65–18	380 (715)	380 (715)	…	…	…	…	…
C75400	Nickel silver, 65–15	…	…	400 (750)	350 (660)	380 (715)	…	…
C75700	Nickel-silver, 65–12	…	…	350 (660)	300 (570)	340 (645)	…	…
C77000	Nickel silver, 55–18	340 (645)	340 (645)	…	…	…	…	…

DLP, phosphorus deoxidized, low-residual phosphorus. DHP, phosphorus deoxidized, high-residual phosphorus. DPA, phosphorus deoxidized, arsenical. Note: Annealing time is 1 h with the exception of tube. (a) Extra hard. (b) 1/2 hard. (c) Spring. (d) Annelaing time for tube is now min. (e) Hard drawn

Table 5 Typical stress-relieving temperatures for cast copper alloys

	Temperature	
Copper alloy number	°C	°F
C81300–C82200	260	500
C82400–C82800	200	390
C83300–C84800	260	500
C95200–C95800	315	600
C96600–C97800	260	500
C99300	510	950

Note: Time is 1 h per 25 mm (1 in.) of section thickness except for copper alloy C99300, for which it is 4 h per 25 mm (1 in.).

Table 6 Typical heat treatments and resulting properties for several low-temperature-hardening alloys

	Solution-treating temperature(a)		Aging treatment				
			Temperature				
Alloy	°C	°F	°C	°F	Time, h	Hardness	Electrical conductivity(b), %IACS
Precipitation hardening							
C15000	980	1795	500–550	930–1025	3	30 HRB	87–95
C17000, C17200, C17300	760–800	1400–1475	300–350	575–660	1–3	35–44 HRC	22
C17500, C17600	900–950	1650–1740	455–490	850–915	1–4	95–98 HRB	48
C18000(c), C81540	900–930	1650–1705	425–540	800–1000	2–3	92–96 HRB	42–48
C18200, C18400, C18500, C81500	980–1000	1795–1830	425–500	800–930	2–4	68 HRB	80
C94700	775–800	1425–1475	305–325	580–620	5	180 HB	15
C99400	885	1625	482	900	1	170 HB	17
Spinodal hardening							
C71900	900–950	1650–1740	425–760	800–1400	1–2	86 HRC	4–4
C72800	815–845	1500–1550	350–360	660–680	4	32 HRC	…

(a) Solution treating is followed by water quenching. (b) International Annealed Copper Standard. (c) Alloy C18000 (81540) must be double aged, typically 3 h at 540 °C (1000 °F) followed by 3 h at 425 °C (800 °F) (U.S. Patent 4,191,601) in order to develop the higher levels of electrical conductivity and hardness.

Hydrogen is highly reducing to copper oxide at elevated temperatures and is recommended for elevated-temperature bright annealing and brazing.

Commercial hydrogen contains about 0.2% O, which, if not removed, may cause internal oxidation of the reactive alloying elements in the copper.

When mixed with air, hydrogen is explosive at elevated temperature. Therefore, the furnace must be purged before being heated to high temperature, and air must not enter the furnace.

Heating below 705 °C (1300 °F). Combusted gas (lean exothermic atmosphere) is the most widely used protective atmosphere for the anneal of copper and copper alloys. Because of its low sulfur content, natural gas is the preferred fuel for the production of combusted gas. The air-to-gas ratio is adjusted to produce a hydrogen content of 0.5 to 1%. Combusted gas is dried before entering the furnace to prevent discoloration and staining of the metal by water vapor during the cooling cycle.

Steam is the most economical atmosphere for protecting copper alloys during annealing. Although the annealed metal is not as bright as when heated in a combusted-fuel-gas atmosphere, it is satisfactory for some applications. For products such as tightly wound coils of strip, steam can be used during the heating cycle, and combusted fuel gas can be used during cooling.

Inert gases, dissociated ammonia burned with air, and vacuum are more expensive and are not in common use for the annealing of copper

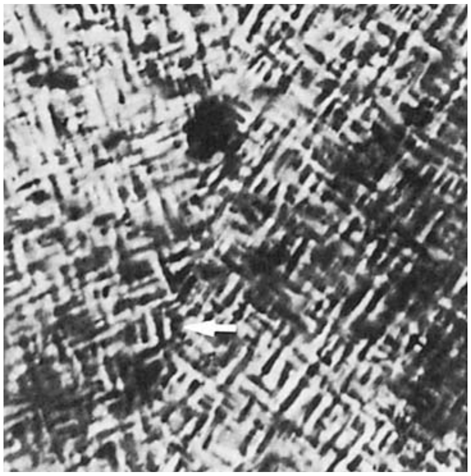

Fig. 12 Transmission electron micrograph of spinodal microstructure developed in a 66.3 Cu-30Ni-2.8Cr (wt%) alloy during slow cooling from 950 °C (1740 °F). The microstructure is homogenous up to the grain boundary indicated by the arrow. 35,000×

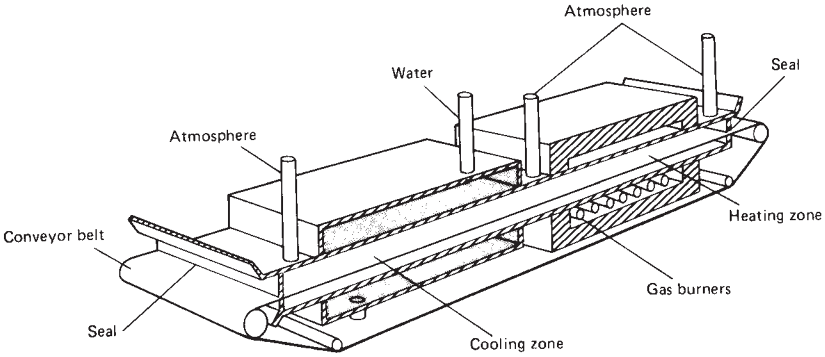

Fig. 13 Continuous conveyor furnace for heat treating copper alloys in a controlled atmosphere

alloys. A major disadvantage of vacuum is that heating and cooling are slow because heat is transferred by radiation only.

Heat Treating of Beryllium-Copper Alloys

Because the solid solubility of beryllium in an α-copper matrix decreases as the temperature is lowered, beryllium-copper alloys are precipitation hardenable. Heat treatment typically consists of solution annealing, followed by precipitation hardening. Table 7 gives recommended schedules for the solution treating and precipitation hardening of the five major beryllium-copper alloys that are produced in wrought form. Optimal mechanical and physical properties for specific applications can be attained by varying these schedules, but the temperatures and times given in this table constitute the most conventional practice and typically provide maximum tensile strength. In addition, better age hardening characteristics can be obtained if the material is cold worked after the solution anneal.

There is a wide variety of copper-base casting alloys (C81300 through C82800), in addition to the wrought beryllium-copper alloys, that contain beryllium. Appropriate solution-treating and aging schedules for these alloys are dictated by the levels of beryllium and other additives.

Solution Treating

Wrought beryllium-copper alloy mill products are generally supplied solution treated or solution treated and cold worked (Table 8). Material in these conditions can be fabricated without further heat treatment. Thus, solution treating is not typically a part of the fabricating process unless it is necessitated by a special requirement such as softening of the material for additional forming or is used as a salvage operation for parts that have been incorrectly heated for precipitation hardening.

In the quenched condition, beryllium-copper alloys are easily fabricated by standard production methods. Strip can be readily blanked, formed, deep drawn, or spun. Rod and bar respond to hot or cold forming, including forging, machining, and swaging. However, even though fully solution-annealed material is the softest form available, better age-hardening properties can be obtained if the material is cold worked after the final solution anneal. Therefore the alloy is often used in one of the cold-worked tempers shown in Table 8. The selection of a proper temper for a particular application is based on the severity of cold forming and the mechanical property requirements.

Solution-treating temperature limits must be adhered to if optimal properties are to be obtained from the precipitation-hardening treatment. Solution treating below the specified minimum temperature results in insufficient solution of the beryllium-rich phase. This results in lower hardness after precipitation hardening (Fig. 16).

Also, solution treating must be carefully controlled to produce the desired grain size, dimensional tolerances, and mechanical properties and to prevent oxidation. Exceeding the upper temperature limit causes grain coarsening in wrought material and overheating in wrought and cast materials. A coarse grain size impairs formability; overheating results in a brittle material that does not fully respond to precipitation hardening.

Effect of Solution-Treating Time. The time at the solution-treating temperature depends on the amount of beryllium-rich phase that must be dissolved. Solution of this phase must be complete to produce maximum strength after precipitation hardening.

In cast products, the as-cast structure usually contains a large amount of microsegregation within the dendritic pattern. Therefore, castings must be heated for a length of time sufficient to homogenize the structure. A minimum of 3 h at temperature is recommended for this purpose.

The solution treating of wrought material also removes the effects of cold working and permits additional forming. Some grain growth will occur during softening for additional forming because the solution-treating temperature is above the recrystallization temperature. Therefore, to minimize grain growth, excessive time at temperature must be avoided. It is recommended that wrought alloys be held at temperature 1 h for each inch or fraction of an inch of section thickness. The optimal amount of time for a specific application must be determined by mechanical testing and microscopic examination of the alloy.

Effect of Oxidation. When beryllium-copper alloys are solution treated in air or in an oxidizing atmosphere, two types of oxidation are encountered. A continuous and tenacious oxide surface layer forms on alloys with high beryllium contents. Low-beryllium alloys form a loosely adhering scale and are subject to internal oxidation.

The oxide layer on high-beryllium alloys does not significantly affect the mechanical properties of the precipitation-hardened material, but it is abrasive and causes severe wear of tools and dies if not removed. The oxidation of low-beryllium alloys not only has an abrasive effect, it decreases mechanical properties. This is caused by the surface layer of internal oxidation, which reduces the effective section thickness of the material. For both types of alloys, oxides may be removed by chemical or abrasive cleaning methods.

Quenching is a critical phase of the solution-treating process. Successful treatment requires that the material be quenched immediately, and at the highest possible rate, after being removed from the furnace. Any time lapse during transfer from the furnace to the quenching medium permits some cooling and causes precipitation. Precipitation is rapid at elevated temperatures and its occurrence significantly affects the properties obtained during subsequent precipitation hardening. The maximum allowable delay before quenching depends on the mass of the load, the size of the parts, and the transfer equipment. Mechanical testing and microscopic examination of the structure should be used to evaluate the effectiveness of the quenching operation.

Water quenching is the most common method of retaining the solid-solution condition in both wrought and cast products; however, because of their shape, some castings may crack as the result of the rapid cooling. Such castings may be quenched in oil or forced air; however, the slower cooling rates may cause some precipitation. Thin-gage strip is typically cooled in forced air.

Precipitation Hardening

The cold working of solution-treated beryllium-copper alloys influences the strength attainable through subsequent aging; the greatest response to aging occurs in material in the cold-rolled hard temper. In general, work hardening offers no advantage beyond the hard temper because formability is poor and control of the precipitation-hardening treatment for maximum strength is critical. For some applications, however, wire is drawn to higher levels of cold work prior to precipitation hardening.

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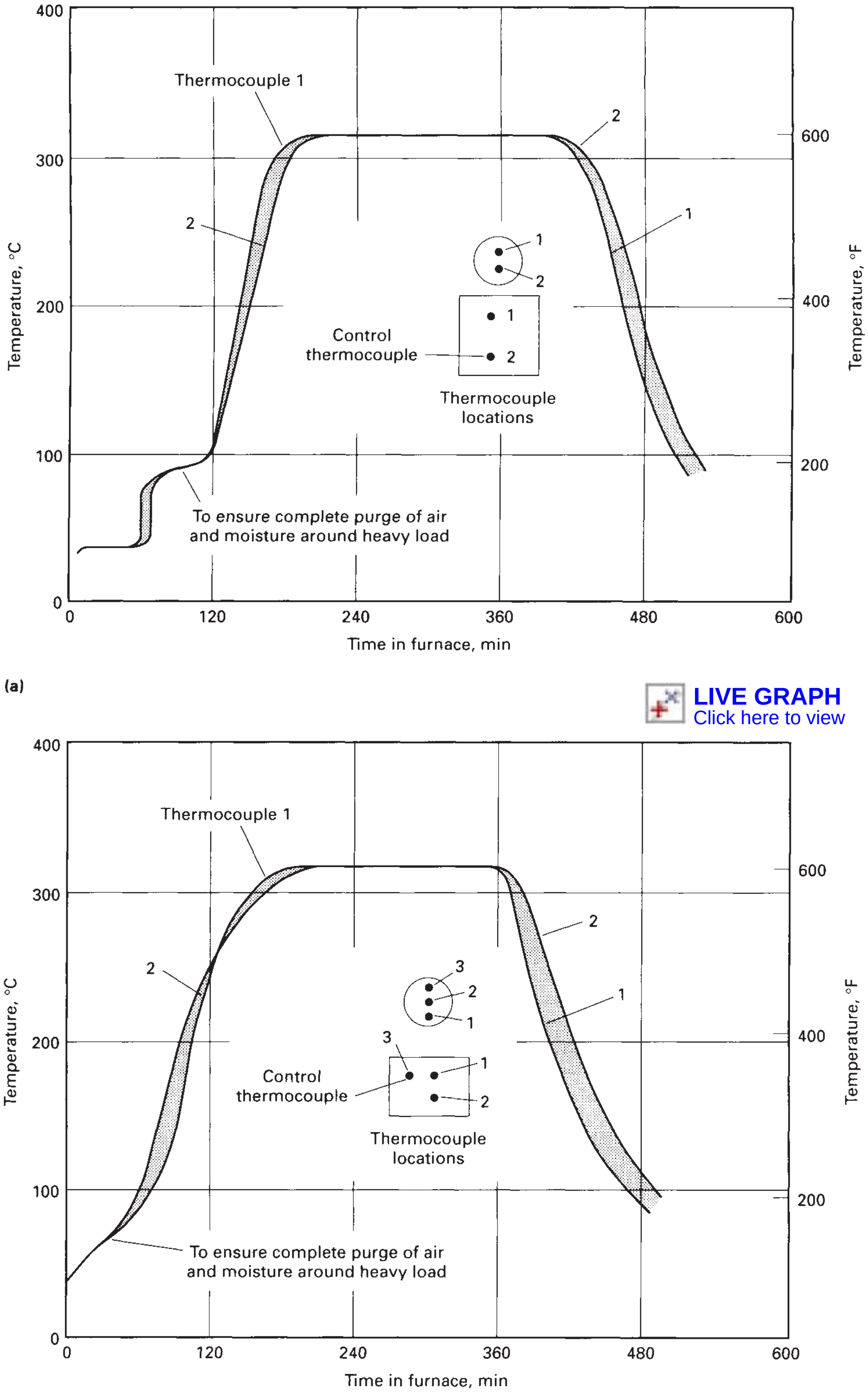

Fig. 14 Temperature variations in two types of furnaces (Example 1). (a) Bell furnace. (b) Retort furnace

Table 9 lists the properties typically specified for mill products of the common beryllium-copper alloys, and Fig. 17 shows the time required to develop maximum tensile strength in one of these alloys aged at various temperatures. The aging times in Fig. 17 vary slightly from those given in Table 9 for the same alloy; the latter are primarily for acceptance-test purposes.

Special combinations of properties can be obtained by varying either the aging time or the aging temperature. Table 10 shows the age-hardening response from underaging to overaging for cold-rolled material in various tempers. As tensile strength increases, elongation decreases and does not recover substantially with overaging, but electrical conductivity continues to increase. The response of alloy C17200 (1.9Be-0.2Co + Ni) at other aging temperatures within the hardening range (290 to 400 °C, or 550 to 750 °F) are similar to the response at 370 °C (700 °F), but the corresponding time cycles vary. Recommended precipitation-hardening cycles for solution-treated beryllium-copper castings are given in Table 11.

Effect of Temperature. The close control of temperature is critical in the conventional aging of beryllium-copper alloys. As indicated by the data in Tables 9 and 10, a change in temperature affects the time required for the development of maximum properties. Also, the higher temperatures can result in lower property values. Normal commercial control of ±6 °C (±10 °F) is adequate for temperatures in the range from 315 to 370 °C (600 to 700 °F).

Problems involving temperature usually arise when test data are translated into production control data. A strip specimen of the material tested at the mill may just meet the minimum specification requirements; however, when the fabricator heat treats a large mass of parts made of the same material, tests may indicate properties below the minimum requirements. The low properties may result from heat treating too large a mass of parts relative to the capacity of the furnace, inadequate time at the proper temperature, or the use of a higher temperature to gain production speed or to obtain fixture conformity when the parts are in fixtures.

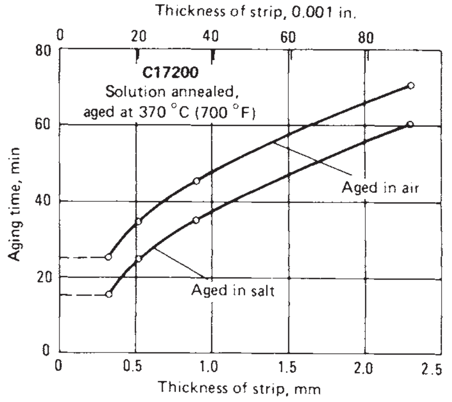

Fig. 15 Effect of metal thickness and heating medium on aging time required to develop maximum strength in C17200 strip

LIVE GRAPH
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Table 7 Solution treating and precipitation hardening of wrought beryllium–copper alloys

	Solution treatment(a)			Aging treatment		
	Temperature			Temperature		
Alloy	°C	°F	Time(b), h	°C	°F	Time, h
C17000	775–800	1425–1475–3	½–3	300–330	575–625	1–3
C17200	775–800	1425–1475	½–3	300–330	575–625	1–3
C17300	775–800	1425–1475	½–3			
C17500	900–925	1650–1700	½–3	455–480	850–900	1–3
C17510	900–925	1650–1700	½–3	455–480	850–900	1–3

(a) All alloys are cooled immediately and rapidly from the solution-treating temperature. Thin sections such as strip can be cooled in circulating atmosphere; heavier sections require water quenching. (b) Shorter times may be desirable to minimize grain growth, particularly for thin sections.

Effect of Grain Size. The effect of grain size on the properties of heat-treated material is less significant for beryllium-copper alloys than for solid-solution alloys such as brass and phosphor bronze. The relatively high temperatures required for solution treating beryllium-copper alloys usually override the effects of cold work and time at temperature. Low solution-treating temperatures will result in a fine grain size, but, if the temperature is too low to dissolve the beryllium-rich phase, the response to aging will be affected adversely and the benefits obtained from the fine grain size will be nullified. For this reason, grain sizes below about 0.015 mm (0.0006 in.) are not practical for most beryllium-copper products, regardless of dimensions. With normal commercial practice, and depending on the product, the grain size of solution-treated material will range from about 0.015 to 0.060 mm (0.6 to 2.4 mils).

Fixturing for Close Tolerances. Excellent dimensional accuracy can be achieved by properly supporting beryllium-copper parts during aging. Usually, overaging is necessary to hold close tolerances. Fixture design should be based on certain principles:

- Fixtures should be of minimum weight
- Excessive clamping pressure should be avoided, to prevent stripping of clamping-screw threads and warping of fixtures
- Parts should be held only at critical locations
- A maximum number of parts should be held by a minimum number of clamping screws
- Design should minimize warping of the fixture, maximizing its service life
- When the configuration of the part permits, the fixture should be designed so that parts can be stacked. Often parts having no more than two planes can be stacked (see Fig. 18), provided that no burrs are present.

An understanding of the behavior of beryllium-copper alloys during the hardening treatment is helpful in the design and use of fixtures for parts with a controlled gap or opening. These may be U-shaped parts, circular parts, or clips of various designs. During heating for hardening, the material will move in the direction in which it was plastically formed or elastically deflected. If both conditions occur before hardening, movement due to the elastic effect will prevail. These phenomena may be illustrated by the subsequent examples.

Table 8 Typical conditions of beryllium-copper mill products

		Tensile strength before aging	
Temper	Description	MPa	ksi
TB00	Solution treated	480	70
TD01	Solution treated and cold worked to ¼ hard	550	80
TD02	Solution treated and cold worked to ½ hard	625	91
TD04	Solution treated and cold worked to hard	760	110

Example 2: Reduction in Dimensional Variation with Fixturing. A comparison was made of the dimensional variations that occurred during the aging of solenoid guides heated as loose pieces and as fixtured pieces. The fixture that was used supported, with adequate pressure, all inside and outside surfaces of the part. Although the total cost of aging the guides as fixtured pieces was nearly two and a half times the cost of aging them as loose pieces (total cost per piece, based on the aging of 100,000 pieces per year), a significant improvement (reduction) in dimensional variation was achieved by the use of fixtures (Table 12).

Example 3: Fixturing and Aging Procedure for Dimensional Control of a Beryllium-Copper Spring Clip. Spring clips like the one shown in Fig. 19 were press formed to a slightly undersized inside diameter (24.9 to 25.2 mm, or 0.980 to 0.990 in.) so that they would fit snugly on a mandrel 25.4 ±0.03 mm (1 ±0.001 in.) in diameter. However, during aging for $\frac{1}{2}$ h at 350 °C (660 °F), the metal moved in the direction of elastic deflection, which caused the clips to be loose on the mandrel. Because precipitation hardening of beryllium-copper is a cumulative time-temperature reaction, the hardening treatment can be interrupted. Therefore, the clips (without being placed on the mandrel) were partially aged for 5 min at 350 °C (660 °F) (decreasing the original dimension to 24.8 to 25.0 mm, or 0.975 to 0.985 in.) and then were placed on the mandrel and aged at the same temperature for the remaining 25 min.

Following this aging treatment, none of the clips was larger than the diameter of the mandrel; the actual final dimension was governed by the time and temperature of aging, that is, by the amount of stress relief that occurred.

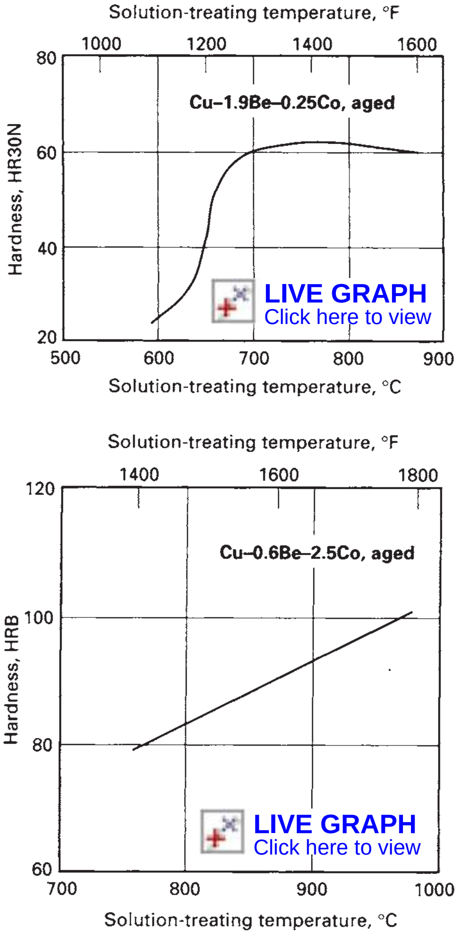


Fig. 16 Effect of solution-treating temperature on hardness of C17200 and C17500 after aging

Interrupted Aging. The selection of the time and temperature for the first step of the interrupted aging sequence (Example 3, mentioned previously) is important but not critical. If the time is inadequate, the direction of movement will not be established; if excessive, there will be insufficient time for heating the parts on the fixture to allow enough stress relief for close conformity. Usually the duration of the preliminary treatment should be about 15% of the total aging time. Allowance must be made for the mass effect of the load on the time required for it to reach furnace temperature. Also, interrupted aging procedures can be used to restrict increases in the outside diameters of various parts.

Inspection and Quality Control. In most instances, the completeness of aging can be verified by hardness testing. Exceptions are the tension testing of specimens taken from large parts and simulated service testing to determine elastic performance. Figure 20 is an example of variations observed from tensile testing.

Hardness measurements should always be made using the method and load most suitable for the thickness of the material and the normal level of hardness expected. Table 13 indicates suggested methods for testing various thicknesses of a hardened beryllium-copper alloy. Variations obtained with heat-treated parts and with strip are presented in the subsequent examples.

Example 4: Hardness Variations in Beryllium-Copper Springs. Terminal springs made of a beryllium-copper alloy of the composition 0.8 to 1% Be, 0.85% (max) Ni + Co + Fe, 3% (max) Zn + Sn were solution annealed and then aged for 5 h at 343 ±6 °C (650 ±10 °F) in a batch-type recirculating-air furnace (Fig. 21). The furnace load consisted of 280,000 pieces. Hardness tests were conducted on specimens of strip material representative of the parts. Specifications required a hardness of 70 to 75 HR15N. Results of hardness tests on 41 production lots within a three-month period are presented in Fig. 21.

Table 9 Properties and precipitation treatments usually specified for beryllium-copper alloys

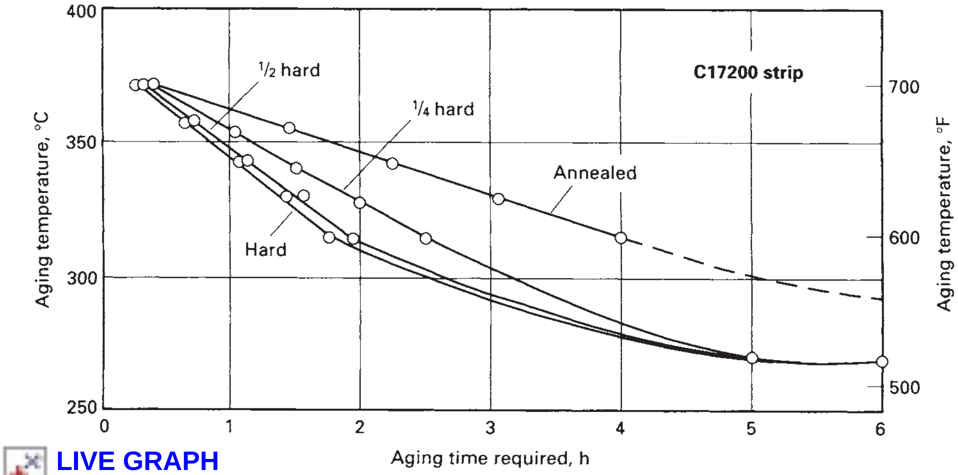
	Standard aging treatment									
		Temperature		Tensile strength		Yield strength(a)				Electrical conductivity,
Initial condition	Time, h	°C	°F	MPa	ksi	MPa	ksi	Elongation(b), %	Hardness(c)	%IACS
					C17200					
Flat products										
Annealed	None	…	…	415–540	60–78	195–380	28–55	35–60	45–78 HRB	17–19
1/4 hard	None	…	…	515–605	75–88	415–550	60–80	10–40	68–90 HRB	16–18
1/2 hard	None	…	…	585–690	85–100	515–655	75–95	10–25	88–96 HRB	15–17
Hard	None	…	…	690–825	100–120	620–770	90–112	2–8	96–102 HRB	15–17
Annealed(d)	3	315	600	1140–1345	165–195	965–1205	140–175	4–10	35–40 HRC	22–25
Annealed	1/2	370	700	1105–1310	160–190	895–1205	130–175	3–10	34–40 HRC	22–25
1/4 hard(d)	2	315	600	1205–1415	175–205	1035–1275	150–185	3–6	37–42 HRC	22–25
1/4 hard	1/3	370	700	1170–1380	170–200	965–1275	140–185	2–6	36–42 HRC	22–25
1/2 hard(d)	2	315	600	1275–1485	185–215	1105–1345	160–195	2–5	39–44 HRC	22–25
1/2 hard	1/4	370	700	1240–1450	180–210	1070–1345	155–195	2–5	38–44 HRC	22–25
Hard(d)	2	315	600	1310–1575	190–220	1140–1415	165–205	1–4	40–45 HRC	22–25
Hard	1/4	370	700	1275–1480	185–215	1105–1415	160–205	1–4	39–45 HRC	22–25
Rod, bar, plate										
Annealed	None	…	…	415–585	60–85	185–205	20–30	35–60	45–85 HRB	17–19
Hard	None	…	…	585–895	85–130	515–725	75–105	10–20	88–103 HRB	15–17
Annealed(d)	3	315	600	1140–1345	165–200	1000–1205	145–175	3–10	36–41 HRC	22–25
Hard(d)	2	315	600	1205–1550	175–225	1035–1380	150–200	2–5	39–45 HRC	22–25
Wire(e)										
Annealed	None	…	…	450–590	65–85	185–240	20–35	35–55	…	17–19
1/4 hard	None	…	…	620–795	90–115	485–655	70–95	10–35	…	15–17
1/2 hard	None	…	…	760–930	110–135	620–760	90–110	4–10	…	15–17
3/4 hard	None	…	…	895–1070	130–155	760–930	110–135	2–8	…	15–17
Annealed(d)	3	315	600	1140–1310	165–190	1000–1205	145–175	3–8	…	22–25
Annealed	1/2	370	700	1105–1310	160–190	930–1205	135–175	3–8	…	22–25
1/4 hard(d)	2	315	600	1205–1415	175–205	1105–1310	160–190	2–5	…	22–25
1/4 hard	1/4	370	700	1170–1415	170–205	1035–1310	150–190	2–5	…	22–25
1/2 hard(d)	1 1/2	315	600	1310–1480	190–215	1205–1380	175–200	1–3	…	22–25
1/2 hard	1/4	370	700	1275–1480	185–215	1170–1380	170–200	1–3	…	22–25
3/4 hard(d)	1	315	600	1345–1585	195–230	1245–1415	180–205	1–3	…	22–25
3/4 hard	1/4	370	700	1310–1585	190–230	1205–1415	175–205	1–3	…	22–25
					C17000					
Flat products										
Annealed	None	…	…	415–540	60–78	170–365	25–55	35–60	47–78 HRB	17–19
1/4 hard	None	…	…	515–605	75–88	310–515	45–75	10–40	68–90 HRB	16–18
1/2 hard	None	…	…	585–690	85–100	450–620	65–90	10–25	88–96 HRB	15–17
Hard	None	…	…	690–825	100–120	550–760	80–110	2–8	96–102 HRB	15–17
Annealed	3	315	600	1035–1240	150–180	895–1105	130–165	4–10	33–39 HRC	22–25
Annealed(d)	3	345	650	1105–1275	160–185	860–1140	125–165	4–10	34–40 HRC	22–25
1/4 hard	2	315	600	1105–1310	160–190	860–1140	135–170	3–6	34–40 HRC	22–25
1/4 hard(d)	3	330	625	1170–1345	170–195	895–1170	130–170	3–6	36–41 HRC	22–25
1/2 hard	2	315	600	1170–1380	170–200	895–1170	145–175	2–5	36–41 HRC	22–25
1/2 hard(d)	2	330	625	1240–1380	180–200	965–1240	140–180	2–5	38–42 HRC	22–25
Hard	2	315	600	1240–1450	180–210	965–1240	155–180	2–5	38–42 HRC	22–25
Hard(d)	2	330	625	1275–1415	185–205	1070–1345	155–195	2–5	39–43 HRC	22–25
Rod, bar										
Annealed	None	…	…	415–585	60–85	185–205	20–30	35–60	45–85 HRB	17–19
Hard	None	…	…	585–895	85–130	515–725	75–105	10–20	88–103 HRB	15–17
Annealed	3	315	600	1035–1240	150–180	860–1070	125–155	4–10	32–39 HRC	22–25
Annealed(d)	3	345	650	1105–1275	160–185	930–1140	135–165	4–10	34–40 HRC	22–25
Hard	2	315	600	1140–1380	165–200	930–1140	135–165	2–5	36–41 HRC	22–25
Hard(d)	2	345	650	1205–1415	175–205	965–1170	140–170	2–5	38–42 HRC	22–25
					C17500, C17510					
Rod, bar, plate, flat products										
Annealed	None	…	…	240–380	35–55	185–205	20–30	20–35	20–43 HRB	25–30
Hard	None	…	…	515–585	75–85	380–550	55–80	3–10	78–88 HRB	20–30
Annealed	3	480	900	690–760	100–120	550–690	80–100	10–20	92–100 HRB	45–60
Annealed(d)	3	455	850	725–825	105–120	550–725	80–105	8–12	93–100 HRB	45–52
Hard	2	480	900	760–860	110–130	690–825	100–120	8–15	95–103 HRB	45–60
Hard(d)	2	455	850	795–930	115–135	725–860	105–125	5–8	97–104 HRB	45–52

(a) At 0.2% offset. (b) In 50 mm (2 in.). (c) Rockwell B and C hardness values are accurate only if metal is at least 1 mm (0.040 in.) thick. (d) Heat treatment that provides optimal strength. (e) For wire diameters greater than 1.3 mm (0.050 in.)

Example 5: Hardness Variations in Beryllium-Copper Spring Receptacle. Spring contact receptacles stamped from ¼ hard beryllium-copper strip (alloy C17200) were aged in a salt bath at 300 °C (575 °F) for 30 min. The salt pot, 915 × 840 × 760 mm (36 × 33 × 30 in.), contained 1090 kg (2400 lb) of nitrate-nitrite salt (see Fig. 22).

A strip of about 1000 of these parts was wound onto a birdcage reel 265 mm (10½ in.) in diameter and 305 mm (12 in.) wide. Each receptacle weighed about 0.6 g (0.02 oz); therefore, the total weight of the receptacles on each reel was about 565 g (20 oz). Each reel weighed about 0.9 kg (2 lb), and one furnace load consisted of eight reels.

Specified hardness for these parts was 75 to 79 HR15N. Figure 22 shows the variation in hardness for 50 batches.



LIVE GRAPH
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Fig. 17 Time-temperature relationships in aging of C17200 strip, showing aging time required for the development of maximum strength in annealed, ¼ hard, ½ hard, and hard C17200 strip aged at various temperatures in a recirculating-air furnace

Heat Treating of Chromium-Copper Alloys

Chromium-copper alloys of 0.5 to 1.0% Cr are solution treated, in molten salt or in controlled-atmosphere furnaces to avoid scaling, at 980 to 1010 °C (1800 to 1850 °F) and rapidly quenched. Solution-treated chromium-copper is soft and ductile; therefore, it can be cold worked in a manner similar to that used for unalloyed copper.

After being solution treated, the material may be aged for several hours at 400 to 500 °C (750

Table 10 Effects of special precipitation-hardening treatments on mechanical properties and electrical conductivity of Cu-1.9Be strip

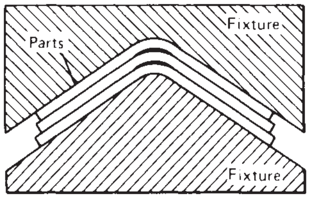
	Aging treatment											
		Temperature		Tensile strength		Yield strength(a)			Electrical conductivity,	Fatigue strength(c)		Modulus of elasticity	
Initial condition	Time, min	°C	°F	MPa	ksi	MPa	ksi	Elongation(b), %	%IACS	MPa	ksi	GPa	10^6 psi
Alloy C17200													
Annealed	None	…	…	465	67.5	250	36	49	18.0	205	30	115	16.5
	5	370	700	855	124	695	101	18	19.5	…	…	120	17.5
	15	370	700	1195	173	1055	153	10	22.0	…	…	125	18.0
	30	370	700	1260	182.5	1060	153.5	6	23.0	…	…	125	18.0
	60	370	700	1240	180	1055	153	5	25.5	255	37	130	18.5
	120	370	700	1195	173.5	1040	151	6	26.0	…	…	130	18.5
	240	370	700	1150	167	980	142	6	26.5	…	…	130	19.0
¼ hard	None	…	…	570	82.5	485	70.5	21	17.0	220	32	115	17.0
	5	370	700	1115	162	945	137	9	18.5	…	…	125	18.0
	15	370	700	1250	181	1115	162	6	20.5	…	…	130	18.5
	30	370	700	1290	187	1125	163.5	4	23.5	290	42	130	18.5
	60	370	700	1230	178.5	1060	154	3	25.5	…	…	130	18.5
	120	370	700	1185	172	1000	145	4	26.5	…	…	130	19.0
	240	370	700	1155	167.5	970	141	6	27.0	…	…	130	19.0
½ hard	None	…	…	605	87.5	555	80.5	17	16.0	230	33	115	17.0
	3	370	700	1010	146.5	885	128	11	18.0	230	33	125	18.0
	5	370	700	1280	186	1110	161	3	21.0	295	43	125	18.0
	15	370	700	1310	190	1175	170.5	2	23.0	305	44	130	18.5
	30	370	700	1325	192.5	1180	171	2	24.5	305	44	130	18.5
	60	370	700	1280	185.5	1105	160	2	25.0	295	43	130	18.5
	120	370	700	1200	174	1040	150.5	3	26.0	275	40	130	18.5
	240	370	700	1185	172	1035	150	3	27.0	275	40	130	19.0
	420	370	700	1010	146.5	860	125	10	27.0	200	29	130	19.0
Hard	None	…	…	730	106	690	100	5	15.0	270	39	120	17.5
	5	370	700	1300	188.5	1125	163	3	18.0	…	…	125	18.0
	15	370	700	1360	197	1195	173	2	21.0	…	…	130	18.5
	30	370	700	1310	190	1170	170	1	24.5	315	46	130	19.0
	60	370	700	1295	188	1105	160	1	26.5	…	…	130	19.0
	120	370	700	1240	180	1090	158	2	27.5	…	…	130	19.0
	240	370	700	1215	176	1055	153	2	27.5	…	…	130	19.0
Alloy C17500													
Annealed	None	…	…	350	51	170	25	30	25	…	…	110	16.3
	120	425	800	805	117	625	91	14	44	…	…	135	19.3
	120	455	850	835	121	675	98	14	48	…	…	140	20.0
	120	480	900	805	116.5	625	91	14	48	215	31	140	20.0
	120	510	950	795	115	600	87	16	48.5	…	…	140	20.0
Hard	None	…	…	440	63.5	425	61.5	2	27.8	…	…	125	18.3
	120	425	800	985	142.5	860	125	11	44.0	…	…	140	20.0
	120	455	850	915	133	800	116	13	45.0	…	…	140	20.0
	120	480	900	850	123	760	110.5	13	47.5	250	36	140	20.0
	120	510	950	800	116	705	102	12	49.0	…	…	140	20.0

(a) At 0.2% offset. (b) In 50 mm (2 in.). (c) 10^7 cycles

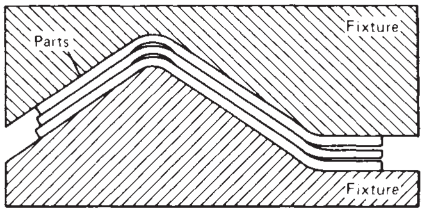
Table 11 Recommended precipitation-hardening schedules and resulting properties for solution-treated beryllium-copper castings

	Solution treatment			Aging treatment									
	Temperature			Temperature			Tensile strength		Yield strength(a)				
Alloy	°C	°F	Time, min	°C	°F	Time, min	MPa	ksi	MPa	ksi	Elongation(b), %	Hardness	Electrical conductivity, %IACS
C81300	980–1010	1800–1850	60	480	900	120	365	53	250	36	11	89 HB(c)	60
C81700	900–925	1650–1700	60	455	850	180	635	92	470	68	8	217 HB(d)	48
C81800	900–925	1650–1700	60	480	900	180	705	102	515	75	8	92 HRB	45
C82000	900–925	1650–1700	180	480	900	180	690	100	515	75	8	195 HB(d)	45
C82100	900–925	1650–1700	60	455	850	180	635	92	470	68	8	217 HB(d)	48
C82200	900–925	1650–1700	60	445–455	835–850	120	655	95	515	75	8	96 HRB	45
C82400	785–850	1450–1560	60	345	650	180	1035	150	965	140	1	34 HRC	25
C82500	785–800	1450–1475	60	345	650	180	1105	160	795	115	1	40 HRC	20
C82600	785–800	1450–1475	60	345	650	180	1105	160	1035	150	1	40 HRC	19
C82700	785–800	1450–1475	180	345	650	180	1070	155	895	130	0	39 HRC	20
C82800	785–800	1450–1475	60	345	650	180	1140	165	1000	145	1	42 HRC	18

(a) At 0.2% extension under load. (b) In 50 mm (2 in.). (c) 500 kg load. (d) 3000 kg load



Parts can be stacked satisfactorily (2 planes)



Stacking not feasible (3 planes)

Fig. 18 Parts that can and those that cannot be stacked in fixtures for the control of dimensional tolerances during aging

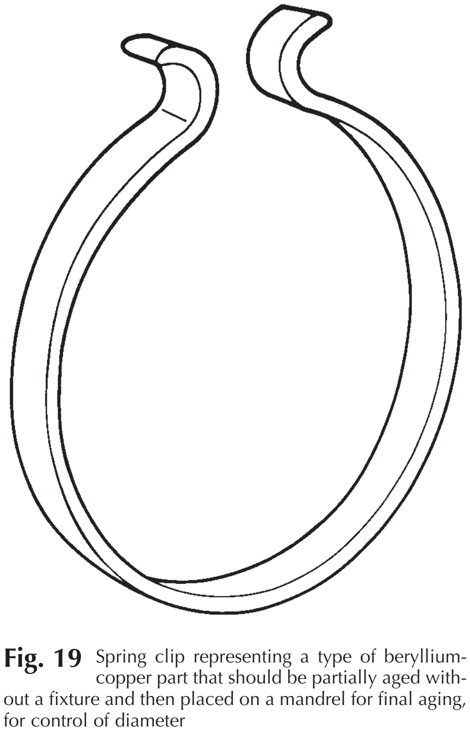
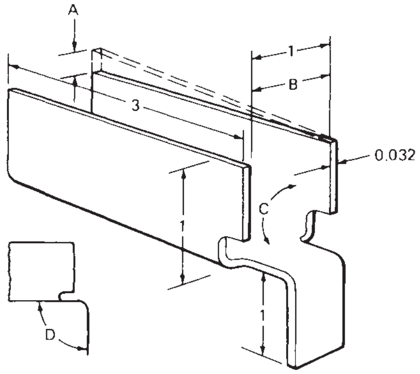


Fig. 19 Spring clip representing a type of beryllium-copper part that should be partially aged without a fixture and then placed on a mandrel for final aging, for control of diameter

Table 12 Dimensional variations in beryllium-copper solenoid guides aged with and without fixtures (Example 2)

	Dimensional variation(a)	
Dimension	Loose pieces	Fixtured pieces
A(b)	≤3/16 in.	1/32 in. max
B	−1/8 to 1/16 in.	±0.010 in.
C	–4 to 2°	± 1/2°
D	–4 to 2°	± 1/2°



Note: Linear dimensions are in inches. (a) Assuming no deviations from the die operation. (b) Twist in 3 in.

Table 13 Suggested methods for measuring the hardness of heat-treated C17200

Thickness			
mm	in.	Hardness test method	Load, kg
0.03–0.08	0.001–0.003	Diamond pyramid	0.2
0.08–0.38	0.003–0.015	Diamond pyramid	0.5
0.38–0.51	0.015–0.020	Rockwell superficial 15N	15
0.51–1.02	0.020–0.040	Rockwell superficial 15N	30
≥ 1.02	≥ 0.040	Rockwell B or C	Standard

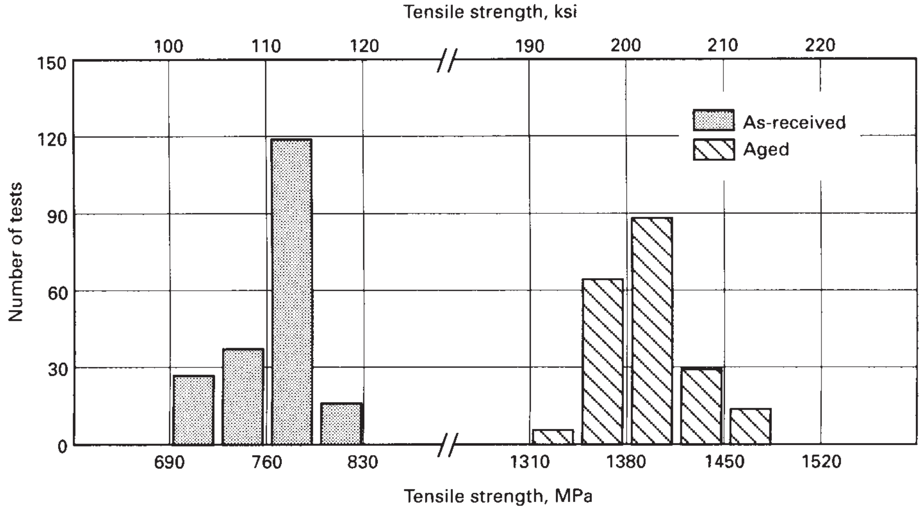


Fig. 20 Variation in tensile strength of hard C17200 strip after aging. The strip was 0.17 to 0.19 mm (0.0065 to 0.0075 in.) thick and was aged 3 h at 315 °C (600 °F). The number of tests of each group was 200.

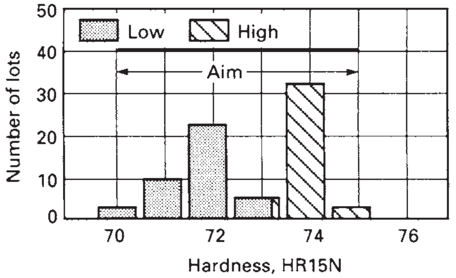


Fig. 21 Variation in hardness for 41 lots of heat-treated beryllium-copper terminal springs tested over a three-month period. High and low values in each lot are plotted.

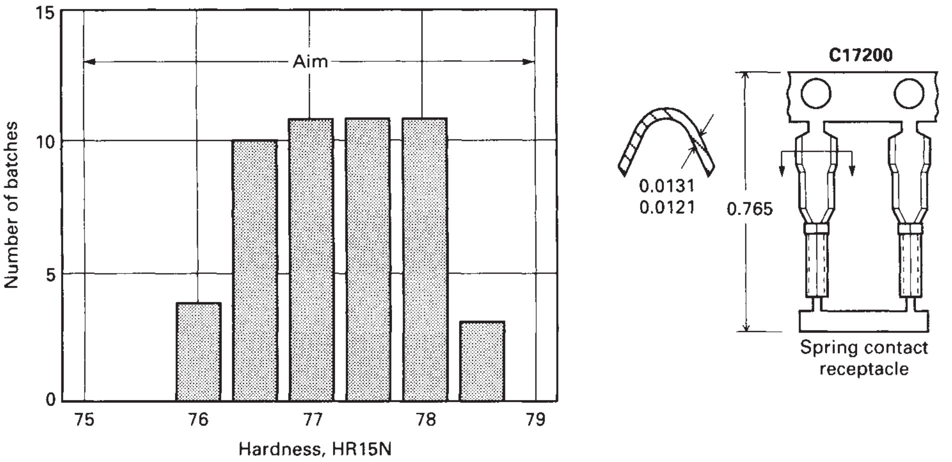


Fig. 22 Variation in hardness for 50 batches of aged spring contact receptacles stamped from ¼ hard C17200 strip

Table 14 Typical effects of heat treatment and cold work on properties of 1% Cr-Cu alloys

	Ultimate tensile strength		Yield strength(a)				
Condition	MPa	ksi	MPa	ksi	Elongation(b), %	Hardness	Electrical conductivity, %IACS
Alloy C18200							
Solution treated	240	35	105	15	42	50 HRF	35–42
Solution treated and aged	350	51	275	40	15	90 HB(c)	75–82
Solution treated and drawn 40%	415	60	310	45	15	65 HRB	40
Solution treated, hard drawn, and aged	435	63	385	56	18	68–75 HRB	80
Solution treated, aged, and drawn 30%	480	70	425	62	18	75–80 HRB	80
Alloy C81500							
Cast, solution treated, and aged	350	51	275	40	17	105 HB(c)	75–80

(a) At 0.5% extension under load. (b) In 50 mm (2 in.). (c) 500 kg load

to 930 °F) to produce special mechanical and physical properties. A typical aging cycle is 4 h or more at 455 °C (850 °F).

Typical effects of heat treatment and cold work on the properties of chromium-copper are shown in Table 14. The hard drawn specimens were obtained by reducing the cross-sectional area of solution-annealed specimens by approximately 40%.

Heat Treating of Zirconium-Copper Alloys

The solution treatment of zirconium-copper of the composition 99.7% Cu (min), 0.13 to 0.30% Zr consists of heating to 900 to 980 °C (1650 to 1795 °F) and quenching in water. The material may then be precipitation hardened for 1 to 4 h at 500 to 550 °C (930 to 1020 °F). If cold working is done prior to aging, the aging temperature is reduced to 370 to 480 °C (700 to 900 °F) for 1 to 4 h.

Time at the solution-treating temperature should be minimized in order to limit grain growth and possible internal oxidation by a reaction of the zirconium with the furnace atmosphere. Because the solution and diffusion of the zirconium occur rapidly at the solution-treating temperature, holding at temperature is not required.

Optimal mechanical properties and resistance to softening are developed with a maximum solution of zirconium. If material containing 0.15% Zr or more is heated above 980 °C (1795 °F), the Cu_3Zr phase will begin to melt. A slight amount of melting will not affect mechanical properties, but if excessive melting occurs, the ductility of the alloy will decrease.

Normally, as the solution temperature is increased from 900 to 980 °C (1650 to 1795 °F), the aging temperature should also be increased to maintain high electrical conductivity. Aging treatments that produce the best combination of mechanical properties and electrical conductivity are:

	Temperature		
Condition	°C	°F	Time, h
Solution treated			
At 900 °C (1650 °F)	500	930	3
At 900 °C (1650 °F) and cold worked	400	750	3
At 980 °C (1795 °F)	550	1020	3
At 980 °C (1795 °F) and cold worked	450	840	3

The increase in the strength of zirconium-copper depends primarily on cold working. Although aging results in some increase in strength, its chief effect is to increase electrical conductivity. The properties developed by various combinations of heat treatment and cold working are given in Table 15.

Heat Treating of Miscellaneous Precipitation-Hardening Alloys

Other alloys that can be age hardened are the nickel-tin bronze alloys C94700 and C94800, copper-nickel-beryllium alloy C96600, and the complex, special alloys C99400 and C99500. The solution-treating and precipitation-hardening treatments for these alloys are shown in Table 16.

A protective atmosphere of exothermic gas or dissociated ammonia is recommended during the aging of these alloys to produce bright surfaces. Parts heated in gas-fired or oil-fired furnaces in which the products of combustion are used as a protective atmosphere may tarnish slightly and require cleaning. Aging in an oxidizing atmosphere results in scaling.

Alloys C19000 and C19100 (Cu-4Ni-0.25P) also respond to precipitation hardening. The alloys are solution treated at 705 to 790 °C (1300 to 1450 °F). A reducing or neutral atmosphere should be used to prevent internal oxidation, especially on thin sections. Water quenching is preferred, although rapid air cooling may be adequate for separate small parts. Precipitation hardening is accomplished by aging the alloy at 425 to 480 °C (800 to 900 °F) for 1 to 3 h. While annealing is required to facilitate cold working prior to aging, temperatures as low as 620 °C (1150 °F) followed by normal air cooling are adequate.

Heat Treating of Spinodal-Hardening Alloys

Spinodal structures are composed of a fine, homogenous mixture of two phases that form by the growth of composition waves in a solid solution during a suitable heat treatment. The phases of the spinodal product differ in composition from each other and from the parent phase but have the same crystal structure as the parent phase. The fineness of spinodal structures is characterized by the distance between regions of identical composition, which is of the order of 50 to 1000 Å.

Table 15 Effect of heat treatment and cold work on properties of zirconium-copper alloy C15000

Solution-treating temperature(a)		Amount of cold work, %	Aging			Tensile strength		Yield strength		Elongation(b), %	Hardness, HRB	Electrical conductivity, %IACS
			Temperature									
°C	°F		°C	°F	Time, h	MPa	ksi	MPa	ksi			
900	1650	20	475	885	1	310	45	260	38	25	48	85 min
900	1650	80	425	795	1	425	62	380	55	12	64	85 min
980	1795	None	…	…	…	200	29	41(c)	6(c)	54	…	64
980	1795	20	…	…	…	270	39	250(c)	36(c)	26	37	64
980	1795	80	…	…	…	440	64	420(c)	61(c)	19	73	64
980	1795	None	500	930	3	205	30	90	13	51	…	87
980	1795	None	550	1025	3	205	30	90	13	49	…	95
980	1795	20	400	750	3	330	48	260	38	31	50	80
980	1795	20	450	840	3	330	48	275	40	28	57	92
980	1795	85	400	750	3	495	72	440	64	24	79	85
980	1795	85	450	840	3	470	68	425	62	23	74	91

(a) Hold 30 min, water quench. (b) In 50 mm (2 in.). (c) 0.5% extension under load

Table 16 Typical heat-treating schedules and resulting properties for miscellaneous precipitation-hardening alloys

Alloy	Solution treatment			Tempering treatment			Tensile strength		Yield strength(a)		Elongation(b), %	Hardness, HB(c)
	Temperature			Temperature								
	°C	°F	Time, min	°C	°F	Time, min	MPa	ksi	MPa	ksi		
C94700	775–800	1425–1475	120	305–325	580–620	300	585	85	415	60	10	180
C94800	…	…	…	305–325	580–620	360–1000	415	60	205	30	8	120
C96600	995	1825	60	510	950	180	760	110	485	70	7	230
C99400	885	1625	60	480	900	60	545	79	370	54	…	170
C99500	885	1625	60	480	900	60	595	86	425	62	8	196

(a) At 0.2% extension under load for C96600; at 0.5% extension under load for all other alloys. (b) In 50 mm (2 in.). (c) 3000 kg load

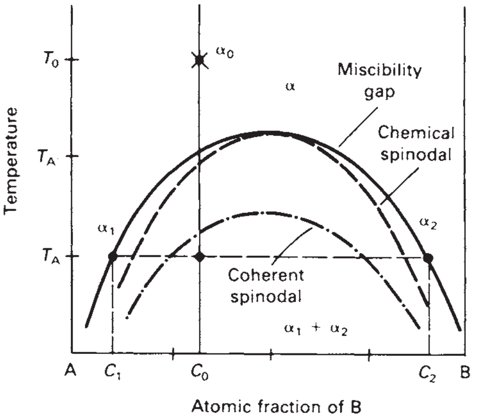


Fig. 23 Phase diagram of a binary alloy system that contains a miscibility gap in the solid state. An equilibrium structure for alloy C_0 at temperature T_A would contain two α phases of compositions C_1 and C_2. Spinodal decomposition can occur in the temperature-composition range below the chemical-spinodal line, which is the locus of points defined by the inflection points of the isothermal free energy (G) composition curves ($\partial^2G/\partial C^2 = 0$).

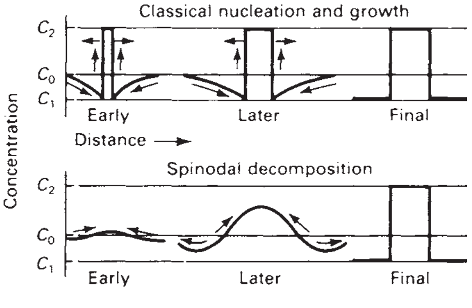


Fig. 24 Two sequences for the formation of a two-phase mixture by diffusion processes: nucleation and growth, and spinodal decomposition

The conditions for the formation of a spinodal structure are thermodynamic and diffusional; the particular alloy system must have a miscibility gap (either stable or metastable), and the atoms of the two component metals must possess sufficient mobility at the heat-treating temperature. A phase diagram of a hypothetical binary alloy system with a stable miscibility gap is shown in Fig. 23. An alloy of composition C_0 that is homogenized in the single-phase α region and then held within the spinodal region is unstable to composition variations and will transform spontaneously to the two product phases α_1 and α_2 without requiring nucleation. If an alloy decomposes within the spinodal region by a diffusional process that allows composition variations to increase in magnitude, it is said to decompose spinodally. The resulting spinodal structures refer to phase mixtures that are derived from a particular kinetic process governing the initial stages of phase separation. The chemical spinodal line shown in Fig. 23 is not a phase boundary but a demarcation indicating a difference in thermodynamic stability.

The spinodal reaction is a spontaneous unmixing or diffusional clustering distinct from classical nucleation and growth in metastable solutions. This different kinetic behavior, which does not require a nucleation step, was first described by Gibbs in his treatment of the thermodynamic stability of undercooled or supersaturated phases. At small undercoolings or low supersaturations ($T_{A'}$), the solution is metastable; the appearance of a second phase requires relatively large localized compositional fluctuations. This is the classical nucleation process, giving rise to so-called critical nuclei, which can grow spontaneously. As the particles of the new phase grow by diffusion, the matrix composition is adjusted toward equilibrium. At large supersaturations (T_A), the solution is unstable, and the two-phase mixture gradually emerges by the continuous growth of initially small amplitude fluctuations (Fig. 24). The rate of reaction is controlled by the rate of atomic migration and the diffusion distances involved, which depend on the scale of decomposition (undercooling).

The essential features of the spinodal process can be understood by considering this diffusional clustering as the inverse of the homogenization of a nonuniform solid solution exhibiting a sinusoidal variation of composition with distance. Long wavelength fluctuations grow sluggishly because of the large diffusion distances; short wavelength fluctuations are suppressed by the so-called gradient, or surface energy, of the diffuse or incipient interfaces that evolve during phase separation. Therefore, the microstructure that develops during spinodal decomposition has a characteristic periodicity that is typically 2.5 to 10 nm (25 to 100 Å) in metallic systems.

The heat treatment that causes the spinodal decomposition of a hypothetical alloy of composition C_0 (Fig. 23) is:

- Homogenize at a temperature above the miscibility gap, such as T_0, so that only statistical variations in composition exist within the specimen
- Cool rapidly to a temperature within the spinodal region, such as T_A, and hold at that temperature, or continuously cool the specimen from T_0 to room temperature

Table 17 lists the recommended solution treatment for the copper-nickel-chromium and copper-nickel-tin spinodal-hardening alloys. It is important to maintain control within the limits shown in order to obtain the proper heat-treating response in the subsequent spinodal aging treatment. Exceeding the upper limit may result in excessive grain growth in wrought materials, which could impair formability in the solution-annealed condition. Overheating cast material may cause incipient melting, resulting in brittle material that does not respond to spinodal hardening, particularly in the copper-nickel-tin alloys. Solution treating below the minimum temperature results in incomplete solution and failure of the material to harden fully during the spinodal aging treatment.

Wrought materials of some of these alloys can be extensively cold worked, with up to 90% reduction, after an effective solution treatment and quench. Solution anneals used between working schedules must be controlled toward the lower end of the temperature range and the minimum holding times to minimize grain growth because the solution temperature is above the recrystallization temperature. However, wrought alloys should be solution treated for approximately ½ h for each inch of section thickness (or fraction thereof).

Homogenization. Cast microstructures of spinodal-hardening alloys generally require homogenization to encourage a uniform distribution of hardening elements and adequate response to the hardening treatments. The C71900 alloy may be homogenized by a prolonged solution-treating temperature. The copper-nickel-tin alloys have a tendency to develop porosity at higher temperatures, and therefore homogenization is best accomplished by first heating the alloys to 725 °C (1335 °F) and holding long enough to spheroidize the γ phase (3 to 12 h). The temperature is then increased to the regular solution temperature in preparation for the quench.

Oxidation. When spinodal copper-nickel-tin alloys are solution treated in air or oxidizing atmospheres, oxidation is encountered, which can be extremely abrasive to tools although it will not substantially affect the mechanical properties of the spinodal-hardened material. The oxide generally does not penetrate far below the surface of these alloys, and it can be removed by mechanical, chemical, or abrasive cleaning methods.

Quenching is a critical step of the solution process for copper-nickel-tin alloys. Successful heat treating requires that the material be quenched at the highest possible rate from the solution-treating temperature. It is therefore necessary to provide both rapid transfer from furnace to quench tank and an efficient quenching medium. Delays sufficient to cause the loss of temperature before the quench could allow the copper-nickel-tin intermetallic γ phase to form, reducing the effectiveness of the entire heat treatment. The quenching medium, which is generally water, must be sufficiently cold and agitated to maintain a rapid cooling rate to below the 200 °C (400 °F) level to ensure that no premature spinodal hardening occurs.

In some circumstances, particularly with the low-tin alloys (C72600 and C72700), oil, air, or cold-gaseous-medium quenching may be used for small parts or very thin sections, but a careful evaluation of these methods should be conducted to ensure the adequacy of the quench. Both mechanical testing of fully treated materials and metallographic examination of the microstructure should be employed to evaluate the quenching practice. The overall cooling rate of the quenching of spinodal-hardening C71900 (copper-nickel-chromium) alloy is somewhat less critical, but it is equally important to begin the quench at a temperature above the 900 °C (1650 °F) temperature.

Spinodal Hardening (Aging). Table 18 gives typical aging treatments and some resultant properties of various spinodal-hardening alloys. The effect of cold working between the solution quench and aging steps is also given for the copper-nickel-tin alloys. The copper-nickel-chromium (C71900) alloy can be hardened by slow cooling from the solution-treating (full annealing) range through 760 °C (1400 °F) or by a spinodal aging treatment in the 425 to 760 °C (800 to 1400 °F) range after a solution treatment. Slow cooling from solution temperature tends to produce slightly greater ductility.

The Cu-Ni-Sn alloys are hardened by treating in the rather narrow temperature range of 350 to 360 °C (660 to 680 °F). The development of the optimal properties requires the careful control of temperature and time at temperature. The use of hardness alone to evaluate results may not be adequate because high hardness may be maintained where excessive aging causes a decrease in elastic properties. Variations in tensile properties of 70 to 100 MPa (10 to 15 ksi) are possible without a significant hardness change.

Microduplexing. The copper-nickel-tin spinodal alloys can be treated using a combination of cold working and heat treatment called microduplexing. The alloys are cold worked to significant reductions (typically 40 to 60%) and given a partial solution treatment below the single-phase boundary, typically at 725 °C (1335 °F). The alloy is then aged at the higher spinodal-hardening temperature level of 425 °C (800 °F) for an extended time. The higher aging temperature is used to keep the aging time within reason, as microduplex age hardening takes place much more slowly than full spinodal hardening. This treatment results in moderately high tensile properties and significantly greater ductility. The curves in Fig. 25 show the effect of the microduplex treatment in comparison to conventional spinodal treatment using a 425 °C (800 °F) age.

Table 17 Recommended solution-heat-treating temperatures and times for spinodal alloys

Alloy	Alloy number	Solution-heat-treating temperature		Time at temperature, h
		°C	°F	
Cu-30Ni-3Cr	C71900	900–950	1650–1740	½–2
Cu-4Ni-4Sn	C72600	700–760	1300–1400	½–2
Cu-9Ni-6Sn	C72700	730–790	1350–1450	½–2
Cu-10Ni + 8Sn + 0.2Nb	C72800	805–845	1480–1550	½–2
Cu-15Ni-8Sn	C72900	815–860	1500–1575	½–2

Table 18 Typical strengths and recommended aging times for various spinodal alloys

Alloy	Alloy number	Solution-treated and cold-worked temper(a)	Aging cycle, h at °C (°F)	Tensile strength		Yield strength(b)		Elongation, %
				MPa	ksi	MPa	ksi	
Cu-4Ni-4Sn	C72600	TD 02(½H)	1½ at 350 (660)	635–690	92–100	495–570	72–83 (0.05)	12
Cu-4Ni-4Sn	C72600	TD 06(XH)	1½ at 350 (660)	690–725	100–105	565–620	82–90 (0.05)	9
Cu-4Ni-4Sn	C72600	TD 08(S)	1½ at 350 (660)	705–795	102–115	565–655	82–95 (0.05)	7
Cu-9Ni-6Sn	C72700	TD 04(H)	1½ at 350 (660)	860–1035	125–150	760–895	110–130 (0.05)	8
Cu-9Ni-6Sn	C72700	TD14(SS)	1½ at 350 (660)	1055–1145	153–166	930–985	135–143 (0.05)	...
Cu-10Ni-8Sn-0.2Nb	C72800	TB 00 cast and solution treated	4–6 at 350 (660)	830–965	120–140	550–690	80–100 (0.01)	3
Cu-10Ni-8Sn-0.2Nb	C72800	TB 00 hot worked and solution treated	3–5 at 350 (660)	965–1070	140–155	690–825	100–120 (0.01)	6–14
Cu-10Ni-8Sn-0.2Nb	C72800	TD 01(¼H)	3 at 350 (660)	1140–1240	165–180	895–930	130–135 (0.01)	7
Cu-10Ni-8Sn-0.2Nb	C72800	TD 04(H)	3 at 350 (660)	1205–1380	175–200	930–1000	135–145 (0.01)	7
Cu-10Ni-8Sn-0.2Nb	C72800	TD 06(XH)	3 at 350 (660)	1205–1380	175–200	965–1035	140–150 (0.01)	5
Cu-10Ni-8Sn-0.2Nb	C72800	TD 08(S)	3 at 350 (660)	1240–1380	180–200	1000–1070	145–155 (0.01)	4
Cu-10Ni-8Sn-0.2Nb	C72800	TD 14(SS)	1½ at 350 (660)	1240–1380	180–200	1070–1140	155–165 (0.01)	2.5
Cu-15Ni-8Sn	C72900	TD 14(SS)	1½ at 350 (660)	1140–1380	165–200	1035–1170	150–170 (0.05)	3
Cu-30Ni-3Cr	C71900	Hot extruded	1½ at 760 (405)	550	80	345	50 (0.20)	25

(a) Temper designations are defined in the article "Standard Designations for Wrought and Cast Copper and Copper Alloys" in this Handbook. (b) Offset shown in parentheses

Table 19 Typical heat treatments and resulting properties for complex (α-β) aluminum bronzes

Alloy	Typical condition(a)	Tensile strength		Yield strength(b)		Elongation(c), %	Hardness, HB
		MPa	ksi	MPa	ksi		
C62400	As-forged or extruded	620–690	90–100	240–260	35–38	14–16	163–183
	Solution treated at 870 °C (1600 °F) and quenched, tempered 2 h at 620 °C (1150 °F)	675–725	98–105	345–385	50–56	8–14	187–202
C63000	As-forged or extruded	730	106	365	53	13	187
	Solution treated at 855 °C (1575 °F) and quenched, tempered 2 h at 650 °C (1200 °F)	760	110	425	62	13	212
C95300	As-cast	495–530	72–77	185–205	27–30	27–30	137–140
	Solution treated at 855 °C (1575 °F) and quenched, tempered 2 h at 620 °C (1150 °F)	585	85	290	42	14–16	159–179
C95400	As-cast	585–690	85–100	240–260	35–38	14–18	156–179
	Solution treated at 870 °C (1600 °F) and quenched, tempered 2 h at 620 °C (1150 °F)	655–725	95–105	330–370	48–54	8–14	187–202
C95500	As-cast	640–710	93–103	290–310	42–45	10–14	183–192
	Solution treated at 855 °C (1575 °F) and quenched, tempered 2 h at 650 °C (1200 °F)	775–800	112–116	440–470	64–68	10–14	217–234

(a) As-cast condition is typical for moderate sections shaken out at temperatures above 540 °C (1000 °F) and fan cooled or mold cooled, annealed at 620 °C (1150 °F), and fan (rapid) cooled. (b) At 0.5% extension under load. (c) In 50 mm (2 in.)

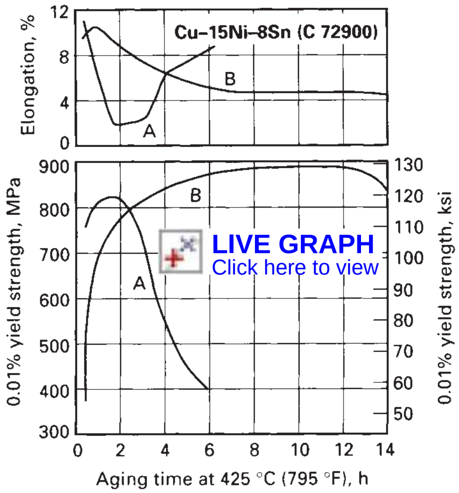


Fig. 25 Aging response of Cu-15Ni-8Sn (C72900) solution treated below the single-phase boundary (microduplexed) and above the single-phase boundary. Treatments prior to aging: A, solution treated above the single-phase boundary at 825 °C (1520 °F) for 30 min and water quenched; B (microduplexed), solution treated below the single-phase boundary at 725 °C (1340 °F) for 1 h and water quenched

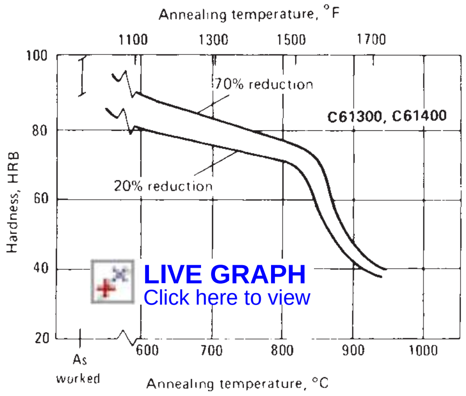


Fig. 26 Annealing curves for cold-reduced α-aluminum bronzes. Time at annealing temperature, 1 h

Effect of Grain Size. The temperatures required for solution treatment are well into the recrystallization/growth range for spinodal-hardening alloys. The normal grain size obtained in properly treated wrought products is in the 0.010 to 0.090 mm (0.0004 to 0.0035 in.) range, but coarser grain sizes have been used without adverse results. Maintaining low solution temperatures in an attempt to minimize grain growth is good practice, but is second in importance to ensuring a complete solution treatment and adequate quench. An extremely fine grain size (2 to 4 µm) may be produced in the microduplexing treatment of copper-nickel-tin alloys because of the much lower solution-treating temperature and the nucleating effects of undissolved γ phase particles.

Fixturing in Close Tolerances. Excellent dimensional reproducibility can be achieved without fixturing during heat treatment. This is because the spinodal alloys do not undergo a crystallographic change during hardening. The chemical segregation (spinodal decomposition) is not accompanied by a second phase that can cause distortion during the aging process. Therefore, stability is greatly increased over that of precipitation-hardening alloys. Fixturing may nonetheless be necessary for extremely tight dimensional control, but this is rare.

Heat Treating of Aluminum Bronzes

The microstructures and consequent heat treatabilities of aluminum bronzes vary with aluminum content much the same as these characteristics vary with carbon content in steels. Unlike steels, aluminum bronzes are tempered above the normal transformation temperature, typically in the range from 565 to 675 °C (1050 to 1250 °F). In the selection of tempering temperatures, consideration must be given to both required properties and the hardness obtained upon quenching. Normal tempering time is 2 h at temperature. Moreover, heavy or complex sections should be heated slowly to avoid cracking. After the tempering cycle has been completed, it is important that aluminum bronzes be cooled rapidly using water quenching, spray cooling, or fan cooling. Slow cooling through the range from 565 to 275 °C (1050 to 530 °F) can cause the residual tempered martensitic β phase to decompose, forming the embrittling α-β eutectoid. The presence of appreciable amounts of this eutectoid structure can result in low tensile elongation, low energy of rupture, severely reduced impact values, and reduced corrosion resistance in some media. For adequate protection against detrimental eutectoid transformation, cooling after tempering should bring the alloy to a temperature below 370 °C (700 °F) within about 5 min, and to a temperature below 275 °C (530 °F) within 15 min. Normally, the danger of eutectoid transformation is much lower in nickel-aluminum bronzes, and these alloys can be air cooled after tempering.

The normal precautions used in the heat treating of steel have been found to be applicable to aluminum bronze, with critical cooling rates being somewhat lower than those for steel. Soaking time should be at least 45 min at temperature, and longer times may be used without fear of excess surface oxidation. Oil quenching is used on heavy, complex sections to avoid quench cracking, particularly in nickel-aluminum bronzes such as C63000.

Alpha-aluminum bronzes are those aluminum bronzes that contain less than 9% Al, or less than 8.5% Al with up to 3% Fe. They are essentially single-phase alloys, except for fine iron-rich particles in those alloys that contain iron. For α-aluminum bronzes, effective strengthening can be attained only by cold work, and annealing and/or stress relieving is the only heat treatment of practical use. The most prevalent alloys of this group are C60600, C61000, C61300, and C61400. In addition, alloys containing up to 9.6% Al, with microstructures containing small amounts of β phase at high temperatures, have such limited heat treatability that they, too, can be hardened only by cold work.

Annealing of α-aluminum bronzes is carried out at temperatures from about 540 to about 870 °C (1000 to 1600 °F), with the iron-containing alloys requiring temperatures nearer the high end of this range. Alloys of intermediate composition (containing small amounts of β phase), such as C61900, are normally annealed at 595 to 650 °C (1100 to 1200 °F). Figure 26 presents annealing curves for typical α-aluminum bronze alloys C61300 and C61400.

Complex α-β aluminum bronzes are those aluminum bronzes whose normal microstructures contain more than one phase to the extent that beneficial quench and temper treatments are possible. These copper-aluminum alloys, with and without iron, are heat treated by procedures somewhat similar to those used for the heat treatment of steel and have isothermal transformation diagrams that resemble those of carbon steels. For these alloys, the quench-hardening treatment is essentially a high-temperature soak intended to dissolve all of the α phase into the β phase. Quenching results in a hard room-temperature β martensite structure, and subsequent tempering reprecipitates fine α needles in the structure, forming a tempered β martensite. Table 19 gives typical tensile properties and hardnesses of α-β aluminum bronzes after various stages of heat treatment.

ACKNOWLEDGMENTS

This article was adapted from:

- A. Cohen, Heat Treating of Copper Alloys, *Heat Treating,* Vol 4, *ASM Handbook,* ASM International, 1991, p 880–898
- C.R. Brooks, Plastic Deformation and Annealing, *Heat Treatment, Structure and Properties of Nonferrous Alloys,* American Society for Metals, 1982, p 1–73

Machining*

MACHINABILITY of copper and copper alloys can be related to the type of chips (turnings) they produce during high-speed machining operations, including machining in automatic screw machines. As described in this article, the machinability of copper and copper alloys is generally considered quite good in comparison with other structural materials, particularly steels.

Defining Machinability

Machinability can be defined in terms of power consumption, tool wear rates, surface finish, chip morphology, or combinations of these criteria (Ref 1). In fact, the meaning of "machinability" depends on the particular needs of the individual observer (or product).

Another difficulty in defining machinability is that it depends on the combined influences of a large number of factors, many of which are quite complex. For example, machinability is certainly closely linked to the physical and mechanical properties of the workpiece: hard, brittle metals being generally more difficult to machine than soft, ductile ones (Fig. 1). But very ductile metals, such as pure copper, stainless steels, and some aluminum alloys tend to form long stringy chips, which makes them troublesome to machine. Machinability is also strongly dependent on the type and geometry of tool used, the cutting operation, the machine tool, metallurgical structure of the tool and workpiece, the cutting/cooling fluid, and the machinist's skill and experience.

For an automatic screw machine operator, a definition based on some combination of production rate (the bottom-line criterion), tool wear, and surface finish has the most practical significance. Such a definition can be provided using the standard test method described in ASTM E 618, "Standard Method for Evaluating Machining Performance Using an Automatic Screw/Bar Machine." The method calls for manufacture of large quantities of the standard test piece shown in Fig. 2. The test piece simulates typical screw machine products in size, scrap ratio (the amount of chips removed relative to the weight of starting material), and machining operations.

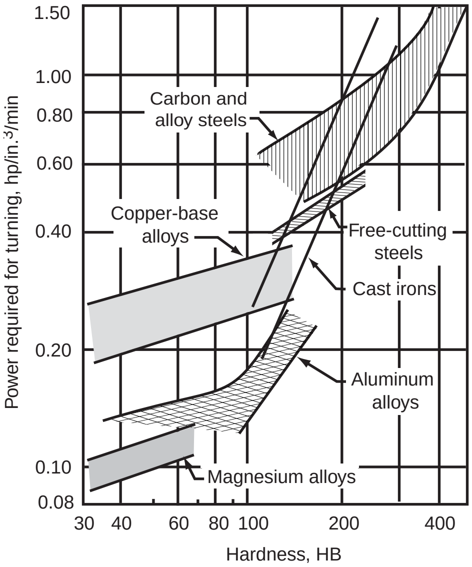


Fig. 1 Influence of workpiece hardness on machinability

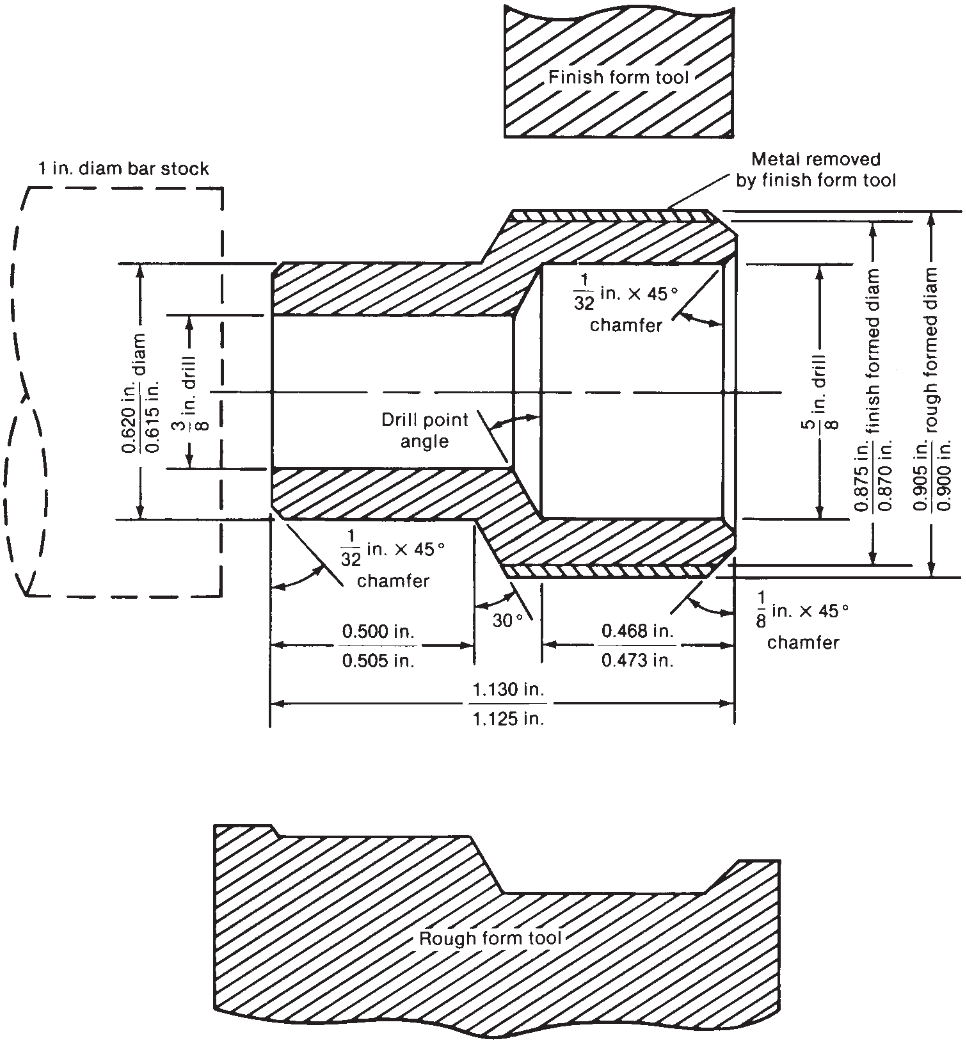


Fig. 2 Details of the ASTM E 618 machinability test specimen and the relative position of the form tools. As shown in this figure, the standard automatic screw machine part is designed to be made from 25 mm (1 in.) diam bar stock. The part used in the machinability tests for brasses, steels, and aluminum alloys was downsized to permit use of 19 mm (0.75 in.) diam rod; this is permitted under ASTM E 618, if done for all materials.

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*Portions of this article are adapted from *Copper Rod Alloys for Machined Products,* Copper Development Association Inc., New York, 1996. Used with permission.

The ASTM test evaluates the machinability of a material by determining the effect of production rate (spindle speed and cutting tool feed rate) on tool wear. Tool wear is measured indirectly by monitoring the dimensions of the test piece and surface finish, just as in commercial machine shop practice, where tools are resharpened when parts go out of tolerance. The ASTM test method makes it possible to interpolate the production rate that provides an "optimal" eight-hour tool life, and that production rate is taken as the machinability rating of the test material (Fig. 3a).

The most important advantage of the ASTM E 618 method is that it permits a fair comparison of completely different materials. Such a comparison, particularly between free-cutting brass (63Cu-3.1Pb-34.5Zn) and leaded American Iron and Steel Institute/Society of Automotive Engineers (AISI/SAE) 12L14 steel, has always been difficult, and the several machinability indexes currently in use only confuse the issue. When rated according to ASTM E 618, brass is nearly five times as machinable as the leaded steel, meaning that if C36000 were assigned an index rating of 100, AISI/SAE 12L14 would have a rating of 21. ASTM E 618-based machinability ratings of a few common screw machine feedstock metals are shown in Fig. 3(b).

Machinability of Copper Alloys

All copper alloys are machinable in the sense that they can be cut with standard machine tooling. High-speed steel suffices for all but the hardest alloys. Carbide tooling can be used but is rarely necessary, and while grinding may be required for a few alloys in very hard tempers, these are not conditions to be expected in high-speed production. For mass-produced screw machine parts made from free-cutting brass or one of the other leaded copper alloys, high-speed steel is the standard tool material.

It is not possible to present a full series of ASTM E 618-based machinability indexes in this article because data of the type plotted in Fig. 3 are not yet available for the hundreds of copper alloys. The conventional index ratings listed in Tables 1 and 2 for wrought and cast alloys, respectively, are based on allowable machining speed, tool wear, finish, accuracy, and power requirements, plus a degree of subjective judgment. They provide a reasonable, approximate guide to machinability.

Effect of Chip Appearance on Machinability. Chip appearance is a good indicator of the machinability of copper and copper alloys. It also relates to the microstructure of the material and permits categorization of copper alloys in terms of reasonably similar machining characteristics. Copper alloys produce three distinct types of chips:

- Type I (free-cutting) alloys yield small, fragmented chips, making them well suited for high-speed machining. They contain lead or alternative free-cutting additives.
- Type II (short-chip) materials, which are generally multiphase alloys, produce curled but brittle turnings.
- Type III (long-chip) materials, which are usually single-phase alloys, produce long and continuous chips that are often tightly curled.

Examples of the three types of chips are shown in Fig. 4. How these chip characteristics influence machinability is addressed subsequently.

Type I (Free-Cutting) Alloys

Strictly speaking, lead-bearing copper alloys are composite structures rather than true alloys. This is because lead is insoluble in copper and appears as a dispersion of microscopic globules, as shown in Fig. 5. The stress-raising effect of these lead particles causes chips to break up into tiny flakes as the metal passes over the tool face. (This is what is meant by the term "free-cutting.")

Careful observations have shown that chips from leaded alloys remain in contact with the tool face for only a very short time before the energy of fracture actually propels them away from the cutting tool. The short contact time reduces friction, which in turn minimizes tool wear and energy consumption. It has been suggested that lead also acts as an "internal lubricant" as it smears over the tool face.

The beneficial effect of lead on free-cutting behavior increases with lead content, but the rate of improvement decreases as lead content rises. Significantly improved machinability can be measured in leaded alloys containing less than 0.5% Pb, although optimal free-cutting behavior occurs at concentrations between 0.5% and 3.25% (Fig. 6). The specified nominal lead content in C36000 is 3.1%.

Effects of Lead on Properties. Lead does not have a significant effect on strength; however, leaded alloys can be difficult to cold work extensively. The effect becomes more pronounced as lead content rises; therefore alloys such as C34500 and C35300, which have lower lead contents than C36000, may be better choices for products that require both high-speed machining and extensive cold deformation.

Other detrimental effects of lead include an impairment in welding and brazing properties.

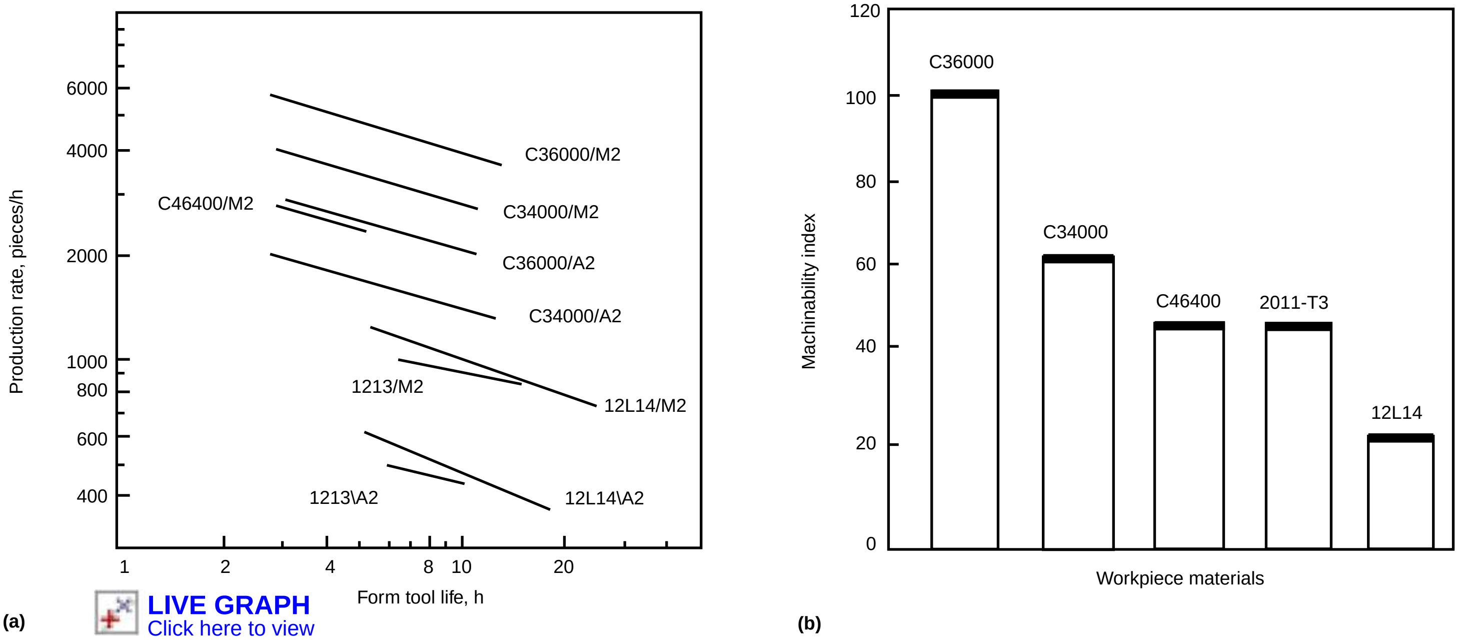


Fig. 3 Results of a universal machinability index test for various alloys. (a) Tool life data plotted to determine the maximum theoretical production rate for an 8 h tool life. This value of production rate is taken as the machinability rating of the material under test. (b) Universal machinability ratings (maximum theoretical production rates for 8 h M2 tool life) of common automatic screw machine materials using ASTM E 618. Data are normalized to alloy C36000 (free-cutting brass = 100). Source: Ref 2

Lead may cause related problems in products such as welding electrodes and cutting torch tips, which operate at high temperatures.

Lead causes no significant changes in the corrosion behavior of an alloy, but trace quantities can be dissolved from machined surfaces by sufficiently aggressive media, including some potable waters. If lead exposure is a problem, wetted surfaces can be protected with electroplated or organic coatings. Surface lead can also be removed by a relatively simple etching process that leaves nothing but "pure" brass exposed to the environment.

Alternative Free-Cutting Additives. Additions of tellurium, sulfur, and bismuth also produce free-cutting behavior in copper alloys. These elements can be more effective than lead in terms of the amounts needed to produce optimal improvements, but they are not without shortcomings. Bismuth and tellurium can cause serious embrittlement and/or directionally sensitive ductility when present in uncontrolled concentrations, while sulfur cannot be used in many alloy systems because of its reactivity. Generally, unleaded free-cutting alloys are considerably more expensive than leaded versions and therefore should be considered only when lead must be avoided entirely. Such is the case with plumbing fixtures, which have strict regulations regarding lead contents. Sand-cast faucets and other plumbing components have traditionally been made from leaded red or semi-red brasses that not longer meet the lead content restrictions established by the Environmental Protection Agency or the National Sanitation Foundation. This has led to the development of low-lead red brass casting alloys containing bismuth and selenium. Examples include C89510 and C89520, which contain between 0.5 and 2.2% Bi and 0.35 to 1.1% Se (Bi:Se ratio ≥2:1). These alloys have machinability ratings between 75 and 85 (C36000 = 100). Selenium enhances the effect of bismuth in red brasses; therefore, it reduces the amount of bismuth needed to improve machinability and lessens the chances of embrittlement.

Table 1 Machinability ratings of wrought copper alloys

UNS No.	Alloy name	Machinability index rating
Type I: free-cutting copper alloys for screw machine production (suitable for automatic machining at the highest available cutting speeds)		
C36000	Free-cutting brass	100
C35600	Extra-high-leaded brass	100
C32000	Leaded red brass	90
C34200	High-leaded brass, 64½%	90
C35300	High-leaded brass, 62%	90
C35330	Arsenical free-cutting brass	90
C38500	Architectural bronze	90
C14500	Tellurium-bearing copper	85
C14520	Phosphorus deoxidized, tellurium-bearing copper	85
C14700	Sulfur-bearing copper	85
C18700	Leaded copper	85
C31400	Leaded commercial bronze	80
C31600	Leaded commercial bronze (nickel-bearing)	80
C34500	Leaded brass	80
C37700	Forging brass	80
C54400	Phosphor bronze, B-2	80
C19100	Nickel copper with tellurium	75
C19150	Leaded nickel copper	75
C34000	Medium-leaded brass, 64½%	70
C35000	Medium-leaded brass, 62%	70
C37000	Free-cutting Muntz metal	70
C48500	Naval brass, high-leaded	70
C67300	Leaded silicon-manganese bronze	70
C69710	Leaded arsenical silicon red brass	70
C17300	Leaded beryllium copper	60
C33500	Low-leaded brass	60
C67600	Leaded manganese bronze	60
C48200	Naval brass, medium-leaded	50
C66100	Leaded silicon bronze	50
C79200	Leaded nickel silver, 12%	50
Type II: short-chip copper alloys. (Usually multiphase alloys. Short, curled or serrated chips. Screw machine production depends on type of cutting operation.)		
C64200	Arsenical silicon-aluminum bronze	60
C62300	Aluminum bronze, 9%	50
C62400	Aluminum bronze, 10½%	50
C17410, C17500, C17510	Beryllium coppers	40
C28000	Muntz metal, 60%	40
C61800	Aluminum bronze, 10%	40
C63000	Nickel-aluminum bronze, 10%	40
C63020	Nickel-aluminum bronze, 11%	40
C63200	Nickel-aluminum bronze	40
C46200	Naval brass, 63½%	30
C46400	Naval brass, uninhibited	30
C67400	Silicon-manganese-aluminum brass	30
C67500	Manganese bronze A	30
C69400	Silicon red brass	30
C69430	Arsenical silicon red brass	30
C15715, C15725, C15760	Aluminum oxide dispersion-strengthened coppers	20
C17000	Beryllium copper	20
C17200	Beryllium copper	20
C62500	Aluminum bronze, 13%	20
Type III: long-chip copper alloys. (Usually single phase alloys. Stringy or tangled chips, somewhat "gummy" behavior. Not for screw machine work.)		
C63200	Nickel-aluminum bronze, 9%	40
C22600	Jewelry bronze, 87½%	30
C23000	Red brass, 85%	30
C24000	Low brass, 80%	30
C26000	Cartridge brass, 70%	30
C26130	Arsenical cartridge brass, 70%	30
C26800	Yellow brass, 66%	30
C27000	Yellow brass, 65%	30
C61000, C61300, C61400	Aluminum bronzes, 7%	30
C65100	Low silicon bronze B	30
C65500	High silicon bronze A	30
C65600	Silicon bronze	30
C67000	Manganese bronze B	30
C10100	Oxygen-free electronic copper	20
C10200	Oxygen-free copper	20
C10300	Oxygen-free extra low phosphorus copper	20
C10400, C10500, C10700	Oxygen-free coppers with silver	20
C10800	Oxygen-free low phosphorus copper	20
C11000	Electrolytic tough pitch copper	20
C11300, C11400, C11500, C11600	Tough pitch coppers with silver	20
C12000	Phosphorus-deoxidized, low-residual phosphorus copper	20
C12100	Phosphorus-deoxidized, low-residual phosphorus copper	20
C12200	Phosphorus-deoxidized, high-residual phosphorus copper	20
C12900	Fire-refined tough pitch copper with silver	20
C15000	Zirconium copper	20
C16200	Cadmium copper	20
C16500	Cadmium-tin copper	20
C18000	Nickel-chromium-silicon copper	20
C18100	Chromium-zirconium-magnesium copper	20
C18135	Chromium-cadmium copper	20
C18150	Chromium-zirconium copper	20
C18200, C18400	Chromium coppers	20
C21000	Gilding, 95%	20
C22000	Commercial bronze, 90%	20
C50700	Tin (signal) bronze	20
C51000	Phosphor bronze, 5% A	20
C52100	Phosphor bronze, 8% B-2	20
C61000	Aluminum bronze, 7%	20
C64700	Silicon-bronze	20
C70600	Copper-nickel, 10%	20
C71500	Copper-nickel, 30%	20
C74500	Nickel silver, 65-10	20
C75200	Nickel silver, 65-18	20
C75400	Nickel silver, 65-15	20
C75700	Nickel silver, 65-12	20

Source: Ref 1

Table 2 Machinability ratings of copper casting alloys

UNS No.	Alloy name	Machinability
Type I free-cutting alloys		
C83600	Leaded red brass	90
C83800	Leaded red brass	90
C84400	Leaded semi-red brass	90
C84800	Leaded semi-red brass	90
C94320	High-leaded tin bronze	90
C93700	High-leaded tin bronze	80
C93720	High-leaded tin bronze	80
C85200	Leaded yellow brass	80
C85310	Leaded yellow brass	80
C93400	High-leaded tin bronze	70
C93200	High-leaded tin bronze	70
C97300	Leaded nickel brass	70
Type II short-chip alloys (moderately machinable)		
C83500	Leaded tin bronze	60
C83520	Leaded tin bronze	60
C86500	Leaded high-strength manganese bronze	60
C63380	Silicon-aluminum bronze	50
C64200	Silicon-aluminum bronze	50
C90500	Tin bronze	50
C90300	Tin bronze	50
C95300	Aluminum bronze	35
C61800	High-strength manganese bronze	30
C67000	High-strength manganese bronze	30
…	Beryllium bronze	20–40
Type III long-chip alloys (less easy to machine)		
C86100	High-strength manganese bronze	20
C95200	Aluminum bronze	20
C95400	Aluminum bronze	20
C95500	Aluminum bronze	20

Note: Additional machinability ratings for copper casting alloys can be found in the article "Cast Copper and Copper Alloys" in this Handbook. Source: Ref 3

Fig. 4 Broken chips typical of free-cutting brass, type I (center), flanked by type II, short-chip turnings (right), and type III, long-chip turnings (left)

Type II (Short-Chip) Alloys

Two or more phases may appear in the microstructure when alloy concentration is sufficiently high (for example, high-zinc brasses containing both alpha and beta phases). Beta makes cold work more difficult, but it improves the capacity for hot deformation considerably. Heterogeneous (two or more phases) type II alloys tend to be stronger than single-phase materials, but ductility is correspondingly reduced.

Figure 4 (right side) shows turnings from a multiphase type II alloy. As the metal passes over the cutting tool, it tends to shear laterally in a series of closely spaced steps, producing ridges on the short, helical chips. This intermittent shear process raises the potential for tool chatter and poor surface quality, but these problems can be avoided by adjusting machining parameters appropriately. Chip breakers can be used to reduce the length of the coiled turnings.

The machinability of type II alloys depends on the complex relationships between alloy microstructure and mechanical properties. Power consumption varies with mechanical properties and work hardening rate, while the shape of the turnings depends on the ductility of the metal.

In part because of their relatively manageable chips, multiphase alloys are considered to have better machinabilities than ductile type III metals. The higher power consumption for the harder type II alloys is generally taken as being less important than tool wear or chip management, both of which are less favorable in type III alloys. Type II alloys are often processed on automatic screw machines, although production rates are considerably lower than those attainable with free-cutting alloys.

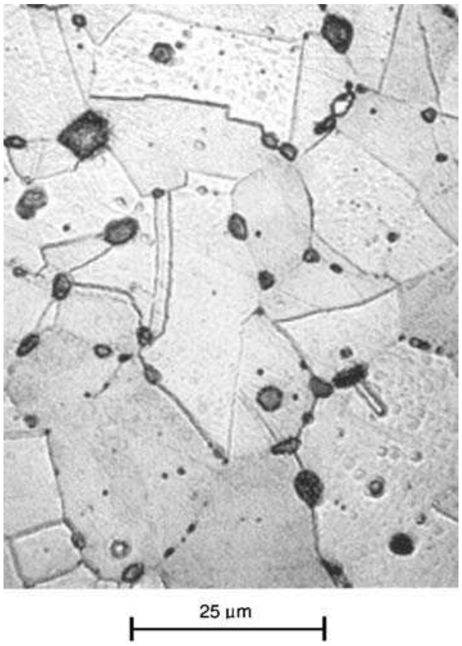


Fig. 5 Microstructure of alloy C36000 (free-cutting brass) showing globules of lead (dark) and alpha grains (light). 270×

Type III (Long-Chip) Alloys

The simplest copper alloys are those with essentially uniform microstructures. In pure copper, the structure contains only one phase, or crystal form, commonly designated alpha. This single-phase structure is retained within fairly broad limits when alloying elements are added, but the alloy content at which additional phases begin to appear differs with the individual alloying element and with processing conditions.

For example, up to approximately 39% Zn can be added to copper to form a single-phase alpha brass. The alpha structure can also accommodate up to 9% Al and remain homogeneous. The equilibrium room temperature solubility limit for tin in copper is quite low, near 1% by weight, but wrought copper-tin alloys (tin bronzes), which are heated during processing, remain structurally homogeneous up to almost 15% Sn because the transformation that produces the second phase is rather sluggish. Copper-nickel alloys have homogeneous alpha structures no matter how much nickel is present.

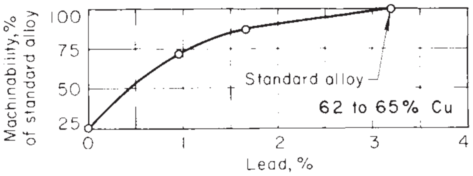


Fig. 6 Effect of lead content on the machinability of yellow brass

Type III copper alloys are soft and ductile in the annealed state. Their mechanical properties are governed by alloying and the degree of cold work. Pure copper can be strengthened only by cold working; whereas, the strength of single-phase brasses, bronzes, aluminum bronzes, and copper-nickels derives from the combined effects of cold work and alloying.

Even highly alloyed single-phase alloys retain a considerable degree of ductility, as can be seen in their turnings. Figure 4 (left side) shows the long, stringy chips typical of type III alloys. The smooth and uniform chip surface reflects the uninterrupted passage of the cutting tool. The chip is thicker than the feed rate because the copper is upset as it passes over the face of the tool. The accompanying cold work makes the chip hard and springy, but it also consumes energy that, converted to heat in the chip and cutting tool, increases tool wear.

The machinability of type III alloys therefore can be related to the following factors:

- *Initial hardness,* either from prior cold work or alloy content. Soft materials generally consume less energy than harder alloys, and other factors aside, produce less tool wear. On the other hand, softer materials tend to deflect under the pressure of the cutting tool, reducing dimensional accuracy. Improperly ground tools have a tendency to dig into such metals, leading to chatter and poor surface finish.

- *Work hardening rate,* as a function of deformation. A high work hardening rate results in high energy consumption, hard chips, and high tool wear. Severely work-hardened chips can tear away from the underlying soft matrix, causing smearing and poor surface finish.
- *Chip appearance.* Although the type III metals are machinable, their tendency to form long, stringy chips makes them less than ideal candidates for high-speed production on automatic screw machines, where clearing chip tangles may cause difficulty.

There is a considerable range in machining performance among alloys in this group. Soft coppers and brasses machine quite readily, while high-strength alloys may require carbide tooling, grinding, and in a few cases, heat treatment for optimal manufacture.

Additional Factors Affecting Machinability

Grain Size. Finer grain sizes are generally beneficial to mechanical properties, finer-grained metals being stronger and more ductile than those with coarse structures. These benefits extend to machinability. The effect is more pronounced in leaded multiphase alloys, although some improvement in machinability can be observed in fine-grained type III alloys as well.

Texture. The grain structure in wrought, rolled, or extruded metals will reflect the direction of deformation. That is, the grains of the metals, grain boundaries, and second phases, if any, tend to become elongated in the direction of hot or cold work, leading to the familiar fibrous texture of heavily wrought metals.

Since any nonuniformity in the structure of a metal can influence chip behavior, and therefore machining properties, it is understandable that machinability is somewhat enhanced in cutting directions that cross the direction of deformation. For example, rods and bars machine better circumferentially than longitudinally; plates machine better in the transverse or through-thickness direction than parallel to the rolling direction.

Temper. Mechanical properties affect cutting power requirements. Generally, the harder the metal the higher the power needed. In most cases, however, the economic effect of temper on attainable cutting speed and surface finish is more important than power consumption. It has already been pointed out that soft, annealed tempers can cause galling and smearing. This is especially true of type III alloys and is one reason such metals are often machined in a slightly cold-worked condition.

Heat Treatment. Beryllium coppers are rough-machined best in the solution annealed state, then heat treated to full hardness before finish machining, or if necessary, grinding. Not only does this produce better results, it also avoids potential distortion effects caused by the slight (0.5%) volume change that occurs during heat treatment.

Selecting Copper Alloys for Machinability

It is difficult to assign machinability ratings unambiguously since machinability itself can have several meanings. All ranking systems therefore have strengths and weaknesses depending on the individual observer's needs. Tables 1 and 2 group the copper alloys in three broad categories. Note that the groups are related to the manner of chip formation described earlier. Note also that there is a considerable difference in machinability between the free-cutting compositions, type I alloys, and metals that exhibit types II and III behavior.

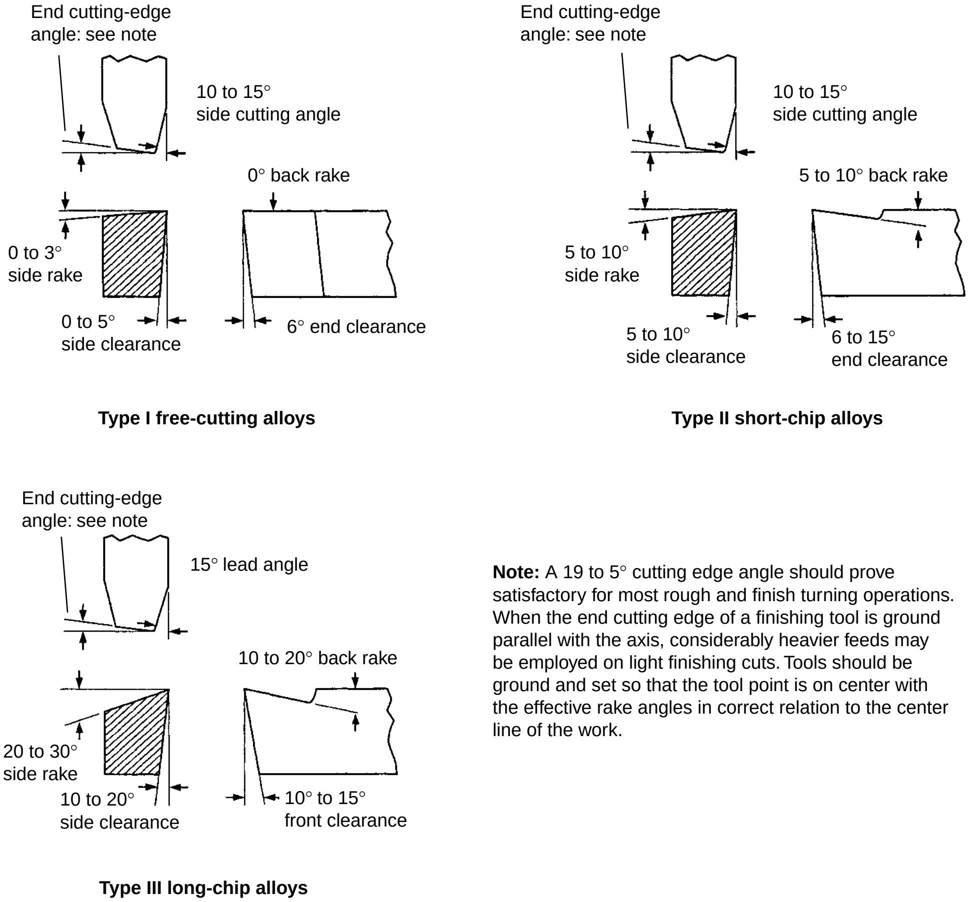
Differences among metals within the groups, especially the latter two, are relatively small. This is another way of saying that when materials selection is based on factors other than free-cutting behavior, machinability assumes less critical importance.

Products manufactured on automatic screw machines and other high-speed machine tools are usually specified in free-cutting grades to maximize cutting speeds and avoid chip clearance problems. The most common choice by far in such cases is free-cutting brass. Other free-cutting alloys are specified when the electrical, chemical, or mechanical property requirements of the product exclude brass.

Screw machine parts that require severe cold deformation, as in deep knurling or coarse-rolled threads, may require an alloy with a reduced lead content. Candidates include C34000 (medium-leaded brass, 64½%), C34500 (high-leaded brass) and C35300 (high-leaded brass, 62%), all of which contain 2% Pb.

Type II alloys can be used with automatic tooling, although production rates will be significantly lower than with free-cutting alloys. The curly-chip alloys have a tendency to produce chatter, with resulting degradation in surface finish, unless the tool and workpiece are rigidly supported. If proper care is exercised, the alloys are readily machinable.

Although the type III alloys can be cut relatively easily, they are considered less machinable than other alloy types because of the more rapid tool wear they generate and because of their tendency to form long, stringy chips. Attaining fine surface finishes also requires greater attention to cutting conditions than it does with other alloys. Since the metals are used for reasons other than high-speed machining characteristics, these factors do not have an overriding effect on alloy selection.



Type I free-cutting alloys

Type II short-chip alloys

Type III long-chip alloys

Note: A 19 to 5° cutting edge angle should prove satisfactory for most rough and finish turning operations. When the end cutting edge of a finishing tool is ground parallel with the axis, considerably heavier feeds may be employed on light finishing cuts. Tools should be ground and set so that the tool point is on center with the effective rake angles in correct relation to the center line of the work.

Fig. 7 Carbon and high-speed steel turning tools used for copper and copper alloys. Source: Ref 1

Recommended Machining Practices

The conditions recommended in this section for type I, II, and III alloys should only be used as starting points from which to optimize a machining operation. The machining conditions used with a given copper or copper alloy—speed, feed, tool geometry, and lubricant—will be determined by the needs of the individual job, the condition of the machine, and the skill of the machinist/operator.

Single-Point and Form Turning

Type III (Long-Chip) Alloys. The long, continuous turnings generated from unleaded, single-phase alloys deform and work harden as they pass over the cutting tool. The deformation generates heat and increases tool wear. Both of these effects can be minimized by providing generous rake angles to ease the chip off the tool face. Single-point tools should be ground with a back rake of 10 to 20° and a side rake of as much as 20 to 30° (see Fig. 7 and 8 for a description of the machining terminology used in this article).

Steep rake angles should be used with caution, however, because they tend to force the tool into the work, and the tearing action this produces leads to poor surface finishes. The effect is particularly noticeable with nonrigid setups and on machines with worn spindles or slides, that is, conditions that encourage chatter.

Rake angles can be reduced somewhat with single-point carbide tools and with either dovetail or circular form tools (Fig. 9 and 10). In all cases, finely polished or burnished cutting surfaces will reduce friction and heat buildup.

Coppers and copper-nickels tend to build up (weld) on the cutting tool. Built-up particles can break away and jam between the tool and workpiece, damaging the surface finish. Burnishing the cutting tool face to a smooth finish helps reduce sticking, as does the application of low-friction coatings such as titanium nitride.

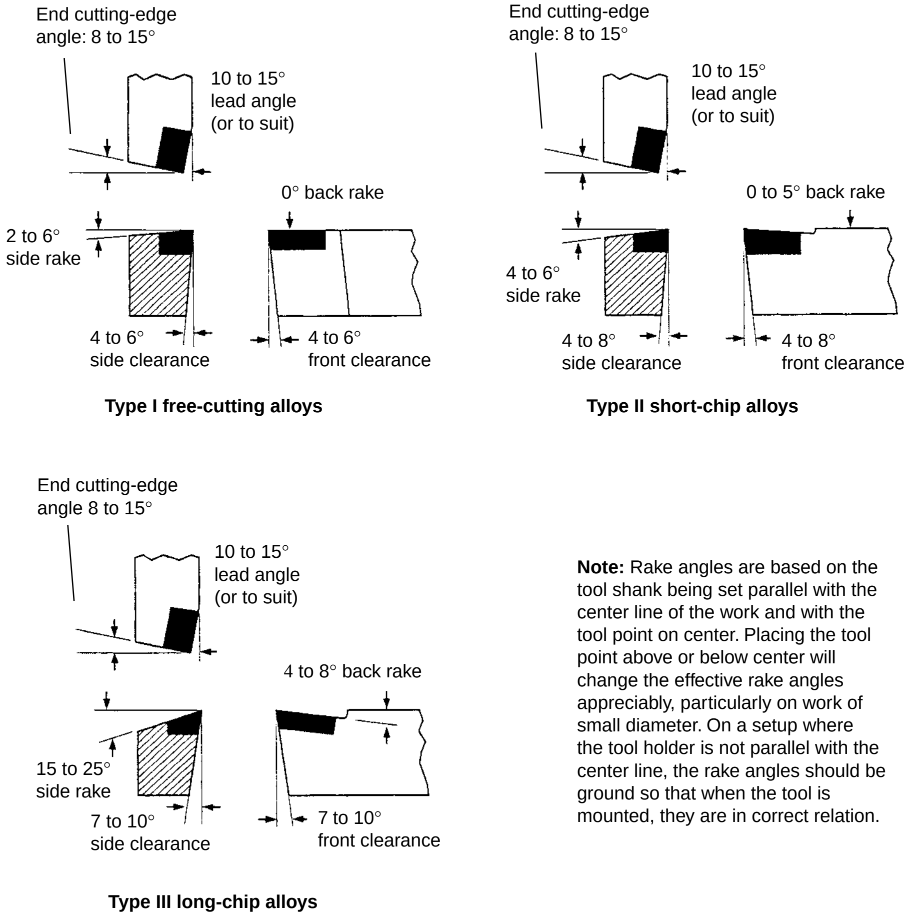
For single-point high-speed steel tools, a front clearance of from 10 to 15° and a side clearance of 10 to 20° is sufficient to permit loose particles to escape (Fig. 7). Smaller clearances can be tolerated in single-phase brasses and bronzes. Form tools should be ground with a front clearance angle between 7 and 12° (Fig. 10). Corresponding angles for carbide tools are given in Fig. 8 and 10.

Excessive clearance angles reduce tool support and, when combined with large rake angles, produce a fragile, chisel-like cutting edge. It is therefore best to begin with intermediate clearance angles, adjusting them up or down, as necessary.

The type III long-chip alloys require somewhat lower cutting speeds and feed rates than type I and II copper-base materials, although speeds can be increased significantly if carbide tooling is used in place of the more common high-speed steel. Recommended conditions are listed in Table 3.

Cutting Fluids. Because of the "sticky" nature of the alloys, it is important to use cutting fluids that provide both good lubrication and efficient cooling. Mineral oils augmented with 10 to 20% lard oil are generally satisfactory. Sulfurized cutting fluids help prevent sticking in soft copper and copper-nickels, but they may stain freshly machined surfaces if not removed quickly.

Type II (Short-Chip) Alloys. The materials within this group display a wide range of



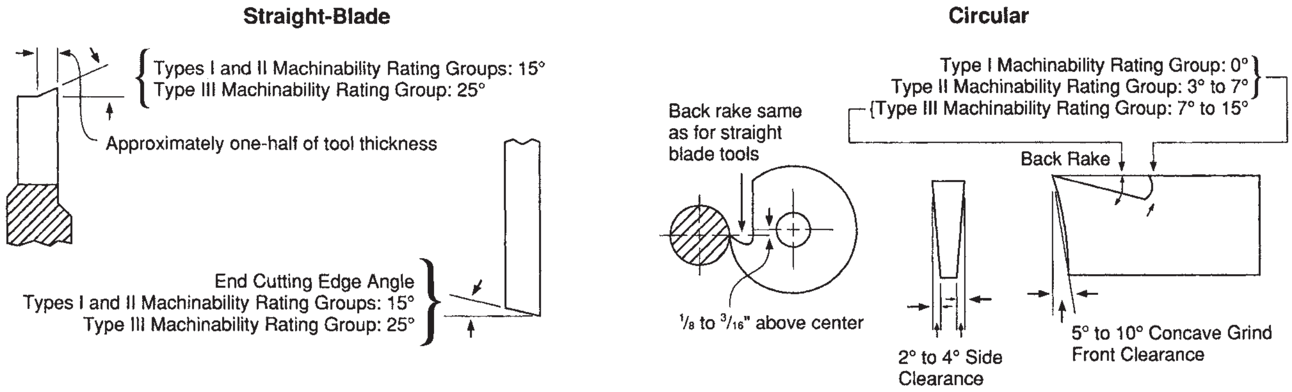
Type I free-cutting alloys

Type II short-chip alloys

Type III long-chip alloys

Note: Rake angles are based on the tool shank being set parallel with the center line of the work and with the tool point on center. Placing the tool point above or below center will change the effective rake angles appreciably, particularly on work of small diameter. On a setup where the tool holder is not parallel with the center line, the rake angles should be ground so that when the tool is mounted, they are in correct relation.

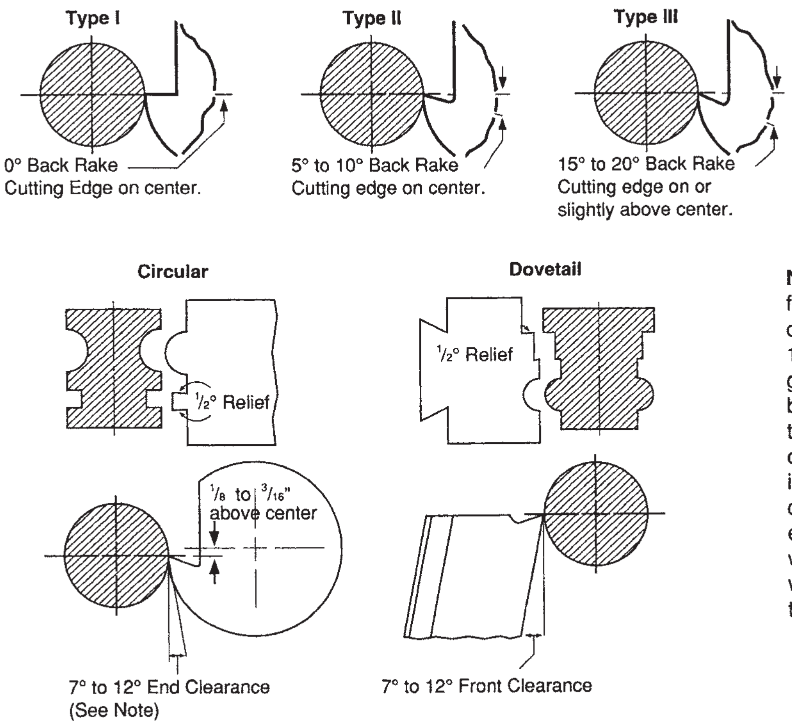
Fig. 8 Carbide turning tools for copper and copper alloys



Straight-Blade

Circular

Fig. 9 Design of straight-blade and circular cutoff tools for turning copper and copper alloys. Source: Ref 1



Note: Front clearance of a circular form tool depends principally on the diameter of the tool. It is usually 7° to 12°, but it can be accentuated by grinding the cutting edge of the tool below center, then raising the toolholder so that the cutting edge is on the center line of the work. It is important to bear in mind that the contour of a machined part will be in exact reverse of the form tool only when all cutting edges are parallel with the center line of the work and of the form tool.

Fig. 10 Design of circular and dovetail form tools for turning copper and copper alloys. Source: Ref 1

Table 3 Turning data applicable to single-point and form tools for copper alloys

	For single-point tools only				Surface speed		Roughing feed		Finishing feed	
Tool material	Side relief angle, degrees	Front relief angle, degrees	Back rake angle, degrees	Side rake angle, degrees	m/min	sfm	µm/rev	mil/rev	µm/rev	mil/rev
Free-cutting type I alloys										
HSS(a)	0–5	6	0–5	0–3	92–305	300–1000	51–381	2–15	51–76	2–3
Carbide	4–6	4–6	0	2–6	152–488	500–1600	51–381	2–15	51–76	2–3
Short-chip type II alloys										
HSS(a)	5–10	6–15	5–10	5–10	46–92	150–300	51–203	2–8	51–76	2–3
Carbide	4–8	4–8	0–5	4–8	122–183	400–600	51–203	2–8	51–76	2–3
Long-chip type III alloys										
HSS(a)	10–20	10–15	10–20	20–30	23–46	75–150	51–203	2–8	51–76	2–3
Carbide	7–10	7–10	4–8	15–25	92–152	300–500	51–203	2–8	51–76	2–3

(a) HSS, M2 high-speed steel. Source: Ref 1

strength and ductility, and cutting conditions must be adjusted accordingly. At one end of the spectrum are the ductile, high-zinc brasses, which can be cut using conditions approaching those used with high-strength long-chip alloys, that is, rake angles up to 10° and reasonably generous clearance. The less ductile grades of phosphor and aluminum bronze should be cut using little or no rake, because the duplex structure of these metals makes them prone to chatter.

Cutting speeds between 46 and 92 m/min (150 and 300 sfm) are recommended for single-point or form cutting with high-speed steel; speeds can be increased to between 122 and 183 m/min (400 and 600 sfm) with carbide tooling. Optimal feed rates should be determined by beginning with a fairly light cut, approximately 0.05 mm/rev (0.002 in./rev), increasing this gradually until surface finish and/or tool wear rates deteriorate.

Cutting fluids should match the workpiece material. Alloys with machinability ratings similar to high-strength long-chip alloys require a cutting fluid that provides effective lubrication as well as effective cooling. For these, a mineral oil fortified with between 5 and 15% lard oil or a sulfurized fatty-oil base thinned with a light mineral oil will give good lubrication. The alloys in this group that have relatively high machinability ratings can be cut satisfactorily using soluble oils.

Type I (Free-Cutting) Alloys. These materials require little or no rake since chips tend to break up almost immediately after they form. Modest clearance angles up to 5° can be used but are not necessary unless the tool tends to drag.

Free-cutting brass, C36000, can be cut at the maximum attainable speed. In fact, in the range of diameters normally encountered in screw machine products, there are no commercially available machine tools that exceed the speed capacity of brass. Recommended cutting speeds for leaded copper metals other than free-cutting brass range from 91 to 305 m/min (300–1000 sfm).

Cutting Fluids. Straight light mineral oils are generally preferred as cutting fluids for the free-cutting alloys. Soluble oils also give good results.

Milling

Type III (Long-Chip) Alloys. The chip clearance problems these ductile metals present during milling are similar to those encountered during turning. Milling cutters with tooth spacings no finer than four to eight teeth per inch will facilitate chip removal. Combined cutters can also be used, but teeth should be interlocked to prevent chips from collecting between cutter elements. Spiral cutters are useful for wide cuts; helix angles as large as 53° have been found to be satisfactory for cutting copper.

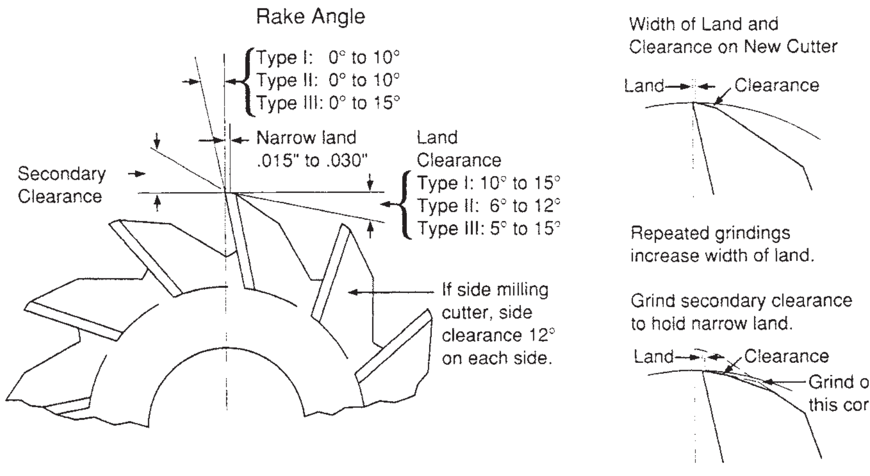


Fig. 11 Milling cutter used for copper and copper alloys. Source: Ref 1

Table 4 Milling data for copper alloys

Workpiece material	Rake angle, degrees	Clearance angle, degrees	Land		Surface speed	
			mm	in.	m/min	sfm
Free-cutting type I alloys	0–10	10–15	0.38–0.76	0.015–0.030	61–152	200–500
Short-chip type II alloys	0–10	5–15	0.38–0.76	0.015–0.030	46–61	150–200
Long-chip type III alloys	0–15	5–15	0.38–0.76	0.015–0.030	15–46	50–150

Source: Ref 1

Generous rake angles and adequate clearance should be provided on face-, side-, and end-milling cutters to prevent burnishing of the workpiece. Up to 15° clearance can be incorporated on tooth sides in side and face cutters and on tooth ends in end cutters (Fig. 11). A radial undercut will prevent tooth edges from dragging along the workpiece. Cutting edges should be finely polished and/or coated to reduce loading.

Recommended milling speeds range from 15 to 45 m/min (50–150 sfm), although considerably higher speeds can be used. Feed rates range from 0.18 to 0.76 mm/rev (0.007–0.030 in./rev) depending on the type of cutter. Recommended milling conditions are listed in Table 4.

Type II (Short-Chip) Alloys. As with turning operations, rake angles should generally be reduced from those used with ductile long-chip alloys, but optimal conditions must be selected for each alloy. Small-diameter cutters should be ground with radial teeth (0° rake) for hard aluminum bronzes.

Recommended milling speeds for these alloys can be as high as 61 m/min (200 sfm). Recommended feeds range from 0.4 to 0.56 mm/rev (0.016–0.022 in./rev) per tooth for spiral cutters and from 0.25 to 0.56 mm/rev (0.010–0.022 in./rev) per tooth for end mills.

Soluble-oil coolants are satisfactory for these alloys. Mineral oils containing about 5% lard oil can also be used.

Type I (Free-Cutting) Alloys. These alloys can be milled at speeds up to 152 m/min (500 sfm). As with turning operations, carbide tooling permits the highest cutting speeds. Cutting fluids are generally necessary at high speeds and feeds, primarily for heat removal, but are often not used under moderate milling conditions. Recommended tool geometries are listed in Table 4.

Drilling

Most copper alloys can be drilled with standard twist drills, although high-production conditions usually call for special drill configurations. Some authorities claim that ductile alloys perform better with fast-twist drills, while others hold that moderate or slow twists are better able to clear long, stringy chips. There is general agreement that small-diameter holes in copper are best cut with fast-twist drills. Free-cutting grades, including C36000, can be drilled very rapidly with straight-fluted brass drills, which permit easy escape for the tiny fragmented chips of the alloys.

Full rake angles are normally retained in drills used on long-chip copper alloys. Drill-tip angles should be between 100 and 110°, and lip clearance angles may have to be as steep as 20° (Fig. 12). Notching the cutting edge helps break up long, stringy turnings. Drills for short-chip and free-cutting alloys should be flat-ground to a 0° rake. Standard 118° tip angles should be used; lip clearance can range from 12 to 15° (Fig. 12).

Recommended speeds are similar to those used for turning operations, meaning that small-diameter holes can usually be drilled at the maximum possible spindle speed. Feed rates should range between 0.05 and 0.76 mm/rev (0.002 and 0.030 in./rev), depending on alloy type. Readily machinable brasses and free-cutting alloys drill best with high feeds, while ductile coppers and long-chip alloys fare better with lighter feeds.

Cutting fluids are beneficial but not absolutely necessary when drilling highly machinable free-cutting alloys; they are, however, required for other compositions.

Boring

Tool geometry is most important in boring in order to achieve the required smooth finished surface and to direct chip flow away from the cut surface. Tools for boring copper alloys are shown in Fig. 13; relevant machining data are presented in Table 5.

Reaming

Fluted reamers used with copper alloys are similar to those used with steel, except that

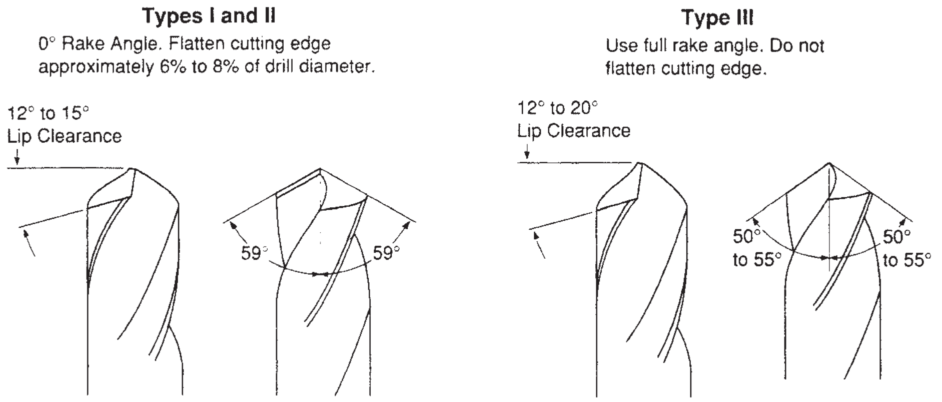


Fig. 12 Drill point and clearance angles for twist drills. Source: Ref 1

Table 5 Boring data for copper alloys using carbide tooling

Workpiece material	Back rake angle, degrees	Side rake angle, degrees	Speed	
			m/min	sfm
Free-cutting type I alloys	0	5	152–305	500–1000
Short-chip type II alloys	0–5	5–10	122–183	400–600
Long-chip type III alloys	5–10	15–20	61–152	200–500

Source: Ref 1

clearances should be increased to 8 to 10°. All types of reamers can be used; however, fluted reamers are less prone to chatter, an important consideration with tough short-chip alloys. A rake angle (hook) of 5° is used on all copper alloys except free-cutting leaded compositions, which are generally reamed with zero or negative rake (Fig. 14). It is important that cutting tools be lapped to a fine surface finish.

Copper and long-chip metals should be reamed at a speed of 12 to 27 m/min (40–90 sfm); short-chip alloys at 23 to 46 m/min (75–150 sfm); and free-cutting leaded alloys at 30 to 61 m/min (100–200 sfm). Table 6 gives recommended feeds and depths of cut for holes up to 25 mm (1 in.) in diameter.

Threading and Tapping

Free-cutting brass accepts fine- to medium-pitch rolled threads quite well; however, coarse or deep threads may call for alloys such as medium-leaded brass, C34000, or the high-leaded brasses C34500 and C35300, which have somewhat lower lead contents than C36000 and are therefore more ductile. The ductile unleaded copper alloys can also be roll threaded. If conditions permit, threading should be performed with alloys in the softest available temper.

Thread die cutting generally follows the recommendations for turning operations: soft, ductile long-chip alloys require large rake angles (17–25°, and up to 30° for pure copper); hard multiphase alloys such as tin bronzes and high-strength yellow brasses require intermediate rake angles (generally 12–17°, but up to 25° for high-strength aluminum bronzes). Free-cutting brass and highly leaded tin bronzes require zero rake. Tools for threading and tapping are shown in Fig. 15 and 16.

Table 7 lists recommended rake angles and chamfers for taps used with the copper metals. Refer to Fig. 16 for descriptions of the terms used. Threading and tapping speeds are listed in Table 8, while tool geometries for tap and die chasers and circular chasers are given in Tables 9 and 10, respectively.

Sawing (Ref 3)

Selection of the proper width of saw, number of teeth, pressure, feed, and speed is as important as the condition of the machine involved. Width of the hacksaw or bandsaw blade is usually governed by type of equipment. It is advisable that the blade be wide enough to withstand normal feeding pressures. Correct tension is vital. A loose blade will cause crooked cuts, buckling, and twisting as well as stripped teeth. Too great a tension will also cause snapping and throw too great a load on guides and the machine itself.

Feeding pressure should be determined by size and machinability of the alloy. On gravity- or hand-fed bandsaw machines, moderate feed is desirable on small sections or readily machined alloys. Increased pressure is recommended on heavy sections or alloys with low machinability ratings to reduce saw wear. Modern power hacksaw machines employ either mechanical or hydraulic feeds, permitting increased feed setting on small sections of soft alloys. Large sections and hard alloys require reduced feed settings.

Correct tooth specification is important to permit adequate chip clearance. Coarse teeth are desirable on soft or thick material and finer teeth are indicated on thin sections or hard alloys. Care must be taken to ensure correct set. If the set is worn to any great extent, crooked cuts and excessive heat with subsequent saw failure will result. Solid and inserted tooth shapes for circular saws are shown in Fig. 17; relevant circular sawing data are given in Table 11. For band sawing of copper alloys, blades of 13 or 19 mm (0.5 or 0.75 in.) width are most commonly used, and only for short radius cutting should narrow blades be used. The

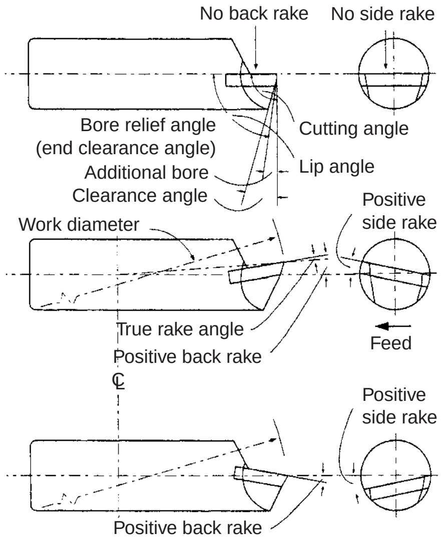
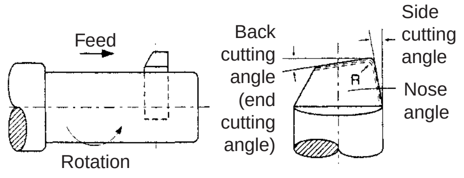
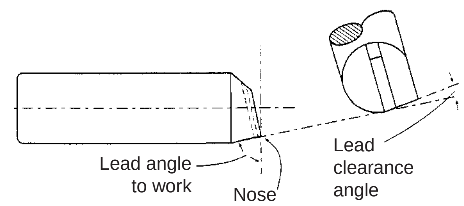


Fig. 13 Design of boring tools used for copper alloys. Source: Ref 1





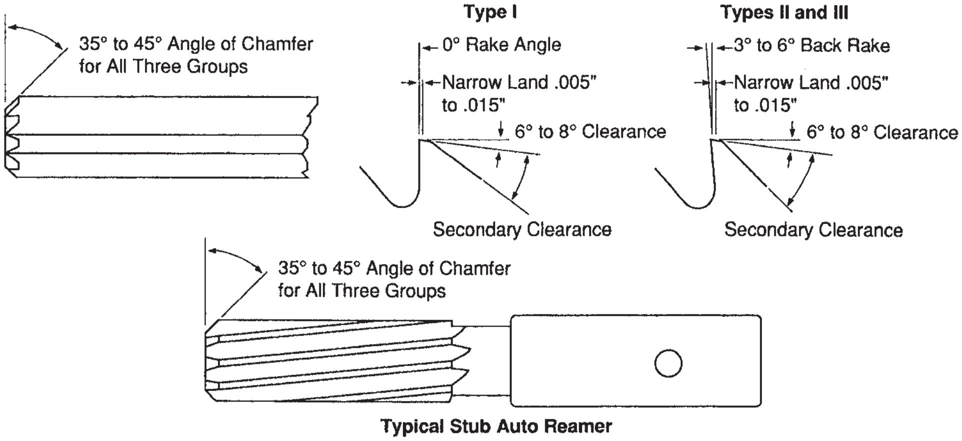


Fig. 14 Reamer angles and clearances. Source: Ref 1

Table 6 Reaming data for copper alloys using high-speed steel tooling

Hole diameter		Feed				Depth of cut	
		Copper		Brass and bronze			
mm	in.	mm/rev	in./rev	mm/rev	in./rev	mm	in.
<3.2	<1/8	0.15	0.006	0.25	0.010	0.08–0.10	0.003–0.004
3.2–9.5	1/8 – 3/8	0.15–0.25	0.006–0.010	0.25–0.41	0.010–0.016	0.08–0.18	0.004–0.007
>9.5	>3/8	0.23–0.61	0.009–0.024	0.41–0.91	0.016–0.036	0.18–0.38	0.007–0.015

Source: Ref 1

Table 7 Tapping data for copper alloys

Workpiece material	Tap rake angle, degrees	Die chamfer, degrees
Free-cutting type I alloys	2–4	10–30(a)
Short-chip type II alloys	5–8	10–15(a)
Long-chip type III alloys	8–10	10–15(a)

(a) Two or three threads. Source: Ref 1

Table 8 Threading and tapping speeds for copper alloys using high-speed steel tooling

Workpiece material	Lineal threading or tapping speed(a) m/min	sfm
Free-cutting type I alloys	30–61	100–200
Short-chip type II alloys	15–27	50–90
Long-chip type III alloys	12–15	40–50

(a) Recommended cutting speeds are for moderate-pitch threads. Use speeds in the lower ranges for coarse threads. Source: Ref 1

Table 9 Tool geometry for tap and die chasers

Workpiece material	Tap: Rake angle, degrees	Tap: Throat angle, degrees	Die: Rake angle, degrees	Die: Throat angle, degrees
Free-cutting type I alloys	–5 to +5	15	–10 to 0	15
Short-chip type II alloys	5–12	20	1–10	20
Long-chip type III alloys	15–25	30	12–30	30

Source: Ref 1

Table 10 Tool geometry for circular chasers

Workpiece material	Rake angle, degrees	Face angle, degrees	Throat angle, degrees	Clearance, degrees
Free-cutting type I alloys	–5 to +5	0	25	12
Short-chip type II alloys	10–20	1–2	25	12
Long-chip type III alloys	15–35	2–3	25	12

Source: Ref 1

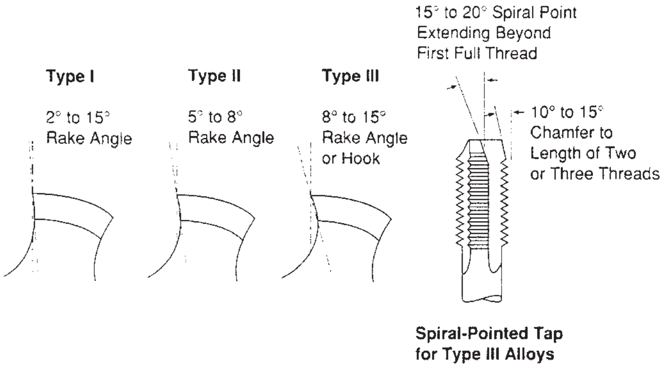


Fig. 15 Threading tap design used for copper and copper alloys. Source: Ref 1

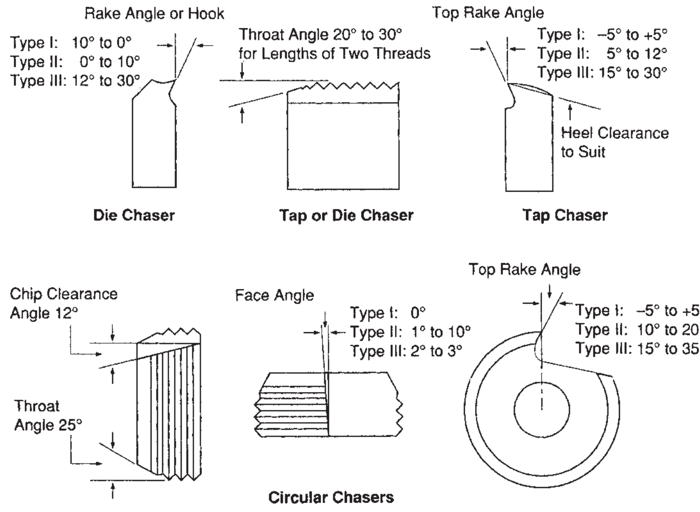


Fig. 16 Chasers for die heads and collapsible taps. Source: Ref 1

Table 11 Circular sawing data for copper alloys

Machinability(a)	Tooth type(b)	Diameter mm	Diameter in.	Thickness mm	Thickness in.	Number of teeth	Hook angle, degrees	Rim speed m/min	Rim speed sfm	Feed mm/min	Feed in./min	Coolant, lubricant	Hardness HRC	Chromium plated to 0.05 mm (0.002 in.)	Hollow ground taper per mm	Hollow ground taper per in.
Rod, ≤38 mm (≤1½ in.)																
I	SST(c)	305	12	2.4	3/32	150–200	10–15	1220–2440	4000–8000	1524	60	Grease stick	52–56	Yes	0.09	0.0035
II	TST(c)	305	12	2.4	3/32	100–125	10–15	1219–1524	4000–5000	762	30	Grease stick	52–56	Yes	0.09	0.0035
III	Ins. SST	305	12	3.2	1/8	75–100	5–10	610–914	2000–3000	508–762	20–30	Grease stick	60–62	No	0.025	0.0010
Rod, 38–102 mm (1½–4 in.)																
I	Ins. Alt. SST & BST	406	16	4.8	3/16	60–64	10–15	305	1000	762–1016	30–40	Compound(d)	64–66	No	0.09	0.0035
II	Ins. Alt. SST & BST	406	16	4.8	3/16	60–64	10–15	305	1000	508–762	20–30	Compound(d)	62–64	No	0.025	0.0010
III	Ins. Alt. SST & BST	406	16	6.3	1/4	60–64	5–10	229	750	254–508	10–20	Compound(d)	62–64	No	0.025	0.0010
Rod, 102–204 mm (4–8 in.)																
I	Ins. Alt. SST & BST	711	28	6.3	1/4	60–80	10–15	183–229	600–750	508–762	20–30	Compound(d)	62–64	No	0.025	0.0010
II	Ins. Alt. SST & BST	711	28	6.3	1/4	60–80	10–15	183–229	600–750	381–635	15–25	Compound(d)	62–64	No	0.025	0.0010
III	Ins. Alt. SST & BST	711	28	6.3	1/4	60–80	5–10	152–198	500–650	254–381	10–15	Compound(d)	62–64	No	0.025	0.0010

(a) Machinability: I, free-cutting; II, short-chip; III, long-chip. (b) SST, standard square tooth; TST, topped square tooth; BST, bevel standard tooth; Ins., inserted; Alt., alternating. (c) Using semihigh-speed steel, all others are high-speed steel. (d) Compound, soluble oil 10% and 1 lb heavy soap per 20 gal. Source: Ref 1

Table 12 Band saw teeth and speeds

	Stock diameter of thickness, mm (in.)											
	1.6–6.4 (1/16 – 1/4)				6.4–25 (1/4 – 1)				>25 (>1)			
	Teeth		Velocity		Teeth		Velocity		Teeth		Velocity	
Machinability rating of alloys	per cm	per in.	m/s	ft/min	per cm	per in.	m/s	ft/min	per cm	per in.	m/s	ft/min
70–100	7	18	2.5–5.1	500–1000	4	10	1.8–2.3	350–450	1.5	4	1.3–1.8	250–350
30–60	7	18	1.3–1.8	250–350	4	10	1.2–1.3	230–250	1.5	4	1.0–1.2	200–230
20 (except copper)	7	18	1.3–1.5	250–350	4	10	1.0–1.3	200–250	1.5	4	0.8–1.0	150–200
Copper	7	18	4.1–7.6	800–1500	4	10	3.0–5.1	600–1000	1.5	4	1.5–3.0	300–600

Source: Ref 3

data in Table 12 will aid considerably in selecting a good combination of saw tooth and linear speed.

For power hacksaws, a good rule in selecting saw tooth pitch is to use fewer teeth for thick sections to provide for better chip clearance, and more teeth for thinner sections. Data for power hacksawing are listed in Table 13.

Grinding (Ref 4)

The grinding of copper alloys is not common, but in some applications grinding is the best means of obtaining accuracy and finish. Sometimes, when finish grinding must supplement machining, one grinding operation can be used to replace both operations.

Speeds, feeds, and wheels are given in Table 14. Aluminum oxide wheels are recommended for all types of grinding except for surface grinding softer alloys. For these conditions, silicon carbide wheels are preferred. In all cases, vitrified bond wheels of medium grade (J to N) are recommended. Emulsions of soluble oil and water are satisfactory grinding fluids.

Nontraditional Machining Methods

Nontraditional machining methods commonly carried out on copper and copper alloys include electrical discharge machining (EDM), electrochemical machining (ECM), and photochemical machining (PCM). Each of these processes are briefly described subsequently. More detailed information can be found in *Machining,* Volume 16 of *ASM Handbook.*

Electrical Discharge Machining. In the EDM process, metal is removed by rapid spark discharges between an electrode and a conductive workpiece separated by a 0.013 to 0.9 mm (0.0005–0.035 in.) gap filled with a dielectric fluid. The workpiece is melted, vaporized in part, and expelled from the gap. Figure 18 shows a typical EDM setup.

Electrical discharge machining is often used to produce beryllium-copper mold components for injection molding of plastics. The effectiveness of EDM is not dependent on the strength or hardness of the workpiece, and the beryllium copper can be machined in the age-hardened condition without affecting strength and with no need for further heat treatment. The EDM process is also used to drill small, burr-free holes in miniature components and for making prototype quantities of contacts for aerospace and electronic components.

Electrochemical machining is the controlled removal of metal by anodic dissolution in an electrolytic cell in which the workpiece is the anode and the tool is the cathode. The electrolyte is pumped through the cutting gap between the tool and the workpiece, while direct current is passed through the cell at a low voltage, to dissolve metal from the workpiece. Figure 19 shows a typical setup for ECM.

The ECM process is used to machine oddly shaped, small deep holes in copper and copper alloys that would be difficult, if not impossible, to make by mechanical machining. Electrochemical machining is used for operations as widely different as milling, drilling, deburring, etching, and marking.

Photochemical machining, also known as chemical blanking, is a metal-etching process that uses a photoresist (photosensitive masking) to define the locations where the metal will be etched (removed) (Ref 7). The PCM process is used to produce intricate and close-tolerance patterns in a variety of flat parts (including foil) with a thickness range of 0.01 to 1.6 mm (0.005–0.062 in.).

Copper and copper alloys are among the most etchable metals used in photochemical machining. Electrolytic copper, oxygen-free copper, beryllium copper, brass, phosphor bronze, copper nickel, and nickel silver flat products are readily processed using the PCM process. Products include contacts and terminals, lead frames, and copper foil/plastic printed circuit board laminates.

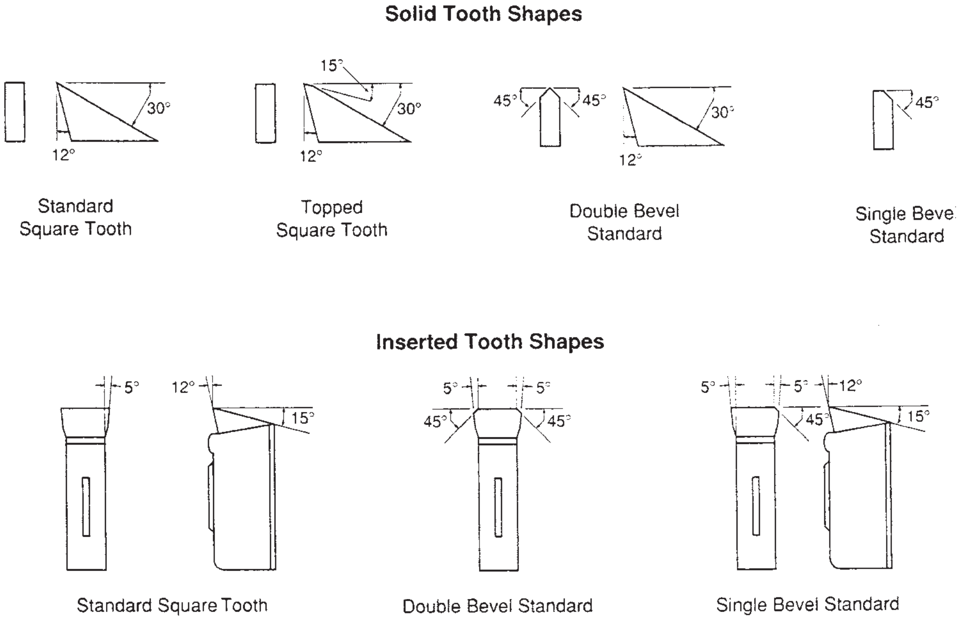


Fig. 17 Solid and inserted tooth shapes for circular saws used for copper and copper alloys. Source: Ref 1

Table 13 Power hacksaw teeth and speeds

	Stock diameter or thickness, mm (in.)					
	6.35–25.4 (1/4 – 1)			>25.4 (>1)		
	Teeth			Teeth		
Workpiece material	per cm	per in.	Strokes per minute	per cm	per in.	Strokes per minute
Free-cutting type I alloys	2.4–4	6–10	130–150	1.6–2.4	4–6	130–150
Short-chip type II alloys	2.4–4	6–10	90–120	1.6–2.4	4–6	90–120
Long-chip type III alloys	2.4–4	6–10	60–90	1.6–2.4	4–6	60–90

Source: Ref 1

Table 14 Conditions for the grinding of copper alloys

Surface grinding	
Wheel classification	
Workpiece 20–70 HRB	C-46-K-V
Workpiece 60–100 HRB	A-46-K-V
Wheel speed, m/min (sfm)	1680–1980 (5500–6500)
Table speed, m/min (sfm)	15–30 (50–100)
Downfeed	
Rough, mm/pass (in./pass)	0.075 (0.003)
Finish, mm/pass (in./pass)	0.01 (0.0005) max
Crossfeed	1/3 wheel width/pass

Cylindrical grinding	
Wheel classification	
Workpiece 2–70 HRB	A-60-N-V
Workpiece 60–100 HRB	A-46-L-V
Wheel speed, m/min (sfm)	1680–1980 (5500–6500)
Work speed, m/min (sfm)	30 (100)
Infeed	
Rough, mm/pass (in./pass)	0.05 (0.002)
Finish, mm/pass (in./pass)	0.01 (0.0005) max
Traverse	
Rough	1/3 wheel width/work rev
Finish	1/6 wheel width/work rev

Centerless grinding	
Grinding wheel classification	A-60-L-V
Wheel speed, m/min (sfm)	1680–1980 (5500–6500)
Work feed, mm/min (in./min)	125 (50)
Infeed	
Rough, mm/pass (in./pass)	0.13 (0.005)
Finish, mm/pass (in./pass)	0.04 (0.0015) max
Regulating wheel	
Angle	3°
Speed	30 rev/min

Internal grinding	
Wheel classification	
Workpiece 20–70 HRB	A-46-J-V
Workpiece 60–100 HRB	A-60-L-V
Wheel speed, m/min (sfm)	1520–1980 (5000–6500)
Work speed, m/min (sfm)	30–60 (100–200)
Infeed	
Rough, mm/pass (in./pass)	0.05 (0.002)
Finish, mm/pass (in./pass)	0.005 (0.0002)
Traverse	
Rough	1/3 wheel width/work rev
Finish	1/6 wheel width/work rev

Source: Metcut Research Associates Inc.

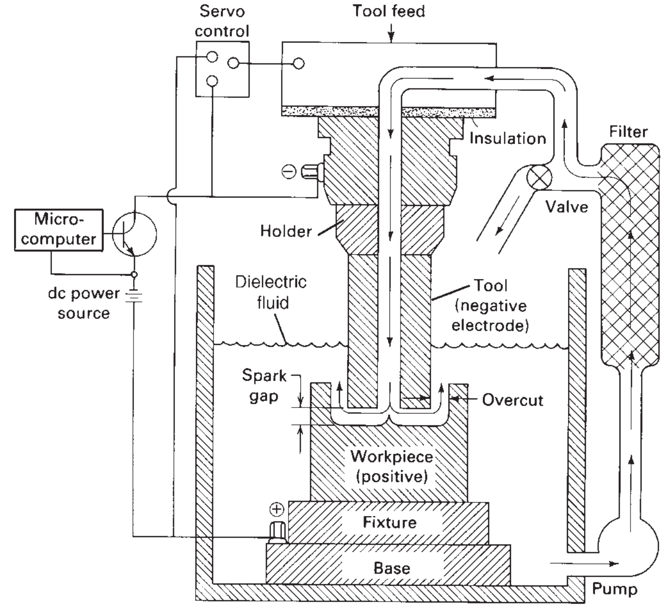


Fig. 18 Typical setup for electrical discharge machining. Negative (standard) polarity is shown. Positive (reverse) polarity is also extensively used. Source: Ref 5

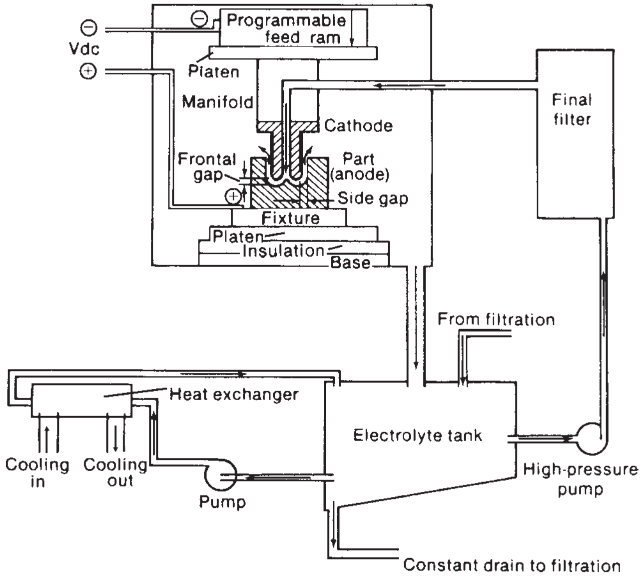


Fig. 19 Schematic of the electrochemical machining system. Source: Ref 6

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Welding

COPPER AND COPPER ALLOYS can be welded by a variety of fusion and solid-state processes. Fusion welding processes involve localized melting and solidification of the base metal and filler metal, or the base metal only if no filler metal is used (i.e., autogenous welds). Fusion welding methods commonly used to join copper and its alloys include arc welding processes, resistance welding processes, oxyfuel welding, and electron beam welding. Solid-state welding is the joining of base metals by chemical bond formation without heating the base metals above their respective melting points. Solid-state welding processes used to join copper and its alloys include cold welding, explosion welding, roll welding, friction welding, and ultrasonic welding. Table 1 summarizes the applicability of the most commonly used welding processes for major alloy classifications.

Arc Welding

In manufacturing, copper and copper alloys are often joined by welding. The arc welding processes are of prime concern. Arc welding can be performed using shielded metal arc welding (SMAW), gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), plasma arc welding (PAW), and submerged arc welding (SAW). These welding processes will be discussed with reference to specific copper alloy groups. The effects of various alloying agents are also addressed relative to welding metallurgy and process considerations. Examples of standard joint geometry, process parameters, and specific applications are described. More detailed information on the specific welding processes discussed can be found in Welding, Brazing, and Soldering, Volume 6 of ASM Handbook, and in the Selected References listed at the conclusion of this article.

Alloy Metallurgy and Weldability

Many common metals are alloyed with copper to produce the various copper alloys. The most common alloying elements are aluminum, nickel, silicon, tin, and zinc. Other elements and metals are alloyed in small quantities to improve certain material characteristics, such as corrosion resistance or machinability. Copper and its alloys are divided into nine major groups. These major groups are:

- *Coppers*, which contain a minimum of 99.3% Cu
- *High-copper alloys*, which contain up to 5% alloying elements
- *Copper-zinc alloys (brasses)*, which contain up to 40% Zn
- *Copper-tin alloys (phosphor bronzes)*, which contain up to 10% Sn and 0.2% P
- *Copper-aluminum alloys (aluminum bronzes)*, which contain up to 10% Al
- *Copper-silicon alloys (silicon bronzes)*, which contain up to 3% Si
- *Copper-nickel alloys*, which contain up to 30% Ni
- *Copper-zinc-nickel alloys (nickel silvers)*, which contain up to 27% Zn and 18% Ni
- *Special alloys*, which contain alloying elements to enhance a specific property or characteristic, for example, machinability

Many copper alloys have common names, such as oxygen-free copper (99.95% Cu min), beryllium copper (0.2 to 2.0% Be), Muntz metal (Cu-40Zn), Naval brass (Cu-39.25Zn-0.75Sn), and commercial bronze (Cu-10Zn).

A more standardized system of identification is the Unified Numbering System (UNS). In this system, wrought alloys of copper are designated by numbers 1*xxxx* to 7*xxxx*, and cast alloys are designated 8*xxxx* to 9*xxxx*; thus, the same alloy can be produced as a wrought and cast product. The UNS system is described in the article "Standard Designations for Wrought and Cast Copper and Copper Alloys" in this Handbook.

Table 2 lists various copper alloys that are frequently arc welded, their UNS numbers, and their physical properties. Many of the physical properties of copper alloys are important to the welding processes, including melting tempera-

Table 1 Applicable welding processes for copper and copper alloys

		Weldability(a) by						
Alloy	UNS No.	Oxyfuel gas welding	SMAW	GMAW	GTAW	Resistance welding	Solid-state welding	Electron beam welding
ETP copper	C11000–C11900	NR	NR	F	F	G	NR	NR
Oxygen-free copper	C10200	F	NR	G	G	E	NR	G
Deoxidized copper	C12000	G	NR	E	E	E	NR	G
	C12300	G	NR	E	E	E	NR	G
Beryllium copper	C17000–C17500	NR	F	G	G	F	F	F
Cadmium/chromium copper	C16200	NR	NR	G	G	F	NR	F
	C18200	NR	NR	G	G	F	NR	F
Red brass—85%	C23000	F	NR	G	G	G	F	…
Low brass—80%	C24000	F	NR	G	G	G	G	…
Cartridge brass—70%	C26000	F	NR	F	F	G	G	…
Leaded brasses	C31400–C38590	NR	NR	NR	NR	NR	NR	…
Phosphor bronzes	C50100–C52400	F	F	G	G	G	G	…
Copper-nickel—30%	C71500	F	F	G	G	G	G	F
Copper-nickel—10%	C70600	F	G	E	E	G	G	G
Nickel silvers	C75200	G	NR	G	G	G	F	…
Aluminum bronze	C61300	NR	G	E	E	G	G	G
	C61400	NR	G	E	E	G	G	G
Silicon bronzes	C65100	G	F	E	E	G	G	G
	C65500	G	E	E	E	G	G	G

ETP, electrolytic tough pitch; SMAW, shielded metal arc welding; GMAW, gas metal arc welding; GTAW, gas tungsten arc welding.(a) E, excellent; G, good; F, fair; NR, not recommended ture, coefficient of thermal expansion, and electrical and thermal conductivity. As shown in Table 2, certain alloying elements greatly decrease the electrical and thermal conductivities of copper and copper alloys. This will in turn significantly affect the weldability of the alloys. The copper and copper alloys listed in Table 2 are rated for their relative weldability using SMAW, GTAW, and GMAW.

Several alloying elements have pronounced effects on the weldability of copper and copper alloys. Small amounts of volatile, toxic alloying elements are often present in copper and its alloys. As a result, the requirement of an effective ventilation system to protect the welder and/or the welding machine operator is more critical than when welding ferrous metals.

Zinc reduces the weldability of all brasses in relative proportion to the percent of zinc in the alloy. Zinc has a low boiling temperature, which results in the production of toxic vapors when welding copper-zinc alloys. Effective forced ventilation is mandatory, and source-capture systems are necessary to contend with the fumes.

Tin increases the hot-crack susceptibility during welding when present in amounts from 1 to 10%. These alloys are typically the phosphor bronzes and tin brasses. Tin, when compared with zinc, is far less volatile and toxic. During welding, tin may preferentially oxidize relative to copper. The results will be an oxide entrapment, which may reduce the strength of the weldment.

Table 2 Nominal compositions, melting points, relative thermal conductivities, and weldabilities of wrought coppers and copper alloys that are commonly arc welded

UNS No.	Alloy name	Nominal composition, %	Melting point (liquidus)		Relative thermal conductivity(a)	Weldability(b) by		
			°C	°F		GTAW	GMAW	SMAW
OFC and ETP coppers								
C10200	Oxygen-free copper (OFC)	99.95 Cu	1083	1981	100	G	G	NR
C11000	Electrolytic tough pitch (ETP) copper	99.90 Cu, 0.04 O_2	1083	1981	100	F	F	NR
Deoxidized coppers								
C12000	Phosphorus-deoxidized copper, low-P	99.9 Cu, 0.008 P	1083	1981	99	E	E	NR
C12200	Phosphorus-deoxidized copper, high-P	99.9 Cu, 0.02 P	1083	1981	87	E	E	NR
Beryllium coppers								
C17000	High-strength beryllium copper	98.3 Cu, 1.7 Be	982	1800	27–33(c)	G	G	G
C17200	High-strength beryllium copper	98.1 Cu, 1.9 Be	982	1800	27–33(c)	G	G	G
C17500	High-conductivity beryllium copper	96.9 Cu, 0.6 Be, 2.5 Co	1068	1955	53–66(c)	F	F	F
Low-zinc brasses								
C21000	Gilding	95 Cu, 5 Zn	1065	1950	60	G	G	NR
C22000	Commercial bronze	90 Cu, 10 Zn	1043	1910	48	G	G	NR
C23000	Red brass	85 Cu, 15 Zn	1026	1880	41	G	G	NR
C24000	Low brass	80 Cu, 20 Zn	999	1830	36	G	G	NR
High-zinc brasses								
C26000	Cartridge brass	70 Cu, 30 Zn	954	1750	31	F	F	NR
C26800	Yellow brass	65 Cu, 35 Zn	932	1710	30	F	F	NR
C28000	Muntz metal	60 Cu, 40 Zn	904	1660	31	F	F	NR
Tin brasses								
C44300	Admiralty brass	71 Cu, 28 Zn, 1 Sn(d)	937	1720	28	F	F	NR
C46400	Naval brass	60 Cu, 39.25 Zn, 0.75 Sn(d)	899	1650	30	F	F	NR
Special brasses								
C67500	Manganese bronze A	58.5 Cu, 39 Zn, 1.4 Fe, 1 Sn, 0.1 Mn	888	1630	27	F	F	NR
C68700	Aluminum brass, arsenical	77.5 Cu, 20.5 Zn, 2 Al (0.06 As)	971	1780	26	F	F	NR
Nickel silvers								
C74500	Nickel silver	65 Cu, 25 Zn, 10 Ni	1021	1870	12	F	F	NR
C75200	Nickel silver	65 Cu, 17 Zn, 18 Ni	1110	2030	8	F	F	NR
C75400	Nickel silver	65 Cu, 20 Zn, 15 Ni	1076	1970	9	F	F	NR
C75700	Nickel silver	65 Cu, 23 Zn, 12 Ni	1037	1900	10	F	F	NR
C77000	Nickel silver	55 Cu, 27 Zn, 18 Ni	1054	1930	8	F	F	NR
Phosphor bronzes								
C50500	Phosphor bronze, 1.25% E	98.7 Cu, 1.3 Sn (0.2 P)	1076	1970	53	G	G	F
C51000	Phosphor bronze, 5% A	95 Cu, 5 Sn (0.2 P)	1049	1920	18	G	G	F
C52100	Phosphor bronze, 8% C	92 Cu, 8 Sn (0.2 P)	1026	1880	16	G	G	F
C52400	Phosphor bronze, 10% D	90 Cu, 10 Sn (0.2 P)	999	1830	13	G	G	F
Aluminum bronzes								
C61300	Aluminum bronze D, Sn-stabilized	89 Cu, 7 Al, 3.5 Fe (0.35 Sn)	1046	1915	14	G	E	G
C61400	Aluminum bronze D	91 Cu, 6–8 Al, 1.5–3.5 Fe, 1 max Mn	1046	1915	17	G	E	G
C63000	Aluminum bronze E	82 Cu, 10 Al, 5 Ni, 3 Fe	1054	1930	10	G	G	G
Silicon bronzes								
C65100	Low-silicon bronze B	98.5 Cu, 1.5 Si	1060	1940	15	E	E	F
C65500	High-silicon bronze A	97 Cu, 3 Si	1026	1880	9	E	E	F
Copper-nickel								
C70600	Copper nickel	88.6 Cu, 9–11 Ni, 1.4 Fe, 1.0 Mn	1149	2100	12	E	E	G
C71500	Copper nickel	70 Cu, 30 Ni	1238	1238	8	E	E	E

(a) Based on the thermal conductivity of alloy C10200 (2553.8 kJ/m^2 in meters per hour at 20 °C) as 100. For comparison, carbon steel has a thermal conductivity of 339 kJ/m^2 in meters per hour at 20 °C, which is 13 on this scale. (b) E, excellent; G, good; F, fair; NR, not recommended. (c) In the precipitation hardened condition. (d) Alloys C44300 and C46400 contain nominal 0.06% As; alloys C44400 and C46600, a nominal 0.06% Sb; alloys C44500 and C46700, a nominal 0.06% P.

Beryllium, aluminum, and nickel form tenacious oxides that must be removed prior to welding. The formation of these oxides during the welding process must be prevented by shielding gas or by fluxing, in conjunction with the use of the appropriate welding current. The oxides of nickel interfere with arc welding less than those of beryllium or aluminum. Consequently, the nickel silvers and copper-nickel alloys are less sensitive to the type of welding current used during manufacture. Beryllium-containing alloys also produce toxic fumes during welding.

Silicon has a beneficial effect on the weldability of copper-silicon alloys because of its deoxidizing and fluxing actions. The combination of this effect and the low thermal conductivity makes silicon bronzes the most weldable of the copper alloys for any arc process.

Phosphorus is beneficial to certain copper and copper alloys as a strengthener and deoxidizer. When added to brass, phosphorus inhibits dezincification corrosion. In the amounts normally present in most copper alloys, phosphorus does not adversely affect or hinder welding.

Chromium like beryllium and aluminum, can form a refractory oxide on the surface of the molten weld pool. Arc welding should be done in an inert protective atmosphere to prevent formation of chromium oxides.

Cadmium has no serious effect on the weldability of copper. However, the low boiling temperature of cadmium does result in evaporation of this alloy at welding temperatures, thereby creating a potential health hazard. Cadmium will also form an oxide in the molten weld metal, but the oxide can be easily reduced by fluxing agents.

Oxygen can cause porosity and reduce the strength of welds made in certain copper alloys that do not contain sufficient quantities of phosphorus or other deoxidizers. Oxygen may be found as a free gas or as cuprous oxide. Most commonly welded copper alloys contain deoxidizing elements—usually phosphorus, silicon, aluminum, iron, or manganese. These elements will readily combine with oxygen and eliminate the potential for porosity. The same deoxidizers are also included in the filler metals. The soundness and strength of arc welds made in commercial coppers depend upon the cuprous oxide content. As the oxide content decreases, weld soundness increases. Deoxidized coppers provide the best results because they are free from cuprous oxides and contain residual amounts of phosphorus.

Iron and manganese do not significantly affect the weldability of the alloys that contain them. Iron is typically present in some special brasses, aluminum bronzes, and copper-nickel alloys in amounts of 1.4 to 3.5%. Manganese is commonly used in these same alloys, but at lower concentrations than iron.

Free-Machining Additives. Lead, selenium, tellurium, and sulfur are added to copper alloys to improve machinability. Bismuth (or bismuth plus selenium) is also used for this purpose as well when lead-free alloys are desired. These minor alloying agents, while improving machinability, adversely affect the weldability of copper alloys by rendering the alloys hot-crack susceptible. The adverse effect on weldability begins to be evident at about 0.05% of the additive and is more severe with larger concentrations. Lead is the most harmful of the alloying agents with respect to hot-crack susceptibility. However, alloys that contain 0.5 to 4% Pb are not recommended for welding, as indicated in Table 1, and are not included in Table 2.

Factors Affecting Weldability

Besides the alloying elements that comprise a specific copper alloy, several other factors affect weldability. These factors are the thermal conductivity of the alloy being welded, the shielding gas, the type of current used during welding, the joint design, the welding position, and the surface condition and cleanliness. The effects of the shielding gas, type of current, and joint design used during welding are discussed under the sections for each individual process and alloy, described later in this article.

Effect of Thermal Conductivity. The behavior of copper and copper alloys during welding is strongly influenced by the thermal conductivity of the alloy. Table 2 shows the relative thermal conductivities based on the conductivity of alloy C10200 (oxygen-free copper). As shown in Table 2, the thermal conductivity varies greatly from this baseline value, which is 339 kJ/m^2 in meters per hour at 20 °C (226 Btu/ft^2 in feet per hour at 68 °F). The range is from 100 for alloys C10200 and C11000 to lows of 8 to 12 for nickel silvers and copper-nickel alloys and 9 for alloy C65500. In comparison, carbon steel has a thermal conductivity of 13 on this scale.

When welding commercial coppers and lightly alloyed copper materials with high thermal conductivities, the type of current and shielding gas must be selected to provide maximum heat input to the joint. This high heat input counteracts the rapid heat dissipation away from the localized weld zone. Depending on section thickness, preheating may be required for copper alloys with lower thermal conductivities. The interpass temperature should be the same as for preheating. Copper alloys are not postweld heat treated as frequently as steels, but some alloys may require controlled cooling rates to minimize residual stresses and hot shortness.

Welding Position. Due to the highly fluid nature of copper and its alloys, the flat position is used whenever possible for welding. The horizontal position is used in some fillet welding of corner joints and T-joints.

Vertical and overhead positions and the horizontal position are less frequently used in welding butt joints. These positions are ordinarily restricted to GTAW, GMAW, and PAW of the less conductive aluminum bronzes, silicon bronzes, and copper-nickel alloys. Small-diameter electrodes and filler-metal wires are used in conjunction with low welding currents for out-of-position welding. Current pulsation is used with GTAW, GMAW, and PAW to control weld pool fluidity.

When using SMAW, out-of-position welding is usually limited to the joining of aluminum bronzes and copper-nickel alloys, but it can also be done on some phosphor bronzes and silicon bronzes.

Precipitation-Hardenable Alloys. The most important precipitation-hardening reactions are obtained with beryllium, chromium, boron, nickel, silicon, and zirconium. Care must be taken when welding precipitation-hardenable copper alloys to avoid oxidation and incomplete fusion. Whenever possible, the components should be welded in the annealed condition, and then the weldment should be given a precipitation-hardening heat treatment.

Hot Cracking. Copper alloys, such as copper-tin and copper-nickel, are susceptible to hot cracking at solidification temperatures. This characteristic is exhibited in all copper alloys with a wide liquidus-to-solidus temperature range. Severe shrinkage stresses produce interdendritic separation during metal solidification. Hot cracking can be minimized by reducing restraint during welding, preheating to slow the cooling rate and reduce the magnitude of welding stresses, and reducing the size of the root opening and increasing the size of the root pass.

Porosity. Certain elements (for example, zinc, cadmium, and phosphorus) have low boiling points. Vaporization of these elements during welding may result in porosity. When welding copper alloys containing these elements, porosity can be minimized by fast weld speeds and a filler metal low in these elements.

Surface Condition. Grease and oxide on work surfaces should be removed before welding. Wire brushing or bright dipping can be used. Millscale on the surfaces of aluminum bronzes and silicon bronzes is removed for a distance from the weld region of at least 12.7 mm (0.5, or $\frac{1}{2}$ in.), usually by mechanical means. Grease, paint, crayon marks, shop dirt, and similar contaminants on copper-nickel alloys may cause embrittlement and should be removed before welding. Millscale on copper-nickel alloys must be removed by grinding or pickling; wire brushing is not effective.

Arc Welding Processes

Copper and most copper alloys can be joined by arc welding. The commercial alloys that are readily arc welded are listed in Table 2. Welding processes that use gas shielding are generally preferred, although SMAW can be used for many noncritical applications.

Argon, helium, or mixtures of the two are used as shielding gases for GTAW, PAW, and GMAW. Generally, argon is used when manually welding material that is less than 3.2 mm (0.13, or $\frac{1}{8}$ in.) thick, has low thermal conductivity, or both. Helium or a mixture of 75% helium and 25% argon is recommended for machine welding of thin sections and for manual welding of thicker sections of alloys that have high thermal conductivity. Small amounts of nitrogen can be added to the argon shielding gas to increase the effective heat input.

Shielded metal arc welding can be used to weld a wide range of thicknesses of copper alloys. Covered electrodes for SMAW of copper alloys are available in standard sizes ranging from 2.4 to 4.8 mm ($\frac{3}{32}$ to $\frac{3}{16}$ in.). Other sizes are available in certain electrode classifications, and the reader is referred to American National Standards Institute/American Welding Society (ANSI/AWS) A5.6 "Specification for Covered Copper and Copper Alloy Arc Welding Electrodes."

Higher thermal conductivity and thermal expansion of copper and copper alloys result in greater weld distortion than in comparable steel welds. The use of preheat, fixtures, proper welding sequence, and tack welds can minimize distortion or warping.

Gas Tungsten Arc Welding

Gas tungsten arc welding is well suited for copper and copper alloys because of its intense arc, which produces an extremely high temperature at the joint and a narrow heat-affected zone (HAZ). In welding copper and the more thermally conductive copper alloys, the intensity of the arc is important in completing fusion with minimum heating of the surrounding, highly conductive base metal. A narrow HAZ is particularly desirable in the welding of copper alloys that have been precipitation-hardened.

The most frequent use of GTAW for copper and copper alloys is on sections up to 3.2 mm (0.13, or $\frac{1}{8}$ in.) thick that have been prepared with a square edge. Often no filler metal is used in joining these thicknesses. Filler metal is usually required in GTAW of sections thicker than 3.2 mm (0.13, or $\frac{1}{8}$ in.). Gas tungsten arc welding of sections thicker than 12.7 mm (0.5, or $\frac{1}{2}$ in.) is performed only if GMAW equipment is not available or if special conditions exist. These conditions would include hot shortness of the base metal or adjacent heat-sensitive features that make it necessary to limit the heat input to the base material. Under certain conditions, pulsed GMAW would be the preferred process.

Type of Current. Direct current electrode negative (DCEN) is used for GTAW of most copper and copper alloys. This permits the use of an electrode that has a minimum diameter for a given welding current and that provides maximum penetration of the base material. Alternating current stabilized by high frequency is used on beryllium coppers and aluminum bronzes to prevent the buildup of tenacious oxide film on the base metals.

Electrodes. Many of the standard tungsten or alloyed tungsten electrodes can be used in GTAW of copper and copper alloys. The selection factors normally considered for tungsten electrodes apply in general to the copper and copper alloys. Except as noted for the specific classes of copper alloys, thoriated tungsten (usually EWTh-2) is preferred for its better performance, longer life, and greater resistance to contamination.

Gas Metal Arc Welding

Gas metal arc welding is used to join all of the coppers and copper alloys listed previously in Table 2. Gas tungsten arc welding is preferred for thicknesses less than 3.2 mm (0.13, or $\frac{1}{8}$ in.), while GMAW is preferred for section thicknesses above 3.2 mm (0.13, or $\frac{1}{8}$ in.) and for the joining of aluminum bronzes, silicon bronzes, and copper-nickel alloys.

The major application of GMAW of copper alloys is in the joining of material thicknesses between 3.2 and 12.7 mm (0.13 and 0.5, or $\frac{1}{8}$ and $\frac{1}{2}$ in.) thick, and the process is almost invariably selected for arc welding sections of copper alloys thicker than 12.7 mm (0.5, or $\frac{1}{2}$ in.). The high deposition rate for GMAW is a major advantage in this application when compared to GTAW or SMAW. The greater heat input to the weld, compared with that for GTAW, is a disadvantage in some applications due to the formation of a wider HAZ.

Direct current electrode positive (DCEP) is used exclusively for GMAW of copper alloys. Typically, argon is used as a shielding gas. Helium or mixtures of argon and helium are often used when hotter arc voltages are needed with standard operating current levels. A square-groove joint is not ordinarily used for welding thicknesses greater than 3.2 mm (0.13, or $\frac{1}{8}$ in.), except for coppers. Single-V-grooves are used for thicknesses of 3.2 to 12.7 mm (0.13 to 0.5, or $\frac{1}{8}$ to $\frac{1}{2}$ in.). When section thicknesses exceed 12.7 mm (0.5, or $\frac{1}{2}$ in.), double-V-grooves or double-U-grooves are used as joint preparations.

Welding Position. Most GMAW of copper alloys is done in the flat position with spray transfer; fillet welds acceptable for many applications can be produced in a horizontal position. Gas metal arc welding is preferred to GTAW or SMAW when weld positions other than flat are required. Out-of-position welding is usually restricted to the less-fluid copper alloys, such as aluminum bronzes, silicon bronzes, and copper-nickel alloys. Small-diameter filler metals and low welding currents are preferred for such applications, and a globular or short-circuiting transfer is ordinarily used. The development of pulsed spray transfer has been quite advantageous for welding of coppers and copper alloys. Small- to medium-diameter wires can be readily used out-of-position for vertical and overhead welding of most alloys.

Shielded Metal Arc Welding

When compared with SMAW of low-carbon steels, SMAW of copper and copper alloys uses larger root openings, wider groove angles, more tack welds, higher preheat and interpass temperatures, and higher welding currents. Welding of coppers and copper alloys using SMAW is almost always restricted to flat-position welding. Out-of-position welding using this process is usually limited to the joining of phosphor bronzes and copper-nickel alloys.

Plasma Arc Welding

The welding of coppers and copper alloys using PAW is comparable to GTAW of these alloys. Argon, helium, or mixtures of the two are used for the welding of all alloys. Hydrogen gas should never be used when welding coppers. Plasma arc welding has two distinct advantages over GTAW: (1) the tungsten is concealed and entirely shielded, which greatly reduces contamination of the electrode, particularly for alloys with low-boiling-temperature constituents such as brasses, bronzes, phosphor bronzes, and aluminum bronzes; and (2) the constricted arc plume gives rise to higher arc energies while minimizing the growth of the HAZ. As with GTAW, current pulsation and current ramping may also be used. Plasma arc welding equipment has been miniaturized for intricate work, known as microplasma welding.

Plasma arc welding of coppers and copper alloys may be performed either autogenously or with filler metal. Filler metal selection is identical to that outlined for GTAW. Automation and mechanization of this process is readily performed and is preferable to GTAW where contamination can restrict production efficiencies. Welding positions for PAW are identical to those for GTAW. However, the plasma keyhole mode has been evaluated for thicker sections in a vertical-up position. Generally, all information presented for GTAW is applicable to PAW.

Submerged Arc Welding

The welding of thick gage material, such as seamed pipe formed from heavy plate, can be achieved by continuous metal-arc operation under a granular flux. Effective deoxidation and slag-metal reactions to form the required weld-metal composition are critical, and the SAW process is still under development for copper-base materials. A variation on this process can be used for weld cladding or hardfacing. Promising results have been seen with the copper-nickel alloys for section thicknesses greater than 12.7 mm (0.5, or $\frac{1}{2}$ in.). V-groove and U-groove joint designs similar to those used in GMAW are satisfactory.

Commercially available fluxes should be used for the copper-nickel alloys. Welding conditions, which are greatly dependent upon the flux used, are provided by the flux manufacturer. Special attention should be given to the weld bead sequence when multi-pass welds are deposited, to ensure complete fusion while maintaining proper bead contour. X-ray quality results can be obtained when the technique is correctly performed.

Filler Metals

Both covered electrodes and bare electrode wire and rods are available for welding copper and copper alloys. Tables 3, 4, and 5 list the various American Welding Society (AWS) classifications for the filler metals for GTAW, GMAW, and SMAW, respectively.

Copper Filler Metals. The electrodes and rods used to weld the coppers, primarily deoxidized and electrolytic tough pitch (ETP) coppers, are designated as ERCu and have a minimum copper content of 98%. These filler metals, which can be used with GMAW, GTAW, and PAW processes, have electrical conductivity ratings of 25 to 40% International Annealed Copper Standard (IACS).

The covered electrodes used for SMAW are designated as ECu. These are normally used with DCEP. Compared to carbon steel electrodes of the same diameter, the required welding current for ECu electrodes is typically 30 to 40% greater.

Copper-Zinc Filler Metals. Copper-zinc (brass) weld rods are available in three classifications: RBCuZn-A (Naval Brass), RCuZn-B (Low-Fuming Brass), and RCuZn-C (Low-Fuming Brass). These particular welding rods are used for braze welding of copper, bronze, and nickel alloys. Their electrical conductivity is about 25% IACS; thermal-conductivity values are about 30% of those of copper.

Copper-zinc filler metals cannot be used as electrodes for the arc welding processes. The high zinc content tends to become volatile during arc welding and boils from the molten weld pool. This boiling of the low-melting-temperature constituents results in a porous weld.

Copper-Tin Filler Metals. The copper-tin (phosphor bronze) welding electrodes and rods are designated as ECuSn-A, ERCuSn-A, and ECuSn-C. The ECuSn-A and ECuSn-C electrodes contain approximately 5 and 8% Sn, respectively. Phosphorus is used as a deoxidizer for both electrodes. These electrodes are suitable for welding bronze, brass, and copper if the presence of tin in the weld metal is not objectionable. These filler metals are also commonly used for repair welding of castings. Greater weld-metal strength and hardness are obtained with the ECuSn-C electrodes than with the ECuSn-A electrodes.

The ERCuSn-A rods can be used with GTAW and PAW for joining phosphor bronzes. Preheat temperatures of about 200 °C (400 °F) are required when welding with these electrodes, particularly for heavy sections.

Copper-Silicon Filler Metals. Copper-silicon (silicon bronze) electrodes are used in bare-wire form for GMAW, GTAW, PAW, and sometimes for oxyfuel welding. The designation for these electrodes is ERCuSi-A. Chemical compositions contain between 2.8 and 4.0% Si with approximately 1.5% Mn, 1.0% Sn, and 1.0% Zn. These filler metals are frequently used to weld silicon bronzes and brasses. They are also used for braze welding of galvanized steel. The electrical conductivity is about 6.5% IACS, and the thermal conductivity is approximately 8.4% of that of copper. The covered electrodes in this filler metal classification are designated as ECuSi and are used primarily for welding copper-zinc alloys with the DCEP setting. The covered electrode can also be used for welding of silicon bronze, copper, and galvanized steel. Weld-metal mechanical properties are slightly higher than those of silicon bronze base metal.

Copper-Aluminum Filler Metals. There are a number of copper-aluminum (aluminum bronze) filler metals for both hardfacing and joining applications. The first of these is designated as ERCuAl-A1 and is an iron-free aluminum bronze. It is used as a surfacing alloy for wear-resistant surfaces with relatively light loads and for resistance to corrosive media, such as salt water and some commonly used acids. This alloy is not recommended for joining applications. Another hardfacing filler metal is ECuAl-B, which is a covered electrode containing 7.5 to 10% Al. These electrodes are used for surfacing applications and repair welding of aluminum bronze castings with similar compositions.

The covered electrodes for SMAW are designated as ECuAl-A2 and contain from 6.5 to 9% Al. The bare-wire electrodes for GTAW, GMAW, and PAW contain from 8.5 to 11% Al and are designated as ERCuAl-A2. This electrode has a higher strength than the covered electrode. Both filler metals can be used for joining aluminum bronzes, silicon bronzes, copper-nickel alloys, copper-zinc alloys, manganese bronzes, and many combinations of dissimilar metals.

ERCuAl-A3 electrodes and rods are used for repair welding of aluminum bronze castings using GMAW and GTAW. The high aluminum content produces welds with less tendency to crack in highly stressed cross sections.

Repair of both wrought and cast aluminum bronze materials containing nickel can be performed with copper-nickel-aluminum electrodes and bare wire. The designations for these metals are ECuNiAl and ERCuNiAl. These electrodes offer good corrosion resistance as well as good cavitation resistance in both salt water and brackish water.

Joining of manganese-nickel-aluminum bronzes is performed with covered electrodes, designated as ECuMnNiAl, and bare filler metals, designated

Table 3 Filler metals for GTAW of copper and copper alloys

Filler metal	AWS classification	Principle constituents(a)
Copper	ERCu	98.0 min Cu + Ag, 1.0 Sn, 0.5 Mn, 0.50 Si, 0.15 P
Phosphor bronze	ERCuSn-A	93.5 min Cu + Ag, 4.0–6.0 Sn, 0.10–0.35 P
Aluminum bronze	ERCuAl-A2	1.5 Fe, 9.0–11.0 Al, bal Cu + Ag
Aluminum bronze	ERCuAl-A3	3.0–4.25 Fe, 11.0–12.0 Al, bal Cu + Ag
Silicon bronze	ERCuSi-A	2.8–4.0 Si, 1.5 Zn, 1.5 Sn, 1.5 Mn, 0.5 Fe
Copper-nickel	ERCuNi	1.00 Mn, 0.40–0.70 Fe, 29.0–32.0 Ni + Co, 0.20–0.50 Ti, bal Cu + Ag

Note: These data are based on AWS A5.27, A5.6, and A5.7; see current editions of those specifications for complete compositions and qualifications. (a) Single percentages are maximums unless otherwise stated. Optional elements and impurities have been omitted.

Table 4 Filler metals for GMAW of copper and copper alloys

Electrode designation(a)	Common name	Base-metal applications
ERCu	Copper	Coppers
ERCuSi-A	Silicon bronze	Silicon bronzes, brasses
ERCuSn-A	Phosphor bronze	Phosphor bronzes, brasses
ERCuNi	Copper-nickel	Copper-nickel alloys
ERCuAl-A2	Aluminum bronze	Aluminum bronzes, brasses, silicon bronzes, manganese bronzes
ERCuAl-A3	Aluminum bronze	Aluminum bronzes
ERCuNiAl	…	Nickel-aluminum bronzes
ERCuMnNiAl	…	Manganese-nickel-aluminum bronzes
RBCuZn-A	Naval brass	Brasses, copper
RCuZn-B	Low-fuming brass	Brasses, manganese bronzes
RCuZn-C	Low-fuming brass	Brasses, manganese bronzes

(a) See the most recent edition of AWS A5.7, "Specification for Copper and Copper Alloy Bare Welding Rods and Electrodes," or AWS A5.27, "Specification for Copper and Copper Alloy Gas Welding Rods."

Table 5 Filler metal for SMAW of copper and copper alloys

Covered electrode(a)	Common name	Base-metal applications
ECu	Copper	Coppers
ECuSi	Silicon bronze	Silicon bronzes, brasses
ECuSn-A, ECuSn-C	Phosphor bronze	Phosphor bronzes. brasses
ECuNi	Copper-nickel	Copper-nickel alloys
ECuAl-A2	Aluminum bronze	Aluminum bronzes, brasses, silicon bronzes, manganese bronzes
ECuAl-B	Aluminum bronze	Aluminum bronzes
ECuNiAl	…	Nickel-aluminum bronzes
ECuMnNiAl	…	Manganese-nickel-aluminum bronzes

(a) See the most recent edition of AWS A5.6, "Specification for Covered Copper and Copper Alloy Arc Welding Electrodes."

as ERCuMnNiAl. Like the copper-nickel-aluminum electrodes, these electrodes have good resistance to cavitation, erosion, and corrosion.

Copper-Nickel Filler Metals. Covered electrodes for this classification are designated as ECuNi, and bare electrode wire and rods are designated as ERCuNi. The nominal compositions are 70% Cu and 30% Ni. Titanium is used as a deoxidizer in these filler metals, which are used for the joining of copper-nickel alloys.

Welding of Coppers

As indicated in Table 2, coppers include oxygen-free, ETP, and deoxidized grades that contain ≥99% Cu (UNS Numbers C10100 to C15760). The coppers are welded using GTAW, GMAW, and SMAW. Additional information on the properties and applications of coppers can be found in the articles "Wrought Copper and Copper Alloys" and "Properties of Wrought Copper and Copper Alloys" in this Handbook.

Gas Tungsten Arc Welding

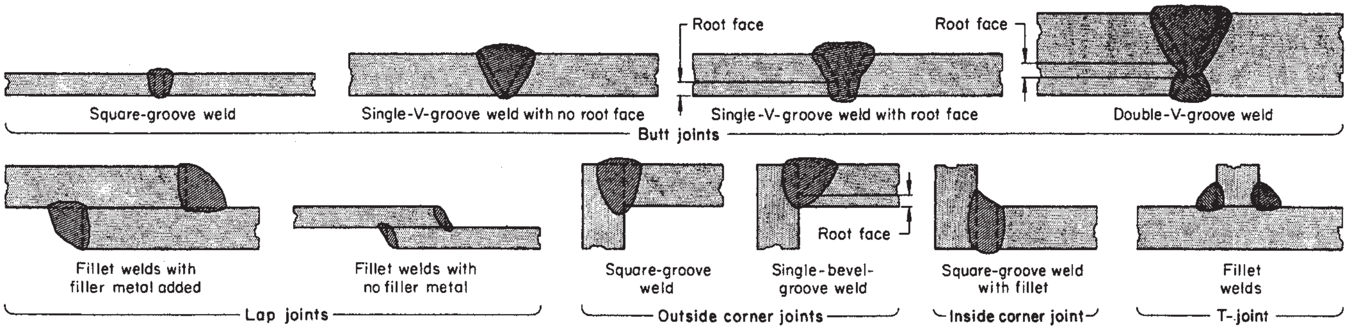
When using GTAW to join commercial coppers, weld quality will differ depending on the cuprous oxide content of the copper. The nominal welding conditions, however, for a given thickness and joint design are approximately the same. Table 6 lists several representative welding conditions for GTAW of commercial coppers.

Effect of Cuprous Oxide. Cuprous oxide may be present within the base metal or introduced through oxidation of the molten weld pool during, the arc welding process. Migration of cuprous oxides to the grain boundaries lowers the strength and ductility of the weld and adversely affects fatigue properties.

The best results in the arc welding of copper are obtained on the deoxidized coppers because these alloys are free of cuprous oxides and they contain residual phosphorus. This phosphorus combines with oxygen, which is absorbed during the heating or welding, and prevents the for-

Table 6 Nominal conditions for GTAW of commercial coppers using EWTh-2 electrodes, ERCu welding rod, and DCEN

Workpiece thickness		Root opening(a)		Electrode diameter		Welding rod diameter		Shielding gas(b)	Gas flow rate		Current, A	Travel speed		Preheat		Number of passes
mm	in.	mm	in.	mm	in.	mm	in.		L/min	ft^3/h		m/min	in./min	°C	°F	
Butt joints—square groove																
1.6	1/16	0	0	1.6	1/16	None used		Argon	7.1	15	110–114	0.30	12	None used		1
3.2	1/8	0	0	2.4	3/32	None used		Argon	7.1	15	175–225	0.28	11	None used		1
3.2	1/8	3.2	1/8	2.4	3/32	2.4	3/32	Argon	7.1	15	175–225	0.28	11	None used		1
4.8	3/16	4.8	3/16	3.2	1/8	3.2	1/8	Helium	15.0	30	190–225	0.25	10	95	200	1
Butt joints—60° single-V groove, 1.6 mm (1/16 in.) root face																
6.4	1/4	1.6	1/16	3.2	1/8	3.2	1/8	Helium	15.0	30	225–260	0.23	9	150	300	1
9.5	3/8	1.6	1/16	4.8	3/16	4.8	3/16	Helium	18.9	40	280–320	…	…	260	500	2
Butt joints—60° double-V groove, 3.2 mm (1/8 in.) root face(c)																
12.7	1/2	1.6	1/16	6.4	1/4	6.4	1/4	Helium	18.9	40	375–525	…	…	260	500	3
Lap joints—fillet welded(d)																
1.6	1/16	0	0	1.6	1/16	1.6	1/16	Argon	7.1	15	130–150	0.25	10	None used		1
3.2	1/8	0	0	2.4	3/32	3.2	1/8	Argon	7.1	15	200–250	0.23	9	None used		1
4.8	3/16	0	0	3.2	1/8	3.2	1/8	Helium	15.0	30	205–250	0.20	8	95	200	1
6.4	1/4	0	0	3.2	1/8	3.2	1/8	Helium	15.0	30	250–280	0.18	7	150	300	1
9.5	3/8	0	0	4.8	3/16	4.8	3/16	Helium	18.9	40	300–340	…	…	260	500	3
Outside corner joints—square groove																
3.2	1/8	3.2	1/8	2.4	3/32	3.2	1/8	Argon	7.1	15	170–225	0.28	11	None used		1
4.8	3/16	4.8	3/16	3.2	1/8	3.2	1/8	Helium	15.0	30	190–225	0.25	10	95	200	1
6.4	1/4	4.8	3/16	3.2	1/8	3.2	1/8	Helium	15.0	30	225–260	0.23	9	150	300	1
9.5	3/8	6.4	1/4	4.8	3/16	4.8	3/16	Helium	18.9	40	280–320	…	…	260	500	2
Outside corner joints—50° single-bevel groove, 1.6 mm (1/16 in.) root face																
4.8	3/16	1.6	1/16	3.2	1/8	3.2	1/8	Helium	15.0	30	205–250	0.20	8	95	200	1
6.4	1/4	1.6	1/16	3.2	1/8	3.2	1/8	Helium	15.0	30	250–280	0.18	7	150	300	1
9.5	3/8	1.6	1/16	4.8	3/16	4.8	3/16	Helium	18.9	40	300–340	…	…	260	500	3
Inside corner joints—square groove, fillet welded																
3.2	1/8	3.2	1/8	2.4	3/32	3.2	1/8	Argon	7.1	15	200–250	0.23	9	None used		1
T-joints—fillet welded																
3.2	1/8	1.6	1/16	2.4	3/32	3.2	1/8	Argon	7.1	15	200–250	0.23	9	None used		1
4.8	3/16	1.6	1/16	3.2	1/8	3.2	1/8	Helium	15.0	30	205–250	0.20	8	95	200	1
6.4	1/4	1.6	1/16	3.2	1/8	3.2	1/8	Helium	15.0	30	250–280	0.18	7	150	300	1
9.5	3/8	1.6	1/16	4.8	3/16	4.8	3/16	Helium	18.9	40	300–340	…	…	260	500	3



Note: The data in this table are intended to serve as starting points for the establishment of optimal joint design and conditions for welding of parts on which previous experience is lacking. They are subject to adjustments necessary to meet the special requirements of individual applications. (a) Copper, carbon, graphite, or ceramic tape backing strips or rings may be used (see text). (b) Mixtures of argon and helium are also used (see text). (c) Depth of back V is 9.5 mm (3/8 in.) of stock thickness. (d) Use of filler metal is optional for thickness of 6.4 mm (1/4 in.) or less.

mation of cuprous oxide. The strength, ductility, and porosity of welds made in alloy C10200 (oxygen-free copper) are intermediate between the same properties for welds made in deoxidized coppers (alloys C12000 and C12200) and those made in alloy C11000 (ETP copper), which contains 0.02 to 0.5% oxygen.

While cuprous oxide does have an adverse effect on the mechanical properties of coppers, weld properties of arc welded coppers containing cuprous oxide are superior to those obtained from oxyacetylene welding of oxygen-bearing coppers. Welds made by oxyfuel welding are subject to gassing and embrittlement.

Shielding Gases. Argon is the preferred shielding gas when welding copper sections up to 1.6 mm (0.06, or $^1/_{16}$ in.) thick. As sections grow thicker, slower travel speeds and higher preheat temperatures are required when using argon shielding gas. For sections in excess of 1.6 mm (0.06, or $^1/_{16}$ in.), helium is the preferred gas. The risk of oxide entrapment in the weld pool is greatly reduced when using helium. Also, compared to argon, helium provides deeper penetration or higher travel speed for the same welding current.

Mixtures of argon and helium shielding gases result in intermediate welding characteristics. For welding positions other than the flat position, a mixture of 65 to 75% He with argon provides a good balance between the penetrating effect of helium and the ease of control for argon. Gas flow rate usually ranges from 7.1 to 19 L/min (15 to 40 ft^3 /h), with higher values being used for high currents in the welding of thick sections.

Type of Current. As indicated in Table 6, DCEN is preferred for GTAW of commercial coppers.

Electrodes. In GTAW of coppers, best results for electrode life and maintenance are obtained using a thoriated tungsten electrode containing 2% thoria (EWTh-2). Proper electrode preparation for the welding of copper is usually a pointed electrode with an included angle of 60°. The tip of the point is truncated with a diameter approximately one-third the diameter of the electrode.

Welding without Filler Metal. Square-groove butt joints on copper up to 3.2 mm (0.13, or $^1/_8$ in.) thick can be gas tungsten arc welded without the use of filler metal. However, filler metal is sometimes required as thicknesses approach this value. Copper sections greater than 3.2 mm (0.13, or $^1/_8$ in.) may be gas tungsten arc welded without the use of filler metal by making two passes, one from each side.

Filler Metals. As shown in Table 6, copper sections greater than 3.2 mm (0.13, or $^1/_8$ in.) that are joined by GTAW typically require the use of filler metals. As discussed previously, the adverse effect of the formation of cuprous oxide requires that the filler metal contain a residual deoxidizer. The deleterious effect of oxygen is even more severe within the filler metal than within the base metal because the filler metal has greater exposure to welding heat.

In most cases, copper filler metal is selected that contains a maximum of 0.15% P and 0.50% Si as deoxidizers. This filler metal is known as ERCu, as shown in Table 3. Alloys such as C12000 and C12200 (deoxidized coppers) do not contain enough residual phosphorus to ensure sound welds and are not used as filler metal. The ERCu filler metal has other advantages, such as relatively high electrical conductivity (30 to 40% IACS) and good color match to the copper base metal. Any of the other filler metals listed in Table 3 can be used in GTAW of commercial coppers. Most of the alloys contain adequate amounts of deoxidizing elements such as phosphorus, silicon, iron, aluminum, or titanium. These filler metals offer the advantage of greater joint strengths, but they have lower electrical conductivity and poor color match.

Welding Technique. Either the forehand or backhand welding technique can be used when GTAW is used for coppers. Forehand welding is preferred for all welding positions. It produces a smaller and more uniform bead size than is possible with backhand welding; however, a greater number of passes may be required to fill the joint.

The weld joint should be filled using one or more stringer beads or narrow weave beads. Wide oscillation of the arc while welding should be avoided, lest the edges of the bead be intermittently exposed to the atmosphere and consequently to oxidation. The first bead should penetrate the root of the joint and be relatively thick, to provide time for deoxidation of the weld metal and to avoid cracking of the bead.

Joint Designs. Welding of butt joints with thicker cross sections requires the use of filler metal and a root opening, due to the high thermal conductivity of copper. Clearance is needed to prevent the base metal from conducting the heat away too rapidly and solidifying the filler metal, thus choking the joint before it is filled.

Because of the high fluidity of copper, backing rings or strips are ordinarily used in GTAW of butt joints. The backing rings are typically made of copper, carbon, graphite, or ceramic tape. Backing is needed both for tightly fitted butt joints used in thin metal and for loosely fitted butt joints in thick metal, to prevent the loss of the fluid weld pool. Backing may also be used when needed for this purpose with other joint geometries.

Preheating. For GTAW of sections greater than 3.2 mm (0.13, or $^1/_8$ in.), preheating of the base material is typically required to maintain the base metal at welding temperature. Without preheating, the high thermal conductivity of coppers results in excessive loss of heat away from the weld zone. The small arc that is typically used in GTAW cannot maintain sufficient welding heat in thick sections of copper, even under the most favorable conditions. Preheat temperatures are also shown in Table 6.

Deoxidized Copper. When copper weldments require the strength of the base metal, deoxidized coppers are usually used. Even with the localized heat input of GTAW, special fixturing and other welding conditions may be needed to minimize distortion, as shown in the following example.

Example 1: Redesign of Joint and Fixture to Minimize Distortion in GTAW of Alloy C12000. A wafer of nuclear fuel was encapsulated in a can and cover assembly constructed of alloy C12000 using automatic GTAW. The completed weldment is shown in Fig. l(a). As shown in detail A in Fig. 1, the can has a machined recess for the wafer and a 0.13 mm (0.005 in.) thick bottom. The can-to-cover joint had raised lips, which eliminated the need for filler metal.

The weld had to provide a hermetic seal without distortion of the assembly, including the thin can bottom that was only 4.8 mm (0.19, or $^3/_{16}$ in.) from the welded area. A mass spectrometer was used to conduct leak testing of the weldment.

The welds were made in a controlled atmosphere chamber with the can mounted in a rotating copper chill-block clamping fixture underneath a stationary electrode. Welding conditions are given in the table accompanying Fig. 1.

Originally the fixture and joint shown in Fig. 1 and detail A were used. However, at currents high enough for fusion, the welds were porous the joint leaked, and the can warped unacceptably.

The porosity that caused leaking resulted from the machining operation of the can. The lubricant was wiped under the surface of the metal by the cutting tool, and subsequent cleaning operations failed to remove it. Machining without a lubricant eliminated the difficulty. To minimize distortion, the joint and fixture were improved as follows. The square lips of the joint were chamfered (40°) to a sharp edge, as shown in detail B in Fig. 1. This was done to reduce the heat input required to make the weld. With the chamfered lips, the welding current could be lowered because a smaller mass of metal was being melted at any instant. The mass of the fixture was increased, as shown in Fig. 1(b), to increase heat withdrawal. The redesigned fixture also provided complete support for the thin can bottom against pressure during leak testing.

Before welding, the assembly was retained in the fixture, which was held by a small chuck with all of the 0.13 mm (0.005 in.) thick can bottom resting on the thick copper backing, as shown in detail B of Fig. 1. The fixture assembly was welded in a chamber that was first vacuum-purged and then filled with 100% Ar under slightly positive pressure.

The torch was rigidly mounted on a sliding base with locating stops with which the electrode tip was positioned over the seam and clamped into position. In the argon atmosphere it was not necessary to provide a shielding gas to the electrode tip or to use an electrode cup. The electrode was ground to a sharp point to reduce current flow and arc wander.

During welding, the chuck holding the fixture was rotated by a variable-speed drive. Arc stability was maintained by a superimposed high-frequency current that was continuous. Current upslope was not controlled. Two revolutions at 3.5 rev/min were used, because slight variations in pressure between the cover and the can caused variations in the thickness of the weld bead after the first revolution. The second revolution smoothed out these irregularities and ensured adequate penetration of the base metal along the circumference of the joint. After the second revolution, the current was tapered to 0 A in 5 s.

Distortion was minimized because of the low welding current, the high heat-sink efficiency, and rigid support by the fixture. Control of heat input was also helpful in preventing excessive internal gas expansion after the joint was closed.

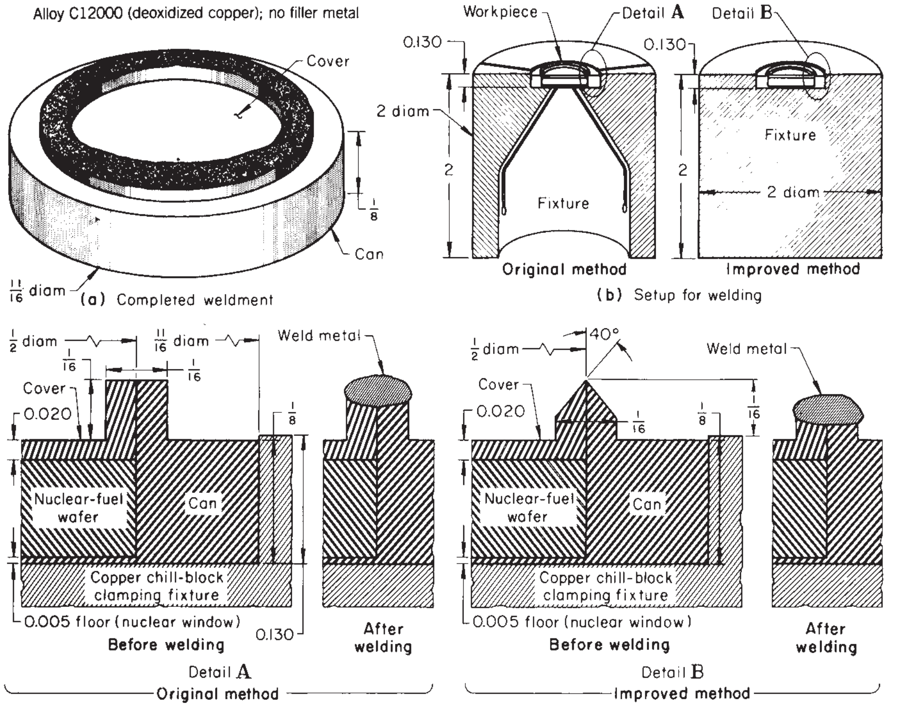
After welding, the chamber was evacuated to 1.3×10^{-4} Pa (10^{-6} torr). The interior of the can remained at approximately 0.1 MPa (15 psi). Under the pressure differential, the can, still in the fixture, was inspected for leaks by use of a mass spectrometer. The fixture supported the can bottom against internal pressure.

Oxygen-Free and ETP Coppers. Compared to GMAW or other processes with nonlocalized heat input, GTAW is preferred for the joining of either oxygen-free copper (alloy C10200) or ETP copper (alloy C11000) for thicknesses up to approximately 13 mm (0.5, or $\frac{1}{2}$ in.).

Because of the absence of a deoxidizer, gas tungsten arc welds in alloy C10200 have slightly lower strength and ductility and are slightly more porous. Gas tungsten arc welds in alloy C11000 have somewhat lower tensile strength than those in deoxidized coppers, and they are also more porous (see the subsequent discussion "Effect of Cuprous Oxide"). However, the properties of gas tungsten arc welds in ETP copper are acceptable in most applications involving welded electrical conductors, particularly when tensile strength is relatively unimportant, as in the induction-coil weldment described in the following example.

Example 2: Automatic GTAW of Joints between Alloy C11000 Bar and Tubing. A solid bar approximately 9 m (30 ft) long of alloy C11000 was gas tungsten arc welded automatically to a comparable length of tubing of the same alloy. The weldment was used in making water-cooled induction coils for low frequency (60 to 180 Hz) induction heating that required more cross-sectional area for electrical conduction than was provided by the tubular section alone. Figure 2 shows a weldment with a cross section of typical size. The 9 m (30 ft) length was standard for inductor stock. The weldment was bent into coils with an inside diameter of 100 mm (4 in.). The bar stock was located to the inside of the coil. The requirement of the joint was to maintain good electrical conductivity.

Originally, the bar and tubing were torch brazed along the entire length using a silver alloy filler metal. Not only was the filler metal expensive, but brazing was slow, requiring two operators to handle the lengths of tubing and bar. A faster and less costly method was developed by mechanizing a GTAW procedure in which no filler metal was used, thus increasing the production rate.

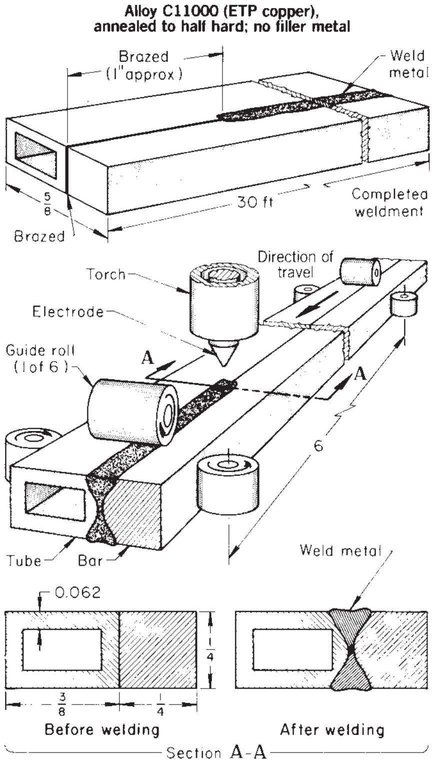


Automatic GTAW

Joint type	Circumferential edge	Current	16 A (DCEN)(c)
Weld	Edge flange	Arc starting	(d)
Power supply	250 A rectifier	Arc length	0.38 mm (0.015 in.)
Electrode	1.0 mm (0.040 in.) diam EWTh-2	Shielding gas	Argon(e)
Torch	110 A, air-cooled(a)	Welding position	Flat
Filler metal	None	Travel speed	0.14 m/min (5.5 in./s)
Fixture	(b)		

(a) Modified by elimination of ceramic cup and by use of bare connecting cable to avoid the presence of organic material in the chamber. (b) Copper chill-block clamping fixture held by a small chuck that was rotated by a variable-speed drive. (c) With continuous superimposed high-frequency current, for arc stability. (d) Superimposed high-frequency current, which was continuous as described in note (c). (e) In a vacuum-purged welding chamber, under slight positive pressure

Fig. 1 Conditions for GTAW of a nuclear fuel container. Distortion in welding was minimized by increasing the mass of the fixture to increase heat withdrawal and by chamfering joint edges to permit reduction of welding current. Dimensions in figure given in inches



Automatic GTAW

Joint type	Butt
Weld type	Square groove, zero root opening
Power supply	500 A rectifier(a)
Electrode	3.2 mm (1/8 in.) diam EWTh-2(b)
Torch	350 A, water-cooled(c)
Filler metal	None
Fixture	6 guide rolls(d)
Number of passes	2 (one per side)
Current	220 A (DCEN)
Arc starting	Torch start
Arc length	3.2 mm (1/8 in.)
Shielding gas (helium) flow rate	9.5 L/min (20 ft^3/h)
Welding position	Flat
Travel speed	0.33 m/min (13 in./min)
Cup-to-work distance	7.9 mm (5/16 in.)
Preheat/postheat	None

(a) Constant voltage. (b) Taper ground. (c) Fixed, on an adjustable mount. (d) Variable-speed drive and chain used to pull assembly through rolls

Fig. 2 Conditions for automatic GTAW of alloy C11000 tubing and bar inductor coils. The positions of the assembly, guide rolls, and torch during welding are shown.

Welding conditions for the application are given in the table accompanying Fig. 2. The fixture, designed to accommodate the sizes of inductor bar and tubing regularly used, consisted of six guide rolls, as shown in Fig. 2. These guide rolls properly aligned the assembly during welding. A chain and variable-speed drive was used to pull the assembly through the rolls during welding. Positioning of the torch over the joint was achieved by using an adjustable mount.

The first 25 mm (1 in.) of the leading edge of the joint was brazed prior to welding, to prepare the assembly for feeding through the guide rolls. The position of the assembly, guide rolls, and electrode holder during welding is shown in Fig. 2. The relative travel speed of the assembly as pulled through the rolls was 5.5 mm/s (13 in./min). A single pass was used without coolant for each side of the weldment and the ends were trimmed after welding.

The high thermal conductivity of alloy C11000 caused rapid dissipation of the heat energy. However, this difficulty was overcome without preheating by the use of helium as the shielding gas. Helium provided a hotter arc than could be obtained with argon. Thus, it was possible to produce the relatively deep, narrow beads at the stated travel speed. Oxygen from the oxide in alloy C11000 caused some porosity, but this was minimized by the fast freezing promoted by the high travel speed. The required joint properties were obtained in spite of the potential for porosity.

Gas Metal Arc Welding

As has been previously discussed, oxygen has a detrimental effect when copper is welded. The resulting porosity and reduced weld strength described for GTAW of copper are more pronounced in GMAW. This is due to the greater heat input associated with the process. Gas metal arc welds of deoxidized coppers compare favorably in density and strength with the welds made using GTAW. However, the greater heat input and lesser localization of heat obtained with GMAW result in greater porosity and lower strength in the HAZ of the welds. This is especially true in coppers that contain insufficient amounts of deoxidizer, particularly ETP copper. Consequently, GMAW has less applicability than GTAW to the welding of ETP copper, oxygen-free copper, or low-phosphorus-deoxidized copper up to approximately 13 mm (0.5, or $\frac{1}{2}$ in.) thick.

Nominal Conditions. Table 7 gives the nominal conditions for gas metal arc butt welding of copper and copper alloys. In welding joints for which the root opening is between 1.6 and 3.2 mm (0.06 and 0.13, or $\frac{1}{16}$ and $\frac{1}{8}$ in.), mixtures of helium and argon are used as shielding gas instead of pure argon. This results in lower requirements for preheat, deeper penetration into the weld joint, and higher rates of filler metal deposition.

Filler Metals (Electrode Wires). The recommended ERCu electrode contains phosphorus, tin, silicon, and manganese as deoxidizers to minimize porosity. The electrode produces sound, trouble-free welds that also provide good color match to the copper base metal and have good electrical conductivity. The ERCu electrode was used as a basis for the conditions listed in Table 7.

Copper electrodes of higher purity than ERCu are seldom used in GMAW of copper because these usually result in welds that are porous, due to the absence of deoxidizers. Most of the electrodes listed in Table 4 can be used. Any of the electrodes other than ERCu will produce dense, strong welds, but they will result in poor color match and unacceptable electrical conductivities. Filler metals should be deposited as stringer beads or narrow weave beads using the spray-transfer mode; weaving of the electrodes may result in oxidation at the edges of the weld.

Welding Technique. The forehand welding technique should be used in the flat position. For vertical-position welding, an upward progression should be utilized. Gas metal arc welding of copper is not recommended for the overhead position due to poor bead contour. The preferred process for overhead-position welding is GTAW.

Joint Design. A square-groove joint is used for the single-pass welding of coppers up to 3.2 mm (0.13, or $\frac{1}{8}$ in.) thick. A backing bar is used for zero root openings, and a grooved copper backing bar is used for root openings of 1.6 mm (0.06, or $\frac{1}{16}$ in.) maximum. The square-groove joint can also be used for one-pass-per-side welding of coppers up to 6.4 mm (0.25, or $\frac{1}{4}$ in.) thick.

Single-V-groove joints are used when welding coppers of sections above 6.4 mm (0.25, or $\frac{1}{4}$ in.). The filler metal is deposited on one side using three or more passes, and the root pass is back gouged to sound metal before the last pass is applied to the back of the joint. In some applications, the root pass is applied using GTAW and subsequent passes are completed via GMAW for rapid buildup.

If heavy sections (thicker than 12.7 mm, or 0.5 in.) are to be welded, these should be prepared with a double-V- or a double-U-groove joint. Welding is performed by applying alternating passes to opposite sides of the joint, if readily accessible, to minimize distortion. In a small, closed vessel, limited access may prevent the use of this technique, and in addition, heat buildup often prevents welding on both sides.

Preheating. Because of the high thermal conductivity of copper, sections thicker than 6.4 mm (0.25, or $\frac{1}{4}$ in.) are usually preheated. As shown in Table 7, single-V-groove joints in 6.4 mm (0.25, or $\frac{1}{4}$ in.) thick copper, welded using 1.6 mm ($\frac{1}{16}$ in.) diameter filler metal, are also preheated.

Deoxidized Coppers. Heavy-wall copper pressure vessels (up to about 40 mm, or 1.5 in., wall thickness), which are usually made from phosphorus-deoxidized copper, are frequently gas metal arc welded. Residual phosphorus helps obtain maximum weld strength while minimizing porosity. In order to meet the high heat demand in welding these heavy-walled vessels, welding currents and preheat temperatures may be higher than those shown in Table 7.

Similar operating conditions are employed in welding crucibles for arc melting of refractory metals in controlled atmospheres. These crucibles are typically heavy-wall deoxidized copper cylinders with wall thicknesses up to 32 mm (1.25 in.), diameters of 0.3 to 1.2 m (1 to 4 ft), and lengths of 1 to 7.5 m (3 to 25 ft). Formed and welded copper plate is used because seamless tubes of this size are not available. Longitudinal seams are welded, and flanges are welded to each end of the cylinders by GMAW. Such cylinders are preheated to 650 °C (1200 °F) before welding. Welding is done automatically, to avoid exposing operators to such heavy sections at elevated temperatures.

Oxygen-Free and ETP Coppers. The GMAW process is also used for welding oxygen-free copper in the production of the crucibles previously described. These crucibles are also used for arc melting of refractory metals. However, the weld properties are inferior to those produced with deoxidized copper. Because oxygen-free copper contains no residual deoxidizer, heating and welding cycles must be kept as short as possible, and gas shielding must be completely effective to avoid excessive porosity. Although the strength and soundness of welds in oxygen-bearing coppers, such as ETP copper, are substantially less than in oxygen-free copper, the reduced properties are seldom important for welds in electrical conductors. Busbars made of ETP copper are frequently joined using the GMAW process. The use of filler metals such as ERCu or another of the standard filler metals listed in Table 4 significantly lowers the electrical conductivity of the joint. In order to minimize this adverse effect, large root faces are used to increase the contact area at the joint line. For improved electrical conductivity, a filler metal with chemical composition approximately 0.75% Sn, 0.25% Si, and 0.20% Mn is sometimes used for welding ETP copper busbars.

Shielded Metal Arc Welding

Problems with porosity and low weld strength, due to oxygen content of the base metal and oxygen absorption during welding, are more severe in joining coppers by SMAW than by the gas-shielded processes. The resulting lower mechanical properties greatly limit the usefulness of weldments produced using SMAW. Additionally, electrical conductivity suffers greatly.

Welding of High-Strength Beryllium Coppers

The wrought high-strength beryllium coppers include alloys C17000 and C17200, which contain nominally 1.7 and 1.9% Be, respectively, and up to 0.25% Co. A free-machining grade version of C17200 is available that is modified with a small lead addition, but this grade is not recommended for welding. The high-strength beryllium coppers are joined by GTAW and GMAW. Additional

Table 7 Nominal conditions for gas metal arc butt welding of commercial coppers and copper alloys

Weld types for butt joints, as described	Workpiece thickness(a)		Root face		Root opening(b)		Electrode type	Electrode diameter		Shielding gas(c)	Gas flow rate		Current (DCEP), A	Voltage, V	Travel speed		Preheat temperature		Number of passes
	mm	in.	mm	in.	mm	in.		mm	in.		L/min	ft^3/h			m/min	in./min	°C	°F	
Commercial coppers																			
Square groove(b)	3.2	1/8	3.2	1/8	0	0	ERCu	1.6	1/16	Argon	15	30	310	27	0.76	30	None used		1
Square groove(c)	3.2	1/8	3.2	1/8	0–1.6	0–1/16	ERCu	1.6	1/16	Argon(d)	15–16.5	30–35	325–350	28–33	…	…	None used		1
Square groove	6.4	1/4	6.4	1/4	0	0	ERCu	2.4	3/32	Argon	15	30	460	26	0.50	20	95	200	2
	6.4	1/4	6.4	1/4	0	0	ERCu	2.4	3/32	Argon	15	30	500	27	0.50	20	95	200	1
75–90° single-V-groove(c)	6.4	1/4	3.2	1/8	0–3.2	0–1/8	ERCu	1.6	1/16	Argon(d)	15–16.5	30–35	400–425	32–36	…	…	200–260	400–500	2
	12.7	1/2	0–3.2	0–1/8	0–3.2	0–1/8	ERCu	1.6	1/16	Argon(d)	15–16.5	30–35	425–450	35–40	…	…	425–480	800–900	4
90° single-V-groove(c)	9.5	3/8	4.8	3/16	0	0	ERCu	2.4	3/32	Argon	15	30	500	27	0.35	14	200	400	(e)
	9.5	3/8	4.8	3/16	0	0	ERCu	2.4	3/32	Argon	15	30	550	27	0.35	14	200	400	(e)
	12.7	1/2	6.4	1/4	0	0	ERCu	2.4	3/32	Argon	15	30	540	27	0.30	12	200	400	(e)
	12.7	1/2	6.4	1/4	0	0	ERCu	2.4	3/32	Argon	15	30	600	27	0.25	10	200	400	(e)
Alloys C17000 and C17200 (high-strength beryllium coppers)(f)																			
90° single-V-groove	6.4–9.5	1/4–1/2	0.8–1.6	1/32–1/16	…	…	Alloy C17000, C17500	1.2	0.045	Ar/He	21	45	175–200	…	…	…	150–200	300–400	3–4(g)
30° double-U-groove(h)	19–38.1	3/4–1/2	1.6	1/16	…	…	Alloy C17000, C17500	1.6	1/16	Ar/He	28	60	325–350	…	…	…	150–200	300–400	10–20(i)
Alloy C17500 (high-conductivity beryllium coppers)(f)																			
90° single-V-groove	6.4–9.5	1/4–1/2	0.8	1/32	…	…	Alloy C17500	1.2	0.045	Ar/He	15	30	200–240	…	…	…	315	600	3–4(j)
	19.0	3/4	0.8	1/32	…	…	Alloy C17500	1.2	0.045	Ar/He	15	30	200–240	…	…	…	480	900	6(j)
Low-zinc brasses																			
Square groove(c)	3.2	1/8	3.2	1/8	0	0	ERCuSi-A	1.6	1/16	Argon	15	30	275–285	25–28	…	…	None used		1
	3.2	1/8	3.2	1/8	0	0	ERCuSi-A	1.6	1/16	Helium	16.5	35	275–285	25–28	…	…	None used		1
60° single-V-groove(c)	9.5	3/8	0	0	3.2	1/8	ERCuSi-A	1.6	1/16	Argon	15	30	275–285	25–28	…	…	None used		2
	12.7	1/2	0	0	3.2	1/8	ERCuSi-A	1.6	1/16	Argon	15	30	275–285	25–28	…	…	None used		4
70° single-V-groove(c)	9.5	3/8	0	0	3.2	1/8	ERCuSi-A	1.6	1/16	Helium	16.5	35	275–285	25–28	…	…	260(k)	500(k)	2
	12.7	1/2	0	0	3.2	1/8	ERCuSi-A	1.6	1/16	Argon	15	30	275–285	25–28	…	…	260(k)	500(k)	4
High-zinc brasses, tin brasses, special brasses, nickel silvers																			
Square groove(c)	3.2	1/8	3.2	1/8	0	0	ERCuSn-A	1.6	1/16	Argon	15	30	275–285	25–28	…	…	None used		1
70° single-V-groove(c)	9.5	3/8	0	0	3.2	1/8	ERCuSn-A	1.6	1/16	Argon	15	30	275–285	25–28	…	…	None used		2
	12.7	1/2	0	0	3.2	1/8	ERCuSn-A	1.6	1/16	Argon	15	30	275–285	25–28	…	…	None used		4
Phosphor bronzes(l)																			
90° single-V-groove(c)	9.5	3/8	0	0	3.2	1/8	ERCuSn-A	1.6	1/16	Helium	16.5	35	275–285	25–28	…	…	95–150	200–300	3–4(m)
	12.7	1/2	0	0	3.2	1/8	ERCuSn-A	1.6	1/16	Helium	16.5	35	275–285	25–28	…	…	175–200	350–400	5–6(m)
Aluminum bronzes(n)																			
Square groove(o)	3.2	1/8	3.2	1/8	0	0	ERCuAl-A2	1.6	1/16	Argon	15	30	280–290	27–30	…	…	None used		1
60–70° single-V-groove(c)	9.5	3/8	0	0	3.2	1/8	ERCuAl-A2	1.6	1/16	Argon	15	30	280–290	27–30	…	…	None used		2
	12.7	1/2	0	0	3.2	1/8	ERCuAl-A2	1.6	1/16	Argon	15	30	280–290	27–30	…	…	None used		3
Silicon bronzes(p)																			
Square groove(q)	3.2	1/8	3.2	1/8	0	0	ERCuSi-A	1.6	1/16	Argon	15	30	260–270	27–30	…	…	None used		1
70° single-V-groove(c)	9.5	3/8	0	0	3.2	1/8	ERCuSi-A	1.6	1/16	Argon	15	30	260–270	27–30	…	…	None used		2
	12.7	1/2	0	0	3.2	1/8	ERCuSi-A	1.6	1/16	Argon	15	30	260–270	27–30	…	…	None used		3
Copper nickels																			
Square groove(c)	3.2	1/8	3.2	1/8	0	0	ERCuNi	1.6	1/16	Argon	15	30	280	27–30	…	…	None used		1
60° single-V-groove(c)	9.5	3/8	0	0	3.2	1/8	ERCuNi	1.6	1/16	Argon	15	30	280	27–30	…	…	None used		2
	12.7	1/2	0	0	3.2	1/8	ERCuNi	1.6	1/16	Argon	15	30	280	27–30	…	…	None used		4

Note: The data in this table are intended to serve as starting points for the establishment of optimal joint design and conditions for welding of parts on which previous experience is lacking. They are subject to adjustments necessary to meet the special requirements of individual applications. (a) Thicknesses up to 38.1 mm (1 1/2 in.) are sometimes welded by use of slightly higher current and lower travel speed than shown for a thickness of 12.7 mm (1/2 in.). (b) Copper backing. (c) Grooved copper backing. (d) Or 75Ar-25He. (e) Special welding sequence is used (see text). (f) See Table 2 for compositions. (g) The final pass is made on the root side after back chipping. Wire brush after each pass. (h) Similar to the double-V-groove weld, but with a groove radius of 9.5 mm (3/8 in.). (i) Several passes are made on the face side, then several on the back side, until the weld is completed. Back chip the root pass before making the first pass on the back side. Wire brush after each pass. (j) The final pass is made on the root side after back chipping. (k) Should not be overheated; as little preheat as possible should be used. (l) Welding conditions based on alloys C51000, C52100, and C52400; current is increased or speed is decreased for alloy C50500. (m) Hot peening between passes is recommended for maximum strength. (n) Slight preheat may be needed on heavy sections; interpass temperature should not exceed 315 °C (600 °F). (o) With aluminum bronze backing. (p) No preheat is used on any thickness; interpass temperature should not exceed 95 °C (200 °F). (q) With silicon bronze backing

Table 8 Nominal conditions for GTAW of beryllium coppers

For butt joints having zero root openings; welding with a zirconiated tungsten electrode, filler metal of the same composition as the base metal, argon-helium gas at 12 L/min (25 ft^3/h)

Workpiece thickness			Electrode diameter			Travel speed		Preheat temperature		
mm	in.	Butt-joint groove	mm	in.	Current(a), A	m/min	in./min	°C	°F	Number of passes
Alloy C17500 (high-conductivity beryllium copper)(b)										
0–2.4	0–3/32	Square	2.4	3/32	150	0.13–0.25	5–10	None used		1
2.4–3.2	3/32–1/8	90° single-V(c)	4.8	3/16	250	0.13–0.25	5–10	None used		1–2
6.4	1/4	90° single-V(c)	4.8	3/16	250	0.13–0.25	5–10	425	800	4–5
Alloys C17000 and C17200 (high-strength beryllium coppers)(b)										
0–2.4	0–3/32	Square	2.4	3/32	150	0.13–0.25	5–10	None used		1
2.4–3.2	3/32–1/8	90° single-V(c)	2.4	3/32	180	0.13–0.25	5–10	None used		1
6.4–12.7(d)	1/4–1/2(d)	90° single-V(c)	4.8	3/16	250	0.13–0.25	5–10	150	300	3–4
12.7(d)	1/2(d)	90° single-V(c)	4.8	3/16	250	0.13–0.25	5–10	200	400	5–8

Note: The data in this table are intended to serve as starting points for the establishment of optimal joint design and conditions for welding of parts on which previous experience is lacking. They are subject to adjustments necessary to meet the special requirements of individual applications. (a) High-frequency-stabilized alternating current is preferred; DCEN, with a thoriated tungsten electrode, is suitable under some conditions (see text). (b) For composition, see Table 2. (c) Maximum root face is 1.6 mm (1/16 in.). (d) Gas tungsten arc welding is used on these thicknesses only when GMAW cannot be used.

Table 9 Three applications of GTAW of high-strength beryllium coppers

	Pressure vessel (Example 3)	Generator liner (Example 4)	Cover to housing (Example 5)
Alloy	C17000	C17000 to C17200	Cast Be-Cu (1.7% Be) to C17000
Size of workpiece	483 mm diam by 1016 mm (19 in. diam by 40 in.)	495 mm diam by 1219 mm (19.5 in. diam by 48 in.)	295 mm (11.6 in.)
Thickness of work metal	19 mm (3/4 in.)	(a)	1.6 mm (1/16 in.)
Filler metal	1.6 mm (1/16 in.) diam alloy C17200	None	None
Current, A	100–150 DCEN	122, ac(b)	275, ac(b)
Shielding gas	Argon and helium	Argon and helium	Argon and helium
Gas flow rate	12 L/min (25 ft^3/h)	12 L/min (25 ft^3/h)	9.5 L/min (20 ft^3/h)
Travel speed	0.50 m/min (20 in./min)	0.25 m/min (10 in./min)	0.30 m/min (12 in./min)
Number of passes	10	1	1
Postweld heat	345 °C (650 °F), 3 h	None	None
Testing method	X-ray(c)	...	(d)

ac, alternating current. (a) Reinforcing rings, 40 by 32 mm (1 1/2 by 1 1/4 in.) welded to 6 by 6 mm (1/4 by 1/4 in.) longitudinal ribs. (b) High-frequency-stabilized. (c) Weld was tested by dye-penetration techniques; leak testing was by helium mass spectrometry and x-ray radiography. (d) Weld depth of 1.6 mm (1/16 in.) minimum was determined ultrasonically; weld was leak-tested by helium mass spectrometry at 76 MPa (11 ksi).

information on the properties and application of these materials can be found in the articles "Wrought Copper and Copper Alloys" and "Properties of Wrought Copper and Copper Alloys" in this Handbook.

Gas Tungsten Arc Welding

Copper alloys C17000 and C17200, high-strength beryllium coppers, are readily welded using GTAW. These alloys are more easily welded than the high-conductivity beryllium coppers, which exhibit higher melting temperature and less fluidity. Gas tungsten arc welding can be used for section thicknesses in excess of 12.7 mm (0.5 in.) when the use of the preferred GMAW process is not practical.

Nominal Conditions. Table 8 lists the suggested starting points for nominal conditions for GTAW of high-strength beryllium coppers. The shielding gas is usually a mixture of argon and helium to obtain a hot arc, smooth and spatter-free welds, and maximum electrode life.

Electrodes. The preferred electrode when using alternating current is zirconiated tungsten (EWZr); noncritical applications can use the more economical pure tungsten (EWP). For DCEN, the thoriated electrodes (such as EWTh–2) are preferred.

Filler Metals. The addition of filler metals is almost always required to provide proper fill for the joint or to provide joint reinforcement in a V-groove weld. This is due to the high concern for strength when welding these alloys. Rods or strips of the same composition as the base metal are generally used as filler metals; the standard filler metals of other copper alloys are weaker and offer no advantages.

Joint Design. As Table 8 indicates, the typical joint designs for GTAW of high-strength beryllium copper are square-groove or 90° single-V-groove butt joints with a 1.6 mm (0.06, or 1/16 in.) maximum root face and zero root opening. The 90° single-V-groove butt welds can be used for thicknesses in excess of 12.7 mm (0.5, or 1/2 in.).

Preheating and Postweld Heat Treatment. As shown in Table 8, preheat temperatures of 150 to 200 °C (300 to 400 °F) are recommended for GTAW of section thicknesses greater than 3.2 mm (0.13, or 1/8 in.). Maximum weld strength is obtained by solution annealing and aging after welding. Aging treatments are 3 h at 315 °C (600 °F) for alloy C17000 and 3 h at 345 °C (650 °F) for alloy C17200. This postweld treatment does not consistently provide the full strength of solution-annealed and aged base metal, even for welds made under optimal conditions. Higher strength can be obtained by cold working the annealed metal to a higher temper and modifying the aging treatment.

For some applications, the intermediate weld metal strength obtained by aging after welding, without a solution anneal, is adequate. Omission of solution annealing avoids the expense and distortion associated with this high-temperature operation. Following are three applications of GTAW of high-strength beryllium coppers.

Examples 3, 4, and 5: Gas Tungsten Arc Welding of High-Strength Beryllium Coppers. Welding conditions for GTAW for three applications are shown in Table 9. Example 3 is a weldment in an alloy C17000 pressure vessel. In Example 4, a cylindrical generator liner was constructed using alloy C17000 and alloy C17200. Example 5 shows a cast beryllium-copper cover made from alloy C17000 that was welded to a housing of the same alloy.

The pressure vessel in Example 3 was used to scavenge propane from a freon bubble chamber. Use of GTAW was dictated because the vessel could not be solution-annealed after welding because of danger of warpage. The service conditions for this vessel included pressure of 41 MPa (6 ksi) and rapid thermal cycling.

The cylindrical generator liner (Example 4) was back-extruded from a cast billet. Longitudinal rings about 6 by 6 mm (0.25 by 0.25 in.) were machined on the outer surface. Nine reinforcing rings were rolled from extruded alloy C17000, equally spaced along the longitudinal rings, and welded to them. The reinforcing rings measured 40 mm (1.5 in.) wide and 32 mm (1.25 in.) high. The liner, used in a magneto-hydrodynamic electrical power generator, contained plasma at 1650 to 1925 °C (3000 to 3500 °F). The cover-to-housing weldment was for ocean-cable use. The cast cover was welded to an extruded housing to produce a joint that was watertight at 83 MPa (12 ksi). This application is shown as Example 5 in Table 9.

Gas Metal Arc Welding

Alloys C17000 and C17200 are more easily welded using the GMAW process than is high-conductivity alloy C17500. These alloys have lower melting temperatures, greater fluidity, and

50% lower thermal conductivities. The GMAW process is generally preferred for the welding of precipitation-hardened, high-strength beryllium coppers in thicknesses of 6.4 mm (0.25, or $\frac{1}{4}$ in.) and greater. This process is also preferred for thicknesses from 6.4 mm (0.25, or $\frac{1}{4}$ in.) down to 2.4 mm (0.09, or $\frac{3}{32}$ in.) if heat treatment is to be done after welding.

Nominal Conditions. Table 7 gives the nominal welding conditions for GMAW of high-strength beryllium coppers. The shielding gas used for GMAW is typically a mixture of argon and helium. Direct current electrode positive is used to prevent the buildup of oxides during welding. The filler metal is ordinarily of the same composition as the base metal, for joints requiring maximum strength. However, electrode wires ERCuSi-A and ERCuAl-A2 can be used when joint strength is less critical. Preheating, postweld heat treating, and joint designs are generally the same as discussed in the section on GTAW of high-strength beryllium coppers.

Welding of High-Conductivity Beryllium Copper

The traditional wrought high-conductivity alloys (C17500 and C17510) contain 0.2 to 0.7% Be and nominal 2.5% Co (or 2% Ni). The leanest high-conductivity alloy is C17410, which contains somewhat less than 0.4% Be and 0.6% Co. This section will describe the GTAW and GMAW of alloy C17500, the most frequently welded high-conductivity beryllium copper alloy. Additional information on the properties and applications of these materials can be found in the articles "Wrought Copper and Copper Alloys" and "Properties of Wrought Copper and Copper Alloys" in this Handbook.

Gas Tungsten Arc Welding

Gas tungsten arc welding of precipitation-hardened copper alloy C17500 (high-conductivity beryllium copper) is performed for thicknesses up to 6.4 mm (0.25, or $\frac{1}{4}$ in.). This process produces a narrow HAZ, which is desirable. Ordinarily, the maximum thickness that can be gas tungsten arc welded without substantial decrease in strength is about 13 mm (0.5 in.). However, thicker sections have been gas tungsten arc welded. For weldments that require postweld heat treatments, GTAW is generally used only for thicknesses up to 2.4 mm (0.09, or $\frac{3}{32}$ in.), with GMAW being used for thicker sections.

High-conductivity beryllium copper is more difficult to weld than the high-strength beryllium coppers because of its higher thermal conductivity, which is about twice that of the high-strength beryllium coppers. A difficulty common to the beryllium coppers is the formation of surface oxides, both beryllium oxide and cuprous oxide. The beryllium oxide is a tenacious oxide that inhibits wetting and fusion during welding. Cleanliness of the joint faces and surrounding surfaces before and during welding is necessary to ensure weld soundness.

Nominal Conditions. Table 8 gives the nominal starting conditions for GTAW of high-conductivity beryllium copper alloy C17500. Shielding gas, type of current, and electrode type are the same as for C17000 and C17200 high-strength alloys.

Type of Current. Variation in arc length or welding speed during GTAW can result in the formation of tenacious films on beryllium coppers. For this reason, high-frequency stabilized alternating current is preferred in automatic welding and must be used in manual welding. The alternating current continually breaks up the oxide coating, and high-frequency adds to the cleaning action during welding. Direct current electrode negative can be employed in the automatic welding of beryllium coppers. The advantage is found with the high heat input to the work and the deep penetration of this polarity. Close control of the arc length and welding speed must be maintained to minimize oxide formation.

High-conductivity beryllium coppers are more susceptible to porosity and cracking than welds made in high-strength beryllium copper. This is particularly true in multi-pass welding. However, successfully welded joints exhibit improved mechanical properties in HAZ compared with similar joints in high-strength beryllium coppers.

Filler Metals. Material with the same composition as the base alloy (C17500) is generally used, since high electrical conductivity is desired in the welds. If maximum electrical conductivity through the weld joint is not a requirement, silicon bronze filler metal is satisfactory. Aluminum bronze filler metals can be used but are less satisfactory than silicon bronze.

Joint Design. As Table 8 indicates, the usual joint designs for GTAW of high-conductivity beryllium copper are square-groove or 90° single-V-groove butt joints with a 1.6 mm (0.06, or $\frac{1}{16}$ in.) root face and zero root opening. All joints should be backed with grooved copper or graphite backing strips or rings.

Preheating. Preheating is not ordinarily needed for welding alloy C17500 up to about 3 mm (0.13, or $\frac{1}{8}$ in.) thick. However, thicker stock that may require multipass welds is usually preheated to approximately 425 °C (800 °F).

Gas Metal Arc Welding

Gas metal arc welding is preferred to GTAW for joining alloy C17500 with section thicknesses greater than 2.4 mm (0.09, or $\frac{3}{32}$ in.) when the weldment is to be heat treated to obtain maximum weld strength. It is also the process of choice for joining thicknesses in excess of 6.4 mm (0.25, or $\frac{1}{4}$ in.) if the welding is done on precipitation-hardened material. Gas metal arc welding can be used for thicknesses up to 19 mm (0.75, or $\frac{3}{4}$ in.).

As pointed out in the discussion of GTAW of alloy C17500, the three important factors in arc welding this alloy are: (1) high thermal and electrical conductivities; (2) oxide-forming characteristics; and (3) responsiveness to heat treatment. Although compromise is necessary between weld strength and conductivity, high thermal conductivities are typically the prime objectives in welding assemblies using this alloy.

Nominal Conditions. Table 7 lists the typical conditions for GMAW of high-conductivity beryllium coppers. Typically, DCEP is used. Argon is a suitable shielding gas; however, greater heat input, which is usually required when welding this alloy, can be obtained through the use of an argon-helium gas mix.

Filler Metals. As with GTAW for high-conductivity beryllium coppers, GMAW utilizes a filler metal of similar composition to the base metal. If reduced conductivity is an acceptable result of the weld metal, wires made of high-strength beryllium copper alloys C17000 and C17200 can be used for greater welding ease. Because of the precipitation-hardening characteristics of beryllium coppers, the joint strength is always somewhat lower than that of the base material and depends on the initial condition of the base metal, the welding conditions, and the filler-metal selection.

Other electrodes, such as ERCuSi-A or ERCuAl-A2, can be used for GMAW of alloy C17500. Because of their lack of beryllium content, however, these alloys do not develop the high strength attained when beryllium copper filler metal is used.

Preheating and Postweld Aging. Section thicknesses of alloy C17500 greater than 3.2 mm (0.13, or $\frac{1}{8}$ in.) are usually preheated at 315 to 480 °C (600 to 900 °F), depending on section thickness. When a beryllium copper filler metal is used, strength can be increased by aging after welding. The aging heat treatment for alloy C17500 is 480 °C (900 °F) for 3 h.

Properties of Weldments. Based on its high thermal conductivity and moderate to high strength, alloy C17500 is used for welded water-cooled assemblies such as tuyeres for blast furnaces, attrition mills for grinding beryllium chips to powder, and molds for the continuous casting of steel. While some strength is lost in the weld metal and the adjoining HAZ when alloy C17500 is welded, the magnitude of this decrease is affected by the condition and thicknesses of the base metal, and by joint design, welding process, and parameters.

Welding of Cadmium and Chromium Coppers

Typically, the welding procedures for GTAW of coppers are a satisfactory basis for determining initial welding parameters for cadmium and chromium coppers. These alloys have lower thermal and electrical conductivities than copper, and they can be welded with lower preheats and heat inputs than those required for copper. Section thickness limitations are the same as for GTAW of coppers. In addition to GTAW, GMAW can be used for the joining of cadmium and chromium coppers. The nominal conditions previously stated for GMAW welding of coppers are satisfactory for the welding of cadmium and chromium coppers.

The filler metal types, welding currents, polarities, and shielding gas mixtures for either GTAW or GMAW of coppers are suitable for the joining of cadmium and chromium coppers. These alloys should be welded using the standard joint geometries listed for GTAW and GMAW of coppers.

Welding of Copper-Zinc Alloys

Brasses are basically copper-zinc alloys and are the most widely used group of copper alloys. As shown in Table 2, brasses can be categorized as low-zinc brasses (5 to 20% Zn), high-zinc brasses (30 to 40% Zn), tin brasses, and special brasses. Copper-zinc alloys are joined by GTAW, GMAW, and SMAW. Additional information on the properties and applications of copper-zinc (brass) alloys can be found in the articles "Wrought Copper and Copper Alloys" and "Properties of Wrought Copper and Copper Alloys" in this Handbook.

Gas Tungsten Arc Welding

Table 2 lists the copper-zinc (brass) alloys and shows their relative weldability. The low-zinc brasses are shown to have good weldability using GTAW. High-zinc brasses, tin brasses, special brasses, and nickel silvers have only fair weldability. This is because of the high zinc content or the moderate zinc content in combination with other elements, such as oxide-forming aluminum or nickel.

Gas tungsten arc welding is sometimes used for the welding of copper-zinc alloys with 20% Zn or less. Alloys containing up to 1% Pb can also be welded with this process. Gas tungsten arc welding is used because of its ability to weld rapidly with a highly localized heat input. It should be noted that most leaded copper alloys are generally not recommended for arc welding.

Section thicknesses of copper-zinc alloys ordinarily welded using GTAW are limited to about 9.5 mm (0.38, or 3/8 in.). However, thick sections of cast alloys such as manganese bronze are sometimes repair welded in localized areas. Preheating is not normally required for the welding of these alloys.

Shielding Gas. Selection of the proper shielding gas for GTAW of copper-zinc alloys is influenced by the heat required to fuse the metals together. This requirement is directly related to the thermal conductivity of the base metal. Normally argon is used for GTAW of the less conductive materials. Helium or helium mixes are the preferred shielding gases for alloys having higher thermal conductivities. However, the use of helium and helium-rich gas mixes can reduce the fumes produced when welding the less conductive alloys, such as high-zinc brasses, tin brasses, special brasses, and nickel silvers.

Filler Metals. Filler metals used in GTAW of copper-zinc alloys should not contain zinc. The addition of filler metal is recommended when welding sections greater than 1.6 mm (0.06, or 1/16 in.) thick. The arc is concentrated on the filler metal, thus reducing the zinc loss and fuming of the base material. For the welding of low-zinc brass, ERCuSn-A is recommended; RCuSi-A and ERCuAl-2 are recommended for high-zinc alloys.

The silicon found in ERCuSi-A helps to decrease the zinc fumes. For this reason and to provide reinforcement, ERCuSi-A is sometimes used, with alternating current, on copper-zinc alloys 1.3 mm (0.05 in.) or less. Thinner sections of high-zinc alloys are sometimes gas tungsten arc welded using ERCuAl-A2. The addition of this filler metal produces sound welds but does not decrease zinc vaporization.

Thin brass sheets less than 1.6 mm (0.06, or 1/16 in.) thick can be welded without the addition of filler metal. Zinc fuming can be limited through the use of high electrode travel speed, which generates short weld pool arc times. Tube sheet joints can be made with brass members, using the same kind of joint preparation, if high electrode speed is maintained.

Gas Metal Arc Welding

Unleaded brasses can be welded using GMAW. These brasses include both the low-zinc alloys (red brasses) and the high-zinc alloys (including yellow brasses, tin brasses, and special brasses). Copper-zinc alloys are not used as filler metals for GMAW due to the violent fuming and loss of zinc that accompanies arc welding of these zinc-bearing alloys.

Low-Zinc Brasses. Table 7 lists nominal conditions for butt welding of low-zinc brasses, using GMAW. These alloys include up to 20% Zn. Direct current electrode positive is always used.

Silicon bronze (ERCuSi-A) wire provides easy welding, since it has good fluidity at low welding currents. A 60° single-V-groove is used with this filler metal. When ERCuSn-A electrode wire is used, its sluggish flow characteristics make a 70° V-groove advisable for heavier sections, as shown in Table 7. ERCuSn-A is primarily used for a better color match on low-zinc copper alloys. The wider groove provided with the 70° V-groove joint allows more room for manipulation of the molten weld pool. Except for color, weld metal properties are comparable when using either of these two types of electrodes. A preheat in the range of 95 to 315 °C (200 to 600 °F) is sometimes required for low-zinc brasses due to their relatively high thermal conductivities.

High-Zinc Copper Alloys. Nonleaded copper alloys that have zinc contents from 20 to 40% or more can be gas metal arc welded. However, the weldability is less than with nonleaded low-zinc brasses. The evolution of zinc fumes is more severe, and the welds experience greater porosity and lower strength than with low-zinc brasses. Both wrought and cast alloys can be joined by GMAW. Massive sections, such as for manganese bronze ship propellers, are regularly repair welded using this process.

The nominal conditions for gas metal arc butt welding of high-zinc copper alloys (yellow brasses, tin brasses, special brasses, and nickel silvers) are given in Table 7. Welding parameters and variables are generally the same when using either ERCuAl-A2 or ERCuSn-A filler metals. The difference between the two filler metals is a higher weld-metal strength with ERCuAl-A2 and better color match with ERCuSn-A. Preheating is seldom necessary since these alloys have relatively low thermal conductivities. However, preheating does help to limit zinc fuming in some applications because it permits the use of lower welding amperages.

Shielded Metal Arc Welding

Brasses can be welded using SMAW. A variety of covered electrodes can be used, including phosphor bronze, silicon bronze, or aluminum bronze (ECuSi, ECuSn-A, ECuSn-C, ECuAl-A2, ECuAl-B). Relatively large welding grooves are required for good joint penetration and to avoid the entrapment of slag. Welding is typically done using a backing strip of copper or brass.

Phosphor bronze electrodes, such as ECuSn-A and ECuSn-C, have been used for SMAW of low-zinc brasses. Preheating of the base metal from 200 to 260 °C (400 to 500 °F) is required. Application of filler metal should be in narrow, shallow stringer beads.

The high-zinc copper alloys can be welded with aluminum bronze (ECuAl-A2) electrodes. Preheat and interpass temperatures are 260 to 370 °C (500 to 700 °F). The arc is held directly on the molten weld pool rather than toward the base metal, and it is advanced slowly to minimize zinc volatilization and fuming.

Welding of Copper-Zinc-Nickel Alloys

Nickel silvers, which are alloys composed of copper (65%), zinc (17 to 25%), and nickel (10 to 18%), can be joined by GMAW and GTAW processes, although welding of these alloys is not widely practiced. From a welding standpoint, nickel silvers are similar to brasses, having comparable zinc content.

Nickel silvers are frequently used for decorative purposes where color match is important. However, there are no zinc-free filler metals that are suitable for arc welding that give good color match. Therefore, GTAW is usually restricted to thicknesses of 2.4 mm (0.094, or 3/32 in.) or less without the addition of filler metal. Square-groove butt, lap, or edge joints are used. The joint faces must be in contact before and during welding.

Welding of Phosphor Bronzes

The phosphor bronzes (C50100-C52400) contain additions of tin (up to 10%) and phosphorus (0.2%), which produce good resistance to flowing seawater and to most nonoxidizing acids (except hydrochloric acid). Phosphor bronzes are joined by GTAW, GMAW, and SMAW. Additional information on the proper-

Table 10 Nominal conditions for GTAW of square-groove butt joints in phosphor bronzes

Workpiece thickness		Root opening		Electrode (EWTh-2) diameter		Welding rod diameter(a)			Gas flow rate			Travel speed		Preheat temperature		
mm	in.	mm	in.	mm	in.	mm	in.	Shielding gas	L/min	ft^3/h	Current (DCEN), A	m/min	in./min	°C	°F	Number of passes
1.6	1/16	0	0	3.2	1/8	None used		Argon	15	30	90–150	1.78	70	None used		1
3.2	1/8	1.6	1/16	3.2	1/8	3.2	1/8	Argon	15	30	100–220	1.27	50	None used		1

Notes: (1) The data in this table are intended to serve as starting points for the establishment of optimal joint design and conditions for welding of parts on which previous experience is lacking. They are subject to adjustments necessary to meet the special requirements of individual applications. (2) Higher welding current or lower welding travel speed is used in welding alloy C50500. (a) ERCuSn-A, or rod of composition close to that of the base metal

Table 11 Suggested conditions for GMAW of phosphor bronzes

Workpiece thickness		Joint design			Electrode diameter(a)			
			Root opening					
mm	in.	Groove type	mm	in.	mm	in.	Arc voltage, V	Welding current (DCEP), (a) A
1.6	1/16	Square	1.3	0.05	0.8	0.030	25–26	130–140
3.2	1/8	Square	2.4	0.09	0.9	0.035	26–27	140–160
6.4	1/4	V	1.6	0.06	1.2	0.045	27–28	165–185
12.7	1/2	V	2.4	0.09	1.6	0.062	29–30	315–335
19.0	3/4	Double-V or double-U	2.4	0.09	2.0	0.078	31–32	365–385
25.4	1.0	Double-V or double-U	2.4	0.09	2.4	0.094	33–34	440–460

(a) ERCuSn-A phosphor bronze electrodes and argon shielding gas

ties and applications of phosphor bronzes can be found in the articles "Wrought Copper and Copper Alloys" and "Properties of Wrought Copper and Copper Alloys" in this Handbook.

Gas Tungsten Arc Welding

Sheet and other wrought forms of phosphor bronze can be gas tungsten arc welded up to approximately 13 mm (0.5, or 1/2 in.). The process can also be used to join or repair phosphor bronze castings. Copper-tin alloys solidify with large, weak, dendritic grain structures that are susceptible to cracking. Hot peening each layer of multipass welds reduces cracking and stresses and therefore the likelihood of weld metal cracking.

Nominal Conditions. The use of GTAW for joining nonleaded phosphor bronzes is described in Table 10. Square-groove butt joints are employed, and the current used is DCEN or a stabilized alternating current arc.

The nominal conditions shown in Table 10 are based primarily on the three phosphor bronzes given in Table 2, which have low thermal conductivities. These include alloys C51000, C52100, and C52400. When welding alloy C50500, higher welding currents or slower welding travel speeds are required. This alloy commonly known as phosphor bronze 1.25% E, contains approximately 98.7% Cu and has 3 to 4 times the thermal conductivity of the other alloys in this grouping.

Shielding Gas. The use of argon as a shielding gas is most common, since argon restricts the size of the HAZ. This minimizes the area where mechanical properties are decreased. When necessary for thicker sections, helium shielding gas can be used, along with an argon backup gas shield.

Filler metal may be added to the weld joint using either ERCuSn-A or wire of approximately the same composition as the base metal. When matching the composition of the base metal is not essential, ERCuSi-A filler metal can be used instead, producing stronger welds. When welding section thicknesses less than 3 mm (0.13, or in.), phosphor bronze strip can be butt welded using autogenous GTAW.

Preheating is not normally required for GTAW of thin sections of phosphor bronzes. Thick sections usually require preheating to 175 or 200 °C (350 or 400 °F) and are slowly cooled after welding. Due to the hot-short nature of phosphor bronze, weld layers should be thin, and interpass temperature should not exceed 200 °C (400 °F). Hot peening is often used to refine grain size and minimize distortion.

Gas Metal Arc Welding

Table 7 gives the nominal conditions for GMAW of butt joints using phosphor bronze. Lead-bearing or other free-machining types are not welded. Table 11 gives GMAW conditions that can be used as starting points for establishing welding conditions for joining phosphor bronzes. As with GTAW, the welding conditions are based on three poorly conductive phosphor bronze alloys (C51000, C52100, and C52400). When welding the more conductive alloy C50500, higher welding currents or slower welding speeds are needed. For joining thicknesses of 9.5 to 12.7 mm (0.38 to 0.5, or 3/8 to 1/2 in.), 90° single-V-grooves are used rather than the narrow grooves used for most other poorly conductive alloys.

Filler Metals. For joining phosphor bronzes, ERCuSn-A electrode wire is generally used. The filler metal wire that contains about 0.5% Si is sometimes used to minimize porosity in the weld.

Preheating. As with other copper alloys, preheating of the phosphor bronzes helps in obtaining complete fusion. Also, porosity is minimized because the freezing rate of the weld pool is decreased, and more gas is permitted to evolve before solidification. However, preheating increases the susceptibility of the weld to the formation of large columnar grains and the risk of hot cracking. This susceptibility requires that welding be performed with a stringer bead technique and that each weld layer be peened. A small weld pool and rapid electrode travel speed are required. Interpass temperatures while welding should not exceed the preheat temperatures because of the hot shortness of the phosphor bronze alloys.

Shielded Metal Arc Welding

Shielded metal arc welding is done on a limited basis for phosphor bronzes. The covered electrodes typically used are ECuSn-A and ECuSn-C. These electrodes may be used interchangeably and are designed for use with DCEP.

Preheating is required in the range of 150 to 200 °C (300 to 400 °F), since the phosphor bronzes are very sluggish. However, because of the hot shortness of these alloys, the interpass temperature must not exceed the preheat temperature. This is extremely important in thicker sections. Stringer beads with rapid travel speed are normally used. In groove welding, the first two passes are made with a weaving technique. The width of the weave should not exceed two electrode diameters. The remaining passes are made without appreciable traverse weaving and with the use of narrow stringer beads. The development of the coarse, dendritic structure with low strength and ductility is minimized by the control of preheat and interpass temperatures. Hot peening is often used after welding to reduce grain size. For the maximum ductility, the welded assembly should be postweld heat treated to 480 °C (900 °F) and cooled rapidly. Groove joints should be wide, with an included angle of 80 to 90° to achieve proper washing and tie-in at the walls of the groove.

Welding of Aluminum Bronzes

As shown in Table 2, aluminum bronzes (C60600-C64400) are complex alloys based on the Cu-Al-Ni-Fe-Si-Sn system. They are welded using GTAW, GMAW, or SMAW. Some aluminum bronzes are also used as hardfacing alloys (see the article "Copper and Copper Alloy Coatings" in this Handbook). Additional information on the properties and applications of aluminum bronzes can be found in the articles "Wrought Copper and Copper Alloys" and "Properties of Wrought Copper and Copper Alloys" in this Handbook.

Gas Tungsten Arc Welding

Gas tungsten arc welding is readily used for joining aluminum bronzes up to 9.5 mm (0.38, or 3/8 in.). Aluminum bronze castings are also repair welded by GTAW. Conditions differ somewhat from those of most other copper alloys. Porosity is minimized in the weld metal by the presence of iron, manganese, or nickel in the filler metal or base metal.

Nominal Conditions. Table 12 lists the nominal conditions for welding of aluminum bronze alloys. Conditions must be selected to avoid difficulties that result from the tenacious refractory aluminum oxide films that form almost instantaneously during any heating process such as welding unless oxygen is completely excluded from the metal. Heat input requirements are not high, since aluminum bronzes have a thermal conductivity near that of carbon steel.

Shielding Gas. Argon is typically used with alternating current as a shielding gas for the welding of aluminum bronzes. For better penetration or faster travel speed, direct current can be used with argon, helium, or a mixture of these two gases. While the shielding gas protects the weld pool and adjacent base metal, the use of a special flux augments the shielding effect of the gas. The flux is applied to the edge of the weld joints to increase fluidity and help protect the base metal from oxide formation. Aluminum oxide forms even at room temperature, and the flux prevents air from reaching the prepared edges until the protective argon shielding gas can become effective in the localized area.

Type of Current. As stated above, alternating current is used for GTAW of aluminum bronzes. The alternating current is stabilized by continuous high frequency and is preferred to DCEN, since it prevents oxide formation on the surface of the weld pool. High-frequency-stabilized alternating current is particularly desirable when multi-pass welding of these alloys is performed. Direct current electrode negative can be used in a single-pass welding, particularly for automatic welding. Surfaces must be well cleaned and protected, and the arc must be closely controlled.

Electrodes. Gas tungsten arc welding of aluminum bronzes typically uses zirconiated tungsten (EWZr) or unalloyed tungsten (EWP) electrodes. Thoriated tungsten electrodes are used with direct current; however, these electrodes cause the arc to wander when they are used with alternating current. The thoriated tungsten gives a longer tip life and is easier to start. Electrode preparation for use with direct current is a tapered cone-shaped tip. For alternating current, the end of the electrode is typically balled via an arc melting process.

Filler Metals. ERCuAl-A2 is ordinarily used for joining aluminum bronzes. ERCuAl-A3 or other aluminum bronze wire of matching chemical composition can be used when the composition and color of the weld metal must closely match that of the base metal.

Preheating of aluminum bronzes for GTAW of sections thinner than approximately 6 mm (0.25 in.) is not necessary. Aluminum bronzes have a low thermal conductivity but may require preheating for section thicknesses greater than 6 mm (0.25 in.). When preheating is required, the preheat and interpass temperature should not exceed 150 °C (300 °F) for alloys with less than 10% Al. In the following example, preheating was used for joining of a 9.5 mm (0.38, or 3/8 in.) thick aluminum bronze.

Example 6: Use of GTAW versus GMAW to Avoid Melt-Through of Neighboring Sections. The propeller housing for the Kort nozzle shown in Fig. 3 was originally made as a one-piece sand casting from aluminum bronze alloy C95500 (aluminum bronze 9B), which contains 10% Al and 1% Fe. Difficulties were experienced in the coring necessary to produce the thin outer shell. This led to the production of this outer shell as a separate piece that was welded to the casting to make a two-piece structure.

The inner section was cast in propeller bronze as one intricate piece that included a central hub and shaft-mounting flange connected to the main body of the nozzle by four arms. The outer shell was cut from 9.5 mm (0.38, or 3/8 in.) thick alloy C61300 (aluminum bronze) with soft temper and was wrapped around the cast intersection after being cold formed into a truncated cone. Before cold forming, all edges of the shell were machined to a 35° bevel to provide a groove for subsequent welding.

The assembly was tack welded together, and then circumferential seams at the top and bottom were gas metal arc welded. Next, to avoid melt-through of the cast intersection (and resultant poor effect on the propeller stream), GTAW was used for the longitudinal seam in the shell and for joining two brackets to the shell. The brackets were used for mounting the shell to the hull of the vessel. Figure 3 illustrates the weldment as constructed.

Not only was the cost of production reduced by eliminating the complex and expensive coring in the casting, but the weight of the welded housing was less than that of the completed cast housing. Furthermore, the cast housing had been made of an alloy that, although easy to cast, did not resist erosion, corrosion, or cavitation as well as did the alloys used in the welded assembly.

Gas Metal Arc Welding

Gas metal arc welding with aluminum bronze electrode wire is the preferred technique for welding aluminum bronzes. Because of the comparatively high surface tension of the molten weld pool and the relatively low thermal conductivity of the base metal, welding can be performed in all positions. Welding in the vertical and overhead positions is usually performed with either the globular or short-circuiting mode of metal transfer, using filler metal up to 1.6 mm (1/16 in.) in diameter.

Nominal Conditions. The nominal conditions for gas metal arc butt welding of aluminum bronze are given in Table 7. Backing strips or rings of aluminum bronze are used when welding material up to 3.2 mm (0.13, or 1/8 in.) thick. These conditions make it necessary to use helium or argon-helium mixes for shielding gas instead of the argon shown in Table 7. These hotter shielding gases provide adequate heat input.

Filler Metals. ERCuAl-A2 ordinarily is used in the GMAW of aluminum bronze. The 1.5% Fe present in this wire reduces the hot-short cracking susceptibility of the weld metal. The use of ERCuAl-A3 also produces welds that are free from hot shortness. Joints made with ERCuAl-A3 are also stronger and harder, but lower in ductility.

Joint Design. The joining of aluminum bronzes thicker than about 13 mm (0.5 in.) requires wider root openings and groove angles than those indicated in Table 7. This is necessary to avoid incomplete fusion and to improve the penetration resulting from the use of a thicker section, which increases the weld heat-sink characteristics.

Preheating. For most thin sections of aluminum bronzes, preheating is not required prior

Table 12 Nominal conditions for GTAW of aluminum bronzes

Workpiece thickness(a)		Root opening		Electrode diameter(b)		Welding rod diameter(c)		Flow rate of argon		Current (ac, HF-stabilized) (d) A	Number of passes
mm	in.	mm	in.	mm	in.	mm	in.	L/min	ft³/h		
Square-groove butt joints											
0–1.6	0–1/16	0	0	1.6	1/16	1.6	1/16(e)	9.5–15	20–30	25–80	1
1.6–3.2	1/16–1/8	1.6 max	1/16 max	2.4	3/32	3.2	1/8	9.5–15	20–30	60–175	1
3.2	1/8	3.2 max	1/8 max	4.8	3/16	4.0	5/32	15	30	210	1
70° single-V-groove butt joints											
9.5	3/8	0	0	4.8	3/16	4.0	5/32	15	30	210–330	4
Fillet-welded T-joints of square-groove inside corner joints											
9.5	3/8	(f)		4.8	3/16	4.0	5/32	15	30	225	3

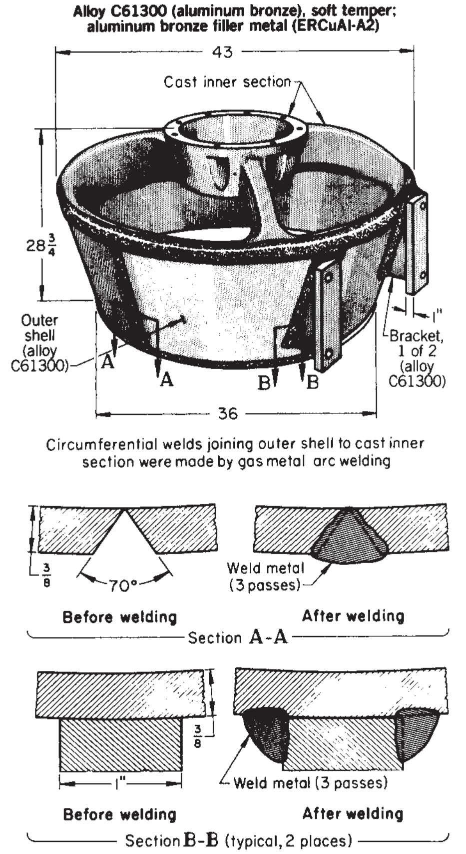
ac, alternating current; HF, high frequency. Note: The data in this table are intended to serve as starting points for the establishment of optimal joint design and conditions for welding of parts on which previous experience is lacking. They are subject to adjustments necessary to meet the special requirements of individual applications. (a) Preheating is not ordinarily used in welding the thicknesses shown. (b) Zirconiated or unalloyed electrodes are recommended with high-frequency-stabilized alternating current. (c) Preferred welding rod is ERCuAl-A2; otherwise ERCuAl-A3 or rod of the same composition as the base metal. (d) Direct current electrode negative can also be used in making single-pass welds (see text). (e) Use of welding rod is optional for thicknesses up to 1.6 mm (1/16 in.). (f) Zero root opening for T-joints; 9.5 mm (3/8 in.) max for corner joints to welding. If preheat is used, the preheat and interpass temperatures should not exceed 150 °C (300 °F) for alloys that contain less than 10% Al. When aluminum content exceeds 10%, preheat temperatures should be elevated to 260 °C (500 °F). Again, interpass temperatures should not exceed preheat temperatures, due to the hot shortness of these alloys.

Shielded Metal Arc Welding

Aluminum bronzes are readily welded using SMAW for both the wrought and cast forms. The fluxing action of the electrode coating removes the aluminum oxides that form on the surface of the alloys.

Except for thin sections, a 70 to 90° V-groove joint is used. Typically, a backing strip of the same composition as the base metal is also utilized. Deposition technique and bead thickness are not critical because the weld metal has excellent hot strength and ductility.

Electrodes. Aluminum bronze electrodes ECuAl-A2 and ECuAl-B are used for SMAW of aluminum bronze alloys C61300 and C61400. Preheating of thick sections of these alloys may be needed and is usually in the range of 200 °C (400 °F) with a controlled interpass temperature not exceeding 200 °C (400 °F). Depending upon section thickness and overall mass, preheat and interpass temperatures may vary from 65 to 425 °C (150 to 800 °F). Weldments made of aluminum bronze alloys containing 7% Al need not be heat treated after welding. Aluminum bronzes having an aluminum content greater than 7% are usually welded with electrodes that contain more aluminum than do ECuAl-A2 and ECuAl-B. These higher-aluminum bronze electrodes, ECuAl-C, ECuAl-D, and ECuAl-E, are best known as surfacing electrodes and have nominal aluminum contents of 10, 11.5, and 13%, respectively. These electrodes are described in AWS A5.13 and have strength corresponding to the aluminum content. In welding high-aluminum bronzes, thick sections may require preheating up to 620 °C (1150 °F), and fan cooling may be necessary to avoid cracking. These alloys may also require annealing at 620 °C (1150 °F), followed by fan cooling for stress relief.



Conditions for GTAW

Joint types	Butt and T
Weld types	Single-V-groove and fillet
Welding position	Flat
Number of passes	3
Power supply	300 A rectifier, constant-current type
Torch	Water-cooled
Electrode	2.4 mm ($^3/_{32}$ in.) diam EWTh-2
Filler metal	2.4 mm ($^3/_{32}$ in.) diam ERCuAl-A2
Shielding gas	Argon; flow rate, 9.5 L/min (20 ft^3/h)
Preheat and interpass temperature	150 °C (300 °F)
Voltage	35 V
Current	225 A (DCEN)
Arc starting	Contact and high frequency

Fig. 3 Conditions for GTAW of a propeller housing. The weldment replaced a single-piece casting, thereby reducing cost and improving serviceability.

Welding of Silicon Bronzes

Silicon bronzes (C64700–C66100), which are based on the Cu-Si-Sn system, are the most weldable of the copper alloys. Silicon bronzes can be welded by most arc welding processes, the most commonly utilized being GTAW, GMAW, and SMAW. Additional information on the properties and applications of silicon bronzes can be found in the articles "Wrought Copper and Copper Alloys" and "Properties of Wrought Copper and Copper Alloys" in this Handbook.

Gas Tungsten Arc Welding

Silicon bronze alloys that do not contain lead can be gas tungsten arc welded in thin and moderately thick sections. These alloys are typically the most weldable of all copper alloys. Inherent characteristics of these bronzes that contribute to their weldability include low thermal conductivity, good deoxidation of the weld metal by silicon, and protection offered by the resulting slag. Silicon bronzes have a relatively narrow hot-short range just below the solidus, and they must be rapidly cooled through this range to avoid weld cracking.

Nominal Conditions. Table 13 lists the nominal welding condition for GTAW of silicon bronzes. The data for manual welding include welding conditions for various positions. Because of their low fluidity, silicon bronzes are the only group of copper alloys where GTAW is applied extensively in the vertical and overhead positions. Direct current electrode negative with argon or helium shielding can be used for section thicknesses less than 1.6 mm (0.06, or $^1/_{16}$ in.). Zirconiated (EWZr) or pure tungsten (EWP) electrodes are recommended.

Filler Metals. The conventional silicon bronze filler metal, ERCuSi-A, which is similar in composition to alloy C65500 (high-silicon bronze A), can be used to weld any of the silicon bronzes. Alloy C65500 is the most commonly used of all the silicon bronzes. Thin sections of this alloy are readily welded using GTAW without the addition of filler metal.

Joint Design. On metal thicknesses greater than 6.4 mm (0.25, or $^1/_4$ in.) a V-groove with a 60° included angle is used. Butt joints in thin sections can be welded without special preparation.

Preheating. Silicon bronzes have the lowest thermal conductivity of all copper alloys. The thermal conductivity of these alloys is less than that of carbon steels. Further, these alloys exhibit hot shortness. Based on this, preheating can be harmful to the welding of these alloys, and interpass temperature on multi-pass welds should not exceed 95 °C (200 °F).

Gas Metal Arc Welding

The nonleaded silicon bronzes are readily welded using GMAW. Nominal conditions for GMAW of silicon bronzes in various thicknesses and joint designs are given in Table 7. This process is used for section thicknesses greater than 6.4 mm (0.25, or $^1/_4$ in.). Rapid travel speeds (minimum of 3.5 mm/s, or 8 in./min) should be used to avoid excessive heat buildup. As shown in Table 7, the welding current used for these alloys is slightly lower than that used for other copper alloys. Because of the low thermal conductivity of silicon bronzes (Table 2), the resulting low heat input to the weld is adequate for complete fusion and good penetration. Argon shielding gas is preferred. A thin layer of oxide forms on the weld metal after each pass and must be removed by wire brushing prior to the next weld pass.

All silicon bronze alloys can be gas metal arc welded using ERCuSi-A filler metal. The chemical composition of this wire is similar to that of alloy C65500 (high-silicon bronze A), which is the most frequently used silicon bronze. These wires may include up to 1.5% Sn instead of, or in addition to, the 1.5% Mn specified as a maximum for alloy C65500.

Joint Preparation. Metal thicknesses of 6.4 to 19 mm (0.25 to 0.75, or $^1/_4$ to $^3/_4$ in.) should utilize a single 60° V-groove. For silicon bronze alloys of section thicknesses greater than 19 mm (0.75 in.), U-grooves or 60° double-V-groove joints can be used.

Preheating. As with GTAW of silicon bronze alloys, preheating is not required and should not be used with GMAW of silicon bronze. Interpass temperatures must be held below 95 °C (200 °F) to prevent weld cracking. Stress relieving of silicon bronze weldment is recommended to prevent stress-corrosion cracking failures.

Shielded Metal Arc Welding

Shielded metal arc welding of silicon bronze alloys is usually done using ECuAl-A2 aluminum bronze electrodes. Welding temperatures are easily attained, due to the low thermal conductivity of silicon bronzes. As with other arc welding processes, preheat and interpass temperatures should not exceed 95 °C (200 °F) to prevent hot-short cracking.

Groove dimensions are similar to those used for steel joints. Metal thicknesses up to 4 mm (0.16, or 5/32 in.) can be welded with square grooves. Thicker sections can he welded with a single-V- or double-V-groove of 60° included angle.

Weld properties in silicon bronzes joined using SMAW are usually substantially lower than those of welds made by the gas-shielded processes. Based on this, these welds may not meet code or design requirements for strength. Peening of welds reduces residual stress and minimizes weld distortion.

Welding of Copper-Nickel Alloys

Copper-nickel alloys (C70000–C79900) are the most corrosion-resistant copper-base alloys. Alloy C71500 (Cu-30Ni) has the best general resistance to aqueous corrosion, but alloy C70600 (Cu-10Ni) is often selected because it offers good resistance at lower cost. Copper-nickel alloys are readily welded by GTAW, GMAW, and SMAW. Additional information on the properties and applications of copper-nickel alloys can be found in the articles "Wrought Copper and Copper Alloys" and "Properties of Wrought Copper and Copper Alloys" in this Handbook.

Gas Tungsten Arc Welding

Gas tungsten arc welding is the preferred process for joining copper-nickel alloys with section thicknesses up to 1.6 mm (0.06, or 1/16 in.). This process may also be used for thicker sections. Automatic welding produces satisfactory results in thin sections of tube sheets. Manual welding is normally used for sheet and plate thicknesses up to 6.4 mm (0.25, or 1/4 in.).

Nominal Conditions. Conditions by which copper-nickel alloys can be manually and automatically welded using GTAW are given in Table 14. These include butt joints with square- and single-V-groove preparation.

Preferred conditions include the use of argon shielding gas, DCEN, and thoriated tungsten electrodes. However, these variables are not critical for copper-nickel, since these alloys have low heat conductivities. Helium may be substituted for argon as a shielding gas, but argon provides better arc control and stability. Alternating current can be employed for automatic welding if there is adequate control of arc length.

During GTAW of alloy C70600, slightly higher welding currents or slower travel speeds should be used, due to the higher thermal conductivity of this alloy. Preheating is not necessary, and backing strips or rings can be used. Backing strips or rings should be made of copper or copper-nickel alloy not carbon, graphite, or steel.

Table 13 Nominal conditions for GTAW of silicon bronzes using zero root opening, no preheat, EWTh-2 electrodes, ERCuSi-A welding rod, and argon shielding gas

Workpiece thickness(a)		Electrode diameter		Welding rod diameter(b)		Gas flow rate		Current	Travel speed		Number of passes
mm	in.	mm	in.	mm	in.	L/min	ft^3/h	(DCEN), A	m/min	in./min	
Automatic welding											
Square-groove butt joints, flat position											
0.3–1.3	0.012–0.050	3.2	1/8	None used		7.1–16.5	15–35	80–140	1.52–2.03	60–80	1
1.6–3.2	1/16–1/8	3.2	1/8	None used		7.1–16.5	15–35	90–210	1.14–1.52	45–60	1
3.2	1/8	3.2	1/8	1.6	1/16	7.1–16.5	15–35	250	0.46–0.50	18–20	1
Manual welding											
Square-groove butt joints, flat position											
1.6	1/16	1.6	1/16	1.6	1/16	7.1	15	100–120	0.30	12	1
3.2	1/8	1.6	1/16	2.4	3/32	7.1	15	130–150	0.30	12	1
4.8	3/16	2.4	3/32	3.2	1/8	9.5	20	150–200	…	…	1
6.4	1/4	3.2	1/8	3.2	1/8	9.5	20	250–300	…	…	1
6.4	1/4	3.2	1/8	3.2	1/8	9.5	20	150–200	…	…	3
Square-groove butt joints, vertical and overhead positions											
1.6	1/16	1.6	1/16	1.6	1/16	7.1	15	90–110	…	…	1
3.2	1/8	1.6	1/16	2.4	3/32	7.1	15	120–140	…	…	1
60° single-V-groove butt joints, flat position											
9.5	3/8	3.2	1/8	3.2	1/8	9.5	20	230–280	…	…	3–4
12.7	1/2	3.2	1/8	4.8	3/16	9.5	20	250–300	…	…	4–5
19.0	3/4	3.2	1/8	4.8	3/16	9.5	20	300–350	…	…	9–10
25.4	1	3.2	1/8	6.4	1/4	9.5	20	300–350	…	…	13
Fillet-welded lap joints, flat position											
1.6	1/16	1.6	1/16	1.6	1/16	7.1	15	110–130	0.25	10	1
3.2	1/8	2.4	3/32	2.4	3/32	7.1	15	140–160	0.25	10	1
4.8	3/16	2.4	3/32	3.2	1/8	9.5	20	175–225	…	…	1
6.4	1/4	2.4	3/32	3.2	1/8	9.5	20	175–225	…	…	3
9.5	3/8	3.2	1/8	4.8	3/16	9.5	20	250–300	…	…	3
12.7	1/2	3.2	1/8	4.8	3/16	9.5	20	275–325	…	…	6
19.0	3/4	3.2	1/8	4.8	3/16	9.5	20	300–350	…	…	12
25.4	1	3.2	1/8	6.4	1/4	9.5	20	325–350	…	…	16
Fillet-welded lap joints, vertical and overhead positions											
1.6	1/16	1.6	1/16	1.6	1/16	7.1	15	100–120	…	…	1
3.2	1/8	2.4	3/32	2.4	3/32	7.1	15	130–150	…	…	1
Square-groove outside corner joints, flat position											
1.6	1/16	1.6	1/16	1.6	1/16	7.1	15	100–130	0.30	12	1
3.2	1/8	1.6	1/16	2.4	3/32	7.1	15	130–150	0.30	12	1
4.8	3/16	2.4	3/32	3.2	1/8	9.5	20	150–200	…	…	1
Square-groove outside corner joints, vertical and overhead positions											
1.6	1/16	1.6	1/16	1.6	1/16	7.1	15	90–110	…	…	1
3.2	1/8	1.6	1/16	2.4	3/32	7.1	15	120–140	…	…	1
50° single-bevel-groove outside corner joints, flat position(c)											
6.4	1/4	2.4	3/32	3.2	1/8	9.5	20	175–225	…	…	3
9.5	3/8	3.2	1/8	4.8	3/16	9.5	20	230–280	…	…	3
12.7	1/2	3.2	1/8	4.8	3/16	9.5	20	275–325	…	…	7
19.0	3/4	3.2	1/8	4.8	3/16	9.5	20	300–350	…	…	14
25.4	1	3.2	1/8	6.4	1/4	9.5	20	325–350	…	…	20
Fillet-welded square-groove inside corner joints, flat position(d)											
1.6	1/16	1.6	1/16	1.6	1/16	7.1	15	110–130	0.25	10	1
3.2	1/8	2.4	3/32	2.4	3/32	7.1	15	140–150	0.25	10	1
4.8	3/16	2.4	3/32	3.2	1/8	9.5	20	175–225	…	…	1
Fillet-welded T-joints, flat position											
1.6	1/16	1.6	1/16	1.6	1/16	7.1	15	110–130	0.25	10	1
3.2	1/8	2.4	3/32	2.4	3/32	7.1	15	140–160	0.25	10	1
4.8	3/16	2.4	3/32	3.2	1/8	9.5	20	175–225	…	…	1
6.4	1/4	2.4	3/32	3.2	1/8	9.5	20	175–225	…	…	3
9.5	3/8	3.2	1/8	4.8	3/16	9.5	20	230–280	…	…	3
12.7	1/2	3.2	1/8	4.8	3/16	9.5	20	275–325	…	…	7
19.0	3/4	3.2	1/8	4.8	3/16	9.5	20	300–350	…	…	14
25.4	1	3.2	1/8	6.4	1/4	9.5	20	325–350	…	…	20

Note: The data in this table are intended to serve as starting points for the establishment of optimal joint design and conditions for welding of parts on which previous experience is lacking. They are subject to adjustments necessary to meet the special requirements of individual applications. (a) Thicknesses greater than about 12.7 mm (1/2 in.) are gas tungsten arc welded only when it is not practical to use GMAW. (b) Wire feed rate of 2.9–3.2 m/min (115–125 in./min). (c) Root face is 1.6 mm (1/16 in.) for thicknesses of 12.7 mm (1/2 in.) or less, and 3.2 mm (1/8 in.) for thicknesses greater than 12.7 mm (1/2 in.). (d) Maximum root opening is equal to base metal thickness, *t*.

Table 14 Nominal conditions for gas tungsten arc butt welding of copper-nickel alloys

Workpiece thickness			ERCuNi Electrode diameter(a)		welding rod diameter(b)		Flow rate of argon		Current	Travel speed		Number of passes
mm	in.	Butt-joint groove	mm	in.	mm	in.	L/min	ft^3/h	(DCEN), A	m/min	in./min	
Automatic welding of alloy C70600 (copper-nickel, 10%)												
3.2	1/8	Square	4.8	3/16	1.6	1/16	15	30	310–320	0.38–0.46	15–18	1
Manual welding of alloy C70600 (copper-nickel, 10%)												
3.2	1/8	Square	4.8	3/16	3.2	1/8	15	30	300–310	0.13	5	1
9.5	3/8	70–80° single-V	4.8	3/16	4.8	3/16	15	30	300–310(c)	0.15	6	2–4
Manual welding of alloy C71500 (copper-nickel 30%)												
3.2	1/8	Square	4.8	3/16	3.2	1/8	15	30	270–290	0.13	5	1
9.5	3/8	70–80° single-V	4.8	3/16	4.0	5/32	15	30	270–290(c)	0.15	6	4

Data in this table are intended to serve as starting points for the establishment of optimal joint design and conditions for welding of parts on which previous experience is lacking. They are subject to adjustments necessary to meet the special requirements of individual applications. Root opening is zero. Preheating is not needed. (a) Preferred electrode material is EWTh-2. (b) Filler metal (ERCuNi) must be used on all welded joints (see text). (c) Current should be increased in equal increments with each pass, up to a maximum of about 375 A, with larger welding rods.

Table 15 Suggested conditions for GMAW of copper-nickel alloy plate

Workpiece thickness		Electrode feed(a)		Arc voltage, V	Welding current (DCEP), A
mm	in.	m/min	in./min		
6.4	1/4	4.5–5.6	180–220	25–26	130–140
9.5	3/8	5.1–6.1	200–240	26–27	140–160
12.7	1/2	5.6–6.1	220–240	27–28	165–185
19.0	3/4	5.6–6.1	220–240	29–30	315–335
25.4	1.0	5.6–6.1	220–240	31–32	365–385
>25.4	>1.0	6.1–6.6	240–260	33–34	440–460

(a) ERCuNi electrode, 1.6 mm (1/16 in.), argon shielding gas

Filler Metals. ERCuNi is used as a filler metal in GTAW of copper-nickel alloys. This filler metal contains 0.20 to 0.50% Ti to minimize porosity and the possibility of oxygen embrittlement in either the weld metal or the HAZ. Because the standard copper-nickel alloys do not contain titanium or a comparable deoxidizer, filler metal should be used even in welding thin sheets of copper-nickel. This will avoid the formation of porosity. However, special compositions of alloys C70600 and C71500 are available that do contain titanium. Thin sheets of these special alloys can be welded without the use of a filler metal. In multi-pass welding of copper-nickel alloys, the filler metal diameter and welding current may be increased with successive passes to provide efficient deposition. Autogenous welds can sometimes be made on sheet thicknesses up to 1.6 mm (0.06, or $\frac{1}{16}$ in.), but porosity may be a problem due to the absence of deoxidizers in the base metal.

Gas Metal Arc Welding

Gas metal arc welding is the preferred welding process for non-leaded copper-nickel alloys thicker than approximately 1.6 mm (0.06, or $\frac{1}{16}$ in.). Table 15 lists welding conditions for GMAW of copper-nickel alloy plate. The preferred welding position is the flat position. Argon is the preferred shielding gas; however, argon-helium mixes give better penetration on thick sections. Direct current electrode positive is recommended.

Nominal conditions for gas metal arc butt welding of non-leaded copper-nickel alloys for various joint designs and thicknesses are given in Table 7. These alloys can be satisfactorily welded using either spray or short-circuiting transfer. Spray transfer is normally used for sections greater than 6.4 mm (0.25, or $\frac{1}{4}$ in.). Pulsed spray transfer or short-circuiting transfer can be used to weld thin sections. These transfer methods provide better control of the molten weld pool when welding in the vertical and overhead positions. Selection of processing conditions is not critical in GMAW of these poorly heat-conductive alloys. Alloy C70600 is usually welded at a slightly higher current or slower travel speed than alloy C71500.

Filler Metals. ERCuNi electrode wire is the common choice for GMAW of copper-nickel alloys. This wire resembles alloy C71500 in composition, since it has a 70 to 30 copper-to-nickel ratio. ERCuNi contains 0.15 to 1.00% Ti, which serves as a deoxidizer to minimize porosity and prevent oxygen embrittlement. Titanium also improves the fluidity of the weld pool.

Joint Design. For GMAW of butt joints in non-leaded copper-nickels 3.2 mm (0.13, or $\frac{1}{8}$ in.) thick, the joint design usually includes a square-groove weld and grooved copper backing. This is indicated in Table 7. For thicknesses between 3.2 and 12.7 mm (0.13 and 0.5, or $\frac{1}{8}$ and $\frac{1}{2}$ in.), single-V-grooves of 60 to 80° and grooved copper backing are typically used. For section thicknesses greater than 12.7 mm (0.5, or $\frac{1}{2}$ in.), double-V-groove or double-U-groove joints are used. As with GTAW of copper-nickel alloys, backing material should be made of copper or copper-nickel rather than carbon, graphite, or steel.

Preheating and Postheating. The copper-nickel alloys have thermal conductivity equal to or lower than that of low-carbon steel. Therefore, no preheating or postheating is needed. However, interpass temperatures should be maintained below 65 °C (150 °F).

Shielded Metal Arc Welding

Both wrought and cast forms of copper-nickel alloys can be welded using SMAW. The weldability of these alloys is similar to that of low-carbon steels because the thermal conductivity of these alloys is quite similar to that of steel. Copper-nickel electrode ECuNi is used in welding the copper-nickel alloys C70600 and C71500 with DCEP.

The weld deposits ordinarily have a high center crown, and the slag is viscous when molten and quite adherent when cold. Therefore, special care is needed to ensure complete slag removal before complete solidification of the weld metal, to prevent slag entrapment when cleaning between passes. Welding in both the vertical and overhead positions using SMAW provides good results in these alloys, although best results are obtained in the flat position. This process is preferred in some applications where access to the joint is limited, as in the butt welding of copper-nickel pipe.

Welding of Dissimilar Metals

Copper and many copper alloys can be welded to other (dissimilar) copper alloys, to carbon and alloy steels, to stainless steels, and to nickel and nickel alloys using GTAW and GMAW. Tables 16 and 17 provide guidelines for joining copper and copper alloys to dissimilar metals.

Gas Tungsten Arc Welding

Copper and many copper alloys can be gas tungsten arc welded to other materials with good results. The use of a filler metal is typically required. Copper and its alloys have been readily gas tungsten arc welded to steels, stainless steels, nickel, and nickel alloys. Gas tungsten arc welding for the joining of these dissimilar metals is usually restricted to thin sections less than 3.2 mm (0.13, or $\frac{1}{8}$ in.) thick. Preliminary surface welding, also known as buttering, is ordinarily not required for thin sections. For section thicknesses exceeding 3.2 mm (0.13, or $\frac{1}{8}$ in.), the preferred joining process is GMAW or SMAW. Usually, when GTAW is used to join copper alloys to dissimilar metals, the arc is directed at the more conductive metal being welded. Table 16 shows combinations of dissimilar metals that are joined by GTAW with the aid of copper alloy or nickel alloy filler metals. The recommended filler metals, preheat temperature, and interpass temperature for each combination are given.

Except when one or both members of the joint being welded have high thermal conductivity, preheating is not required for GTAW of copper and dissimilar metals. This is restricted to section thicknesses of 3.2 mm (0.13, or $\frac{1}{8}$ in.) or less.

Gas Metal Arc Welding

The GMAW process can be used for joining nearly all combinations of the weldable copper alloys. Two major considerations when developing the GMAW procedures are: (1) the composition of the welding wire to be used as an electrode;

and (2) the preheat temperatures required. As with the other arc welding processes, the arc is typically directed at the more conductive material to concentrate the heat energy on this base metal.

The electrodes as well as preheat and interpass temperatures for GMAW of copper and copper alloys to dissimilar metals are given in Table 17. This table includes all alloys listed in Table 16 for GTAW, plus the high-zinc brasses, tin brasses, and special brasses. As is shown in Table 17, ERCuAl-A2 comes close to being the universal electrode for GMAW of dissimilar copper alloys. However, this filler metal is incompatible with phosphor bronzes. Silicon bronze (ERCuSi-A) and phosphor bronze (ERCuSn-A) electrodes are useful for many combinations of copper alloys that do not contain nickel. Copper electrodes (ERCu) are suitable for final welding passes (cap or cover passes) of coppers to any of the commonly welded copper alloys. Underlying or preliminary weld deposits are typically made with alloy electrodes. For joining copper to copper-nickel alloys, ERCuNi (copper-nickel) electrodes are generally used.

Generally, for welding dissimilar copper alloys, the electrode selected should be suitable for welding one of the materials within the combination to itself. The primary exception to this general rule is in the welding of silicon bronzes to copper-nickel alloys. The only electrode that can be used successfully for the joining of this combination is ERCuAl-A2.

As has been stated in earlier sections dealing with specific alloy groups, alloys which have susceptibility to hot cracking, oxide formation, or other deterrents to weld strength characteristics should be noted when welding a dissimilar-metal combination. Typically, the restrictions for preheat, interpass temperature, and surface cleansing that apply to the individual alloy also apply to that alloy when joining it to other copper alloys or other metal groups. Of particular importance is preheat and interpass temperature for alloys that exhibit hot shortness.

For GMAW of copper or copper alloys to ferrous or nickel alloys, the primary consideration is dilution. Strength is not a factor because it is quite easy to generate weld metal whose strength is equal to that of the two base materials. The difficulty is in retaining the ductility demanded by the in-service requirements of the weldment. The most serious effect of excessive dilution is the formation of shrinkage cracks. These can start in the weld metal itself and propagate into the base metal.

Two methods are frequently used to control dilution in GMAW of combinations involving copper alloys. The first is to braze one side of the joint, thus promoting a minimum amount of dilution on that side, and weld the other side of the joint. The second technique is to overlay one or both joint surfaces with a buffer material. This technique, known as buttering, is typically used on thicker sections. Filler-metal selection again should be based upon the composition of the base alloy and the requirements for weld-metal strength and ductility.

Safe Welding Practices

Many of the elements used in producing copper alloys, as well as copper itself, have low or very low permissible exposure limits, as set by the American Conference of Governmental Industrial Hygienists. These would include such elements as arsenic, beryllium, cadmium, chromium, lead, manganese, and nickel. When welding, brazing, or soldering copper or copper alloys, adequate ventilation is required to ensure that contaminant levels do not exceed the human exposure limits. Precautions may include local exhaust ventilation, general area exhaust ventilation, operator respiratory protection, or a combination of these. The reader is referred to ANSI/AWS Z49. 1, "Safety in Welding and Cutting," for detailed information.

Copper alloys that contain appreciable amounts of beryllium, cadmium, or chromium may present health hazards to the welder and others. Exposure to welding fumes containing these elements can produce adverse health defects. The user should consult the Occupational Safety and Health Administration guidelines for the specific element.

Fumes and dust of copper and zinc can cause irritation of the upper respiratory tract, nausea, metal-fume fever, skin irritation, dermatitis, and eye problems. It should be noted that cadmium and beryllium fumes are toxic when inhaled.

Fluxes used during welding, brazing, and soldering of certain copper alloys may contain fluorides and chlorides. Again, these fumes can be irritating to the eyes, nose, throat, and skin. Additionally, some fluorine compounds are toxic.

Proper personal hygiene must be emphasized, particularly before eating. Food and beverages should not be stored or consumed in and/or around the work area. Contaminated clothing

Table 16 Electrodes and preheat and interpass temperatures used in GTAW of copper and copper alloys to dissimilar metals

	Electrodes (with preheat and interpass temperatures) for welding metal in column 1 to:				
Metal to be welded	**Coppers**	**Phosphor bronzes**	**Aluminum bronzes**	**Silicon bronzes**	**Copper-nickel alloys**
Copper alloys					
Low-zinc brasses	ERCuSn-A or ERCu (540 °C, or 1000 °F)	…	…	…	…
Phosphor bronzes	ERCuSn-A or ERCu (540 °C, or 1000 °F)	…	…	…	…
Aluminum bronzes	ERCuAl-A2 (540 °C, or 1000 °F)	ERCuAl-A2 or ERCuSn-A (200 °C, or 400 °F)	…	…	…
Silicon bronzes	ERCuSn-A or ERCu (540 °C, or 1000 °F)	ERCuSi-A (65 °C max, or 150 °F max)	ERCuAl-A2 (65 °C max, or 150 °F max)	…	…
Copper-nickel alloys	ERCuAl-A2 or ERCuNi or ERCu (540 °C, or 1000 °F)	ERCuSn-A (65 °C max, or 150 °F max)	ERCuAl-A2 (65 °C max, or 150 °F max)	ERCuAl-A2 (65 °C max, or 150 °F max)	…
Nickel alloys					
Nickel and Ni-Cu alloys	ERCuNi or ERCuNi-7 (540 °C, or 1000 °F)	(a)	(a)	(a)	ERCuNi or ERCuNi-7 (65 °C max, or 150 °F max)
Ni-Cr, Ni-Fe, and Ni-Cr-Fe alloys	ERCuNi-3 (540 °C, or 1000 °F)	(a)	(a)	(a)	ERCuNi-3 (65 °C max, or 150 °F max)
Steels					
Low-carbon steels	ERCuAl-A2 or ERCu or ERCuNi-3 (540 °C, or 1000 °F)	ERCuSn-A (200 °C, or 400 °F)	ERCuAl-A2 (150 °C, or 300 °F)	ERCuAl-A2 (65 °C max, or 150 °F max)	ERCuAl-A2 or ERCuNi-3 (65 °C max, or 150 °F max)
Medium-carbon steels	ERCuAl-A2 or ERCu or ERCuNi-3 (540 °C, or 1000 °F)	ERCuSn-A (200 °C, or 400 °F)	ERCuAl-A2 (200 °C, or 400 °F)	ERCuAl-A2 (65 °C max, or 150 °F max)	ERCuAl-A2 or ERCuNi-3 (65 °C max, or 150 °F max)
High-carbon steels	ERCuAl-A2 or ERCu or ERCuNi-3 (540 °C, or 1000 °F)	ERCuSn-A (260 °C, or 500 °F)	ERCuAl-A2 (200 °C, or 400 °F)	ERCuAl-A2	ERCuAl-A2 or ERCuNi-3 (65 °C max, or 150 °F max)
Low-alloy steels	ERCuAl-A2 or ERCu or ERCuNi-3 (540 °C, or 1000 °F)	ERCuSn-A (260 °C, or 500 °F)	ERCuAl-A2 (260 °C, or 500 °F)	ERCuAl-A2 (200 °C, or 400 °F)	ERCuAl-A2 or ERCuNi-3 (65 °C max, or 150 °F max)
Stainless steels	ERCuAl-A2 or ERCu or ERCuNi-3 (540 °C, or 1000 °F)	ERCuSn-A (200 °C, or 400 °F)	ERCuAl-A2 (65 °C max, or 150 °F max)	ERCuAl-A2 (65 °C max, or 150 °F max)	ERCuAl-A2 or ERCuNi-3 (65 °C max, or 150 °F max)

Filler metal selections shown are based on weldability, except where mechanical properties are usually more important. Preheating usually is used only when at least one member is thicker than 3.2 mm (1/8 in.) or is highly conductive (see text). Preheat and interpass temperatures are subject to adjustment based on size and shape of weldment. (a) These combinations are seldom welded; as a starting point in developing welding procedures, use of ERCuAl-A2 filler metals is recommended, except for combinations including phosphor bronze.

Table 17 Electrodes and preheat and interpass temperatures used in GMAW of copper and copper alloys to dissimilar metals

	Electrodes (with preheat and interpass temperatures) for welding metal in column 1 to:						
Metal to be welded	Coppers	Low-zinc brasses	High-zinc brasses, tin, brasses, and special brasses	Phosphor bronzes	Aluminum bronzes	Silicon bronzes	Copper-nickel alloys
Copper alloys							
Low zinc brasses	ERCuSn-A or ERCu (540 °C, or 1000 °F)	…	…	…	…	…	…
High-zinc, tin, special brasses	ERCuSi-A or ERCuSn-A or ERCu (540 °C, or 1000 °F)	ERCuSn-A (315 °C, or 600 °F)	…	…	…	…	…
Phosphor bronzes	ERCuSn-A or ERCu (540 °C, or 1000 °F)	ERCuSn-A (260 °C, or 500 °F)	ERCuSn-A (315 °C, or 600 °F)	…	…	…	…
Aluminum bronzes	ERCuA1-A2 (540 °C, or 1000 °F)	ERCuA1-A2 (315 °C, or 600 °F)	ERCuA1-A2 (315 °C, or 600 °F)	ERCuA1-A2 or ERCuSn-A (200 °C, or 400 °F)	…	…	…
Silicon bronzes	ERCuSn-A or ERCu (540 °C, or 1000 °F)	ERCuA1-A2 or ERCuSi-A (65 °C, or 150 °F)	ERCuA1-A2 or ERCuSi-A (65 °C, or 150 °F)	ERCuSi-A (65 °C, or 150 °F)	ERCuA1-A2 (65 °C, or 150 °F)	…	…
Copper-nickel alloys	ERCuA1-A2 or ERCuNi or ERCu (540 °C, or 1000 °F)	ERCuA1-A2 (65 °C, or 150 °F)	ERCuA1-A2 (65 °C, or 150 °F)	ERCuSn-A (65 °C, or 150 °F)	ERCuA1-A2 (65 °C, or 150 °F)	ERCuA1-A2 (65 °C, or 150 °F)	…
Nickel alloys							
Nickel and Ni-Cu alloys	ERCuNi or ERCuNi-7 (540 °C, or 1000 °F)	(a)	(a)	(a)	(a)	(a)	ERCuNi or ERCuNi-7 (65 °C, or 150 °F)
Ni-Cr, Ni-Fe, and Ni-Cr-Fe alloys	ERCuNi-3 (540 °C, or 1000 °F)	(a)	(a)	(a)	(a)	(a)	ERCuNi-3 (65 °C, or 150 °F)
Steels							
Low-carbon steels	ERCuA1-A2 or ERCu or ERCuNi-3 (540 °C, or 1000 °F)	ERCuSn-A (315 °C, or 600 °F)	ERCuA1-A2 (260 °C, or 500 °F)	ERCuSn-A (200 °C, or 400 °F)	ERCuA1-A2 (150 °C, or 300 °F)	ERCuA1-A2 (65 °C, or 150 °F)	ERCuA1-A2 or ERCuNi-3 (65 °C, or 150 °F)
Medium-carbon steels	ERCuA1-A2 or ERCu or ERCuNi-3 (540 °C, or 1000 °F)	ERCuA1-A2 (315 °C, or 600 °F)	ERCuA1-A2 (260 °C, or 500 °F)	ERCuSn-A (200 °C, or 400 °F)	ERCuA1-A2 (150 °C, or 300 °F)	ERCuA1-A2 (65 °C, or 150 °F)	ERCuA1-A2 or ERCuNi-3 (65 °C, or 150 °F)
High-carbon steels	ERCuA1-A2 or ERCu or ERCuNi-3 (540 °C, or 1000 °F)	ERCuA1-A2 (315 °C, or 600 °F)	ERCuA1-A2 (260 °C, or 500 °F)	ERCuSn-A (260 °C, or 500 °F)	ERCuA1-A2 (260 °C, or 500 °F)	ERCuA1-A2 (200 °C, or 400 °F)	ERCuA1-A2 or ERCuNi-3 (65 °C, or 150 °F)
Low-alloy steels	ERCuA1-A2 or ERCu or ERCuNi-3 (540 °C, or 1000 °F)	ERCuA1-A2 (315 °C, or 600 °F)	ERCuA1-A2 (315 °C, or 600 °F)	ERCuSn-A (260 °C, or 500 °F)	ERCuA1-A2 (260 °C, or 500 °F)	ERCuA1-A2 (200 °C, or 400 °F)	ERCuA1-A2 or ERCuNi-3 (65 °C, or 150 °F)
Stainless steels	ERCuA1-A2 or ERCu or ERCuNi-3 (540 °C, or 1000 °F)	ERCuA1-A2 or ERCuSn-A (315 °C, or 600 °F)	ERCuA1-A2 (315 °C, or 600 °F)	ERCuSn-A (200 °C, or 400 °F)	ERCuA1-A2 (95 °C max, or 200 °F max)	ERCuA1-A2 (95 °C max, or 200 °F max)	ERCuA1-A2 or ERCuNi-3 (65 °C max, or 150 °F max)
Cast irons							
Gray and malleable irons	ERCuA1-A2 or ERCu (540 °C, or 1000 °F)	ERCuA1-A2 or ERCuSn-A (315 °C, or 600 °F)	ERCuA1-A2 (315 °C, or 600 °F)	ERCuSn-A (200 °C, or 400 °F)	ERCuA1-A2 (200 °C, or 400 °F)	ERCuA1-A2 or ERCuSi-A (150 °C, or 300 °F)	ERCuA1-A2 or ERCuNi-3 (65 °C max, or 150 °F max)
Ductile irons	ERCuA1-A2 or ERCu (540 °C, or 1000 °F)	ERCuA1-A2 (315 °C, or 600 °F)	ERCuA1-A2 (315 °C, or 600 °F)	ERCuSn-A (200 °C, or 400 °F)	ERCuA1-A2 (95 °C max, or 200 °F max)	ERCuA1-A2 or ERCuSi-A (150 °C max, or 300 °F max)	ERCuA1-A2 or ERCuNi (65 °C max, or 150 °F max)

Electrode selections in table are based on weldability, except where mechanical properties are usually more important. Preheating usually is used only when at least one member is thicker than 3.2 mm (1/8 in.) or is highly conductive (see text). Preheat and interpass temperature are subject to adjustment based on size and shape of weldment. (a) These combinations are seldom welded; as a starting point in developing welding procedures, use of ERCuA1-A2 electrodes is recommended, except for combinations including phosphor bronze.

should be changed. For more detailed information on safety considerations, see the article "Safe Practices" in *Welding, Brazing, and Soldering*, Volume 6 of *ASM Handbook*.

Other Non-Arc Fusion Welding Processes

Although the arc welding processes described earlier in this article are the most frequently employed welding methods, there are other fusion welding processes associated with joining of copper and copper alloys. These include oxyfuel gas welding, various resistance welding methods, electron beam welding, and, to a lesser extent, laser beam welding. Table 1 summarizes the applicability of these processes for major alloy classifications. More detailed information on non-arc fusion welding processes can be found in *Welding, Brazing, and Soldering*, Volume 6 of *ASM Handbook*, and in the selected references listed at the conclusion of this article.

Oxyfuel Gas Welding

General Welding Considerations. Oxyfuel gas welding (OFW) can be used for small, noncritical applications, including repair welding. Copper, with the exception of ETP copper, and some copper alloys, most notably the brasses, can be welded with the OFW process. The prime disadvantage of the OFW process is that the low heat input of the oxyacetylene flame makes welding slow compared to arc welding. To counterbalance the low heat input, higher preheat temperatures or an auxiliary heat source is often required, particularly with alloys with high conductivity or with thick sections. Welding fluxes are often required to exclude air from the weld metal at elevated temperatures.

Welding of Copper. Oxygen-free and deoxidized coppers can be welded using the OFW process. Because of the slow welding travel speed, preheat and auxiliary heating are recommended with thicknesses over 3.2 mm (0.13, or $\frac{1}{8}$ in.).

Type ERCu or ERCuSi filler metal can be used, depending on the desired joint properties. Both the welding rod and the joint surfaces should be coated with the appropriate flux, although oxygen-free copper can be welded without the use of a flux. The OFW flame should be neutral when flux is used, and slightly oxidizing when welding without flux.

Backhand welding is generally preferred for the flat position. Backhand technique can give a thicker bead than forehand welding, and oxide entrapment is less. Control of the molten weld pool is greatly improved when the joint axis is tilted about 10 to 15° and the direction of welding is uphill.

Completed weld beads may be peened to relieve welding stresses and increase the weld metal strength by cold working. Peening may be done either while the weld metal is still warm or after it cools to room temperature.

Welding of Cadmium and Chromium Coppers. Oxyfuel gas welding of cadmium copper requires a flux containing sodium fluoride and either fused borax or boric acid, or both, to dissolve cadmium oxides. The OFW process should not be used to join chromium copper because of problems caused by chromium oxide formation on weld faces.

Welding of Beryllium Coppers. The OFW process is not recommended for joining beryllium coppers because of problems caused by the tenacious surface oxide that inhibits wetting and fusion during welding.

Welding of Brasses. The OFW procedures outlined for copper are also suitable for brasses. The low brasses are readily joined by OFW, and the process is particularly suited for piping because it can be performed in all welding positions. Silicon bronze (ERCuSi-A) welding rod or one of the brass welding rods (RBCuZn-A, RBCuZn-B, or RBCuZn-C) may be used. Brass welding rods containing 38 to 41% Zn develop a significant proportion of the hard, strong beta phase in the weld metal. This beta phase is soft and ductile at elevated temperatures, and cracking is not a problem.

Very little zinc oxide appears on the molten weld metal surfaces when OFW with a neutral or slightly oxidizing flame. When a strongly oxidizing flame is used, an oxide film forms on the molten weld metal surface that suppresses evaporation of zinc, provided the weld metal is not overheated.

For OFW of high brasses, RBCuZn-B or RBCuZn-C welding rods are used. These low-fuming rods have compositions similar to the high brasses. A flux of AWS classification FB3-C, FB3-D, or FB3-K is required, and the torch flame should be adjusted to slightly oxidizing to control fuming. Preheating and an auxiliary heat source may also be necessary.

Welding of Phosphor Bronzes. Oxyfuel gas welding is not recommended for joining the phosphor bronzes. The wide HAZ and the slow cooling rate may result in hot cracking since phosphor bronzes are hot short susceptible. In an emergency, OFW with ERCuSn-A welding rods can be used if arc welding equipment is not available. If a color match is not essential, braze welding can be done with an OFW torch and RBCuZn-C welding rod. A commercial brazing flux and a neutral flame should be used.

Welding of Aluminum Bronzes. Problems with fluxing aluminum oxide from weld metal precludes the use of OFW for joining aluminum bronzes.

Welding of Silicon Bronzes. Oxyfuel gas welding should only be used when arc welding equipment is not available. Silicon bronzes can be oxyfuel gas welded using ERCuSi-A welding rod with a suitable flux and using a slightly oxidizing flame. Fixturing should not unduly restrict movement of the components during welding, and welding should be performed rapidly. Either forehand or backhand welding can be used, with the former preferred for thin sections.

Welding of Copper-Nickel Alloys. Oxyfuel welding of copper-nickel alloys should also be limited to applications where arc welding equipment is not available. Welding is performed using ERCuNi welding rods with a soft and slightly reducing flame. An oxidizing flame will form a cuprous oxide that will dissolve in molten metal, reduce corrosion resistance, and cause embrittlement. Preheat is not recommended. Liberal use of a flux made especially for nickel or copper-nickel alloys is necessary to protect the welding rod and base metal from oxidation.

Resistance Welding

Resistance welding incorporates a group of processes in which heat for welding is generated by the resistance to the flow of electrical current through the parts being joined. It is most commonly used to weld two overlapping sheets or plates that may have different thicknesses. Specific resistance welding processes used to join copper and copper alloys include resistance spot welding (RSW), resistance seam welding (RSEW), projection welding (PW), flash welding (FW), and high-frequency resistance welding (HFRW).

Copper and copper alloys that are frequently resistance welded are listed in Table 18, which gives nominal compositions, melting points (liquidus temperatures), relative thermal and electrical conductivities, and welding indexes for RSW. Leaded and other free-machining copper alloys, which are seldom resistance welded, are not listed in this table.

Resistance spot welding is widely used for joining coppers and copper alloys. Principal applications include welding sections up to about 1.52 mm (0.060 in.) thick, particularly those alloys with low electrical conductivities. Many copper alloys with low conductivities can be seam welded easily. Coppers are difficult to seam weld. Projection welding is not recommended for copper or for most brasses. Bronzes can be projection welded with satisfactory results in many applications. Flash welding can be used for joining round stock, tubing, sheet, and mill shapes made of copper and copper alloys, including some leaded copper alloys. Abutting ends, as they become plastic, must be pushed together with minimum upsetting force to produce a satisfactory weld. Copper and copper alloy tubing is frequently manufactured from strip in a tube mill using high-frequency resistance welding. The edges of the weld joint are resistance heated to welding temperature utilizing the skin effect with high-frequency current. The heated edges are forged together continuously in the tube mill to consummate a weld.

Welding Characteristics

The resistance weldability of any copper or copper alloy is inversely proportional to its electrical and thermal conductivities. Generally, alloys with lower conductivities are easier to weld (see Table 18) and require lower welding currents (see Tables 18 and 19). Compared to steel, most copper alloys require shorter weld time, lower electrode force, higher current, and different electrode materials that are compatible with the alloy being welded. The conditions for spot welding various copper alloys are given in Table 19.

Minimum spot spacing and contacting overlap for RSW of high-zinc brasses are given in Table 20. When workpieces of unequal thickness are welded, spot spacing should be equal to the minimum spacing recommended for the average thickness. The values listed for contacting overlap are designed to prevent bulging of the edge and expulsion of weld metal in welding workpieces that are manually positioned between the electrodes. The contacting overlap can sometimes be less than shown when the workpieces are held in fixtures. Breaking loads in shear of spot welded joints are also listed in Table 20.

Welding Equipment

Single-phase and three-phase direct-energy and electrostatic stored energy (capacitor-discharge) welding machines are used for resistance welding of copper and copper alloys. The addition of slope control to single-phase direct-energy welding machines is not necessary for spot welding most copper alloys. In welding high-zinc brasses, the use of upslope can result in an increase of as much as 20% in weld strength. Downslope is not recommended for welding of any of the copper alloys.

Welding Machine Controls. Copper alloys are particularly sensitive to variations in welding conditions, and therefore all direct-energy machines used for welding these alloys should be equipped with synchronous electronic controls, especially in applications requiring short weld times. These devices are capable of controlling weld time and welding current for repeated operations with extreme accuracy.

Electrodes

The current used for resistance welding of copper alloys is much higher than that used for welding low-carbon steel, and therefore, the electrode must have high electrical conductivity to minimize heat buildup.

Electrode Materials. The Resistance Welder Manufacturers Association (RWMA) class 1 electrode materials (typically tungsten or molybdenum alloys), containing copper and cadmium, are sometimes used for welding copper and high-conductivity brass and bronze. Class 2

Table 18 Nominal compositions, melting points, relative thermal conductivities, relative electrical conductivities, and RSW indexes for some coppers and copper alloys

		Nominal composition, %					Melting point (liquidus)				
UNS No.	Alloy name	Cu	Zn	Sn	Ni	Other	°C	°F	Relative thermal conductivity(a), %	Relative electrical conductivity(b), % IACS	Welding index(c)
OF and ETP coppers											
C10200	Oxygen-free copper (OF)	99.95	…	…	…	…	1083	1981	100	101	(d)
C11000	Electrolytic tough pitch copper (ETP)	99.90	…	…	…	0.04 O	1083	1981	100	101	H-350
Deoxidized coppers											
C12000	Phosphorus-deoxidized copper, low residual phosphorus (DLP)	99.9	…	…	…	0.008 P	1083	1981	99	98	(d)
C12200	Phosphorus-deoxidized copper, high residual phosphorus (DHP)	99.9	…	…	…	0.02 P	1083	1981	87	85	(d)
Beryllium coppers											
C17500	High-conductivity beryllium copper, 0.6%	96.9	…	…	…	0.6 Be, 2.5 Co	1068	1955	53–66(e)	45(e)	(f)
C17000	High-conductivity beryllium copper, 1.7%	98.3	…	…	…	1.7 Be	982	1800	27–33(e)	22(e)	C-150
C17200	High-strength beryllium copper, 1.9%	98.1	…	…	…	1.9 Be	982	1800	27–33(e)	22(e)	C-150
Chromium copper											
C18400	Chromium copper	99.2	…	…	…	0.8 Cr	1075	1967	83(e)	80(e)	(d)
Low-zinc brasses											
C21000	Gilding, 95%	95	5	…	…	…	1066	1950	60	56	H-200
C22000	Commercial bronze, 90%	90	10	…	…	…	1043	1910	48	44	H-200
C23000	Red brass, 85%	85	15	…	…	…	1027	1880	41	37	H-200
C24000	Low brass, 80%	80	20	…	…	…	999	1830	36	32	G-175
High-zinc brasses											
C26000	Cartridge brass, 70%	70	30	…	…	…	954	1750	31	28	E-150
C26800, C27000	Yellow brass, 65%	65	35	…	…	…	932	1710	30	27	F-150
C28000	Muntz metal, 60%	60	40	…	…	…	904	1660	31	28	F-150
Tin brasses											
C44300 to C44500	Inhibited admiralty brass	71	28	1	…	(g)	938	1720	28	25	(f)
C46400 to C46700	Naval brass	60	39	0.8	…	(h)	899	1650	30	26	(f)
Special brasses											
C66700	Manganese brass	70	28	…	…	1.2 Mn	1093	2000	25	17	(f)
C67500	Manganese bronze A	58.5	39	1	…	1.4 Fe, 0.1 Mn	888	1630	27	24	C-125
C68700	Aluminum brass, arsenical	77.5	20.5	…	…	2 Al, 0.06 As	971	1780	26	23	(f)
C69400	Silicon red brass	81.5	14.5	…	…	4 Si	918	1685	7	6.2	(f)
Nickel silvers											
C74500	Nickel silver 65–10	65	25	…	10	…	1021	1870	12	9	C-125
C75200	Nickel silver 65–18	65	17	…	18	…	1110	2030	8	6	C-125
C75400	Nickel silver 65–15	65	20	…	15	…	1077	1970	9	7	C-125
C75700	Nickel silver 65–12	65	23	…	12	…	1038	1900	10	8	(f)
C77000	Nickel silver 55–18	55	27	…	18	…	1054	1930	8	5½	(f)
Phosphor bronzes											
C50500	Phosphor bronze, 1.25% E	98.7	…	1.3	…	0.3 P	1077	1970	53	48	G-200
C51000	Phosphor bronze, 5% A	94.8	…	5	…	0.2 P	1049	1920	18	15	D-125
C52100	Phosphor bronze, 8% C	92	…	8	…	0.3 P	1027	1880	16	13	D-125
C52400	Phosphor bronze, 10% D	90	…	10	…	0.3 P	999	1830	13	11	D-125
Aluminum bronzes											
C61300	Aluminum bronze D, Sn-stabilized	92.7	…	0.30	…	7 Al, 3.5 Fe	1046	1915	14	12	(f)
C61400	Aluminum bronze D	91	…	…	…	7 Al, 2 Fe, 1 Mn	1046	1915	17	14	(f)
C63000	Aluminum bronze	82	…	…	5	1.5 Mn, 3 Fe, 10 Al	1054	1930	10	7	(f)
Silicon bronzes											
C65100	Low-silicon bronze B	98.5	…	…	…	1.5 Si	1060	1940	15	12	B-125
C65500	High-silicon bronze A	97	…	…	…	3 Si	1027	1880	9	7	B-125
Copper-nickels											
C70600	Copper-nickel, 10%	88.6	…	…	10	1.4 Fe, 1.0 Mn	1149	2100	12	9	(f)
C71500	Copper-nickel, 30%	69.5	…	…	30	0.5 Fe	1238	2260	8	4.6	C-125

(a) Based on alloy C10200, which has a thermal conductivity of 226 Btu · ft/h · °F, as 100%. For comparison, 1010 steel has a thermal conductivity of 30 Btu · ft/h · °F or about 13% on this relative scale. (b) The ratio of the resistivity of the International Annealed Copper Standard at 20 °C to the resistivity of the material at 20 °C, expressed in percent and calculated on a volume basis. (c) Welding index from the Third Edition of Volume 1 of the "Resistance Welding Manual," published by the Resistance Welder Manufacturers Association. A is the basis of comparison and is the equivalent of conditions for clean, cold rolled steel. B indicates that the alloy is readily weldable, but not as easily as steel, C, D, E, F, and G represent progressive stages of increasing difficulty. G indicates that the alloy can be successfully welded, but 100% uniform results cannot be expected. H includes those metals which are considered commercially impractical to spot weld. The numbers following the letters indicate the approximate percentage of secondary current required, based on mild steel = 100. (d) Alloys not having a spot welding index by RWMA, but which are listed as not recommended for spot welding by the Copper Development Association. (e) In precipitation-hardened condition. (f) Alloys not having a spot welding index by RWMA, but which are listed as good or excellent under suitability for being joined by spot welding by the Copper Development Association. (g) Alloys C44300, C44400, and C44500 contain 0.02 to 0.10% As, Sb, or P, respectively. (h) Alloys C46500, C46600, and C46700 contain 0.02 to 0.10% As, Sb, or P, respectively.

materials, containing copper and chromium, are used on low-conductivity brass and bronze and the copper-nickel alloys. Class 3 materials are used in electrodes for seam welding.

Electrodes must be sufficiently water cooled to minimize sticking to the work metal and to prolong their life. Face contours must be carefully prepared and the electrodes must be properly aligned for welding.

Table 19 Guidelines for resistance spot welding of selected copper alloys

		Welding parameter(a)			
			Electrode force		
UNS No.	Alloy name	Weld time, cycles	kN	lbf	Welding current, A
C23000	Red brass	6	1.8	400	25,000
C24000	Low brass	6	1.8	400	24,000
C26000	Cartridge brass	4	1.8	400	25,000
C26800–C27000	Yellow brass	4	1.8	400	24,000
C28000	Muntz metal	4	1.8	400	21,000
C51000–C52400	Phosphor bronze	6	2.3	510	19,500
C62800	Aluminum bronze	4	2.3	510	21,000
C65100–C65500	Silicon bronze	6	1.8	400	16,500
C66700	Manganese brass	6	1.8	400	22,000
C68700	Aluminum brass	4	1.8	400	24,000
C69200	Silicon brass	6	2.3	510	22,000

(a) For spot welding 0.91 mm (0.036 in.) thick sheet using RWMA type E electrodes with 4.8 mm (3/16 in.) diam face and 30° chamfer and made of RWMA class 1 material

Table 20 Guidelines for resistance spot welding of high-zinc brasses

Thickness of thinnest sheet		Minimum spot spacing		Minimum contacting overlap(a)		Shear load of joint	
mm	in.	mm	in.	mm	in.	kN	lbf
0.81	0.032	16	5/8	13	1/2	1.47	330
1.27	0.050	16	5/8	16	5/8	2.28	512
1.63	0.064	19	3/4	19	3/4	3.02	680
2.39	0.094	25	1	25	1	5.20	1168
3.18	0.125	38	1 1/2	32	1 1/4	8.33	1872

(a) Minimum edge distance is equal to one half the contacting overlap.

Selection of Process

Weldability of the work metal often determines which process should be used for a given application. Some of the coppers and copper alloys can be spot welded, but not seam welded because of high conductivity, and not projection welded because of low compressive strength of the projections at elevated temperature. For further discussion, see the subsequent sections of this article on specific alloys. In welding dissimilar metals, heat balance can also be important in the choice of process.

Spot and seam welds can be made in work metal as thin as 0.025 mm (0.001 in.). Spot welding of metal as thick as 3.2 mm (0.125 in.) has been reported for copper alloys. Projection welding is best suited for work thicker than 0.5 mm (0.020 in.).

The use of projection welding frequently can increase the quality of joints in high-conductivity alloys because welding current can be concentrated where needed. Distortion and electrode pickup are minimized because the electrode contacts a large area of the work metal. Projection welding may be preferred when the components are self-locating or to simplify fixturing or improve dimensional accuracy.

Lap joints that must be liquid-tight usually are made most efficiently by seam welding. However, if a seam does not require the leak-tightness provided by over-lapping spots, spot welding is frequently preferred.

Electrode forces lower than those needed for welding low-carbon steel are used, but extremely low forces, which can cause electrode pickup and weak welds, should be avoided. Low electrode force can also cause high-zinc alloys to flash or burn through.

Seam welding is nearly impossible on copper and many of the high-copper alloys, but most low-conductivity copper alloys can be seam welded readily using higher welding current and lower electrode force than those used for welding low-carbon steel. The usual spot spacing is 12 to 18 spots per inch. If fewer than 12 spots per inch are used, the spots sometimes do not overlap. Spots that are too closely spaced can cause excessive hot working of the base metal. Cooling by flooding, immersion, or mist protects the work metal and electrodes from overheating and electrode pickup.

Projection welding is best suited for copper alloys of less than 30% IACS electrical conductivity. The design of the projections in relation to the thickness and type of work metal is important. In general, to prevent collapse of the metal in the projection before welding temperature is reached, coined projections are preferred to formed projections.

Flash welding techniques produce very good results on copper and copper alloys. The design of the equipment must provide accurate control of all factors, including upset pressure, platen travel, flash-off rate, current density, and flashing time.

Leaded copper alloys can be flash welded, but the integrity of the joint depends upon the alloy composition. Lead content of up to 1.0% is usually not detrimental.

Rapid upsetting at minimum pressure is necessary as soon as the abutting faces are molten because of the relatively low melting temperature and narrow plastic range of copper alloys. Low pressure is usually applied to the joint before the flashing current is initiated so that platen motion will begin immediately after flashing starts. Termination of flashing current is critical. Premature termination of current will result in lack of fusion at the weld interface. Excessive flashing will overheat the metal and result in improper upsetting.

Preweld Cleaning

Dirt, scale, oil, drawing compound, or other foreign matter on the surface of the workpiece should be removed before resistance welding. An indication of surface cleanness is the surface contact resistance, which should be uniform for best welding results. High or erratic contact resistance usually causes poor welds rather than reduced electrode life, although increased electrode pickup is an indication of high surface resistance. Surface cleaning can be done by various mechanical or chemical methods described in the article "Surface Engineering" in this Handbook.

Resistance Welding of Specific Alloy Groups

Copper. Copper and copper alloys having electrical conductivity higher than about 30% IACS (see Table 18) are the least well suited for resistance spot, projection, or seam welding, mainly because of severe electrode pickup. Thin copper stock can be welded using electrodes faced with RWMA class 13 (tungsten) or class 14 (molybdenum), but surface appearance is poor and frequent electrode maintenance is required. A tinned coating on wire or sheet is helpful in welding copper.

Beryllium-copper alloys can be resistance welded most successfully in thin gages. Spot welding produces satisfactory welds; seam welding is less successful. Projection welding is satisfactory, provided that the projections can be formed with the work metal in the annealed condition and without cracking the work metal around the projection. Close control of welding conditions is required for consistent weld size and joint strength.

Oxide films produced by heat treating must be removed to ensure low and consistent contact resistance. Work metals that have not been heated after rolling frequently need only degreasing before welding.

Low electrical conductivity (22% IACS for alloys C17000 and C17200) contributes to the weldability of beryllium-copper alloys. However, they are more difficult to resistance weld than low-carbon steel. Alloy C17500 has an electrical conductivity of 45% IACS and is more difficult to resistance weld than higher-strength, lower-conductivity beryllium copper.

Low- and High-Zinc Brasses. The low-zinc brasses are difficult to weld, although easier than copper, and are subject to electrode pickup. Welds made in these brasses may lack strength, principally because of comparatively high electrical conductivity (32 to 56% IACS).

The high-zinc brasses have an electrical conductivity of 27 to 28% IACS and can be both spot and projection welded over a wide range of conditions. Electrode pickup can be a problem unless weld time, welding current, and electrode force are properly selected.

Excessive electrode pickup and blowthrough of the weld may occur when long weld times, high energy input, and low electrode forces are used. Yellow brasses (alloys C26800 and C27000) are less susceptible to electrode pickup than cartridge brass except when long weld times and high energy input are used. Electrode force should be sufficient to prevent arcing or expulsion of molten metal, to which these alloys are subject because of their 30 to 40% Zn content, which boils at about 905 °C (1665 °F). As shown in Table 19, the recommended electrode force, when using electrodes having a face diameter of 4.8 mm ($^3/_{16}$ in.), is approximately 1.8 kN (400 lbf).

The copper-nickel alloys have electrical conductivities of 4.5 to 11% IACS, are readily spot and seam welded with relatively low welding current, and generally do not alloy with the electrode material and cause electrode pickup.

Bronzes. The phosphor bronzes, except alloy C50500, which is not recommended for resistance spot and seam welding because of its high electrical conductivity (48% IACS), have relatively low electrical conductivity (11 to 20% IACS) and are readily spot and seam welded using low welding currents. Electrode pickup can be reduced by use of a type F (radius) electrode face and frequent redressing to keep the face clean and smooth. Hot shortness can be minimized by supporting the workpieces to prevent strain during welding and by using a greater minimum overlap than recommended by the data in Table 20.

Silicon bronze alloys (7 to 12% IACS conductivity) are the most easily resistance spot and seam welded of all copper alloys. Low welding current and low electrode force (see Table 19) usually are required. Short weld times should be avoided, to prevent shrinkage voids. The surface oxides that develop during annealing must be removed to ensure low and consistent surface contact resistance.

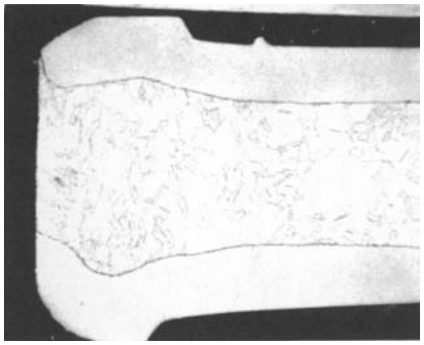


Fig. 4 Metallographic cross section of the edge of a cupronickel-clad copper coin.

Resistance welding of aluminum bronze is similar to resistance welding of silicon bronze, but with much more electrode pickup and expulsion of weld metal, which can be controlled by careful adjustment of weld time, welding current, and electrode force.

Nickel silvers, which have about the same conductivities (6 to 10.9% IACS) as copper-nickels, are spot welded as readily as copper-nickels but are more difficult to seam weld. Surface contaminants such as lead and bismuth (which form low-melting eutectics with copper and nickel) or sulfur (which may be introduced in forming) must be removed before resistance welding.

Safety

In resistance welding of copper alloys, a ventilation system may be needed because many copper alloys contain at least small amounts of toxic alloying elements. However, the need for ventilation is less critical for resistance welding operations than for arc welding operations because a smaller volume of metal is heated and a smaller volume of fumes is generated.

Electron Beam and Laser Beam Welding

The high-heat-intensity electron beam welding (EBW) and laser beam welding (LBW) processes are used for more specialized applications. Although these methods offer improved productivity because of their high travel speed, equipment costs are much higher than arc, oxyfuel, and resistance welding processes.

The EBW of copper and its alloys is influenced by the same factors that affect the arc welding of these metals. The high thermal conductivity of copper causes less difficulty in EBW than in arc welding.

Molten metal may be expelled from the weld joint during EBW of nondeoxidized coppers (especially alloy C11000, tough pitch copper), causing spatter and uneven weld surfaces. This can usually be remedied by the use of a cosmetic pass. The vacuum environment eliminates possible hydrogen embrittlement; nevertheless, root voids and porosity still can occur.

The presence of low-melting elements ordinarily makes the welding of free-machining copper alloys impractical, and the volatility of zinc prevents the welding of the brasses and other zinc-containing copper alloys. As shown in Table 1, the remaining zinc-free copper alloys can generally be electron-beam welded without any unusual problems.

The LBW of copper and its alloys has very limited applications. The primary difficulties with LBW of copper are the high reflectivity to the incident laser beam and the high thermal conductivity of copper and copper alloys. Copper reflects approximately 99% of the incident light energy of the far infrared wavelength of the CO_2 laser. This is the reason copper is commonly used for mirrors in CO_2 laser beam delivery systems. Reflectivity is temperature dependent; when a material gets hotter, the absorption of the incident light increases. However, the high thermal conductivity of copper prevents the metal from getting hotter, thereby maintaining high reflectivity.

Solid-State Welding

Solid-state welding processes are those that produce coalescence of the faying surfaces at temperatures below the melting point of the base metal being joined without the addition of brazing or soldering filler metal. Pressure may or may not be applied. These processes involve either the use of deformation or of diffusion and limited deformation in order to produce high-quality joints between both similar and dissimilar materials.

Diffusion welding, also referred to as diffusion bonding, involves minimal pressurization, but relatively high temperatures and long periods of time. In its simplest form, the process involves holding premachined and cleaned parts in intimate contact, and then heating them in a protective atmosphere. As its name implies, diffusion has a major role in the joining of mating parts, although other mechanisms, such as microyielding and oxide dissolution, are also critical steps in successful welding.

Industrial applications for diffusion welded copper or copper alloys are limited. Copper bonds to itself readily, if the surface oxide can be disrupted, and temperatures ranging from 850 to 950 °C (1560 to 1740 °F) have been employed. Alternatively, a liquid-phase procedure that utilizes silver as an interlayer has been adopted to reduce welding times. Copper/aluminum dissimilar welds have also been processed by diffusion welding.

Friction welding is a solid-state welding process that uses compressive force of the workpieces that are rotating or moving relative to one another, producing heat and plastically displacing material from the faying surface, thereby creating a weld. Friction welding has been used to join similar metals (e.g., copper to copper and brass to brass) and dissimilar metals. Examples of the latter include friction welding of copper, brass, bronze, and copper-nickel to carbon steel, stainless steel, titanium, and aluminum. Copper/aluminum alloy 1100 dissimilar welds are the most common.

Roll welding, also referred to as roll cladding, is a process in which two or more sheets or plates are stacked together and then passed through rolls until sufficient deformation has occurred to produce solid state welds. Both cold roll welding and hot roll welding methods are employed.

As shown in Table 21, copper and copper alloys are commonly roll welded with carbon steels, aluminum alloy 1100, and stainless steels. A key roll welding/cladding application is the production of coins by the U.S. Mint. Silver shortages in the 1960s and 1970s resulted in the introduction of coins made from new materials.

These coins required a unique set of properties for acceptance by the general public and use in automatic vending machines. Copper clad with cupronickel was found to meet these requirements (Fig. 4). The cladding process is relatively simple, although stringent in its requirement for surface preparation. Cladded strips are produced by continuous rolling with the surfaces prepared just prior to rolling by processes such as wire brushing. Welding typically is accomplished in a single rolling pass. Subsequent heat treatments may be employed to improve the weld quality by processes such as sintering, diffusion, and recrystallization.

The starting material for the U.S. quarter is two outer layers of 75Cu-25Ni, each 1.2 mm (0.048 in.) thick, with an inner layer of pure copper that is 5.1 mm (0.20 in.) thick. To obtain good bond strength, the surfaces are chemically cleaned and wire brushed. The strips are then roll welded to a combined thickness of 2.29 mm (0.090 in.) (Fig. 5). A second rolling operation reduces the final thickness 1.36 mm (0.0535 in.). The strips thus undergo a total reduction of 82%.

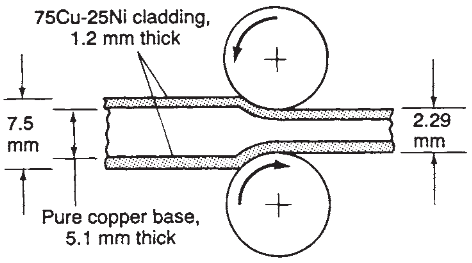


Fig. 5 Schematic showing 70% reduction in cross section of a U.S. Mint quarter coin (composed of an inside layer of pure copper sandwiched between two thin layers of cupronickel material) as it undergoes an initial roll welding operation. A second rolling operation further reduces the material to a final thickness of 1.36 mm (0.0535 in.) for a total reduction of 82%.

Cold welding, also referred to as cold pressure welding, is a solid-state joining process in which pressure is used at room temperature to produce coalescence of metals with substantial deformation at the weld. During cold welding, oxide layers are destroyed, exposing clean metal surfaces on the two components to be welded. Cold pressure welding can be accomplished by deforming in lap or butt configurations, drawing, or extrusion. Examples of copper/aluminum dissimilar welds are shown in Fig. 6 and 7.

Ultrasonic welding is a quasi-solid-state process that produces a weld by introducing high-frequency vibration to the weldment as it is held under moderately high clamping forces. The weld is produced without significant melting of the base materials. Ultrasonic welding is

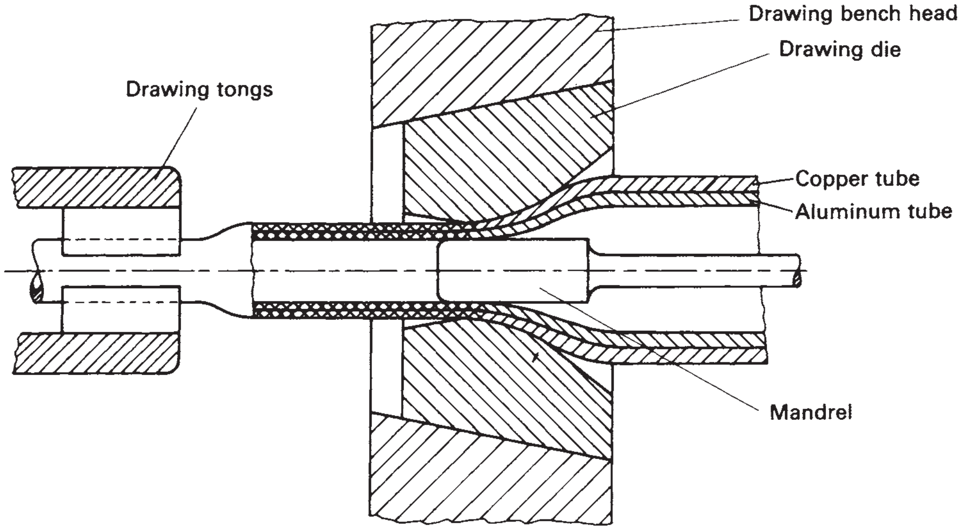


Fig. 6 Multilayer copper-aluminum tube produced by cold pressure draw welding

Table 21 Typical properties and applications of common roll welded clad laminates

Materials system	Composite ratio, %	Thickness		Width		Tensile strength		Yield strength		Elongation, %	Application
		mm	in.	mm	in.	MPa	ksi	MPa	ksi		
Copper 10300/ low-carbon steel	50:50	0.25–2.54	0.010–0.100	12.7–50	0.5–2	260(a)	38(a)	215(a)	31(a)	40(a)	Typically used for commutators in electric motors, replacing copper 10400. The lower conductivity of steel causes less heat loss during welding, resulting in faster, better quality welds. The added strength of steel allows thickness reduction.
Deoxidized copper/ carbon steel/ deoxidized copper	5:90:5, 10:80:10, 15:70:15	0.25–2.54	0.010–0.100	≤610	≤24	420(b)	61(b)	250(b)	36(b)	35(b)	Used in heat exchangers, replacing brazing shim material. One-piece manufacturing eliminates separate shims and reduces assembly cost. Because no ferrous surfaces are exposed, no flux is needed.
Copper 11000/ 1100 aluminum	50:50	0.51–2.54	0.020–0.100	50–510	2–20	180(c)	26(c)	12(c)	1.7	35(c)	Developed specifically for transition joints between copper and aluminum in refrigeration equipment. Usually used in the form of deep-drawn tubing.
Copper 10300/ type 430 stainless steel/ copper 10300	17:66:17, 20:60:20, 33:34:33	0.10–0.15	0.004–0.006	12.7–150	0.5–6	415(d)	60(d)	275	40	20(d)	Replaces heavier gages of copper and bronze in buried communications cable. The stainless steel provides resistance to gnawing by rodents, which is a serious problem in underground installations.
Phosphor bronze 51000/ carbon steel/copper	10:85:5	0.38–1.52	0.015–0.060	≤610	≤24	455(e)	66(e)	435	63	16(e)	Used in automotive applications, such as windshield-wiper bearings. The bronze provides the bearing qualities, the steel provides strength, and the copper aids tooling life and provides corrosion resistance in service.

(a) In eighth hard-temper. (b) 10:80:10 material. (c) In three-quarter-hard temper. (d) 20:60:20 material. (e) In quarter-hard temper

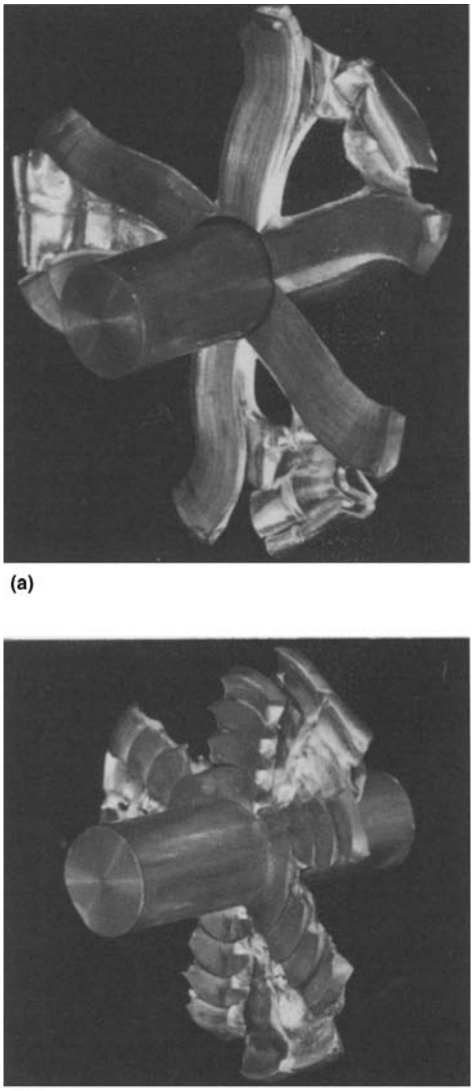


Fig. 7 Copper-aluminum butt joints obtained by cold pressure welding two 20 mm (in.) bars using two different methods. (a) Cold pressure butt welding with continuous thrust. (b) Multiple-step upsetting method. Note the substantial deformation at the weld interface. This upset metal is normally removed automatically.

an attractive technique for fabricating electrical and electronic assemblies requiring the joining of thin-gage metals. As described subsequently, many such applications involve combinations of copper, brass, and aluminum.

Both single and stranded wires can be welded to other wires and to terminals. In joining stranded or braided wires, the individual wires are consolidated into a single mass. Typical examples are shown in the brush assemblies of Fig. 8. In the starter brush plate, two stranded copper wires are welded to copper-plated steel. The truck starter brush involves stranded copper wire welded to brass. Formerly, this type of assembly required rivet attachment and crimping of a copper bridge, followed by soldering to achieve electrical conductivity. The ultrasonic joints, made with a contoured tip within about 1 s for each weld, provide low resistance, as well as savings in time and material.

Fig. 8 Ultrasonically welded brush assemblies. (a) Starter brush plate. (b) Truck starter brush

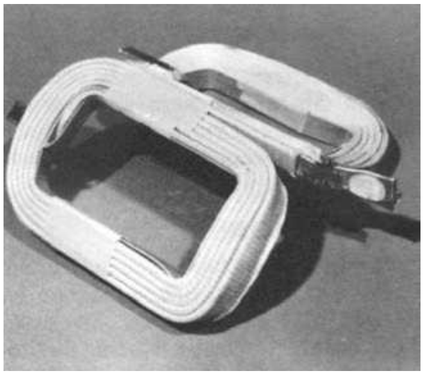


Fig. 9 Portion of ultrasonically welded field coil assembly

Reliable welds in field coil assemblies, wire harness systems, induction coils, and transformer terminations can also be made with ultrasonic welding. Figure 9 shows one joint of a typical field coil. To assemble the complete device, stranded copper wire is joined to aluminum ribbon, copper ribbon to aluminum ribbon, and aluminum ribbon to itself. These joints are made ultrasonically to achieve high strength and conductivity.

Completely automated equipment has been developed for welding automotive starter motor armatures such as that in Fig. 10. The armature has a slotted commutator with risers into which pairs of copper wires 3.2 mm (0.125 in.) thick are inserted. Previously, the wires were soldered into the slots; when the armature was exposed to excessive electrical current, however, as in cold starting conditions, the solder would soften and melt, the wires would spin free, and the armature failed. With ultrasonic welding, the wires are welded to each other and to the sides of the slot with a single weld pulse. Such joints do not lose strength at temperatures up to at least 150 °C (300 °F). An automated index-and-weld system permits joining pairs of wires into a 25-slot commutator in a cycle time of 20 s for a production rate of three armatures/min or 180/h.

ACKNOWLEDGMENTS

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- Resistance Welding of Copper and Copper Alloys, *Welding, Brazing, and Soldering*, Vol 6, 9th ed., *Metals Handbook*, American Society for Metals, 1983, p 545–556

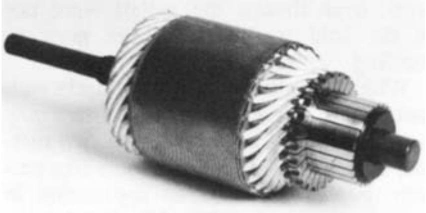

Fig. 10 Automotive starter motor armature with ultrasonically welded wires to commutator

In addition, information was included from numerous articles dealing with solid-state welding methods that have been published in both Volume 6 of *ASM Handbook* (current edition) and *Metals Handbook* (9th edition).

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Brazing, Soldering, and Adhesive Bonding

BRAZING AND SOLDERING processes are frequently used to join copper and copper alloys. Brazing, by definition, employs filler metals having a liquidus above 450 °C (840 °F) and below the solidus of the base metal. Brazing is distinguished from soldering by the melting point of the filler metal; solders melt below 450 °C (840 °F). Brazing and soldering are used to join structural components, commercial and consumer products, and electrical and electronic devices.

Adhesive bonding is a materials joining process in which an adhesive (usually a thermosetting or thermoplastic resin) is placed between faying surfaces and solidifies to produce an adhesive bond. In terms of production cost, ability to accommodate manufacturing tolerances and component complexity, facility and tooling requirements, reliability, and repairability, adhesive bonding is very competitive when compared to other joining methods.

Brazing

Copper and copper alloys are among the most easily brazed metals available. A wide range of filler metals is used to join the many different copper and copper alloys, and all the conventional brazing processes can be employed. These include furnace, torch, induction, resistance, and dip brazing. The selection of the brazing process and filler metal depends on the alloy composition, the shape and dimension of the parts to be joined, and the intended application.

Metallurgical Considerations

Because the brazeability of most copper alloys is very good, the material considerations are generally not as difficult as those of some other metals. However, the specific metallurgy of the individual copper or copper alloy is an important factor and should be considered when selecting a manufacturing method. Most brazing operations will result in recrystallization of the copper alloy being joined. Fine grain sizes can be eliminated and the cold-working step removed, which may or may not be desirable. Often, electrical conductivity is an important factor in a copper alloy brazed joint when overall resistance across the joint must be controlled. Therefore, the finished metallurgical structures, grain sizes, and mechanical properties of the specific copper alloy must be considered when brazing is utilized.

The metallurgical structures of brazed joints are largely those of the brazing filler metal, enriched with copper from the parent material. Because some surface melting of the copper alloys being joined occurs, the interfaces usually show primary dendrites of a copper-rich phase growing from the copper alloy and braze metal interface. The brazing filler metal becomes more copper-rich, producing additional dendritic growth with increased brazing temperature and time.

Brazeabilty

As shown in Table 1, the brazeabilty of copper and copper alloys generally ranges from good to excellent. With some alloys, however, some difficulties may be encountered. For example, some lead-containing alloys can form a dross that interferes with wetting; tin-containing alloys, if not stress relieved before brazing, may crack when subjected to rapid localized heating. Aluminum bronzes containing more than 8% Al require special techniques because of the tenacious refractory oxides that form on their surfaces.

Coppers. Included in this group are oxygen-containing or tough pitch, phosphorus-deoxidized, and oxygen-free coppers, together with coppers containing not more than about 1% of an additive element, such as silver, zirconium, chromium, lead, selenium, tellurium, or sulfur.

Tough pitch coppers are subject to embrittlement when heated in reducing atmospheres containing hydrogen. At temperatures above 480 °C (900 °F), even relatively small amounts of hydrogen lead to embrittlement and internal cavitation caused by the reduction of copper oxide and the formation of high-pressure steam within the solid metal. Consequently, although tough pitch coppers are generally rated as having good to excellent brazeability, they should not be brazed in a furnace that contains hydrogen at a reducing potential such as dissociated ammonia or in an exothermic-based or endothermic-based atmosphere. Heating by open flame or by torch also may result in hydrogen diffusion and embrittlement.

Phosphorous-deoxidized and oxygen-free coppers can be brazed without flux in hydrogen-containing atmospheres without risk of embrittlement, provided self-fluxing filler metals (BCuP series) are used. The use of flux is required, however, when the silver alloy filler metals that contain additives such as zinc, cadmium, or lithium (BAg series) are used to braze these coppers or to braze these coppers to copper alloys or other metals.

The coppers, including those that contain small additions of silver, lead, tellurium, selenium, or sulfur (generally no more than 1%), are

Table 1 Brazing and soldering characteristics of the major classes of coppers and copper alloys

Alloy	UNS No.	Rating(a) Brazing	Rating(a) Soldering
ETP copper	C11000–C11900	E	G
Oxygen-free copper	C10200	E	E
Deoxidized copper	C12000–C12300	E	E
Beryllium copper	C17000–C17500	G	G
Cadmium/chromium copper	C16200–C18200	G	G
Red brass, 85%	C23000	E	E
Low brass, 80%	C24000	E	E
Cartridge brass, 70%	C26000	E	E
Leaded brasses	C31400–C38590	E	G
Phosphor bronzes	C50100–C52400	E	E
Copper-nickel, 30%	C71500	E	E
Copper-nickel, 10%	C70600	E	E
Nickel silvers	C75200	E	E
Aluminum bronze	C61300, C61400	F	NR
Silicon bronzes	C65100–C65500	E	G

ETP, electrolytic tough pitch. (a) E, excellent; G, good; F, fair; NR, not recommended readily brazed with the self-fluxing BCuP filler metals, but wetting action is improved when a flux is used and when a sliding motion between components is provided while the filler metal is molten. Precipitation-hardenable copper alloys that contain beryllium, chromium, or zirconium form oxide films that impede the flow of filler metal. To ensure proper wetting action of the joint surface by the filler metal, beryllium copper parts, for example, should be freshly machined or mechanically abraded before being brazed. Removal of beryllium oxide from joint surfaces requires the use of a high-fluoride-content flux.

Brazing precipitation-hardenable coppers in the aged condition reduces their mechanical properties. Properties can sometimes be partly restored by a subsequent aging treatment. Beryllium copper, for example C17200, which contains 1.8 to 2.0% Be, can be brazed and solution heat treated by heating to 790 °C (1450 °F), followed by rapid quenching. Subsequent aging at approximately 315 °C (600 °F) develops adequate hardness. When the sections to be brazed are thin and can be cooled very rapidly, solution heat treated beryllium copper may be brazed in the temperature range of 620 to 650 °C (1150 to 1200 °F).

Coppers that contain metals that are more refractory, such as chromium or zirconium, will form oxide films that slow or prevent the flow of the brazing filler metal. Under these conditions, cleaning operations are often needed to remove the surface oxides prior to brazing. The brazing operation is then carried out in either a protective atmosphere or one that has essentially reducing conditions. Fluxes can be used to assist in the surface oxide removal or to prevent their reformation during the brazing process.

When chromium coppers are brazed at a temperature within the solution treatment range (980 °C, or 1800 °F, for example), brazing and solution treatment can be combined. Brazed chromium copper parts can then be aged in a subsequent operation to develop improved mechanical properties and electrical conductivity.

Zirconium coppers do not precipitation harden without the benefit of prior cold working, a sequence that is incompatible with brazing. In the absence of cold working, the strength of zirconium coppers is not improved by aging treatments, although electrical conductivity is improved.

Red brasses (copper-zinc alloys that contain up to 20% Zn) are readily brazed with a variety of filler metals. Flux is normally required for best results, especially when the zinc content is above 15%.

Yellow brasses (copper-zinc alloys that contain 25 to 40% Zn) are readily brazed, but low-melting filler metals should be used to avoid dezincification of the base metal.

Leaded Brasses. If added to red brass or yellow brass, lead forms a dross on heating that can seriously impede wetting and the flow of filler metal. Consequently, in brazing leaded brasses, the use of a flux is mandatory to prevent dross formation in the joint area.

The susceptibility of leaded brasses to hot cracking varies directly with lead content. Therefore, these alloys must have low residual stresses before brazing. Heating to the brazing temperature should be uniform to minimize thermal stressing. Brazing results are poor at a lead content of 3% and above because of liquidation and the brittleness of phases formed in the joint by lead and the filler metal. Alloys containing more than 5% Pb are usually not brazed.

Tin-containing brasses, which include admiralty brass, naval brass, and leaded naval brass, contain up to 1% Sn and may contain other alloying elements such as lead, manganese, arsenic, nickel, and aluminum. Except for the aluminum-containing alloys, these brasses are readily brazed; they have greater resistance to thermal shock and are less susceptible to hot cracking than the high-lead brasses. For proper wetting, brasses that contain aluminum require a special flux, such as American Welding Society (AWS) type FB4-A.

Phosphor Bronzes. These copper-tin alloys contain small amounts of phosphorus, up to about 0.25%, added as a deoxidizer. Although susceptible to hot cracking in the cold worked condition, alloys in this group have good brazeability and are adaptable to brazing with any of the common filler metals that have melting temperatures lower than that of the base metal. The use of a flux is generally preferred. To avoid cracking, parts made from phosphor bronzes should be stress relieved at approximately 290 to 345 °C (550 to 650 °F) before brazing.

Silicon bronzes, which contain up to about 3.25% Si and are in a highly stressed condition, are susceptible to hot shortness and stress cracking by molten filler metal. To avoid cracking, the alloys should be stress relieved at approximately 290 to 345 °C (550 to 650 °F) before brazing. For best brazing results, joint surfaces should be freshly machined or mechanically cleaned. Silicon bronzes containing aluminum require the use of AWS type FB4-A flux.

Aluminum Bronzes. Because of their aluminum content, which results in the formation of aluminum oxide on the surface, aluminum bronzes are generally considered difficult to braze. However, alloys containing 8% Al or less are brazeable, provided AWS type FB4-A flux is used to dissolve the aluminum oxide. The oxide, which inhibits the flow of filler metal, cannot be reduced in dry hydrogen. Use of the low-melting high-silver filler metals is recommended for these bronzes.

Copper nickels, which may contain from about 5 to 40% Ni, are susceptible both to hot cracking and to stress cracking by molten filler metal. The silver alloy filler metals (BAg series) are preferred for brazing these alloys. In general, the use of filler metals containing phosphorus should be avoided, because the copper nickels are susceptible to the formation of brittle nickel phosphides at the interface, which lower joint strength and ductility.

Nickel silvers (brasses that contain up to approximately 20% Ni but that do not contain silver) are highly susceptible to hot cracking and should be stress relieved at approximately 290 °C (550 °F) before being brazed. They have low thermal conductivity and should be heated and cooled uniformly.

Brazing Dissimilar Alloys. Most of the alloys belonging to any one of the above groups can be brazed to an alloy of another group. However, to achieve compatibility, some compromise may be required in the selection of brazing temperature, filler metal, and flux. For example, if a component made of copper is to be brazed to a component made of aluminum bronze, the brazing temperature should be predicated on the lower melting temperature of the bronze, and a suitable flux should be selected to accommodate the bronze. It is not uncommon for three or more different copper alloys to be brazed together in a single assembly.

Filler Metals

Table 2 presents the nominal compositions, solidus and liquidus temperatures, and electrical conductivities of some filler metals used in brazing of copper and copper alloys, as well as the joint clearance used with each. The filler metals listed in Table 2 represents four series: (1) copper-zinc (RBCuZn) alloys, (2) copper-phosphorus and copper-silver-phosphorus (BCuP) alloys, (3) silver (BAg) alloys, and (4) gold (BAu) alloys. The copper (BCu) filler metals are omitted. Because of their high liquidus temperature (1080 °C, or 1980 °F), these filler metals are restricted to use with the copper-nickel alloys only. Of the filler metals listed in Table 2, the BCuP and BAg alloys are by far the most widely used in brazing copper and its alloys.

Copper-Zinc (RBCuZn) Filler Metals. Because of their high liquidus temperature, poorer corrosion resistance, anodic position relative to copper, and sensitivity to overheating, copper-zinc filler metals are seldom used in brazing copper and copper alloys. Overheating causes the zinc to vaporize and form voids in the joint. In applications where corrosion resistance is not important, these filler metals can be used for joining copper, copper nickel, or silicon bronze. They are sometimes used in joining copper to steel, stainless steel, and nickel alloys. These filler metals generally require the use of a flux.

Copper-Phosphorus and Copper-Phosphorus-Silver (BCuP) Filler Metals. The BCuP alloys are self-fluxing when used for brazing unalloyed coppers, but the use of a flux is generally recommended when these filler metals are used in brazing special coppers and copper alloys. In general, BCuP filler metals are not suitable for use in brazing copper-nickel alloys containing 20% or more nickel. The BCuP filler metals have good corrosion resistance, but they are severely attacked in sulfur-bearing atmospheres at elevated temperature. Among the advantages of these filler metals is their relatively low cost.

Silver Alloy (BAg) Filler Metals. The silver-alloy filler metals listed in Table 2 are suitable for use with all brazeable coppers and copper alloys as well as most dissimilar alloy combinations. The lower brazing temperatures indicated in Table 2 for some of the silver-alloy filler metals make them particularly well suited for brazing copper alloys with an appreciable zinc content. These include yellow brasses, which are subject to dezincification. The corrosion resistance of silver-alloy filler metals ranges from good to excellent, although the cadmium-containing silver alloys are avoided when brazing equipment for the dairy, food, and pharmaceutical industries, because of the high toxicity of cadmium. The principal disadvantage of silver alloy filler metals is high cost, but this disadvantage can be largely offset by correct joint design. Flux is generally required for all but the lithium-containing filler metals (BAg-8a and BAg-19), which are self-fluxing in dry, nonoxidizing protective atmospheres. This is because of the ability of lithium to reduce refractory oxides on the base-metal surfaces at brazing temperature.

Gold alloy (BAu) filler metals, such as BAu-4 in Table 2, are high-cost compositions that are generally restricted to highly specialized applications such as joining vacuum tube components that are hermetically sealed. In this application, the low vapor pressure of gold is advantageous. The high liquidus temperatures of gold alloy filler metals further limit their use to brazing coppers and a few high melting temperature copper-nickel alloys.

Brazing Fluxes

The AWS brazing flux classifications for copper and copper alloys are given in Table 3. Major ingredients, filler metal type for which the flux is suitable, activity temperature range, application process, and recommended base metals are also given in Table 3. It should be noted that all fluxes are marketed as proprietary compositions, and there are no standard compositions. They are classified by type only. Of the fluxes listed in Table 3, there are four primary categories used most frequently.

Type FB3-A is the general-purpose, low-temperature flux used with all coppers and copper alloys, except those with high levels of aluminum. The filler metals that are compatible with this flux include most of the copper-phosphorus alloys listed in Table 2 (with the exception of BCuP-1) and most of the silver alloys, including those with liquidus temperatures below 760 °C (1400 °F).

Types FB3-C and FB3-D have higher activity temperature ranges, respectively, up to 1205 °C (2200 °F). These fluxes can be used with any filler metal that is listed in Table 2.

Type FB4-A flux is specifically designed for aluminum-containing copper alloys and has a wide range of activity from 595 to 879 °C (1100 to 1600 °F). This flux is generally used with the silver alloy filler metals.

The highest-temperature fluxes are types FB3-I, FB3-J, and FB3-K, which work at temperatures from 760 to 1205 °C (1400 to 2200 °F). These are generally used with the RBCuZn filler metals, with long and active conditions at temperature, although they can be used with all other brazing filler metals for copper alloys.

Surface Preparation

Cleaning. Good wetting and flow of filler metal in brazed joints can only be achieved when the joint surfaces are clean and free of oxides, dirt, and other foreign substances. Standard solvent or alkaline degreasing procedures are suitable for cleaning copper-base metals. Mechanical methods may be used to remove surface oxides, but care should be taken to leave the metal free of undesirable films or deposits. Chemical removal of surface oxides requires an appropriate pickling solution. Cleaning solutions for copper and copper alloys are described in the article "Surface Engineering" in this Handbook.

Copper Plate. It is often desirable to copper plate the faces of copper alloys that contain strong oxide-forming elements to simplify brazing and fluxing requirements. Copper plate about 0.025 mm (0.001 in.) thick is used on chromium-copper alloys while about 0.013 mm (0.0005 in.) thickness is sufficient on beryllium copper, aluminum bronze, and silicon bronze.

Joint Clearance and Design

Both lap and butt joints may be used for brazements. Joint clearances are primarily related to the brazing filler metals being used and their capillary attraction. If the gap is too small, then the brazing filler metal will not flow into the joint. Typical joint clearances are identified in Table 2.

Clearance can also influence the mechanical strength of the brazed joints. Allowances should be made in joint design for relative expansion of the parts at the brazing temperature, especially where dissimilar metals are involved. Penetration of the brazing filler metal through a joint to the opposite side of placement can be an effective measure of brazing filler metal flow, and a preferable joint design allows this observation to be made. Generally, braze joints should be designed for an effective joint area of 80%, in order to allow for voids.

In the case of a lap joint, the joint length should be, at a minimum, three times the thickness of the thinnest component being joined.

Selection of Brazing Process

The selection of the brazing process is as important as the selection of the brazing filler metal. In fact, one often depends on the other. When a specific process is required, the range of allowable filler metals may be restricted. The number of parts to be made and the production rates desired also influence brazing process selection. Another consideration is the materials to be joined, because brazing may affect their mechanical properties. Table 4 compares the characteristics of the commonly used brazing processes.

Furnace Brazing

Furnace brazing is a mass-production process. Its primary advantage is that it can be used to process a large number of assemblies on a batch

Table 2 Compositions and selected properties of filler metals commonly used in brazing of copper and copper alloys

AWS filler metal designation	Nominal composition, %							Solidus temperature		Liquidus temperature		Conductivity (a), %IACS	Typical diametral joint clearance	
	Ag	Cu	P	Zn	Cd	Ni	Other	°C	°F	°C	°F		mm	in.
RBCuZn-A	…	59.25	…	40	…	…	0.75 Sn	890	1630	900	1650	26	0.05–0.13	0.002–0.005
RBCuZn-D	…	48	…	42	…	10	…	920	1690	935	1715	…	…	…
BCuP-1	…	95	5	…	…	…	…	710	1310	900	1650	…	0.05–0.13	0.002–0.005
BCuP-2	…	92.75	7.25	…	…	…	…	710	1310	795	1460	…	0.025–0.075	0.001–0.003
BCuP-4	6	86.75	7.25	…	…	…	…	645	1190	725	1335	…	0.025–0.075	0.001–0.003
BCuP-5	15	80	5	…	…	…	…	645	1190	800	1475	10	0.025–0.13	0.001–0.005
BAg-1	45	15	…	16	24	…	…	605	1125	620	1145	28	0.05–0.13	0.002–0.005
BAg-1a	50	15.5	…	16.5	18	…	…	625	1160	635	1175	24	0.05–0.13	0.002–0.005
BAg-2	35	26	…	21	18	…	…	605	1125	700	1295	29	0.05–0.13	0.002–0.005
BAg-3	50	15.5	…	15.5	16	3	…	630	1170	690	1270	18	0.05–0.13	0.002–0.005
BAg-5	45	30	…	25	…	…	…	675	1250	745	1370	19	0.05–0.13	0.002–0.005
(b)	75	22	…	3	…	…	…	…	…	740	1365	…	0.05–0.13	0.002–0.005
BAg-8	77	23	…	…	…	…	…	780	1435	780	1435	…	0.05–0.13	0.002–0.005
BAg-8a	72	27.8	…	…	…	…	0.2 Li	765	1410	765	1410	89(c)	0.05–0.13	0.002–0.005
BAg-19	92.5	7.3	…	…	…	…	0.2 Li	780	1435	890	1635	88(c)	0.05–0.13	0.002–0.005
BAu-4	…	…	…	…	…	18	82 Au	950	1740	950	1740	6	0.05–0.13	0.002–0.005

(a) Ratio of the resistivity of the material at 20 °C (68 °F) to that of IACS, expressed as a percentage and calculated on a volume basis. (b) Special filler metal used in brazing nickel silver knife handles. (c) Conductivity of filler metal after volatilization of lithium in brazing

Table 3 AWS brazing flux classifications

Classification	Form	Filler metal type	Typical ingredients	Application	Activity temperature range °C	Activity temperature range °F	Recommended base metals
FB3-A	Paste	BAg and BCuP	Borates, fluorides	General-purpose flux for most ferrous and nonferrous alloys. (Notable exception aluminum bronze, etc. See flux 4-A)	565–870	1050–1600	All brazeable ferrous and nonferrous metal, except those with aluminum or magnesium as a constituent. Also used to braze carbides
FB3-C	Paste	BAg and BCuP	Borates, fluorides, boron	Similar to 3-A, but with capability for extended heating times or temperature through use of a deoxidizing additive	565–925	1050–1700	All brazeable ferrous and nonferrous metal, except those with aluminum or magnesium as a constituent. Also used to braze carbides
FB3-D	Paste	BAg, BCu, BNi, BAu, and RBCuZn	Borates, fluorides	Similar to 3-C, but with a higher active-temperature range	760–1205	1400–2200	All brazeable ferrous and nonferrous metal, except those with aluminum or magnesium as a constituent. Also used to braze carbides
FB3-E	Liquid	BAg and BCuP	Borates, fluorides	Low-activity liquid flux used in brazing jewelry or to augment furnace brazing atmospheres	565–870	1050–1600	All brazeable ferrous and nonferrous metal, except those with aluminum or magnesium as a constituent. Also used to braze carbides
FB3-F	Powder	BAg and BCuP	Borates, fluorides	Similar to 3-A in a powder form	650–870	1200–1600	All brazeable ferrous and nonferrous metal, except those with aluminum or magnesium as a constituent. Also used to braze carbides
FB3-G	Slurry	BAg and BCuP	Borates, fluorides	Similar to 3-A in a slurry form	565–870	1050–1600	All brazeable ferrous and nonferrous metal, except those with aluminum or magnesium as a constituent. Also used to braze carbides
FB3-H	Slurry	BAg and BCuP	Borates, fluorides, boron	Similar to 3-C in a slurry form	565–925	1050–1700	All brazeable ferrous and nonferrous metal, except those with aluminum or magnesium as a constituent. Also used to braze carbides
FB3-I	Slurry	BAg, BCu, BNi, BAu, and RBCuZn	Borates, fluoride	Similar to 3-D in a slurry form	760–1205	1400–2200	All brazeable ferrous and nonferrous metal, except those with aluminum or magnesium as a constituent. Also used to braze carbides
FB3-J	Powder	BAg, BCu, BNi, BAu, and RBCuZn	Borates, fluorides	Similar to 3-D in a slurry form	760–1205	1400–2200	All brazeable ferrous and nonferrous metal, except those with aluminum or magnesium as a constituent. Also used to braze carbides
FB3-K	Liquid	BAg, BCuP, and RBCuZn	Borates	Exclusively used in torch brazing by passing fuel gas through a container of flux. Flux applied by the flame	760–1205	1400–2200	All brazeable ferrous and nonferrous metal, except those with aluminum or magnesium as a constituent. Also used to braze carbides
FB4-A	Paste	BAg and BCuP	Chlorides, fluorides, borates	General-purpose flux for many alloys containing metals that form refractory oxides	595–870	1100–1600	Brazeable base metals containing up to 9% Al (aluminum brass, aluminum bronze, Monel K500). May also have application when minor amounts of titanium or other metals are present, which form refractory oxides

Note: The selection of a flux designation for a specific type of work may be based on the filler metal type and the description above, but the information here is generally not adequate for flux selection.

Table 4 Characteristics of the brazing processes used to join copper and copper alloys

Method	Characteristics(a) Capital cost	Running cost	Basic output	Flux required	Versatility	Operator skill required
Torch (flame)	L/M	M/H	L	Yes	H	Yes
Electrical resistance	M	M	M/H	Yes	L	No
Induction	M/H	M	M/H	Y/N	M	No
Furnace (atmosphere)	M/H	M/H	H	Y/N	M	No
Furnace (vacuum)	H	L	H	No	M	No
Dip (flux bath)	L/M	M/H	L/M	Yes	L	Yes

(a) H, high; M, medium; L, low

or continuous basis at low unit cost. Furnace brazing can be used to braze a number of joints on the same assembly simultaneously or to braze a variety of different assemblies simultaneously. Furnace brazing also provides an enclosed container for atmospheres that can protect assemblies against surface oxidation and other undesirable effects encountered when heating in air.

Advantages of furnace brazing that are more specifically applicable to the joining of copper and copper alloys relate to the furnace as a source of heat and to the cooling chamber that is provided on conveyor belt furnaces as a means for cooling assemblies from the brazing temperature to 150 °C (300 °F) or below. To a lesser degree, the prepared protective atmospheres that can be used most conveniently in furnace brazing, notably the exothermic-based and endothermic-based atmospheres, constitute another advantage when brazing deoxidized coppers and copper alloys in a furnace.

The rate of heating assemblies in a brazing furnace is low when compared with rates normally used in torch, induction, and resistance brazing. Few furnace heating cycles are less than 5 min in duration. For heating copper alloys susceptible to hot cracking, however, the slower, more uniform heating of a furnace is desirable.

In conveyor furnaces with multiple-zone heating chambers, the heating rate can be controlled with great accuracy. Depending on furnace capacity and the size of the assemblies to be brazed, the production rate in furnace brazing may equal or exceed that obtainable in induction brazing for the same amount of energy expended (assemblies per kilowatt-hour of input, for example).

The cooling rates that can be obtained in the cooling chambers of brazing furnaces can be closely controlled to ensure slow, uniform cooling. For copper alloys susceptible to hot cracking, the control of cooling rate from the brazing temperature is as important as control of the rate of heating to the brazing temperature.

Limitations. Apart from the high initial equipment costs and the floor space required to accommodate a furnace with both a heating chamber and a cooling chamber (the length of the cooling chamber is usually at least three times that of the heating chamber), most of the limitations of furnace brazing are related to the deleterious effects of furnace temperatures and brazing fluxes on furnace muffles and linings, electrical heating elements, rails, trays, conveyor belts, and other components. These effects increase in seriousness as the operating temperature of the furnace increases. A furnace used for brazing copper and copper alloys with silver alloy filler metals and operating at a temperature below 815 °C (1500 °F) could be expected to require considerably less maintenance, repair, and replacement of components than a similar furnace used to braze carbon steel with copper filler metals and operating at a temperature of 1095 °C (2000 °F). The use of flux, required for brazing with most silver alloy filler metals, could offset the advantage of a lower operating temperature, however, by introducing corrosion and corrosive deterioration not encountered in a flux-free furnace chamber.

A furnace operating at 815 °C (1500 °F) requires idling at elevated temperature when not in use, as does a furnace operating at 1095 °C (2000 °F), adding to power costs. Idling prevents thermal cycling that can cause serious damage to components such as furnace brickwork. Lower operating temperatures usually permit the use of lower idling temperatures. However, for furnaces operating with combustible protective atmospheres, the hazard of explosion is greatest when the furnace is operating at temperatures below approximately 760 °C (1400 °F), and special precautions must be scrupulously observed in this range.

Furnaces. In design and equipment, the furnaces used for brazing copper and copper alloys are essentially the same as those used for brazing steel.

Because of the damaging effects of sulfur and sulfur-bearing compounds on copper and copper alloys, the products of combustion in gas-fired furnaces operating without a muffle must be completely free of sulfur. Electric furnaces may be operated without a muffle unless damage to brickwork and other furnace components caused by volatilized flux and flux droppings warrants use of a muffle. Muffles may also be used to ensure the purity and to maintain the dew point of a protective atmosphere, particularly when the atmosphere is serving in place of a flux and its effectiveness depends on freedom from contamination.

Temperatures for furnace brazing depend on the filler metal used, the melting temperature of the base metal, and any harmful effects, such as dezincification and hot-short cracking, that result from exceeding prescribed temperature limits. The brazing temperature selected is usually at least 28 °C (50 °F) higher than the liquidus temperature of the filler metal; even higher brazing temperatures may be used to promote fluidity or to achieve other desired results (such as combining brazing and solution heat treatment in the same furnace operation). Some filler metals can be used at a temperature below the liquidus; for example, BCuP-3, with a liquidus of 805 °C (1485 °F), and BCuP-5, with a liquidus of 800 °C (1475 °F) flow freely and make good joints at 705 °C (1300 °F). In the following example, furnace brazing was done at 42 °C (75 °F) below the liquidus of the filler metal (a self-fluxing silver-containing BCuP alloy), without using a protective atmosphere.

Example 1: Brazing at 42 °C (75 °F) below the Liquidus of the Filler Metal—without Protective Atmosphere. The contact arm assembly (Fig. 1) was a component of a line voltage thermostat. The two contacts were made of fine silver and, when brazed to the copper arm, required a highly conductive joint to accommodate high-service currents without overheating. Neither a flux nor a protective atmosphere was used, because the brazing temperature was considerably below the liquidus of the filler metal. The copper-silver-phosphorus (BCuP-5) filler metal is self-fluxing on both copper and silver, and its unusually wide temperature range between solidus and liquidus (645 and 800 °C, or 1190 and 1475 °F) permits brazing at a temperature below the liquidus. The assembly was brazed at 760 °C (1400 °F), below the liquidus temperature, in a mesh belt conveyor furnace at a production rate of 377 assemblies per hour.

Accelerated Heating. The furnace temperature setting used in a given brazing operation may exceed that attained by the workload during the heating cycle to accelerate the heating of the work. Temperature differentials between the thermocouple and the work being processed must be closely monitored and controlled. Experimentation is required to establish the time spent by the workload in the heating zone when using higher furnace temperatures. Above 955 °C (1750 °F), the substitution of a reducing protective atmosphere for a brazing flux helps extend the life of heating elements and other furnace components by eliminating both oxidation and the corrosive reactions of volatized flux.

Furnace Atmospheres. Protective atmospheres are used in furnace brazing of copper and copper alloys, although numerous exceptions exist. Combusted fuel gases are economical protective atmospheres for copper and copper alloys, except for oxygen-bearing copper. Atmospheres with a high-hydrogen content cannot be used when brazing oxygen-bearing copper; hydrogen diffuses into the copper, reduces copper oxide, and forms water vapor that will rupture the copper. Inert gases that have proper dew points also are suitable atmospheres for brazing copper and copper alloys. Table 5 lists AWS atmosphere types, as well as approximate compositions, filler metals, and braze-metal combinations.

Vacuum is a suitable brazing environment, provided neither base metal nor filler metal contains elements that have high vapor pressures at brazing temperature. Zinc, phosphorus, and cadmium are examples of elements that vaporize when heated in vacuum.

Assembly for Brazing. The component parts to be furnace brazed must be assembled in an essentially fixed position with filler metal preplaced before entering the furnace, and they must maintain this position throughout brazing and cooling. Self-jigging is the preferred method of assembly. An assembly is self-jigging when its component parts incorporate design features that ensure that each component, when assembled, remains in proper relationship throughout the brazing cycle without the aid of auxiliary fixtures. When self-jigging is not feasible or when the assembly requires positioning or support in addition to that provided by self-jigging, auxiliary fixtures are used. These fixtures may take the form of a simple bracket or wire stand, ceramic blocks, clamps, or cast supports.

Venting Fully Enclosed Assemblies. Fully enclosed assemblies, whether assembled by self-jigging or supported by auxiliary fixturing, must be vented to permit the escape of entrapped air. When heated, entrapped air expands and, unless adequately vented, escapes from a sealed assembly in the area of the joint, resulting in flux spatter, joint porosity, and misalignment of brazed components. A small pinhole or slot, located safely away from the area of the joint, is usually sufficient to provide adequate venting and to avoid damage to the joint.

Torch Brazing

Torch brazing of copper and copper alloys is used on many components and in numerous industrial applications. The properties of copper and copper alloys introduce certain specific considerations in torch brazing.

Applications. Joining components of various types of heat exchangers probably represents the largest field of application for torch brazing of copper and copper alloys; products include condensers, evaporators, air conditioners, radiators, and refrigerators, all of which depend on the high thermal conductivity of copper. Torch brazed

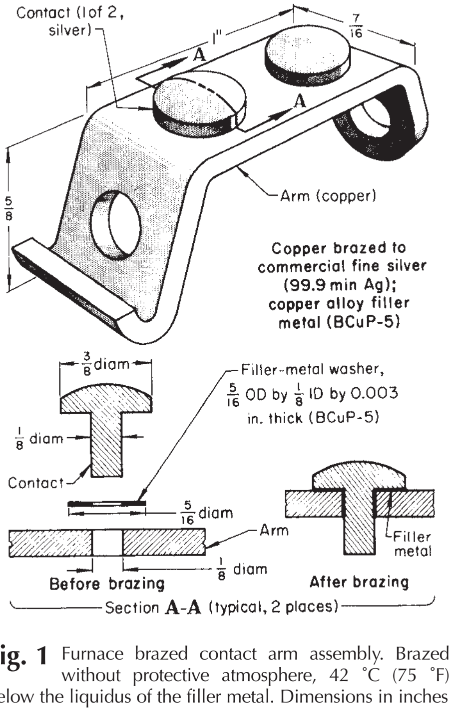

Fig. 1 Furnace brazed contact arm assembly. Brazed without protective atmosphere, 42 °C (75 °F) below the liquidus of the filler metal. Dimensions in inches

products that depend on the high electrical conductivity of copper include motor windings, reactor coils, switches, contactors, and terminal leads.

Process Selection. The selection of torch brazing in preference to another brazing process, such as furnace or induction brazing, depends largely on feasibility and cost. Torch brazing is often used when workpiece limitations preclude the use of alternative brazing processes.

Manual Torch Brazing. Low equipment cost is a major advantage in manual torch brazing, which is particularly useful for assemblies involving unequal masses. A brazer with moderate skill can adjust and apply the heating flame so that unequal masses are brought uniformly to brazing temperature. The brazer can also apply the heat selectively to the joints of assemblies involving both large and small areas. The size of brazing flames may range from those of extremely small torches, the size of a hypodermic needle used for electronic leads, up to those of large torches used in brazing assemblies weighing hundreds of pounds.

Several precautions should be taken when torch brazing certain coppers and copper alloys. Where it is necessary to braze oxide-containing (tough pitch) coppers, a reducing atmosphere in the flame must be avoided because it can promote hydrogen embrittlement. For these coppers, a neutral or slightly oxidizing flame and a short brazing cycle are necessary. Brasses are subject to volatilization of zinc when overheated or when held too long at brazing temperature. Application of flux suppresses zinc volatilization.

Alloys containing elements that readily form refractory oxides (aluminum, beryllium, chromium, and silicon) must be protected by flux and should not be exposed to an oxidizing flame.

One of the notable differences between the torch brazing of steel and the torch brazing of copper alloys is that steel can withstand very rapid heating rates, whereas some of the copper alloys (the phosphor bronzes, for example) are subject to cracking if heated too rapidly when the metal is under high restraint during brazing.

Filler metals used for torch brazing of copper and copper alloys include the lower melting BAg silver alloys, the lower melting BCuP copper-phosphorus alloys, and the copper-zinc filler metal RBCuZn-A.

The BAg-1 and BAg-1a alloys have the lowest melting temperatures of all the filler metals used in torch brazing of copper and copper alloys and possess excellent flow characteristics. These filler metals contain more silver than BAg-2 (Table 2) and are therefore more costly. For this reason, BAg-2 is sometimes preferred, although it has a higher liquidus temperature than either BAg-1 or BAg-1a.

The color of silver alloy filler metals does not match that of most copper alloys. Joints that are visible are plated or painted if appearance is important. Face-fed filler metal in the form of wire, powder, or a paste with flux is less neat in appearance than filler metal deposited from preplaced preforms. The latter, made from either wire or strip, are used in deep joints or in joints having a change in direction of the mating surfaces.

The BCuP filler metals contain phosphorus, which makes them self-fluxing on copper; however, when these fillers are used with copper alloys, an AWS type FB3-A flux is advised.

Of the types of filler metal used in torch brazing, BCuP-2 and 4 are the most fluid, and fill joints having diametral clearances of 0.025 to 0.075 mm (0.001–0.003 in.). BCuP-5 can tolerate looser fits. Acceptable diametral clearance is 0.025 to 0.13 mm (0.001–0.005 in.). BCuP alloys are lower in cost than silver alloy filler metals and also provide a better color match on copper after the oxide film that forms during cooling has been removed. The following example describes the use of BCuP-5 in torch brazing.

Example 2: Use of Self-Fluxing Filler Metal in Torch Brazing Return Bends for a Heat Exchanger. Return bends were brazed to heat exchanger tubes (Fig. 2). The tubes and return bends were made of alloy C12200 (phosphorus-deoxidized copper, DHP), 9.5 mm (3/8 in.) outside diameter, with 0.4 mm (0.016 in.) and 0.5 mm (0.020 in.) wall thicknesses, respectively. Ends of the tubes were expanded to fit over the ends of the return

Table 5 Atmospheres for brazing copper and copper alloys

AWS brazing atmosphere type No.	Source	Maximum dew point incoming gas	Composition of atmosphere, %				Filler metals	Base metals	Remarks
			H_2	N_2	CO	CO_2			
1	Combusted fuel gas (low hydrogen)	Room temperature	5–1	87	5–1	11–12	BAg(a), BCuP, RBCuZn	Copper, brass(a)	Referred to commonly as exothermic generated atmospheres
2	Combusted fuel gas (decarburizing)	Room temperature	14–15	70–71	9–10	5–6	BCu, BAg(a), RBCuZn, BCuP	Copper(b), brass(a), low nickel, Monel, medium-carbon steel(c)	Decarburizes. Referred to commonly as endothermic generated atmospheres
3	Combusted fuel gas, dried	–40 °C (–40 °F)	15–16	73–75	10–11	…	Same as 2	Same as 2 plus medium- and high-carbon steels, Monel, nickel alloys	Referred to commonly as endothermic generated atmospheres
4	Combusted fuel gas, dried (decarburizing)	–40 °C (–40 °F)	38–40	41–45	17–19	…	Same as 2	Same as 2 plus medium- and high-carbon steels	Carburizes
5	Dissociated ammonia	–54 °C (–65°F)	75	25	…	…	BAg(a), BCuP, RBCuZn(a), BCu, BNi	Same as for 1, 2, 3, 4 plus alloys containing chromium	…
6A	Cryogenic or purified $N_2 + H_2$	–68 °C (–90 °F)	1–30	70–99	…	…	Same as 5	Same as 3	…
6B	Cryogenic or purified $N_2 + H_2 + CO$	–29 °C (–20 °F)	2–20	70–99	1–10	…	Same as 5	Same as 4	…
6C	Cryogenic or purified N_2	–68 °C (–90 °F)	…	100	…	…	Same as 5	Same as 3	…
7	Deoxygenated and dried hydrogen	–59 °C (–75 °F)	100	…	…	…	Same as 5	Same as 5 plus cobalt, chromium, tungsten alloys and carbides (d)	…
8	Heated volatile materials	Inorganic vapors (zinc, cadmium, lithium, volatile fluorides)	…	…	…	…	BAg	Brasses	Special purpose. May be used in conjunction with 1 through 5 to avoid use of flux
9	Purified inert gas	Inert gas (helium, argon, etc.)	…	…	…	…	Same as 5	Same as 5 plus titanium, zirconium, hafnium	Special purpose. Parts must be very clean and atmosphere must be pure.
9A	Purified inert gas + H_2	Inert gas (helium, argon, etc.)	1–10	…	…	…	…	…	…

(a) Flux required in addition to atmosphere when alloys containing volatile components are used. (b) Copper should be fully deoxidized or oxygen-free. (c) Heating time should be minimized to avoid objectionable decarburization. (d) Flux must be used in addition to the atmosphere if appreciable quantities of aluminum, titanium, silicon, or beryllium are present.

bends with diametral clearance of 0.1 to 0.23 mm (0.004–0.009 in.). Brazed joints had to be leaktight at 2760 kPa (400 psi) pressure.

All parts were vapor degreased before brazing. Each leg of the return bends was mechanically fitted with a preformed ring of 0.75 mm (0.030 in.) diameter BCuP-5 filler wire, which does not require a flux when used for brazing copper. The wire ring had to fit tightly on the tube, so that the filler metal would be heated by conduction as the base metal was heated to brazing temperature. If heated directly, the filler metal might have melted before the base metal reached brazing temperature.

The joints were assembled and manually brazed using a Y-shaped oxyacetylene torch with two tips. The opposing tips surrounded the joint with flame, making heating faster and more uniform than it would have been with only one flame. The joint was brought up to temperature as rapidly as possible to prevent liquidation of the filler metal. Each joint took 5 s to braze. Because no flux was used, brazed joints did not have to be cleaned.

The manufacturer also used multiple-flame gas-air burners for this product. Such equipment was used for high production on a given size of return bend. Multiple burners heated both joints at one time while the assemblies were on a conveyor line. Natural gas was used in preference to acetylene for economy and heating control; some joints were overheated and others underheated when using the rapid heating of acetylene. Radiant gas burners were also used for this work. Furnace brazing could not be used, because the remainder of the assembly, including the aluminum fins, could not be heated.

Fluxes. Selection of flux for torch brazing of copper and copper alloys depends not only on the filler metal used (as it does for brazing of steel), but also on the base metal. Some copper alloys form refractory oxides, and this influences choice of flux.

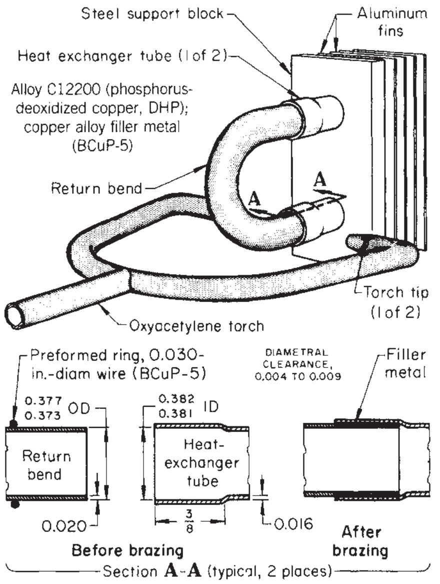

Fig. 2 Return bend assembly of a heat exchanger. Includes a dual-tip torch used for rapid heating of the self-fluxing filler metal. Dimensions in inches

When BAg or BCuP filler metal is used in brazing copper or in brazing a copper alloy that contains no elements that cause it to form refractory oxides (aluminum, beryllium, chromium, and silicon), a type FB3-A flux is used. When brazing copper alloys that form refractory oxides, a more active flux is usually required. For instance, aluminum bronzes require a type FB4-A flux to inhibit the oxidation of aluminum.

Gas fluxing, by entraining volatilized flux in the gas flame, is used in torch brazing copper and copper alloys. When used on copper and its alloys, gas fluxing protects the surface of the base metal from becoming oxidized or discolored, eliminating postbraze cleaning. The joint surfaces are also protected with an appropriate flux.

Fuel Gases. The fuel gas mixtures generally used in torch brazing of copper and copper alloys are oxyacetylene, oxy-natural gas, oxypropane, oxyhydrogen, and air/natural gas. Oxyfuel gases are highest in cost, flame temperature, and heating rate, with oxyacetylene the highest in the group in each respect. Oxyfuel gases are widely used in manual torch brazing where temperature can be controlled by torch manipulation. The cost advantage of air/natural gas is exploited particularly in mechanized and automatic high-production torch brazing, where the lower flame temperature offers protection from damage caused by overheating. Desired heating rates are obtained economically by using high flow rates together with multiple torches or radiant burners. Neutral or slightly reducing flames are used to help the fluxes prevent oxidation of base-metal surfaces.

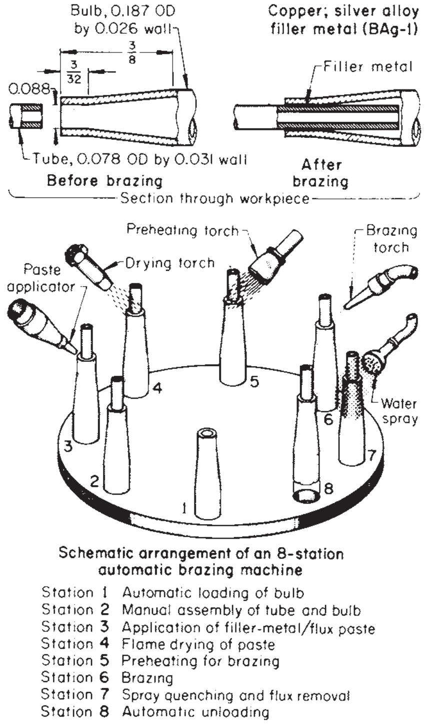

Fig. 3 Bulb and tube assembly. Brazed by mechanically held torches on an eight-station turntable. Dimensions in inches

Although high heat input is necessary to overcome high thermal conductivity, many copper alloys cannot withstand the rapid heating rates that can be used on steel. Under too rapid heating, high thermal expansion can cause local stresses, resulting in distortion and cracking in some alloys. Accidental overheating can cause damage to copper and copper alloy assemblies more readily than to those made of steel. Particular care should be taken with phosphor bronzes, leaded brasses, nickel silvers, and silicon bronzes. The use of gases of lower flame temperature requires less skill in avoiding these difficulties.

Mechanized and automatic torch brazing equipment and operations are the same as those applied on steel assemblies, except for the special considerations discussed earlier in this section. Mechanized torch brazing is widely used in manufacturing air conditioners, radiators, and other types of heat exchangers that use hairpin coils of copper tubing with aluminum fins. Conveyor belts and turntables are used extensively for both mechanized and automatic torch brazing. The following example illustrates the use of a turntable in an operation that was wholly automatic except for assembly.

Example 3: Use of an Eight-Station Turntable for Automatic Brazing of Bulb and Tube Assemblies. An eight-station automatic setup (Fig. 3) replaced a manual torch brazing setup that required two operators and used a rotating fixture for brazing copper bulb and tube assemblies. Production rate (about 700 joints per hour, gross) was not increased with the automatic method, and improvement in quality was negligible. However, only one unskilled operator was needed. Therefore, the cost of direct labor was reduced more than 50%. The sequence of operations is given in Fig 3. The air/natural gas torches at stations 4, 5, and 6 were adjusted to produce neutral or slightly reducing flames. Filler metal was BAg-1 in flux-paste form. The completed assemblies were leak tested with air at 415 kPa (60 psi). Rejection rate was 1%, which was considered satisfactory. The joints were clean and ductile.

Joint Design. For widely used silver alloy and copper-zinc alloy filler metals, diametral clearances differ; clearances of 0.05 to 0.13 mm (0.002–0.005 in.) are suitable. For BCuP filler metals, diametral clearances of 0.025 to 0.075 mm (0.001–0.003 in.) are suitable for BCuP-2 and BCuP-4, and 0.025 to 0.13 mm (0.001–0.005 in.) for BCuP-5. Much torch brazing is done by face feeding of filler metal, and when this is desired, joints should be limited to a depth that can be quickly and adequately fed by the filler metal used. Deep joints and those that change direction sharply require the use of preplaced filler metal.

Induction Brazing

The efficiency of heating by induction varies directly with the electrical resistivity of the alloy. Brass, because it has higher electrical resistivity, can be heated more efficiently

LIVE GRAPH
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than copper; steel, which has even higher resistivity, can be heated more efficiently than brass. In terms of the high-frequency power input and the time required to heat 1 lb of metal in a joint assembly to a brazing temperature of about 700 °C (1300 °F), a power input of 15 kW (at 450 kHz) can heat a steel joint to this temperature in about 16 s, whereas brass requires about 30 s and copper about 55 s (Fig. 4).

Despite the fact that induction brazing is less efficient with copper-base alloys than with other metals, the process is widely used because of its high-production capability, especially in situations where flames cannot be tolerated and atmosphere protection is an alternative to fluxing. Induction brazing usually minimizes the possible warping of parts. However, the initial cost of the induction heating equipment is high.

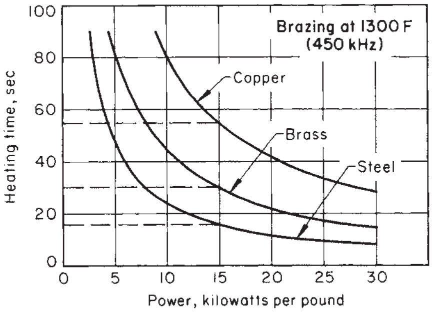


Fig. 4 Power input and heating time required for high-frequency induction brazing. Power is expressed as kilowatts required to heat 1 lb of metal at the joint to 700 °C (1300 °F).

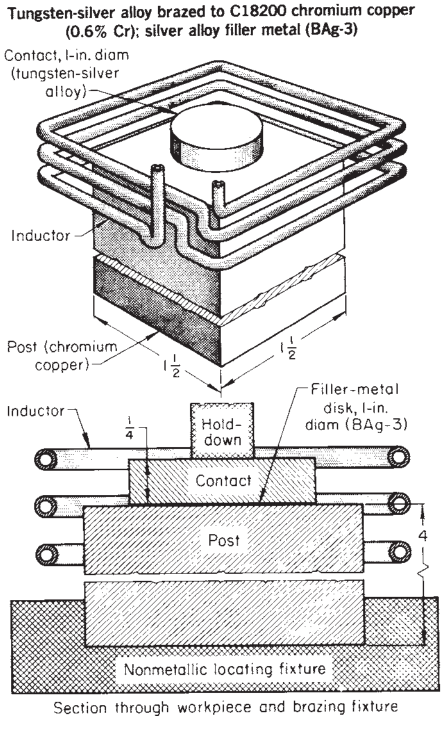


Fig. 5 Tungsten-silver alloy contact and chromium post in position for induction brazing. Used three-turn inductor. Dimensions in inches

The low efficiency of the process also demands relatively high power requirements.

Inductor design is similar to that needed for other metals. The objective is controlled heat input and distribution. Single- or multiple-turn inductors are utilized, sometimes in conjunction with concentrators, to focus heat in desirable locations. In the following example, the control of heat input and distribution was critical, and excellent results were obtained at a relatively low operating frequency (10 kHz) using a three-turn inductor. This example also illustrates another advantage of induction brazing, that is, it is the best option for retaining material properties.

Example 4: Use of a Multiple-Turn Inductor to Control Heat Input and Minimize Overaging of Chromium Copper. Chromium copper (C18200, 0.6% Cr) has high electrical conductivity (78% IACS) and develops improved mechanical properties in the precipitation-hardened condition. After solution heat treatment, it is aged at 400 to 500 °C (750 to 930 °F). Heating for brazing is critical, because the copper can overage or partly anneal at temperatures above 500 °C (930 °F), the overaging effect increasing with increasing temperature and time at temperature. Consequently, in brazing a tungsten-silver alloy contact to a precipitation-hardened chromium copper post (Fig. 5), heat input to the post required careful control to minimize overaging. The joint required high electrical conductivity and impact strength, and the chromium copper post had to retain its hardness and strength to resist distortion when subjected to repeated impact. Brazing the tungsten-silver alloy contact required the use of a nickel-containing silver-alloy filler metal for adequate wetting. BAg-3 was chosen rather than BAg-4 or BAg-13, because BAg-3 has a lower brazing range (690 to 815 °C, or 1270 to 1500 °F); induction brazing was selected to control heat input and minimize the duration of the brazing cycle. Optimum control of heat input to the chromium-copper post was obtained using the square three-turn inductor shown in Fig. 5.

Before brazing, the chromium copper base was bright dipped, and the tungsten-silver alloy contact was cleaned with an abrasive cloth. Type FB3-A flux paste was applied to both components with a brush. They were then assembled with a disk of filler metal placed between them (Fig. 5). Power supply was a 50 kW, 10 kHz motor-generator set. When the brazing alloy melted and flowed, the contact was rotated to release any entrapped gases and improve wetting. Production rate was ten joints per hour.

Inductors for Mass Production. Induction heating is suited for mass producing brazed assemblies, primarily because inductors can be designed that heat a line of assemblies as they are carried through the induction field by conveyor belt or turntable. Hairpin and pancake inductors are most widely used for conveyorized applications, because they do not obstruct passage of the assemblies as they travel through the induction field.

Because steel assemblies heat more efficiently (Fig. 4), they are generally more adaptable to brazing in a conveyorized setup than are assemblies made of copper and copper alloys. An alternative design for use with copper alloys is the multiple-station inductor. With this type of inductor, two or more (often as many as six) assemblies can be brazed simultaneously or in a selective sequence that permits loading at one or more stations while other stations are heating. An example of the application of a multiple-station inductor for brazing armatures for motors follows.

Example 5: Use of Two Four-Station Inductors for High-Production Brazing of Motor Armatures. In the production of motor armatures, copper end rings were induction brazed to both ends of 14 copper rivets that held the armature laminations (Fig. 6) at a rate of 433 assemblies per hour (two joints per assembly) in

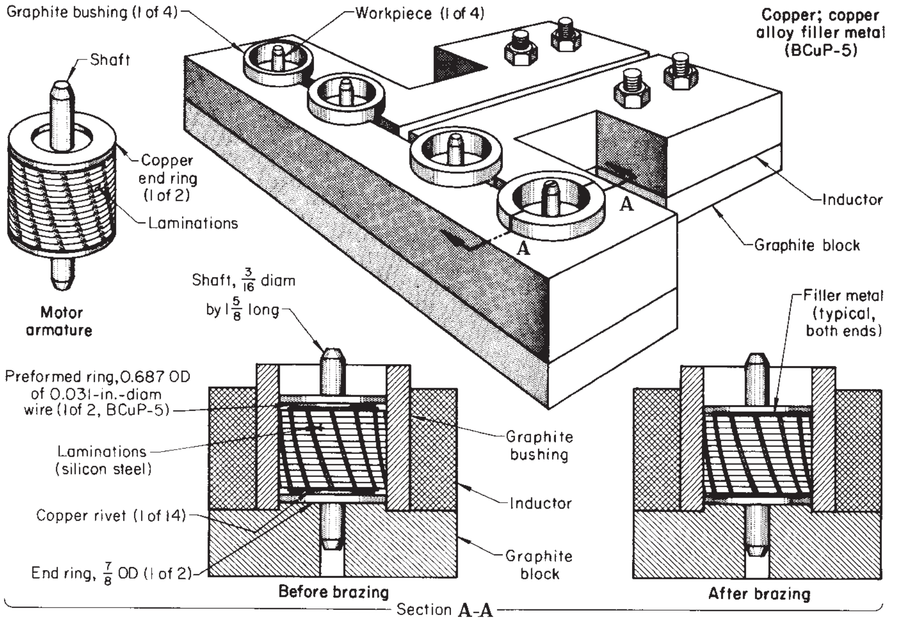


Fig. 6 Motor armature and a four-station inductor. Used for high-production brazing of copper end rings to rivets holding armature laminations. Dimensions in inches

two four-station, single-turn inductors, using a 5 kW, 450 kHz vacuum tube power supply. Induction brazing was selected for this application partly because the rapid rate of heating left the magnetic properties of the silicon steel armature laminations relatively unaffected.

Each of the eight inductor stations contained a graphite bushing into which an armature assembly could be placed. The inductors and bushings were attached to graphite blocks that supported the armatures during the brazing cycle.

Silver-containing filler metal BCuP-5 was selected for its brazing range and because it is self-fluxing on copper. Because the filler metal would not wet the graphite holders, there was no difficulty in brazing rings to both ends of the armatures simultaneously. Conductivity was adequate.

Before brazing, the copper rings were degreased and bright dipped. Each inductor station was loaded by first placing a copper end ring at the bottom of the graphite bushing, followed by a preform of brazing alloy. The armature was then inserted in the hole in the graphite block (Fig. 6, section A-A), and a second ring of filler metal was placed on top of the armature, followed by another end ring of copper. When one of the four-station inductors was loaded in this manner, power was applied and the brazing cycle began. The operator then began loading the second four-station inductor.

Filler Metals. As indicated in Examples 4 and 5, brazing filler metals for induction heating are usually the silver-containing alloys and the copper-phosphorus and copper-phosphorus-silver alloys.

Resistance Brazing

Resistance brazing is a resistance joining process in which the workpieces are heated locally and filler metal that is preplaced between the workpieces is melted by the heat obtained from resistance to the flow of electric current through the electrodes and the work. In the usual application of resistance brazing, the heating current is passed through the joint itself. Equipment is the same as that used for resistance welding, and the pressure needed for establishing electrical contact across the joint is ordinarily applied through the electrodes (Fig. 7). The electrode pressure also is the usual means for providing the tight fit needed for capillary behavior in the joint. The heat for resistance brazing can be generated mainly in the workpieces themselves, in the electrodes, or in both, depending on the electrical resistivity and dimensions.

Applicability. Resistance brazing is often used in the joining of copper conductors, terminals, and other parts in lap joints for electrical connections where heating must be localized and closely controlled while brazing the joint and where the brazed joint must have low electrical resistance. Generation of heat in the filler metal and nearly complete filling with a thin layer of the filler metal in the joint help in meeting both of these objectives.

Filler Metals. The filler metal most frequently used is BCuP-5, which is used without a flux when brazing copper in most applications. In spite of the comparatively low electrical conductivity of BCuP-5 (approximately 10% IACS, Table 2), producing brazed joints having a low voltage drop acceptable for nearly all applications is not difficult, because the layer of filler metal in the brazed joint is very thin and the joints are designed to provide a conducting area larger than the cross section of the smaller member. Silver (BAg-type) brazing alloys are also used for resistance brazing applications.

Brazing of Multiple-Strand Copper Wire. Resistance brazing is preferred for making connections of terminals or assemblies to stranded or braided copper electrical conductors. Torch brazing does not provide sufficiently localized or controlled heating for most applications of this type. Induction brazing, the only other brazing process that permits selective heating, provides well-controlled but somewhat less localized heating than resistance brazing, and the equipment for induction brazing is more costly. Resistance brazing, like other brazing processes, is often selected over soldering because of the higher strength of the filler metal.

The major arc welding processes are usually ruled out on the same basis as torch brazing, and arc processes that involve impact, such as stud and percussion welding, generally cannot be used because the stranded or braided copper conductors do not provide a rigid workpiece for the lap connections in use. T-joints of multiple-strand wires to flat surfaces have been made by percussion welding in some instances.

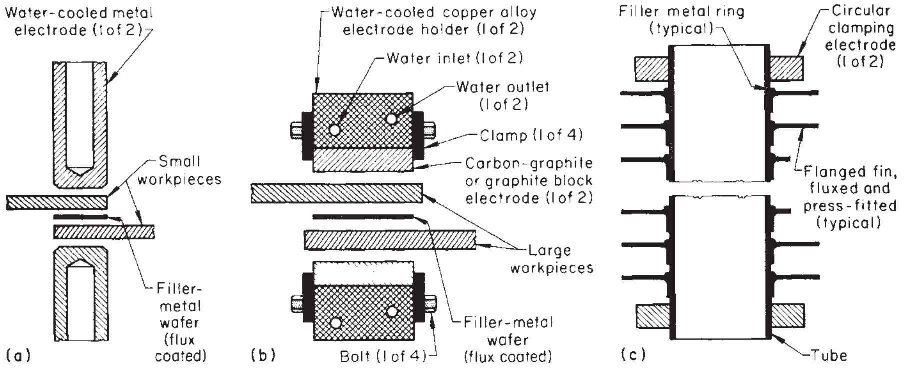


Fig. 7 Typical setups for resistance brazing. (a) For small flat parts or small flat portions of larger components, using opposed water-cooled metal electrodes of the conventional resistance welding type. (b) For large flat parts, typically of a highly conductive metal such as copper, using opposed carbon block electrodes attached to water-cooled copper alloy electrode holders. (c) For joining flanged fins to tube, using circular clamping electrodes

Resistance welding cannot be used on multiple-strand copper electrical conductors rated to carry a current higher than about 60 A, because the amount of current needed to make the weld is prohibitively large. Such connections are made by resistance brazing.

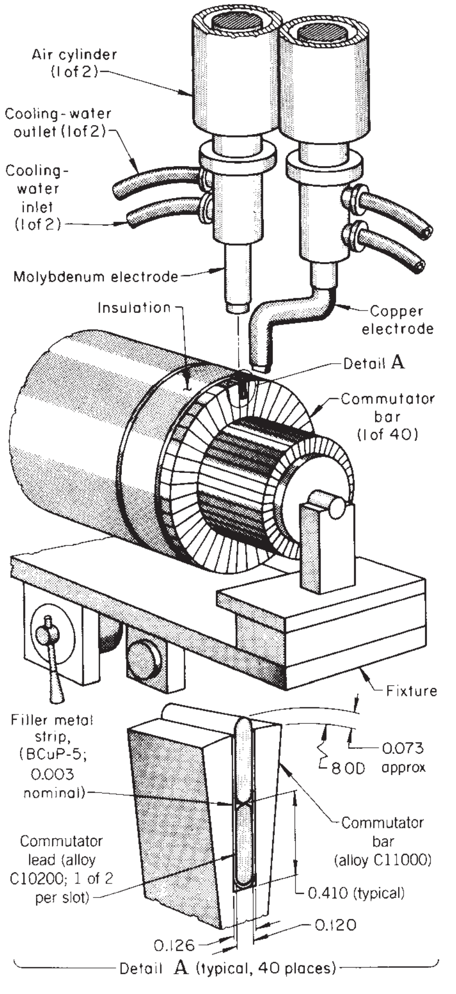
Brazing of Leads to Commutator Bars. The success with resistance brazing for joining small copper electrical conductors to massive copper assemblies has led to the use of the process for attaching armature leads to commutator bars on large electrical motors and generators. Joints made by this method provide a large conducting cross section that prevents significant resistive heating at the connections in service. The joints are made at much lower temperature than would be possible by resistance welding, which could be done only with excessively high current and would produce weaker joints with too small a conducting area at the joint.

The use of conventional resistance welding equipment and high-resistivity electrodes with specially contoured tips makes it possible to concentrate the heating at the joint, to keep the heating time to a minimum, and to obtain efficient handling and comparatively high production rates. In the example that follows, joint quality, localization and control of heat input, and initial cost of equipment were major factors in the selection of resistance brazing for attaching dual armature leads to commutator bars.

Example 6: Resistance Brazing for Joining Armature Leads to Commutators. When carbon arc brazing was used for joining alloy C10200 armature leads to alloy C11000 commutator bars (Fig. 8), the joints were porous and high in electrical resistance. This caused excessive temperature rise in the motors in which they were used. Changing the method of making the connections to resistance brazing using BCuP-5 filler metal and the conditions listed with Fig. 8 eliminated the porosity and reduced the electrical resistance across the joint. A temperature of 705 to 730 °C (1300–1350 °F) was required to ensure an acceptable joint. Torch brazing was ruled out because of excessive width of heating and inadequate heat control. Induction heating was rejected because the initial investment for equipment would have been too great.

The setup used for resistance brazing is shown in Fig. 8. The width of the slots in the riser portions of the commutator bars was increased by 0.15 mm (0.006 in.) to accommodate a U-shaped strip of filler metal. Detail A shows the work arranged for brazing with the upper lead extending about 1.8 mm (0.073 in.) above the commutator bar to be contacted by the molybdenum electrode. Neither fluxing nor prebraze cleaning was required.

To initiate the brazing sequence, a valve was manually actuated. The air cylinders were positioned and applied pressure to the electrodes. The contactor switch was then activated by a push button to energize the primary of the transformer. High secondary current heated the commutator bar in the area between the electrode tips. A red color was visible, starting at the tips and progressing to a point between them. The filler metal melted, the leads in the slot partially melted, and the leads were compressed approximately flush with the bar surface. Use of a controlled amount of filler metal made final grinding unnecessary.



Machine	Press, air operated 50 kV·A resistance welding machine
Electrodes contacting commutator bar	RWMA class 1 (cadmium copper)
Electrodes contacting armature lead	RWMA class 14 (molybdenum)
Electrode force	355 N (80 lbf)(a)
Voltage	5.0 V(a)
Filler metal	BCuP-5, 0.003 in. thick strip
Flux	None
Production per hour	Four commutators(b)

(a) Squeeze time, 10 s; five heating pulses, each 2 s long. (b) Forty-slot commutators

Fig. 8 Resistance brazing of armature leads to commutator bars. Alloy C10200 (OF copper) brazed to alloy C11000 (tough pitch copper); copper alloy filler metal (BCuP-5). Dimensions in inches

Observation by the operator permitted termination of the heating sequence as soon as the leads in the commutator slot reseated themselves. The transformer circuit was then opened by a push button and cooling began. The electrodes were then retracted by releasing the air valve. As a safety measure, a timer in the circuit limited brazing time to a maximum of 1 min. If required time exceeded this setting, the operator had to release and repush the operating button.

Brazing with Portable Machines. One common use of portable resistance welding machines for resistance brazing is attaching bus bar terminals or similar strip connectors to large electrical equipment that cannot be brought to or positioned for brazing in a conventional fixed-position resistance welding machine. Electrical connections to such equipment can often be made more economically by resistance brazing than by mechanical means and are made more readily by resistance brazing than by arc welding.

Resistance brazing done with portable resistance welding machines is a convenient and economical way of interconnecting large copper electrical bus bars or of attaching either large or small copper bus bars to motor-generators, transformers, and other electrical equipment. Lap joints made in this way have a bonding area that provides adequate strength and current-carrying capacity. Joints that have a large area of contact are brazed by making a series of spot brazes that overlap to provide full-joint or nearly full-joint bonding.

The low melting temperature of the filler metal helps to avoid overheating and excessive annealing of the work, and the usual selection of self-fluxing BCuP-5 alloy for the filler metal avoids corrosion problems and the need for flux removal.

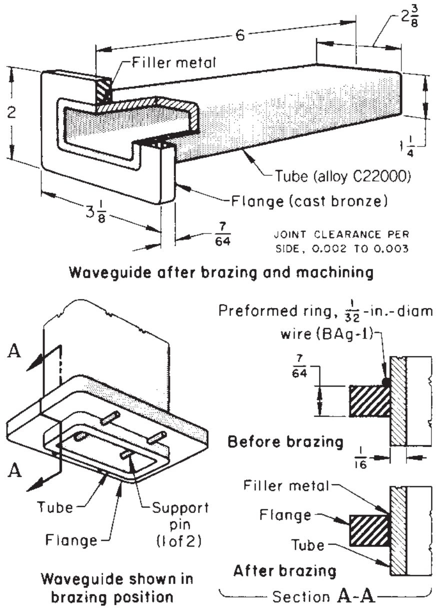


Fig. 9 Waveguide assembly brazed by partial immersion in a molten salt bath. Alloy C22000 (commercial bronze, 90%) brazed to cast bronze; silver alloy filler metal (BAg-1). Dimensions in inches

Dip Brazing

Dip brazing in molten salt is also referred to as salt-bath dip brazing and molten chemical-bath dip brazing. In this process, the assembly to be joined is immersed in a bath of molten salt, which provides the heat and may supply the fluxing action for brazing as well. The bath temperature is maintained above the liquidus of the filler metal but below the melting range of the base metal. Applications of dip brazing of copper alloys included waveguides and waveguide hardware, flowmeter hardware, and capillary tube and bellows assemblies. Neutral chloride-base salts are used. The most commonly used filler metal is BCuP.

The support given immersed workpieces by the buoyancy of the molten salt and the rapid and even heating afforded by dip brazing make this process especially useful for joining assemblies requiring minimum distortion, such as waveguides. When a waveguide assembly has a large number of brazed joints, both external and internal, a salt bath is particularly efficient for simultaneous brazing of all joints in a single immersion in the molten salt. With dip brazing, a flange fitting and the end of a waveguide tube to be joined to it can be brazed by immersing only the joint portion in the molten salt bath, as in the example that follows.

Example 7: Use of Dip Brazing to Minimize Distortion. A waveguide assembly (Fig. 9), which consisted of a straight tube of alloy C22000 (commercial bronze, 90%) and a flange of cast bronze, was used in electrical equipment. The dimensions of the thin-walled tube (38 by 60 by 1.6 mm wall, or $1\frac{1}{4}$ by $2\frac{3}{8}$ by $\frac{1}{16}$ in. wall) had to be maintained to close tolerances, and dip brazing was chosen as the joining process to avoid unacceptable amounts of warpage. Torch brazing had been tried but resulted in excessive distortion.

After burrs were removed from the joint area, tube and flange were degreased, bright dipped, rinsed in water, and dried. The parts were assembled so that the tube extended through the flange. Two accurately located sets of holes were drilled through the longer sides of the rectangular tube, and a pin was inserted through each set of holes to support the flange in the vertical position during brazing.

Filler metal in the form of a rectangular preform of 0.8 mm ($\frac{1}{32}$ in.) diameter BAg-1 wire was placed around the tube and adjacent to the flange (opposite the face). Type FB3-A flux was applied to the joint area, and the assembly was preheated in an oven to 315 °C (600 °F) for 5 min to dry the flux and shorten the time required in the brazing bath.

For brazing, the assembly was supported vertically (flange down) on a rack, which was suspended from a rod extending through the tube. Supported in this manner, the assembly was self-jigged, with gravity locating the flange. Self-jigging by staking was used on similar waveguide assemblies, and tack welding was used on others. Several assemblies simultaneously were partly immersed to a depth of about 75 mm (3 in.) for $1\frac{1}{4}$ min in a molten bath of neutral chloride salt (55% barium chloride, 25% sodium chloride, and 20% potassium chloride) operated at 732 °C (1350 °F). After brazing, the assemblies were allowed to cool in air approximately 260 to 315 °C (500 to 600 °F) before they were washed in hot water to remove any residue of salt and flux, rinsed in hot water, bright dipped to remove slight oxidation that formed during cooling, rinsed in cold water, and dried. Uniform fillets were formed and satisfactory joint penetration was obtained. The flange face was subsequently machined, which removed the portion of the tube that extended beyond the flange. The final dimensions of the assembly were within tolerance.

Soldering

Copper and copper alloys are among the most frequently soldered engineering materials. In fact, copper joining is practically synonymous with soldering. With most copper and copper alloys, the copper surface oxide is easily disrupted and displaced by most flux types. The presence of alloying elements such as beryllium, chromium, silicon, and aluminum modifies the nature of the oxide, making it more tenacious. For these alloys, a special flux is recommended to remove the oxide from the surface and enhance the solderability of the base metal groups. As shown in Table 1, the degree of solderability for copper and copper alloys generally ranges from good to excellent.

Solders

The most widely used solders for joining copper and its alloys are the tin-lead solders listed in Table 6, although tin-antimony (95Sn-5Sb) and tin-silver (95Sn-5Ag) solders are used in drinking water applications to eliminate possible lead contamination of the water. Zinc-base solders containing 3% Cu and small but important amounts of titanium, chromium, nickel, and aluminum have also been developed for copper and brass radiators.

Copper and tin react readily to form two intermetallic compounds, Cu6Sn3 and Cu3Sn, at the faying surfaces of the solder joint. These intermetallic layers form when the solder is molten, as well as after solidification, by means of solid-state diffusion during storage or service at elevated temperature. Although intermetallic compounds are a necessary part of solder wetting, excessively thick layers can be detrimental to joint integrity. Specifically, the brittle nature of intermetallic compounds can jeopardize the mechanical strength of the joint, particularly at high loading rates, such as those that occur under impact or vibration conditions. Therefore, a thin intermetallic layer is desirable. The kinetics of intermetallic phase growth are controlled by the amount of tin and other elements in the solder, the soldering temperature, and time. Thus, to minimize the thickness of the intermetallic phase, a low-tin solder or a short soldering time should be utilized. Another way to minimize the intermetallic formation is to use a barrier coating, such as nickel, silver, or gold. Additional information on intermetallic phase growth can be found in the section "Solder Joint Metallurgy."

Fluxes

The major role of the flux is the removal of thin oxide layers during the initial stages of the soldering process, thereby permitting the molten solder to react with the substrate and to spread. Organic and rosin types of noncorrosive fluxes are excellent for soldering coppers and may be used with some success on copper alloys containing tin and zinc, if surfaces to be soldered are precleaned. These fluxes are used for soldering electrical connections and electronic components. A light coat of flux should be applied to precleaned faying surfaces.

The inorganic corrosive fluxes can be used on all the copper alloys, but they are required only on those alloys that develop refractory surface oxides, such as silicon and aluminum bronze. Aluminum bronze is especially difficult to solder and requires special fluxes or copper plating. Inorganic chloride fluxes are useful for soldering the silicon bronzes and copper nickels.

Table 6 Tin-lead solders for joining copper and copper alloys

Specification			Nominal composition(a), wt%	Melting range, °C (°F)		Preferred soldering processes(b)				Applications
DIN 1707	ISO 3677	ASTM(c)		Solidus	Liquidus	F	I	K	T	
Antimony-containing solders										
L-PbSn12Sb	BPb88Sn250–295	…	12Sn; 0.45Sb; bal Pb	250 (482)	295 (563)	X	…	…	X	Radiator construction
L-PbSn20Sb	BPb80Sn186–270	20B	20Sn; 0.70Sb; bal Pb	186 (367)	270 (518)	X	…	…	X	…
L-PbSn25Sb	BPb75Sn186–260	25B	25Sn; 0.85Sb; bal Pb	186 (367)	260 (500)	X	…	…	X	Radiator construction, tin-lead bearing
L-PbSn40Sb	BPb60SnSb186–225	40B	40Sn; 1.45Sb; bal Pb	186 (367)	205 (401)	X	…	X	X	Radiator construction
Low-antimony-content solders										
L-PbSn8(Sb)	BPb92Sn280–305	…	8Sn; 0.31Sb; bal Pb	280 (536)	305 (581)	X	X	…	X	Radiator construction, thermostats
L-PbSn33(Sb)	BPb67Sn183–242	…	33Sn; 0.31Sb; bal Pb	183 (361)	242 (468)	X	…	…	…	Cable cover soldering
L-Sn50Pb(Sb)	BSn50Pb183–215	50B	50Sn; 0.31Sb; bal Pb	183 (361)	215 (419)	X	…	X	X	Precision soldering and plumbers
L-Sn60Pb(Sb)	BSn60Pb183–190	60B	60Sn; 0.31Sb; bal Pb	183 (361)	190 (374)	X	X	X	X	Electrical engineering, precision work soldering
Antimony-free solders										
L-PbSn40	BPb60Sn183–235	40A	40Sn; bal Pb	183 (361)	235 (455)	X	…	X	X	Tableware
L-Sn50Pb	BSn50Pb183–215	50A	50Sn; bal Pb	183 (361)	215 (419)	X	…	X	X	Electrical engineering
L-Sn60Pb	BSn60Pb183–190	60A	60Sn; bal Pb	183 (361)	190 (374)	X	X	X	X	Electrical engineering, printed circuits
L-Sn63Pb	BSn63PB183	…	63Sn; bal Pb	183 (361)	183 (361)	X	X	X	X	Electrical engineering, electronic
Solders with copper addition										
L-Sn50PbCu	BSn60Pb183–215	…	50Sn; 1.4Cu; bal Pb	183 (361)	215 (419)	…	…	X	…	Electrical engineering, electronic
L-Sn60PbCu	BSn60Pb183–190	…	60Sn; 0.15Cu; bal Pb	183 (361)	190 (374)	…	…	…	X	Electrical engineering, electronic
L-Sn60PbCu2	BSn60Pb183–190	…	60Sn; 1.8Cu; bal Pb	183 (361)	190 (374)	…	…	X	X	Printed circuits
Solders with silver addition										
L-Sn50PbAg	BSn50PbAg178–210	…	50Sn; 3.5Ag; bal Pb	178 (352)	210 (410)	…	…	X	X	Electrical engineering
L-Sn60PbAg	BSn60PbAg178–180	…	60Sn; 3.5Ag; bal Pb	178 (352)	180 (356)	…	X	X	X	Electronic
L-Sn63PbAg	BSn63Pb178	…	63Sn; 1.4Ag; bal Pb	178 (352)	178 (352)	…	X	X	X	Printed circuits
Solders with phosphorus addition										
L-Sn50PbP	BSn50Pb183–215	…	50Sn; bal Pb(d)	183 (361)	215 (419)	…	…	…	X	Electrical engineering, printed circuits
L-Sn60PbP	BSn60Pb183–190	…	60Sn; bal Pb(d)	183 (361)	190 (374)	…	…	…	X	Principally for immersion soldering
L-Sn63PbP	BSn63Pb183	…	63Sn; bal Pb(d)	183 (361)	183 (361)	…	…	…	X	Electrical engineering, printed circuits
L-Sn60PbCuP	BSn60Pb183–190	…	60Sn; 0.15Cu; bal Pb(d)	183 (361)	190 (374)	…	…	…	X	Principally for immersion soldering

(a) Tolerance is tin contents ± 0.5%. Other tolerances and accepted impurities after DIN 1707. (b) F = flame furnaces; I = induction soldering; K = soldering iron; T = immersion (dip) soldering. (c) After ASTM B 32. (d) Phosphorus addition from 0.001 up to 0.004%

Oxide films reform quickly on cleaned copper alloys, and fluxing and soldering should be done immediately after cleaning. Copper tube systems soldered with 50% tin-50% lead or 95% tin-5% antimony solder require a mildly corrosive liquid flux or petrolatum pastes containing zinc and ammonium chlorides. Many liquid fluxes for plumbing application are self-cleaning, but there is always a risk of corrosive action continuing after soldering.

A highly corrosive flux can remove some oxides and dirty films, but there is always an uncertainty whether uniform cleaning has been achieved and whether corrosive action continues after soldering. Optimal soldering always starts with clean surfaces and a minimum amount of flux.

Precleaning and Surface Preparation

Oil, film, grease, tarnish, paint, pencil markings, machining lubricants, and general atmospheric dirt interfere with the soldering process. A clean surface is imperative to ensure a sound and uniform quality soldered joint. Fluxing alone cannot substitute for adequate cleaning. Solvent or alkaline cleaning and pickling are used to clean copper surfaces as well as remove oxides. Mechanical preparation with abrasives can also be used to remove oxides. Chemical removal of oxides requires proper choice of pickling solution followed by rinsing. Typical procedures for cleaning are described in the article "Surface Engineering" in this Handbook.

Flux Removal

After the soldering operation, the workpiece is cleaned, primarily to remove flux residues that can cause corrosion of the part while in storage or during service. Flux residues should be removed as soon as possible after the soldering process because their ability to be removed decreases with time, whereas their tenacity and potential for corrosive damage increase with time.

Removal of Rosin-Flux Residues. Nonactivated rosin-flux residues may remain on the soldered joint unless appearance is important or the joint area is to be painted or otherwise coated. Activated rosin fluxes are treated in the same manner as organic fluxes for structural soldering, but they should be removed for critical electronic applications. When rosin residues are to be removed, alcohol or chlorinated hydrocarbons are used. Certain rosin activators are soluble in water but not in organic solvents. This flux residue is removed using organic solvents, followed by water rinsing.

Removal of Organic-Flux Residues. The residues from the organic fluxes are quite soluble in hot water. Double rinsing is always advisable. Oily or greasy paste flux residues may be removed with an organic solvent. Soldering pastes are emulsions of petroleum jelly and a water solution of zinc-ammonium chloride. The corrosive chloride residue must be removed from the soldered joint.

Removal of Inorganic-Flux Residues. Zinc chloride fluxes leave a fused residue that absorbs water from the atmosphere. Removal of this residue is best accomplished by thorough washing in a hot solution of 2% concentrated hydrochloric acid (20 mL/L, or 2.5 oz/gal), followed by a hot-water rinse and air blast drying. The acid solution removes the white zinc oxychloride crust, which is insoluble in water. Complete removal sometimes requires additional rinsing in hot water that contains some washing soda (sodium carbonate) before a clear water rinse. Mechanical scrubbing may also be necessary.

Pipe and Tube Soldering

Solder joints are widely used in the plumbing industry. The universal application of soldered copper tubing attests to the relative simplicity of performing the task and the reliability of the joints that are made. There are several important rules to ensure the correct application of soldering technology to pipe joining. Preparation of pipe ends for soldering is dependent on the material and size of the pipe. Essentially, the objective is to obtain a clean surface for joining. Pipe ends should be cut square and prepared so that fittings can be placed evenly to allow for uniform gaps for good capillary joining. Sound soldered joints usually can be made with a 0.1 mm (0.004 in.) joint clearance. Tube end cleaning prior to solder joining can be achieved by light abrasion with fine grades of abrasive paper.

A wide range of fluxes is available for tube end pipe joining. These vary in quality and effectiveness, and care should be taken to select a flux known to provide good joint solder spread with low residual corrosion tendencies. Paste fluxes usually are applied by a small brush or clean cloth to the pipe end and internally in the fitting. The parts then are pushed together and the joint assembly heated to make the solder joint.

Pipe and tube soldering usually is accomplished with gas torches fueled with propane or natural gas. For larger sized copper piping, acetylene torches sometimes are used because of the high heat conductivity of the material. Generally, neutral to very slightly reducing flames should be used and the pipe and fitting heated as uniformly as possible until the solder temperature is reached. Soldering temperature can be determined by the ability to melt the end of a solder wire when applied to the surface of the pipe or fitting. When the solder begins to melt, the normal practice is to feed additional solder into the capillary space while moving the torch around the fitting on the opposite side to that at which the solder is being applied. This ensures that the joint is heated sufficiently so that cold soldered joints are not made. Penetration of the solder around the joint can be visually observed, and usually some fillet should form between the pipe and fitting.

Other methods of joint heating are in use, including induction furnace heating, radiant heating, and direct resistance heating. Portable equipment for resistance heating using tongs with graphite electrodes can be directly applied to the tube in applications where the presence of a flame may be undesirable. Care must be taken to ensure that the joint has reached the soldering temperature, which can be tested by the uniformity of the observed heat and oxidation pattern and the capability of melting the solder wire into the joint.

Solder joints are made on pipe and tubing rapidly and effectively. The solder alloys used depend on the strength requirements of the piping system, but solders from 40 to 60% Sn with the balance lead are often used. Where creep conditions are known to exist or are required in the load-carrying capability of the tube, a higher lead solder is desirable. Changes to the higher lead solder generally require a change in flux. Tests should be made to ensure that the appropriate solder alloy and flux combination has been selected. Pipe and tubing used for potable water applications or elevated temperatures at higher pressure usually are manufactured with 95%Sn-5%Sb solder. Soldering techniques with this alloy are different, and care should be taken to ensure that the techniques used are capable of producing the desired sound joints.

Solder Joint Metallurgy

When a solder joint is produced by the spread of a liquid metal or alloy over a solid base metal or alloy, a metallurgical reaction between the two frequently occurs, resulting in the formation of intermetallic compounds. As mentioned earlier, there are two main intermetallics in the copper-tin system, $Cu6Sn5$ and $Cu3Sn$, both of which are found at joint interfaces between copper or brass and tin-lead solders. In this particular joint, lead shows little tendency to react with the base metal. Tin diffuses quite deeply into the brass, in addition to forming an interfacial compound. An important effect is the dissolution of the base metal into the solder alloy. The effect of time and temperature on the reaction of copper and copper alloys with two separate solders is shown in Fig. 10. The temperature effect is dominant, followed by the effect of alloy addition or modification to the base metal. The effect of tin content on the time required to react with a base-metal strip is presented in Fig. 11 for the entire tin-lead system. This figure gives an indication of the relative reaction rates of different solder alloys at various processing temperatures. These effects are summarized in a nomograph presented as Fig. 12.

The dissolution of base metal into the solder alloy and formation of an intermetallic compound, should this occur naturally in the system, results simultaneously during a soldering operation. Examination of soldered joints in brass with one particular solder is shown in Fig. 13, which demonstrates that as the intermetallic compound thickness increases, the strength properties of the joint are decreased. After a solder joint is complete, intermetallic compound formation can occur by diffusion of solder alloy elements and base-metal elements. The extent of diffusion depends on the service temperature of the joint. Figure 14 shows various curves with a 60%Sn-40%Pb solder after exposure at various temperatures for extended periods of time.

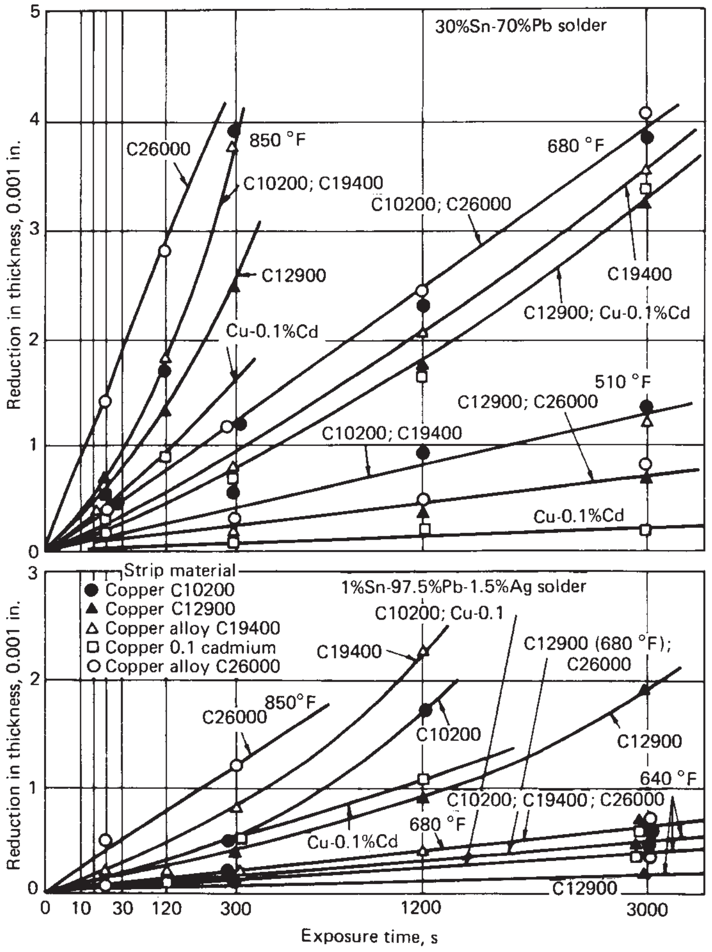


Fig. 10 Effect of time and temperature on the reaction of copper and copper alloys with two solders. (a) 30%Sn-70%Pb solder. (b) 1%Sn-97.5%Pb-1.5%Ag solder. Source: Copper Development Association

Intermetallic compounds form in copper-tin system through solid-state diffusion, resulting in a reduction in strength properties of the joints, as shown in Fig. 15.

Intermetallic compounds are very important to soldering technology. Potential problems with rapid compound formation sometimes can be overcome by changes in base-metal composition or by plating of surfaces prior to the joining operation. Dissolution rate during soldering, reaction rate during soldering, and solid-state diffusion after soldering must be taken into account in any concerned manufacturing program. Intermetallic compounds can be influential in soldered joint reliability over a long period of time. In addition, these compounds also can affect electrical properties in solder joints and may become very significant in microelectronic applications.

Soldered Joint Properties

Physical and mechanical property values of bulk solders give an indication of their capabilities in providing the desired joint properties for service. However, the specific nature of the solder joint/base metal relationship requires that for practical purposes, measurement of soldered joint properties directly is advisable for successful application.

Shear Strength. The most widely reported joint strengths for soldered joints are shear strengths in lap joints as presented in Table 7, where data are given for a wide range of tin-lead and antimony-containing solders. Generally, the higher tin content solders provide a higher shear strength.

The relationship of shear strength to tin content is more clearly illustrated in Fig. 16, which shows that the maximum shear strength is obtained at approximately 60% Sn content. A limited number of short-term shear strength data for soldered joints at 20 and 100 °C (68 and 212 °F) are presented in Table 8. Differences between these data and those shown in Table 7 are due to different sources of information. Note the loss in strength as the temperature of testing is increased to 100 °C (212 °F).

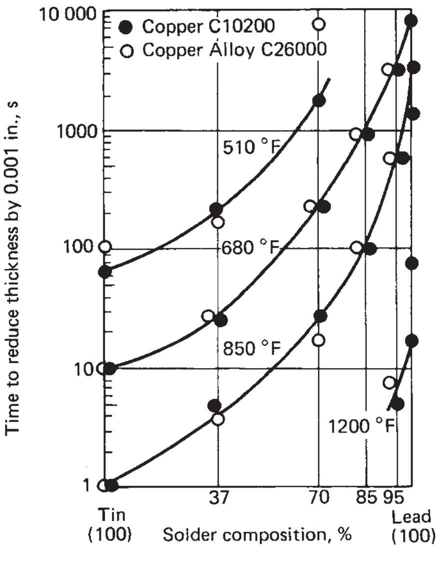


Fig. 11 Effect of tin content on the time required for tin-lead solders to react with 1 mil of base metal strip thickness at four temperatures. Source: Copper Development Association

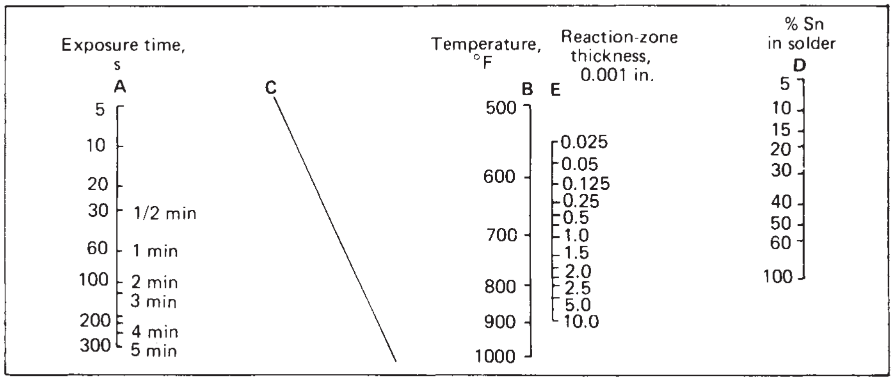


Fig. 12 Reaction of tin-lead solder with copper alloys C10200 and C26000 under static infinite-volume conditions. Select the exposure conditions on scales A and B. With a straight edge between the conditions, find the intersection with base line C. Using a straight edge, connect this point on line C with the tin content of the solder on scale D. Read the reaction-zone thickness on scale E. The nomograph may also be used in reversed sequence to select operating conditions given a permissible reaction zone thickness and solder composition. Source: Copper Development Association

Elevated-Temperature Properties. An important measure of the capability of the soldered joint is its ability to sustain stress for long periods of time, which is good creep resistance. Table 9 shows a number of tin-lead solders and strength properties at three separate test temperatures. Note that the higher lead content solders perform much better in a creep situation than the higher tin content solder alloys. Additional data are presented graphically in Fig. 17 for three separate solder alloys. The 95%Sn-5%Sb solder alloy has the best creep strength of the three materials shown. Tin-antimony solders are therefore utilized at higher temperatures. However, the costs of the alloy must be taken into account in overall design of any system using soldered joints. Good high-temperature properties are also obtained with a 95%Sn-5%Ag alloy, for which curves for creep tests under shear are presented in Fig. 18.

For elevated-temperature usage, tin-lead-silver solders frequently are selected. Table 10 shows results obtained with a specific loading program comparing several tin-lead-silver alloys and tin-lead solders. The advantages of the silver-containing materials are clearly evident in their ability to withstand much higher stresses on creep loading. These tests were carried out initially at a low load, which was increased daily to obtain the values presented. Although this is not a creep test, the results are comparable to creep tests and can be used on a relative basis for design purposes. Sufficient data are presented, however, to demonstrate to the designer that specific material selection can be made in relation to a product, depending on loading requirements in service. From an economic standpoint, it is essential to use the advantages of a silver addition for its inherent benefits. Conversely, sometimes savings can be made where silver-bearing solders are used without properly assessing the need for them.

Fracture Initiation Strength. There are a number of applications involving soldered joints where the applied stresses tend to open or peel the joint apart, rather than pull or shear the joint. Tearing a joint apart produces a fracture curve similar to that presented in Fig. 19. The load increases until fracture initiation occurs, at which point the load value drops to a lower level and proceeds at a constant value as the joint is peeled apart. Peel strength, or fracture initiation strength, is a specific mechanical property of a soldered joint and should be determined for each particular system and design. An example of data obtained in this way at various processing temperatures and with various fluxes is shown in Fig. 20. The importance of the total solder system in determining strength properties is clearly evident. The solder alloy has an inherent strength property that it can give to the joint. The realization of this property depends on the application of an appropriate flux to obtain maximum adhesion at the joint and also the performance of soldering at a precise temperature to obtain optimum strength values. This method of testing is

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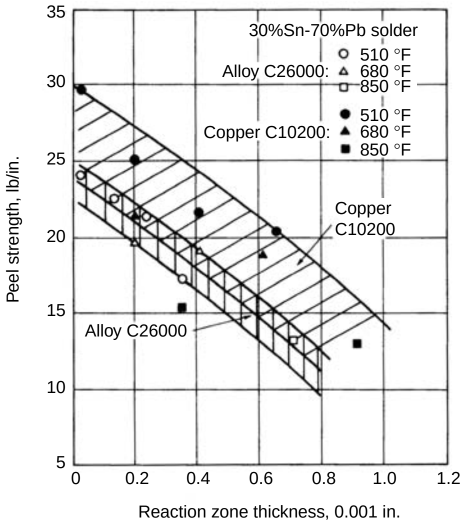

Fig. 13 Effect of intermetallic compound at soldered joint on peel strength. Source: Copper Development Association

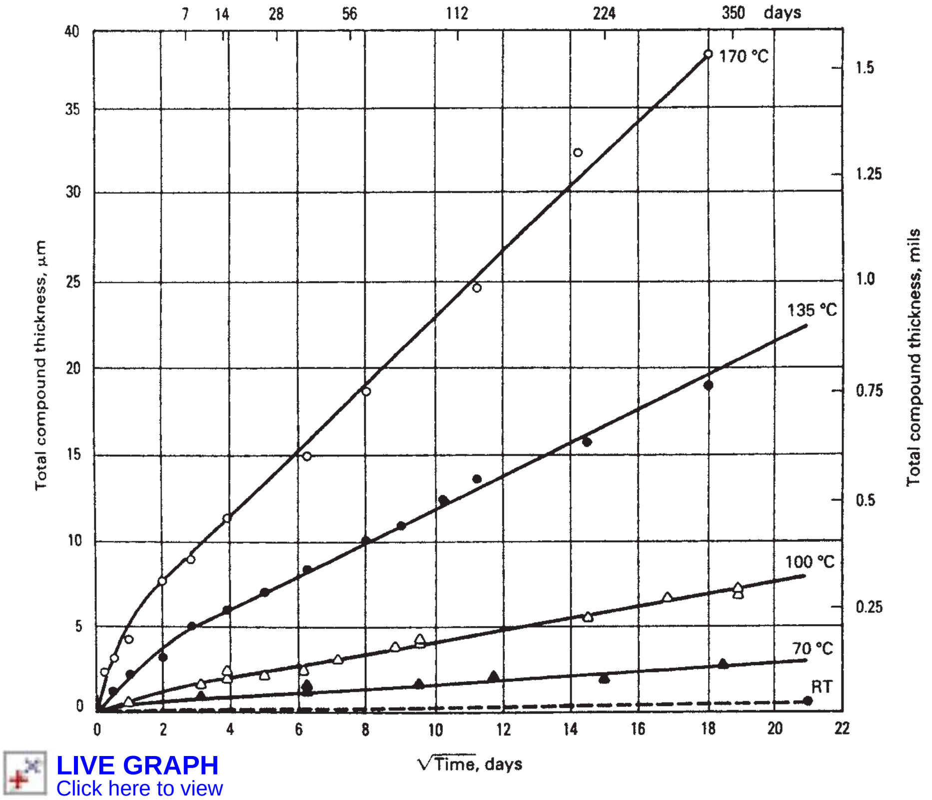

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Fig. 14 Curves showing rate of growth of layers of intermetallic compound between a 60Sn-40Pb coating and copper at various temperatures. RT, room temperature. Source: Tin Research Association

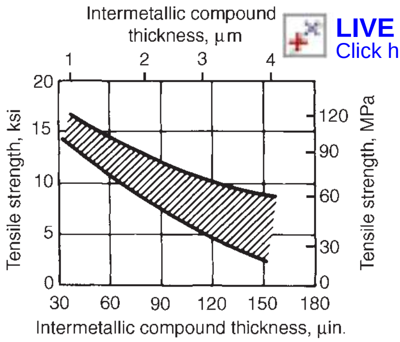

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Fig. 15 Effect of thickness of intermetallic compound in soldered joints on tensile strength at room temperature

Table 7 Shear strength of soldered lap joints

	Joint between copper members		Joint between brass members	
Tin content, %	MPa	ksi	MPa	ksi
ASTM grade A tin-lead solders				
10	14.5	2.1	12.4	1.8
20	20.7	3.0	19.3	2.8
30	27.6	4.0	22.8	3.3
40	34.5	5.0	27.6	4.0
50	38.6	5.6	31.0	4.5
60	39.3	5.7	29.6	4.3
ASTM grade C tin-lead-antimony solders				
10	14.5	2.1	12.4	1.8
20	21.4	3.1	19.3	2.8
30	28.9	4.2	22.8	3.3
40	34.5	5.0	27.6	4.0
50	39.3	5.7	27.6	4.0
60	42.1	6.1	27.6	4.0

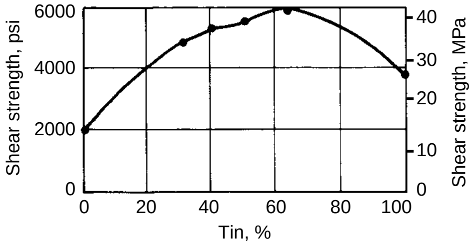

Fig. 16 Shear strengths of copper joints soldered with tin-lead solders. Source: International Tin Research Institute

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appropriate to lead attachments in electronics, solder joints in containers under pressure, and in the tanks of automotive radiators. A comparison of the peel property or fracture initiation strength with various solder alloys and alloy C26000 brass under this type of load at various test temperatures from room to 150 °C (300 °F) is presented in Fig. 21. The superiority of a tin-lead-silver solder alloy over various tin-lead materials can be observed. The particular alloy selected for joining should depend on the economics of the materials and the loading required on the joint.

The fatigue strength of soldered joints is a complex and difficult subject to examine. Because solder alloys are strain-rate sensitive and have large elongation capabilities, the performance of fatigue tests under constant stress causes progressive and rapid relaxation of the joint, and conversely, tests under constant strain do not reflect a practical application situation. The influence of the rate of stress cycling in terms of rate of straining on the fatigue life of copper soldered joints with 60%Sn-40%Pb alloy is presented in Fig. 22. Fatigue of soldered joints

Table 8 Short-term shear strength of soldered joints tested at 0.002 in./min

Composition, %			Shear strength				Loss in strength (68 to 212 °F), %
			20 °C (68 °F)		100 °C (212 °F)		
Tin	Lead	Other	MPa	ksi	MPa	ksi	
60	40	…	19.6	2.84	12.8	1.85	35
10	90	…	16.5	2.42	10.8	1.56	35
62	36	(a)	26.9	3.98	11.8	1.71	57
40	58	(b)	23.5	3.41	10.8	1.56	54
95	…	(c)	27.4	3.98	13.7	1.99	50
5	93.5	(d)	17.7	2.56	11.8	1.71	33

(a) 2% Ag. (b) 2% Sb. (c) 5% Sb. (d) 1.5 Ag

Table 9 Maximum sustained stress at various temperatures

Values will not cause failure of soldered lap joints in 10 years (in air).

Tin content, %	Sustained stress					
	20 °C (68 °F)		100 °C (212 °F)		150 °C (300 °F)	
	kPa	psi	kPa	psi	kPa	psi
5	3450	500	1720	250	1030	150
10	3240	470	1380	200	690	100
20	2480	360	830	120	340	50
30	2070	300	620	90	210	30
40	1790	260	520	75	210	30
50	1720	250	520	75	210	30
60	1720	250	520	75	210	30

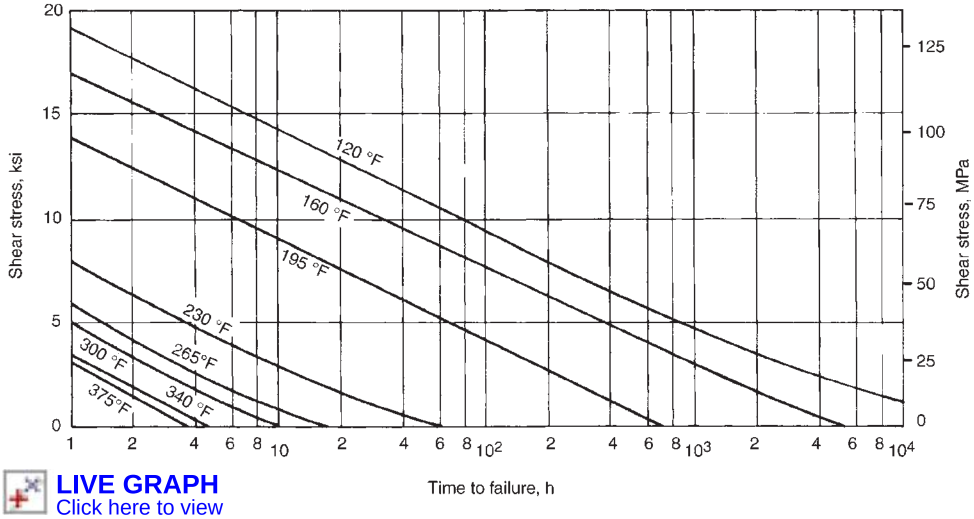

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Fig. 18 Stress-time to failure curves at various temperatures for overlap joints between brass components soldered with 95%Sn-5%Ag alloy. Source: International Tin Research Institute

Table 10 Stepped loading creep tests on nominal ½ by ⅛ in. overlap joints on copper

Composition, %			Temperature, °C (°F)		Breaking stress, kPa (psi)		
Lead	Tin	Silver	Liquidus	Solidus	20 °C (68 °F)	100 °C (212 °F)	150 °C (300 °F)
98	2	…	320 (608)	304 (580)	…	4,137 (600)	< 2,070 (< 300)
95	5	…	312 (594)	270 (518)	…	3,720 (540)	< 2,070 (< 300)
97.5	1	1.5	313 (595)	301 (573)	11,310 (1,640)	6,205 (900)	4,830 (700)
96.5	2	1.5	306 (583)	301 (573)	10,340 (1,500)	6,070 (880)	4,830 (700)
93.5	5	1.5	304 (579)	301 (573)	14,820 (2,150)	5,520 (800)	3,860 (560)
70	30	…	255 (491)	183 (361)	6,205 (900)	2,590 (375)	…
60	40	…	241 (466)	183 (361)	5,860 (850)	2,070 (300)	…
50	50	…	216 (421)	183 (361)	6,030 (875)	2,070 (300)	…

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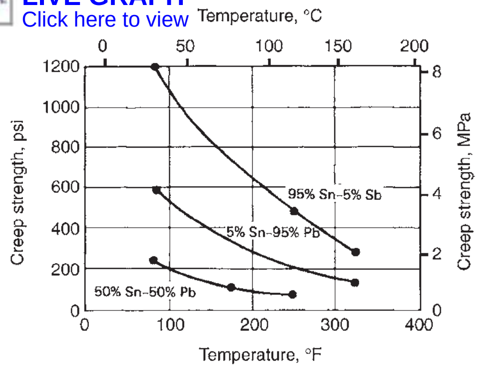

Fig. 17 Creep strengths at elevated temperatures for copper joints soldered with several alloys. Source: International Tin Research Institute

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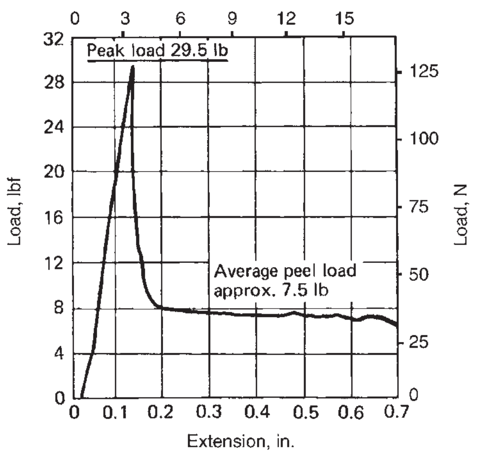

Fig. 19 Stress-strain relationship for test of soldered joint with peel-type failure. Source: Copper Development Association

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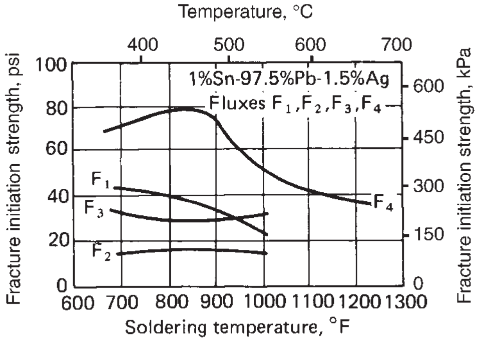

Fig. 20 Fracture initiation strength for copper joints soldered with four fluxes over a range of temperatures. Source: Copper Development Association

has been obtained from a thermal cycling of printed circuit joints where the only stresses implied are those imposed by the joint itself during the thermal cycle. Metallurgical change during thermal cycling and straining occurs by internal diffusion, complicating analysis of fatigue in soldered joints. The fatigue life of different solder alloys at two test temperatures at a strain rate of 5 reversals/min is shown in Table 11. A lead-indium solder alloy composition gives best results under these conditions.

Adhesive Bonding

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The largest use of adhesive bonding of copper and copper alloys is in the field of microelectronics. For example, copper foil clad laminates are joined by adhesive bonding during construction of printing wiring boards. Epoxy adhesives are commonly employed. Epoxies are also used to join copper plumbing tube used for both potable water and for waste, vent, and drain service. One example, sold under the tradename Copper-Bond (Ref 1, 2), is suitable for use with capillary spaces between 0.05 and 0.13 mm (0.002 and 0.005 in.) wide. Epoxies have also been found safe for use in food and beverage contact applications.

Surface Preparation. For structural applications under which high stresses occur, surface preparation is critical. Common practice is to prepare the surface by mechanical abrasion. Although this produces adequate bond strength, the resultant durability is poor. Several chemical etch treatments have been developed for copper and copper alloys (most notably brasses and bronzes) that are suitable for long-term structural applications. Two of these, an Ebonol C etch and an alkaline-chlorite etch (Ref 3–5), result in black oxide surfaces that have microrough morphologies. These porous oxides facilitate bonding. Microrough surfaces have also been produced by anodizing copper in a sodium hydroxide solution (Fig. 23).

The processing steps for the Ebonol C and the alkaline-chlorite etches are shown in Table 12. These etches are used for alloys containing at least 95% Cu. An etching procedure for other copper alloys, based on a ferric chloride-nitric acid solution, is also shown in Table 12.

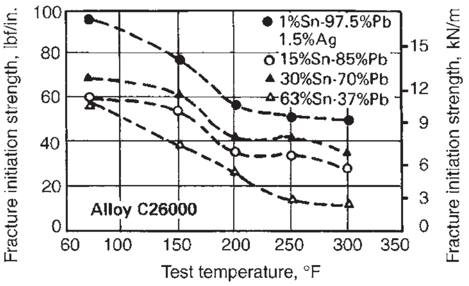

Fig. 21 Fracture initiation strength for several solders. Source: Copper Development Association

Table 11 Fatigue life of solder alloys subjected to 5 strain reversals/min

Composition, %			Life at 3% shear strain imposed at	
Tin	Lead	Other	20 °C (68 °F)	100 °C (212 °F)
63	37	…	16,000	3,000
40	60	…	13,000	5,100
95	…	(a)	6,300	3,600
42	…	(b)	8,500	6,300
50	…	(c)	17,000	6,700
95	…	(d)	20,000	4,900
…	50	(c)	52,000	5,400

(a) 5% Sb. (b) 58% Bi. (c) 50% In. (d) 3.5% Ag, 0.5% Sb, and 1% Cd

ACKNOWLEDGMENTS

This article was adapted from:

- M. Prager, Brazing of Copper and Copper Alloys, *Welding, Brazing, and Soldering,* Vol 6, Metals Handbook, American Society for Metals, 1983, p 1033–1048
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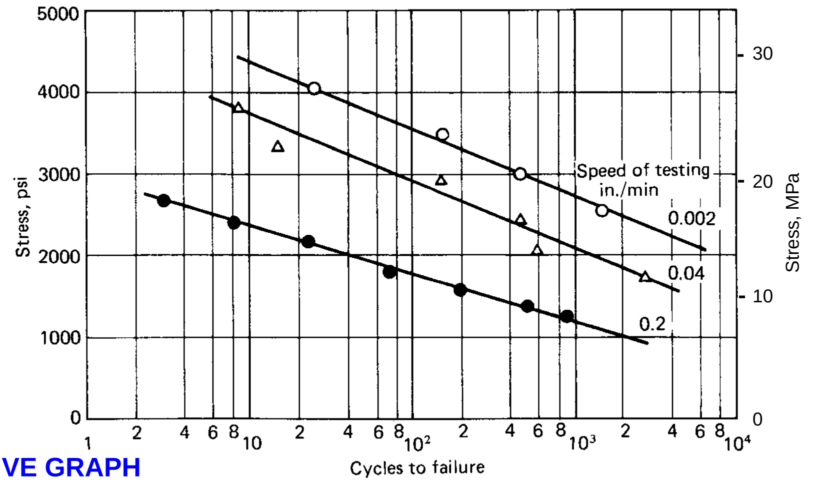

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Fig. 22 Influence of rate of stress cycling. In terms of straining on the fatigue life of ring-and-plug joints of copper soldered with 60%Sn-40%Pb alloy. The minimum stress imposed was nominally zero and the maximum stress in the loading cycle is the ordinate. Source: International Tin Research Institute

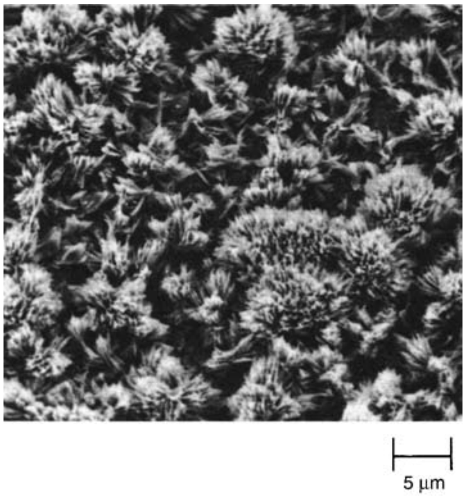

Fig. 23 Microrough copper surface prepared by anodizing in a sodium hydroxide solution. Source: Ref 6

Table 12 Etching procedures for copper adherends

Step	Ebonol C	Ferric chloride/ alkaline chlorite	Ferric chloride/nitric acid
1. Degreasing	Trichloroethane (vapor), 87–90 °C (190–194 °F) as needed	Trichloroethane	Trichloroethane (vapor), 87–90 °C (190–194 °F) as needed
2. Cleaning	10 vol% HNO_3 (70%); 90 vol% H_2O, 30 s, 25 °C (77 °F)	11 vol% HNO_3; 68 vol% H_3PO_4; 10 vol% 11 vol% acetic anhydride; H_2O, 4 min, 25 °C (77 °F)	…
3. Rinse	H_2O, running transfer to etchant	Distilled H_2O, then acetone	…
4. Etch	Ebonol C, 6.8 kg (240 oz); H_2O to make 3.8 L (1 gal), 2 min, 36 °C (95 °F)	30 g/L (4 oz/gal) $NaClO_2$; 100 g/L (13 oz/gal) Na_3PO_4; 50 g/L (6.6 oz/gal) NaOH, 15 min, 95 °C (205 °F)	6 wt% FeCl (42%); 12 wt% HNO_3; 82 wt% deionized H_2O, 2 min, 25 °C (77 °F)
5. Rinse	H_2O, 2–3 min, 10–15 °C (50–60 °F)	Deionized H_2O, 25 °C (77 °F), then acetone	H_2O, 3–5 min, 10–15 °C (50–60 °F)
6. Dry	Air or dry N_2	Air	Air or dry N_2

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Surface Engineering

THE SELECTION OF SURFACE ENGINEERING TREATMENTS for copper and copper alloys is generally based on application requirements for appearance and corrosion resistance. These treatments range from simple low-cost chemical processes that provide a uniform surface appearance, to expensive electroplates that provide maximum corrosion resistance.

Cleaning and Finishing Processes

Prior to subsequent processing or the application of a protective or decorative coating, the copper or copper alloy surface must be prepared by suitable cleaning procedures. The severity of these cleaning procedures will depend on the past processing history of the metal. Copper and copper alloys obtained from major materials suppliers should be received reasonably clean (free from heat treat scale or tarnish) and should only require minimal cleaning prior to further processing.

Table 1 Pickling conditions for copper-base materials

Constituent or condition	Amount or value
Sulfuric acid bath	
Sulfuric acid(a)	15–20 vol%
35% hydrogen peroxide	3–5 vol%
Water	bal
Temperature of solution	Room temperature to 60 °C (140 °F)
Immersion time	15 s to 5 min
Hydrochloric acid bath	
Hydrochloric acid(b)	40–90 vol%
Water	bal
Temperature of solution	Room temperature
Immersion time	1–3 min

(a) 1.83 sp gr. The bath needs additives to stabilize peroxide and accelerators to maintain etch rate. Proprietary products are available from metal finishing suppliers. (b) 1.16 sp gr

Heat treating of copper and copper alloys in air results in the formation of copper oxides; further cleaning will be necessary to remove these oxides, as discussed subsequently. The need for such cleaning can be prevented by heat treating in reducing atmospheres, such as nitrogen with 1 to 4% H, in which the formation of copper oxides will be completely suppressed. Such atmospheres will not, however, prevent the oxidation of reactive alloying constituents such as aluminum, silicon, or zinc.

Pickling and Bright Dipping

Pickling in solutions containing 4 to 15 vol% sulfuric acid or 40 to 90 vol% hydrochloric acid is used for the removal of oxides formed on the surface of copper-base materials during mill processing and fabricating operations. The sulfuric acid solution is used to remove black copper oxide scale on brass extrusions, forgings, and machined parts; oxide on copper tubing, forgings, and machined parts; and light annealing scale or tarnish. The hydrochloric acid solution is primarily used for finishing, but is also used to remove scale and tarnish from brass forgings and machined parts, and oxide on copper forgings and machined parts. Conditions for pickling copper-base metals with sulfuric acid and hydrochloric acid are shown in Table 1. Sometimes no additional surface preparation is necessary to produce the uniformity of appearance required for further finishing of copper; however, heavily scaled material may need a bright dip or color dip after pickling.

Except for bright annealed material, copper alloys must be pickled after each annealing treatment, completely descaled, and bright dipped to produce a natural surface color and luster suitable for other finishing treatments such as electroplating or painting. Scale dip and bright dip solutions are given in Table 2. Bright dips for copper-base materials consist of sulfuric and nitric acids in varying proportions with a small amount of water and hydrochloric acid. Proprietary pickle and bright dips, using sulfuric acid and stabilized hydrogen peroxide, are also available. Whereas the conventional bright dips use highly concentrated acids, this sulfuric acid-hydrogen peroxide bath is dilute and reduces worker safety hazards.

Table 2 Scale dip and bright dip conditions for copper-base metals

These solutions remove scale that is not removed by sulfuric or hydrochloric acid solutions; lower concentrations of nitric acid and higher concentrations of sulfuric acid produce a bright lustrous finish; these solutions can remove 0.0255 mm (0.001 in.) of metal and should not be used when close dimensional tolerances must be maintained. Solutions are used at room temperature.

			Hydrochloric acid(c)			
Solution	Sulfuric acid(a), vol%	Nitric acid(b), vol%	g/L	oz/gal	Water, vol%	Immersion time, s
Scale dip						
Solution A	0	50	4	½	50	15–60
Solution B	25–35	35–50	4	½	35–40	15–60
Bright dip	50–60	15–25	4	½	bal	5–45

(a) 1.83 sp gr. (b) 1.41 sp gr. (c) 1.16 sp gr. Excess hydrochloric acid spots brass. Wood soot and activated charcoal are added to the solution to prevent this condition.

After bright dipping and thorough rinsing in cold running water, stain or tarnish may be removed by dipping in a cyanide solution. Some proprietary bright dips, incorporated with corrosion inhibitors, eliminate the use of toxic cyanides and chromates and are easy to waste treat.

When a semibright finish is satisfactory, a dichromate color dip is less expensive and more convenient to use than the conventional acid dip. Color dip should not be used if parts are to be plated or soldered. The following conditions for color dipping include a solution that removes red copper oxide and imparts a film that resists discoloration during storage and work:

Sodium dichromate	30 to 90 g/L (4 to 12 oz/gal)
Sulfuric acid, 1.83 sp gr	5 to 10 vol%
Water	bal
Immersion time	30 s
Temperature of solution	Room temperature

Extruded yellow brass rod may be pickled, usually in dilute sulfuric acid, to remove light oxide prior to drawing, forging, or machining. Yellow brass forgings are similarly treated for the removal of oxide scale and forging lubricant. Hydrochloric acid solutions may be used instead of sulfuric acid in some applications. Bright dipping follows pickling to complete the removal of all oxide. The yellow brass is then given a color dip to produce a uniform cartridge-brass color. Although brass sand castings are seldom pickled, a solution similar to that used for forgings may be used when pickling is indicated.

A typical acid treatment cycle for copper-base materials is given in the following list. The cycle may be terminated after any water rinse if the desired finish and color have been obtained:

- Pickling
- Cold water rinse
- Scale dip or bright dip
- Cold water rinse (repeat once)
- Color dip
- Cold water rinse (repeat once)
- Hot water rinse
- Air-blast dry

Aluminum bronzes form a tough, adherent aluminum oxide film during hot fabrication. This film can be removed or loosened by the following strong alkaline solution:

Sodium hydroxide	10 wt%
Water	bal
Temperature of solution	75 °C (170 °F)
Immersion time	2 to 6 min

After this treatment the material can be treated in acid solutions by some of the same cycles used for other copper-based materials.

Alloys containing silicon may form oxides of silicon that are removable only by hydrofluoric acid. Proprietary fluorine-bearing compounds are also available for this purpose. If a dull brown-to-gray appearance is not objectionable, the material may be pickled in the conventional sulfuric acid solution to remove the copper oxides. If a brighter finish is required, one of the solutions in Table 3 may be used.

Alloys containing beryllium that have been heat treated at relatively low temperatures (below 400 °C, or 750 °F) can be pickled or bright dipped as any other copper alloy; however, alloys containing beryllium that have been heat treated at temperatures above 400 °C (750 °F) in operations such as solution annealing and those that have been bright annealed will generally possess a surface oxide that contains beryllium oxide as a major constituent. This oxide can be difficult to remove if present in a thickness greater than 0.04 to 0.05 μm (1.6 to 2.0 μin.). A 1 or 2 min soak in a solution of 50% sodium hydroxide at 130 °C (265 °F) before acid pickling facilitates removal of any beryllium oxide.

Nickel silvers and copper-nickel alloys do not respond readily to the pickling solution usually used for brasses because nickel oxide has a limited solubility in sulfuric acid. Heavy scaling of these alloys should be avoided during annealing by using a reducing atmosphere. For example, the annealing of 18% nickel silver in a rich reducing atmosphere results in a slight tarnish that is easily removed in the sulfuric acid pickle and dichromate solutions ordinarily used for descaling brass. Controlling the atmosphere during annealing produces a bright metal finish.

Tubing made of 30% copper-nickel may be annealed in a reducing atmosphere, but not in a brightening atmosphere, to produce a clean surface that does not require acid treatment; 18% nickel silver wire is pretreated in a proprietary hot alkaline cleaning solution and then annealed in a controlled atmosphere furnace to produce a clean and bright surface. The wire is subsequently pickled in sulfuric acid and treated in a dichromate solution to remove zinc sweat. The wire is then finish pickled in 10 to 15% sulfuric acid solution at 60 °C (140 °F).

Tarnish Removal. Tarnish, the surface discoloration formed on copper-base materials during exposure to the atmosphere or to alkaline cleaning, usually consists of a thin film of oxide or sulfide. One of the most commonly used dips for removing tarnish is an aqueous solution of 8 to 60 g/L (1 to 8 oz/gal) of sodium cyanide. The metal to be cleaned is immersed for 1 to 2 min in the cyanide solution at room temperature. Steel tanks are used to contain the solution. Thorough rinsing is required after the dip treatment.

Extreme safety precautions must be followed when cyanide solutions are being used because cyanide is highly poisonous. To prevent the formation of ammonia, metal previously cleaned in an alkaline solution must be thoroughly rinsed before it is brought into contact with the cyanide solution. Cyanide must not come in contact with acid because lethal hydrocyanic acid is produced. Despite the strict safety precautions that are necessary, cyanide solutions are commonly used.

A solution containing 5 to 10 vol % hydrochloric or sulfuric acid may also be used to remove tarnish from copper-base materials. Immersion time is a few seconds in either of these solutions at room temperature. Thorough rinsing in water is required after the treatment. The hydrochloric acid solution may be contained in a vitrified crock, or in a rubber-lined or glass-lined tank. A vitrified crock or lead-lined tank may be used as a container for the sulfuric acid solution. Plastics such as polypropylene or polyvinyl chloride are also suitable containers for hydrochloric and sulfuric acid solutions. These materials are resistant to 50% sulfuric acid and 37% hydrochloric acid up to 65 to 70 °C (150 to 160 °F).

Another noncyanide solution sometimes used for removing tarnish consists of 10% citric acid at 70 to 80 °C (160 to 175 °F). This solution removes most tarnish stains and poses no health or ecological hazards.

Tarnish Prevention. Tarnishing of copper alloys after pickling or degreasing operations is accelerated when the metal is inadequately dried following rinsing and can be particularly rapid if the final rinse solution is contaminated with the cleaning solutions. Significant resistance to tarnishing after cleaning can be rendered by incorporating benzotriazole (BTA) or tolyltriazole (TTA) into the final rinse. Typical concentrations are 0.1 to 0.5% with the rinse water being used at 40 to 60 °C (104 to 140 °F).

Pickling Equipment. Equipment requirements for the automatic pickling of brass forgings of various sizes are given in Table 4. The automatic pickling machine is similar to automatic plating equipment. Solution conditions for automatic pickling of brass forgings are as follows:

- Hydrochloric acid solution at room temperature
- Nitric-sulfuric acid solution, 38 °C (100 °F) maximum
- Sodium dichromate solution, room temperature
- Cold water rinse, 2300 L/h (600 gal/h)
- Hot water rinse, 66 to 82 °C (150 to 180 °F), 4 L/h (1 gal/h)

Compositions of pickling tanks are determined by the type of solution used, such as:

Solution	Tank material
Hydrochloric acid	Plastic-lined steel
Nitric-sulfuric acid	Type 316 stainless steel
Color dip (dichromate solution)	Plastic-lined steel
Cold water rinse (four tanks)	Steel
Hot water rinse	Steel or rubber-lined steel

Work baskets require type 316 stainless steel or plastic composition with dimensions of 330 by 635 by 155 mm (13 by 25 by 6 in.) and 610 by 205 by 180 mm (24 by 8 by 7 in.). Equipment requirements for pickling brass tubes or rods and the equipment for pickling brass tubing are listed in Table 5.

Table 3 Pickling conditions for copper alloys containing silicon

Solutions are used at room temperature.

Constituent or condition	Solution A	Solution B
Sulfuric acid(a)	5–15 vol%	40–50 vol%
Hydrofluoric acid(b)	1/2–15 vol%	1/2–5 vol%
Nitric acid(c)	…	15–20 vol%
Water	bal	bal
Immersion time	1/2–10 min	5–45 s

(a) 1.83 sp gr. (b) 52%. (c) 1.41 sp gr

Table 4 Production capacity of equipment for automatic pickling of brass forgings

Immersion time, 40 s; total cycle time, 6 min

	Size of forgings		
Item or condition	Small	Medium	Large
Number of pieces per hour	2500	500	250
Pieces per basket	250	50	25
Pounds pickled per hour	2500	2500	2500
Configuration of forgings	Irregular	Irregular(a)	Irregular(a)

(a) May contain cavities; require hand loading into baskets

Table 5 Equipment requirements for pickling brass tubes or rods

Oxide scale is removed from 25 mm (1 in.) diam brass tubing and rods that are 1.9 to 21 m (6 to 70 ft) in length; immersion time varies from 5 to 30 min; the source of heat is steam, 105,000 kJ (100,000 Btu)

			Temperature		
Tanks(a)	Material	Solution	°C	°F	Overflow(b)
Acid tank	Stainless steel	10% sulfuric acid	38–60	100–140	…
Cold water rinse tank	Wood	…	…	…	380 L/h (100 gal/h)
Hot water rinse tank	Wood	…	54–71	130–160	38 L/h (10 gal/h)

(a) All tanks measure 1.1 by 0.9 by 21 m (3.5 by 3 by 70 ft) and hold 6738 L (1780 gal) for a 0.6 m (2 ft) depth of solution. (b) Connected to bottom of tank

Tanks for sulfuric acid may be lined with natural rubber. Tanks intended to contain nitric and hydrofluoric acids may be lined with polyvinyl chloride or polypropylene. Additional information on materials and construction of acid tanks is given in the article "Acid Cleaning" in *Surface Engineering*, Volume 5 of the *ASM Handbook*.

Defects from Pickling. By far the most common defect encountered in pickling brass is the presence of red stain on the metal. Caused by cuprous oxide, this defect may be removed by pickling in a solution of 10% sulfuric acid containing 98 g/L (13 oz/gal) of ferric sulfate at temperatures up to 60 °C (140 °F), or in a solution of 12% sulfuric acid containing 45 g/L (6 oz/gal) of sodium dichromate at room temperature. Alternatively, sulfuric acid-hydrogen peroxide solution can be used. Red stains may result from the presence of metallic iron in the pickling solution, causing copper to plate out on the parts when the parts come in contact with iron or steel. This is because iron is anodic to copper. Care must be taken to prevent any stray pieces of iron, such as nails or tools, from entering the pickling solution. Red stains can also result from the reaction of sulfuric acid on cuprous oxide (Cu_2O), forming cupric oxide (CuO) and copper. This can be removed in any of the previously mentioned oxidizing acids.

Oil and lubricants remaining on formed metal must be removed before pickling and dipping. If formed material is to be bright dipped, it should first be degreased, or the lubricant remaining will prevent the bright dip from being effective. If the work is to be annealed and pickled, it should be degreased, usually in a hot water rinse, because the oil may cause excess cuprous oxide and unwanted red staining to form during annealing. In extreme instances, the more volatile constituents of the oil burn off readily, leaving a carbonaceous deposit that must be removed mechanically.

Acid stains will appear on the metal if it is not thoroughly rinsed and cleansed of all remaining acid after pickling or dipping. At least two separate washings in water or one thorough running water wash should be used before drying. Dipping in a soap solution or a buffered salt solution will neutralize traces of acid.

The metal is etched or pitted if it is immersed for too long in a pickling solution or dip, or if the solution is too strong or too hot. The proper time, temperature, and concentration of solution may be determined quickly during trial runs.

Safety Practices. Acids, even in dilute solution, can cause serious injuries to the eyes and other portions of the body. Operators should wear face shields, rubber boots, and rubber aprons for protection. Eye fountains and showers adjacent to acid tanks, for use in the event of an accident, should be provided. Adequate ventilation and suitable hoods for the tanks are recommended.

Extreme caution should be exercised when adding acid to a water solution, especially if sulfuric acid is used. Sulfuric acid should be added slowly and only while stirring the solution.

Abrasive Blast Cleaning

Abrasive cleaning is used to remove molding, core sand, and investment material from the exterior and interior surfaces of copper-base castings. Selection of the proper kind and particle size of grit determines the type and color of the finish. The coarser grits clean faster but give a rougher finish.

Dry abrasive cleaning of beryllium copper is usually confined to castings. Steel shot is used for general cleaning to remove sand and slight surface imperfections from the casting after mold shakeout. Sands are used to blend in surface areas, to remove heat treat scale, and to produce a uniform surface texture. Graded bronze chips, together with the regular commercial abrasives, are used in some applications to impart a better color and finish. Abrasive blast cleaning is seldom used to produce decorative finishes on copper alloys.

Wet Blasting offers a means of cleaning previously blasted and machined surfaces without damaging the finished or threaded areas. Wet blasting produces various degrees of satin finish. The process is ideal for removing oxide film acquired during brazing, soldering, welding, or heat treating and for removing smudges, stains, and finger marks. For example, bronze castings that have been machined and brazed often are wet blasted with quartz (140-grit) for $\frac{1}{2}$ to 5 min to remove braze discoloration and shop dirt. The parts are normally degreased before wet blasting. After the castings are wet blasted, they are cleaned ultrasonically, inspected, and assembled.

Surfaces cleaned by wet blasting are uniform in appearance, although their color is not the same as original grit-blasted surfaces because of the abrasive used. Cleaning action is gentle but effective because water is the carrier.

Mass Finishing

Mass finishing is best suited for stamped, formed, or machined parts. Castings with remnants of gates and parting lines; forgings with heavy scale, flash lines, or die marks; and heavily burred, pitted, or dented parts are not well suited for mass finishing. Light burrs can sometimes be removed by a prior bright dip, after which tumbling may be used for radius blending, polishing, and burnishing. High thin burrs of soft alloys are likely to peen over. Mass finishing of soft alloys at excessive speeds with insufficient amounts of solution can result in roughened and indented surfaces. Dry tumbling is generally restricted to small parts of simple shape and maximum dimension less than 50 mm (2 in.).

Abrasives. Aluminum oxide, silicon carbide, limestone, and flintstone are the abrasive materials most often used in mass finishing of copper and copper alloys. Combinations of these abrasives may be used for specific applications. For example, a blend of aluminum oxide and silicon carbide of mesh size 46 to 150 produces a reasonably fine matter surface on parts with heavy burrs. Aluminum oxide has a cutting action, and silicon carbide has a planing action.

Preshaped abrasives of various sizes and shapes also may be used. Although more expensive than material in its natural form, preshaped abrasives permit a more constant and uniform polishing action, are more effective in holes and recesses, and retain their effective cutting shape for a longer period of use.

Compounds. Parts heavily coated with grease or oil or contaminated with dirt or chips should be degreased before mass finishing, preferably in a separate barrel, dip tank, or degreaser. A better practice is to clean parts in the barrel when progressing from rough to finishing cycles and to bright dip before burnishing. A sulfuric-nitric acid or sulfuric acid-hydrogen peroxide bright dip should be used if plating follows burnishing.

Soft water and neutral compounds are preferred for mass finishing copper and copper alloys. The use of liquid soap-free alkaline compounds for mass finishing highly leaded, free-cutting brasses prevents the formation of lead soaps that impair the effectiveness of the operation.

Compounds for mass finishing are classified according to the following categories and are purchased as proprietary materials:

- *Cleaning compounds* possess high detergency and buffering action for removing oils, greases, and residues.
- *Descaling compounds* are used to remove tarnish from copper alloys; neutralizing cycles usually follow the use of these compounds.
- *Grinding compounds* are used with abrasive mediums for softening the water, saponifying oils, and keeping chips clean; these compounds inhibit tarnish and improve the color of parts.
- *Abrasive compounds* contain grits such as aluminum oxide, silicon carbide, emery, quartz sand, or pumice.

Surface Finishes. Although mass finishing produces the final finish for many parts, it is used more extensively for cleaning prior to plating and painting or for deburring and polishing before a final finish is applied. Operating conditions for mass finishing are given in Table 6.

Bright rolling or water rolling in a barrel is an economical bulk method of finishing small parts. The finishes may be dull, semibright, or of high luster. This operation consists of tumbling the parts in water containing a suitable additive. The water acts as the carrier for the fine burnishing materials. Selection of additive and cycle time controls the surface roughness, stock removal, color, and reflective luster. Operating conditions for water rolling are given in Table 7.

A prime consideration for successful water rolling is the cleanness of the parts. Oil, grease, scale, and dirt should be removed before rolling for luster. Basic cleaning and pickling operating conditions used before water rolling are given in Table 8.

For economy, cleaning and pickling should be done in the same barrel by the same operator. For example, oily gripper parts from eyelet machines are placed in an oblique stainless steel barrel and cleaned by a suitable alkaline cleaner.

Table 6 Operating conditions for mass finishing

Material	Medium	Size of abrasive particles		Tumbling time, h	Finish
		mm	in.		
Heavy cutting					
Brass or bronze castings	Aluminum oxide	6.4–19	0.25–0.75	6–16	Matte
Moderate cutting					
Brass stampings	Aluminum oxide	6.4–19	0.25–0.75	1–6	Light matte
Brass screw-machine parts	Aluminum oxide or granite	6.4–19	0.25–0.75	1/2–6	Light matte or bright
Light cutting (a)					
Brass stampings or screws(b)	Limestone	3.2–13	0.13–0.50	2–6	Bright

(a) Submerged tumbling is used for fragile and precision parts. (b) Screw-machine parts

Table 7 Operating conditions for bright rolling or water rolling

Solutions are used at room temperature. Time, 20-60 min. Resulting surface has bright finish.

Parts	Weight of load		Additive(a)	Water		Speed, rev/min
	kg	lb		L	gal	
Blanks or buttons, copper(b)	363–408	800–900	Cream of tartar	95	25	32
Gripper post, nickel over brass	136	300	Proprietary(c)	95	25	32
Fragile tubular part, brass(d)	18	40	Proprietary	20	5	7

(a) 9 g/L (1 oz/gal). (b) Removal of burrs. (c) Additive containing sodium bicarbonate, cream of tartar, sodium acid pyrophosphate, sodium sulfite, and a wetting agent. (d) Wall thickness is 0.150 mm (0.006 in.).

After rinsing, the parts are pickled in a 1 to 2% sulfuric acid solution and rinsed. Clear water and additives, burnishing compounds, are added, and the parts are rolled until the desired finish is obtained. If the work appears to darken during water rolling, the medium should be dumped, the barrel and parts rinsed and then charged with a fresh burnishing compound. Parts suitable for water rolling to a bright finish include posts, sockets, studs, tack buttons, and zipper parts.

Vibratory finishing is particularly effective for deburring, forming radii, descaling, and removing flash from castings and molded parts. It may also be used for burnishing. Vibratory finishers deburr parts 50 to 75% faster and are more versatile than rotary tumbling barrels. There is no cascading of parts, with the attendant possibility of damage by impact. The process is adaptable to both light castings and formed parts. Vibratory finishing is also effective on internal surfaces and recesses that are not usually worked by rotary tumbling.

The mediums for vibratory finishing of copper and copper alloys are similar to those used for rotary tumbling. Dry mediums are used occasionally, but usually a liquid is added to provide lubrication, suspension of worn-off particles, and a more gentle cleaning action. The selection of medium is frequently by trial and error. Conditions for vibratory finishing are given in Table 9.

Table 8 Operating conditions for cleaning and pickling in water rolling barrels

Barrel is made of Type 304 stainless steel. Speed of rotation, 7-32 rev/min; cycle time, 15-20 min. Parts are thoroughly rinsed in hot water after cycle is finished.

Solution	Concentration	Temperature	
		°C	°F
Alkaline cleaner(a)	15–20 g/L (2–3 oz/gal)	71	160
Pickling solution(b)	1–2%	54	130

(a) Sodium hydroxide or proprietary compound. (b) H_2SO_4

Polishing and Buffing

Copper alloy parts are polished after scale removal and dressing or rough cutting, but before final finishing operations, which include buffing, burnishing, or honing. Rough castings normally require two polishing operations before buffing. Forgings and stampings require one polishing operation before buffing. Pipe, tubing, and some stampings can be buffed without previous polishing. Buffing is not required when a brushed or satin finish is desired as the final finish.

Because copper-base materials are softer than steel, fewer stages of successively finer polishing are required to achieve a uniformly fine surface finish. For many parts, especially those having machined surfaces or those free of defects, a single-stage polishing operation using 180- to 200-grit abrasive on a lubricated belt or setup wheel may be all that is required before buffing. Poor-quality surfaces require preliminary rough polishing on a dry belt or wheel with 80- to 120-grit abrasive. Surfaces on intermediate quality may be given a first-stage polishing with 120- to 160-grit abrasive, either dry or lubricated. Belt polishing is generally advantageous for high-production finishing except when special shapes are processed. These are best handled by the contoured faces of setup polishing wheels.

Buffing of copper and copper alloys is usually accomplished with standard sectional cloth wheels operating at moderate speeds of 1200 to 1800 rev/min. Typical wheel speeds for various finishes are:

Finish	Wheel speed	
	m/min	ft/min
Dull(a)	915–1675	3000–5500
Satin	1220–1830	4000–6000
Cutting and coloring	1675–2135	5500–7000
High luster(b)	2135–2440	7000–8000

(a) Using 120- to 200-grit aluminum oxide. (b) Using tripoli, lime, and silica with no-free-grease binder

When is it necessary to mush a buff to the contour of a complicated part, buffing speeds may range between 200 and 1000 rev/min.

Neutral compounds that are free of sulfur must be used to avoid staining in the plating operation when polishing and buffing precede electroplating. Excessively high temperatures during polishing and buffing may cause difficulties in subsequent cleaning and plating operations. When flawless chromium-plated surfaces are required, it is necessary both to buff and color buff the polished copper alloy surfaces before plating. Chromium reproduces all imperfections in the underlying plating or base metal, and because chromium is hard and has a high melting point, it is more resistant to flow and is not readily buffed by normal methods. A good chromium-plated surface can be obtained without the color buff operation, by only polishing and cut-down buffing. An example of offhand belt polishing and wheel buffing operations is given in Table 10.

Scratch brushing is used to produce a contrasting surface adjacent to a bright reflective surface; to produce an uneven surface for better paint adherence; to remove metal during final finishing of parts with intricate recesses that are inaccessible to polishing and buffing wheels; and to remove impacted soil and buffing compounds from previous finishing operations, prior to subsequent finishing in some applications.

Various types of scratching mediums are used to produce different finishes, such as butler, satin, directional, sunburst (or circular), and matte. These mediums are as follows:

- *Wire wheels* are used on copper or brass grill work to clean intricate recesses, holes, or ribbed areas and to produce a decorative noncontinuous scratch pattern on ornamental parts such as vases, lamps, and kitchenware.
- *Emery cloth or paper* is a common medium for producing a series of linear or circular parallel lines on flat objects with no sudden

Table 9 Operating conditions for vibratory finishing

Machined part diam		Material	Medium	Parts per load	Ratio of medium to parts(a)	Vibrations per min	Time, min	Purpose
mm	in.							
25	1	Nickel silver	Steel pins and quartz sand	650	4 to 1	1500	40	Deburr
38	1 1/2	Brass	Steel wire brads	500	2 to 1	1300	60	Deburr and form radii
75	3	Brass	Arkansas stone	150	10 to 1	1500	35	Deburr and finish

(a) 0.03 m^3 (1 ft^3) bowl

changes in contour. This type of decorative finish is applied to fireplace accessories, automotive hub caps, and kitchenware and appliances.

- *Polishing wheels headed with greaseless compounds* produce scratch-brush finishes with parallelism of the directional pattern. Decorative items such as jewelry, building paneling, and built-in refrigerator and stove parts can be finished in this manner.
- *Soft tampico and manila brushes* remove soil from scrollwork and embossed areas on ornate tableware serving sets and jewelry prior to final processing.

Table 11 gives the sequence of operations and mediums for scratch-brush finishing several copper alloy products.

Although scratch-brush finishing is useful for producing eye-appealing finishes and as a mechanical means for preparing surfaces for subsequent processing, certain hazards must be recognized. Extreme care and control are required when the part being worked contains patterns with sharp corners or embossments because the sharpness of detail may be destroyed. In salvage or rework operations, it is difficult and sometimes impossible to blend the original brush pattern into a repaired area from which a defect has been removed by grinding.

Chemical and Electrochemical Cleaning

During fabrication, copper alloys may become coated with lubricating oils, drawing compounds, greases, oxides, dirt, metallic particles, or abrasives. These must be removed by cleaning. The selection of the cleaning process depends on the type of lubricant and other materials to be removed, the equipment available, the environment restrictions, and the degree of cleanness required. The nature and size of the pieces also influence the selection of equipment or process.

Where permissible, mechanical scrubbing, accomplished by turbulent boiling, pressure spraying, or agitating, aids in the removal of any substances that are not exceptionally adherent. Occasionally, hand brushing may be used for small production quantities.

Lubricants made from animal or vegetable oils or greases, such as tallow, lard oil, palm oil, and olive oil, can usually be removed by saponification. In this process, the parts are immersed in an alkaline solution where the oil reacts with the alkali to form water-soluble soap compounds. Mineral oils that are not saponifiable, such as kerosine, machine oil, cylinder oil, and general lubricating oils, are usually removed from the metal by emulsion cleaning.

Dirt particles, abrasives, metal dust, and inert materials are removed by one or both of these processes. To remove undesirable materials by saponification, emulsification, or similar means, it is necessary to use particular chemicals or combinations of chemicals.

Solvent Cleaning and Vapor Degreasing. Solvent cleaning of copper alloys involves immersion in special naphthas with flash points over 38 °C (100 °F) for the removal of light grease and light oil. An example of this type of naphtha is Stoddard solvent. These solvents are preferred to kerosine and to the naphthas used in paints because less residue remains on the work after the special naphthas have evaporated.

The straight-chain naphthas are not effective for complete removal of heavy grease, burned-on hydrocarbons, pigmented drawing compounds, and oils containing solid contaminants. Buffing compounds containing tallow, stearic acid, and metallic soaps require cyclic hydrocarbons such as toluol and xylol for effective cleaning. Table 12 gives cycles for solvent cleaning of copper alloys.

Chlorinated solvents such as methylene chloride (boiling point, 40 °C, or 104 °F), trichloroethylene (boiling point, 90 °C, or 189 °F), and perchloroethylene (boiling point, 120 °C, or 250 °F) have been used instead of naphtha. These compounds are less of a fire hazard than straight petroleum solvents but are much more toxic. Because of environmental constraints their use is gradually being curtailed.

Vapor degreasing effectively removes many soils from copper alloys. Stabilized trichloroethylene is used extensively in vapor degreasing because it does not attack copper alloys during degreasing and because it has high solvency for the oils, greases, waxes, tars, lubricants, and coolants in general use in the copper and brass industry. Perchloroethylene is used especially for removing high-melting pitches and waxes, for drying parts by vaporizing entrapped moisture, and for degreasing thin-gage materials.

Vapor degreasing or solvent cleaning is not effective for removing inert materials and inorganic soils such as metal salts, oxides, or compounds that are not generally soluble in chlorinated solvents. Similarly, vapor degreasing for removal of hard and dry buffing compounds could leave behind the insoluble and hard-to-

Table 10 Offhand belt polishing and wheel buffing operations for sand cast red brass parts

Sand cast lavatory fittings made of red brass are finished in a sequence of six operations in preparation for decorative chromium plating; sequential finishing of spout with flat surfaces

Operation	Type of contact wheel	Wheel speed, rev/min	Pieces per hour	Type of abrasive belt	Belt life, pieces	Polishing lubricant or buffing compound
Rough polishing	Cloth(a)	2100	23	80-grit silicon carbide	29	None or light application of grease stick
Final polishing	Cloth(a)	2100	30	220-grit Al_2O_3	49	Grease stick
Spot polishing	Cloth(a)	2100	46	220-grit Al_2O_3	77	Grease stick
General buffing	Spiral-sewn, treated cloth sections with intermediate airway(b)	2400	32	…	…	Tripoli
Spot buffing	Spiral-sewn, treated cloth sections with intermediate airway(b)	2400	115	…	…	Tripoli
Color buffing	Spiral-sewn, treated cloth sections with intermediate airway(b)	1700	75	…	…	Silica compound

(a) 355 mm (14 in.) diam, 45 mm ($1\frac{3}{4}$ in.) width, 90 density. (b) 355 mm (14 in.) diam, 60.3 mm ($2\frac{3}{8}$ in.) width, 18 ply, 86/93

Table 11 Suggested sequence of operations for scratch brushing of copper alloy parts

Part	Finish desired	Abrasive	Type of wheel	Size of wheel, mm	Size of wheel, in.	Speed, rev/min
Black fuse body, yellow brass(a)	Dull, smooth, black	None	Tampico	80 diam by 75 thick, 5 rows wide	7 diam by 3 thick, 5 rows wide	1200
Silver-plated red brass lipstick case(b)	Semibright	Solution of soap bark and cream of tartar	Nickel-silver wire, 0.100 mm (0.004 in.) diam	150 diam by 75 thick, 6 rows wide	6 diam by 3 thick, 6 rows wide	850
Black-on-bronze bookends, highlights relieved(b)	Black background with colored copper highlights	Pumice in water	Cloth, sewn sections	180 diam by 13 wide	7 diam by $\frac{1}{2}$ wide	850
Silver-plated lipstick cap(c)	Satin	Greaseless rouge, proprietary	Loose cloth wheel	150 diam by 51 wide	6 diam by 2 wide	1800
Nickel-plated refrigerator panels or stove parts(d)	Satin	Greaseless compound	Loose cloth wheel	305 diam by 50–510 wide	12 diam by 2–20 wide	1800

(a) Clean brush often by running pumice stone across face of wheel. (b) Lacquer after scratch brushing. (c) Lacquer after finishing. (d) Chromium plate after finishing clean abrasives. Solvent emulsion cleaners, although slow, are highly effective for complete removal of buffing compounds.

Solid particles of metal dust or chips that are held on the surface by organic soil can be removed mechanically by the washing action of the solvent. Removal of these particles is accelerated and accomplished better with solvent sprays or by immersion in boiling solvent than with the vapor phase of the degreaser.

Emulsion and Alkaline Cleaning. Parts with heavy soils such as machine oils, grease, and buffing compounds are treated first with emulsion cleaners to remove most of the soil. After the parts have been rinsed, the remaining soil is removed by alkaline soak or electrolytic cleaning. Precleaning reduces the contamination of the alkaline solution, extending the life of the solution. Thorough alkaline cleaning must follow the emulsion cleaning cycle before the subsequent acid cycles. Extreme caution must be exercised to avoid dragging emulsifiers through the rinses and into a plating solution, especially an acid solution.

Emulsion cleaning may be accomplished by soaking the work for 3 min or less in a mildly agitated solution. Spraying is helpful only when all surfaces being cleaned can be thoroughly contacted. The thin film of oil remaining after emulsion cleaning acts as a temporary tarnish preventive. Some parts may be stored after drying, depending on the composition of the solution and the metal being cleaned; however, brass may become pitted by prolonged exposure to certain emulsifier films. When emulsion-cleaned zinc-bearing brass parts are cleaned electrolytically by alkalines, sufficient time should be allowed for the dispersal of the emulsifier in the alkaline solution to avoid pitting.

The environmental restrictions placed on the use of chlorinated solvents have resulted in the industry turning more and more to alkaline cleaners for degreasing copper and its alloys. Table 13 lists typical compounds from which these are formulated. A great number of these cleaners, which usually contain proprietary additives, are available on the market. Selection of a cleaner is best achieved by a test program in which several cleaners are evaluated. However, the most critical factor in their effective use is to ensure vigorous flow of the cleaner across the parts being cleaned.

Solutions for soak cleaning usually contain 30 to 60 g/L (4 to 8 oz/gal) of cleaner and are operated at 60 to 88 °C (140 to 190 °F). For every 6 °C (10 °F) rise in temperature above 60 °C (140 °F), the cleaning time is reduced by about 25%. Regardless of the concentration of the cleaning solution, there is a practical limit to the amount of contamination a given volume can accommodate without redepositing soil on the metal. In this condition, the solution should be discarded even though analysis reveals unused cleaner.

Dissolved air in fresh cleaning solutions is frequently the cause of tarnishing of copper alloys. The air can be eliminated by heating the solution to the boiling point for about $\frac{1}{2}$ h before use. This procedure may not be advisable with every proprietary cleaner because of constituents that break down at the boiling temperature. Some uninhibited alkaline cleaners may also cause a slight darkening or tarnishing of the work surface. The darkening may be removed by dipping in dilute hydrochloric acid or in cyanide solution.

Electrolytic alkaline cleaning is the most reliable method for cleaning parts for plating. The work is the cathode, and steel electrodes are the anodes. Reverse-current anodic cleaning cannot be used for more than a few seconds because copper dissolves in the solution. Copper alloys with tarnish readily during exposure to the oxygen that is released at the anode, but this can be minimized by the addition of inhibitors. In many electroplating operations, anodic cleaning for a few seconds is used to develop tarnish because it indicates that all soil has been removed. The small amount of metal dissolved by anodic cleaning exposes a more active surface for electroplating, and the light tarnish formed is readily dissolved by a mild hydrochloric or sulfuric acid solution. Current density during anodic electrocleaning of brass should be about 3 A/dm^2 (30 A/ft^2) at 3 to 4 V. Use of high currents will etch the brass and cause dezincification.

Copper-base materials are electrolytically cleaned by cathodic cleaning followed by short-time anodic cleaning, or by soak cleaning followed by anodic cleaning. Positively charged particles plated onto the work during cathodic cleaning cause smut, which may lead to blistering and poor adhesion of the plated metal if not completely removed. To avoid this condition, a short period of anodic cleaning should follow the cathodic electrocleaning.

Racks and baskets that are used during the application of chromate chemical conversion coatings should not be used in alkaline cleaning solutions. Contamination of the cleaning solution with as little as 10 ppm of hexavalent chromium can cause poor adhesion and blistering of subsequent metal deposits. To avoid the effects of accidental contamination when chromate treatments are used, sodium hydrosulfite should be added to the cleaning solution at the rate of 14 g ($\frac{1}{2}$ oz) per 380 L (100 gal). The sodium hydrosulfite reduces hexavalent chromium to trivalent chromium, which does not affect subsequent plating. Periodic additions are required because trivalent chromium is reoxidized to hexavalent by the oxygen released at the anode.

Ultrasonic cleaning of copper-base materials is used when the size of particles remaining on the surface is less than 5 to 10 μm (0.2 to 0.4 mil) in any one direction and for removing dirt and chips that cause smudge, as indicated by a white cloth wipe test. Remove much of the surface contamination by other more economical cleaning procedures before ultrasonic cleaning. This increases the life of the ultrasonic cleaning solution and maintains production efficiency. After ultrasonic cleaning, the parts may be rinsed in deionized or distilled water and dried with warm filtered air or in a vacuum oven.

Ultrasonic cleaning is used with alkaline cleaning solutions, solvents, vapor degreasing solutions, or acid pickling solutions to increase the rate of cleaning or to complete the removal of soil from areas not completely cleaned by soak or spray procedures. An example of the need for ultrasonic assistance is the cleaning of fine internal threads on brass parts. An alkaline solution containing 15 to 30 g/L (2 to 4 oz/gal) of cleaner may be used for ultrasonic cleaning of such parts.

Chemical and Electrolytic Polishing

Chemical or electrolytic polishing imparts a smooth bright finish and removes burrs selectively from certain areas. Usually the same solution will accomplish both purposes, although variations in operating conditions may be desirable, depending on which feature is required.

For electropolishing, the parts are racked and made the anode in an acid solution. Direct current is applied and the process selectively removes more metal from the high points of the surface than from the low. This results in a high polish and the removal of burrs.

Chemical polishing imparts a finish similar to that obtained by electropolishing, but eletropolished surfaces are usually smoother and brighter.

Electropolishing for 4 to 6 min will reduce the surface roughness to between one-third and one-half the original value. Electropolishing and chemical polishing will remove minor scratches and defects, as well as burrs.

Selection of these processes is influenced by the following considerations:

Table 12 Cycles for cleaning copper alloy parts with a solvent cleaner

Part	Solvent cleaner	Temperature of solvent, °C	Temperature of solvent, °F	Immersion time, min	Soil removed
Dose cap(a)	Stoddard solvent or mineral spirits	RT to 49	RT to 120	2	Heavy drawing compound
Brass retainer ring(a)	Stoddard solvent or mineral spirits	RT to 49	RT to 120	2	Eyelet machine lubricant
Brass rods	Sawdust, dampened with Stoddard solvent or mineral spirits	RT	RT	5(b)	Mill lubricant

RT, room temperature. (a) Hand cleaning necessary with fragile parts. (b) Tumbled in barrel

Table 13 Compounds used for formulating alkaline cleaners

Component	Soak cleaners, %	Electrolytic cleaners, %
Sodium hydroxide	10–20	10–15
Sodium polyphosphates	5–20	5–20
Sodium orthosilicate, sesquisilicate, metasilicate	30–50	30–50
Sodium carbonate, bicarbonate	0–25	0–25
Resin-type soaps	5–10	None
Organic emulsifiers, wetting agents, chelating agents	2–10	1–3

- For complex parts, electropolishing and chemical polishing are easier and less expensive than mechanical polishing.
- Copper-base materials that are polished either electrolytically or chemically do not require the use of buffing or polishing compounds. Thus, they do not encounter the difficulties associated with removal of entrapped compounds and usually do not require any additional cleaning operations other than rinsing.
- Parts racked for electropolishing may be electroplated in the same racks, which results in considerable savings in handling costs.
- Electrolytically or chemically polished surfaces tarnish less readily than mechanically polished surfaces. Some chemical polishing baths can offer passivation and prevent copper from tarnishing during storage.
- Parts that might deform during mechanical polishing or tumbling will not be deformed by electrolytic or chemical polishing.
- Mechanical polishing may result in a deformed surface layer that differs from the base metal and does not accept plating uniformly. Electroplate on electropolished base metal has adhesion superior to that on mechanically finished surfaces.

Parts that are electropolished include fishing lures, plumbing fixtures, furniture arms and legs, lamps and lighting fixtures, wire goods, brass appliance parts, jewelry, nameplates, and bezels. Copper-plated parts, such as automobile tail pipes, die castings that have not been buffed, and high-altitude oxygen bottles are electropolished effectively for an improved finish. The thickness of copper plate should be in excess of 20 μm (0.8 mil) before electropolishing. Most of the commercial solutions used for electropolishing copper alloys contain phosphoric acid with additional agents.

A sequence of operations for electropolishing consists of:

- Racking the parts
- Cleaning to remove oil, grease, dirt, and oxide
- Double rinsing in water at room temperature
- Electropolishing for 2 to 4 min at about 65 °C (150 °F), using a current density of 30 A/dm^2 (300 A/ft^2)
- Double rinsing in water at room temperature and drying

If the parts are to be electroplated after electropolishing, the drying operation in the previously mentioned sequence is omitted and the process continues with anodic alkaline cleaning until the surface is light brown in color. Then the parts are rinsed in water at room temperature, dipped in 5% sulfuric acid solution, double rinsed in water at room temperature, immersed in the cyanide copper strike solution, and plated.

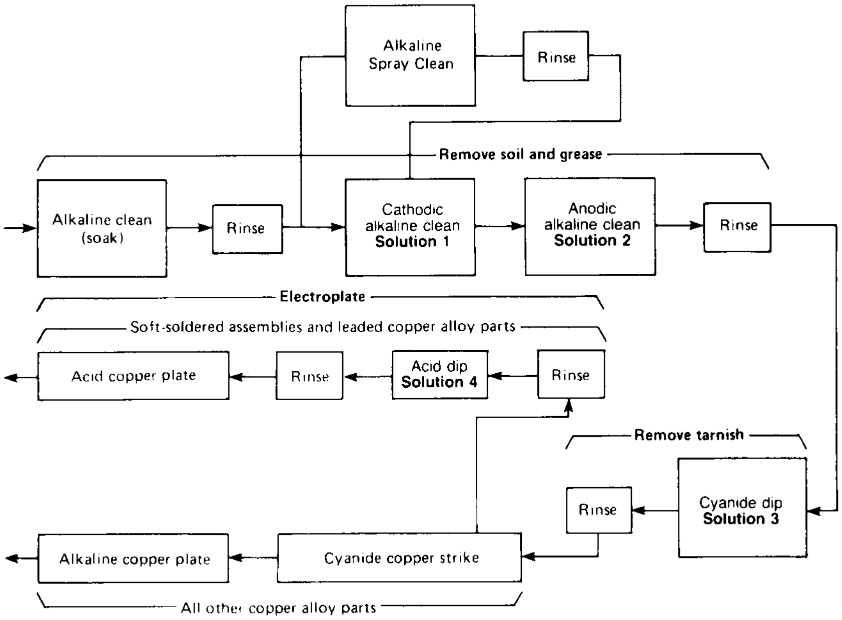
The quality of electrolytically or chemically polished surface is affected by the following factors:

- *Composition of the material.* Most copper alloys are suitable except those containing appreciable amounts of lead, such as the free-machining alloys. Materials successfully treated include copper, beryllium copper, single-phase bronzes, and single-phase nonleaded brasses.
- *Condition of the initial surface.*
- *Grain size of the metal.* The smaller the grain size the better the finish. A grain size of 0.004 mm (0.0002 in.) yields excellent results; satisfactory results are produced with grain sizes up to about 0.01 mm (0.0004 in.).

Preparation for Plating

Before copper alloys are plated, surface oxides are removed and the surfaces chemically activated for adherence of the plate. Heavy oxide scales are usually removed at the mill, so descaling is not normally a part of the preplate treatment. Figures 1 and 2 show sequences of operations required for preparing the surfaces of copper alloys. These operations apply to both lead-free and leaded materials and to soft-soldered assemblies. For many plating operations, where the copper alloy is relatively clean, free of oils, and uncontaminated by buffing compounds, the process can be simplified by eliminating the alkaline soak. If the surface contains buffing compounds, it may require precleaning by soaking in emulsion cleaners. Many plating processes do not use the anodic alkaline clean, especially when an acid dip is used after the cathodic alkaline clean. The acid dip suffices to remove any smut or stain. An acid dip may be simply 15% sulfuric acid or, if the surface needs additional pickling, a bright dip may be used. There are a number of bright dips for copper alloys on the market based on the sulfuric acid-hydrogen peroxide system (see Table 1), in addition to the example in Fig. 2. A chromate bright dip should not be used before plating because of possible chromium contamination of the plating bath, which could lead to blistering, pitting, and peeling of the electrodeposit.

Oxides can be removed from cast or heat-treated copper alloys by either abrasive or chemical cleaning procedures. Castings always require abrasive cleaning; however, they do not necessarily require subsequent pickling or bright dipping for the removal of oxides. If acid treatment is required, thorough rinsing is mandatory to prevent spotting of the plating by entrapped acid. Stampings and drawn parts can be treated in the same manner as castings; however, it may be less expensive to pickle the parts before abrasive finishing if heavy oxides are present. Screw-machine parts made of leaded copper alloys usually require no treatment for oxide removal before plating, but abrasive cleaning can be used when required.

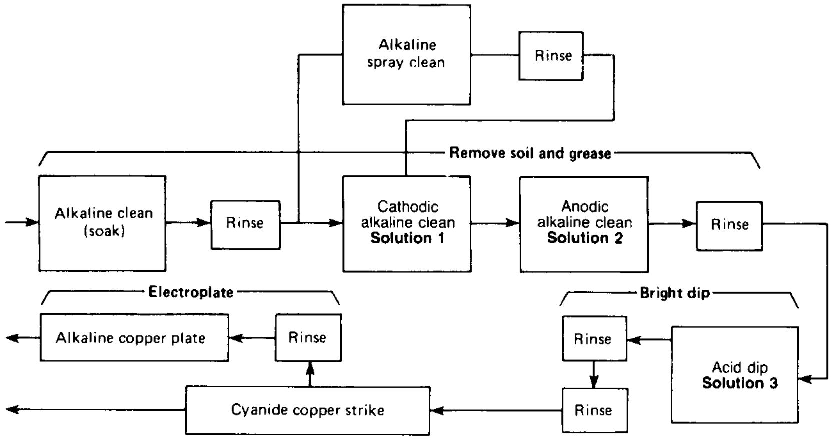


Solution No.	Type of solution	Composition of solution(a)	Operating temperature °C	Operating temperature °F	Cycle time, s
1	Cathodic alkaline cleaner(b)	$Na_2CO_3H_2O$, 40–50%; $Na_3PO_4 \cdot 12H_2O$, 25–40%; NaOH, 10–25%; Na_2SiO_3, 15–40%	60–71	140–160	60–180
2	Anodic cleaner(b)	Same as Solution 1	60–71	140–160	5–10
3	Cyanide dip	NaCN, 15–45 g/L (2–6 oz/gal)	Room	Room	30
4	Acid dip	HBF_4, 5–10%	Room	Room	5–10

(a) By volume, except where otherwise noted. (b) Current density 1 to 3 A/dm^2 (10 to 30 A/ft^2), 3 to 4 V

Fig. 1 Surface preparation required for removal of buffing compounds and tarnish before plating of copper alloys. If the buffing compound is hard and dry, an additional presoak in a solvent emulsion cleaner can be used.

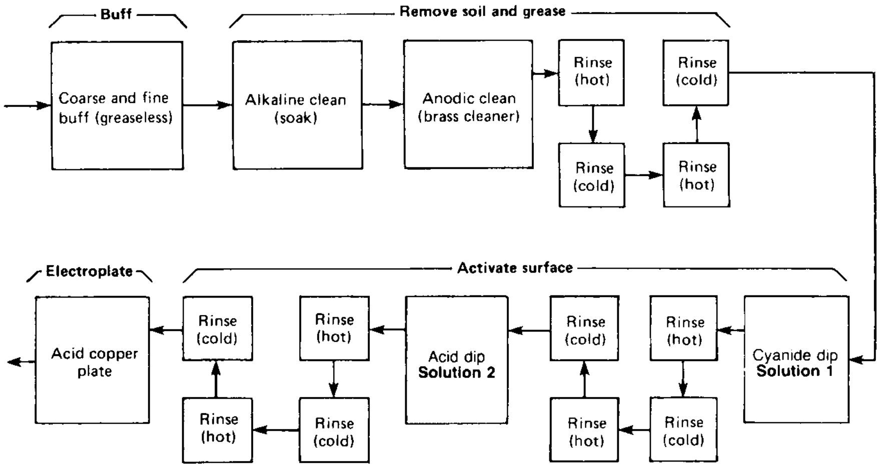
Beryllium Copper. Surface preparation procedures for beryllium copper are the same as for other copper alloys, unless the beryllium copper has been heat treated and still contains surface oxides resulting from that heat treatment. Such oxides on beryllium copper are more difficult to remove than normal oxides on other copper alloys. They can be best removed in strong, hot caustic solutions followed by a good bright dip. The procedure outlined in Fig. 2 should be sufficient if the bright dip cycle is increased to 10 to 15 s. The sulfuric-peroxide bright dips also work well on beryllium copper. The alkaline soak clean and the anodic alkaline clean may or may not be required, depending on the degree of surface contamination resulting from heat treatment. In rare cases, the plaster is required to remove scale resulting from high-temperature (>400 °C, or 750 °F) heat treatments such as in solution annealing. The parts must be soaked in a 50% solution of sodium hydroxide at 130 °C (265 °F) for 1 or 2 min before acid pickling in a good bright dip.



Solution No.	Type of solution	Composition of solution(a)	Operating temperature		Cycle time, s
			°C	°F	
1	Cathodic alkaline cleaner(b)	$Na_2CO_3 \cdot H_2O$, 40–50%; $Na_3PO_4 \cdot 12\ H_2O$, 25–40%; NaOH, 10–25%; Surface active agent, 1%	60–71	140–160	60–180
2	Anodic cleaner(b)	Same as solution 1	60–71	140–160	5–10
3	Bright dip(c)	H_2SO_4, 65–75%; HNO_3, 20–35%; HCl, 1.1 g/L (⅙ oz/gal); H_2O, 5–10%	Cool	Cool	5–10

(a) By volume, except where noted. (b) Current density, 1 to 3 A/dm^2 (10 to 30 A/ft^2), 3 to 4 V. (c) Constant agitation of work

Fig. 2 Surface preparation required for the removal of buffing compounds and for bright dipping before plating of copper alloys



Solution No.	Type of solution	Composition of solution	Operating temperature	Cycle time, s
1	Cyanide dip	NaCN, 7.5 g/L (1 oz/gal)	Room temperature	30–60
2	Acid dip	H_2SO_4, 3–5 vol%	Room temperature	5–10

Fig. 3 Surface preparation of brass powder metallurgy parts before plating

Powder Metallurgy Parts. Technology has advanced to a level where parts sintered from metal powders are not as porous and can be easily electroplated. A sequence of operations for surface preparation of powder metallurgy (P/M) parts before electroplating is shown in Fig. 3. Because P/M parts are made from different alloys and because porosity varies, a suitable surface preparation and electroplating technique must be developed for each part.

The methods applicable to porous cast parts can be used for low-porosity P/M parts with densities more than 95% of theoretical. P/M strip stock bonded to steel is an example of low-porosity material. The surface preparation and plating techniques vary for higher-porosity parts with densities 85 to 90% of theoretical.

During plating of P/M parts, the pores act as thermal pumps. Solutions are released from or absorbed by the pores, depending on whether the solution is hotter or colder than the parts. Deep and interconnecting pores are likely to entrap cleaning or rinsing solutions, which are released slowly during plating. Porosity must be determined before cleaning, and suitable techniques must be used to prevent solution entrapment. Entrapped solutions may cause precipitation of metal compounds on the work surfaces during plating. The porous nature of P/M parts causes contamination and depletion of all solutions and necessitates that the solutions be closely controlled.

Spotty plating is caused by entrapped solutions that seep out of the pores and stain the plated surface as it dries. Spots may not develop for several days after plating or may appear to be insignificant immediately after plating and subsequently enlarge with time.

A continuous plated coating can seldom be attained on P/M parts unless the pores are closed. Methods for closing the pores include buffing, rolling, burnishing, heat treating, and impregnation. Buffing, rolling, or burnishing are used when appearance is important and dimensional tolerances are not critical. These techniques can be applied either before or after plating. Heat treating is one of the most satisfactory methods for closing pores when surface quality and size are more important than appearance. Occasionally, green compacts are electroplated and then sintered. Another technique is to sinter fully, then to plate and heat treat. This procedure requires washing and acid dipping the parts to neutralize alkalinity prior to heat treating.

Impregnation with copper, lead, tin, waxes, resins, or oils is another method for closing the pores of P/M parts before plating. Thermosetting polyester styrene and silicone resins are suitable impregnating materials. When the polyester-styrene resin is used, the parts are degreased, baked to remove moisture, then impregnated under vacuum and pressure. An emulsion cleaner can be used to remove excess resin from blind holes and threads prior to curing the resin at 120 to 150 °C (250 to 300 °F). Tumbling or polishing can be used to remove excess cured resin.

When silicone resin is used, the surfaces of the powder compact are coated with a thin water-repellent film. Then the compact is heated in air to 205 °C (400 °F), quenched in a solution of 4% silicone (type 200) and 96% perchloroethylene, and baked again for $\frac{1}{2}$ to 2 h. After being pickled in acid, the part can be plated in the conventional manner, preferably in an alkaline bath.

Before being impregnated with oil, the parts are heated in a vapor degreaser and, while hot, immersed in cold oil. After cooling in the oil, the parts are removed, drained of oil, and then rinsed in cold solvent. Parts impregnated with oil have been coated with copper by conventional electroplating processes with resultant satisfactory bonding of the coating.

Evalution of Cleanness Prior to Plating. The degree of cleaning required for a copper alloy part depends on its intended end use. In some cases visual observation of the cleaned part is sufficient to determine if adequate cleaning has been accomplished. However, cleaning conducted prior to deposition processes must be very thorough, and methods of evaluating the surface cleanness are often required. For metal that has been degreased, this evaluation can be best achieved by spraying the part with water from an atomizer; areas that are clean show up as a continuous film, while areas that have been inadequately cleaned are covered with small water droplets.

Another technique for evaluating the cleanness of small parts involves suspending them in the mouth of a beaker containing a few mils of 10% ammonium sulfide. After an exposure time of 5 to 10 s, a uniform tarnish film will appear over clean areas. Nonuniformity in the color of the tarnish film indicates the presence of residual soils. With practice, the tarnishing test can provide a rapid assessment of the efficiency of a particular cleaning process. For safety reasons the test must be conducted in a fume hood.

It is often difficult to determine if residual oxides remain on a copper alloy surface following pickling operations, particularly if the oxides are of the refractory type. One evaluation method consists of first immersing the part in rosin flux and then in 60-40 tin-lead solder held at 245 °C (475 °F) for 5 s. The resultant solder coating is compared to the solder coating on a part that is known to be clean. Areas still covered with oxide will appear as areas not wet by the solder.

Plating, Coating, and Coloring Processes

Copper alloys can be plated, coated with organic substances, or chemically colored to further extend the variety of available finishes.

Electroplating

Metals such as gold, silver, rhodium, nickel chromium, tin, and cadmium are electrodeposited on copper and copper alloys. Copper electroplating with these metals is used primarily for decorative purposes and for preventing tarnish or corrosion.

Chromium is occasionally plated directly onto copper and copper alloys as a low-cost decorative coating and color match. A plated nickel undercoat is applied when quality plating of chromium is required to produce color depth and resistance to corrosion, abrasion, and dezincification.

Decorative chromium deposits are characteristically thin and porous. Galvanic action between the chromium and base metal may occur during exposure to aggressive environments and result in accelerated corrosion. With copper alloys of high zinc content, dezincification and eventual lifting and flaking of the deposit may result. For added protection, chromium deposits plated directly on the base metal are coated with clear lacquers or with the more durable combination coatings of silicone and acrylic thermosetting organic resins.

Decorative chromium deposits are usually 0.25 to 0.50 μm (0.01 to 0.02 mil) thick. When chromium is deposited directly onto the base metal, the thickness of the deposit is seldom less than 38 μm (1.5 mils), and for many applications a minimum of 50 μm (2 mils) is specified. The compositions and operating conditions for a general, additive-free, decorative chromium plating bath and a bright, crack-free bath are given in Table 14. Additional information can be found in the article "Decorative Chromium Plating" in *Surface Engineering*, Volume 5 of the *ASM Handbook*.

Hard chromium deposits are used primarily to improve wear resistance and friction characteristics. Because most of the copper-base materials are soft and ductile, the base metal lacks sufficient hardness to support thick deposits of hard chromium against heavy pressures without the risk of scoring or flaking. Hard chromium is electroplated from solutions under conditions similar to those used for decorative chromium plating; however, the deposits are much thicker, frequently dull in appearance, and generally deposited directly on the base metal. To conform to exact dimensional tolerances and to avoid buildup of deposit at corners, an excess of deposit is plated and the final dimension is attained by grinding or lapping. Further information can be found in the article "Industrial (Hard) Chromium Plating" in Volume 5 of the *ASM Handbook*.

Cadmium. Copper-base materials are easily electroplated with cadmium from conventional plating baths. A typical bath has the following composition:

Cadmium oxide	22 to 33 g/L (3.0 to 4.5 oz/gal)
Sodium cyanide	85 to 110 g/L (11.5 to 15.0 oz/gal)
Sodium hydroxide	16 to 24 g/L (2.1 to 3.2 oz/gal)
Brightening agent	As required

Usually, applying an undercoat prior to the deposition of cadmium is unnecessary. Cadmium plating is used to minimize galvanic corrosion between copper-base materials and other cadmium-plated metals in the same assembly. Cadmium-plated copper parts are used in aircraft, marine, and military applications involving atmospheric exposure; however, the use of cadmium is being curtailed because of health and safety concerns associated with its use.

Gold is usually applied over an electroplated undercoating of nickel or silver, but may be electroplated directly on the copper alloy. In the electronics industry, nickel is plated to copper before gold plating. The nickel barrier stops migration of copper into the gold layer. The gold thickness is about 2.5 μm (0.1 mil). The nickel barrier is normally a minimum of 1.3 μm (0.05 mil) thick; however, exposure of the gold-plated part to elevated temperatures for extended periods of time may require a nickel barrier 127 μm (5 mils) thick. If silver is the barrier, government specifications for electronic applications usually require a minimum thickness of 5 μm (0.2 mil) of silver and 1.3 μm (0.05 mil) of gold.

When gold is plated directly on copper alloy, a deposit of 3 μm (0.1 mil) or more is needed because of rapid diffusion, especially at elevated temperatures. This rapid diffusion, especially at elevated temperatures. This rapid diffusion destroys the electrical and decorative properties of the deposit by interdiffusion between the coating and the base metal. Total coverage and freedom from porosity are necessary for corrosion protection.

For greatest adhesion, the part should be plated with a gold strike before the final deposit of gold. One satisfactory strike solution consists of potassium gold cyanide 0.8 g/L (0.1 troy oz/gal as gold) and potassium cyanide 45 g/L (6 oz/gal). To avoid tarnishing, the struck part should be transferred immediately to the plating solution with the current flowing as the work enters the solution. An alternate procedure is to rinse the struck work, then acid dip, rinse, and plate with a suitable current density.

Current density for racked parts varies from 0.2 to 1 A/dm^2 (2 to 10 A/ft^2), depending on the solution used. The rate of deposition depends on the solution and varies from 100 mg/A · min (0.3 A/dm^2, or 3 A/ft^2, for 14.4 min deposits 3 μm, or 0.1 mil, of gold) in most cyanide and neutral solutions to one-third of this rate in most acid solutions. For barrel plating, the limiting current density for all solutions is about one-third of that used in rack plating.

Cyanide solutions are the most efficient and have the best throwing power, whereas

Table 14 Compositions and operating conditions for two chromium plating baths

Constituent or condition	General decorative bath	Bright, crack-free bath
Chromic acid	250 g/L (33.0 oz/gal)	260–300 g/L (35–40 oz/gal)
Ratio of chromic acid to sulfate	100:1 to 125:1	150:1
Operating temperature	38–49 °C (100–120 °F)	52–54 °C (125–130 °F)
Cathode current density	810–1885 A/m^2 (75–175 A/ft^2)	2690–3230 A/m^2 (250–300 A/ft^2)

deposits from acid and neutral solutions are less porous and are not stained by incompletely removed solution.

Patented solutions for plating gold contain 0.03 kg (1 troy oz) of gold per gallon, usually added as potassium gold cyanide, and proprietary brightening agents. Insoluble anodes are used with these solutions. The patent-free hot gold cyanide solution is extremely sensitive to impurities, and the deposits lack brightness. The solution is limited in application. Gold metal anodes are used with this solution.

The proprietary solutions are brightened or colored by codeposited base metals, especially silver, nickel, cobalt, and copper. These base metals may be classed as impurities for some applications. When gold deposits of less than 0.33 μm (0.013 mil) are used on a plated item, the deposit should be protected by lacquer or a chromate passivation.

Nickel is plated onto copper-base materials for decorative purposes and as an undercoating for increased corrosion resistance of nickel-chromium coating systems. Because nickel deposits have a yellow cast and tarnish easily, many nickel-plated parts are finished with electroplated chromium. Costume jewelry, lipstick cases, hardware for doors and windows, automotive hub caps, air valves, and plumbing fixtures are examples of copper-base parts regularly plated with nickel, either as a final coat or an undercoat.

Nickel electrodeposits from some solutions reproduce the irregularities in the base metal surface to a marked degree. The base metal must be polished and buffed before plating if a smooth uniform plated surface is required. Polishing and buffing are not required when nickel is to be plated on a reasonably smooth surface from solutions that produce a high degree of leveling of the deposit as it builds up in thickness. Deposits from these solutions are smooth and bright. Nickel plating with high leveling and brightness can provide an attractive mirorrlike finish. Proprietary leveler brighteners are added to the nickel bath to achieve high leveling with nickel deposits as thin as 7.6 to 10 μm (0.3 to 0.4 mil).

Numerous types of nickel electroplating solutions are available. The solutions differ in basic composition, preferred operating conditions, and quality of the deposit. Three commonly employed nickel electroplating solutions are listed in Table 15. More detailed information on these and other nickel plating solutions and processes can be found in the article "Nickel Plating" in Volume 5 of the *ASM Handbook*.

Most decorative plating is done in solutions that yield bright or semibright deposits. Although dull nickel deposits may be buffed to a high luster, the cost of buffing limits dull nickel to nondecorative or functional uses.

Black nickel is a decorative finish only. It should be plated over a deposit or base metal that is corrosion resistant. Very thin deposits of black nickel are recommended because thick deposits lack the ductility and adhesiveness required to withstand shock.

Rhodium. An undercoat of nickel is used when copper alloys are to be plated with rhodium. For decorative purposes, the thickness of rhodium is usually about 0.25 μm (0.01 mil). Deposits of 25 μm (1 mil) or more are used for functional purposes, but these heavier deposits do not have the brightness or color characteristics of the decorative finishes. Rhodium plating solutions are of the sulfuric acid or phosphoric acid type. Formulas and operating conditions are given in Table 16. Additional information on rhodium plating can be found in the article "Platinum-Group Metals Plating" in *Surface Engineering*, Volume 5 of the *ASM Handbook*.

Silver plating is used for decorative and functional purposes. Its useful characteristics for functional applications include:

- High surface conductivity for radio frequencies. A minimum of 3 μm (0.1 mil) of silver is required for these applications.
- Low resistance for electrical contacts. The thickness of silver used for electrical contacts ranges from very thin deposits, such as those produced by immersion coating to electroplates 13 μm (0.5 mil) thick.
- Antiseizing or antigalling properties for wear surfaces.

Silver can be deposited as a dull plate from cyanide solutions or as a bright plate from baths containing suitable brighteners. Electrolyte compositions and operating conditions are given in Table 17. Plating times for the deposition of 25 μm (1 mil) of silver, as a function of current density, are:

Current density		
A/dm^2	A/ft^2	Plating time, min
1	10	38
2	20	18
3	30	13
4	40	9

Noncyanide plating solutions are also available but the volumes used are very small compared to cyanide solutions. Additional information on silver solution formulations can be found in the article "Silver Plating" in Volume 5 of the *ASM Handbook*.

Tin. As a protective coating, tin is not necessarily anodic to copper alloys. A copper alloy may not always be fully protected against a corrosive environment at the expense of tin. Some corrosion products of tin are more noble than copper and can create the type of galvanic conditions that lead to pitting corrosion. Tin can be

Table 15 Nickel electroplating solutions

Electrolyte composition(a), g/L	Watts nickel	Nickel sulfamate	Typical semibright bath(b)
Nickel sulfate, $NiSO_4 \cdot 6H_2O$	225 to 400	…	300
Nickel sulfamate, $Ni(SO_3NH_2)_2$	…	300 to 450	…
Nickel chloride, $NiCl_2 \cdot 6H_2O$	30 to 60	0 to 30	35
Boric acid, H_3BO_3	30 to 45	30 to 45	45
Operating conditions			
Temperature, °C	44 to 66	32 to 60	54
Agitation	Air or mechanical	Air or mechanical	Air or mechanical
Cathode current density, A/dm^2	3 to 11	0.5 to 30	3 to 10
Anodes	Nickel	Nickel	Nickel
pH	2 to 4.5	3.5 to 5.0	3.5 to 4.5
Mechanical properties(c)			
Tensile strength, MPa	345 to 485	415 to 610	…
Elongation, %	10 to 30	5 to 30	8 to 20
Vickers hardness, 100 gram load	130 to 200	170 to 230	300 to 400
Internal stress, MPa	125 to 210 (tensile)	0 to 55 (tensile)	35 to 200 (tensile)

(a) Antipitting agents formulated for nickel plating are often added to control pitting. (b) Organic additives available from plating supply houses are required for semibright nickel plating. (c) Typical properties of *bright* nickel deposits are as follows: elongation, 2 to 5%; Vickers hardness, 100 gram load, 600 to 800; internal stress, 12 to 25 MPa (compressive).

Table 16 Solutions for decorative rhodium plating

	Rhodium		Phosphoric acid (concentrated) fluid		Sulfuric acid (concentrated) fluid		Current density			Temperature		
Solution type	g/L	oz/gal	mL/L	oz/gal	mL/L	oz/gal	A/dm^2	A/ft^2	Voltage, V	°C	°F	Anodes
Phosphate	2(a)	0.3(a)	40–80	5–10	…	…	2–16	20-160	4–8	40–50	105–120	Platinum or platinum-coated(b)
Phosphate-sulfate	2(c)	0.3(c)	…	…	40–80	5–10	2–11	20-110	3–6	40–50	105–120	Platinum or platinum-coated(b)
Sulfate	1.3–29(c)	0.17–0.3(c)	…	…	40–80	5–10	2–11	20-110	3–6	40–50	105–120	Platinum or platinum-coated(b)

(a) Rhodium as metal, from phosphate complex syrup. (b) Platinum-coated products are also known as platinized titanium. (c) Rhodium, as metal, from sulfate complex syrup plated from alkaline stannate baths or from sulfate or fluoborate acid baths. Compositions and operating conditions of tin electrolytes are given in Tables 18 to 20. Additional information can be found in the article “Tin Plating” in Volume 5 of the *ASM Handbook*.

Tin-Copper Alloys. The 40 to 50% Sn alloy, speculum metal, has been used as a decorative coating because of its silverlike color. The bronze alloy coatings containing 10 to 20% Sn are producible to match the color of gold and have been used as decorative deposits for this reason. Information on bronze plating is given in the article “Copper and Copper Alloy Coatings” in this Handbook.

Tin-lead alloys can be plated on copper alloys in almost any proportion from a fluoborate bath. An alloy of 7% Sn and 93% Pb has been used for corrosion resistance, especially to sulfuric and chromic acids. The 60% Sn, 40% Pb eutectic alloy has excellent solderability and good electrical properties and corrosion resistance. The eutectic alloy may be applied also by hot dipping, but control of thickness is as difficult as with hot dipping in pure tin. Compositions of solutions for plating 7Sn-93Pb and 60Sn-40Pb (solder) are given in Table 21.

Table 17 Plating solutions for silver

Component/parameter	Rack	Barrel
Silver as $KAg(CN)_2$, g/L (oz/gal)	15–40 (2.0–2.5)	5–20 (0.7–2.5)
Potassium cyanide (free), g/L (oz/gal)	12–120 (1.6–16)	25–75 (3.3–10)
Potassium carbonate (min), g/L (oz/gal)	15 (2.0)	15 (2.0)
Temperature, °C (°F)	20–30 (70–85)	15–25 (60–80)
Current density, A/dm^2 (A/ft^2)	0.5–4.0 (5–40)	0.1–0.7 (1–7.5)

Electroless Plating

Electroless plating involves the reduction of a metal salt to its metallic state by electrons supplied from the simultaneous oxidation of a reducing agent. The electroless plating solutions are compounded so that the concentration of the reducing salts, metal salts, buffering salts, and the pH controls the rate of reduction of the metal salt and of the oxidation of the reducing agent. If these reactions are not controlled, the metal deposit is reduced spontaneously to a fine powder. The metal to be plated acts as a catalyst and localizes the deposit of the plate to the part itself. Electroless plating completely plates uniform deposits to any thickness desired over intricately shaped parts or assemblies and into deep recesses and long tubular holes. Fine and close-fitting threads can be plated uniformly over the entire threaded area.

On copper-base materials, the process is limited to the plating of nickel, tin, gold, and silver deposits. Solutions for plating these deposits are affected adversely by contaminants, such as cyanides, lead, zinc, manganese, and cadmium. Tin may render the nickel plating solution inoperative; therefore, tin-containing copper alloys must be plated with copper or gold before final nickel coating is applied. Lead poses another problem for electroless nickel plating. Lead in amount of 0.5 to 10% is often added to copper alloys to make them easier to machine. Unless the free lead present on the surface of the part is removed, adhesion failures and coating porosity result. Surface lead is best removed by immersing parts for 30 s to 2 min in a 10 to 30% solution of fluoboric acid at room temperature.

Electroless plating processes are used to plate copper with gold and silver for decorative purposes. Nickel, gold, and silver are frequently applied to copper electronic components to prevent tarnishing during subsequent processing and to aid in the soldering of semiconductors. Brass parts are plated with electroless nickel for improved wear and corrosion resistance. Electroless tin plating has been used for copper tubes to prevent corrosion by carbonated waters.

Activation Prior to Electroless Nickel Plating. Once a copper alloy surface is clean and oxide-free, it must be activated before electroless nickel can deposit. To prevent reoxidation, this activation should be initiated without long intermediate delays. The preferred method for initiating deposition is an electrolytic strike in the electroless nickel bath. Using a nickel anode, the parts are made cathodic at 5 V for 30 to 60 s. This applies a thin, electyrolytic nickel-phosphorus coating and provides a catalytic surface. After the current is removed, the electroless deposition can continue.

Another method for initiating electroless deposition on copper alloy surfaces is to preplate surfaces with electrolytic nickel. One disadvantage of this method is that blind holes, internal surfaces, or low current density areas may not be coated by the strike, resulting in incomplete coverage or unplated areas. The use of nickel chloride strikes also may result in chloride contamination of the electroless nickel bath through drag-in.

A third method of activating copper alloys in electroless nickel solutions is to touch them with a piece of steel or with another part already coated with electroless nickel after they have been immersed in the bath. This creates a gal-

Table 18 Composition and operating conditions for stannate (alkaline) tin plating electrolytes

Values of composition are for electrolyte startup; operating limits for the electrolyte composition are approximately –10 to +10% of startup values

	Composition										Operating conditions			
	Potassium stannate		Sodium stannate		Potassium hydroxide		Sodium hydroxide		Tin metal(a)		Temperature		Cathode current density	
Solution	g/L	oz/gal	g/L	oz/gal	g/L	oz/gal	g/L	oz/gal	g/L	oz/gal	°C	°F	A/dm^2	A/ft^2
A	105	14	…	…	15(b)	2(b)	…	…	40	5.3	66–88	150–190	3–10	30–100
B	210	28	…	…	22	3	…	…	80	10.6	77–88	170–190	0–16	0–160
C	420	56	…	…	22	3	…	…	160	21.2	77–88	170–190	0–40	0–400
D	…	…	105(c)	14	…	…	10(b)	1.3(b)	42	5.6	60–82	140–180	0.5–3	6–30

(a) As stannate. (b) Free alkali may need to be higher for barrel plating. (c) $Na_2SnO_3 \cdot 3H_2O$; solubility in water is 61.3 g/L (8.2 oz/gal) at 16 °C (60 °F) and 50 g/L (6.6 oz/gal) at 100 °C (212 °F)

Table 19 Composition and operating conditions for sulfate (acidic) tin plating electrolyte

	Amount		Operating limits	
Constituent	g/L	oz/gal	g/L	oz/gal
Stannous sulfate	80	10.6	60–100	8–13
Tin metal, as sulfate	40	5.3	30–50	4–6.5
Free sulfuric acid	50	6.7	40–70	5.3–9.3
Phenolsulfonic acid(a)	40	5.3	30–60	4–8
β-naphthol	1	0.13	1	0.13
Gelatin	2	0.27	2	0.27

Note: Temperature range for sulfate electrolytes is 21 to 38 °C (70 to 100 °F), and they do not require heating. Cooling can be considered if temperature rises to reduce adverse effects of heat on the electrolyte constituents. Cathode current density is 1 to 10 A/dm^2 (10 to 100 A/ft^2). (a) Phenolsulfonic acid is most often used. Cresolsulfonic acid performs equally well and is a constituent of some proprietary solutions.

Table 20 Composition and operating conditions for fluoborate tin (acidic) plating electrolyte

Constituent or condition	Standard	High-speed	High throwing power
Electrolyte, g/L (oz/gal)			
Stannous fluoborate	200 (26.7)	300 (39.7)	75 (9.9)
Tin metal(a)	80 (10.8)	120 (16.1)	30 (4.0)
Free fluoboric acid	100 (13.4)	200 (26.8)	300 (40.2)
Free boric acid	25 (3.35)	25 (3.35)	25 (3.35)
Peptone(b)	5 (0.67)	5 (0.67)	5 (0.67)
β-naphthol	1 (0.13)	1 (0.13)	1 (0.13)
Hydroquinone	1 (0.13)	1 (0.13)	1 (0.13)
Temperature, °C (°F)	16–38(c) (60–100)(c)	16–38 (60–100)	16–38 (60–100)
Cathode current density, A/dm^2 (A/ft^2)	2–20 (20–200)	2–20 (20–200)	2–20 (20–200)

Note: The standard electrolyte composition is generally used for rack or still plating, the high-speed composition for applications like wire plating, and the high-throwing-power composition for barrel plating or applications where a great variance exists in cathode current density as a result of cathode configuration. (a) As fluoborate. (b) Dry basis. (c) Electrolytes do not require heating. Cooling may be considered if temperature rises to reduce adverse effects of heat on the electrolyte constituents.

vanic cell, producing an electric current to initiate the electroless reaction. Deposition spreads until the whole part is covered with electroless nickel. However, two problems can occur with galvanic activation:

- Galvanic currents do not travel well around sharp curves, such as those on threads or corners, and can leave bare spots or areas of reduced thickness
- Passivation of the copper can occur before the deposit spreads across the entire surface, leading to poor adhesion.

More detailed information on preparing copper alloys for electroless nickel plating, bath compositions and characteristics, and properties of electroless nickel deposits can be found in the article "Electroless Nickel Plating" in Volume 5 of the *ASM Handbook*.

Immersion Plating

Immersion plating, sometimes called galvanic plating, depends on the position that the base metal occupies in the electromotive series with respect to the metal to be deposited from solution. Plating occurs when the metal from a dissolved metal salt is displaced by a more active, less noble metal that is immersed in the solution. As the depositing metal is displaced from the bath, metal from the workpiece dissolves in the solution and becomes a contaminant in the bath. Depleted baths are never replenished, but are replaced with fresh solution.

When immersion plating copper-base materials, only those metals more noble than copper can be displaced from solution, thereby limiting this process to metals such as gold and silver. Immersion-plated deposits are thin, usually in the range of 0.050 to 0.50 μm (0.002 to 0.02 mil).

Compositions and operating temperatures of solutions for immersion plating of gold and silver are:

Gold plating	
Potassium gold cyanide	4 g/L (½ oz/gal)
Potassium or sodium cyanide	25 g/L (3½ oz/gal
Sodium carbonate	30 g/L (4 oz/gal)
Temperature of solution	60 to 80 °C (140 to 180 °F)
Silver plating	
Silver cyanide	7.5 g/L (1 oz/gal)
Sodium or potassium	15 g/L (2 oz/gal)
Temperature of solution	18 to 38 °C (65 to 100 °F)

Organic Coatings

Tarnishing or discoloration of copper alloys can be retarded or delayed indefinitely by the application of a lacquer. These clear coatings are organic chemicals formulated from various resins and additives that are usually applied in a solvent vehicle. They harden in air at room temperature (air-drying lacquers) or with baking (thermosetting lacquers). The performance of thermosetting or heat-cured lacquers is superior to that of air-drying lacquers. The use of the thermosetting types is preferred if ovens are available. Distinction should be made, however, between true thermosetting and forced drying. All lacquers can be force dried after a suitable air-flash period to facilitate handling, but thermosetting materials must be heated to an appropriate temperature, 120 to 205 °C (250 to 440 °F) or higher, for 5 to 60 min, to cross-link the polymers present in them and to develop their inherent characteristics.

The catalytic activity of copper is such that essentially complete curing of thermosetting lacquers is obtained at temperatures lower than those required with inert substrates. Consequently, many thermosetting lacquers discolor copper alloys severely when heated to temperatures recommended by their suppliers. Such discoloration can be minimized by curing at lower temperatures.

Selection Criteria. Lacquers should be selected and applied on the basis of the intended service environment of a given product. For exterior service, a dry film thickness of 38 to 50 μm (1.5–2 mils) is recommended. In less severe indoor service, a dry film thickness of about 13 to 18 μm (0.5–0.7 mil) performs satisfactorily. Service characteristics of various resins used in lacquer formulations are listed below:

- *Nitrocellulose*. Nitrocellulose coatings are the least expensive and most common are drying coatings for interior service. They are modified with alkyd or acrylic resins. Nitrocellulose coatings are used in exterior applications; however, they are usually stripped and replaced at intervals of less than one year. They do not have high resistance to chemicals, but they are fast drying and easy to use.
- *Acrylic*. Available in air dying or thermosetting compositions, acrylics are relatively high cost materials. The air drying modifications are popular for exterior applications, while the thermosetting types are useful for interior applications requiring high resistance to heat and abrasion. Since the thermosetting coatings are not conveniently stripped, they are unsuitable for major architectural applications.
- *Epoxy coatings*. Epoxy coatings have excellent resistance to wear and chemicals. They are relatively expensive and are only available in thermosetting or two part (catalyst activated) compositions with relatively short pot lives. They are good for severe indoor applications, but they degrade rapidly and darken in a few months of exterior service.
- *Silicone coatings*. Silicones provide the best potential for coatings that must operate at elevated temperatures. Thin films of these high-cost coatings are used, and protection by a second coat of a more durable abrasion resistant lacquer may be necessary. Ultraviolet absorbing compounds are added to prevent darkening of the silicone during exterior exposures.
- *Alkyd coatings*. Slow drying or baking is required when applying the alkyd coatings. Modified with melamine resins, these coatings are low cost and durable enough for exterior applications. Resistance to chemicals is usually good.
- *Urethane coatings*. Color degradation on exterior exposure has been a problem with urethane coatings. Resistance to chemicals and abrasion are good even for the air drying coatings.
- *Cellulose acetate butyrate*. Usually considered for interior applications, cellulose acetate butyrate coatings are air drying and have moderate cost and properties. They have a tendency to darken during exterior applications.
- *Vinyl*. Vinyl coatings require stabilization against ultraviolet degradation. They are usually relatively soft and flexible coatings.
- *Polyvinyl fluoride (PVF) film*. Applied by roll bonding with an adhesive, PVF films have been used to protect sheet copper in exterior applications. It has been projected that these clear films can protect a properly prepared substrate for twenty years or more.

Coloring

Copper-base materials may be surface treated to produce a variety of colors, ranging from dark reds to black. The final color depends on base metal composition, solution composition, immersion time, and operator skill. Coloring is primarily an art, and practical experience is necessary to develop the skill required to produce uniform finishes consistently. Copper alloys are colored chemically to enhance the appearance of a product, to provide an undercoating for subsequent organic finishes as with brass, and to reduce light reflection in optical systems. Chemical coloring produces a thin layer of a compound on the surface of the base metal. This layer retains some of the characteristics of the metal surface prior to coloring, such as smooth and lustrous or dull.

The procedures for artificial coloring of metals utilize many of the reactions that occur more slowly under natural conditions. Some colored films not found in nature can be produced artifi-

Table 21 Bath compositions and operating conditions for tin-lead plating

Conditions for operating include a cathode current density of 3 A/dm^2 (30 A/ft^2); anode to cathode ratio is 2 to 1; solution has maximum pH of 0.2 and is mildly agitated at a temperature of 16 to 38 °C (60 to 100 °F); air agitation cannot be used because it will oxidize the tin.

	Total tin		Stannous tin		Lead		Free fluoboric acid		Free boric acid		Peptone		
Constituent	g/L	oz/gal	g/L	oz/gal	g/L	oz/gal	g/L	oz/gal	g/L	oz/gal	g/L	oz/gal	Anode Composition
7Sn-93Pb	7.0	0.94	6.0	0.80	88.4	11.8	100.0	13.4	25	3.4	0.50	0.067	7Sn-93Pb
60Sn-40Pb	60.0	8.0	55.0	7.4	25.0	3.4	100.0	13.4	25	3.4	5.0	0.67	63Sn-37Pb

Table 22 Solutions for coloring copper alloys

Desired color	Solution composition	Process conditions	Comments
Solutions for alloys containing ≥85% Cu			
Dark red	Molten potassium nitrate	Temperature, 650–700 °C (1200–1300 °F); immersion time, ≤ 20 s; hot water quench	Parts must be lacquered.
Black(a)	Solution A: liquid sulfur, 28 g (1 oz); sulfurated potash, 57 g (2 oz); ammonium hydroxide (sp gr 0.89), 7 g (1/4 oz); water, 4 L (1 gal)	Room temperature	Produces a dull black finish; a reddish bronze to dark brown finish can be obtained by dry scratch brushing with a fine wire or cloth wheel.
	Solution B: sulfurated potash, 1.9 g/L (1/4 oz/gal) of water	…	Solution strength should be adjusted to blacken the part in approximately 1 min; too rapid formation of coloring film can result in a nonadherent and brittle film.
	Solution C: potassium sulfide, 3.7–7.5 g/L (1/2 –1 oz/gal) of water	Immersion time, ≤ 10 s	Parts must be lacquered.
Steel black	Arsenious oxide (white arsenic), 113 g (4 oz); hydrochloric acid (sp gr 1.16), 240 cm^3 (8 fl oz); water, 4 L (1 gal)	Temperature of solution, ~ 82 °C (180 °F)	Immerse parts in the solution until a uniform color is obtained; scratch brush while wet, then dry and lacquer.
Black anodizing	Sodium hydroxide, 45 g (16 oz); water, 4 L (1 gal)	Temperature, ~ 82–99 °C (180–210 °F); current density, 0.2–1 A/dm^2 (2–10 A/ft^2); anode-to-cathode ratio, 1:1; voltage, 6 V; cathodes, steel, carbon, or graphite; anodizing time, 45 s to 3.75 min; tank material, steel	Adequate ventilation is required. After anodizing, the parts are washed in hot and cold water, rinsed in hot water, dried, buffed lightly with a soft cloth wheel, and lacquered, if desired.
Reddish bronze to dark brown (statuary bronze)	Sulfurated potash, 57 g (2 oz); sodium hydroxide, 85 g (3 oz); water, 4 L (1 gal)	Temperature, 77 °C (170 °F); immersion time depends on final color desired	Parts are usually scratch brushed with a fine wire wheel; lacquering is required.
Verde antique	Solution A: copper nitrate, 113 g (4 oz); ammonium chloride, 113 g (4 oz); calcium chloride, 113 g (4 oz); water, 4 L (1 gal)	…	Verde antique finishes are also known as patina. They are stippled on brass or copper and dried. Parts made of copper or copper plated are usually treated in a sulfide solution to produce a black base color, which results in a dark background. The use of sodium salts in the verde antique solution results in a yellowish color, while ammonium salts impart a bluish cast. Stippling can be repeated, and when the antique green color appears, immersion in boiling water will produce several different color effects. Other color effects are obtained by using some dry colors such as light and dark chrome green, burnt and raw sienna, burnt and raw umber, ivory drop white, and drop black, or Indian red. After coloring, the surface should be lacquered or waxed. A semiglossy appearance of the lacquered surface can be produced by brushing with paraffin, beeswax, or carnuba wax on a goats-hair brush rotated at about 750 rev/min.
	Solution B: acetic acid, 2 L (gal); ammonium chloride, 570 g (20 oz); sodium chloride, 200 g (7 oz); cream of tartar, 200 g (7 oz); copper acetate, 200 g (7 oz); water, 2 L (gal)	…	
Light brown	Barium sulfide, 16 g (1/2 oz); ammonium carbonate, 7 g (1/4 oz); water, 4 L (1 gal)	Room temperature	…
Brown	Potassium chlorate, 155 g (5 1/2 oz); nickel sulfate, 78 g (2 3/4 oz); copper sulfate, 680 g (24 oz); water, 4 L (1 gal)	Temperature, 90–100 °C (195–212 °F)	…
Solutions for alloys containing <85% Cu			
Black	Solution A: copper sulfate, 85 g (3 oz); sodium thiosulfate, 170 g (6 oz); water, 11–19 L (3–5 gal)	Brass parts are placed in oblique tumbling barrel made of stainless steel. The parts are covered with water; the copper sulfate and sodium thiosulfate are dissolved in warm water and added to the contents of the barrel. The parts are tumbled for 15 to 30 min to obtain finish, the solution is drained from barrel, and the parts are washed thoroughly in clean water. The parts are then removed from the barrel and dried in sawdust or air blasted.	Parts must be lacquered.
	Solution B: copper carbonate, 16 g (1/2 oz); ammonium hydroxide (sp gr 0.89), 113 g (4 oz); sodium carbonate, 7 g (1/4 oz); water, 4 L (1 gal)	Temperature, 88–93 °C (190–200 °F)	…
Statuary bronze	Copper carbonate, 16 g (1/2 oz); ammonium hydroxide (sp gr 0.89), 113 g (4 oz); sodium carbonate, 7 g (1/4 oz); water, 4 L (1 gal)	Temperature, 88–93 °C (190–200 °F). Immerse the parts in the hot solution for 10 s; rinse in cold water and dip in solution of dilute sulfuric acid; rinse in hot and then cold water; clean with soft cloth or sawdust.	Parts must be coated with clear lacquer.
Blue black	Copper carbonate, 0.45 kg (1 lb); ammonium hydroxide (sp gr 0.89), 1 L (1 qt); water, 3 L (3 qt)	Temperature, 54–79 °C (130–175 °F) proper color should be obtained in 1 min.	Excess copper carbonate should be present; proper color should be obtained in 1 min.
Brown	Part 1: copper sulfate, 113 g (4 oz); potassium chlorate, 227 g (8 oz); water, 4 L (1 gal). Part 2: liquid sulfur, 28 g (1 oz), or sulfurated potash, 57 g (2 oz); water, 4 L (1 gal)	Immerse parts in Part 1 for 1 min; without rinsing, immerse parts in Part 2 for a short time; rinse in cold water; repeat dipping operation in both solutions until desired color is obtained; rinse work in hot water; dry in hot sawdust or with an air blast; scratch brush with fine wire wheel and lacquer.	

(continued)

(a) Alloys blackened by these solutions include silicon bronzes; beryllium coppers; bronzes containing up to 8% Sn; phosphor bronzes of all types; and brasses, leaded or unleaded, with zinc contents up to 35%. Several other proprietary processes are also available for producing a satisfactory black finish.

Table 22 (continued)

Desired color	Solution composition	Process conditions	Comments
Solutions for alloys containing <85% Cu			
Light brown (old English finish)	Part 1: liquid sulfur, 14 g ($^1/_2$ oz), or sulfurated potash, 28 g (1 oz); water, 4 L (1 gal). Part 2: copper sulfate, 57 g (2 oz); water, 4 L (1 gal)	Immerse parts in Part 1; without rinsing, immerse in Part 2; rinse in cold water; repeat dipping operations until light color is obtained. For uniform finish, scratch brush and repeat dipping operations until desired color is obtained; rinse parts in cold and hot water; dry in sawdust; scratch brush on a fine wire wheel; and lacquer.	…
Antique green on brass	Nickel ammonium sulfate, 227 g (8 oz); sodium thiosulfate, 227 g (8 oz); water, 4 L (1 gal)	Temperature, 71 °C (160 °F)	…
Hardware green on brass	Ferric nitrate, 28 g (1 oz); sodium thiosulfate, 170 g (6 oz); water, 4 L (1 gal)	Temperature, 71 °C (160 °F)	…
Brown on brass or copper	Potassium chlorate, 155 g (5$^1/_2$ oz); nickel sulfate, 78 g (2$^3/_4$ oz); copper sulfate, 680 g (24 oz); water, 4 L (1 gal)	Temperature, 91–100 °C (195–212 °F)	…
Light brown on brass or copper	Barium sulfide, 14 g ($^1/_2$ oz); ammonium carbonate, 7 g ($^1/_4$ oz); water, 4 L (1 gal)	…	Color is made more clear by wet scratch brushing and redipping.

(a) Alloys blackened by these solutions include silicon bronzes; beryllium coppers; bronzes containing up to 8% Sn; phosphor bronzes of all types; and brasses, leaded or unleaded, with zinc contents up to 35%. Several other proprietary processes are also available for producing a satisfactory black finish.

cially. Additional color combinations, such as oxidized and highlighted finishes, can be produced by successive chemical and mechanical operations, to emphasize or to remove partially the chemically colored film.

Coloring copper alloys is essentially a process for coloring copper, because zinc and tin compounds are colorless. These constituents and their concentrations greatly affect many of the chemical reactions and color tones of the coatings formed. A copper content of less than 85% is required to produce a good blue-black finish on brass by an ammoniacal copper sulfate or ammoniacal copper carbonate blackening or blue dip solution. Other solutions are more suitable for coloring high-copper alloys.

After machining and mechanical surface preparation have been completed, the parts should be thoroughly cleaned to remove dirt, oil, grease, and oxide films. Cleaning is important for the development of a uniform film in chemical coloring. The cleaning and deoxidizing procedures should be selected so that the structure of the metal at the surface undergoes a minimum of undesirable change. Acid dipping or bright dipping using nitric-sulfuric acid solution may be necessary to remove oxides and to activate the surface for chemical coloring. A certain amount of trial and error is usually required to establish the most suitable techniques for surface preparation.

Coloring Solutions. Many types of chemical solutions are used for coloring copper alloys. The formulations and conditions commonly used in commercial applications to produce colors are given in Table 22.

Post Treatment. Many chemical films must be scratch brushed to remove excess or loose deposits. In addition, contrast in colors can be obtained by relieving by scratch brushing with a slurry of fine pumice, hand rubbing with an abrasive paste, mass finishing, or buffing to remove some or all of the colored film from the highlights. Clear lacquers are usually necessary for adequate life and service of chemical films used as outdoor decorative finishes. Finishes for exposure indoors are often used without additional protection to the conversion coating.

Passivation

Passivation refers to the process of forming a protective film on metal. The blue-green patina of copper developed during atmospheric exposure of copper alloys is a protective coating that is aesthetically pleasing. The patina may be artificially produced or accelerated by a solution having the formulation:

Ammonium sulfate	2.7 kg (6 lb)
Copper sulfate	85 g (3 oz)
Ammonia (technical grade, 9.90 sp gr)	39.6 cm^3 (1.34 fl oz)
Water	25 L (6.5 gal)
Total solution	27 L (7.3 gal)

A fine spray of the solution should be applied to a chemically clean surface. The film should be permitted to dry before the part is sprayed a second time. Five or six repetitions of the spraying and drying sequence are required. The color begins to develop in about 6 h and at first is somewhat bluer than natural patina. A more attractive color develops as the surface is exposed to natural weathering.

Small copper parts may be coated with an imitation patina by dipping them in or brushing them with the following solution:

Ingredient	Parts by weight
Copper	30
Nitric acid, concentrated	60
Acetic acid, 6%	600
Ammonium chloride	11
Ammonium hydroxide (technical grade, 0.90 sp gr)	20

When preparing the solution, copper is dissolved in the nitric acid, and as soon as the action ceases, the remaining three constituents are added. The solution is allowed to stand several days before use. Parts treated with this solution are coated with linseed oil.

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Metallography, Microstructures, and Phase Diagrams

Metallography and Microstructures of Copper and Copper Alloys

COPPER AND COPPER ALLOYS present no extraordinary problems to the metallographer, and specimens (both wrought and cast) are prepared in much the same way as those of other metals (Ref 1, 2). This article discusses metallographic preparation for macro- and microexamination. The micrographs that follow the text illustrate the effects of alloying elements, heat treatment, percentages of reduction by rolling, welding and brazing, corrosion, and powder metallurgy (P/M) processing.

Macroexamination

Specimens for macroscopic examination are extracted from larger masses using common cutting tools. The tools must be kept sharp to minimize cold working of the specimen.

Surface Preparation. Surfaces suitable for macroetching usually can be obtained in two machining operations. In the first operation, a heavy cut is taken to remove the metal that was cold worked during sectioning; in the second, a light cut is taken using a V-shape tool to remove the remaining effects of cold work.

The need for further surface preparation depends on the amount of detail required. The surface detail revealed by etching increases as the degree of surface irregularity decreases. The machined surface is often ground using 180-grit or finer abrasive—sometimes as fine as 600 grit.

Etching. Deep etching removes the effects of cold work, but produces a rough surface; therefore, it is common practice to deep etch the machined or rough-ground surface, regrind it lightly, then etch it lightly.

Selection of an etchant for a macrospecimen depends primarily on the alloy to be etched and the features to be examined. Because the capabilities of two or more etchants often overlap or are the same, selection of a specific etchant is arbitrary. Table 1 lists compositions of the more commonly used macroetchants, along with etching procedures, purposes of the etchants or characteristics revealed, and alloys for which they are ordinarily used.

Microexamination

Specimens of copper and copper alloys for microscopic examination are extracted from larger masses by sawing, shearing, filing, hollow boring, or abrasive-wheel cutting.

Mounting. In general, the procedures for mounting copper and copper alloy specimens are the same as those for other metals. Coppers and copper alloys are extremely susceptible to work hardening; therefore, when possible, the face used for examination should be the one that has been subjected to the least cutting.

Bakelite (Georgia Pacific Corp.) is the mounting material most often used. Diallyl phthalate, glass or fiber filled, is a suitable alternative to Bakelite. Methyl methacrylate is softer than Bakelite and thus is not as good for edge preservation. However, its transparency is sometimes advantageous.

The combination of heat and pressure needed for compression-mounting materials will sometimes crush or adversely affect specimens, especially those of thin sheet or strip. Under these conditions, one of the epoxies or some other castable mounting material must be used. Edge preservation of copper and copper alloy specimens can be accomplished by the same methods used for specimens of other metals.

Grinding. Wet grinding is preferred for all coppers and copper alloys. Common practice involves rough grinding the specimen surface to remove metal that has been cold worked followed by finish grinding to obtain a suitable surface. Finish grinding is performed using flat wheels and silicon carbide papers of progressively finer grit—usually 240, 320, 400, and 600. Ultrafine 800- and 1200-grit papers are sometimes used.

An acceptable alternative to wet grinding is to dry grind on belts having progressively finer grit sizes (180, 240, and 320 grit), then to hand polish on progressively finer emery papers (1, 0, 00, 000, and 0000). Wet grinding is recommended; during either procedure, the specimen should always be rotated 90° before grinding using the next finer grit size.

Rough Polishing. Most coppers and copper alloys are relatively soft and so require a polishing medium that provides maximum cutting with minimum rubbing. Rough polishing should be performed using diamond-impregnated nylon cloth. Duck canvas, wool broadcloth, and cotton (listed in order of decreasing preference) are also used for polishing.

The preferred abrasive for rough polishing on any of the cloths mentioned above is 3- to 9-μm diamond paste. However, 400-grit or finer alu-

Table 1 Etchants for macroscopic examination of coppers and copper alloys

Procedure for use: immerse at room temperature, rinse in warm water, dry

Composition		Copper or copper alloys	Comments
1.	50 mL HNO_3, 0.5 g $AgNO_3$ (silver nitrate), 50 mL H_2O	All coppers and copper alloys	Produces a brilliant, deep etch
2.	10 mL HNO_3 and 90 mL H_2O	Coppers and all brasses	Grains; cracks and other defects
3.	50 mL HNO_3 and 50 mL H_2O(a)	Coppers, all brasses, aluminum bronze(b)	Same as above; reveals grain contrast
4.	30 mL HCl, 10 mL $FeCl_3$, 120 mL H_2O or methanol	Coppers and all brasses	Same as etchant above(c)
5.	20 mL acetic acid, 10 mL 5% CrO_3, 5 mL 10% $FeCl_3$, 100 mL H_2O(d)	All brasses	Produces a brilliant, deep etch
6.	2 g $K_2Cr_2O_7$, 4 mL saturated solution of NaCl, 8 mL H_2SO_4, 100 mL H_2O(e)	Coppers, high-copper alloys, phosphor bronze	Grain boundaries, oxide inclusions
7.	40 g CrO_3, 7.5 g NH_4Cl (ammonium chloride), 50 mL HNO_3, 8 mL H_2SO_4, 100 mL H_2O	Silicon brass, silicon bronze	General macrostructure
8.	45 mL acetic acid and 45 mL HNO_3	Copper	Grain boundary and macroetch by polish attack
9.	Saturated $(HN_4)_2S_2O_8$ (ammonium persulfate)	Copper and copper alloys	Use after the acetic acid listed above; increases contrast of brass
10.	40 mL HNO_3, 20 mL acetic acid, 40 mL H_2O	Copper and copper alloys	Macroetch 90-10, 70-30 and leaded brass

(a) Solution should be agitated during etching to prevent pitting of some alloys. (b) Aluminum bronzes may form smut, which can be removed by brief immersion in concentrated HNO_3. (c) Excellent for grain contrast. (d) Amount of water can be varied as desired. (e) Immerse specimen 15-30 min; then swab with fresh solution.

mina (Al_2O_3) used with distilled water as the vehicle is usually an acceptable alternative. A wheel speed of approximately 200 rpm is generally recommended.

Finish Polishing. Generally, napped cloths are preferred for finish polishing. The abrasive is usually 0.3 μm α-Al_2O_3 or 0.05 μm γ-Al_2O_3; both abrasives are used with water as a vehicle. Other abrasives that have proved satisfactory for finish polishing are magnesium oxide (MgO) in distilled water, ferric oxide (Fe_2O_3), colloidal silica (SiO_2), and fine diamond paste. Recommended wheel speed is 150 to 200 rpm.

Specimen rotation during polishing elicits numerous opinions. Hand polishing necessitates developing a personal technique that may require a degree of manual dexterity; mechanical polishing gives more reproducible results and is preferred.

After polishing, the specimen is rinsed in water and dried with warm air. Automatic polishing (usually vibratory) has proved highly successful for polishing copper alloys. Automatic polishing greatly minimizes human variables. Attack polishing (combined polishing and etching) using ferric nitrate $Fe(NO_3)_3$ or ammonium hydroxide/ammonium persulfate [NH_4OH-$(NH_4)_2S_2O_8$] solution can be more safely performed using automatic equipment than by hand.

Electrolytic polishing of coppers and copper alloys alleviates many of the difficulties encountered in mechanical polishing. Apart from offering the usual advantages over mechanical polishing of saving time, minimizing the human variable, and minimizing artifacts resulting from disturbed metal, electrolytic polishing offers some advantages for copper and copper alloys:

- It is excellent for revealing grain size and shape on all sides of specimens.
- It is especially well adapted to use on single-phase copper alloys.
- It reveals true microstructure with less difficulty than mechanical polishing.

Disadvantages of electrolytic polishing for copper and copper alloys include:

- Different rates of attack cause some phases of multiphase alloys to stand out in relief.
- The edge effect of electrolytic polishing, whereby edges of specimens are attacked and polished more than other areas, limits application of the process to examination of surfaces in from the edges.
- Attack around nonmetallic particles, voids, and inclusions in the specimen may occur at a more rapid rate than attack of the matrix, and so the size of voids or inclusions may be exaggerated.

Table 2 lists compositions of some electropolishing solutions, together with electropolishing conditions that have proved satisfactory for the coppers and copper alloys shown in the last column in the table. The durations listed in Table 2 are generally based on conditions where electrolytic polishing completely replaces mechanical polishing. Useful results may be obtained when mechanical polishing is followed by electrolytic polishing. Durations for electrolytic polishing are then always under 1 min.

Examination of As-Polished Specimens. As-polished specimens of coppers and copper alloys are frequently examined metallographically. Characteristics revealed include the presence of oxide in as-cast copper, lead particles and cavities in cast red brass, oxides in zirconium copper, and corrosion in brazed joints. As-polished specimens are used also for microprobe examinations. Specimens are also examined under polarized light to differentiate cuprous oxide (Cu_2O) inclusions from other inclusions. Under polarized light, only the Cu_2O inclusions appear ruby red; under white light, copper oxide and other inclusions appear blue-gray. Oxides of arsenic and antimony also are optically active under polarized light.

Chemical Etching. Table 3 lists chemical etchants that are used for coppers and copper alloys and includes etching procedures and the alloys to which each etchant is commonly applied. The ammonium hydroxide/hydrogen peroxide/water solution (etchant 1, Table 3) is by far the most widely used etchant. It is probably optimal for routine work and applies to most coppers and copper alloys. This etchant was

Table 2 Electrolytes and conditions for electrolytic polishing of copper and copper alloys

Composition	Voltage	Current density		Cathode	Duration	Copper or copper alloy
		A/cm^2	A/in.^{2}			
1. 825 mL H_3PO_4 and 175 mL H_2O	1.0–1.6	0.02–0.1	0.13–0.65	Copper	10–40 min	Unalloyed copper
2. 250 mL H_3PO_4, 250 mL ethanol, 50 mL propanol, 500 mL distilled H_2O, 3 g urea	3–6	0.4–0.8	2.6–5.2	Stainless steel	50 s	Coppers and copper alloys
3. 700 mL H_3PO_4 and 350 mL H_2O	1.2–2.0	0.06–0.1	0.39–0.64	Copper	15–30 min	Coppers; α, β, and α-β brasses; aluminum, silicon, tin; and phosphor bronzes; beryllium, iron, lead, or chromium
4. 580 g $H_4P_2O_7$ and 1000 mL H_2O	1.2–1.9	0.08–0.12	0.05–0.77	Copper	10–15 min	Coppers, brasses
5. 300 mL HNO_3 and 600 mL methanol	20–70	0.65–3.1	4.2–20.0	Stainless	10–60 s	Coppers, brasses
	30–50	2.5–3.1	16.1–51.0	Stainless	5–10 s	Silicon bronze, phosphor bronze
6. 170 g CrO_3 and 830 mL H_2O	1.5–12	0.95–2.2	6.1–14.2	Stainless	10–60 s	Brasses
7. 400 mL H_3PO_4 and 600 mL H_2O	1.0–2.0	0.06–0.15	0.39–0.97	Copper or stainless	1–15 min	α, α-β brasses; copper-iron, copper-chromium
8. 30 mL HNO_3, 900 mL methanol, 300 g $Cu(NO_3)_2$ (cupric nitrate)	45–50	1.05–1.25	6.77–8.1	Stainless	15 s	Bronzes (have tendency to etch)
9. 670 mL H_3PO_4, 100 mL H_2SO_4, and 300 mL distilled H_2O	2–3	0.1	0.64	Copper	15 min	Copper; copper-tin containing up to 6% Sn
10. 470 mL H_3PO_4, 200 mL H_2SO_4, 400 mL distilled H_2O	2–2.3	0.1	0.64	Copper	15 min	Copper-tin up to 9% Sn
11. 350 mL H_3PO_4 and 650 mL ethanol	2–5	0.02–0.07	0.13–0.45	Copper	10–15 min	Copper alloys with high lead (to 30%)
12. 540 mL H_3PO_4 and 460 mL H_2O	2	0.065–0.075	0.4–0.5	Copper	5–15 min	Copper
	2–2.2	0.1–0.15	0.64–0.97	Copper	15 min	Nickel silver

used for many of the specimens shown in the micrographs in this article. This etchant is also widely used for determining the inclusion content of brass and bronze strip.

The potassium dichromate/sulfuric acid/sodium chloride/water etchant (usually referred to simply as potassium dichromate, $K_2Cr_2O_7$; see etchant 4 in Table 3) is also used extensively, especially for revealing structures of welded and brazed joints.

Chromic acid (H_2CrO_4, etchant 5 in Table 3) is also prevalent. For the micrographs shown in this article, it was used for electrodeposited copper, nickel silver, and brazed joints in copper. The other etchants listed in Table 3 have limited uses, although some are used for the same alloys and structures as the etchants discussed previously.

Tint etchants for color metallography of copper and copper alloys have also been developed. These include Klemm's reagent I (50 mL saturated aqueous sodium thoisulfate/1 g potassium metabisulfite) for brasses, Klemm's reagent II (50 mL saturated aqueous sodium thiosulfate/5 g potassium metabisulfite) for alpha brasses, Klemm's reagent III (5 mL saturated aqueous sodium thiosulfite/45 mL water/20 g potassium metabisulfite) for bronzes, and Baraha's lead sulfide etchant (240 g sodium thiosulfate/30 g citric acid/24 g lead acetate/1000 mL water) for copper and copper alloys. Recommended practices for copper color metallography can be found in Ref 2 and 3.

Electrolytic etching reveals cold-worked structures of brasses, gives contrast to β phase in brass, and, in copper-nickel alloys, reduces the contrast due to coring that usually appears with chemical etching. It is also used to bring out the general structure of beryllium copper, cartridge brass, free-cutting brass, aluminum bronze, nickel silver, and admiralty metal. Table 4 lists five electrolytes that have proved successful for electrolytic etching.

Table 3 Etchants and procedures for microetching of coppers and copper alloys

Composition(a)		Procedure	Copper or copper alloy
1.	20 mL NH_4OH, 0–20 mL H_2O, 8–20 mL 3% H_2O_2	Immersion or swabbing 1 min; H_2O_2 content varies with copper content of ally to be etched; use fresh H_2O_2 for best results(b)	Use fresh for coppers and copper alloys; film on etched aluminum bronze can be removed using weak Grard's solution, preferred for brasses
2.	1 g $Fe(NO_3)_3$ and 100 mL H_2O	Immersion	Etching and attack polishing of coppers and alloys
3.	25 mL HN_4OH, 25 mL H_2O, 50 mL 2.5% $(NH_4)_2S_2O_8$	Immersion	Attack polishing of coppers and some copper alloys
4.	2 g $K_2Cr_2O_7$, 8 mL H_2SO_4, 4 mL NaCl (saturated solution), 100 mL H_2O	Immersion; NaCl replaceable by 1 drop HCl per 25 mL solution; add just before using; follow with $FeCl_3$ or other contrast etch	Coppers; copper alloys of beryllium, manganese, and silicon; nickel silver; bronzes, chromium copper; preferred for all coppers to reveal grain boundaries, grain contrast, and cold deformation
5.	CrO_3 (saturated aqueous solution)	Immersion or swabbing	Coppers, brasses, bronzes, nickel silver
6.	50 mL 10–15% CrO_3 and 1–2 drops HCl	Immersion; add HCl at time of use	Same as above; color by electrolytic etching or with $FeCl_3$ etchants
7.	8 g CrO_3, 10 mL HNO_3, 10 mL H_2SO_4, 200 mL H_2O	Immersion or swabbing	Grain contrast etch for ETP copper, does not dissolve Cu_2O; use after etchant 3 when etching deoxidized high-phosphorus copper for microstructure
8.	10 g $(NH_4)_2S_2O_8$ and 90 mL H_2O	Immersion; use cold or boiling	Coppers, brasses, bronzes, nickel silver, and aluminum bronze
9.	10% aqueous copper ammonium chloride plus NH_4OH to neutrality or alkalinity	Immersion; wash specimen thoroughly	Coppers, brasses, nickel silver; darkens β in α-β brass
10.	$FeCl_3$, g — HCl, mL — H_2O, mL 5 — 50 — 100 20 — 5 — 100(c)(d) 25 — 25 — 100 1 — 20 — 100 8 — 25 — 100 5 — 10 — 100(e)(f)	Immersion or swabbing; etch lightly or by successive light etches to required results	Coppers, brasses, bronzes, aluminum bronze; darkens b phase in brass; gives contrast following dichromate and other etches
11.	5 g $FeCl_3$, 100 mL ethanol, 5–30 mL HCl	Immersion or swabbing for 1 s to several minutes	Coppers and copper alloys; darkens β phase in α-β brasses and aluminum brass
12.	HNO_3 (various concentrations)	Immersion or swabbing; 0.15–0.3% AgNO3 added to 1:1 solution gives a brilliant, deep etch	Coppers and copper alloys
13.	NH_4OH (dilute solutions)	Immersion	Attack polishing of brasses and bronzes
14.	50 mL HNO_3, 20 g CrO_3, 75 mL H_2O	Immersion	Aluminum bronze free-cutting brass; film from polishing can be removed with 10% HF
15.	5 mL HNO_3, 20 g CrO_3, 75 mL H_2O	Immersion	Same as above
16.	59 g $FeCl_3$ and 96 mL ethanol	Immersion; heat sample first in hot H_2O	Macro- and microetch for annealed copper-nickel alloys
17.	16 g CrO_3, 1.8 g NH_4Cl (ammonium chloride), 10 mL HNO_3, 200 mL H_2O	Immersion	Preferred etch for copper-nickel; preferential attack of copper-rich phase in castings
18.	5 parts HNO_3, 5 parts acetic acid, 1 part H_3PO_4	Immersion, 3 s	Coppers, brasses
19.	Equal parts HN_4Cl and H_2O	Immersion	Coppers and alloys
20.	60 g $FeCl_3$, 20 g $Fe(NO_3)_3$, 2000 mL H_2O	Immersion	Copper-nickel alloys
21.	1 part acetic acid, 1 part HNO_3, 2 parts acetone	Immersion	Copper-nickel alloys

(a) The use of concentrated etchants is intended unless otherwise specified. (b) This etchant may be alternated with $FeCl_3$. (c) Grard's No. 1 etchant. (d) Plus 1 g CrO_3. (e) Grard's No 2 etchant. (f) Plus 1 g $CuCl_2$ and 0.05 g $SnCl_2$ (tin chloride)

Table 4 Electrolytes and operating conditions for electrolytic etching of copper and copper alloys

Composition		Operating conditions	Copper or copper alloy
1.	5–14% H_3PO_4 (8%) and rem H_2O	Voltage range, 1–8; etching time, 5–10 s	Coppers, cartridge brass, free-cutting brass, admiralty, gilding metal
2.	250 mL 85% H_3PO_4, 250 mL 95% ethanol, 500 mL H_2O, 2 mL wetting agent	Voltage range, 1–3; current density, 0.1–0.15 A/cm^2 (0.64–0.97 $A/in.^2$); etching time, 30–60 s	Coppers
3.	30 g $FeSO_4$ (ferrous sulfate), 4 g NaOH, 100 mL H_2SO_4, 1900 mL H_2O	0.1 A at 8–10 V for 15 s; do not swab surface after etching	Darkens β phase in brasses and gives contrast after H_2O_2-NH_4OH etch; also for nickel silver and bronzes
4.	1 mL CrO_3 and 99 mL H_2O	6 V; aluminum cathode; etching time, 3–6 s	Beryllium copper and aluminum bronze
5.	5 mL acetic acid (glacial), 10 mL HNO_3 30 mL H_2O	Voltage range 0.5–1 V; current density, 0.2–0.5 A/cm^2 (1.3–1.9 $A/in.^2$); etching time, 5–15 s	Copper-nickel alloys; avoiding contrast associated with coring

Examination for Inclusions. Microscopic examination has become increasingly valuable for evaluating the fabrication characteristics of certain copper alloys, particularly brass and bronze sheet and strip. A correlation exists between the number of inclusions present, as well as their length and distribution, and fabrication characteristics, especially formability. Inclusions are best revealed by swabbing the specimen quickly with NH_4OH-H_2O_2 (etchant 1, Table 3), followed by washing it in running water and drying with an air blast.

ACKNOWLEDGMENT

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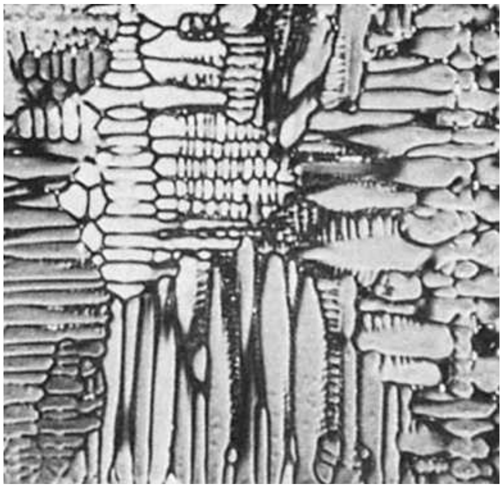

Fig. 1 Alloy C11000 (ETP copper), static cast. Excellent definition of dendritic structure. Etchant 10, Table 3. 5×. (J. Bartholomew)

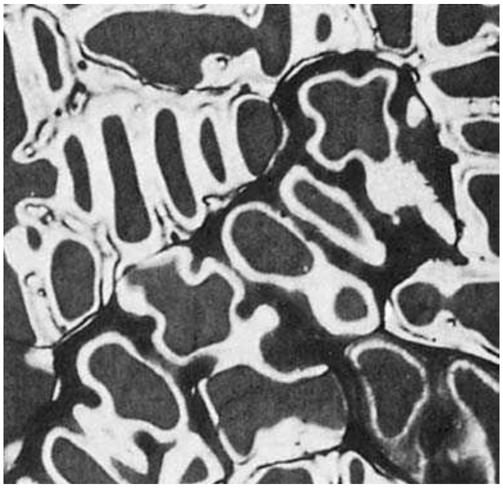

Fig. 2 Same material as Fig. 1, but at higher magnification to show detail of dendritic structure. Etchant 4, Table 3. 75×. (J. Bartholomew)

Fig. 3 Same material as Fig. 1, static cast. Grains from the chilled bottom grew through the dendrite "skeletons," producing a mixed grain structure. Etchant 10, Table 3. 3×

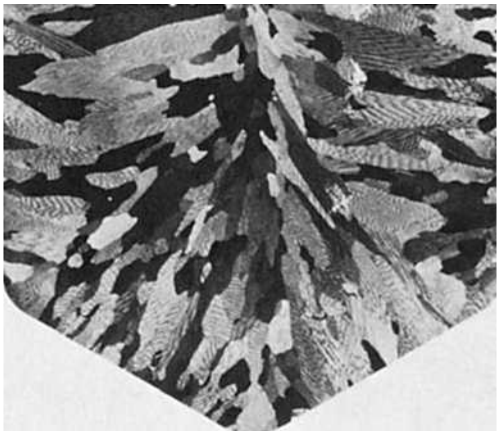

Fig. 4 Alloy C12200 (DHP copper). Longitudinal section of static-cast ingot showing columnar structure. Pouring direction was from top to bottom. Etchant 10, Table 3. 2×. (J. Dibee)

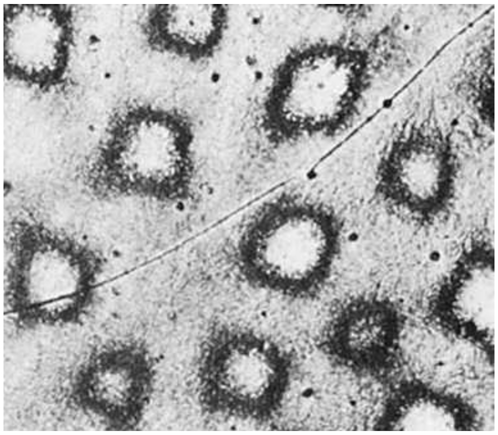

Fig. 5 Same alloy as Fig. 4. Transverse section shows the cross section of the columnar structure and a grain boundary. Etchant 4, then etchant 1, Table 3. 50×. (J. Dibee)

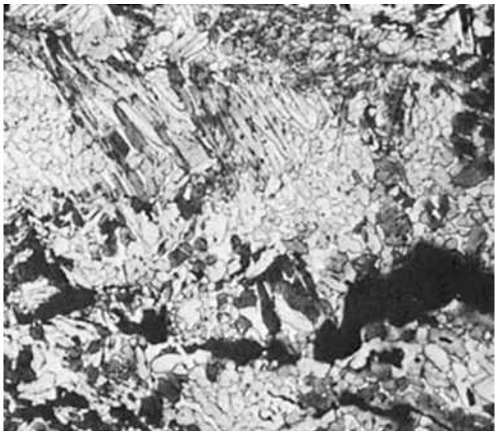

Fig. 6 Alloy C36000 (free-cutting brass), as-cast. Solid-state transformation makes this structure appear unlike an as-cast structure. Etchant 1, Table 3. 50×. (J. Bartholomew)

Fig. 7 Same material as Fig. 6, with primary dendrites of α phase darkened. Lead appears as small spheroids. Etchant 1, Table 3. 50×. (J. Dibee)

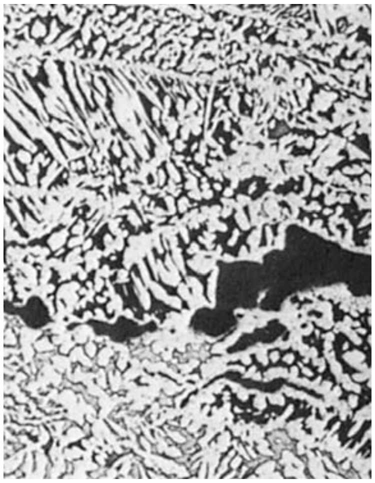

Fig. 8 Same alloy as Fig. 6, with β phase darkened by preferential attack of the etchant. In this case, α phase is formed in the solid state during cooling. Etchant 16, Table 3. 50×. (J. Dibee)

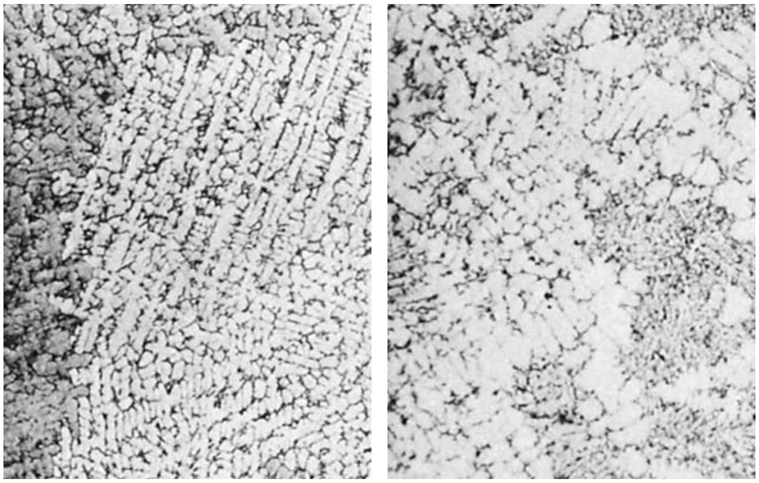

Fig. 9, 10 Same alloy as Fig. 6, semicontinuous cast. Fig. 9: α-phase dendrites in the columnar zone near the outside edge of the ingot. Fig. 10: mixed α- and β-phase dendrites near the center of the ingot. Etchant 1, Table 3. 30×

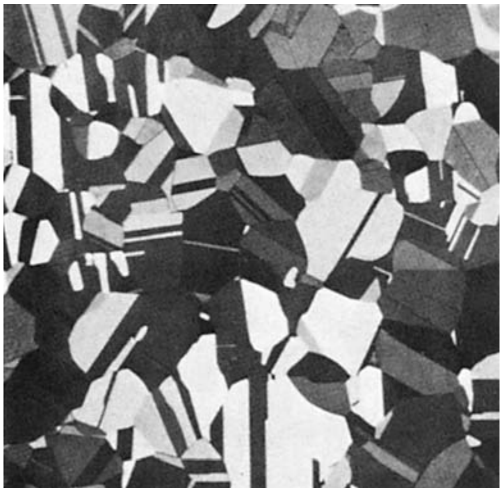

Fig. 11 Alloy C26000 (cartridge brass), annealed. Polarized light illumination was used to increase contrast of the microstructure. Etchant 18, then etchant 19, Table 3. 55×. (J. Dibee)

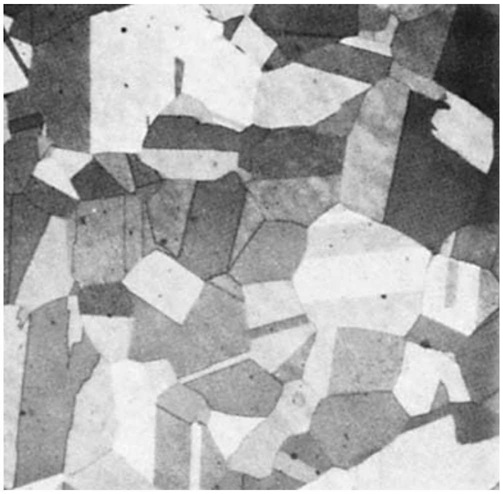

Fig. 12 Alloy C68700 (arsenical aluminum brass), annealed. Structure is α-brass, with the aluminum in solid solution. Etchant 18, Table 3. 55×. (J. Dibee)

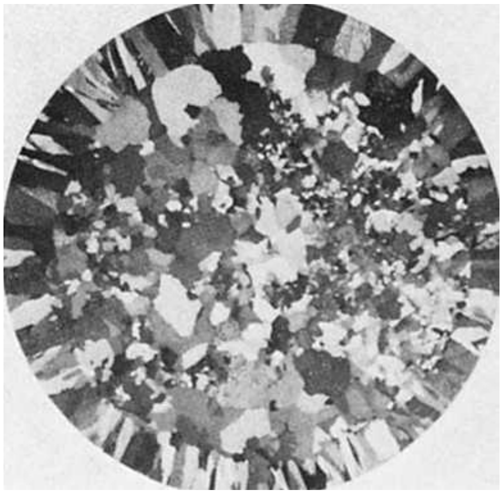

Fig. 13 Alloy C46400 (uninhibited naval brass), as-cast. Transverse macrosection showing the columnar structure of the outer edges of the casting that result from more rapid cooling near the surface of the casting. Etchant 12, Table 3. 1.5×. (J. Dibee)

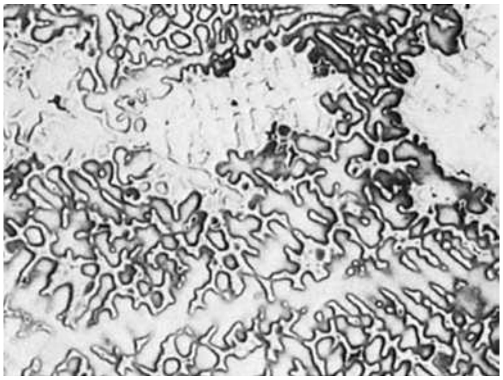

Fig. 14 Same specimen as Fig. 13, except at higher magnification to reveal dendritic microstructure. Etchant 1, then etchant 16, Table 3. 30×. (J. Dibee)

Fig. 15 Alloy C68700 (arsenical aluminum brass), as-cast. Macrosection showing typical dendritic structure. See Fig. 16 for detail. Etchant 18, then etchant 16, Table 3. 4×. (J. Dibee)

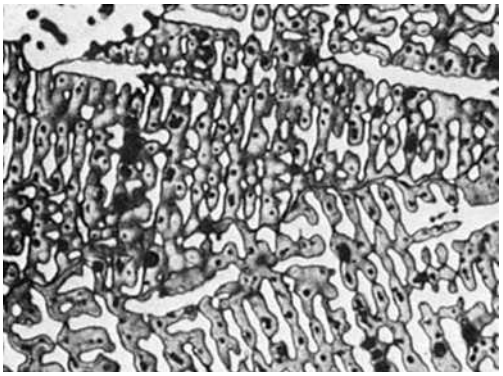

Fig. 16 Same as Fig. 15, except at higher magnification to reveal more detail of the structure. Same etchants as Fig. 15. 75×. (J. Dibee)

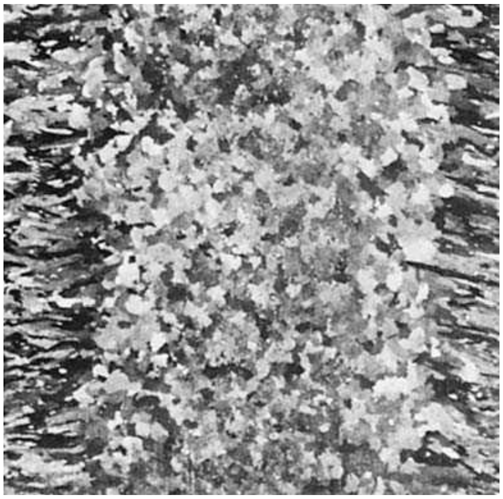

Fig. 17 Alloy C71500 (copper-nickel, 30% Ni), as-cast. Longitudinal section showing columnar structure near the surface of the billet. The grains are inclined upward from horizontal by up to 30° due to convection in the initial state of freezing. Etchant 18, then etchant 16, Table 3. 0.3×. (J. Bartholomew)

Fig. 18 Alloy C26000 (cartridge brass), cast, slowly cooled, and quenched. Primary dendrites aligned in $\langle 100 \rangle$ crystallographic directions. The fine, quenched structure has the same orientation as the coarse dendrites. Etchant 1, Table 3, then electropolished with electrolyte 1, Table 2. 30×. (J. Dibee)

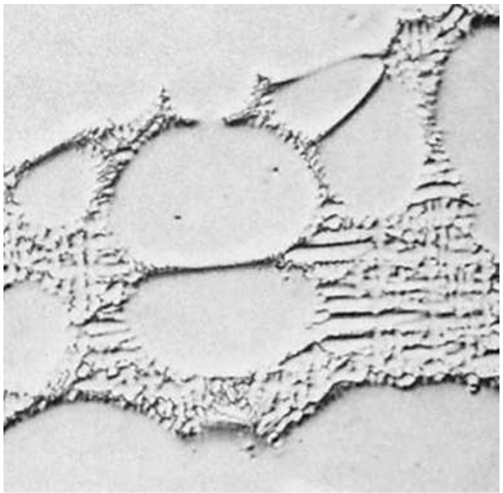

Fig. 19 Same alloy and processing as Fig. 18. Higher magnification shows that fine dendrites originate in the coarse ones and have the same orientation. Dendrites starting in directions that are not $\langle 100 \rangle$ do not grow very far. Same etchant and electrolyte as Fig. 18. 85×. (J. Dibee)

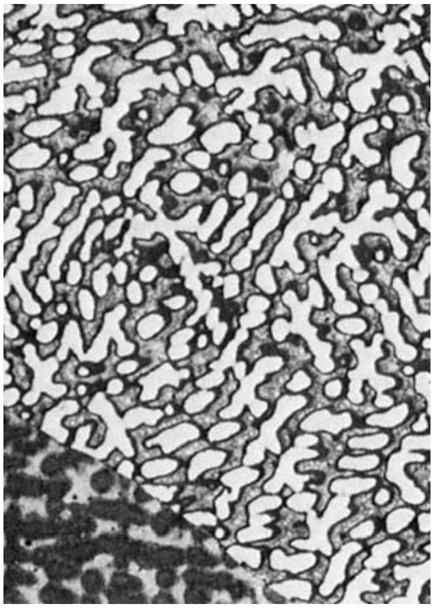

Fig. 20 Alloy C70600 (copper-nickel, 10% Ni), semicontinuous cast. Microstructure shows the distinct segregation of the copper-rich phase (dark) and the nickel-rich phase (light). Etchant 17, Table 3. 50×. (J. Dibee)

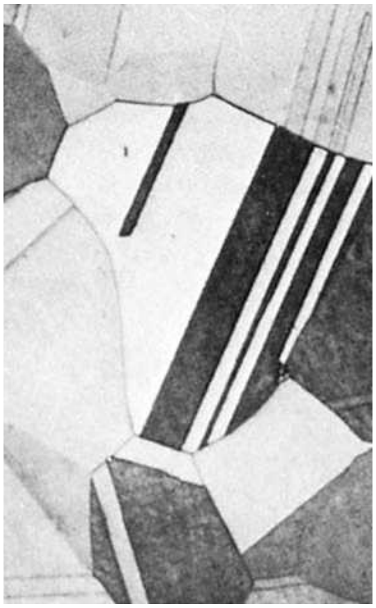

Fig. 21 Alloy C46400 (uninhibited naval brass), extruded, drawn, and annealed. Structure shows twinned grains resulting from annealing. Etchant 16, Table 3. 300×. (J. Dibee)

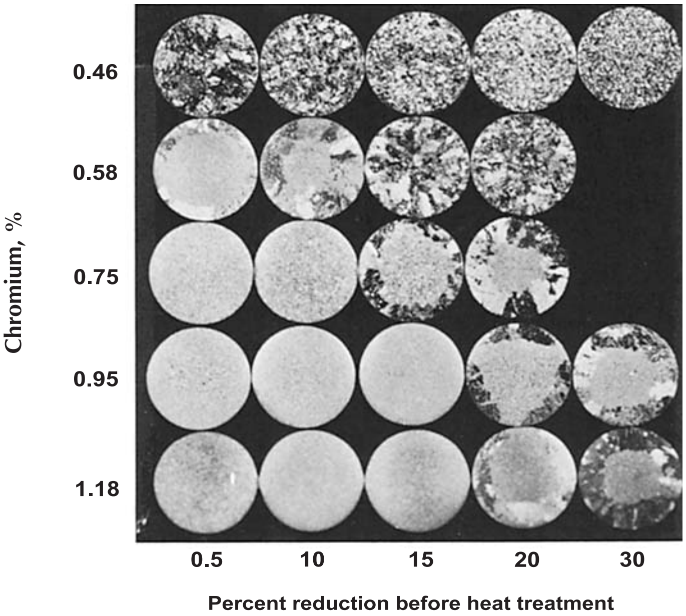

Fig. 22 Alloy C18200 (chromium copper, 0.8% Cr), solutionized 5 min at 1010 °C (1850 °F). Solutionizing increases solubility of chromium, which gives higher hardness after quenching and aging. However, if all chromium goes into solid solution, uncontrolled grain growth results, starting where there is the most cold work before heat treatment (right). Excessive grain growth embrittles grain boundaries; temperature, chromium content, cold work, and time at temperature must be controlled to prevent complete solution of chromium and uncontrolled grain growth. 0.45×. (T. Cobb)

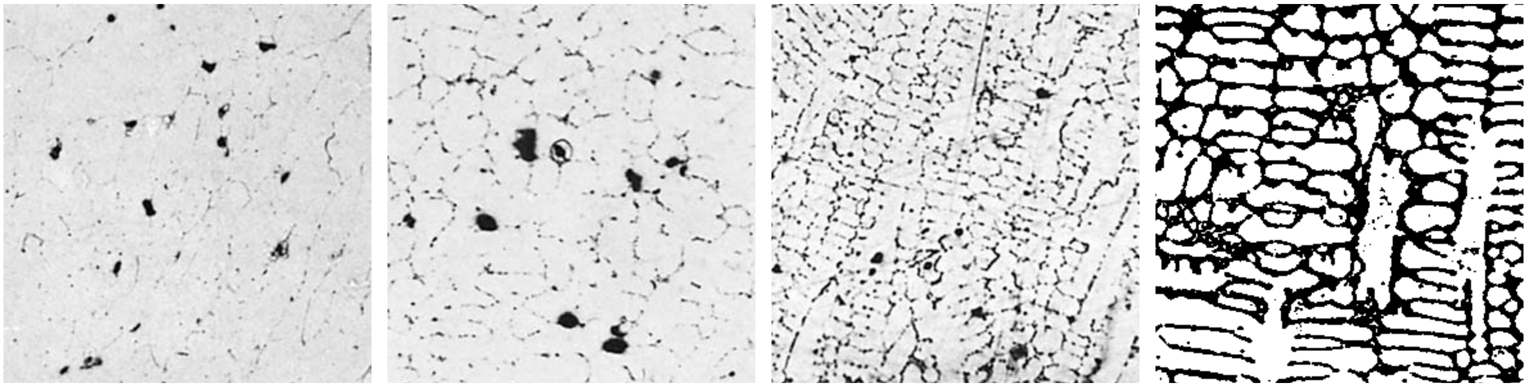

Fig. 23, 24, 25, 26 The effect of oxygen content on the microstructure of as-cast, copper-oxygen alloys. Oxygen contents less than 0.39% result in primary dendrites of copper (light) plus eutectic (mottled areas of small, round oxide in copper). Fig. 23: 0.024% O. Fig. 24: 0.05% O. Fig. 25: 0.09% O. Fig. 26: 0.18% O. As-polished. 100×

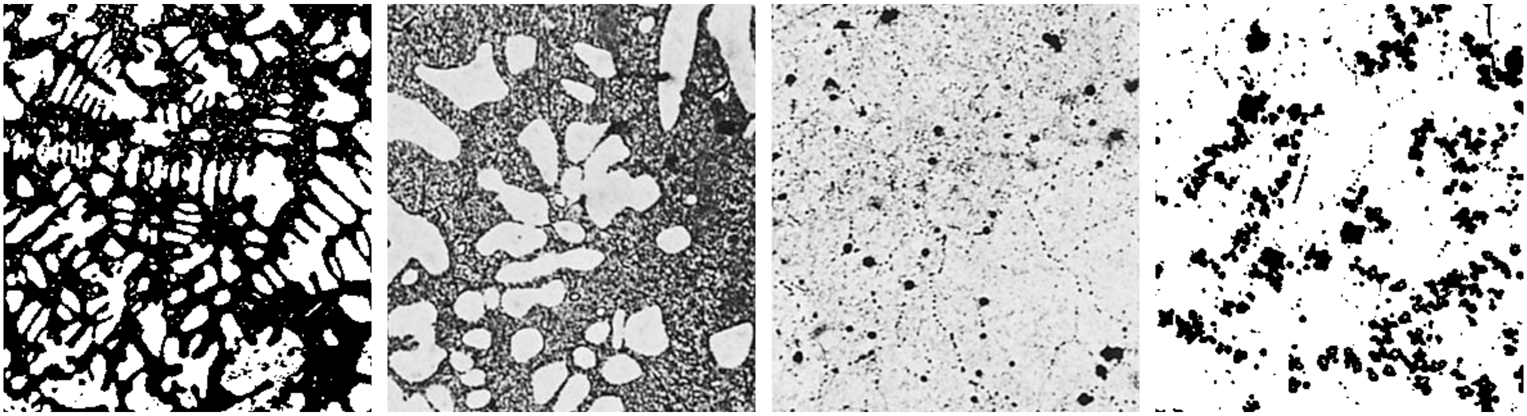

Fig. 27, 28, 29, 30 Same as Fig. 23 to 26. Fig. 27: 0.23% O. Fig. 28: 0.32% O. Figures 29 and 30, containing more than 0.39% O, have structures consisting of particles or dendrites of oxide (dark) and eutectic. Fig. 29: 0.44% O. Fig. 30: 0.50% O. As-polished. 100×

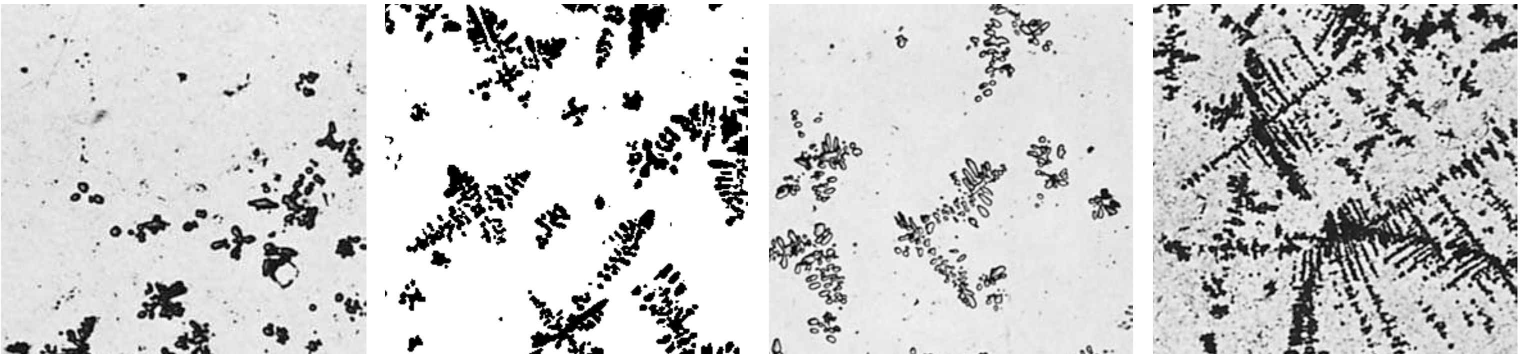

Fig. 31, 32, 33, 34 Same as Fig. 23 to 26, with dark oxide dendrites in a eutectic matrix. Fig. 31: 0.60% O. Fig. 32: 0.70% O. Fig. 33: 0.78% O. Fig. 34: 0.91% O. As-polished. 100×

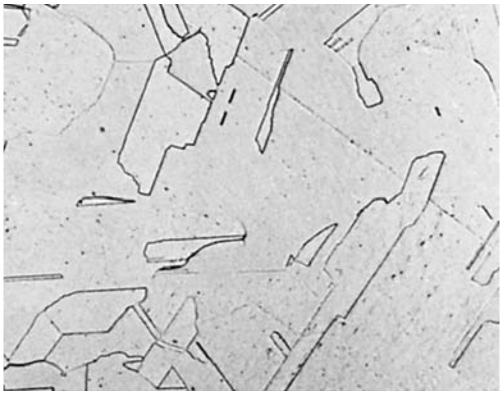

Fig. 35 Copper C10200 (OF copper), hot-rolled bar. Large, equiaxed, twinned grains. Etchant 1, Table 3. 100×

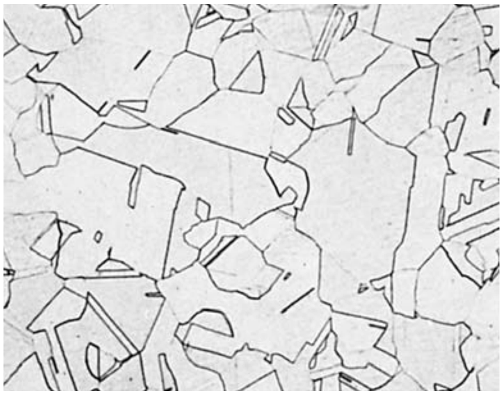

Fig. 36 Same as Fig. 35, cold worked, annealed 30 min at 850 °C (1560 °F). Equiaxed, recrystallized grains, containing twinned areas. Etchant 4, Table 3. 250×

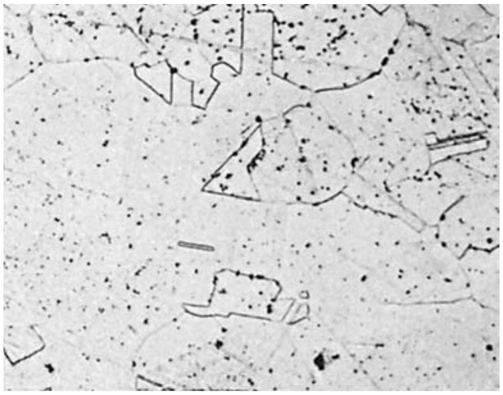

Fig. 37 Same as Fig. 35, hot-rolled bar, heated 1 h in air to 665 °C (1225 °F). Specimen from near surface shows Cu_2O (dark dots) caused by oxygen penetration during heating. Etchant 1, Table 3. 250×

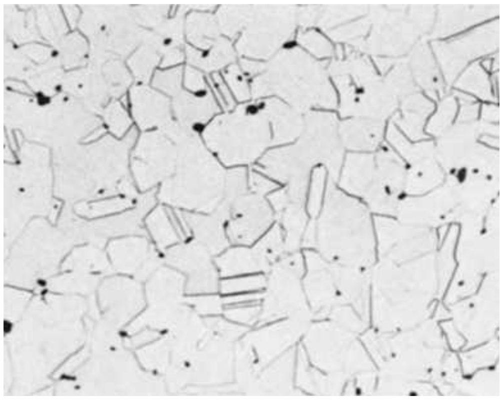

Fig. 38 Copper C11000 (ETP copper) hot-rolled rod. Transverse section shows equiaxed grains and dispersion of Cu_2O particles. Etchant 4, Table 3. 250×

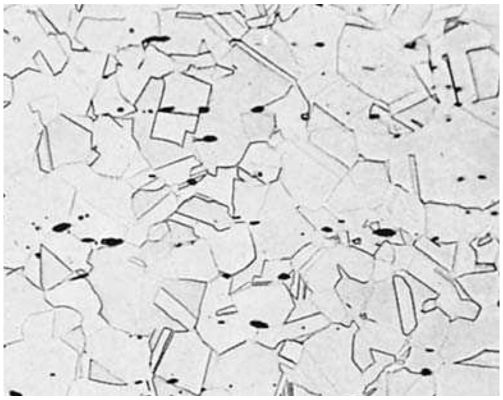

Fig. 39 Same as Fig. 38. Longitudinal section shows equiaxed grains and well-dispersed, slightly elongated Cu_2O particles (dark dots). Etchant 4, Table 3. 250×

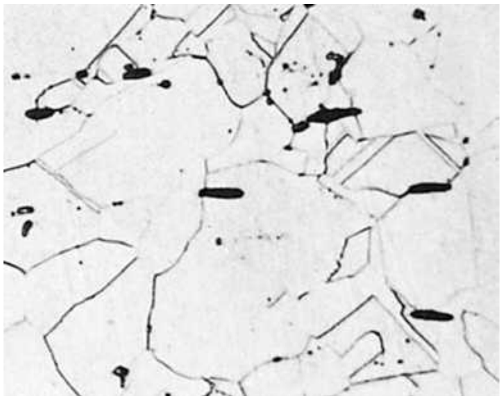

Fig. 40 Same as Fig. 38, extruded rod. Longitudinal section showing equiaxed grains and dispersed Cu_2O (dark dots). Etchant 4, Table 3. 400×

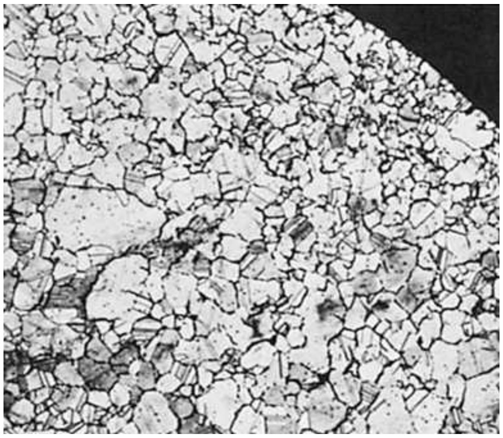

Fig. 41 Same as Fig. 38, heated in hydrogen. Hydrogen diffused into the copper, reacted with Cu_2O at the grain boundaries, formed steam, and forced the copper grains apart, causing embrittlement and porosity. See also Fig. 42. Etchant 4, Table 3. 75×

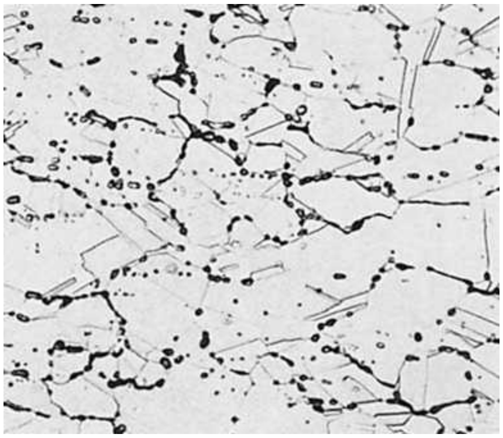

Fig. 42 Same as Fig. 38, heated to 850 °C (1560 °F) in an atmosphere containing hydrogen. Structure shows same voids as Fig. 41. Etchant 4, Table 3. 250×

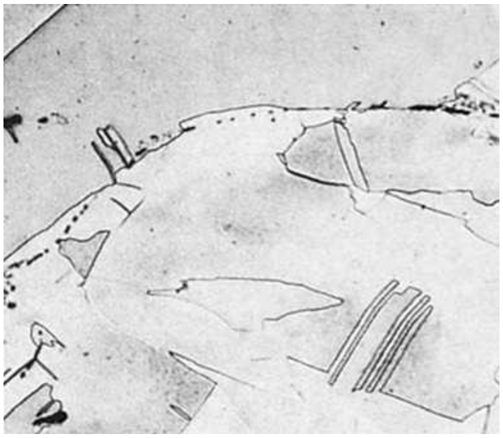

Fig. 43 Copper C12500 (FRTP copper) hot-rolled strip 12.7 mm (0.5 in.) thick. Structure consists of twinned grains of copper, with stringers of Cu_2O particles resulting from segregation of the oxide in the ingot during casting. Etchant 1, Table 3. 200×

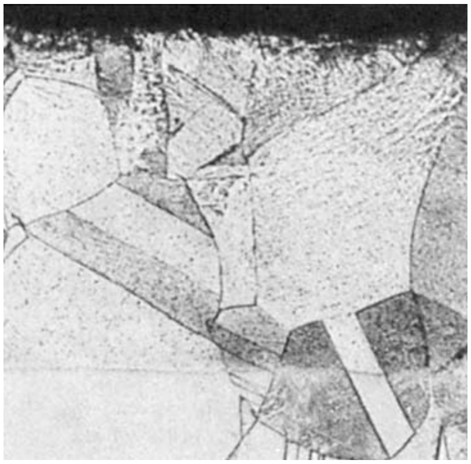

Fig. 44 Copper C12200 (DHP copper). Internal oxidation (presence of dark dots of P_2O_5). Etchant 4, Table 3. 75×

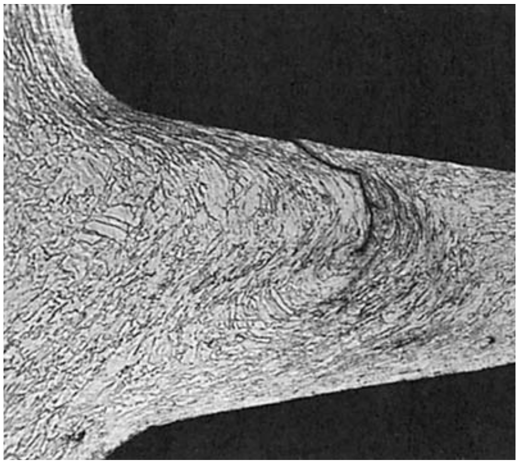

Fig. 45 Same metal as Fig. 44. Lap defect in the fin of a condenser tube. Lap was caused by tool misalignment during the rolling of fins in the tube. Etchant 4, Table 3. 75×

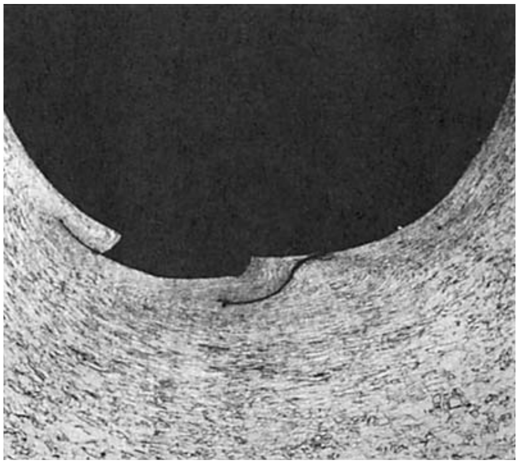

Fig. 46 Same as Fig. 45. Lap defect between fins of a condenser tube, caused by tool misalignment during fin rolling. Etchant 4, Table 3. 75×

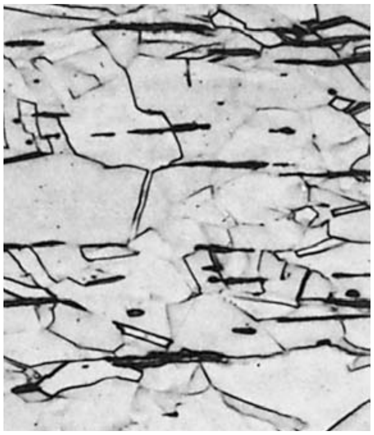

Fig. 47 Copper C14520 (DPTE copper) hot-rolled and drawn rod. Dark particles elongated in the rolling direction are copper telluride, which improves machinability. Etchant, 7, Table 1. 250×

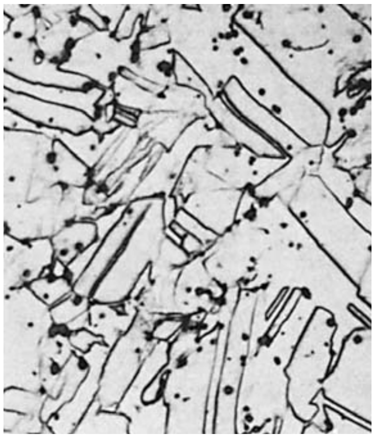

Fig. 48 Copper C14700 (sulfur-bearing copper) rod, cold worked to 50% reduction. Transverse section shows dispersion of round particles of CuS, which improves machinability. Etchant 7, Table 1. 200×

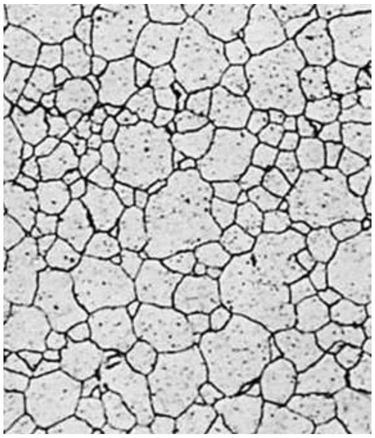

Fig. 49 Alloy C17200 (beryllium copper), solution treated 10 min at 790 °C (1450 °F) and water quenched. Typical hardness is 62 HRB. Structure is equiaxed grains of supersaturated solid solution of beryllium in copper. Etchant 3, Table 3. 300×

Fig. 50 Same alloy and processing as Fig. 49, but aged 3 h at 360 °C (600 °F) after solution treatment. Typical hardness is 37 HRC. Copper-beryllium precipitate at grain boundaries and within α grains. Etchant 3, Table 3. 300×

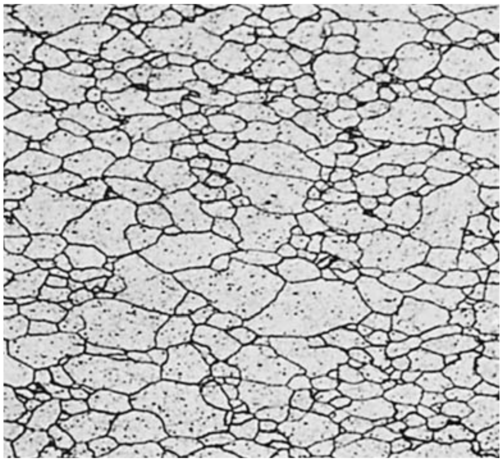

Fig. 51 Same alloy and processing as Fig. 49, except reduced 11% by cold rolling to quarter-hard temper. Typical hardness is 79 HRB. Alpha grains are elongated in the direction of rolling. Etchant 3, Table 3. 300×

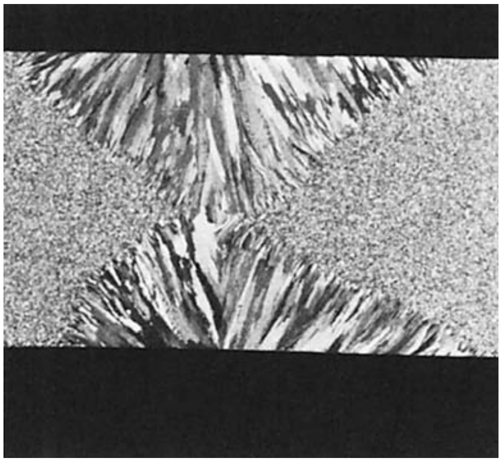

Fig. 52 Copper C11000 (ETP copper) cold-rolled bar, annealed approximately 1 h by holding at 375 °C (705 °F), then tungsten arc welded in two passes using straight-polarity direction current and copper 11000 filler metal. See Fig. 53 for structure details at the fusion zone edge. Etchant 1, Table 3. 2×

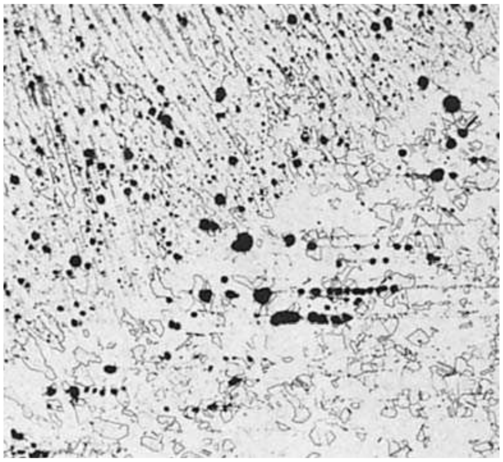

Fig. 53 Edge of fusion zone of weld in Fig. 52. Gas porosity (dark areas) in fusion zone (upper left) and in the heat-affected zone (bottom right). Etchant 1, Table 3. 25×

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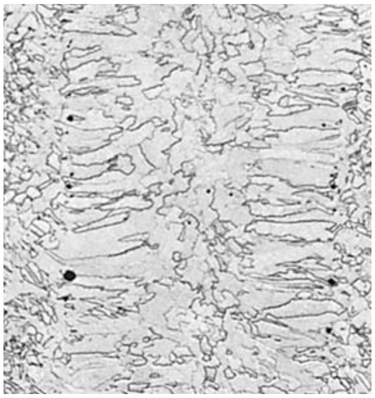

Fig. 54 Copper C10100 (OFE copper) bar, electron beam welded without filler metal. Columnar grains in fusion zone (middle) and original equiaxed grains in base metal. The scattered black dots along the edge of the fusion zone are gas porosity. Etchant 2, Table 3. 35×

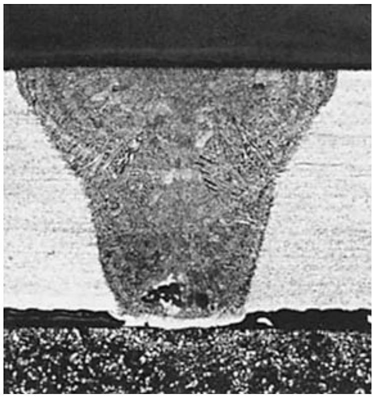

Fig. 55 Alloy C70600 (copper-nickel, 10% Ni), 2.3 mm (0.090 in.) thick. Laser welded to 1020 steel base. Weld made with 2.0 kW of laser input energy at travel speed of 17 to 25.4 mm/s (40 to 60 in./min). No melting of the steel base occurred. Etchant 21, Table 3. 15×

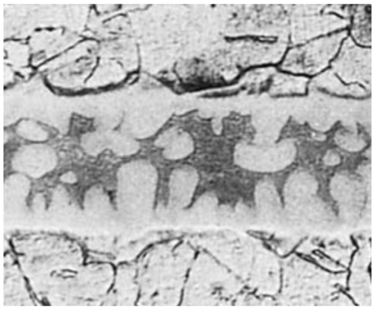

Fig. 56 Copper C10100 (OFE copper) brazed with BCuP-5 filler metal. Silver-copper-phosphorus eutectic (mottled gray) in the joint, with large dendrites of copper solid solution (light gray) extending into the joint from the grains of unalloyed base metal. Grains of unalloyed copper in the base metal are medium size. Compare with Fig. 53. Etchant 5, Table 3. 125×

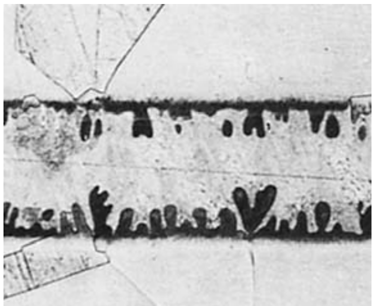

Fig. 57 Same as Fig. 56, brazed with BAg-8a filler metal. Silver-copper eutectic (mottled gray) in the joint, with small dendrites of copper solid solution (dark) extending into the joint from the unalloyed base metal. Grains of unalloyed copper in the base metal are extremely large. Etchant 5, Table 3. 70×

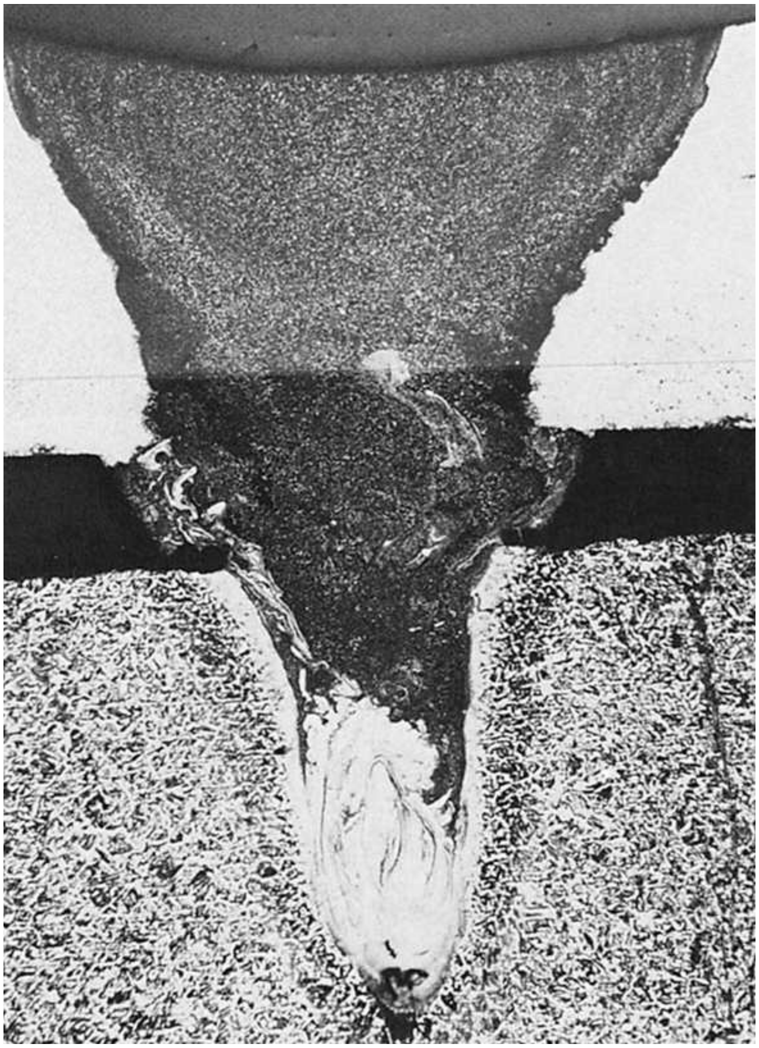

Fig. 58 Same alloy as Fig. 55, except 2.5 mm (0.1 in.) thick. Alloy laser welded to 1020 steel, with a 0.8 mm (0.03 in.) gap between pieces. Laser input energy was 5 kW; travel speed, 17 mm/s (40 in./min). Etchant 21, Table 3. 20×

Fig. 59 Brazed joint between tubes of copper C12200 (DHP copper). Filler metal was BAg-1. See Fig. 61 for details of structure. Etchant 4, Table 3. 75×

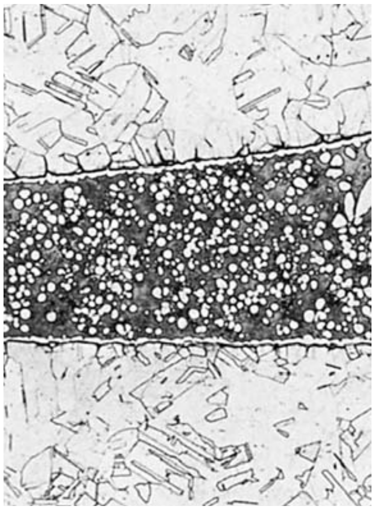

Fig. 60 Brazed joint between tubes of copper C12200. Filler metal was BCuP-5. See Fig. 62 for details of structure. Etchant 4, Table 3. 100×

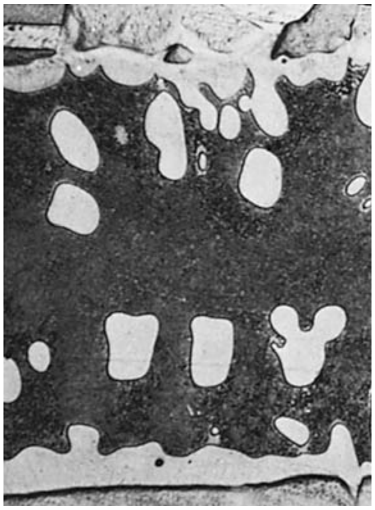

Fig. 61 Brazed joint in Fig. 59, except at higher magnification. Filler metal (middle) has copper-rich dendrites in a matrix of silver-copper-zinc-cadmium eutectic (dark gray, mottled). Etchant 4, Table 3. 540×

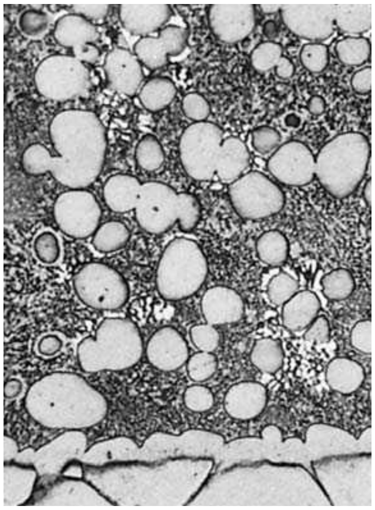

Fig. 62 Brazed joint in Fig. 60, except at a higher magnification. Filler metal (top) has copper-rich dendrites (light gray) in a matrix of silver-copper-phosphorus. Base metal is at the bottom. Etchant 4, Table 3. 540×

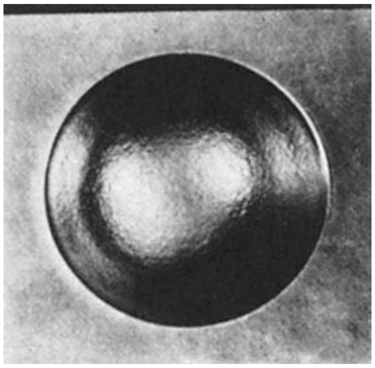

Fig. 63 Alloy C26000 (cartridge brass) drawn cup, showing "orange peel" (rough surface). See Fig. 65 for grain structure. Etchant 1, Table 3. Actual size

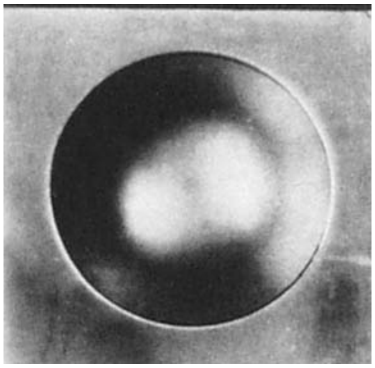

Fig. 64 Same as Fig. 63, with a smooth surface. See Fig. 66 for structural details. Etchant 1, Table 3. Actual size

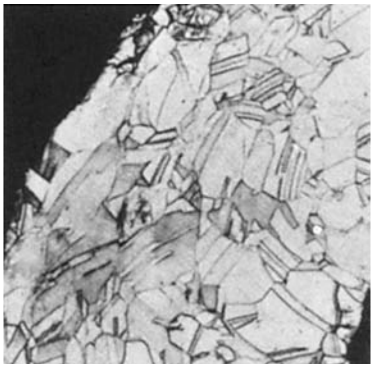

Fig. 65 Grain structure of drawn cup in Fig. 63. The rough surface of the cup was caused by the large grain size. Etchant 1, Table 3. 85×

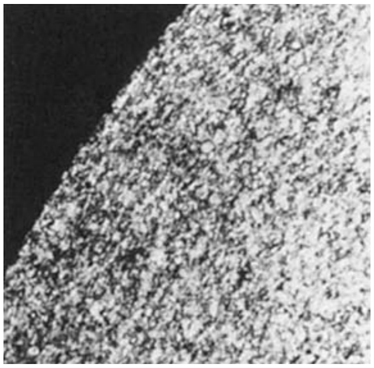

Fig. 66 Structure of the drawn cup in Fig. 64. Because grains are small, the cup has a smooth surface. Etchant 1, Table 3. 85×

Fig. 67 Copper C12200 drawn condenser tube, with a branched intergranular stress-corrosion crack starting at an outside surface. See Fig. 68 for details of a similar crack. Potassium dichromate. 100×

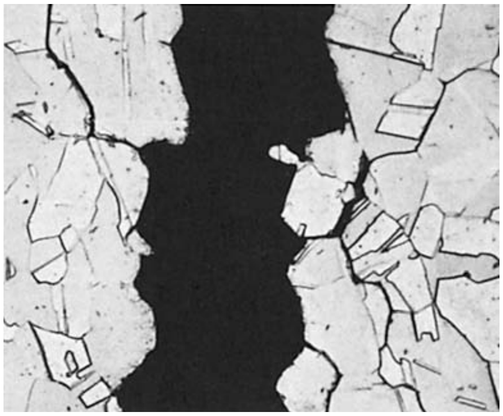

Fig. 68 Same material and processing as Fig. 67. An intergranular stress-corrosion crack, possibly caused by amine boiler-treatment compounds in boiler condensate. Potassium dichromate. 500×

Fig. 69 Alloy C26000 (cartridge brass) tube, drawn, annealed and cold-reduced 5%. Typical intergranular stress-corrosion crack, with some branching. $NH_4OH + H_2O_2$. 150×

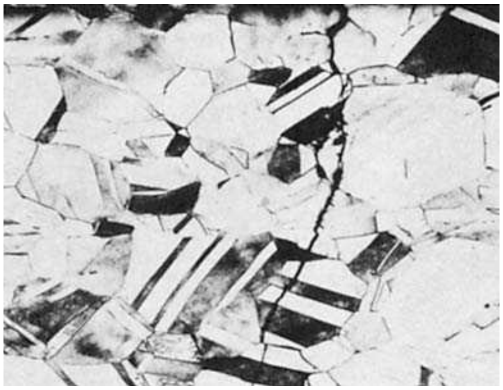

Fig. 70 Alloy C26000 (cartridge brass), showing a transgranular corrosion crack. Note the lack of branching in the inner (fatigue) section of the crack. Etchant 1, Table 3. 130×

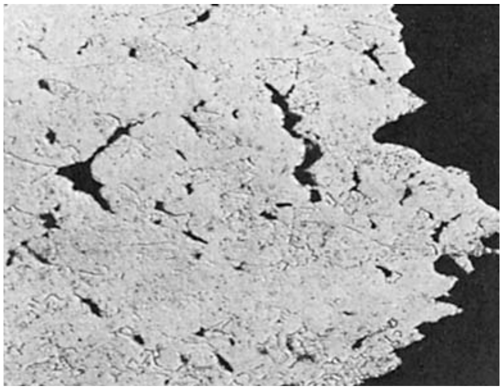

Fig. 71 Copper C11000 (ETP copper) 16 mm (0.625 in.) diam bar, tested at 350 °C (660 °F) at an extension rate of 0.03 mm/s (0.00114 in./s). W-type void formation. Etchant 1, Table 3. 160×

Fig. 72 Same material and processing as Fig. 71. Magnetized view showing a W-type crack. 645×

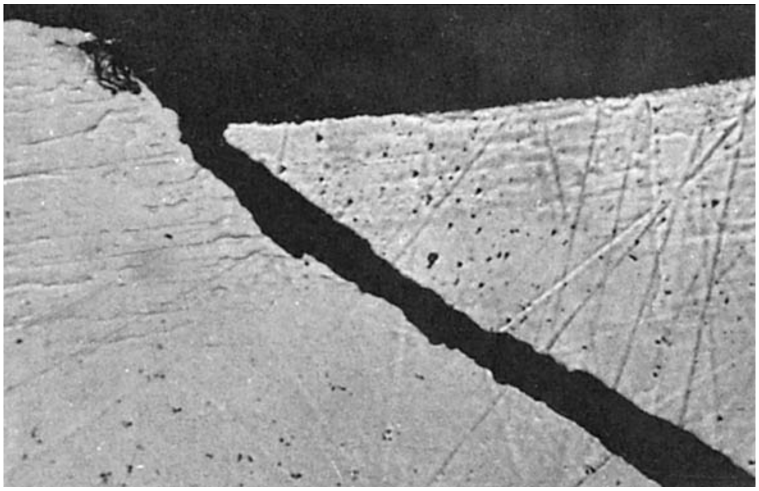

Fig. 73 Copper C10100 (OFE copper) 10 mm (0.375 in.) diam rod, rolled to 1.3 mm (0.052 in.) strip and annealed. Crack formed at the intersection of shearing grain boundary and the surface. The specimen was tested at 550 °C (1020 °F) with an extension rate of 0.03 mm/s (0.001 in./s). Etchant 1, Table 3. 910×

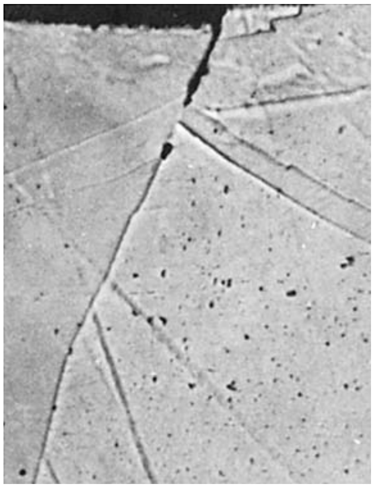

Fig. 74 Same as Fig 73. A small crack formed at the intersection of a grain boundary and the surface. Same testing conditions and etchant as Fig. 73. 1000×

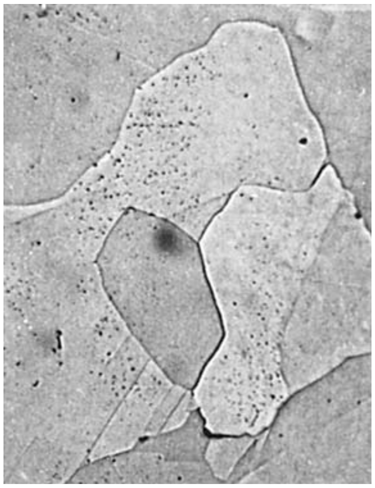

Fig. 75 Copper 10200 (OF copper) 6.3 mm (0.25 in.) diam rod. Microstructure after testing at 550 °C (1020 °F) with an extension rate of 0.03 mm/s (0.001 in./s). Etchant 1, Table 3. 800×

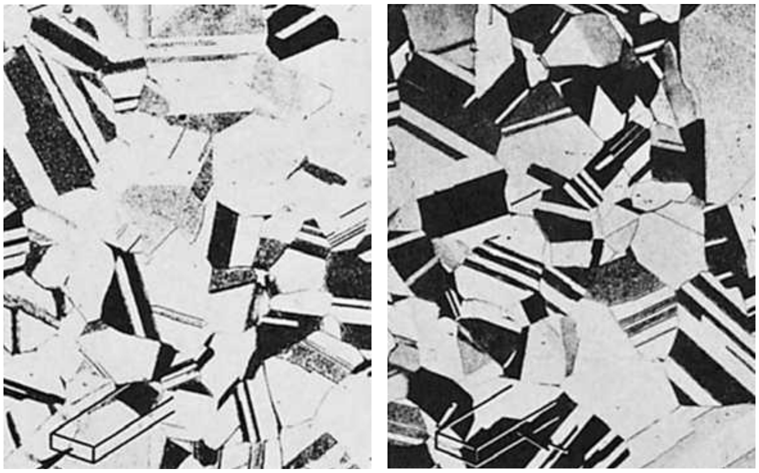

Fig. 76, 77 Alloy C26000 (cartridge brass) hot rolled to 10 mm (0.4 in.) thick, annealed to a grain size of 15 μm, cold rolled to 40% to 6 mm (0.24 in.) thick, and annealed to a grain size of 120 μm. Diagram in lower left corner of each micrograph indicates the view relative to the rolling plane of the sheet. Nominal tensile strength of 296 MPa (43000 psi). Etchant 1, Table 3. 75×

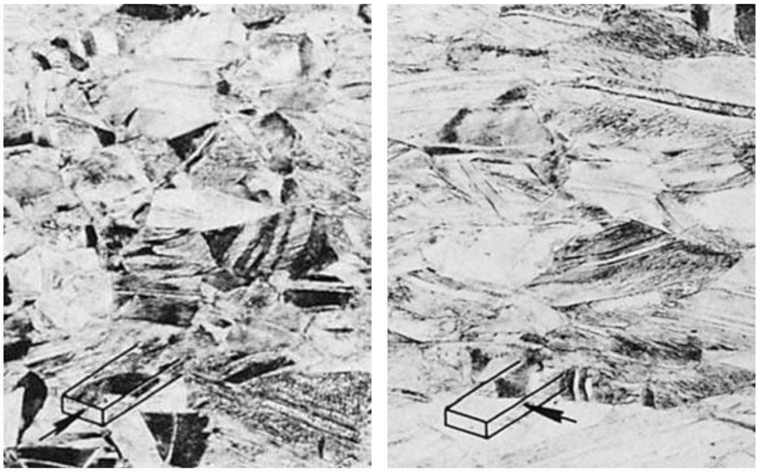

Fig. 78, 79 Same alloy and processing as Fig. 76 and 77, except reduced by cold rolling from 6 mm (0.24 in.) to 4 mm (0.15 in.) thick. Hard temper; nominal tensile strength of 524 MPa (76,000 psi). Etchant 1, Table 3. 75×

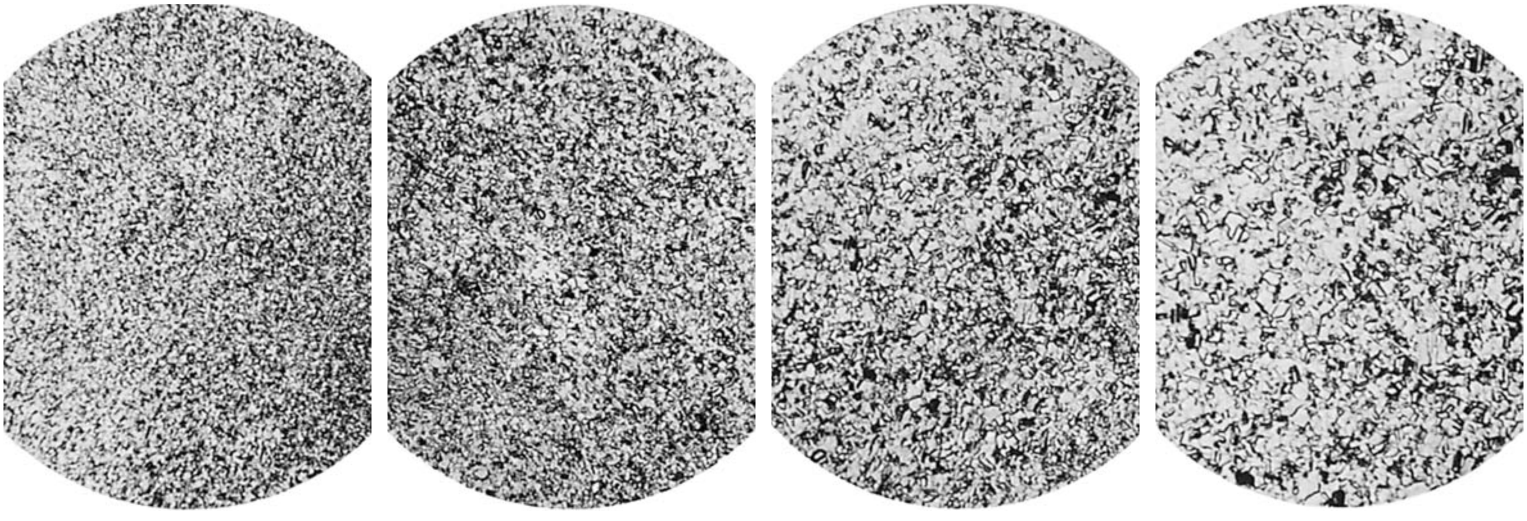

Fig. 80, 81, 82, 83 Alloy C26000 (cartridge brass), processed to obtain various grain sizes. Preliminary processing: hot rolled, annealed, cold rolled, annealed to a grain size of 25 μm, cold rolled to 70% reduction. Final anneal temperature gives difference in grain sizes. Fig. 80: grain size is 5 μm; final annealed at 330 °C (625 °F). Fig. 81: grain size is 10 μm; final annealed at 370 °C (700 °F). Fig. 82: grain size is 15 μm; final annealed at 405 °C (760 °F). Fig. 83: grain size is 20 μm; final annealed at 425 °C (800 °F). Etchant 1, Table 3. 75×

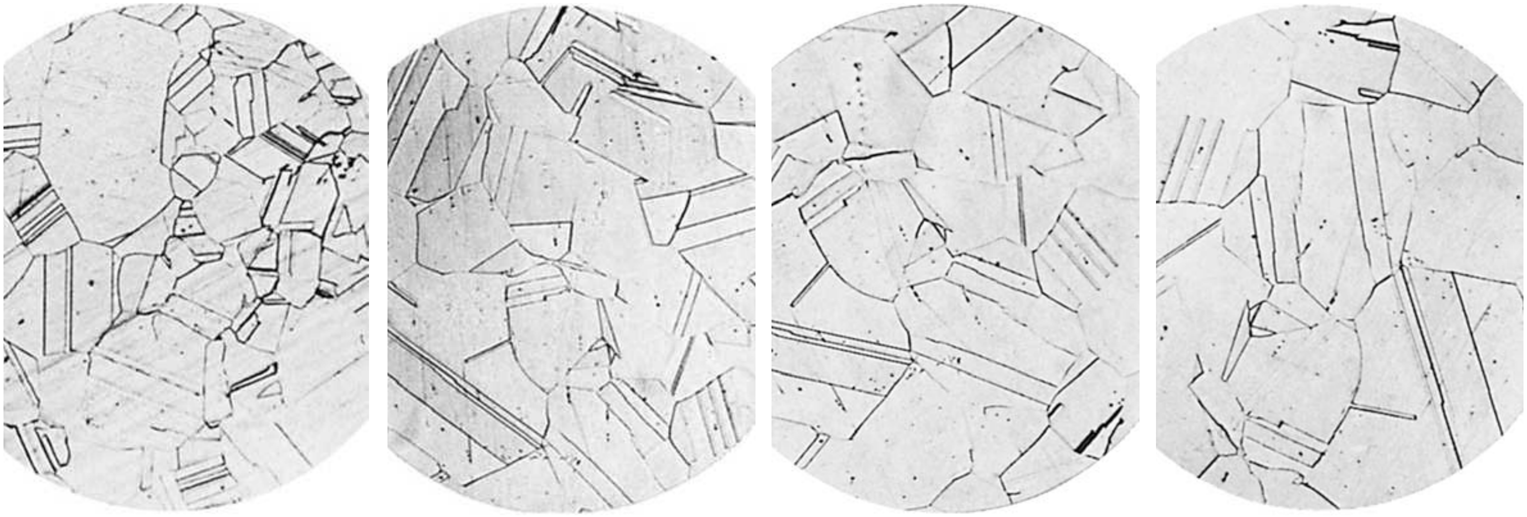

Fig. 84, 85, 86, 87 Same as Fig. 80 to 83. Fig. 84: grain size is 125 μm; final annealed at 640 °C (1180 °F). Fig. 85: grain size is 150 μm; final annealed at 665 °C (1225 °F). Fig. 86: grain size is 175 μm; final annealed at 680 °C (1260 °F). Fig. 87: grain size is 200 μm; final annealed at 705 °C (1300 °F). Etchant 1, Table 3. 75×

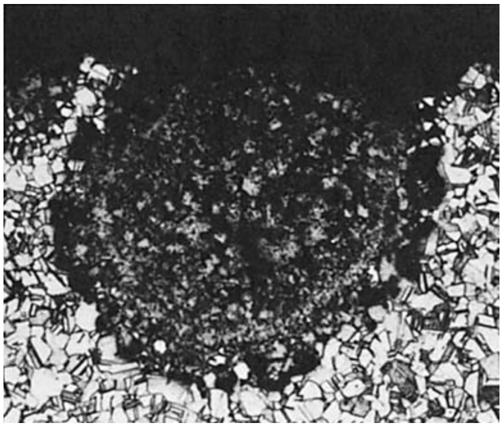

Fig. 88 Same alloy as Fig. 80 to 87. Local (plug-type) dezincification (dark, at specimen surface) consists of a spongy mass of copper that resulted from the selective removal of zinc. Etchant 1, Table 3. 150×

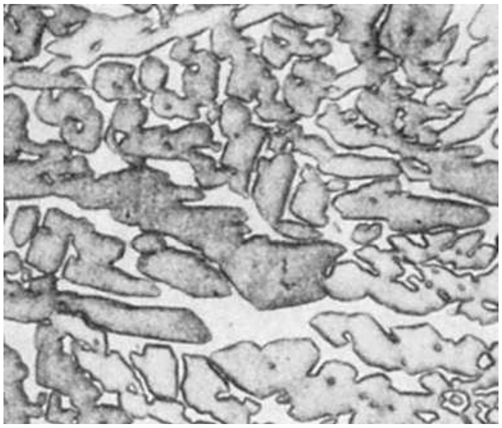

Fig. 89 Alloy C28000 (Muntz metal) ingot, as-cast. Structure is dendrites of α phase in a matrix of β phase. Etchant 1, Table 3. 210×

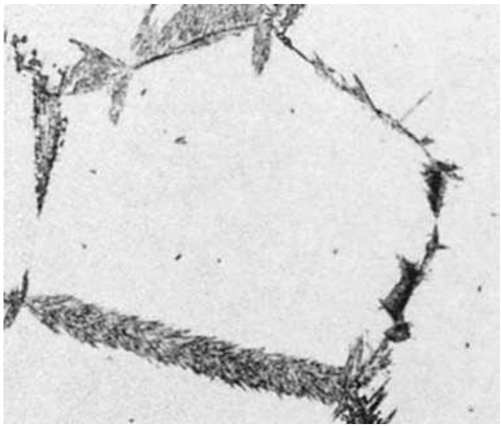

Fig. 90 Same as Fig. 89, showing α feathers that formed at β grain boundaries during quenching of the all-β structure. Etchant 1, Table 3. 105×

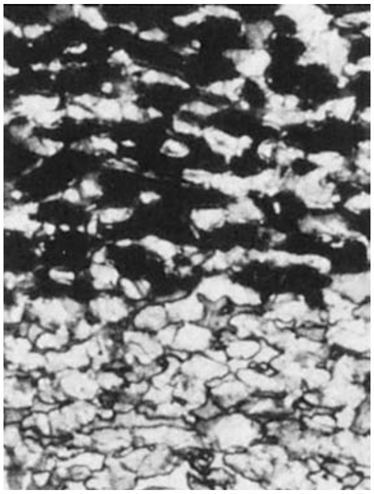

Fig. 91 Same as Fig. 89, hot-rolled plate. Uniform (layer) dezincification. Alpha grains remain in the corroded area (top). Etchant 1, Table 3. 90×

Fig. 92 Cu-27.5Zn-1.0Sn alloy tube. Stress-corrosion crack through the wall of the tube, probably caused by mercury or ammonia. Etchant 1, Table 3. 100×

Fig. 93 Alloy C44300 (arsenical admiralty) tube, drawn, stress relieved, and bent 180°. Transgranular stress-corrosion crack. Etchant 1, Table 3. 200×

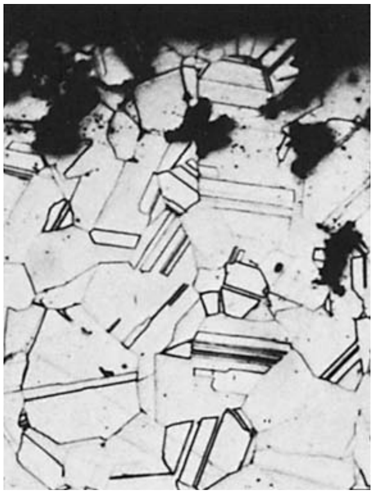

Fig. 94 Same alloy as Fig. 90, drawn and annealed tube. Uniform dezincification, with α grains in the corroded area (dark at the surface). Etchant 1, Table 3. 250×

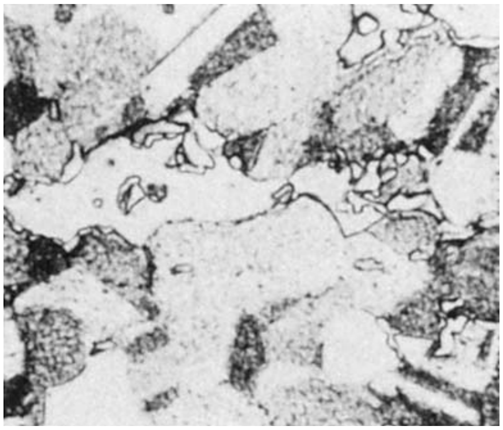

Fig. 95 Alloy C67500 (manganese bronze A) extruded rod. Iron-rich phase (light, outlined) within β phase (smooth etching) and between α and β phases. Etchant 1, Table 3. 875×

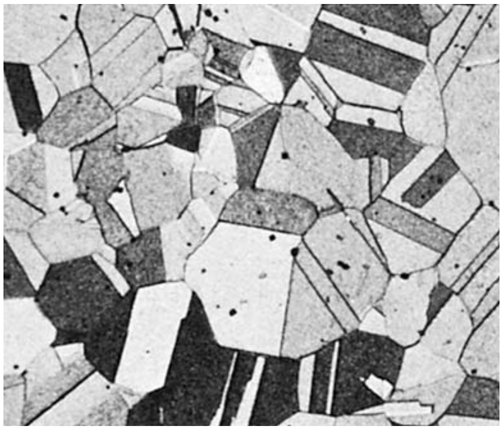

Fig. 96 Alloy C51000 (phosphor bronze, 5% A) rod, extruded, cold drawn, and annealed 30 min at 565 °C (1050 °F). Structure consists of recrystallized α grains with annealing twins. Etchant 4, Table 3. 500×

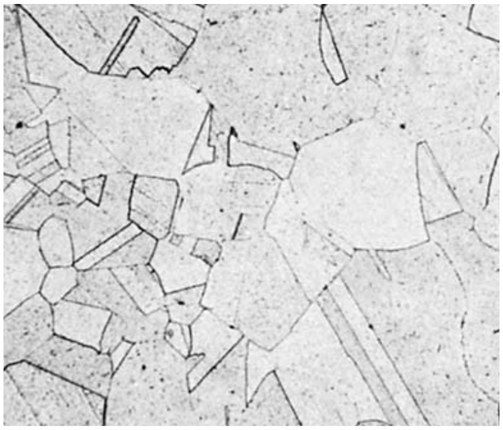

Fig. 97 Alloy C64700 (silicon-nickel bronze), aged 2 h at 480 °C (900 °F) after solution treatment. Alpha grains appear hazy because of unresolved nickel-silicon precipitate. Etchant 4, Table 3. 200×

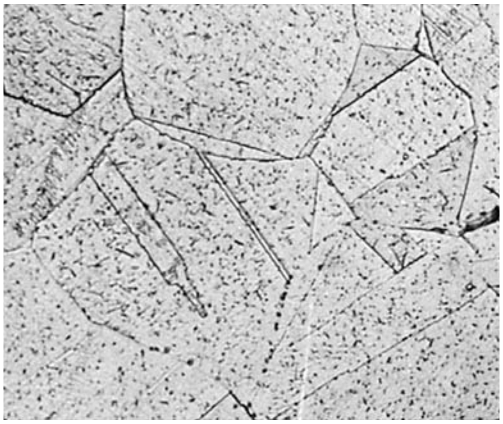

Fig. 98 Same as Fig. 97, but at a higher magnification to reveal nickel-silicon precipitate at grain boundaries and within grains. Etchant 4, Table 3. 500×

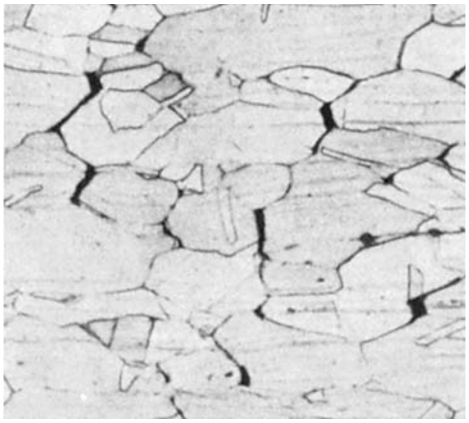

Fig. 99 Alloy C70600 (copper-nickel, 10% Ni), showing the grain-boundary cracks (dark areas) typical of stress-rupture failure. Etchant 4, Table 3. 300×

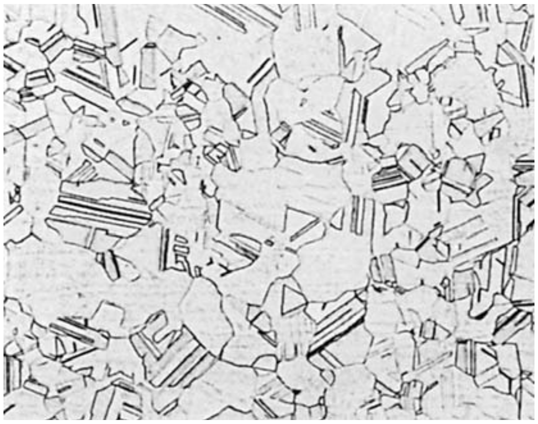

Fig. 100 Alloy C74500 (nickel silver, 65-10) cold-rolled sheet, 2.5 mm (0.10 in.) thick, annealed at 650 to 700 °C (1200 to 1290 °F). Longitudinal section shows equiaxed crystallized grains of α solid solution containing twin bonds. Etchant 20, Table 3. 100×

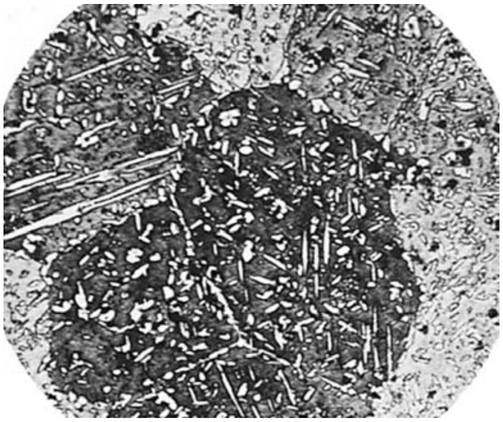

Fig. 101 Alloy C86200 (64Cu-26Zn-3Fe-4Al-3Mn manganese bronze) as sand cast. Small needles of α solid solution in a matrix of β phase (various shades of gray). Black dots of iron-rich phase are well dispersed. Compare with Fig. 102. Etchant 1, then etchant 16, Table 3. 100×

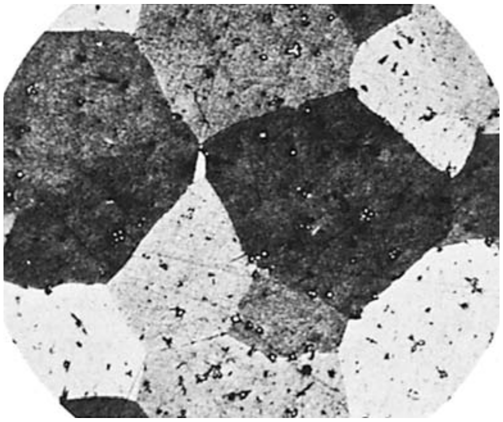

Fig. 102 Alloy C86300 (63Cu-25Zn-3Fe-6Al-3Mn manganese bronze), as sand cast. Essentially the same composition as alloy in Fig. 101, but higher minimum strength requirements. Constituents are the same as Fig. 101, except very little α solid solution is present. Same etchants as Fig. 101. 100×

Fig. 103 Dealuminized alloy C95400 (aluminum bronze), as sand cast. Voids (black) and matrix (medium gray) around α grains at top resulted from dealuminizing in salt water. Small, gray rosettes in grains are an aluminum-rich aluminum-nickel-iron phase. Alpha grains at the bottom are a matrix of eutectoid transformed β phase. Etchant 8, Table 3. 250×

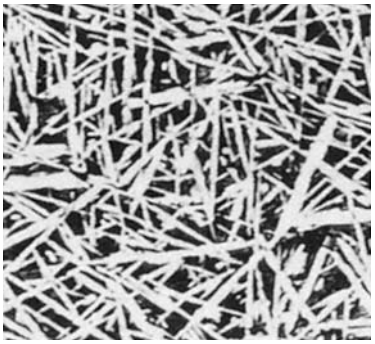

Fig. 104 Alloy C95400 (aluminum bronze), solution treated 2 h at 900 °C (1650 °F), water quenched, tempered 2 h at 650 °C (1200 °F), and water quenched. Alpha grains (white needles) are smaller than in the as-cast condition (Fig. 103). Etchant 4, Table 3. 200×

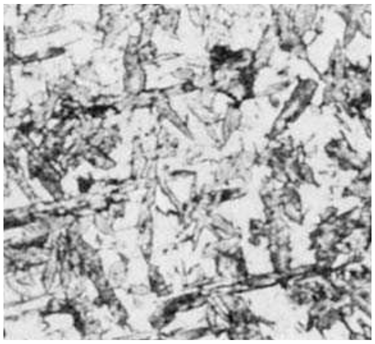

Fig. 105 Alloy C95500 (nickel-aluminum bronze, 11.5% Al) as sand cast. Small α grains (light gray, mottled) in matrix of retained β phase (white), with some eutectoid decomposed β phase (dark gray). Compare with Fig. 106. Electrolytically etched in electrolyte 5, Table 4. 250×

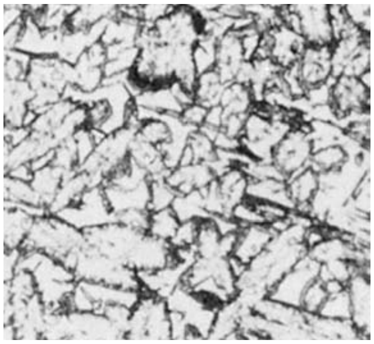

Fig. 106 Same alloy as Fig. 105, except 11.0% Al with larger α grains and a greater amount of eutectoid decomposed β phase in the matrix. Electrolytically etched in electrolyte 5, Table 4. 250×

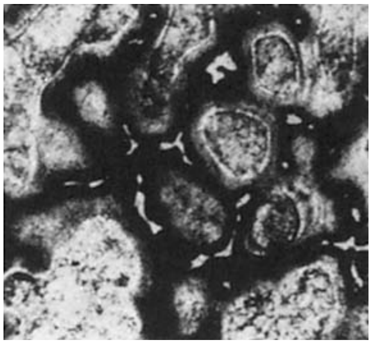

Fig. 107 Alloy C97800 (Cu-5Sn-2Pb-2Zn-25Ni), as sand cast. Structure is dendrites of α phase (variegated gray) showing coring and interdendritic copper-nickel-tin phase (light). Etchant 4, Table 3. 75×

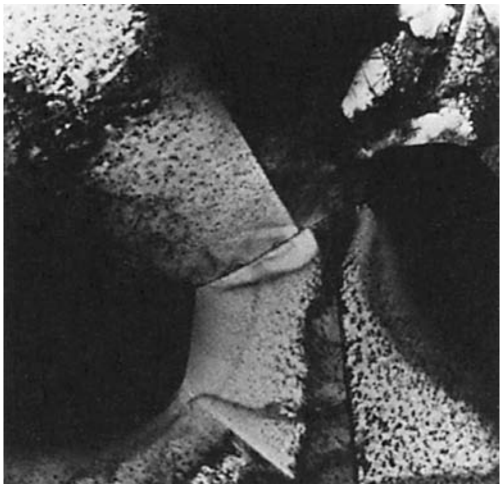

Fig. 108 Transmission electron micrograph of a rapidly solidified Cu-5Ni-2.5Ti alloy, hot extruded at 750 °C (1380 °F), solution heat treated 1 h at 950 °C (1740 °F); air cooled. Fine precipitate is $(Cu,Ni)_3Ti$. As-polished. 18,000×

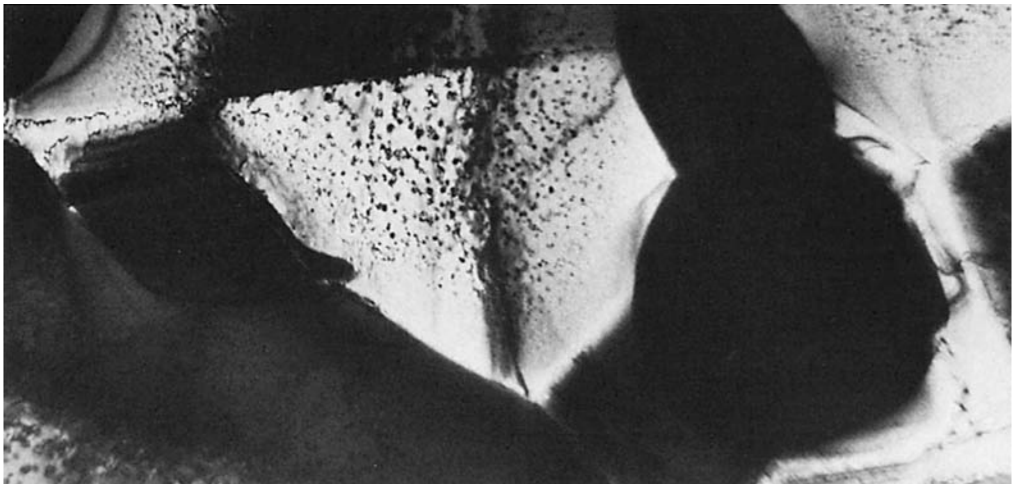

Fig. 109 Transmission electron micrograph of same alloy as in Fig. 108, solution heat treated at 950 °C (1740 °F) for 1 h and air cooled. Grain size is less than 2 μm. The structure is primary Ni_3Ti and a fine precipitate of $(Cu,Ni)_3Ti$. See also Fig. 108 and 110. As-polished. 28,000×

Fig. 110 Transmission electron micrograph of same alloy and processing as Fig. 109, but higher magnification shows the very fine (~0.25 μm) aging precipitate of $(Cu,Ni)_3Ti$. See also Fig. 108 and 109. As-polished. 75,200×

Fig. 111 Transmission electron micrograph of a copper-zirconium (0.57Zr, with $0.31ZrO_2$) powder metallurgy product, as hot extruded. The relatively coarse dark particles are Cu_5Zr precipitates; the finer dark particles are probably ZrO_2. As-polished. 24,480×. (N. Grant)

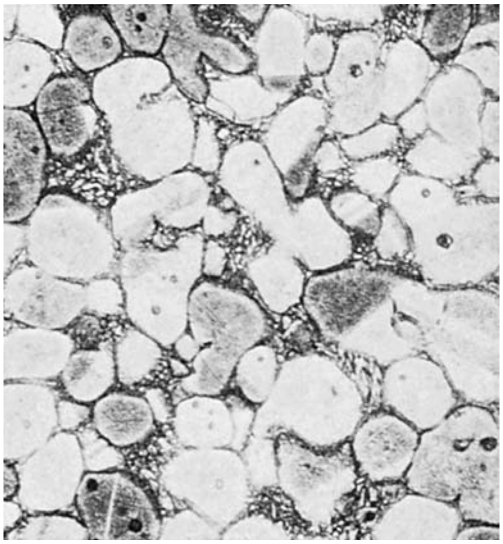

Fig. 112 Alloy 36000 (free-cutting brass) semisolid processed plumbing fitting. The large particles (white, light gray) are solid that was present before casting; the matrix was rapidly solidified to produce the structure shown. $NH_4OH + H_2O_2 + H_2O$. 310×. (K.P. Young)

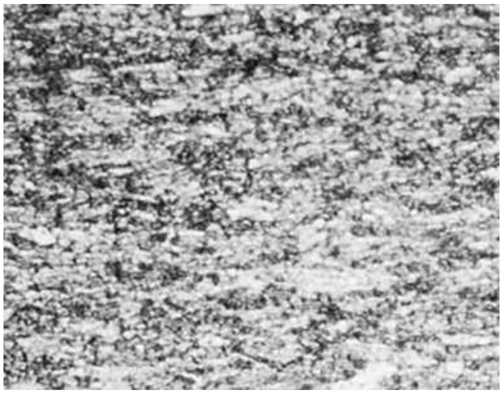

Fig. 113 Temper: spring (H08). Elongated, cold-worked, fine-grained structure

Fig. 114 Temper: extra hard (H06). Elongated, cold-worked, fine-grained structure

Fig. 115 Temper: hard (H04). Elongated, cold-worked, fine-grained structure

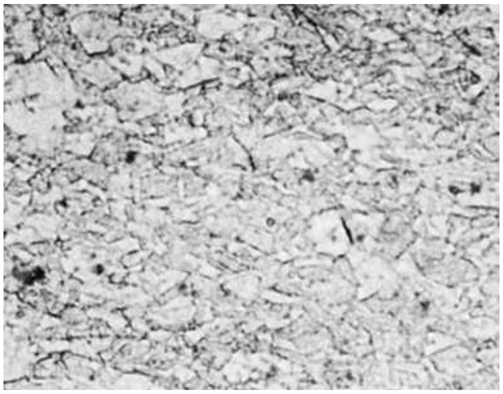

Fig. 116 Temper: half hard (H02). Moderately cold-worked, fine-grained structure

Fig. 117 Temper: quarter hard (H01). Slightly cold-worked, fine-grained structure

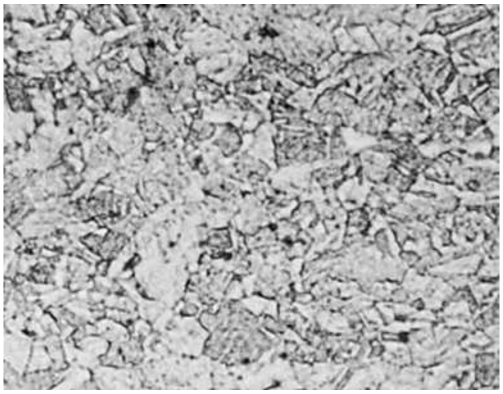

Fig. 118 Temper: annealed (O61). Fine-grained, annealed structure

Fig. 113 to 118 Longitudinal sections of rolled C69000 alloy electrical contact (outlet) material. Processing history: Fig. 113 to 117, rolled to temper; Fig. 118, annealed to temper. Metallographic technique: diamond polish (0.25 μm). Etchant: 85% $NH_4OH + H_2O$ (equal parts), 15% H_2O_2. 1000×. (P. Basalyk, G. Grosse)

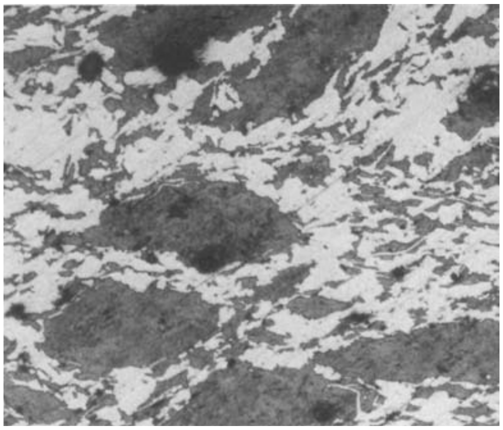

Fig. 119 80Cu-20graphite motor brush pressed from powder and sintered. Dark areas are graphite; light areas are copper. As-polished. 100× (W.H. Rowley, Jr.)

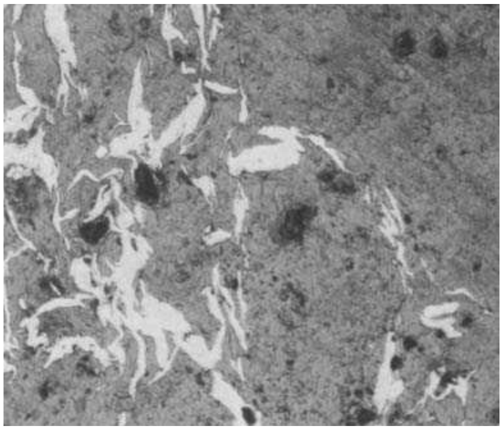

Fig. 120 40Cu-60graphite motor brush pressed from powder and sintered. Gray graphite matrix, light areas are copper, black spots are voids. As-polished. 100× (W.H. Rowley, Jr.)

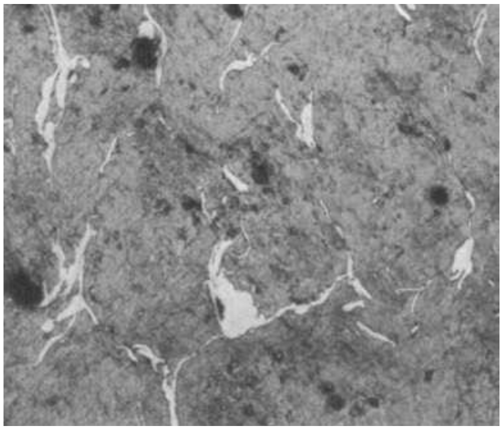

Fig. 121 30Cu-70graphite motor brush pressed from powder and sintered. Gray graphite matrix, light areas are copper, black spots are voids. As-polished. 100× (W.H. Rowley, Jr.)

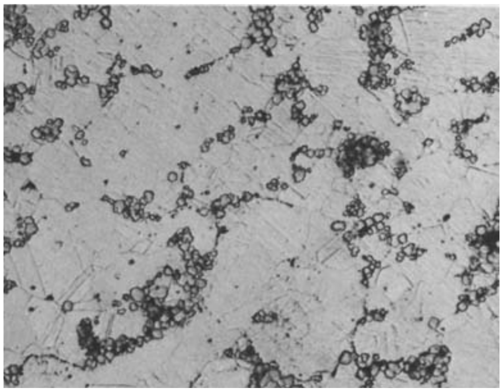

Fig. 122 75Cu-25W, pressed, sintered, and coined; annealed at 980 °C (1800 °F). Tungsten particles (gray) in copper matrix; some porosity (black). Compact was polished with Al_2O_3 slurry in $K_3Fe(CN)_6$ + NaOH, then etched in $NH_4OH + H_2O_2$. 400×

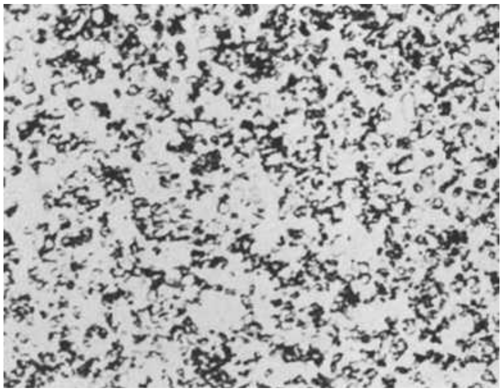

Fig. 123 75Cu-25W disk, produced as a tungsten powder compact infiltrated with copper. The microstructure consists of particles of tungsten (dark constituent) in a matrix of copper (light). Compare with Fig. 124. 1:1 $K_3Fe(CN)_6$ + 10% NaOH. 500×

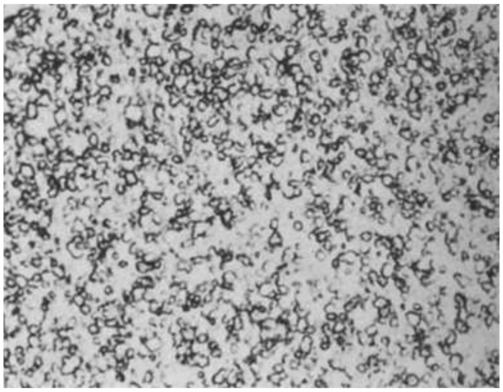

Fig. 124 75Cu-25W powder metallurgy disk, pressed and sintered (not infiltrated). The microstructure consists of particles of tungsten (dark-etching constituent) in a matrix of copper (light). Compare with Fig. 123. 1:1 30% $K_3Fe(CN)_6$ + 10% NaOH. 1000×

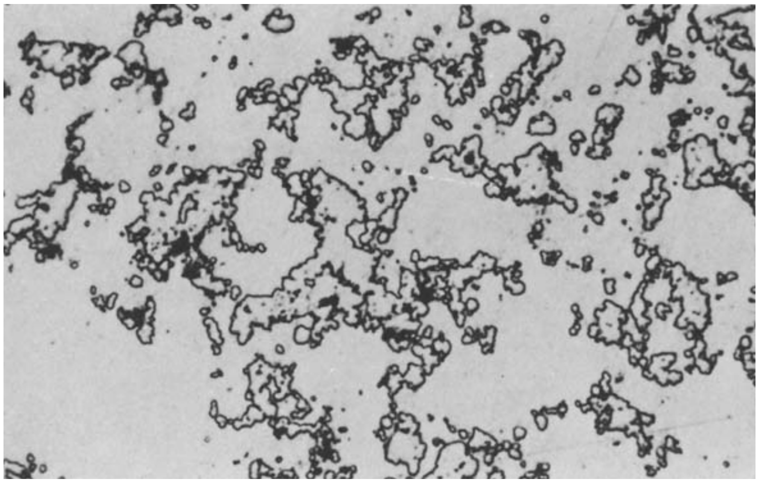

Fig. 125 70Cu-30W contact made by pressing and sintering a mixture of copper and tungsten powders. Structure: tungsten phase (gray areas) in a copper matrix. Black spots are voids. See also Fig. 126. As-polished. 250×

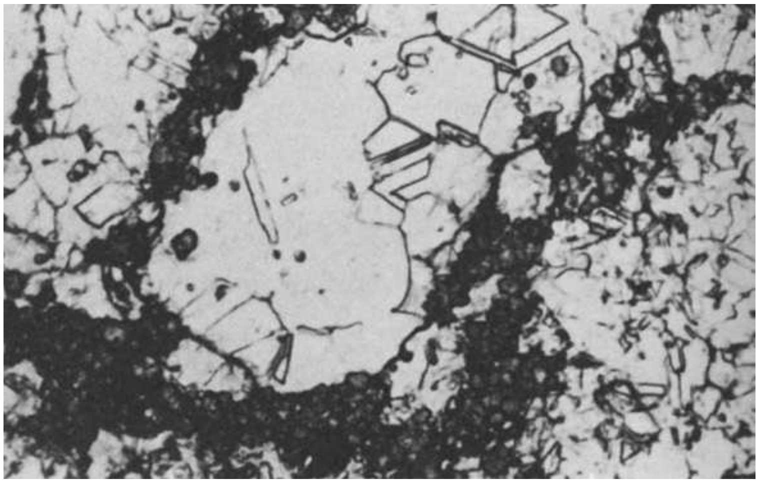

Fig. 126 Same as Fig. 125, except this specimen was etched and is shown at a higher magnification. Dark areas in the structure are the tungsten phase (with some voids); light areas, the copper matrix. $K_3Fe(CN)_6$ + NaOH, then NH_4OH + H_2O_2. 500×

Metallography and Microstructures of Beryllium-Copper Alloys

BERYLLIUM-COPPER ALLOYS are selected as representative metallographic specimens depending on product form. Edge and interior samples are important in castings, forgings, and hot- or cold-finished rod, bar, tube, and plate. Longitudinal and transverse sections, which should be examined in strip and wire, are equally important in heavy-section wrought products. Strip may also be examined by electropolishing and etching a small spot on the rolled surface, although this approach is generally not used by commercial suppliers. Care should be taken when examining components manufactured from these alloys to select sections that reveal the microstructural effects of the parts-fabrication process (stamping and forming, machining, plating) and the undisturbed structure of the raw material. Age hardening of these beryllium-containing alloys by the parts fabricator can produce distinct changes in matrix etching response, but does not alter the grain size or intermetallic-compound particle distribution that are characteristic of the mill production process. Components should be examined before and after fabricator heat treatment.

Health and Safety

Despite low concentrations of beryllium in commercial beryllium-copper alloys (nominally 2 wt% or less), these materials can be hazardous to health if excessive quantities of dust, mists, or fumes containing particles of alloy small enough to enter the lungs (typically 10 μm or less) are inhaled. Precautions are not required for metallographic sectioning, grinding, or polishing performed wet or for shearing of clean, thin-section strip or wire. Adequate ventilation should be provided for dry sectioning, grinding, or polishing operations that produce dust or fumes. Metallographic preparation equipment and laboratory work surfaces should be damp wiped periodically to remove accumulation of dry alloy particles. Beryllium-containing alloys are not harmful in contact with skin or wounds, or if swallowed. For additional information, see the article "Toxicity of Metals" in *Properties and Selection: Nonferrous Alloys and Special Purpose Materials,* Volume 2 of the *ASM Handbook.*

Specimen Preparation

Metallographic equipment and procedures for beryllium-containing alloys are much the same as those recommended for general metallurgical laboratory use.

Sectioning of specimens is carried out by sawing, abrasive cutting, or shearing, depending on section thickness and strength. Abrasive wheels formulated for nonferrous or medium-hardness materials and general-purpose use are satisfactory for beryllium copper. Abrasive cutting should be performed wet to avoid thermal damage to the specimen and to guard health and safety. Sufficient surface metal is then removed from the sectioned face of the specimen by wet rough grinding to eliminate any deformed material introduced during sectioning.

Mounting is usually required for specimens too small to be hand held while polishing or for those requiring edge preservation. Flat strip or transverse sections of small-diameter rod and wire may be stacked and gripped in reusable metal screw clamps for unembedded preparation. Alternatively, samples may be embedded with cold-mounting or compression-molding resins; commercial metal or plastic sample clips are used to stand the sample upright in the mold. Transparent mounting resins are preferred for delicate fabricated parts, such as electrical contacts, to help locate features of interest in the final plane of polish. When distortion of the sample under pressure is to be avoided, cold mounting is preferred over compression molding.

Edge protection may be enhanced by nickel plating prior to mounting or by using hard compression-molding resins formulated for edge preservation. Glass beads or alumina (Al_2O_3) granules added to cold-mounting resins for the same purpose will likely contaminate the polishing wheel and cause undesirable specimen scratching, particularly in the softer forms of beryllium copper.

Grinding. Coarse grinding is performed wet on a belt or disk grinder using 120- or 180-grit abrasive paper to remove any deformed metal layer. Fine grinding is also performed wet, either by hand on strips of abrasive paper or mechanically on 300-rpm or faster disks using 240-, 320-, 400-, then 600-grit abrasives. The sample is rotated 90° between each grinding. Silicon carbide or Al_2O_3 abrasives may be used.

Mechanical polishing is usually accomplished in rough and final stages. Rough polishing is performed using a 6 μm diamond on a wheel covered with a hard, napless chemotextile cloth. Extender oil is applied sparingly, and the wheel is rotated at approximately 300 rpm or less. The specimen is initially positioned so that the direction of polishing is perpendicular to the 600-grit grinding scratches. Maintaining this orientation, it is moved radially back and forth between center and edge of the polishing wheel under moderate pressure until these scratches are removed. The specimen is then briefly rotated counter to the rotation of the wheel to distribute the rough polishing scratches randomly.

Final polishing is performed using 0.05 μm Al_2O_3 in distilled water suspension and a wheel covered with low-nap rayon cloth. Speeds are the same as those used for coarse polishing. The wheel is kept moderately saturated with polishing suspension, and the specimen is counterrotated to vary the direction of final polishing. An exception to this procedure is the case of the softer annealed or lightly cold-worked tempers of beryllium copper, in which unidirectional final polishing, parallel to the specimen long axis, helps to minimize scratching. The specimen is washed under running water after each polishing step with mild soap and a cotton swab, then rinsed with alcohol and dried under a warm air blast.

Automatic Grinding and Polishing. Several automatic metallographic preparation machines are available that provide rapid and reproducible grinding and polishing of multiple specimens through the use of preset pressure control and a cycle timer. These machines use metal sample holder disks that accommodate 4 to 12 or more cylindrical metallographic mounts or various numbers and sizes of unembedded samples. The holders are rotated by the sample mover head of the machine at approximately 150 rpm and are mechanically pressed against the rotating work wheel, which can be a coarse grinding stone, a wheel accepting successively finer grades of abrasive paper, or cloth-covered polishing wheels. Some systems also employ lapping techniques. Work wheels must be manually changed between preparation steps, but the specimens are never removed from the holder until they are ready to be etched. This preserves a common plane of polish and maintains flatness of the prepared surfaces. Due to the high pressures and short cycle times typically used, these automatic machines increase metallographic laboratory productivity and improve edge preservation and inclusion retention.

Automatic metallographic preparation techniques vary according to the machine used and materials being prepared, but the following procedures have been successfully used for beryllium-containing alloys and can be adapted to any automatic system.

Holders containing mounted specimens or relatively square cut, unembedded specimens are rough ground on 120- or 240-grit paper and fine ground on 240-, 320-, 400-, then 600-grit papers. Very uneven, unembedded specimens may require coarse 60- or 80-grit stone or paper grinding to bring all the samples in a holder to a single plane of polish. A copious flow of recirculated water-base coolant is applied to the work wheel during each grinding step; it is not necessary to wash the samples in the holder between grindings. Wheel speeds of 150 rpm, pressures of 150 N (35 lbf), and times of approximately 30 s per grinding are usually sufficient. Zirconia (ZrO_2) abrasive papers will last longer than silicon carbide or Al_2O_3 under these grinding conditions. The loaded sample holder is then ultrasonically cleaned in alcohol, dried in an air blast, and returned to the machine for polishing.

Two or three polishings may be employed. One approach, which applies primarily to holders containing up to six 30 mm (1.25 in.) mounts, begins with 6 μm diamond on a hard, napless chemotextile, proceeds to 3 μm diamond on a low-nap cloth, and finishes with 1 μm diamond on a soft, high-nap cloth. Wheel speed in each case is 150 rpm. The first and second polishings use a pressure of 150 N (35 lbf) for 2 min per step, the final polishing, 100 N (25 lbf) pressure for 35 s. Polishing extender is dripped sparingly on the wheels during each step, and the sample holder and work wheels should rotate in the same direction in each step.

Another approach, useful for high-volume production of embedded and unembedded samples, is to use a 9 μm diamond slurry on a lapping disk, followed by a 0.3 μm Al_2O_3 suspension on a low-nap rayon cloth, with an optional intermediate step of 3 μm Al_2O_3 suspension on a hard chemotextile. Times and pressures are varied to suit the size and number of samples.

The sample holder is ultrasonically cleaned and dried after each polishing, and the samples are then removed from the holder for etching and final examination. Specimens of different alloys and hardnesses usually may be mixed in a single holder without harming the prepared surfaces of the softer samples.

Electropolishing. Clean, as-rolled strip surfaces or sectioned sample faces of beryllium-copper alloys prepared through 400- to 600-grit grinding paper may be electropolished. A satisfactory all-purpose electrolyte for beryllium-copper alloys is a mixture of 1 part nitric acid (HNO_3) and 2 parts methanol used at a temperature of –30 °C (–20 °F), with a voltage of 25 V and a platinum cathode. An electrolyte of 40 mL phosphoric acid (H_3PO_4), 60 mL hydrogen peroxide (H_2O_2), 40 mL methanol, and 20 mL H_2O may also be used for beryllium copper in conjunction with a stainless steel cathode, a mask of 0.5 to 1 cm^2 (0.08 to 0.16 $in.^2$) area, 20 to 30 V, and approximately 0.2 A. This technique is applicable to general polishing, but is particularly suited to examining intermetallic phases in beryllium copper, which can be rendered in high relief. Polishing is accomplished in a few seconds to a few minutes, using a moderately pumped electrolyte.

Macroexamination

Castings, forgings, billet, hot-rolled plate and hot-extruded rod, bar, and tube forms of beryllium-containing alloys are frequently subjected to low-magnification macroexamination. Fracture surfaces of failed components or mechanical test specimens of these product forms may also be examined at low magnification. One purpose of macroexamination is to evaluate grain structure and metal flow patterns indicating thermomechanical processing history. The technique also applies to documentation of differential heat treatment, weld penetration, or localized structural damage due to environmental attack. Fracture surfaces indicate the relative ductility of the material and the mode of failure.

Fracture Surface Characteristics. Tensile fracture surfaces of wrought beryllium copper appear macroscopically ductile. Tensile fractures of annealed material typically exhibit macrocup/cone ductile behavior. Alloys heat treated at temperatures and/or times less than or equal to those required to achieve maximum precipitation hardened strength are underaged or peakaged and exhibit blocky, transgranular fractures. Alloys heat treated at higher temperatures and longer times than those required to produce maximum strength are overaged, have a ductile appearance, and show grain facets.

Fatigue fracture features in wrought beryllium copper depend on stress intensity and bending mode. Low stress intensity tends to produce ductile fracture surfaces with a mixed mode character. Higher levels of stress intensity cause a trend toward transgranular fracture. Beryllium copper resists corrosion in many environments, but can stress-corrosion crack in the presence of ammonia. Such cracks are transgranular and intergranular.

Macroetching. Once ground to at least 320 or 400 grit, beryllium copper is macroetched by an initial, brief immersion in concentrated NHO_3, followed by immersion in or flooding with dilute HNO_3 (1 part concentrated HNO_3 to 2 parts distilled H_2O). The etchant attack is stopped by rinsing in running water. After the etched sample is rinsed in alcohol and dried in a warm air blast, the macrostructure can be preserved by spraying on a coat of clear lacquer, preferably containing a copper tarnish inhibitor such as benzotriazol ($C_6H_4NHN{:}N$).

In addition to grain structure and flow patterns, macroetched samples of beryllium coppers with 1.6 wt% or more Be reveal locally heat-affected zones as light etched areas if reannealed or unaged and as dark etched areas if aged. Light etched or reddish-colored areas adjacent to exterior or crack surfaces in uniformly aged materials usually signal environmental attack leading to local depletion of beryllium and lack of aging response. Matrix darkening on etching is absent in beryllium coppers containing less than 0.6 wt% Be, limiting the information revealed by macroetching of these alloys essentially to matters of grain morphology. Castings and cast billet exhibit columnar dendritic grain growth from solidification. Hot-finished, large-section forms of the beryllium-containing alloys occasionally exhibit in the macrostructure individual large grains, elongated in the direction of working.

Microexamination

Distinctive features in the microstructure of beryllium-copper alloys, which are due to the combined effects of composition, cold work, and thermal treatment, are readily revealed by conventional metallographic and scanning electron microscope techniques. Beryllides, other phases, and surface effects can be examined on as-polished specimens; however, etchants must be used to reveal other features of interest.

Etching procedures for beryllium-containing alloys vary with alloy type and condition or temper. Particularly for beryllium coppers with less than 0.6 wt% Be, general microstructures are more difficult to reveal in the age-hardened conditions than in the hot-finished, solution-annealed, or cold-worked conditions.

Microetchants for beryllium copper are listed in Table 1, along with their compositions, etching procedures, uses, and precautions. Ammonium persulfate hydroxide (etchant 1, Table 1) is a general purpose etchant for beryllium coppers. It reveals grain structure in unaged material, although twinning may be present to complicate grain size measurement. In the case of alloys with 1.6 wt% or more Be, this etchant darkens the matrix of age-hardened material; the degree of coloration varies with the extent of precipitation in the alloy. A variation of this etchant that contains H_2O_2 (etchant 2, Table 1) offers improved grain-boundary delineation in unaged material.

Grains in aged, concentrated alloys of beryllium copper may be highlighted by etching with ammonium persulfate hydroxide, followed by brief swabbing with dichromate (etchant 3, Table 1) to lighten the matrix. Another reliable way to enhance grain boundaries in unaged alloys of these compositions is to age the samples for 15 to 20 min at 370 °C (700 °F), then follow with the two-stage etching procedure described above. This technique eliminates twinning, and grain size can be accurately determined from the decoration of the grain boundaries with dark etching γ precipitate.

Alloys with 0.6 wt% or less Be exhibit little microstructural difference between the aged and unaged conditions, and grain structure is frequently obscured by twinning if ammonium persulfate hydroxide is used. To enhance the general microstructure in these situations, the cyanide (etchant 6, Table 1), persulfate hydroxide/cyanide (etchant 7, Table 1), or two-step cyanide (etchant 6, Table 1)/cyanide peroxide hydroxide (etchant 8, Table 1) etchants are used. Care must be taken to observe all safety precautions of these toxic solutions.

None of the etchants listed differentially attack intermetallic compounds in beryllium copper—to distinguish cobalt or nickel beryllides from β phase, for example. This distinction must be made on the basis of appearance in the as-polished condition. Beryllides are blue gray; β phase is creamy white and surrounded by a thin, dark outline.

Any of the etchants listed, which are intended for bright-field optical microscopy, may be utilized for scanning electron microscopy examination to reveal fine structural details not optically resolvable. One such application is the resolution of the lamellar structure of grain-boundary γ precipitate in high-temperature aged beryllium coppers containing 1.60 to 2.00 wt% Be.

Microstructures of Beryllium-Copper Alloys

The two general categories of beryllium-copper alloys are the high-strength and the high-conductivity alloys. The wrought high-strength alloys contain 1.60 to 2.00 wt% Be, with approximately 0.25 wt% Co. The addition of cobalt promotes fine grain size in the cast form, lessens grain growth during annealing, and reduces the rapid softening of the alloy due to overaging. Solution annealing at temperatures of 760 to 790 °C (1400 to 1450 °F), followed by rapid quenching, retains the beryllium in solid solution at room temperature. Precipitation hardening can be accomplished by aging for 0.1 to 4 h at 260 to 400 °C (500 to 750 °F); the time and temperature depend on the composition, amount of cold work, and strength levels desired. Cold working prior to aging results in faster age hardening and higher strengths.

The most commercially important of the high-strength compositions is C17200, which contains 1.80 to 2.00 wt% Be. This is the strongest of the beryllium-copper alloys; tensile strengths range to 1520 MPa (220 ksi) in the fully age-hardened condition. A leaded version of this alloy, C17300, exhibits improved machinability. A composition slightly lower in cost, C17000, with 1.60 to 1.79 wt% Be, is available with tensile properties in the age-hardened condition approximately 10% lower than those of C17200.

The high-strength alloys are also produced as casting alloys, designated C82400, C82500, C82510, C82600, and C82800. The beryllium content is higher (up to approximately 2.75 wt%) than in wrought alloys, but the general microstructural characteristics are similar. These alloys are produced as cast ingots that can be remelted and cast by foundries using any conventional molding technique.

The high-conductivity alloys have low beryllium levels (0.2 to 0.7 wt%) and high cobalt and nickel levels. The wrought version of the alloy containing 2.4 to 2.7 wt% Co is designated C17500. The cast version is designated C82000. The wrought version containing 1.4 to 2.2 wt% Ni instead of cobalt is designated C17510, and the corresponding casting alloy is C82200. The properties of the nickel-containing alloys are very similar to the cobalt-containing alloys. The solution-annealing temperature range for the high-conductivity alloys is 900 to 955 °C (1650 to 1750 °F). Aging is performed at 425 to 565 °C (800 to 1050 °F) for 3 to 8 h, depending on the amount of cold work and combination of properties sought.

The various commercial beryllium-copper alloys discussed and/or illustrated in this article are listed in Table 2, which provides compositional limits. The phases and constituents resulting from alloying elements and various heat treatments are discussed subsequently.

The Beryllide Phase. Commercial beryllium-copper alloys contain cobalt or nickel or both. These alloying elements are normally in solution in the liquid metal. Because of their strong affinity for beryllium, they combine with it and separate during solidification as particles that are approximately 10 μm in the longest dimension. These constituent particles are termed *beryllides.* During subsequent thermomechanical processing, the beryllides are broken up somewhat but are not dissolved into solid solution during normal solution annealing.

The primary beryllide phase is best observed in the as-polished condition as blue-gray

Table 1 Recommended etching reagents for beryllium-copper alloys

Etchant	Composition(a)	Comments
1. Ammonium persulfate hydroxide	1 part NH_4OH (concentrated) and 2 parts $(NH_4)_2S_2O_8$ (ammonium persulfate) 2.5% in H_2O	Used for observation of the general structure of all beryllium-copper alloys. Preheat sample in hot water (optional); swab etch 2–20 s; use fresh.
2. Ammonium persulfate hydroxide (variation)	2 parts 10% $(NH_4)_2S_2O_8$, 3 parts NH_4OH (concentrated), 1 part 3% H_2O_2, and 5–7 parts H_2O	Used for all beryllium-copper alloys. Offers improved grain boundary delineation in unaged material. A, 1/4 H, 1/2 H, H tempers (unaged, use less H_2O. AT through HT and aged, use more H_2O). Use fresh; swab or immerse 5–60 s. Preheat specimen in hot H_2O if etching rate is slow.
3. Dichromate	2 g $K_2Cr_2O_2$ (potassium dichromate), 8 mL H_2SO_4 (concentrated), 1 drop HCl per 25 mL of solution, and 100 mL H_2O	Used for observation of the grain structure of wrought C17000, C17200, C17300. Use for AT through HT and mill hardened (aged) tempers. Etch first with ammonium persulfate hydroxide (No. 1 or 2); wipe dichromate 1–2 times over specimen to remove dark etch color. Do not overetch; sample may pit. Can be used with laboratory aging of annealed or as-rolled material at 370 °C (700 °F) for 15–20 min to enhance grain boundary delineation for grain size determination
4. Hydroxide/peroxide	5 parts NH_4OH (concentrated), 2–5 parts 3% H_2O_2, and 5 parts H_2O	Common etchant for copper and brass, also applicable to beryllium-copper alloys. Use fresh.
5. Ferric chloride	5 g $FeCl_3$ (ferric chloride), 50 mL HCl, and 100 mL H_2O	Common etchant for copper alloys, also applicable to cold-rolled tempers of beryllium-copper alloys C17500 and C17510 to show grain structure. Immerse 3–12 s.
6. Cyanide	1 g KCN (potassium cyanide) and 100 mL H_2O	General structure of beryllium-copper alloys C17500, C17510 (No. 6). Immerse 1–5 min; stir slowly while etching; use etchant 7 if others are too weak to bring out structure. A two-step technique for improved results on C17510 includes immersion in etchant 6 followed by swabbing with etchant 8. *Caution: Poison fumes.* Use fume hood. Do not dispose of used solutions directly into drains. Pour used solution into beaker containing chlorine bleach. Let stand 1 h, then flush down drain with plenty of running water.
7. Persulfate hydroxide/cyanide	4 parts ammonium persulfate hydroxide etchant (etchant 1 or 2) and 1 part cyanide etchant (etchant 6)	
8. Cyanide peroxide hydroxide	20 mL KCN, 5 mL H_2O_2, and 1–2 mL NH_4OH	
9. Phosphoric acid electrolyte	20 mL H_2O (tap, not distilled), 58 mL 3% H_2O_2, 48 mL H_3PO_4, and 48 mL ethyl alcohol	For deep etching of beryllium-copper. Polished specimen through 1 mm or finer Al_2O_3. Use 0.5–1 cm^2 (0.08–0.16 $in.^2$) mask. 0.1 A to etch (higher amperes to polish). Low-to-moderate flow rate. 3 to 6 s to etch, up to 60 s to polish

(a) Where H_2O is indicated, use distilled water unless otherwise noted.

Table 2 Chemical compositions of beryllium-copper alloys

	Composition, wt%					
Alloy	Be	Co	Ni	Pb	Other	Cu
Wrought alloys						
C17000	1.60–1.79	(a)	(a)	…	…	bal
C17200	1.80–2.00	(a)	(a)	…	…	bal
C17300	1.80–2.00	(a)	(a)	0.20-0.6	…	bal
C17500	0.40–0.7	2.4–2.7	…	…	…	bal
C17510	0.20–0.6	0.30(b)	1.4–2.2	…	…	bal
Cast alloys						
C82000	0.45–0.8	2.4–2.7	0.20	…	0.15 Si	bal
C82200	0.35–0.8	…	1.0–2.0	…	…	bal
C82400	1.65–1.75	0.20–0.40	0.10	…	0.20 Fe	bal
C82500	1.90–2.15	0.35–0.7	0.20	…	0.20–0.35 Si, 0.20 Fe	bal
C82510	1.90–2.5	1.0–1.2	0.20	…	0.20–0.35 Si, 0.25 Fe	bal
C82600	2.25–2.45	0.35–0.7	0.20	…	0.20–0.35 Si, 0.25 Fe	bal
C82800	2.50–2.75	0.35–0.7	0.20	…	0.20–0.35 Si, 0.25 Fe	bal

(a) Nickel + cobalt, 0.20 min.; Nickel + cobalt + iron, 0.60 max. (b) Maximum if no range given

Chinese script in castings. The secondary beryllides forming after solidification of the major phase can have a rodlike morphology with preferred crystallographic orientation with the matrix. In wrought products, the beryllides appear as roughly spherical, blue-gray particles.

The Beta Phase. The β phase forms peritectically from the liquid metal. It is observed in high-strength alloy castings as an interdendritic network surrounding the primary copper-rich α phase. Experiments have shown that the β phase cannot be retained at room temperature because it decomposes into α and γ phases by a eutectoid transformation. The (transformed) β phase stands out in relief in the as-polished state as white angular patches. In wrought metal containing 1.8 to 2.0 wt% Be, long (transformed) β stringers may exist due to insufficient homogenization before hot working.

The Gamma Phase. The γ phase forms in overaged beryllium-copper alloys as an equlibrium precipitate. In concentrated alloys of beryllium-copper, the γ-phase precipitation starts at the grain boundaries and advances into the adjoining grains, consuming the fine, metastable precipitates. This type of precipitation is termed *discontinuous precipitation* or *cellular precipitation.* The γ precipitates formed by this mechanism have a platelike morphology. In the age-hardened state, the grain boundary containing the γ precipitate is soft compared to the hardened matrix.

Precipitation of the γ phase can also occur in the grain boundaries in high-strength beryllium-copper alloys if the rate of quenching from the solution-annealing temperature is not fast enough to retain beryllium in solid solution. In metallographically polished specimens etched using standard procedures, the γ phase stands out at the grain boundaries as dark nodules on a bright matrix. The lamellar morphology of the γ phase is resolved by scanning or transmission electron microscopy.

Hardening Precipitates. Excellent room-temperature mechanical properties of beryllium-copper alloys are derived from the formation of a series of metastable precipitates during aging. Several such metastable phases form before the equilibrium γ phase is observed. The precipitation sequence at large undercoolings is:

$$\text{Supersaturated solid solution} \rightarrow \\ \text{Guinier-Preston (GP) zones} \rightarrow \gamma'' \rightarrow \gamma' \rightarrow \gamma$$

Guinier-Preston zones are the first precipitates to form and are coherent with the matrix. They are nucleated in large densities. The coherency strain fields set up due to the misfit of the zones and the matrix strengthen the alloy. With continued aging, GP zones transform to more stable precipitates.

The metastable precipitates can be detected by transmission electron microscopy. They are identified by the characteristic features observed in the electron diffraction pattern. The presence of hardening precipitates can be recognized only indirectly by light microscopy as striations on the surface of a polished and etched alloy that result from the overlap of coherency strains.

ACKNOWLEDGMENT

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Fig. 1 C82200 alloy casting. As-cast microstructure shows interdendritic networks of large primary beryllide phase in a matrix of α solid solution. Preferred orientation of small secondary beryllides is observed with the matrix. Etchant 6 (Table 1). 400×

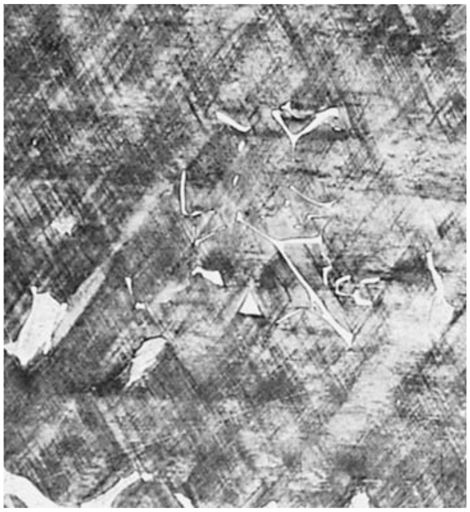


Fig. 2 C82500 alloy casting, solution annealed at 790 °C (1450 °F) and aged to peak hardness at 315 °C (600 °F) for 3 h. Microstructure consists of Chinese-script beryllides in a copper-rich α solid-solution matrix, with angular β phase transformed to a lamellar aggregate of α and γ phases. Striations are the result of metastable precipitation in the alloy. Etchant 1 (Table 1). 400×

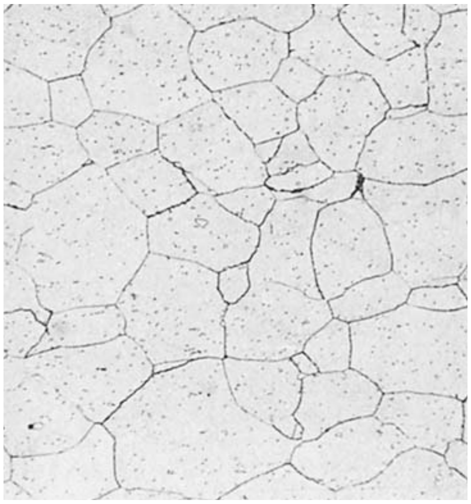


Fig. 3 C17200 alloy strip, mill hardened to AM (TM00) temper to achieve maximum formability at moderate strength. Longitudinal section shows roughly equiaxed grains of α phase and cobalt beryllides. Metastable precipitates that form during hardening and increase strength and hardness are not resolved. Etchant 1 (Table 1). 400×

Fig. 4 C17200 alloy strip, mill hardened to XHMS (TM08) temper for high strength and limited formability. Longitudinal section shows elongated grains of the α phase and cobalt beryllides. Striations result from precipitation of metastable phases not resolved by optical microscopy. Etchant 1 (Table 1). 400×

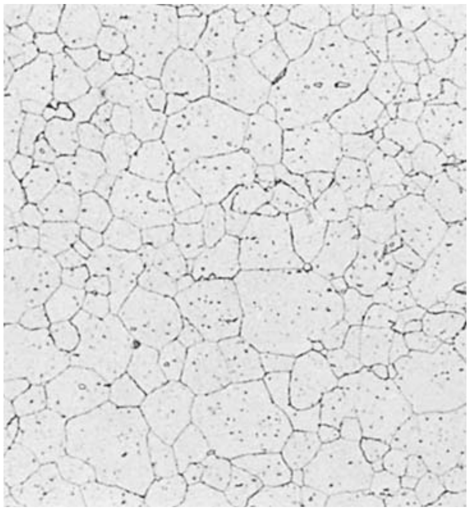


Fig. 5 C17200 alloy strip, solution annealed at 790 °C (1450 °F) and water quenched. Longitudinal section shows equiaxed grains of supersaturated α-phase solid solution of beryllium in copper. Cobalt beryllide particles are uniformly dispersed throughout the structure. Etchant 1 or 2 (Table 1). 400×

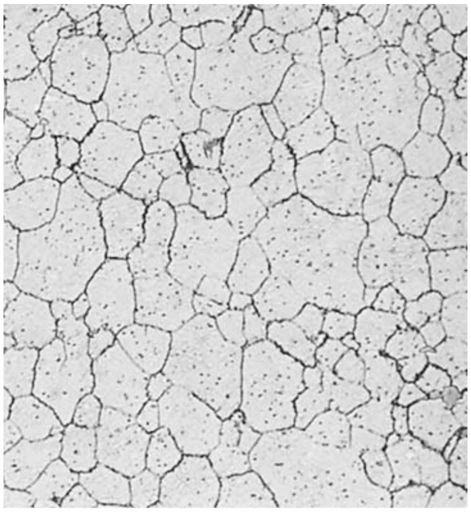


Fig. 6 C17200 alloy strip, solution annealed at 790 °C (1450 °F), quenched rapidly to room temperature, and precipitation hardened at 315 °C (600 °F) for 3 h to achieve maximum hardness. Longitudinal section shows equiaxed α grains and the cobalt-beryllide phase uniformly dispersed. Metastable phases are not resolved, but small quantities of equilibrium γ phase are present in the grain boundaries. Etchant 1 (Table 1). 400×

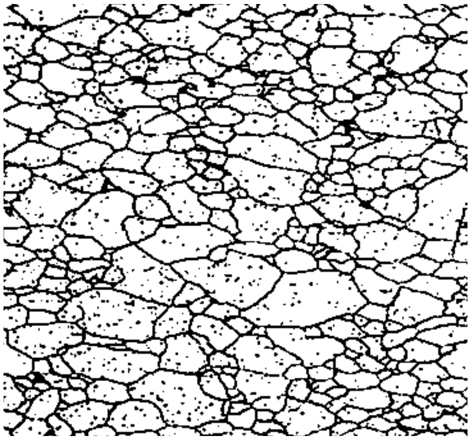


Fig. 7 C17200 alloy strip, solution annealed at 790 °C (1450 °F) and cold rolled at 11% to quarter-hard temper. Typical hardness is 79 HRB. Alpha grains are elongated in the direction of rolling. Etchant 1 (Table 1). 400×

Fig. 8 C17200 alloy strip, solution annealed at 790 °C (1450 °F) and cold rolled at 37% to full hard temper. Longitudinal section shows elongated grains of α phase and cobalt beryllides. Etchant 1 or 2 (Table 1). 400×

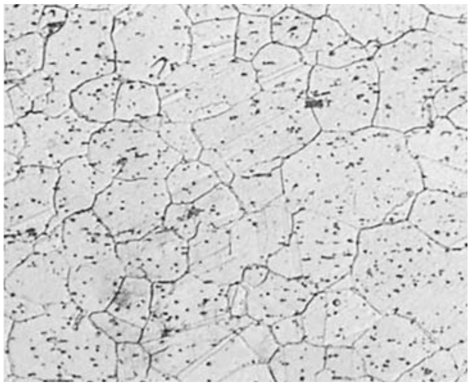


Fig. 9 C17510 alloy strip, solution annealed at 900 °C (1650 °F), quenched rapidly to room temperature, and precipitation hardened at 480 °C (900 °F) for 3 h to achieve maximum hardness. Equiaxed grains of supersaturated solution of beryllium and nickel in copper are shown. Etchant 6 (Table 1). 400×

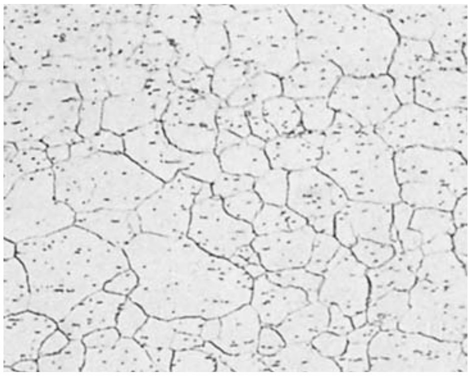


Fig. 10 C17510 alloy strip, solution annealed, cold rolled, and precipitation hardened at 480 °C (900 °F) for 2 h to achieve maximum hardness. Structure consists of α phase and a uniform distribution of the nickel-beryllide phase. Elongated grains are the result of cold work. Metastable precipitates are not resolved. Etchant 6, followed by swabbing with etchant 8 (Table 1). 400×

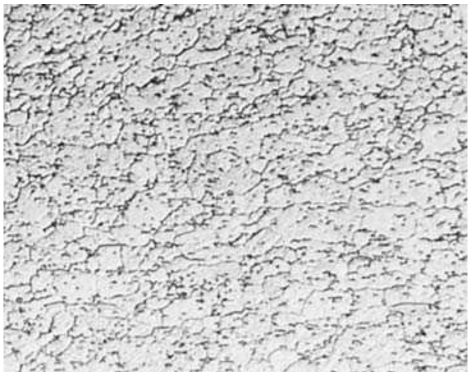


Fig. 11 C17500 alloy strip, solution annealed at 900 °C (1650 °F), quenched rapidly to room temperature, and precipitation hardened at 480 °C (900 °F) for 3 h to achieve maximum hardness. Microstructure shows equiaxed grains of supersaturated solution of beryllium and cobalt in copper. The cobalt-beryllide phase is uniformly distributed, and metastable hardening precipitates are not resolved. Etchant 6 (Table 1). 400×

Fig. 12 C17500 alloy strip, solution annealed, cold rolled, and precipitation hardened at 480 °C (900 °F) for 2 h to achieve maximum hardness. Structure consists of the α phase and a uniform distribution of the beryllide phase. Elongated grains are the result of cold work, and metastable hardening precipitates are not resolved. Etchant 6 (Table 1). 400×

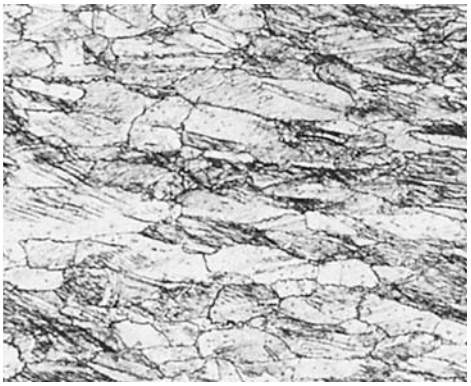


Fig. 13 C17200 alloy strip, solution annealed, cold rolled full hard, and precipitation hardened at 315 °C (600 °F) for 2 h to achieve maximum hardness. Longitudinal section shows elongated grains of α phase and cobalt beryllides. Striations are caused by metastable precipitates not resolved by optical microscopy. Etchant 1 (Table 1). 400×

Fig. 14 C17200 alloy strip, solution annealed and aged at 370 °C (700 °F) for 6 h to attain an overaged condition. The structure shows γ precipitates in the grain boundaries, which appear as dark nodules in a light matrix. Etchant 1 (Table 1). 400×

Fig. 15 C17200 alloy plate, cast, homogenized, and hot worked. The microstructure shows nonuniform distribution of grain sizes, which is typical of a hot-worked product. Greater uniformity in grain size distribution may be achieved in the finished product by successive cold-working and annealing operations. Etchant 1 (Table 1). 700×

Fig. 16 C17200 alloy strip, solution annealed and age hardened. The white constituents of the structure are β stringers. These zones of beryllium segregation are carried through from billet casting and homogenization. Etchant 1 (Table 1). 700×

Fig. 17 C17200 alloy strip heated to 885 °C (1625 °F) and water quenched. The microstructure shows "burned metal" caused by solution annealing at too high a temperature. Partial melting at the grain boundaries, caused by extreme temperatures, resolidifies as β phase. Etchant 1 (Table 1). 700×

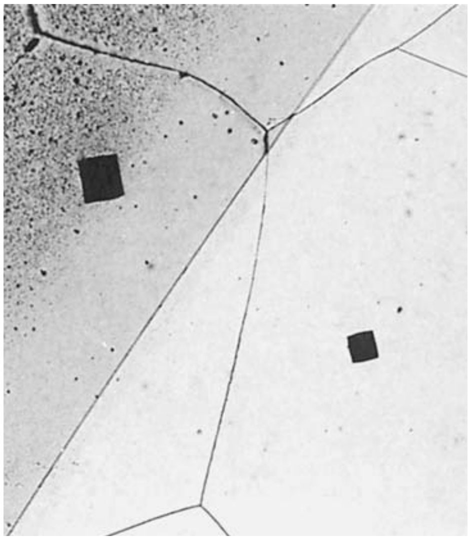


Fig. 18 C17510 alloy rod, solution annealed in air at 980 °C (1800 °F) for 3 h, then aged at 480 °C (900 °F) for 3 h. The microstructure shows internal oxidation resulting from solution annealing without a protective atmosphere. Note the loss in hardness (as indicated by the microhardness indentations) within the internal oxidation zone. Etchant 6 (Table 1). 200×

Solidification Structures of Copper Alloy Ingots

SOLIDIFICATION STRUCTURES OF COPPER ALLOY INGOTS intended for subsequent working are primarily discussed in this article. Ingots intended for remelting and shaped castings produced in foundries are not specifically discussed, although they have solidification structures that, in many respects, are similar to those of ingots intended for subsequent working. Also discussed briefly are cast structures produced by semisolid forming and rapid solidification technologies.

Dendrites

Dendritic structure is an almost universal feature of copper alloy ingots. A variety of dendritic structures are pictured in micrographs in this article.

Figure 1(a) shows the effect, during solidification, of cooling rate on the spacing between adjacent arms in dendrites in two bronze alloys (Ref 1). Increasing the cooling rate (decreasing the solidification time) leads to finer dendrite arm spacing. Solidification time generally is more useful than cooling rate in interpreting dendritic structure of copper alloys, regardless of solute content. Cooling rate has little meaning for pure or nearly pure metals, which have near zero change in temperature during solidification.

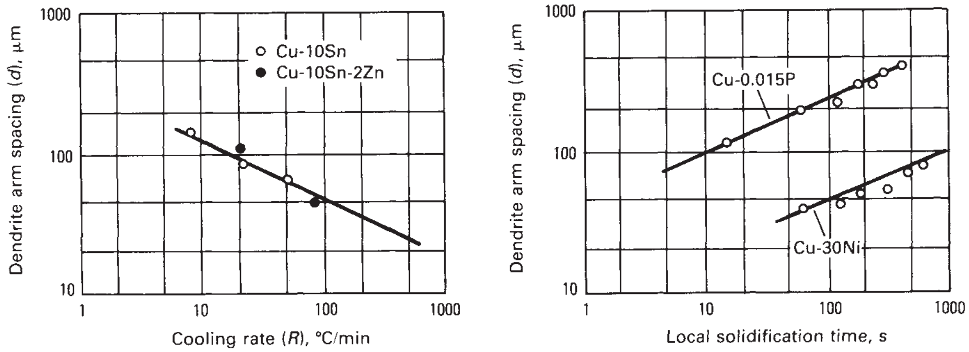
Figure 1(b) provides data on the spacing of dendrite arms for various solidification times in slowly cast laboratory specimens of alloy C12200 (DHP copper). The small amount of solute in alloy C12200 (0.015 to 0.040% P) does not result in thermal behavior different from that of unalloyed copper, but does cause dendritic growth. Figure 1(b) also presents data on the spacing of dendrite arms in alloy C71500 (copper nickel, 30%) (Ref 2).

The phase diagram for the copper-nickel system shows that, although only one phase forms in the solid, solute redistribution occurs during solidification. Dendrite arm spacings in the alloy C71500 ingot were smaller than those in the alloy C12200 ingot because the dendrite arms in the alloy C71500 ingot were branched into secondary arms. Secondary dendrite arm spacing is also called cell size. Branched dendrite arms are typical of highly alloyed ingots.

As shown in Fig. 2(a), dendrite arm spacing varies greatly across this ingot. If these data are compared to those in Fig. 1(b) for the same alloy, the microstructure may be interpreted regarding solidification time; solidification time was shortest—cooling rate was highest—at the center of the ingot.

Figure 2(b) presents a curve of dendrite arm spacing versus position in a 229 mm (9 in.) diam semicontinuous-cast ingot of alloy C71500 (Ref 2). These data and those in Fig. 1(b) for the same alloy indicate that the finest dendrite arm spacing is at the surface, which solidified in the shortest time, or cooled at the highest rate. These results contrast with those for the smaller ingot of continuous-cast DHP copper, which was solidified under conditions of high heat transfer in the secondary cooling zone.

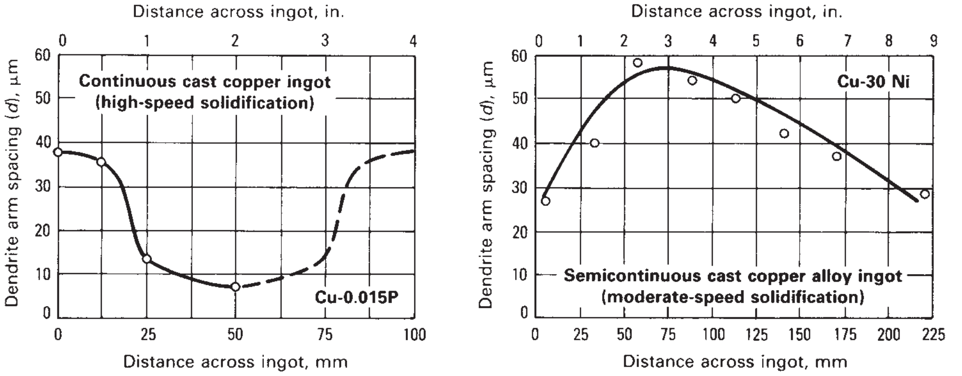
Factors affecting dendritic structure of copper alloy ingots include composition, cooling rate, and agitation during solidification (Ref 3–6). Increasing the cooling rate produces finer secondary dendrite arm spacing. For many alloy systems, increasing the solute content also produces finer spacing. As shown in Fig. 3(a), the relationship between composition and dendrite arm spacing for copper-silver alloys is approxi-



(a) LIVE GRAPH Click here to view

(b) LIVE GRAPH Click here to view

Fig. 1 Dendrite arm spacing as affected by solidification conditions in specimens of four cast copper alloys. (a) Effect of cooling rate on two bronze alloys (Ref 1). (b) Effect of local solidification time on alloy C71500 (copper nickel, 30%) (Ref 2) and on alloy C12200 (DHP copper)



(a) LIVE GRAPH Click here to view

(b) LIVE GRAPH Click here to view

Fig. 2 Variation in dendrite arm spacing across (a) a continuous-cast ingot of alloy C12200 (DHP copper, see Fig. 16 and 17) and (b) a semicontinuous-cast ingot of alloy C71500 (copper nickel, 30%). Source: Ref 2 mated by Eq 1, which was determined by curve-fitting techniques:

$$d = 306 \times R^{-0.39} \times C^{-0.31} \qquad \text{(Eq 1)}$$

where d is dendrite arm spacing in microns, R is the cooling rate in degrees centigrade per minute, and C is silver content in atomic percent. Equations of this form, with different constants, have been shown to fit extensive data in other binary systems.

Dendritic structure also depends on the equilibrium distribution coefficient, k_0. Figure 3(b) illustrates that with the same cooling rate, a finer dendritic structure usually is achieved at lower solute levels in alloy systems having a low k_0 value, such as the copper-lead system, than in those having a higher k_0 value, such as the copper-cobalt system (Ref 4).

Data on dendrite arm spacing in various commercial alloys are presented in Fig. 4. Although freezing range and other solidification characteristics in these nine commercial alloys vary considerably, the data fall between two curves:

$$d = 290R^{-0.42} \qquad \text{(Eq 2)}$$

$$d = 180R^{-0.43} \qquad \text{(Eq 3)}$$

Thus, dependence of dendrite arm spacing on cooling rate is similar over a wide range of commercial alloys, despite wide variations in other characteristics of the alloy systems.

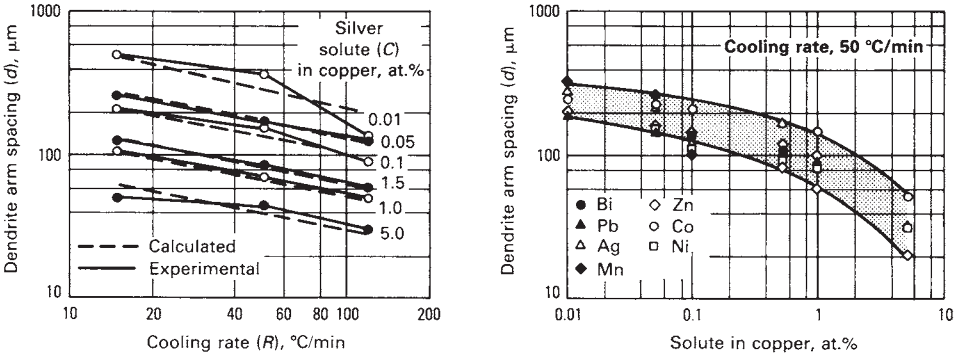
Interpretation of Dendrite Patterns. The dendritic structure in the columnar region of an ingot of alloy C71500, shown in Fig. 5, is typical of many copper-base and other alloy systems. Etching reveals a relatively consistent pattern of coring, or variation in local solute content within each grain. This basic pattern is produced by the intersection of the plane of polish with the randomly oriented platelike regions of equal solute concentration within the three-dimensional dendritic structure (Ref 7). The platelike regions in Fig. 5 are high in solute content, because $k_0 > 1$ for copper-rich copper-nickel alloys. Such platelike regions have low solute content in alloys for which $k_0 < 1$, such as copper-zinc alloys. The wide variation in the angle of intersection of the plane of polish with these relatively planar regions of equal solute content leads to considerable variation in the observed dendritic pattern.

Within one cast grain, there is one crystallographic orientation, to which the dendrite structure has a definite relationship (Ref 8). In copper alloys, dendrites grow in (100) crystallographic directions and tend to develop low solute ($k_0 < 1$) concentration contours in (100) planes (Ref 9). Because grains have various orientations, their dendritic structures are intersected by the plane of polish as determined by the crystallographic orientation of the grain.

At a free or outside surface, various orientations are apparent (Ref 10). In addition, dendrites can be bent and broken, that is, remelted at branching points. Similar effects are visible in the interiors of cast structures. These effects result in structures in which the "dendrites" no longer have one orientation; in crystal multiplication (Ref 5, 6), where new grains form from the detached dendrite arms of other grains; and in nondendritic solidification, where the dendritic structure is disrupted to the point that dendrite fragments produce a grain size equivalent to the dendrite arm spacing (Ref 11).

Disruption of dendrite structure is caused by liquid metal movement in the less extreme case of crystal multiplication. Strong agitation is required to produce the unusual structures in nondendritic solidification. A copper-base cast structure produced by semisolid processing is illustrated in Fig. 6 (Ref 12). Mechanical mixing of the melt creates the spherical microstructure of the casting.

At the opposite end of the spectrum of disrupted dendritic growth are structures solidified in zero gravity (Ref 13) or in other environments that tend to preserve growth of specific dendritic orientations. In electromagnetic casting of copper alloys (Ref 14), casting takes place in an electromagnetic field rather than a mold. Mold contact can lead to some undesirable effects, but also tends to be the source of grains of varying orientation. Dendrites tend to grow along a free surface in the direction of heat flow. In the case of electromagnetic casting, this results in surface dendrites (and grains) that align parallel to the casting direction (Fig. 7).



(a) LIVE GRAPH Click here to view

(b) LIVE GRAPH Click here to view

Fig. 3 Variation of dendrite arm spacing in cast copper alloy specimens with (a) cooling rate during solidification for various amounts of silver solute and (b) amount of solute for various alloying elements (specimens solidified at the same rate). Source: Ref 4

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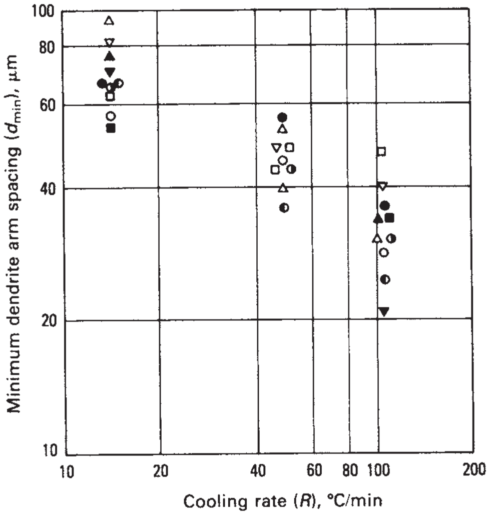

Alloy composition	Minimum dendrite arm spacing, um, for cooling rates, °C/min (°F/min) of: 15 (27)	50 (90)	120 (216)
○ Cu-30Zn (cartridge brass)	58	46	29.5
● Cu-39Zn-3Pb (free-cutting brass)	64	57	36
△ Cu-21Zn-2Al (aluminum brass)	94	56	32
▲ Cu-14Zn-4Si (silicon brass)	79	40	35
▽ Cu-20Zn-18Ni (nickel silver)	82	53	40
▼ Cu-7Sn-0.3P (tin-phosphorus bronze)	73	44	23
□ Cu-4Ni-10Al-4Fe (aluminum bronze)	62	53	50
■ Cu-7Sn-5Pb (bearing alloy)	57	45	35
◐ Cu-5Sn-5Zn-5Pb (leaded red brass)	64	37	26.5
◑ Cu-10Ni-1.3Fe-0.7Mn (copper nickel)	63	45	32

Fig. 4 Minimum dendrite arm spacing as a function of cooling rate for 10 commercial alloys. Higher cooling rates result in smaller dendrite arm spacing.

Fig. 5 Alloy C71500 (copper nickel, 30%) ingot. Dendritic structure in the columnar region of the ingot shows coring (variation in solute concentration). The light areas are nickel-rich; the dark areas are low in nickel. Waterbury reagent. 20×

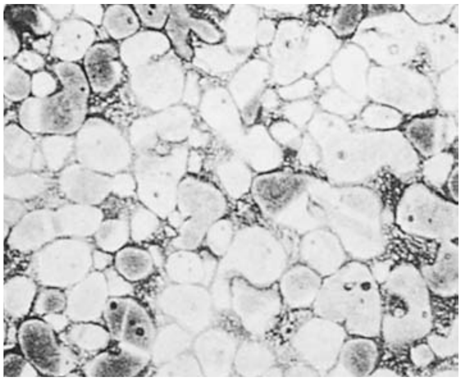

Fig. 6 Alloy C36000 (free-cutting brass), semisolid formed. Large grains originate from solid material present before casting; the remainder of the structure was solidified more rapidly to produce the structure shown. NH_4OH, H_2O_2, and H_2O. 155×

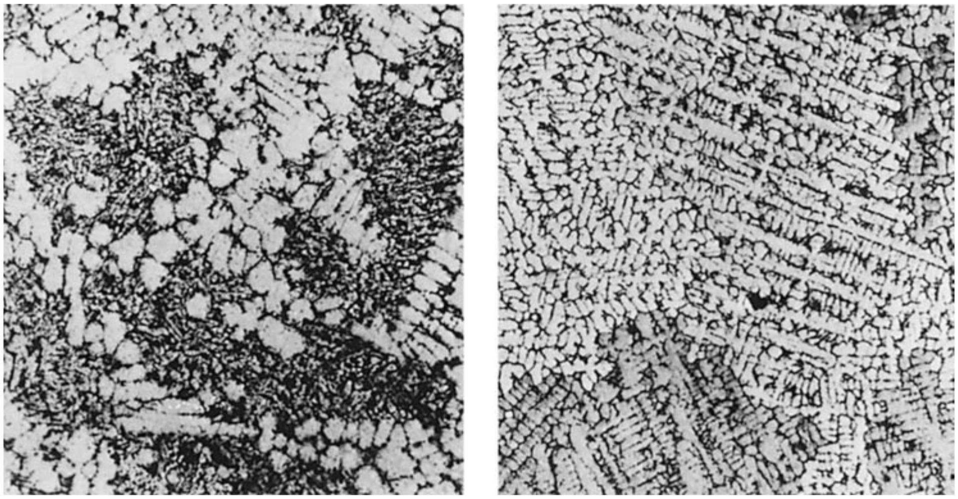

Fig. 8, 9 Alloy C36000 (free-cutting brass), semicontinuous cast. Dendritic structure in specimens from two locations in the ingot. Fig. 8: mixed structure of α dendrites (light) and β phase (dark) at the center of the ingot. Fig. 9: Uniform distribution of α dendrites (light) with interdendritic β phase (dark) near the surface of the ingot. $NH_4OH + H_2O_2$. 30×

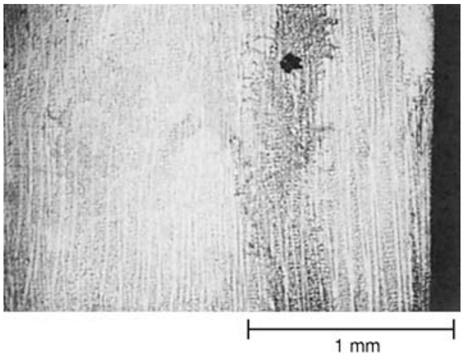

Fig. 7 Alloy C63800 produced by mold-free electromagnetic casting. Surface dendrites are aligned parallel to the casting direction. Compare with Fig. 10. Equal parts saturated NH_4OH, H_2O_2, and H_2O. 25×

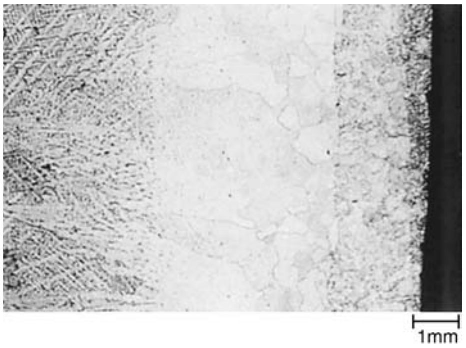

Fig. 10 Alloy C63800, direct-chill cast. Inverse segregation (a high level of solute at the surface of the ingot) has produced a nondendritic structure at the surface (right). Compare with Fig. 7. Same etchant as Fig. 7. 5×

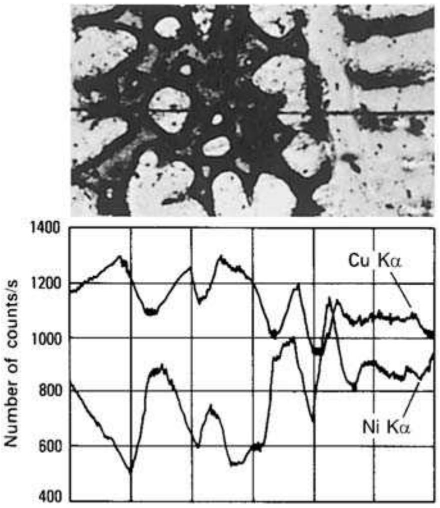

Fig. 11 Alloy C71500 (copper nickel, 30%) ingot, direct-chill semicontinuous cast. Microprobe record of solute distribution in the equiaxed zone of the ingot. 8 mL HNO_3, 15 mL H_2SO_4, 5 mL HCl, 5 g $FeCl_3$, and 145 mL H_2O, then Waterbury reagent. 85×

The preceding discussion of dendritic structures has shown the relationship between dendritic structures and grain structure in ingots. Grains form by a dendritic growth process (with the exceptions noted subsequently). Dendritic fragmentation or disruption changes grain size, columnar/equiaxed relationship, semisolid flow properties, and so on. Thus, factors that influence dendritic structure are significant for grain structure as well. Because dendritic structure is the result of solute redistribution (coring) during solidification, second-phase structures and homogenization are also influenced by dendrite structure, especially the characteristic dimension of solute variations (dendrite arm spacing).

Second Phase. Many commercially produced copper alloy ingots are basically of the single-phase solid-solution type. However, even alloys that should be single phase, such as alloy C26000 (cartridge brass, 70%), can contain nonequilibrium β phase in interdendritic locations. A nonequilibrium second phase also occurs in ingots of alloy C52400 (phosphor bronze D), which contains 10% Sn (Ref 15).

High-zinc brasses generally contain some equilibrium β phase. Figure 8 shows an ingot of alloy C36000 (free-cutting brass) in which α-dendrite arms are separated by regions of β phase. This type of microstructure is caused by cooling conditions and by the resulting grain structure in the region of equiaxed grains at the center of the ingot. In the columnar region near the surface of the same ingot (Fig. 9), the α dendrites are more uniformly distributed in the structure. In addition, the β phase is not concentrated, but has formed in close association with the α dendrites.

Gross macrosegregation is observed in certain alloys, especially those with long freezing ranges. The result can be solute enrichment, or depletion, which produces compositions having unusual second phases. An example is direct-chill cast alloy C63800 shown in Fig. 10; compare this to the electromagnetic-cast ingot surface shown in Fig. 7.

Segregation between grains is a form of macrosegregation that occurs in late stages of freezing as solute-rich liquid fills stressed low-integrity grain boundaries. This problem is most apparent in alloys with a long freezing range, such as alloys with substantial tin, phosphorus, or lead. One recent approach to solving this problem is application of electromagnetic stirring to refine grain size (Ref 16) in copper-base alloys. Similar successful application of electromagnetic stirring has solved problems in steel ingot "hot tear" segregation (Ref 17).

Homogenization variously affects different copper alloys. Coring in brass often is eliminated unintentionally during high-temperature fabrication or even slow cooling of a large ingot after casting (Ref 18). However, coring persists in most cast ingots of copper-nickel alloys. Figure 11 shows segregation in the equiaxed zone at the center of an alloy C71500 direct-chill semicontinuous-cast ingot (Ref 2). Also shown are the results of a microprobe traverse across the section. The dark-etching copper-rich areas illustrated in this micrograph reach copper concentrations of 80%; in the less heavily cored regions near the surface of the ingot (not shown in the micrograph), the maximum copper content was 75%.

High rates of solidification produce fine dendrite arm spacing; such a structure homogenizes more quickly than a coarse dendritic structure. Rapid cooling after solidification reduces the time available for homogenization. Rapid solidification followed by slow cooling can result in a degree of coring very different from that resulting from slow solidification followed by rapid cooling. This accounts for the wide variation in degree of homogenization found in the structure of as-cast ingots of the same alloy. Some solutes, such as nickel, diffuse more slowly in copper at casting and working temperatures than other solutes, such as zinc (Ref 2).

Rapid solidification technology is evolving from a subject of considerable academic interest to a technology with great promise in some applications. Figure 12 shows the range of cooling rates under consideration, which may be compared to cooling rates in Fig. 1. At rapid cooling rates, alloys can be produced with microcrystalline or even glassy structures. For example, Cu-50Zr has a glass transition temperature of 480 °C (895 °F) (Ref 19). Very fine grain structure can be produced from a glass.

Other advantages of rapid solidification include reduced chemical segregation, fine grain microstructure, uniform distribution of very fine precipitates, increased tolerance for residual elements, and extended solid solubilities for solutes as compared to expectations based on equilibrium phase diagrams (Ref 20). An example of a rapidly solidified Cu-Zn-Al alloy is presented in Fig. 13. Possible applications for various alloy systems produced by rapid solidification are listed in Table 1. Although opportunities for applying this technology are numerous, processing technology will require dedicated effort. It is likely that applications will be unrelated to most products made from more conventional copper ingot processing.

Grains

Typical grain structures that occur in continuous-cast ingots, static-cast ingots, and continuous-cast wire bars of various copper alloys are discussed in the following paragraphs. Proper procedures for the investigation of these grain structures are indicated.

Grain Structure in Continuous-Cast Ingots. Figures 14 and 15 show a transverse section and a longitudinal section of a continuous-cast ingot of alloy C12200 (DHP copper). The sections illustrated in Fig. 16 and 17 are from this same ingot. In the transverse section, the grains are essentially radial from the surface to the center. Care was taken to cut the longitudinal section exactly through the center of the ingot. The black line at the middle of the longitudinal section is a columnar grain oriented along the axis of the ingot; this grain is barely discernible in the transverse section. As is typical of relatively pure copper, the grain boundaries are sharply defined.

Figure 18 is a schematic approximation of the freezing front in the continuous process used for casting the ingot in Fig. 14 and 15. At the surface

Table 1 Advantages of rapidly solidified copper alloys

Alloy system	Comments
Cu-Al	Enhanced mechanical properties; superplasticity
Cu-Zr	Amorphous; enhanced mechanical properties
Cu-Fe	Enhanced mechanical properties; (low-cost additive)
Cu-Be	Enhanced mechanical properties
Cu-Be + (Zr, Cr, Mg, Ni, Ti)	Combination of high strength and high thermal conductivity
Cu-Pb	Enhanced lubrication
Cu-Cr	Hot hardness; high strength and electrical conductivity
Cu-Ga, Cu-Si, Cu-Ge, Cu-Sn	Enhanced mechanical properties; strength and ductility
Cu-Ti, Cu-Zr, Cu-40Zr-10Fe	Very low (~0) magnetoresistance
Cu-Zr-P	Amorphous; enhanced corrosion resistance

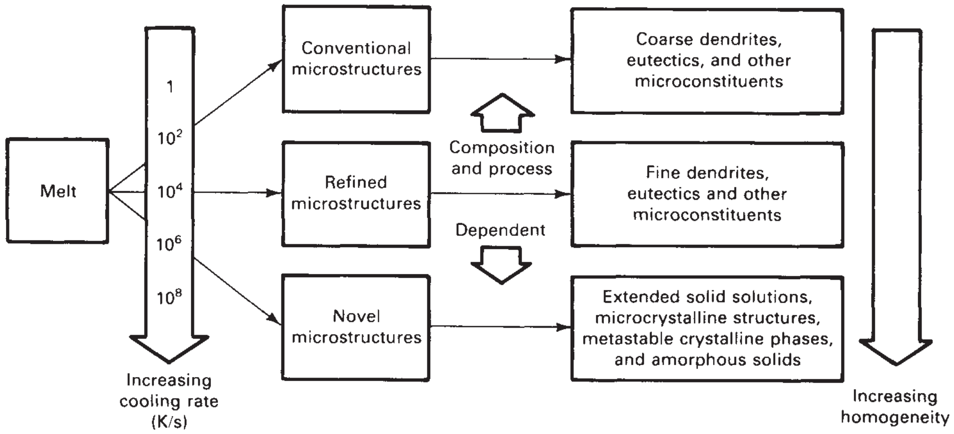

Fig. 12 The effect of cooling rate on microstructure. Rapid solidification increases homogeneity and results in microcrystalline or glassy structures. Classifications are approximate and depend on composition and processing as well as cooling rate.

Fig. 13 Scanning electron micrograph of Cu-24.3Zn-9Al (at.%) alloy, rapidly solidified by melt spinning. Beta-phase grain size is very fine, and the structure shows no evidence of segregation. As-polished. 950×

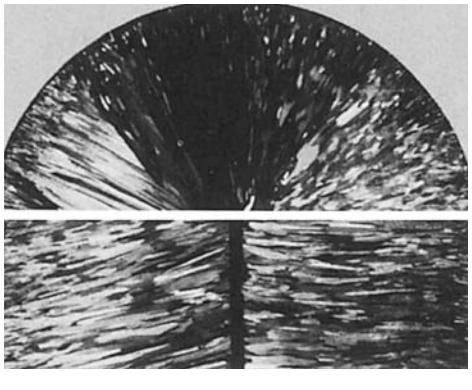

Fig. 14, 15 Alloy C12200 (DHP copper), continuous cast in a 102 mm (4 in.) diam ingot. Fig. 14: transverse section. Fig. 15: longitudinal section. Columnar grains are oriented along the axis. See also Fig. 25 and 26. Waterbury reagent. 0.6×

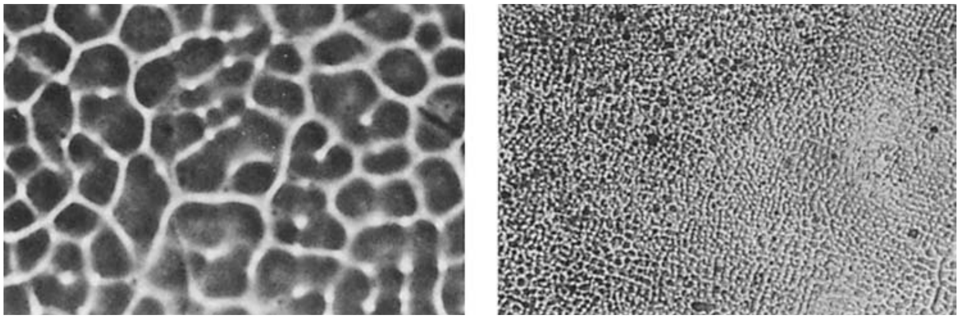

Fig. 16, 17 Same alloy and processing as Fig. 14 and 15. Fig. 16: section normal to the direction of columnar growth taken from near the surface of the ingot. The structure is coarse, unbranched dendrites. Fig. 17: longitudinal section taken from near the center of the ingot. Dendrite spacing is much finer than in Fig. 16. Waterbury reagent. 150×

of the ingot, the interface advances approximately at right angles to the mold wall; at the center of the ingot, the interface advances along the axis of the ingot. Columnar grains usually develop with a preferred crystal orientation in the direction of heat flow and with the grain boundaries parallel to this direction (Ref 8).

In the structure shown in Fig. 15, the grain boundaries near the center of the ingot do not follow the isotherms during growth, but continue parallel to the crystal direction established near the surface, that is, at the start of growth. The longitudinal center grain is an exception. At the very center of the ingot, a grain can grow continuously and still maintain a constant orientation of its direction of growth.

As noted earlier in discussing electromagnetic casting, dendrites at the surface can also grow parallel to the casting direction along the ingot surface. Because the start of freezing is a discontinuity in the freezing front, there are two preferred growth directions—one in the casting direction and one approximately perpendicular to the freezing front. This is true at all mold and chill surfaces and explains the appearance of branched dendrites at chill surfaces as well as their absence in the interior of lightly alloyed castings (Ref 21).

A notable feature of DHP copper ingots is the relationship between grain structure and dendritic structure. The unbranched dendrites characteristic of this alloy are not effective sources of detached arms, which would form new equiaxed grains (Ref 22). As a result, the internal structure of DHP copper ingots is completely columnar. However, the chill surface structure is branched dendritic. Therefore, grain refinement at the chill surface is possible, for example, by stirring at the start-of-freezing position (Ref 23).

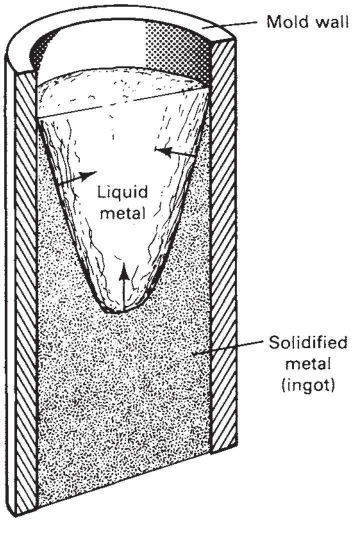

Fig. 18 The freezing front during continuous casting of a copper alloy ingot. Arrows are normal to the liquid-solid interface and show the freezing direction.

Table 2 The effect of dendrite structure on crystal multiplication

	"Low" solute	"High" solute
Surface of ingot	Branched dendrites Crystal multiplication possible	Branched dendrites Crystal multiplication possible
Interior of ingot	Unbranched dendrites No crystal multiplication	Branched dendrites Crystal multiplication possible

The influence of dendrite structure on grain structure is demonstrated by the differing effects of different solute element additions on the change from columnar to equiaxed solidification. A higher concentration of elements produces a result similar to a low partition coefficient. This follows the same trend as reported in aluminum (Ref 24), which is explained by the influence of alloying elements on dendritic branching and therefore crystal multiplication. Table 2 summarizes the possibilities for crystal multiplication at the surface and interior of ingots, depending on the dendritic structure.

Grain Structure in Static-Cast Ingots. Figures 19 and 20 show transverse and longitudinal sections of a static-cast ingot of alloy C36000 (free-cutting brass). In the transverse section, the structure appears completely equiaxed, with finer grains at the edge and coarser grains at the center. In the longitudinal section, columnar grains are visible that extend for almost half the radius toward the center of the ingot. This demonstrates the importance of orientation of the macrosection in providing an accurate representation of grain structure; the transverse section is clearly misleading. In the transverse section and the longitudinal section, close examination shows concentric rings of relatively fine, equiaxed grains within the zone of columnar grains. These fine grains are formed from dendrite arms that are detached by convection during solidification, such as the convection caused by afterpouring to prevent top-pipe formation. Marked variation in local grain size is a typical condition in alloys in which the dendrite arms are branched. Branched dendrites are an effective source of detached arms for the formation of new equiaxed grains (Ref 6).

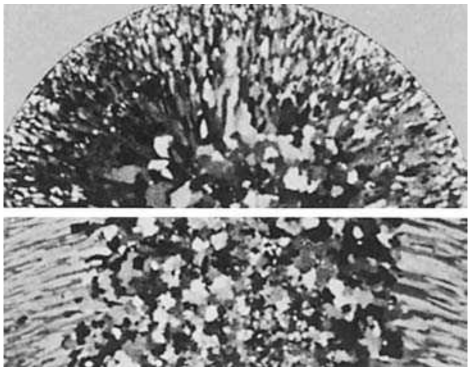

Fig. 19, 20 Alloy C36000 (free-cutting brass), static-cast 203 mm (8 in.) diam ingot. Fig. 19: transverse section. Fig. 20: longitudinal section. Columnar grains extend nearly halfway to the center of the ingot. Boiling 20% HNO_3 + 20% acetic acid. 0.3×

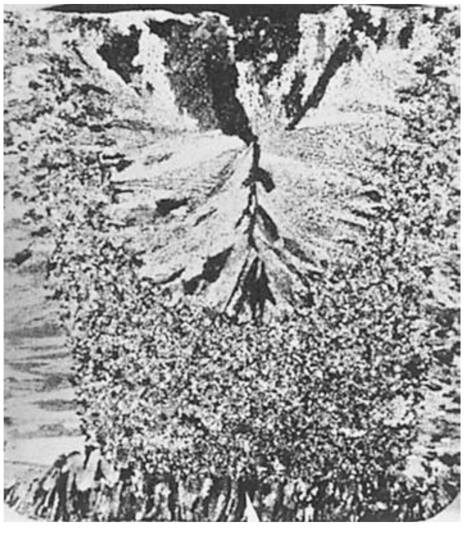

Fig. 21 Alloy C11000 electrolytic tough pitch copper wire bar. Transverse section shows a pattern of coarse and fine grains. 50% HNO_3 + 50% H_2O. 0.6×

Grain Structure in Wire Bars. Figure 21 shows a transverse section through a wire bar of tough-pitch (level-set) copper, which contains approximately 0.04% O. Measurements of dendrite arm spacing indicate the minimal correlation between grain size and dendrite spacing (Ref 25). Interpretation of complex structures of this kind must consider heat loss from the open (top) surface and to the mold as well as the movement of partially formed (dendritic) grains during ingot solidification. Structures rather different from that shown in Fig. 21 are seen in "wire bar" produced by continuous casting processes such as the wheel-and-belt or Hazelett twin-belt methods. Figures 22 and 23 illustrate the grain structure produced in a continuous-cast wire bar (Ref 26). In this copper alloy having only 150 to 200 ppm oxygen, grain size can be varied greatly primarily by changing the casting temperature. Lower casting temperature allows the solid fragments pro-

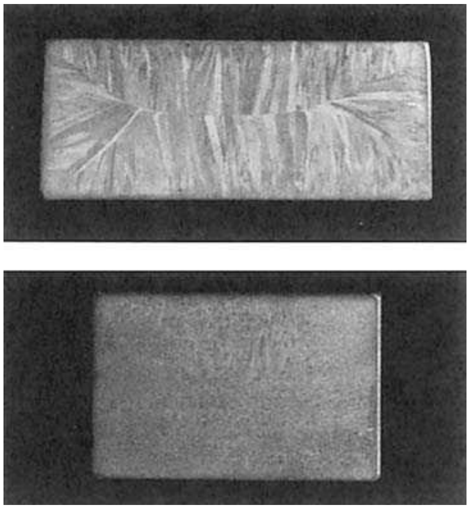

Fig. 22, 23 The effect of casting temperature on continuous-cast copper wire bar. Fig. 22: cast at 1150 °C (2100 °F). Fig. 23: cast at 1120 °C (2050 °F). The higher casting temperature produced a coarser grain structure in the ingot. Etchant not reported. 0.4×

duced by crystal multiplication to survive as the nuclei of new grains. Although grain structure is more uniform, the main improvement in the cast structure of continuous-cast processes for wire rod is control of oxygen content. In static-cast wire bar, the set surface absorbs oxygen from the air. By contrast, continuous-cast wire bar has oxides distributed evenly throughout the cross section. In addition, because feeding of shrinkage in continuous casting differs from static casting, good results are obtained at lower oxygen contents.

Ingot Defects

Defects in ingots are regarded as those nonuniform features of the structure that usually are the direct cause of rejections during subsequent working. Examples of ingot defects are macrosegregation, inclusions, unsoundness, and cracks originating from thermal stresses or frictional forces.

Thermal-Stress Cracking. Longitudinal surface cracks are common in ingots fabricated with poor control conditions (leaving a hot spot). This type of crack is illustrated in Fig. 24. Center cracks, which are also called spider cracks, may form in an ingot that has excessive cooling at the end of solidification combined with intergranular segregation that weakens the grain boundaries.

Dye-penetrant indications of center cracks in such an ingot of alloy C12200 (DHP copper) are shown in transverse and longitudinal sections in Fig. 25 and 26. Etched sections through the same continuous-cast 102 mm (4 in.) diam ingot are shown in Fig. 14 and 15. The cracks, which were not readily visible in the etched cast structure, are easily discernible by dye-penetrant inspection of the transverse section (Fig. 25); the severity of the cracks is further revealed by inspection of the longitudinal section (Fig. 26). Even more sensitive is a leak test of a wafer or a fracture test of suspect material, followed by scanning electron microscopy of the fracture surface. Separation during fracture of solids is easily differentiated from solidification cracks.

Fine, intergranular cracking may occur in the center of ingots having equiaxed grains in the center region. This type of cracking is illustrated in Fig. 27, which shows an ingot of alloy C36000 (free-cutting brass). The cracking discussed to this point results from the thermal stresses of solidification.

Transverse Defects. Transverse cracking is common in continuous-cast ingots. The mechanism of formation of these cracks, called witness marks, has been explained (Ref 27). Surface cold shuts, another transverse defect, are illustrated in Fig. 28 and 29. Cold shuts and similar surface defects often result from low casting speed (Ref 28). Figure 30 shows hot tears at the grain boundaries and between dendrite cells in

Fig. 24 Alloy C36000 (free-cutting brass) semicontinuous cast in a 254 mm (10 in.) diam ingot. A longitudinal crack in the surface of the ingot. Severe macrosegregation can accompany cracks of this type. See also Fig. 39. Not polished, not etched. Actual size

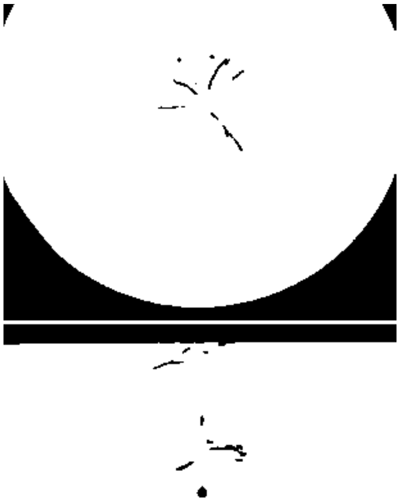

Fig. 25, 26 Spider cracks in the center of the ingot in Fig. 14 and 15. Fig. 25: transverse section. Fig 26: longitudinal section. Dye penetrant. Approximately 0.5×

Fig. 27 Same alloy and processing as Fig. 24, showing fine intergranular cracks in the region of equiaxed grains at the center of the ingot. $HNO_3 + H_2O$ at 60 °C (140 °F). 4×

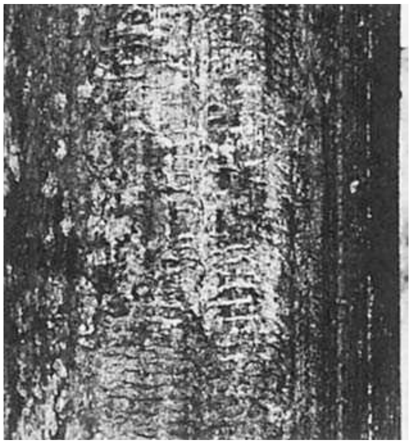

Fig. 28 Alloy C36000 (free-cutting brass), slowly poured semicontinuous-cast ingot showing cold shuts on the surface of the ingot. Cold shuts often result from low casting speeds. See also Fig. 29. Not polished, not etched. 0.25×. Source: Ref 28

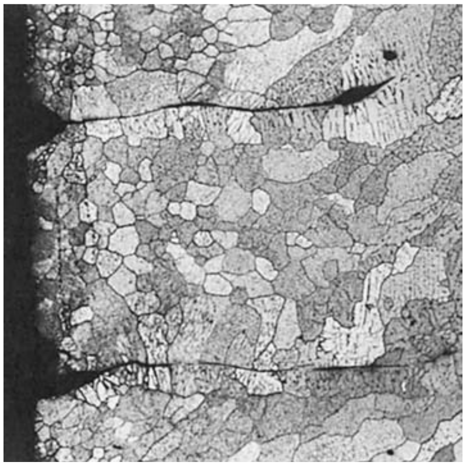

Fig. 29 Semicontinuous-cast ingot of alloy C26000 (cartridge brass). Longitudinal section through cold shuts on the surface of the ingot (left). See also Fig. 28. Etchant not reported. 6×. Source: Ref 28

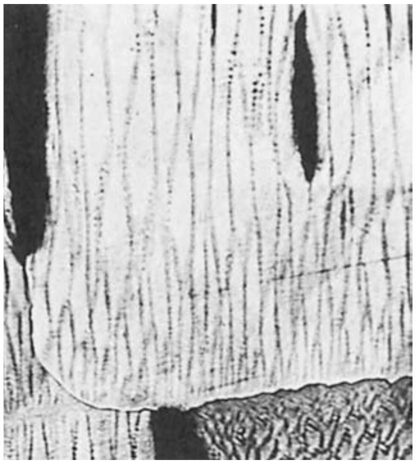

Fig. 30 Low-oxygen, high-purity copper ingot, with hot tears (black) at grain boundaries and between dendrite cells. Some segregation of solute occurs even in high-purity materials and can weaken grain boundaries and hot tears. Alcoholic $FeCl_3$. 60×. Source: Ref 1

an ingot of low-oxygen, high-purity copper. Even in high-purity material, some segregation of solute can occur during solidification, weakening the grain boundaries and leading to hot tears (Ref 1). Solutes at a level of 1 ppm can segregate to very high levels at grain boundaries (Ref 29). This is a result of solute redistribution during solidification combined with favorable energetics for solute buildup at grain boundaries at the atomic level and is best determined by Auger analysis of fracture surfaces.

Unsoundness. Gas that evolved during solidification can result in diverse structural features, including those that clearly constitute defects. The gas is evolved because of its lower solubility in the solid metal than in the liquid phase.

Unsoundness in semicontinuous-cast ingots is usually nonuniform (Ref 2). Shrinkage cavities near the surface of an ingot of alloy C71500 (copper nickel, 30%) are revealed by microradiography (Fig. 31), but not by optical microscopy (Fig. 32). The gross unsoundness at the center of the ingot, which is the result of microshrinkage and gas evolution, is shown in Fig. 33. Usually, gas evolution and microshrinkage result in a higher percentage of porosity in the more slowly cooled central region of the ingot than in the rapidly frozen outer regions (Ref 30).

Macrosegregation. A common type of segregation is macrosegregation, which results from the interdendritic flow of solute-enriched liquid (Ref 31). The variation in tin concentration in a cast slab of tin bronze (8% Sn) is illustrated in Fig. 34. A higher level of solute at the surface is often observed and is termed inverse segregation.

Figure 35 shows a high percentage of an intermetallic tin-rich phase near the bottom surface of an ingot of tin bronze having 5% Sn (Ref 1). The surface layer of tin-rich phase that is nearly pure tin presumably was formed by exudation. The exudation results from the flow of solute-enriched, interdendritic liquid out of the surface region of the casting during the late stages of solidification.

An example of extreme segregation in alloy C36000 (free-cutting brass) is presented in Fig. 36. The segregate is greatly enriched in zinc. Replacing the cover of carbon powder formerly used in casting brass (Fig. 36) with a light glass cover (supplied as proprietary formulations) prevents vaporization of zinc.

Sever macrosegregation can accompany ingot cracks caused by thermal stresses. Figure 37 shows the region adjacent to the longitudinal surface crack in an ingot of alloy C36000 (free-cutting brass) shown in Fig. 24. The light areas have a high coefficient of x-ray absorption and have been identified as lead rich.

Macrosegregation can also result from other mechanisms, such as the reaction of two elements to form an undesirable stable solid constituent in the melt; the constituent agglomerates during melting and often is nonuniformly distributed in the casting. Such constituents having high melting points are usually hard and brittle and thus undesirable. Figure 38 illustrates inclusions in a brass alloy of high tensile strength; this alloy contained 2% Fe (Ref 33). The inclusions formed when 0.01% Si was added to the melt.

Effects of Defects on Fabrication. In some instances, relationships between ingot structure and success of fabrication are clearly established. For example, segregation caused by exudation will persist into the fabricated structure, as shown in Fig. 39. Another example is the extrusion defect of the type presented in Fig. 40 and 41; this defect can result when longitudinal surface cracks in the ingot flow inward during extrusion.

Fig. 31, 32 ,33 Alloy C71500 (copper nickel, 30%), semicontinuous cast in a 229 mm (9 in.) diam ingot. Fig. 31: shrinkage porosity in the ingot is revealed by microradiography. Fig. 32: the same section, but optical microscopy does not reveal the interdendritic shrinkage cavities. Fig. 33: specimen from near the center of the ingot. The pores are larger than in Fig. 31. Fig. 31 and 33: as-polished. Fig. 32: Waterbury reagent. All 50×. Source: Ref 1

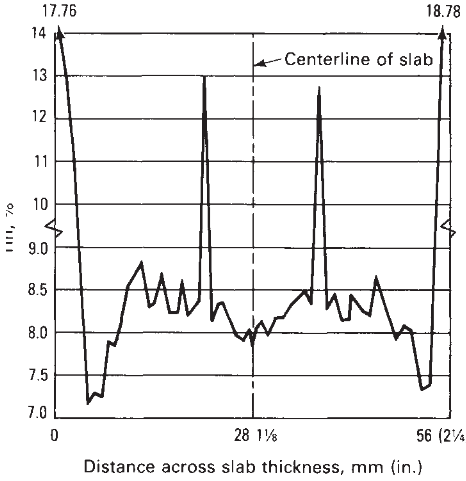

Fig. 34 Variation in tin content across a 56 mm (2.25 in.) thick slab of tin bronze (8% Sn). See also Fig. 35 and Fig. 10. Source: Ref 32

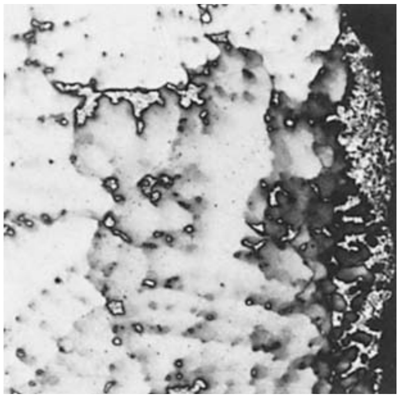

Fig. 35 Horizontal cast strip of tin bronze (5% Sn), showing inverse segregation at the bottom surface of the casting (right). The surface layer is nearly pure tin. 40 mL HNO_3, 25 g CrO_3, and 35 mL H_2O. 100×. Source: Ref 1

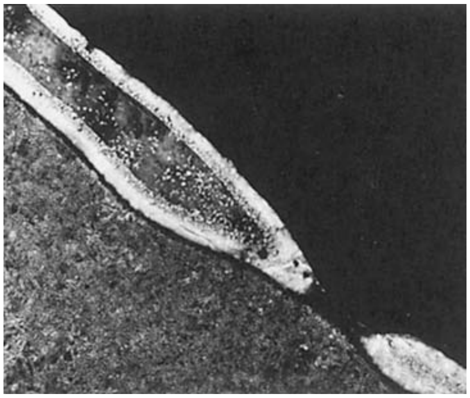

Fig. 36 Alloy C36000 (free-cutting brass) ingot, semicontinuous cast. Zinc-rich "smudges" on the surface (top left to bottom right) are the result of condensation, on the mold wall, of zinc vapor trapped by the layer of carbon powder covering the melt. This problem has been solved by the use of proprietary glass covers that prevent zinc evaporation and recondensation. NH_4OH + H_2O_2. 10×

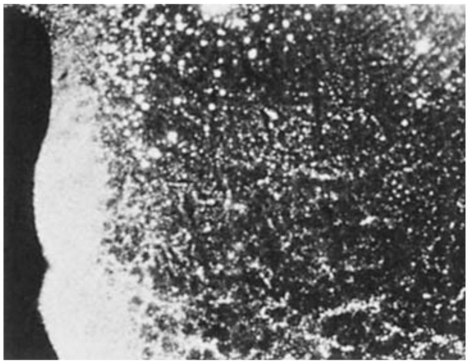

Fig. 37 Alloy C36000 (free-cutting brass) ingot. A microradiograph of a thin section taken from an area near the longitudinal crack in the specimen shown in Fig. 24. Light areas are lead rich. As-polished. 50×

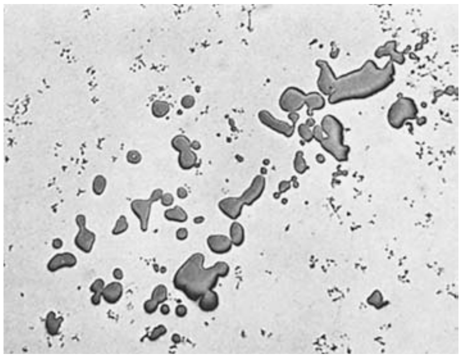

Fig. 38 Cu-37Zn-2Al-2Fe alloy, showing globular inclusions of a hard, iron-rich constituent that precipitated after the addition of 0.01% Si to the melt. The specimen is from a sample quenched from the top of the melt. As-polished. 40×. Source: Ref 33

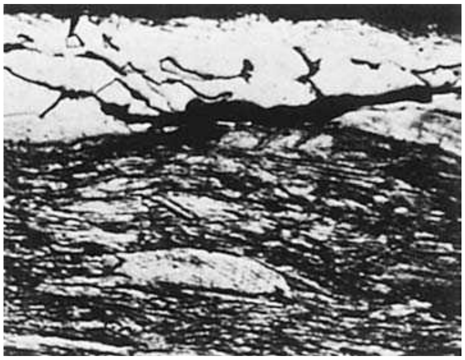

Fig. 39 Phosphor bronze strip rolled from a static-cast ingot, showing gross tin sweat on the surface (top). Illustrates how segregation caused by exudation persists in the fabricated structure. Etchant not reported. 300×. Source: Ref 34

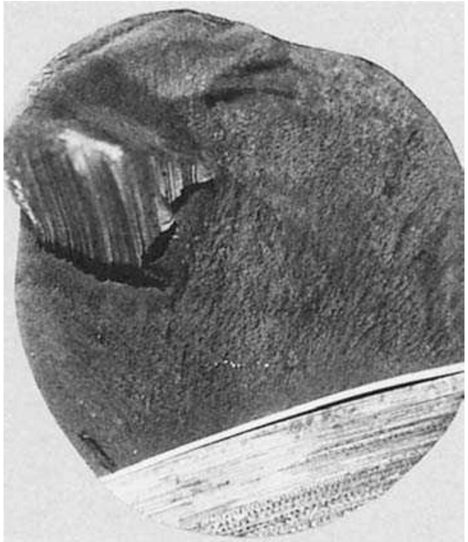

Fig. 40 Alloy C36000 (free-cutting brass) extrusion. Transverse fracture shows internal cracks, which are associated with a pipe, or extrusion, defect. See also Fig. 41. Not polished, not etched. 1.4×

Fig. 41 Same specimen as Fig. 40. Polished and etched transverse section shows internal cracks, which result when longitudinal surface cracks in the ingot flow inward during extrusion. 50 mL HNO_3 + 50 mL acetic acid. 1.4×

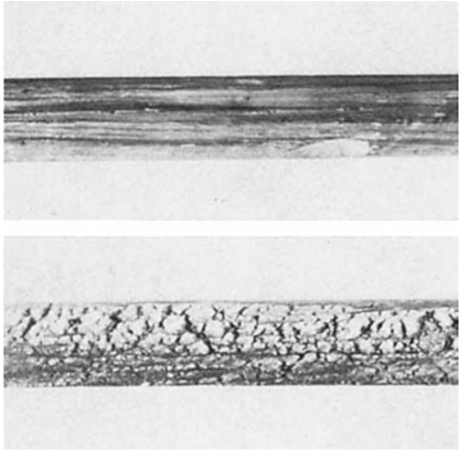

Fig. 42, 43 Alloy C63800 ingot, hot rolled in several passes to 80% total reduction. Fig. 42: the edge was rolled from an ingot without inverse segregation. Fig. 43: the edge was rolled from an ingot with inverse segregation.

Advantages claimed for electromagnetic casting include better surface after hot rolling in material free of inverse segregation (Ref 12). Similarly, edge condition after hot or cold reduction is better when the casting is free of surface defects, which induce edge cracking in hot and cold rolling. Figures 42 and 43 illustrate the edges of alloy C63800 ingots after hot rolling to a total of 80% reduction. The edge rolled from an ingot without surface defects (Fig. 42) is in much better condition than the edge rolled from an ingot with surface defects (Fig. 43).

ACKNOWLEDGMENT

This article was adapted from T.F. Bower and M.R. Randlett, Solidification Structures of Copper Alloy Ingots, *Metallography and Microstructures*, Vol 9, *ASM Handbook*, ASM International, 1985, p 637–645

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Phase Diagrams

PHASE DIAGRAMS covering many of the commercially important copper alloy systems are presented in this article. Crystallographic data in tabular form accompany some of the diagrams. The binary alloy diagrams included here (Fig. 1–26) are the result of critical assessment by experts in the field under the coordination of the International Programme for Alloy Phase Diagrams. The ternary alloy diagrams (Fig. 27–51) were selected from the comprehensive collection of ternary diagrams, the multivolume *Handbook of Ternary Alloy Phase Diagrams,* edited by P. Villars, A. Prince, and H. Okamoto and published by ASM International in 1994. All of the binary and ternary phase diagrams presented herein were also published in *Alloy Phase Diagrams,* Volume 3 of the *ASM Handbook.* This volume should be consulted for original bibliographic citations relating to specific phase diagrams.

Copper Alloy Systems. Copper is one of the few metals that are used mainly in pure form rather than as alloys. Commercially pure coppers, with minimum copper content of 99.3% or higher, are widely used by the electrical industry to produce wire for motors, generators, and power distribution and control equipment. Electrical coppers have different degrees of purity and therefore different characteristics. For example, some contain deliberate small additions of silver, cadmium, or zirconium for improved resistance to thermal softening. Tellurium- and sulfur-bearing coppers have improved machining characteristics.

Copper alloys range from high copper alloys containing nominally 94% Cu to the more highly alloyed brasses, bronzes, copper-nickels, nickel silvers, and some specialty alloys. High copper alloys contain small amounts of various alloying elements, such as beryllium, cadmium, chromium, or iron. Alloying generally serves to impart higher strength, thermal stability, or other mechanical attributes, while retaining sufficient electrical conductivity for the intended use. The brasses are based on the Cu-Zn, Cu-Zn-Pb (leaded brasses), and Cu-Zn-Sn (tin brasses) systems. Bronzes are based on the Cu-Sn-P (phosphor bronzes), Cu-Sn-Pb-P (leaded phosphor bronzes), Cu-Al (aluminum bronzes), and Cu-Sn (silicon bronzes) systems. Other copper alloys are based on the Cu-Ni (copper-nickels) and Cu-Ni-Zn (nickel silvers) systems. Each of these alloy systems may be modified with other alloying elements to create alloys with special properties and/or characteristics (for example, improved wear or corrosion resistance).

The binary systems included in this article include Cu-Ag, Cu-Al, Cu-As, Cu-Au, Cu-Be, Cu-Bi, Cu-Cd, Cu-Co, Cu-Cr, Cu-Fe, Cu-Mn, Cu-Ni, Cu-O, Cu-P, Cu-Pb, Cu-Pd, Cu-S, Cu-Sb, Cu-Se, Cu-Si, Cu-Sn, Cu-Te, Cu-Zn, and Cu-Zr. Ternary systems illustrated include Cu-Ag-Au, Cu-Ag-Cd, Cu-Al-Fe, Cu-Al-Mn, Cu-Al-Zn, Cu-Fe-Ni, Cu-Ni-Sn, Cu-Ni-Zn, Cu-Pb-Zn, Cu-Sb-Sn, and Cu-Sn-Zn. The ternary diagrams are mostly isothermal sections at various temperatures. Solidus and liquidus projections for some of these ternary systems can be found in Volume 3 of the *ASM Handbook.*

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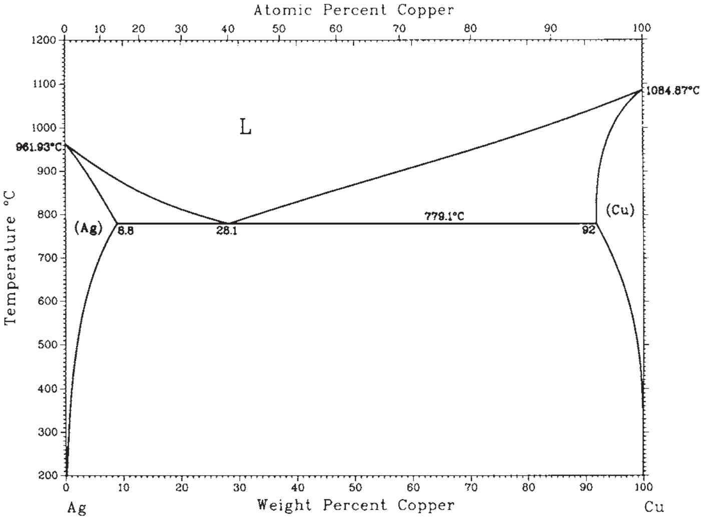

Fig. 1 The copper-silver (Cu-Ag) binary phase diagram and crystal structure data

Phase	Composition, wt% Cu	Pearson symbol	Space group
(Ag)	0–8.8	*cF*4	$Fm\bar{3}m$
(Cu)	92.0–100	*cF*4	$Fm\bar{3}m$

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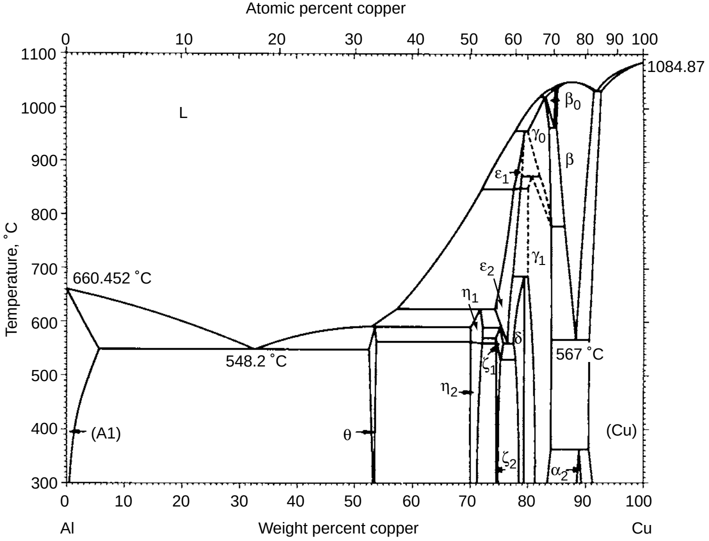

Phase	Composition, wt% Cu	Pearson symbol	Space group
(Al)	0–5.65	$cF4$	$Fm\bar{3}m$
θ	52.5–53.7	$tI12$	$I4/mcm$
η_1	70.0–72.2	$oP16$ or $oC16$	$Pban$ or $Cmmm$
η_2	70.0–72.1	$mC20$	$C2/m$
ζ_1	74.4–77.8	$hP42$	$P6/mmm$
ζ_2	74.4–75.2	(a)	…
ε_1	77.5–79.4	(b)	…
ε_2	72.2–78.7	$hP4$	$P6_3/mmc$
δ	77.4–78.3	(c)	$R3m$
γ_0	77.8–84	(d)	…
γ_1	79.7–84	$cP52$	$P\bar{4}3m$
β_0	83.1–84.7	(d)	…
β	85.0–91.5	$cI2$	$Im\bar{3}m$
α_2	88.5–89	(e)	
(Cu)	90.6–100	$cF4$	$Fm\bar{3}m$
Metastable phases			
θ′	…	$tP6$	…
β′	…	$cF16$	$Fm\bar{3}m$
Al_3Cu_2	61–70	$hP5$	$P\bar{3}m1$

(a) Monoclinic? (b) Cubic? (c) Rhombohedral. (d) Unknown. (e) $D0_{22}$-type long-period superlattice

Fig. 2 The copper-aluminum (Cu-Al) binary phase diagram and crystal structure data

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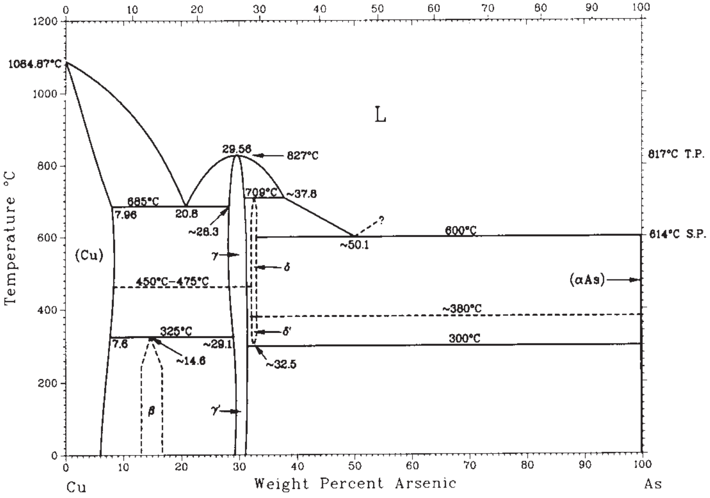

Phase	Composition, wt% As	Pearson symbol	Space group
(Cu)	0 to ~7.96	$cF4$	$Fm\bar{3}m$
β	12.8–16.4	$hP2$	$P6_3/mmc$
γ(HT)	28.2–31.2	$hP8$	$P6_3/mmc$
γ′(LT)	28.8–31.2	$hP24$	$P\bar{3}c1$
δ(HT)	32.1–33.1	$cF16$	$Fm\bar{3}m$
δ′(LT)	32.1–33.1	$oI28$	$Ibam$
(As)	100	$hR2$	$R\bar{3}m$
Metastable phases			
Cu_2As	~37.1	$tP6$	$P4/nmm$
Cu_3As_4	~61.12	$oI28$	$Immm$

Fig. 3 The copper-arsenic (Cu-As) binary phase diagram and crystal structure data

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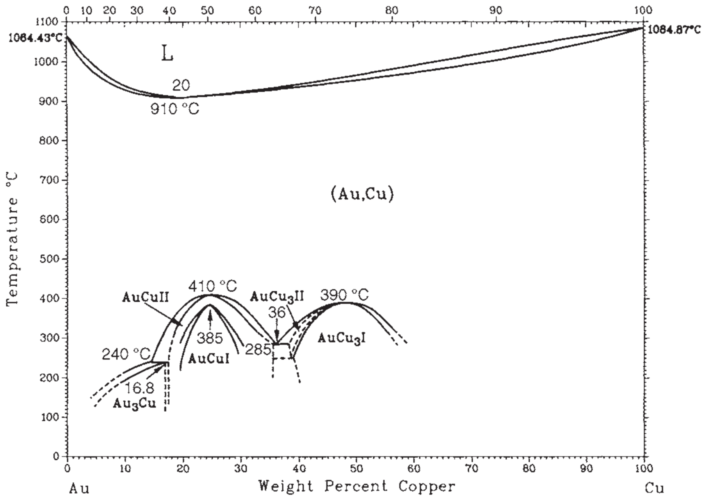

Phase	Composition, wt% Cu	Pearson symbol	Space group
(Au,Cu)	0–100	$cF4$	$Fm\bar{3}m$
Au_3Cu	3–16.8	$cP4$	$Fm\bar{3}m$
AuCu(I)	19–30	$tP4$	$P4/mmm$
AuCu(II)	16.8–35	$oI40$	$Imma$
$AuCu_3$(I)	40–58	$cP4$	$Pm\bar{3}m$
$AuCu_3$(II)	39–?	$tP28$	$P4mm$

Fig. 4 The copper-gold (Cu-Au) binary phase diagram and crystal structure data

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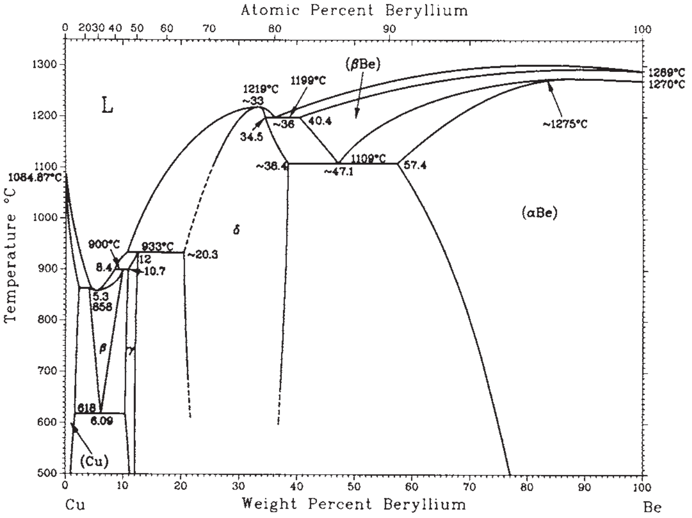

Fig. 5 The copper-beryllium (Cu-Be) binary phase diagram and crystal structure data

Phase	Composition, wt% Be	Pearson symbol	Space group
(Cu)	0–2.2	*cF*4	$Fm\bar{3}m$
β	4.3–9.8	*cI*2	$Im\bar{3}m$
γ	10.3–12.4	*cP*2	$Pm\bar{3}m$
δ	~20.4 to ~38.5	*cF*24	$Fd\bar{3}m$
(βBe)	40.4–100	*cI*2	$Im\bar{3}m$
(αBe)	57.5–100	*hP*2	$P6_3/mmc$

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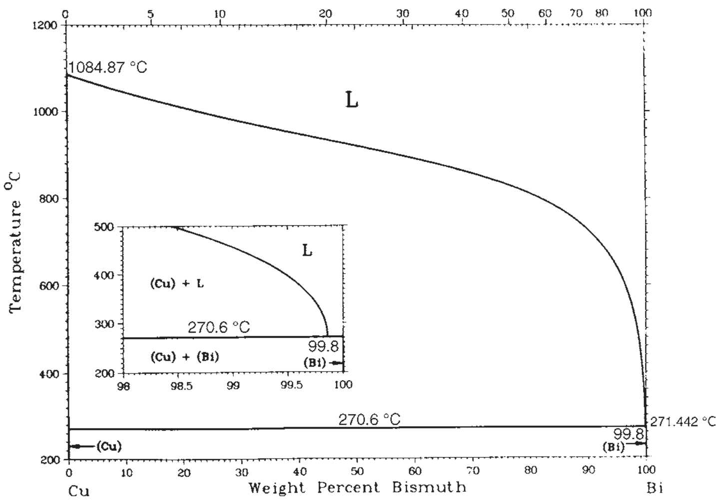

Fig. 6 The copper-bismuth (Cu-Bi) binary phase diagram and crystal structure data

Phase	Composition, wt% Bi	Pearson symbol	Space group
(Cu)	0–0.010	*cF*4	$Fm\bar{3}m$
(Bi)	100	*hR*2	$R\bar{3}m$
Metastable phase			
Cu_5Bi_2	57	…	…

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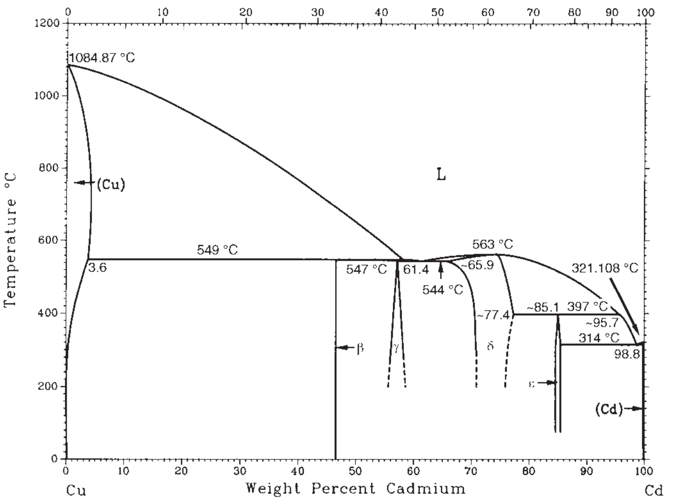

Fig. 7 The copper-cadmium (Cu-Cd) binary phase diagram and crystal structure data

Phase	Composition, wt% Cd	Pearson symbol	Space group
(Cu)	0–3.6	*cF*4	$Fm\bar{3}m$
β	46.9	*hP*24	$P6_3/mmc$
γ	56.0–58.3(a)	*cF*1124	$F\bar{4}3m$
δ	65.9–77	*cI*52	…
ε	84.6–85.9	*hP*28	$P6_3/mmc$
(Cd)	~99.9–100	*hP*2	$P6_3/mmc$

(a) At 300 °C (572.0 °F)

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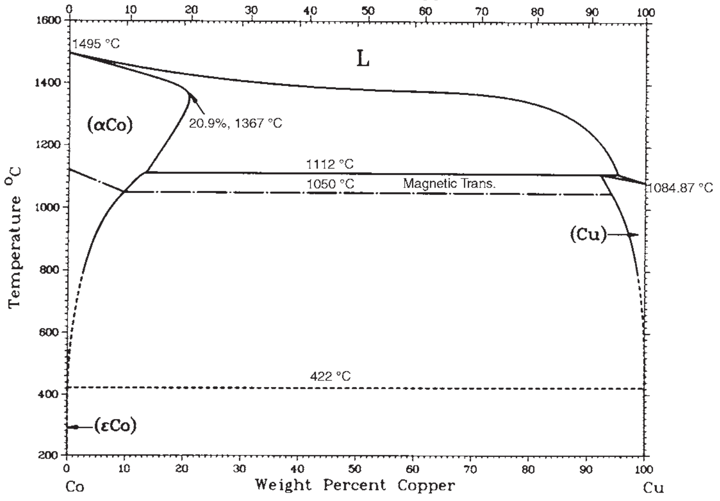

Fig. 8 The copper-cobalt (Cu-Co) binary phase diagram and crystal structure data

Phase	Composition, wt% Cu	Pearson symbol	Space group
(αCo)	0–20.9	*cF*4	$Fm\bar{3}m$
(εCo)	0–9(a)	*hP*2	$P6_3/mmc$
(Cu)	93–100	*cF*4	$Fm\bar{3}m$
Metastable phase			
ε′	9–10	*hR*1	$R\bar{3}m$

(a) The composition of (εCo) is between 0 and 0.3 wt% Cu in equilibrium, but is 0–9 wt% Cu in the metastable state, which is obtained by quenching from high temperatures.

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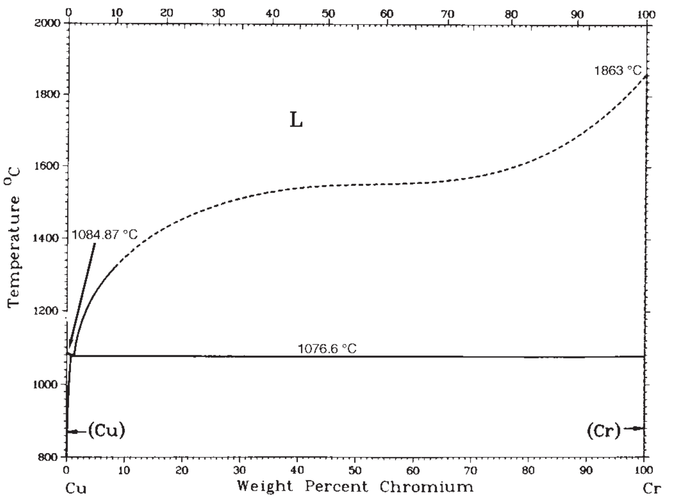

Fig. 9 The copper-chromium (Cu-Cr) binary phase diagram and crystal structure data

Phase	Composition, wt% Cr	Pearson symbol	Space group
(Cu)	0–0.73	*cF*4	$Fm\bar{3}m$
(Cr)	99.8–100	*cI*2	$Im\bar{3}m$

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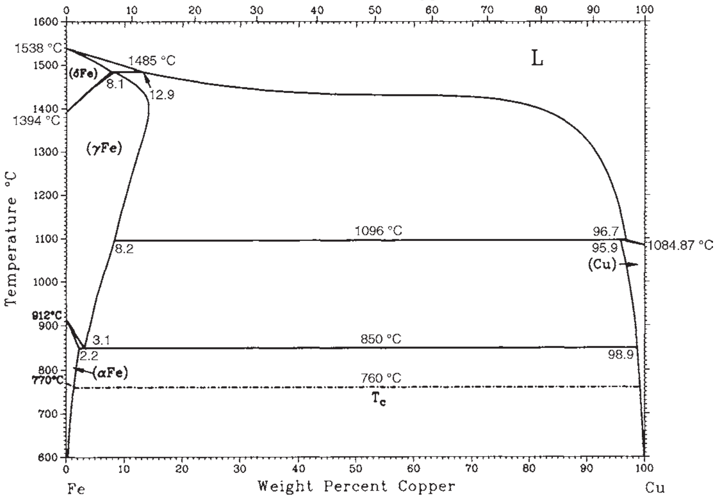

Fig. 10 The copper-iron (Cu-Fe) binary phase diagram and crystal structure data

Phase	Composition, wt% Cu	Pearson symbol	Space group
(δFe)	0–7.6	*cI*2	$Im\bar{3}m$
(γFe)	0–13	*cF*4	$Fm\bar{3}m$
(αFe)	0–2.2	*cI*2	$Im\bar{3}m$
(Cu)	95.9–100	*cF*4	$Fm\bar{3}m$

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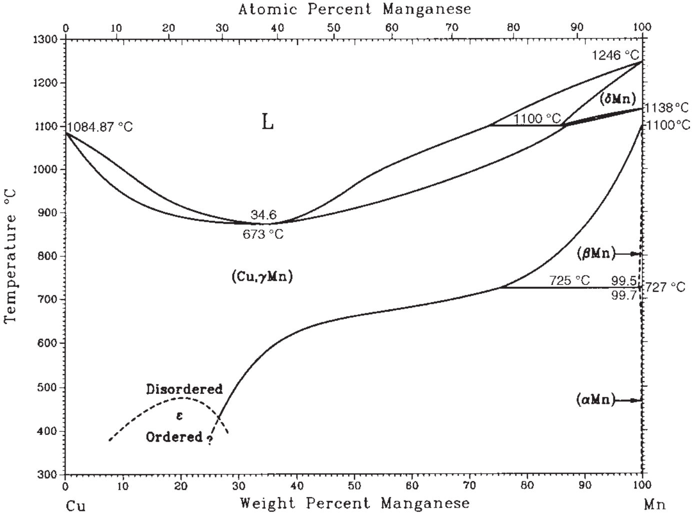

Fig. 11 The copper-manganese (Cu-Mn) binary phase diagram and crystal structure data

Phase	Composition, wt% Mn	Pearson symbol	Space group
(Cu,γMn)	0–100	*cF*4	$Fm\bar{3}m$
(δMn)	85.8–100	*cI*2	$Im\bar{3}m$
(βMn)	99.5–100	*cP*20	$P4_132$
(αMn)	99.7–100	*cI*58	$I\bar{4}3m$

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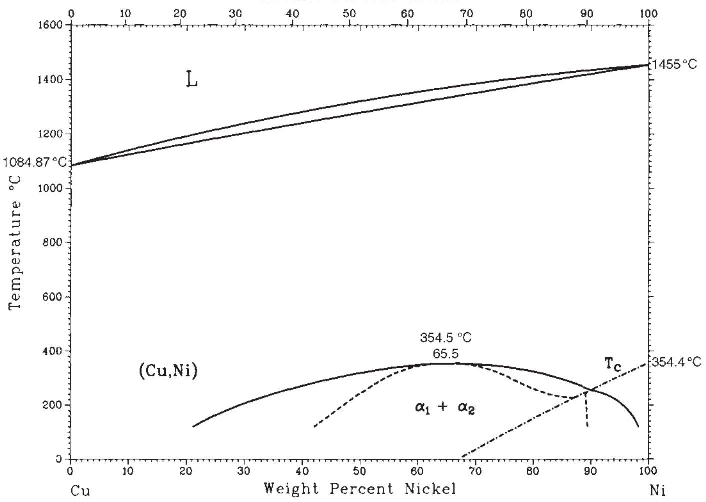

Fig. 12 The copper-nickel (Cu-Ni) binary phase diagram and crystal structure data

Phase	Composition, wt% Ni	Pearson symbol	Space group
(Cu,Ni)	0–100(a)	*cF*4	$Fm\bar{3}m$

(a) Above 354.5 °C (669.2 °F)

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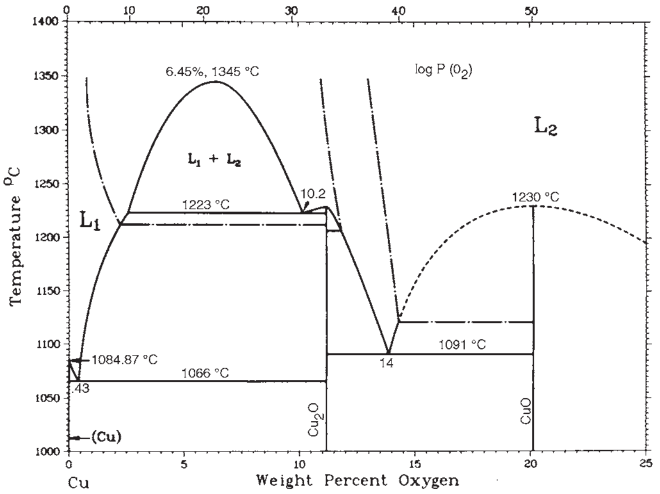

Fig. 13 The copper-oxygen (Cu-O) binary phase diagram and crystal structure data

Phase	Composition, wt% O	Pearson symbol	Space group
(Cu)	0–0.008	*cF*4	$Fm\bar{3}m$
Cu_2O(a)	11.2	*cP*6	$Pn\bar{3}m$
CuO(b)	20	*mC*8	…
Cu_4O_3(c)	15.9	*tI*28	*I*4/*mcm*

(a) κ or cuprite. (b) τ or tenorite. (c) Additional possible phase, π or paramelaconite

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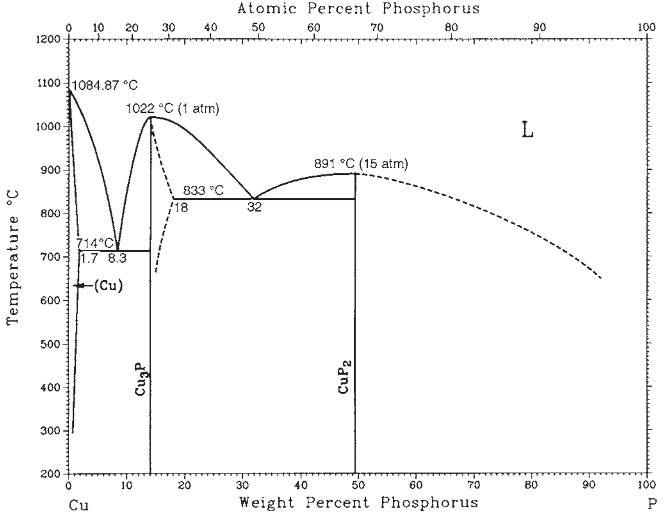

Phase	Composition, wt% P	Pearson symbol	Space group
(Cu)	0–1.7	*cF*4	$Fm\bar{3}m$
Cu$_3$P	14–18	*hP*24	$P6_3cm$
CuP$_2$	49.4	*mP*12	$P2_1/c$
Cu$_2$P$_7$(a)	63.1	*mC*72	$C2/m$

(a) Not shown in the diagram

Fig. 14 The copper-phosphorus (Cu-P) binary phase diagram and crystal structure data

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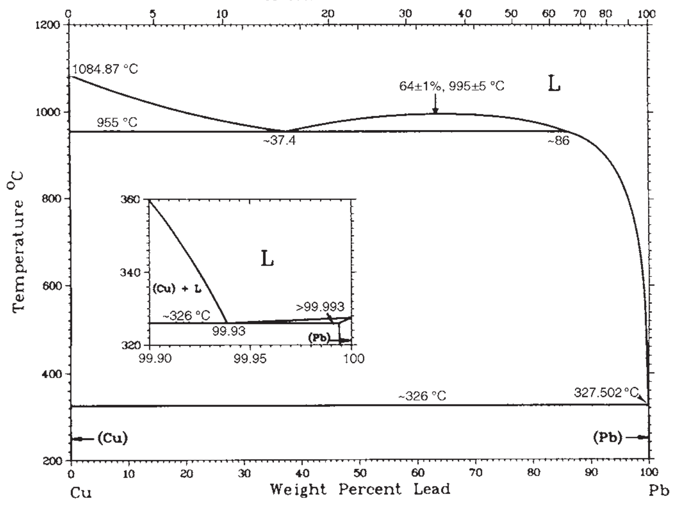

Phase	Composition, wt% Pb	Pearson symbol	Space group
(Cu)	0(a)	*cF*4	$Fm\bar{3}m$
(αPb)	100	*cF*4	$Fm\bar{3}m$
(βPb)(b)	100	*hP*2	$P6_3/mmc$

(a) Metastable solid solubility may extend up to 10.0–12.0 wt% Pb. (b) Above 10.3 GPa

Fig. 15 The copper-lead (Cu-Pb) binary phase diagram and crystal structure data

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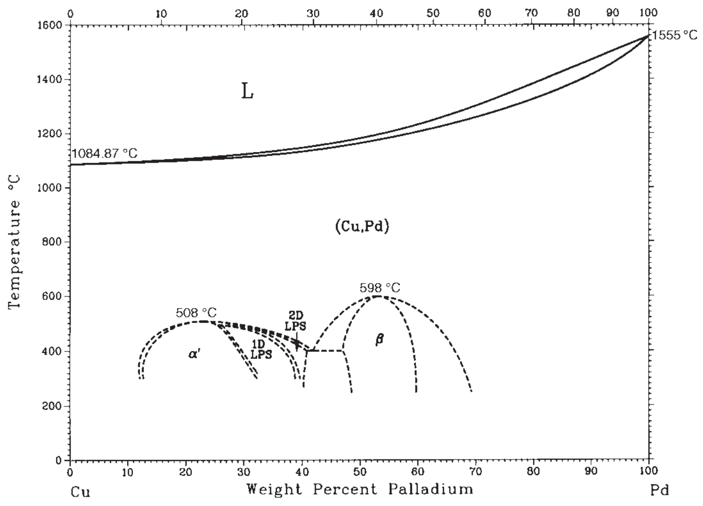

Phase	Composition, wt% Pd	Pearson symbol	Space group
(Cu,Pd)	0–100	*cF*4	$Fm\bar{3}m$
Cu$_3$Pd (α′)	~12.1 to ~32	*cP*4	$Pm\bar{3}m$
Cu$_3$Pd (α′)			
1D-LPS	~26 to ~39	*tP*28	$P4mm$
2D-LPS	~28 to ~43	…	…
CuPd (β)	~49 to ~60	*cP*2	$Pm\bar{3}m$

Fig. 16 The copper-palladium (Cu-Pd) binary phase diagram and crystal structure data

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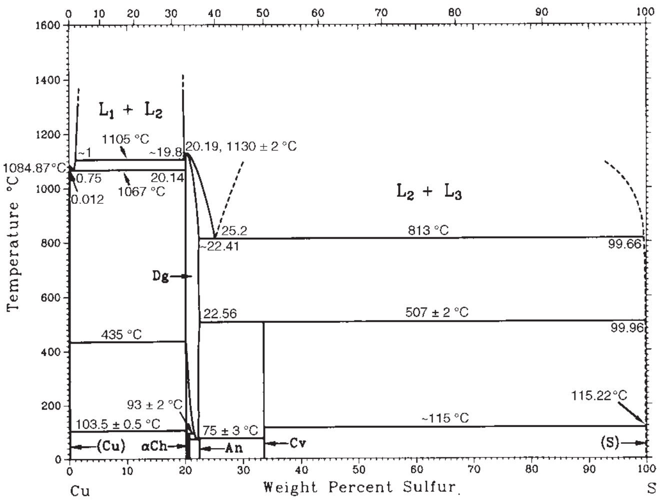

Fig. 17 The copper-sulfur (Cu-S) binary phase diagram and crystal structure data

Phase	Composition, wt% S(Cu/S)	Pearson symbol	Space group
(Cu)	0–0.012	*cF*4	$Fm\bar{3}m$
α chalcocite (αCu_2S)	20.14–20.01	*mP*144(?)	$P2_1/c$
β chalcocite (βCu_2S)	20.14–20.22	*hP*6	$P6_3/mmc$
Djurleite ($Cu_{\sim 1.96}S$)	20.4–20.69	*oP*380(?)	*Pmnm* $P2_1nm$(?) $Pmn2_1$
Digenite ($Cu_{2-\delta}S$)	20.14–22.24	*cF*12	$Fm\bar{3}m$
Anilite ($Cu_{1.75}S$)	22.38 ± 0.03	*oP*44(?)	*Pnma*
Covellite (CuS)	33.5	*hP*12	$P6_3/mmc$
(S)	~100	*oF*128 *mP*48 *hR*6	*Fddd* $P2_1/a$ $R\bar{3}$
Metastable phases			
Protodjurleite	20.4 (1.00)(a) 20.5 (0.999)(b)	…	…
Tetragonal	20.5 (0.999)	*tP*12	$P4_32_12$
Hexagonal-tetragonal Cu_xS	20.7–22.4 (0.98–0.89)	…	…
Low digenite (αDg)	21.99–22.22 (0.911–0.899)(c)	…	$R\bar{3}m$
Blaubleibender covellite I	26.5 ± 1.4 (0.71 ± 0.5)	…	…
Blaubleibender covellite II	31.6 ± 1.95 (0.6 ± 0.1)	…	…
CuS_2	50.23 (0.3)	…	*Pa*3(?)

(a) At 75 °C (167 °F). (b) At 93 °C (199 °F). (c) At 25 °C (77 °F)

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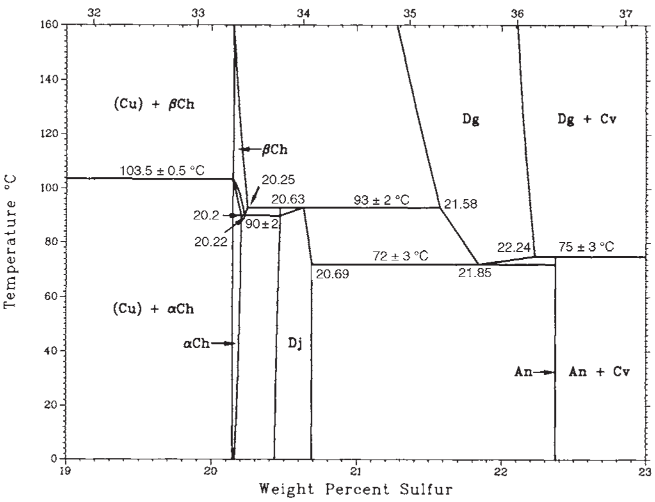

Fig. 18 Enlargement of the Cu-S diagram from 0 to 160 °C (32–320 °F)

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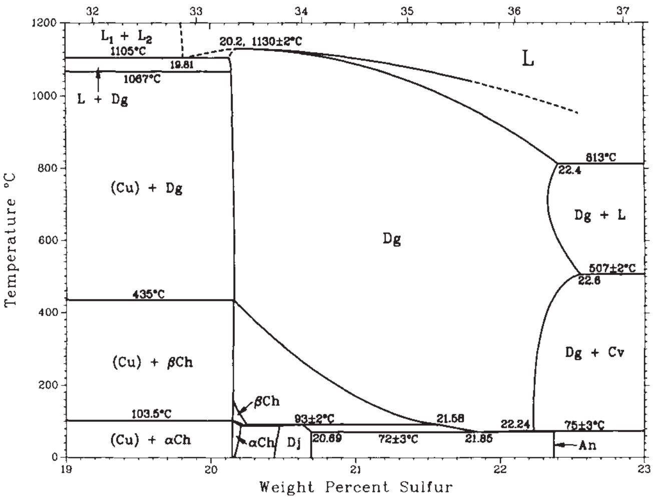

Fig. 19 Copper-saturated boundary of digenite (copper sulfide)

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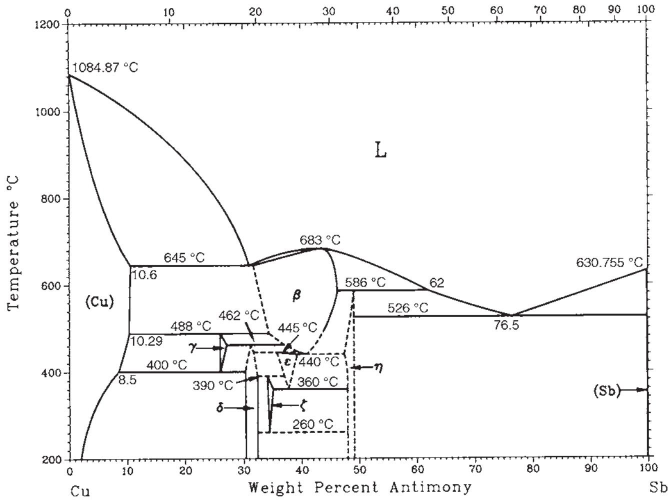

Phase	Composition, wt% Sb	Pearson symbol	Space group
(Cu)	0–10.6	$cF4$	$Fm\bar{3}m$
β	31.6–46.0	$oF16$	$Fm\bar{3}m$
γ	~26.0–26.7	$hP2$	$P6_3/mmc$
δ	30.3–32	$hP?$	$P6_3/mmc$
ε	~36.1–39.4	$oP8$	$Pmmn$
ζ	~34.1–34.5	$hP26$	$P\bar{3}$
η	~47.4–48.9	$tP6$	$P4/nmm$
(Sb)	~100	$hR2$	$R\bar{3}m$

Fig. 20 The copper-antimony (Cu-Sb) binary phase diagram and crystal structure data

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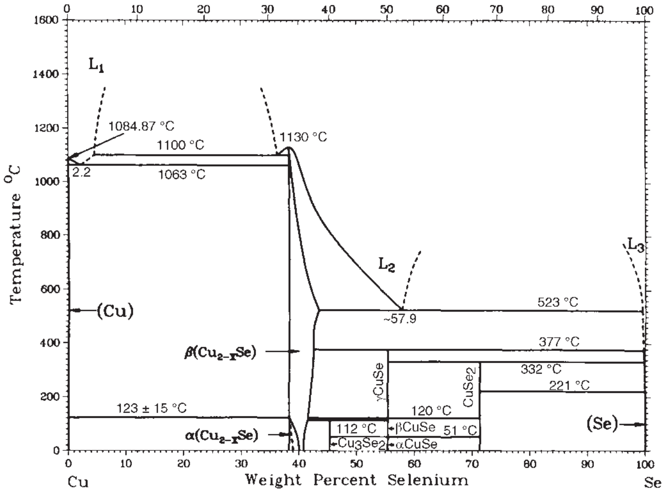

Phase	Composition, wt% Se	Pearson symbol	Space group
(Cu)	~0	$cF4$	$Fm\bar{3}m$
$\alpha Cu_{2-x}Se$	~38.3–38.8	(a)	…
$\beta Cu_{2-x}Se$	~38.3–41.6(b)	$cF12$	$Fm\bar{3}m$
Cu_3Se_2	45	…	$P\bar{4}2_1m$
αCuSe	55.4	…	$P6_3/mmc$
βCuSe	55.4	…	…
γCuSe	55.4	…	$P6_3/mmc$
$CuSe_2$	71.3	$oP6$	$Pnnm$
(Se)	~100	$hP3$	$P3_121$

(a) Monoclinic. (b) Homogeneity range at room temperature, $0.18 \leq x \leq 0.22$, and at 500 °C (932 °F) $x = 0$ to ~0.26

Fig. 21 The copper-selenium (Cu-Se) binary phase diagram and crystal structure data

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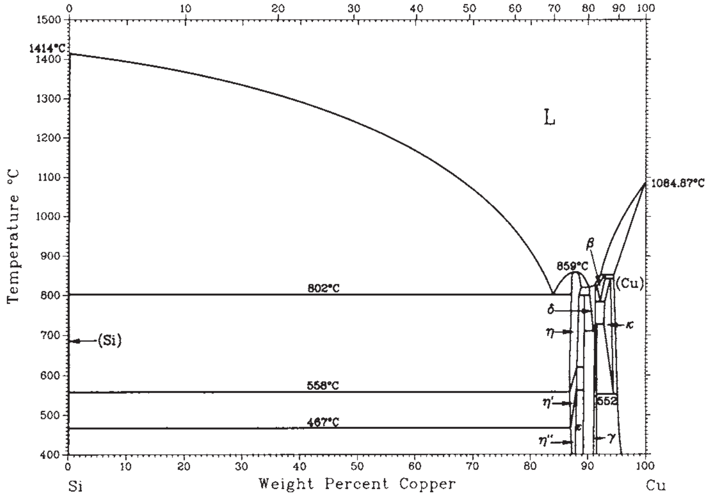

Phase	Composition, wt% Cu	Pearson symbol	Space group
(Si)	0	$cF8$	$Fm\bar{3}m$
SiII (HP)	0	$tI4$	$I4_1/amd$
η′′(a)	87.2–88.16	(b)	…
η′′(a)	87.0–88.22	(c)	$R\bar{3}$
η(a)	87.2–88.8	(c)	$R\bar{3}m$
ε(d)	89.3–89.4	(e)	…
δ	90.3–91.4	(f)	…
γ(g)	91.4–91.62	$cP20$	$P4_132$
β	91.6–93.2	$cI2$	$Im\bar{3}m$
κ(h)	93.0–94.80	$hP2$	$P6_3/mmc$
(Cu)	94.6 to ~100	$cF4$	$Fm\bar{3}m$
Other reported phases			
η′′(i)	…	(f)	…
Metastable	…	(f)	…

(a) Also denoted Cu_3Si. (b) Orthorhombic. (c) Rhombohedral. (d) Also denoted $Cu_{15}Si_4$. (e) Cubic. (f) Tetragonal. (g) Also denoted Cu_5Si. (h) Also denoted Cu_7Si. (i) Originally denoted η′

Fig. 22 The copper-silicon (Cu-Si) binary phase diagram and crystal structure data

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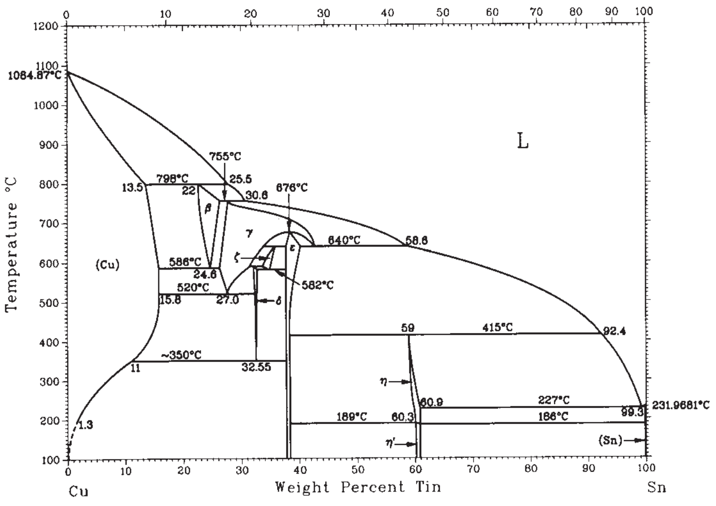

Fig. 23 The copper-tin (Cu-Sn) binary phase diagram and crystal structure data

Phase	Composition, wt% Sn	Pearson symbol	Space group
α	0–15.8	*cF*4	$Fm\bar{3}m$
β	22.0–27.0	*cI*2	$Im\bar{3}m$
γ	25.5–41.5	*cF*16	$Fm\bar{3}m$
δ	32–33	*cF*416	$F\bar{4}3m$
ζ	32.2–35.2	*hP*26	$P6_3$
ε	27.7–39.5	*oC*80	*Cmcm*
η	59.0–60.9	*hP*4	$P6_3/mmc$
η′	44.8–60.9	(a)	…
(βSn)	~100	*tI*4	$I4_1/amd$
(αSn)	100	*cF*8	$Fd\bar{3}m$

(a) Hexagonal; superlattice based on NiAs-type structure

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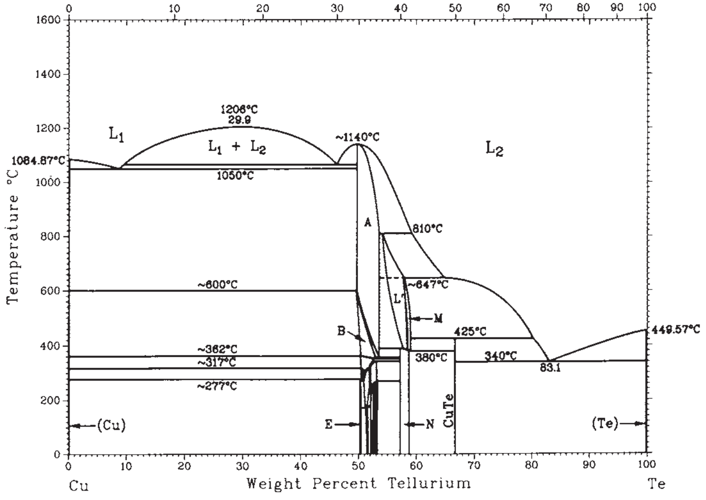

Fig. 24 The copper-tellurium (Cu-Te) binary phase diagram and crystal structure data

Phase	Composition, wt% Te	Pearson symbol	Space group
(Cu)	0	*cF*2	$Fm\bar{3}m$
Cu_2Te group			
A	50–53.6	*cF*12	$Fd\bar{3}m$
B	50–52.99	*hP*6	*P6/mmm*
C	50.4–52.5	*hP**	…
D	50.46–51.1	*o***	…
E	50.3–50.46	*o***	…
F	51.0–52	*o***	…
G	51.3–51.6	*o***	…
H	52.12–53.1	*hP*72	$P\bar{3}m1$
I	52.23–52.88	…	…
J	52.23–52.6	*hP**	…
K	52.9–53.3	*hP*22	$P\bar{3}m1$
L	54–58	*tP*6	*P4/nmm*
L′	55–58	…	…
M	58–59	…	…
N	57–58.8	…	…
CuTe	67	*oP*4	*Pmmn*
(Te)	100	*hP*3	$P3_12_1$
High-pressure phase			
$CuTe_2$	50.1	*cP*12	$Pa\bar{3}$

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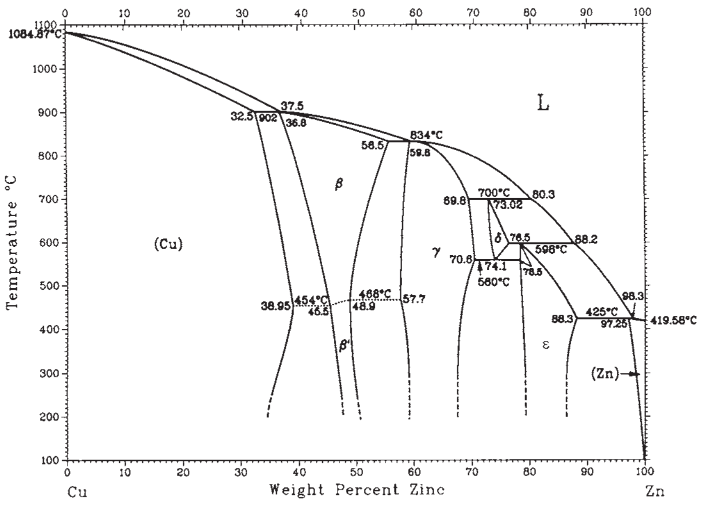

Fig. 25 The copper-zinc (Cu-Zn) binary phase diagram and crystal structure data

Phase	Composition, wt% Zn	Pearson symbol	Space group
α or (Cu)	0–38.95	*cF*4	$Fm\bar{3}m$
β	36.8–56.5	*cI*2	$Im\bar{3}m$
β′	45.5–50.7	*cP*2	$Pm\bar{3}m$
γ	57.7–70.6	*cI*52	$I\bar{4}3m$
δ	73.02–76.5	*hP*3	$P\bar{6}$
ε	78.5–88.3	*hP*2	$P6_3/mmc$
η or (Zn)	97.25–100	*hP*2	$P6_3/mmc$

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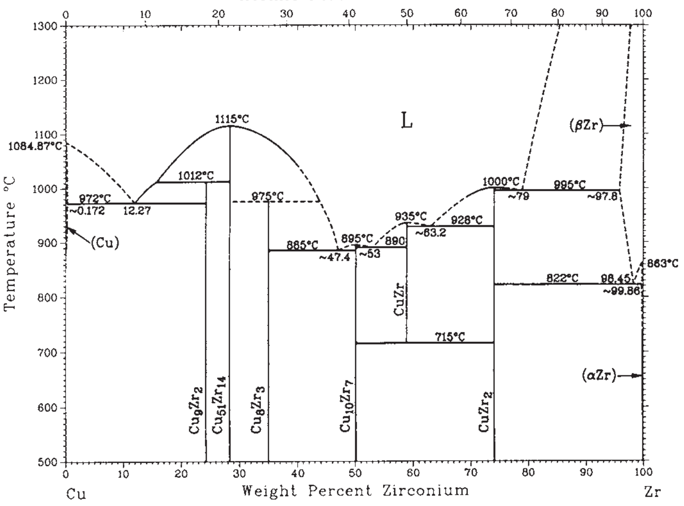

Phase	Composition, wt% Zr	Pearson symbol	Space group
(Cu)	0 to ~0.172	*cF*4	$Fm\bar{3}m$
Cu_9Zr_2(a)	24.18	*tP*24	$P4/m$
$Cu_{51}Zr_{14}$	28.27	*hP*65	$P6/m$
Cu_8Zr_3	34.99	*oP*44	*Pnma*
$Cu_{10}Zr_7$	50.13	*oC*68	…
CuZr	58.9	*cP*2	$Pm\bar{3}m$
$CuZr_2$	74.17	*tI*6	$I4/mmm$
(βZr)	~97.8–100	*cI*2	$Im\bar{3}m$
(αZr)	~99.86–100	*hP*2	$P6_3/mmc$

(a) Tetragonal long-period superlattice derived from the $AuBe_5$-type structure

Fig. 26 The copper-zirconium (Cu-Zr) binary phase diagram and crystal structure data

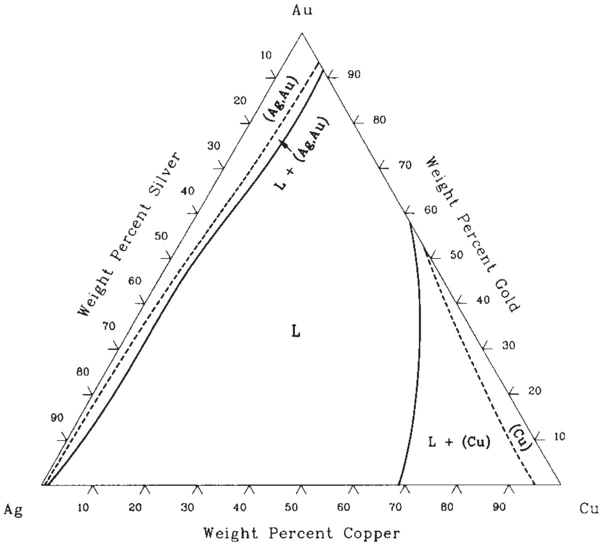

Fig. 27 Cu-Ag-Au isothermal section at 950 °C (1740 °F)

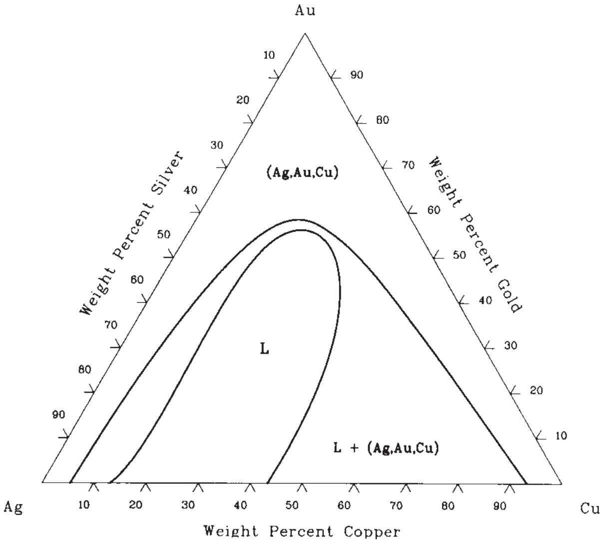

Fig. 28 Cu-Ag-Au isothermal section at 850 °C (1560 °F)

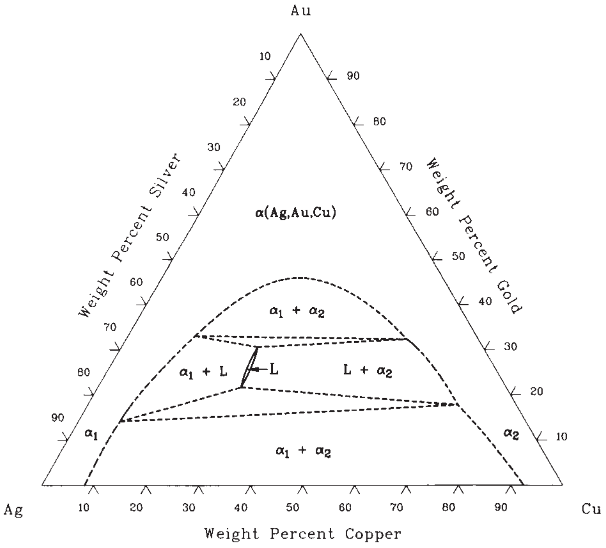

Fig. 29 Cu-Ag-Au isothermal section at 775 °C (1425 °F)

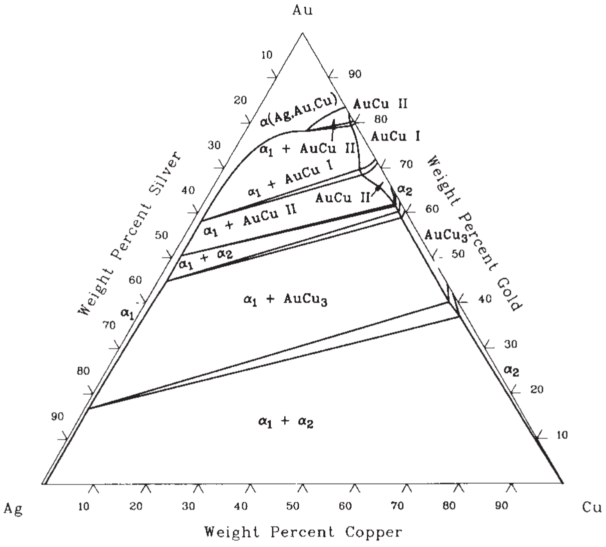

Fig. 30 Cu-Ag-Au isothermal section at 300 °C (570 °F)

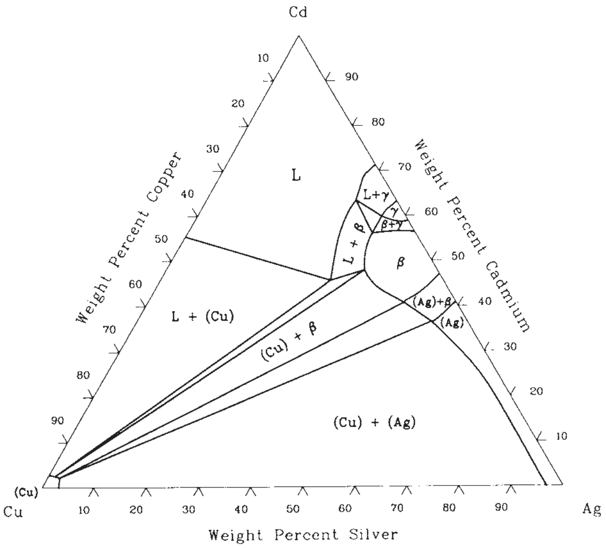

Fig. 31 Cu-Ag-Cd isothermal section at 600 °C (1110 °F)

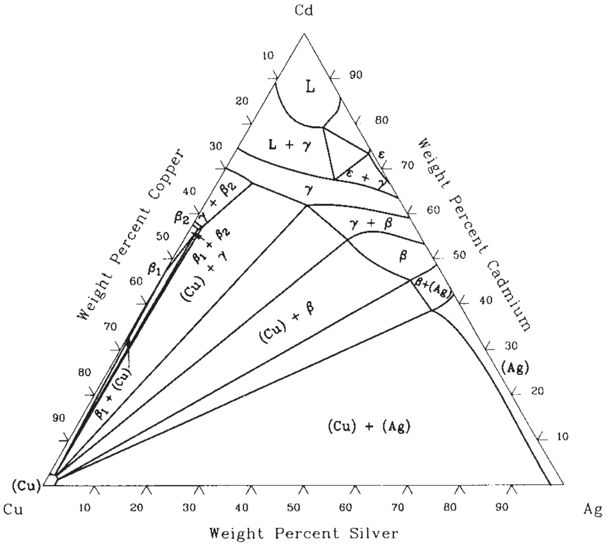

Fig. 32 Cu-Ag-Cd isothermal section at 500 °C (930 °F)

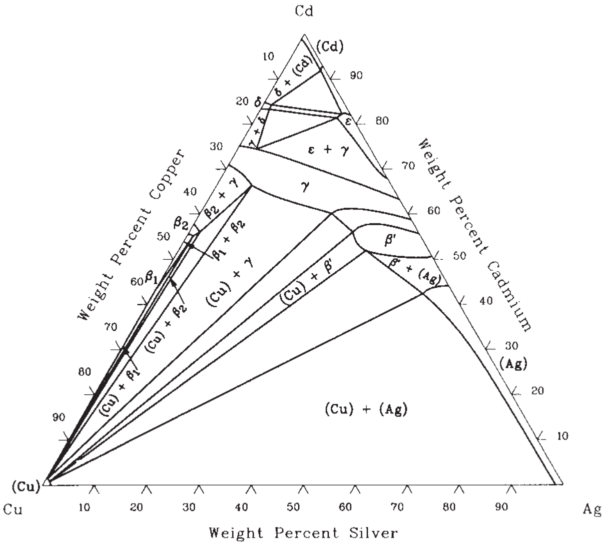

Fig. 33 Cu-Ag-Cd isothermal section at 300 °C (570 °F)

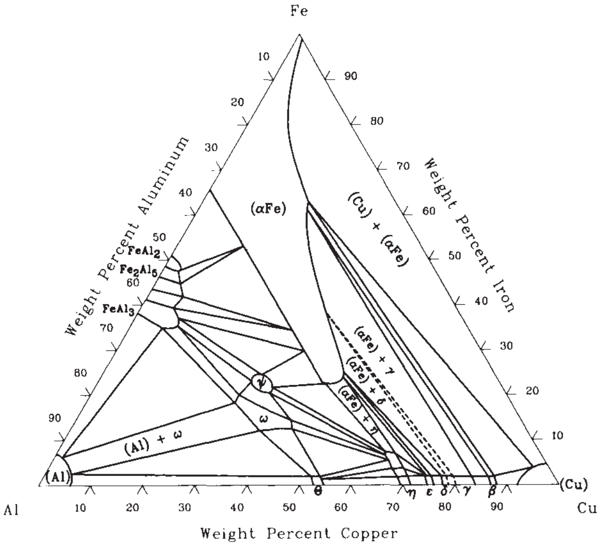

Fig. 34 Cu-Al-Fe isothermal section at 600 °C (1110 °F)

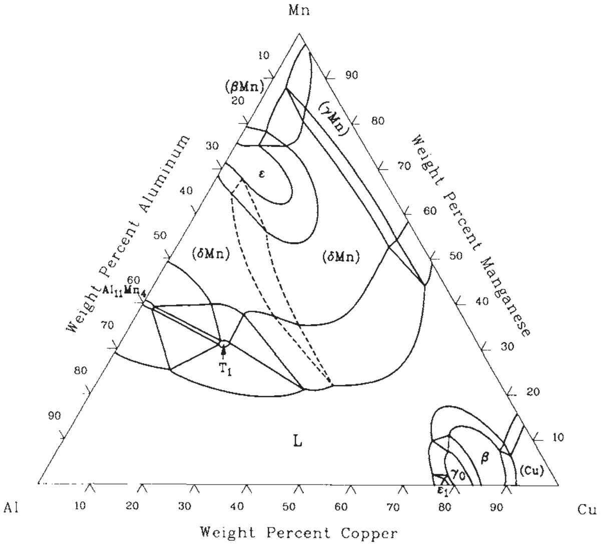

Fig. 35 Cu-Al-Mn isothermal section at 950 °C (1740 °F)

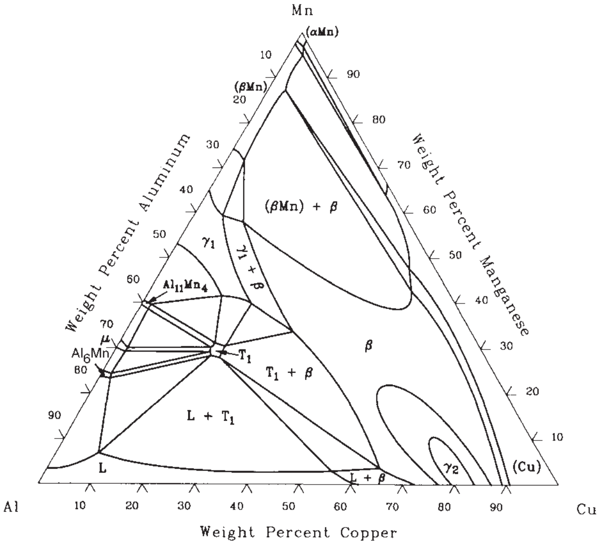

Fig. 36 Cu-Al-Mn isothermal section at 700 °C (1290 °F)

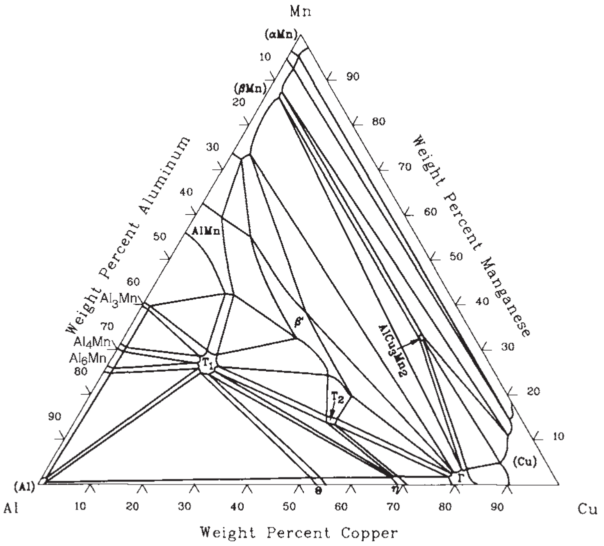

Fig. 37 Cu-Al-Mn isothermal section at 25 °C (75 °F)

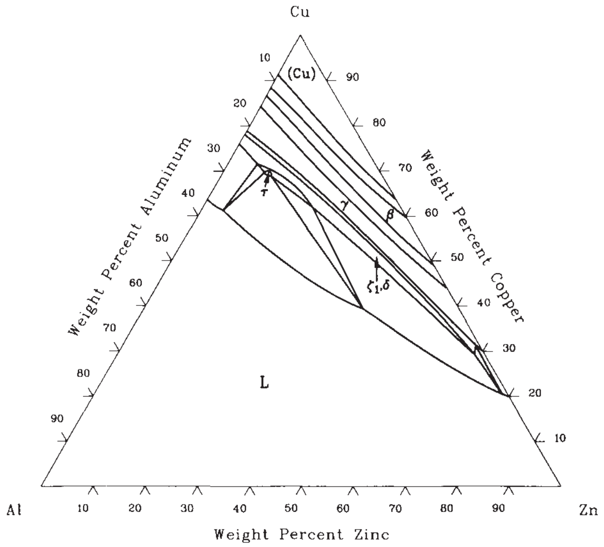

Fig. 38 Cu-Al-Zn isothermal section at 700 °C (1290 °F)

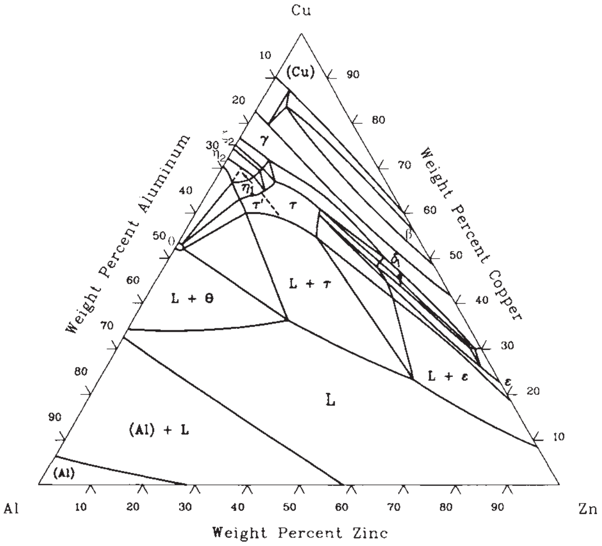

Fig. 39 Cu-Al-Zn isothermal section at 550 °C (1020 °F)

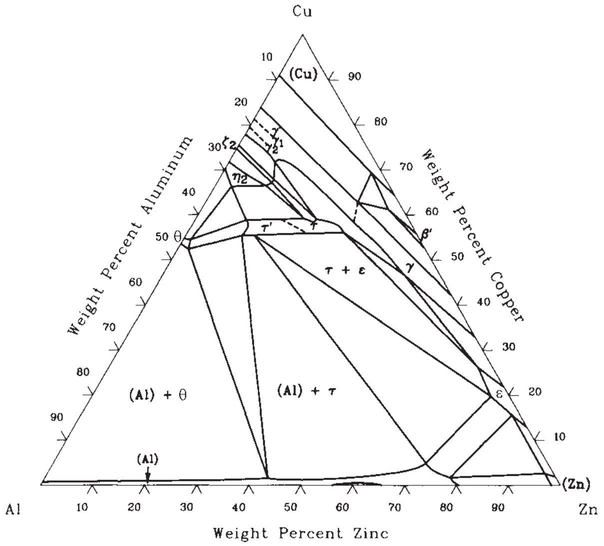

Fig. 40 Cu-Al-Zn isothermal section at 350 °C (660 °F)

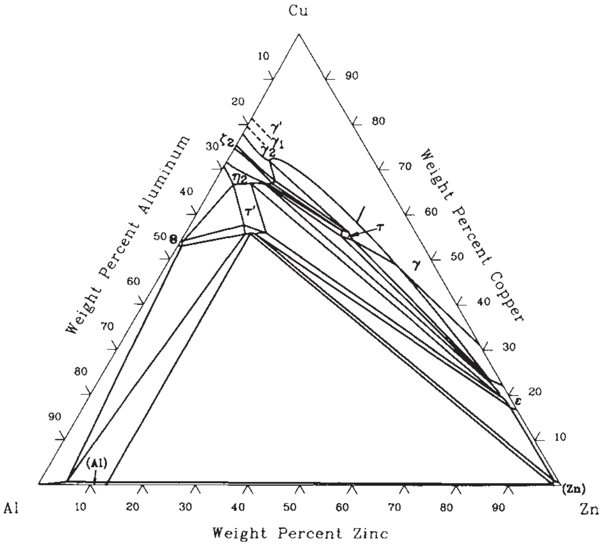

Fig. 41 Cu-Al-Zn isothermal section at 200 °C (390 °F)

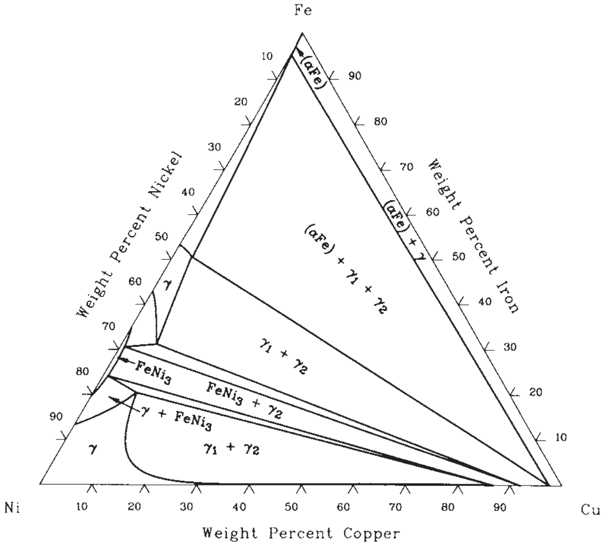

Fig. 42 Cu-Fe-Ni isothermal section at 400 °C (750 °F)

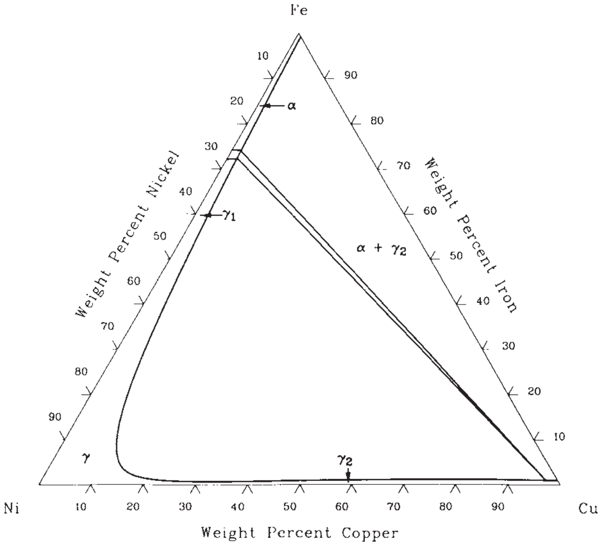

Fig. 43 Cu-Fe-Ni isothermal section at 20 °C (70 °F)

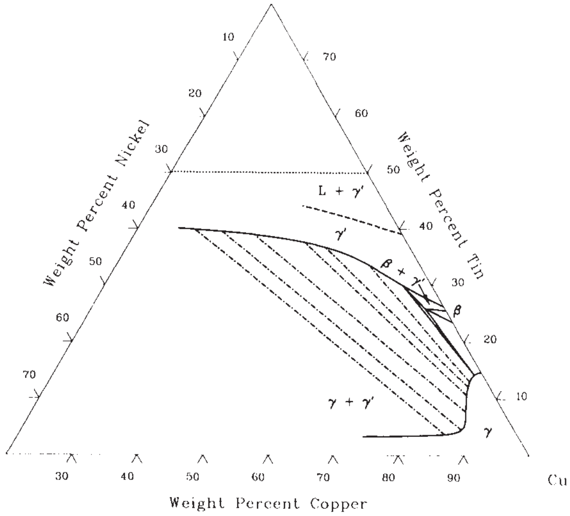

Fig. 44 Cu-Ni-Sn isothermal section at 700 °C (1290 °F)

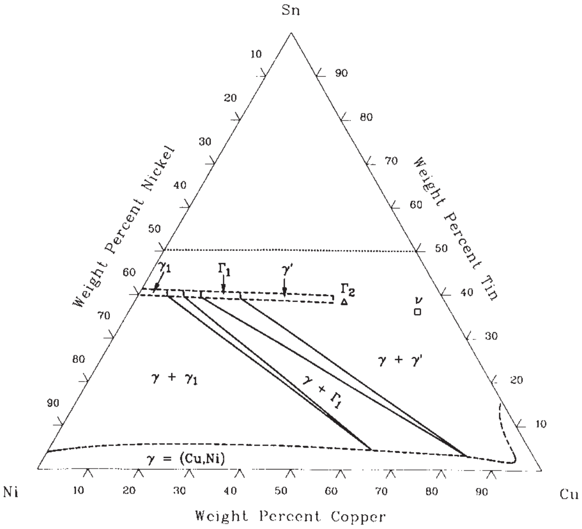

Fig. 45 Cu-Ni-Sn isothermal section at 550 °C (1020 °F)

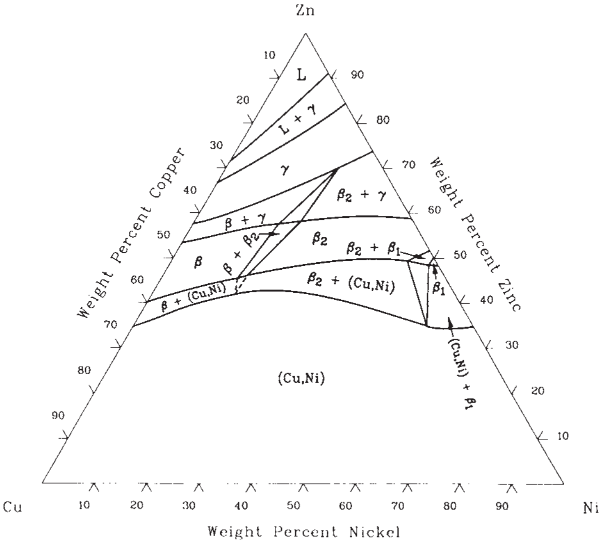

Fig. 46 Cu-Ni-Zn isothermal section at 775 °C (1425 °F)

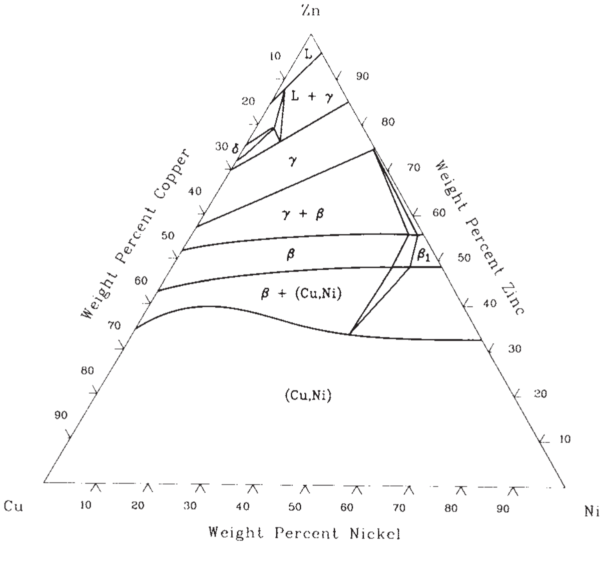

Fig. 47 Cu-Ni-Zn isothermal section at 650 °C (1200 °F)

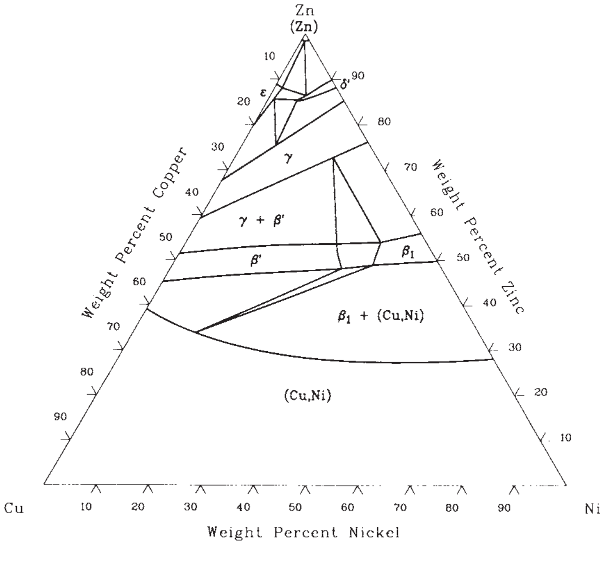

Fig. 48 Cu-Ni-Zn isothermal section at 20 °C (70 °F)

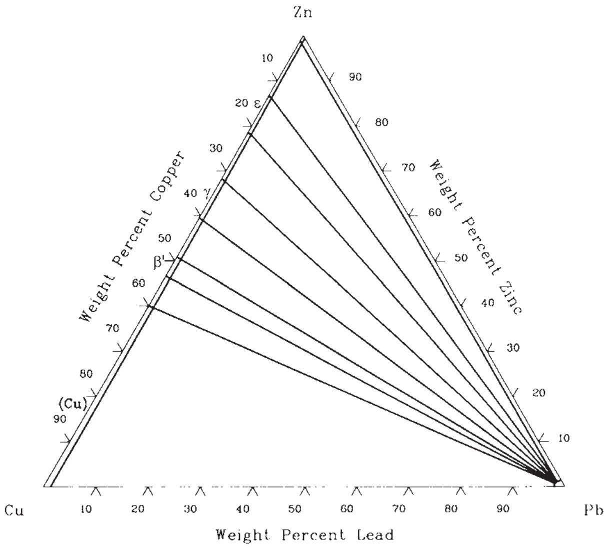

Fig. 49 Cu-Pb-Zn isothermal section at 25 °C (75 °F)

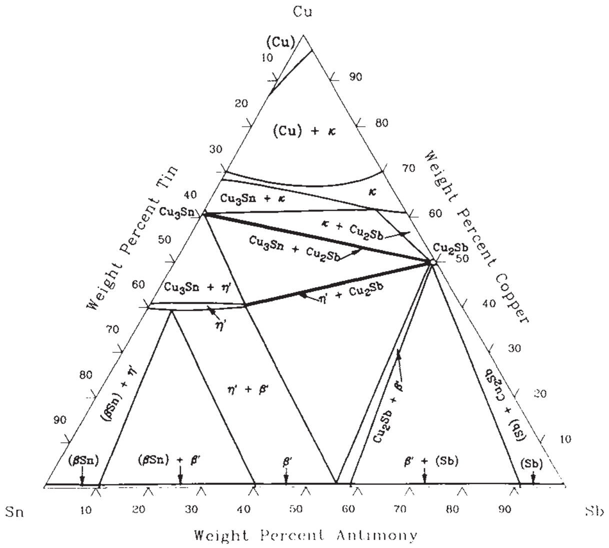

Fig. 50 Cu-Sb-Sn phases present at temperatures below the reactions in the solid state

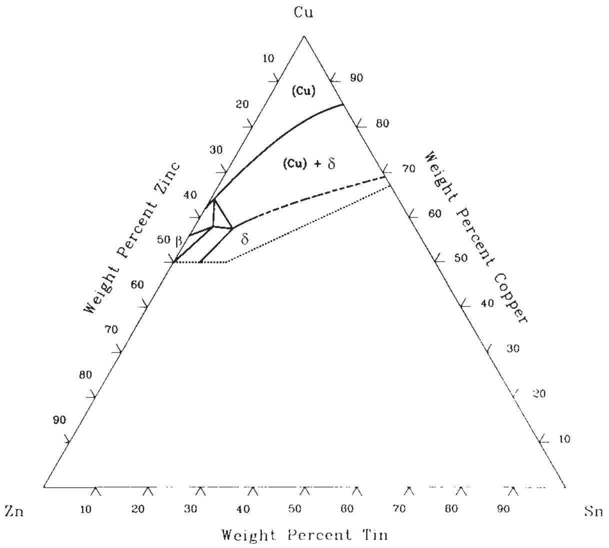

Fig. 51 Cu-Sn-Zn isothermal section at 500 °C (930 °F)

Engineering Properties and Service Characteristics

Corrosion Behavior

COPPER AND COPPER ALLOYS are widely used in many environments and applications because of their excellent corrosion resistance, which is coupled with combinations of other desirable properties, such as superior electrical and thermal conductivity, ease of fabricating and joining, wide range of attainable mechanical properties, and resistance to biofouling. Copper corrodes at negligible rates in unpolluted air, water, and deaerated nonoxidizing acids. Copper alloy artifacts have been found in nearly pristine condition after having been buried in the earth for thousands of years, and copper roofing in rural atmospheres has been found to corrode at rates of less than 0.4 mm (15 mils) in 200 years. Copper alloys resist many saline solutions, alkaline solutions, and organic chemicals. However, copper is susceptible to more rapid attack in oxidizing acids, oxidizing heavy-metal salts, sulfur, ammonia (NH_3), and some sulfur and NH_3 compounds. Resistance to acid solution depends mainly on the severity of oxidizing conditions in the solution. Reaction of copper with sulfur and sulfides to form copper sulfide (CuS or Cu_2S) usually precludes the use of copper and copper alloys in environments known to contain certain sulfur species.

Copper and copper alloys provide superior service in many of the applications included in the following general classifications:

- Applications requiring resistance to atmospheric exposure, such as roofing and other architectural uses, hardware, building fronts, grille work, hand rails, lock bodies, doorknobs, and kick plates
- Freshwater supply lines and plumbing fittings, for which superior resistance to corrosion by various types of waters and soils is important
- Marine applications—most often freshwater and seawater supply lines, heat exchangers, condensers, shafting, valve stems, and marine hardware—in which resistance to seawater, hydrated salt deposits, and biofouling from marine organisms is important
- Heat exchangers and condensers in marine service, steam power plants, and chemical process applications, as well as liquid-to-gas or gas-to-gas heat exchangers in which either process stream may contain a corrosive contaminant
- Industrial and chemical plant process equipment involving exposure to a wide variety of organic and inorganic chemicals
- Electrical wiring, hardware, and connectors; printed circuit boards; and electronic applications that require demanding combinations of electrical, thermal, and mechanical properties, such as semiconductor packages, lead frames, and connectors

Nature of the Protective Oxide Film

Copper and its alloys are unique among the corrosion-resistant alloys in that they do not form a truly passive corrosion product film. In aqueous environments at ambient temperatures, the corrosion product predominantly responsible for protection is cuprous oxide (Cu_2O). This Cu_2O film is adherent and follows parabolic growth kinetics. Cuprous oxide is a *p*-type semiconductor formed by the electrochemical processes:

$$4Cu + 2H_2O \rightarrow 2Cu_2O + 4H^+ + 4e^- \text{ (anode)} \qquad \text{(Eq 1)}$$

and

$$O_2 + 2H_2O + 4e^- \rightarrow 4(OH)^- \text{ (cathode)} \qquad \text{(Eq 2)}$$

with the net reaction: $4Cu + O_2 \rightarrow 2Cu_2O$.

For the corrosion reaction to proceed, copper ions and electrons must migrate through the Cu_2O film. Consequently, reducing the ionic or electronic conductivity of the film by doping with divalent or trivalent cations should improve corrosion resistance. In practice, alloying additions of aluminum, zinc, tin, iron, and nickel are used to dope the corrosion produce films, and they generally reduce corrosion rates significantly.

Effects of Alloy Compositions

Copper alloys are traditionally classified under the groupings listed in Table 1.

Coppers and high-copper alloys have similar corrosion resistance. They have excellent resistance to seawater corrosion and biofouling, but are susceptible to erosion-corrosion at high water velocities. The high-copper alloys are primarily used in applications that require enhanced mechanical performance, often at slightly elevated temperature, with good thermal or electrical conductivity. Processing for increased strength in the high-copper alloys generally improves their resistance to erosion-corrosion. A number of alloys in this category have been developed for

Table 1 Generic classification of copper alloys

Generic name	UNS No.	Composition
Wrought alloys		
Coppers	C10100–C15760	>99% Cu
High-copper alloys	C16200–C19600	>96% Cu
Brasses	C20500–C28580	Cu-Zn
Leaded brasses	C31200–C38590	Cu-Zn-Pb
Tin brasses	C40400–C49080	Cu-Zn-Sn-Pb
Phosphor bronzes	C50100–C52400	Cu-Sn-P
Leaded phosphor bronzes	C53200–C54800	Cu-Sn-Pb-P
Copper-phosphorus and Cu-Ag-P alloys	C55180–C55284	Cu-P-Ag
Aluminum bronzes	C60600–C64400	Cu-Al-Ni-Fe-Si-Sn
Silicon bronzes	C64700–C66100	Cu-Si-Sn
Other copper-zinc alloys	C66400–C69900	...
Copper-nickels	C70000–C79900	Cu-Ni-Fe
Nickel silvers	C73200–C79900	Cu-Ni-Zn
Cast alloys		
Coppers	C80100–C81100	>99% Cu
High-copper alloys	C81300–C82800	>94% Cu
Red and leaded red brasses	C83300–C85800	Cu-Zn-Sn-Pb (75–89% Cu)
Yellow and leaded yellow brasses	C85200–C85800	Cu-Zn-Sn-Pb (57–74% Cu)
Manganese bronzes and leaded manganese bronzes	C86100–C86800	Cu-Zn-Mn-Fe-Pb
Silicon bronzes, silicon brasses	C87300–C87900	Cu-Zn-Si
Tin bronzes and leaded tin bronzes	C90200–C94500	Cu-Sn-Zn-Pb
Nickel-tin bronzes	C94700–C94900	Cu-Ni-Sn-Zn-Pb
Aluminum bronzes	C95200–C95810	Cu-Al-Fe-Ni
Copper-nickels	C96200–C96800	Cu-Ni-Fe
Nickel silvers	C97300–C97800	Cu-Ni-Zn-Pb-Sn
Leaded coppers	C98200–C98800	Cu-Pb
Miscellaneous alloys	C99300–C99750	...

electronic applications—such as contact clips, springs, and lead frames—that require specific mechanical properties, relatively high electrical conductivity, and atmospheric-corrosion resistance. See the article "Applications" in this Handbook for examples of such alloys.

Brasses are basically copper-zinc alloys and are the most widely used group of copper alloys. The resistance of brasses to corrosion by aqueous solutions does not change markedly as long as the zinc content does not exceed about 15%; above 15% Zn, dezincification may occur. Figure 1 shows the effect of zinc content on corrosion of brasses. Quiescent or slowly moving saline solutions, brackish waters, and mildly acidic solutions are environments that often lead to the dezincification of unmodified brasses.

Susceptibility to stress-corrosion cracking (SCC) is significantly affected by zinc content; alloys that contain more zinc are more susceptible. Resistance increases substantially as zinc content decreases from 15 to 0%. Stress-corrosion cracking is practically unknown in commercial copper.

Elements such as lead, tellurium, beryllium, chromium, phosphorus, and manganese have little or no effect on the corrosion resistance of coppers and binary copper-zinc alloys. These elements are added to enhance such mechanical properties as machinability, strength, and hardness.

Tin Brasses. Tin additions significantly increase the corrosion resistance of some brasses, especially resistance to dezincification. Examples of this effect are two tin-bearing brasses: uninhibited admiralty metal (no active Unified Numbering System, or UNS, number) and naval brass (C46400). Uninhibited admiralty metal was once widely used to make heat-exchanger tubes; it has largely been replaced by inhibited grades of admiralty metal (C44300, C44400, and C44500), which have even greater resistance to dealloying. Admiralty metal is a variation of cartridge brass (C26000) that is produced by adding about 1% Sn to the basic 70Cu-30Zn composition. Similarly, naval brass is the alloy resulting from the addition of 0.75% Sn to the basic 60Cu-40Zn composition of Muntz metal (C28000).

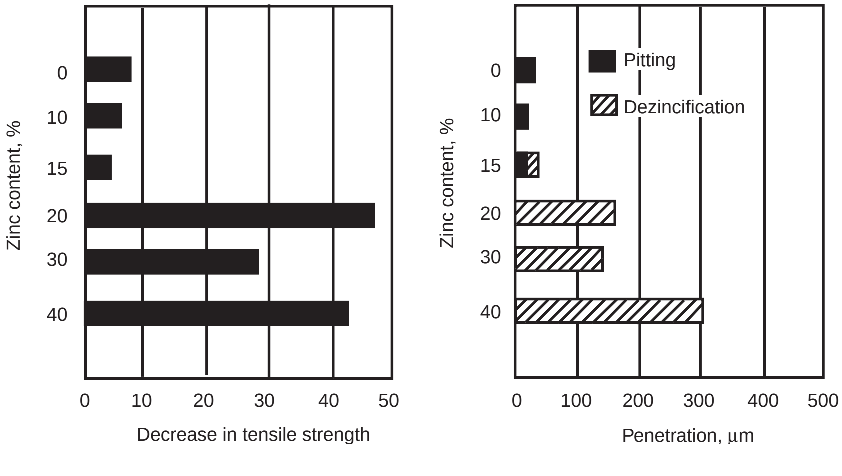

Fig. 1 Effect of zinc content on corrosion of brasses. Brass strip, 0.8 mm (0.032 in.) thick, was immersed for 60 days in 0.01 *M* ammonium chloride (NH_4Cl) solution at 45 °C (113 °F)

Cast brasses for marine use are also modified by the addition of tin, lead, and, sometimes, nickel. This group of alloys is known by various names, including composition bronze, ounce metal, and valve metal. These older designations are used less frequently because they have been supplanted by alloy numbers under the UNS or Copper Development Association (CDA) system. The cast marine brasses are used for plumbing goods in moderate-performance seawater piping systems or in deck hardware, for which they are subsequently chrome plated.

Aluminum Brasses. An important constituent of the corrosion film on a brass that contains a few percent aluminum in addition to copper and zinc is aluminum oxide (Al_2O_3), which markedly increases resistance to impingement attack in turbulent high-velocity saline water. For example, the arsenical aluminum brass C68700 (76Cu-22Zn-2Al) is frequently used for marine condensers and heat exchangers in which impingement attack is likely to pose a serious problem. Aluminum brasses are susceptible to dezincification unless they are inhibited, which is usually done by adding 0.02 to 0.10% As.

Inhibited Alloys. Addition of phosphorus, arsenic, or antimony (typically 0.02 to 0.10%) to admiralty metal, naval brass, or aluminum brass effectively produces high resistance to dezincification. Inhibited alloys have been extensively used for such components as condenser tubes, which must accumulate years of continuous service between shutdowns for repair or replacement.

Phosphor Bronzes. Addition of tin and phosphorus to copper produces good resistance to flowing seawater and to most nonoxidizing acids except hydrochloric (HCl). Alloys containing 8 to 10% Sn have high resistance to impingement attack. Phosphor bronzes are much less susceptible to SCC than brasses and are similar to copper in resistance to sulfur attack. Tin bronzes—alloys of copper and tin—tend to be used primarily in the cast form, in which they are modified by further alloy additions of lead, zinc, and nickel. Like the cast brasses, the cast tin bronzes are occasionally identified by older, more colorful names that reflect their historic uses, such as G Bronze, Gun Metal, Navy M Bronze, and steam bronze. Contemporary uses include pumps, valves, gears, and bushings. Wrought tin bronzes are known as phosphor bronzes and find use in high-strength-wire applications, such as wire rope. This group of alloys has fair resistance to impingement and good resistance to biofouling.

Copper Nickels. Alloy C71500 (Cu-30Ni) has the best general resistance to aqueous corrosion of all the commercially important copper alloys, but C70600 (Cu-10Ni) is often selected because it offers good resistance at lower cost. Both of these alloys, although well suited to applications in the chemical industry, have been most extensively used for condenser tubes and heat-exchanger tubes in recirculating steam systems. They are superior to coppers and to other copper alloys in resisting acid solutions and are highly resistant to SCC and impingement corrosion.

Nickel Silvers. The two most common nickel silvers are C75200 (65Cu-18Ni-17Zn) and C77000 (55Cu-18Ni-27Zn). They have good resistance to corrosion in both fresh and salt waters. Primarily because their relatively high nickel contents inhibit dezincification, C75200 and C77000 are usually much more resistant to corrosion in saline solutions than brasses of similar copper content.

Copper-silicon alloys generally have the same corrosion resistance as copper, but they have higher mechanical properties and superior weldability. These alloys appear to be much more resistant to SCC than the common brasses. Silicon bronzes are susceptible to embrittlement by high-pressure steam and should be tested for suitability in the service environment before being specified for components to be used at elevated temperature.

Aluminum bronzes containing 5 to 12% Al have excellent resistance to impingement corrosion and high-temperature oxidation. Aluminum bronzes are used for beater bars and for blades in wood pulp machines because of their ability to withstand mechanical abrasion and chemical attack by sulfite solutions.

In most practical commercial applications, the corrosion characteristics of aluminum bronzes are primarily related to aluminum content. Alloys with up to 8% Al normally have completely face-centered cubic (fcc) α structures and good resistance to corrosion attack. As aluminum content increases above 8%, α-β duplex structures appear. The β phase is a high-temperature phase retained at room temperature upon fast cooling from 565 °C (1050 °F) or above. Slow cooling for long exposure at temperatures from 320 to 565 °C (610–1050 °F) tends to decompose the β-phase into a brittle $\alpha + \gamma_2$ eutectoid having either a lamellar or a nodular structure. The β-phase is less resistant to corrosion than the α-phase, and eutectoid structures are even more susceptible to attack.

Depending on specific environmental conditions, β-phase or eutectoid structure in aluminum bronze can be selectively attacked by a mechanism similar to the dezincification of brasses. Proper quench-and-temper treatment of duplex alloys, such as C62400 and C95400, produces a tempered β-structure with reprecipitated acicular α-crystals, a combination that is often superior in corrosion resistance to the normal annealed structures.

Iron-rich particles are distributed as small round or rosette particles throughout the structures of aluminum bronzes containing more than about 0.5% Fe. These particles sometimes impart a rusty tinge to the surface, but have no known effect on corrosion rates.

Nickel-aluminum bronzes are more complex in structure with the introduction of the κ-phase. Nickel appears to alter the corrosion characteristics of the β-phase to provide greater resistance to dealloying and cavitation-erosion in most liquids. For C63200 and perhaps C95800, quench-and-temper treatments may yield even greater resistance to dealloying. Alloy C95700, a high-manganese cast aluminum bronze, is somewhat inferior in corrosion resistance to C95500 and C95800, which are low in manganese and slightly higher in aluminum.

Aluminum bronzes are generally suitable for service in nonoxidizing mineral acids, such as phosphoric (H_3PO_4) sulfuric (H_2SO_4), and HCl; organic acids, such as lactic, acetic (CH_3COOH), or oxalic; neutral saline solutions, such as sodium chloride (NaCl) or potassium chloride (KCl); alkalies, such as sodium hydroxide (NaOH), potassium hydroxide (KOH), and anhydrous ammonium hydroxide (NH_4OH); and various natural waters including sea, brackish, and potable waters. Environments to be avoided include nitric acid (HNO_3); some metallic salts, such as ferric chloride ($FeCl_3$) and chromic acid (H_2CrO_4); moist chlorinated hydrocarbons; and moist NH_3. Aeration can result in accelerated corrosion in many media that appear to be compatible.

Exposure under high tensile stress to moist NH_3 can result in SCC. In certain environments, corrosion can lower the fatigue limit to 25 to 50% of the normal atmospheric value.

Types of Attack

Coppers and copper alloys, like most other metals and alloys, are susceptible to several forms of corrosion, depending primarily on environmental conditions. Table 2 lists the identifying characteristics of the forms of corrosion that commonly attack copper metals as well as the most effective means of combating each.

General Corrosion

General corrosion is the well-distributed attack of an entire surface with little or no localized penetration. It is the least damaging of all forms of attack. General corrosion is the only form of corrosion for which weight loss data can be used to estimate penetration rates accurately.

General corrosion of copper alloys results from prolonged contact with environments in which the corrosion rate is very low, such as fresh, brackish, and salt waters; many types of soil; neutral, alkaline, and acid salt solutions; organic acids; and sugar juices. Other substances that cause uniform thinning at a faster rate include oxidizing acids, sulfur-bearing compounds, NH_3, and cyanides.

Galvanic Corrosion

An electrochemical potential almost always exists between two dissimilar metals when they are immersed in a conductive solution. If two dissimilar metals are in electrical contact with each other and immersed in a conductive solution, a potential results that enhances the corrosion of the more electronegative member of the couple (the anode) and partly or completely protects the more electropositive member (the cathode). Copper metals are almost always cathodic to other common structural metals, such as steel and aluminum. When steel or aluminum is put in contact with a copper metal, the corrosion rate of the steel or aluminum increases, but that of the copper metal decreases. The common grades of stainless steel exhibit variable behavior; that is, copper metals may be anodic or cathodic to the stainless steel, depending on conditions of exposure. Copper metals usually corrode preferentially when coupled with high-nickel alloys, titanium, or graphite.

Corrosion potentials of copper metals generally range from -0.2 to -0.4 V when measured against a saturated calomel electrode (SCE); the potential of pure copper is about -0.3 V. Alloying additions of zinc or aluminum move the potential toward the anodic (more electronegative) end of the range; additions of tin or nickel move the potential toward the cathodic (less electronegative) end. Galvanic corrosion between two copper metals is seldom a significant problem, because the potential difference is so small.

Table 3 lists a galvanic series of metals and alloys valid for dilute aqueous solutions, such as seawater and weak acids. The metals that are closely grouped together can be coupled to each other without significant galvanic damage. However, the connecting of metals from different groups leads to damage of the more anodic metal; the larger the difference in galvanic potential between groups, the greater the corrosion. Accelerated damage due to galvanic effects is usually greatest near the junction, where the electrochemical current density is the highest.

Another factor that affects galvanic corrosion is area ratio. An unfavorable area ratio exists when the cathodic area is large and the anodic area is small. The corrosion rate of the small anodic area may be several hundred times greater than if the anodic and cathodic areas were equal in size. Conversely, when a large anodic area is coupled to a small cathodic area, current density and damage due to galvanic corrosion are much less. For example, copper rivets (cathodic) used to fasten steel plates together lasted longer than 1.5 years in seawater, but steel rivets used to fasten copper plates were completely destroyed during the same period.

Prevention. Five principal methods are available for eliminating or significantly reducing galvanic corrosion:

- Select dissimilar metals that are as close as possible to each other in the galvanic series.
- Avoid coupling small anodes to large cathodes.
- Insulate dissimilar metals completely wherever practicable.
- Apply coatings and keep them in good repair, particularly on the cathodic member.
- Use a sacrificial anode; that is, couple the system to a third metal that is anodic to both structural metals.

Table 2 Guide to corrosion of copper alloys

Form of attack	Characteristics	Preventive measures
General thinning	Uniform metal removal	Select proper alloy for environment conditions based on weight loss data.
Galvanic corrosion	Corrosion preferentially near a more cathodic metal	Avoid electrically coupling dissimilar metals. Maintain optimal ratio of anode to cathode area. Maintain optimal concentration of oxidizing constituent in corroding medium.
Pitting	Localized pits, tubercles; water line pitting; crevice corrosion; pitting under foreign objects or dirt	Alloy selection, design to avoid crevices, keeping metal clean
Impingement, erosion-corrosion, cavitation	Erosion attack from turbulent flow plus dissolved gases, generally as lines of pits in direction of fluid flow	Design for streamlined flow; keep velocity low. Remove gases from liquid phase and use erosion-resistant alloy.
Fretting	Chafing or galling, often occurring during shipment	Lubricate contacting surfaces; interleave sheets of paper between sheets of metal. Decrease load on bearing surfaces.
Intergranular corrosion	Corrosion along grain boundaries without visible signs of cracking	Select proper alloy for environmental conditions based on metallographic examination of corrosion specimens.
Dealloying	Preferential dissolution of zinc or nickel, resulting in a layer of sponge copper	Select proper alloy for environmental conditions based on metallographic examination of corrosion specimens.
Corrosion fatigue	Several transangular cracks	Select proper alloy based on fatigue tests in service environment. Reduce mean or alternating stress.
SCC	Cracking, usually intergranular but sometimes transgranular, that is often fairly rapid	Select proper alloy based on stress-corrosion tests; reduce applied or residual stress. Remove mercury compounds or NH_3 from environment.

Pitting

As with most commercial metals, corrosion of copper metals results in pitting under certain conditions. Pitting is sometimes general over the entire surface, giving the metal an irregular and roughened appearance. In other cases, pits are concentrated in specific areas and are of various sizes and shapes.

Localized pitting is the most damaging form of corrosive attack because it reduces load-carrying capacity and increases stress concentration by creating depressions or holes in the metal. Pitting is the usual form of corrosive attack at surfaces on which there are incomplete protective films, nonprotective deposits of scale, or extraneous deposits of dirt or other foreign substances.

Copper alloys do not corrode primarily by pitting, but because of metallurgical and environmental factors that are not completely understood, the corroded surface does show a tendency toward nonuniformity. In seawater, pitting tends to occur more often under conditions of relatively low water velocity, typically less than 0.6 to 0.9 m/s (2–3 ft/s). The occurrence of pitting is somewhat random regarding the specific location of a pit on the surface as well as whether it will even occur on a particular metal sample. Long-term tests of copper alloys show that the average pit depth does not continually increase with extended times of exposure. Instead, pits tend to reach a certain limit beyond which little apparent increase in depth occurs. Of the copper alloys, the most pit resistant are the aluminum bronzes with less than 8% Al and the low-zinc brasses. Copper nickels and tin bronzes tend to have intermediate pitting resistance, but the high-copper alloys and silicon bronzes are somewhat more prone to pitting.

Table 3 Galvanic series in seawater

Anodic
Magnesium
Magnesium alloys
Zinc
Galvanized steel
Aluminum alloy 5052H
Aluminum alloy 3004
Aluminum alloy 3003
Aluminum alloy 1100
Aluminum alloy 6053
Alclad aluminum alloys
Cadmium
Aluminum alloy 2017
Aluminum alloy 2024
Low-carbon steel
Wrought iron
Cast iron
Ni-Resist cast iron
AISI type 410 stainless steel (active)
50Pb-50Sn solder
AISI type 304 stainless steel (active)
AISI type 316 stainless steel (active)
Lead
Tin
Muntz metal (C28000)
Manganese bronze (C67500)
Naval brass (C46400)
Nickel (active)
Inconel (active)
Cartridge brass (C26000)
Admiralty metal (C44300)
Aluminum bronze (C61400)
Red brass (C23000)
Copper (C11000)
Silicon bronze (C65100)
Copper-nickel, 30% (C71500)
Nickel (passive)
Inconel (passive)
Monel
AISI type 304 stainless steel (passive)
AISI type 316 stainless steel (passive)
Silver
Gold
Platinum
Cathodic

Crevice corrosion is a form of localized corrosion that occurs near a crevice formed either by two metal surfaces or a metal and a nonmetal surface. Like pitting, crevice attack is a random occurrence, the precise location of which cannot always be predicted. Also, like pitting, the depth of attack appears to level off rather than to increase continually with time. This depth is usually less than that from pitting, and for most copper alloys, it will be less than 400 μm (15.8 mils).

For most copper alloys, the location of the attack will be outside but immediately adjacent to the crevice due to the formation of metal ion concentration cells. Classic crevice corrosion resulting from oxygen depletion and attack within crevices is less common in copper alloys. Aluminum- and chromium-bearing copper alloys, which form more passive surface films, are susceptible to differential oxygen cell attack, as are aluminum alloys and stainless steels. The occurrence of crevice attack is somewhat statistical in nature, with the odds of it occurring and its severity increasing if the area within a crevice is small compared to the area outside the crevice. Other conditions that will increase the odds of crevice attack are higher water temperatures or a flow condition on the surface outside the crevice.

Figure 2 compares the crevice corrosion behavior for several different materials exposed to ambient-temperature seawater for various periods. In each case, a nonmetallic washer created the crevice. The more classical form of crevice corrosion (that is, beneath the crevice former) is shown for type 904L stainless steel (20Cr-25Ni-4.5Mo-1.5Cu) after only 30 days of exposure (Fig. 2a). For 70Cu-30Ni, corrosion occurred just outside of the crevice mouth and was found to be quite shallow after 6 months (Fig. 2b). In contrast, crevice-related corrosion of alloy 400 (70Ni-30Cu) was more severe after only 45 days (Fig. 2c). In some cases, corrosion may occur within as well as outside of the crevice.

Local cell action similar to crevice attack may also result from the presence of foreign objects or debris, such as dirt, pieces of shell, or vegetation, or it may result from rust, permeable scales, or uneven accumulation of corrosion product on the metallic surface. This type of attack can sometimes be controlled by cleaning the surfaces. For example, condensers and heat exchangers are cleaned periodically to prevent deposit attack.

Water line attack is a term used to describe pitting due to a differential oxygen cell functioning between the well-aerated surface layer of a liquid and the oxygen-starved layer immediately beneath it. The pitting occurs immediately below the water line.

Impingement

Various forms of impingement attack occur where gases, vapors, or liquids impinge on metal surfaces at high velocities, such as in condensers or heat exchangers. Rapidly moving turbulent water can strip away the protective films from copper alloys. When this occurs, the metal corrodes at a more rapid rate in an attempt to reestablish this film, but because the films are being swept away as rapidly as they are being formed, the corrosion rate remains constant and high. The conditions under which the corrosion product film is removed are different for each alloy and are discussed in various sections of this article that deal with corrosion of copper alloys in specific environments.

Erosion-corrosion is characterized by undercut grooves, waves, ruts, gullies, and rounded holes; it usually exhibits a directional pattern. Pits are elongated in the direction of flow and are undercut on the downstream side. When the condition becomes severe, it may result in a pattern of horseshoe-shaped grooves or pits with their open ends pointing downstream (Fig. 3). As attack progresses, the pits may join, forming fairly large patches of undercut pits. When this form of corrosion occurs in a condenser tube, it is usually confined to a region near the inlet end of the tube where fluid flow is rapid and turbulent. If some of the tubes in a bundle become plugged, the velocity is increased in the remaining tubes; therefore, the unit should be kept as clean as possible. Erosion-corrosion is most often found with waters containing low levels of sulfur compounds and with polluted, contaminated, or silty salt water or brackish water. The erosive action locally removes protective films, thus contributing to the formation of concentration cells and to localized pitting of anodic sites.

Cavitation is a phenomenon that occurs in moving water when the flow is disturbed so as to create a local pressure drop. Under these conditions, a vapor bubble will form and then collapse, applying a momentary stress of up to 1379 MPa (200 ksi) to the surface. The current theories of cavitation state that this repeated mechanical working of the surface creates a local fatigue situation that aids the removal of metal. This is in agreement with the observations that the harder alloys tend to have greater resistance to cavitation and that there is often an incubation period before the onset of cavitation attack. Of the copper alloys, aluminum bronze has the best cavitation resistance. Cavitation damage will be confined to the area where the bubbles collapse, usually immediately downstream of the low-pressure zone. On symmetrical components having repeated elements (e.g., impellers) the pattern of damage may repeat itself at identical locations on each element as shown in Fig. 4.

Prevention. Impingement attack can be reduced, and the life of the unit extended, by decreasing fluid velocity, streamlining the flow, and removing entrained air. This is usually accomplished by redesigning water boxes, injector nozzles, and piping to reduce or eliminate

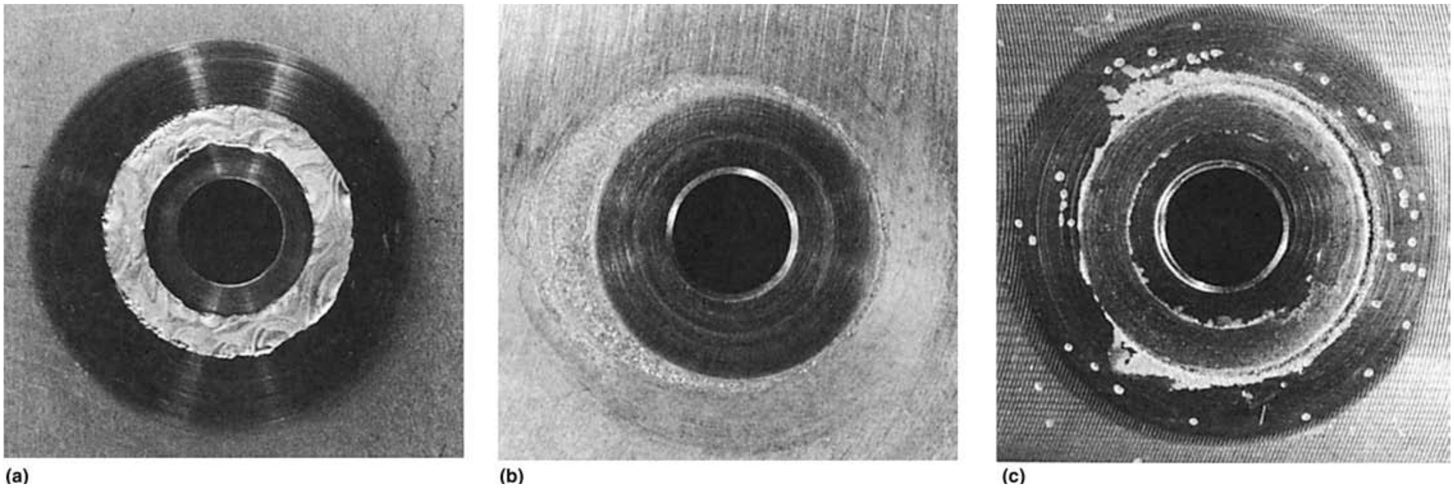

Fig. 2 Crevice-related corrosion for different alloys in natural seawater. (a) Alloy 904L (20Cr-25Ni-4.5Mo-1.5Cu) after 30 days. (b) 70Cu-30Ni after 180 days. (c) Alloy 400 (70Ni-30Cu) after 45 days

Fig. 3 Horseshoe-shaped depressions on the internal surface of a brass heat exchanger tube caused by erosion-corrosion

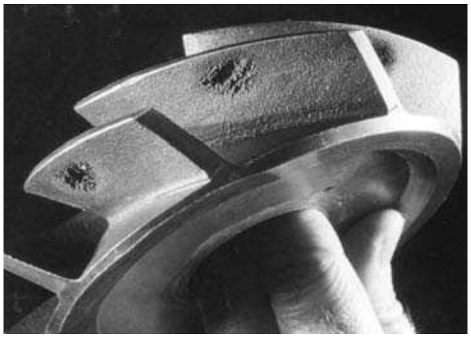

Fig. 4 Cavitation damage repeated on successive vanes of a bronze impeller

low-pressure pockets, obstructions to smooth flow, abrupt changes in flow direction, and other features that cause local regions of high-velocity or turbulent flow. Condensers and heat exchangers are less susceptible to impingement attack if they are made of one of the aluminum brasses or copper nickels, which are more erosion-resistant than the brasses or tin brasses. Erosion-resistant inserts at tube inlets and epoxy-type coatings are often effective repair methods in existing shell and tube heat exchangers. When contaminated waters are involved, filtering or screening the liquids and cleaning the surfaces can be very effective in minimizing impingement attack. The use of cathodic protection can lessen all forms of localized attack except cavitation.

Fretting

Another form of attack, called fretting or fretting corrosion, appears as pits or grooves in the metal surface that are surrounded or filled with corrosion product. Fretting is sometimes referred to as chafing, road burn, friction oxidation, wear oxidation, or galling.

The basic requirements for fretting are as follows:

- Repeated relative (sliding) motion between two surfaces must occur. The relative amplitude of the motion may be very small—motion of only a few tenths of a millimeter is typical.
- The interface must be under load.
- Both load and relative motion must be sufficient to produce deformation of the interface.
- Oxygen and/or moisture must be present.

Fretting does not occur on lubricated surfaces in continuous motion, such as axle bearings, but instead on dry interfaces subject to repeated, small relative displacements. A classic type of fretting occurs during shipment of bundles of mill products having flat faces. Fretting is not confined to coppers and copper alloys, but has been recognized on almost every kind of surface—steel, aluminum, noble metals, mica, and glass.

Prevention. Fretting can be controlled, and sometimes eliminated by:

- Lubricating with low-viscosity high-tenacity oils to reduce friction at the interface between the two metals and to exclude oxygen from the interface
- Separating the faying surfaces by interleaving an insulating material
- Increasing the load to reduce motion between faying surfaces; this may be difficult in practice, because only a minute amount of relative motion is necessary to produce fretting
- Decreasing the load at bearing surfaces to increase the relative motion between parts

Intergranular Corrosion

Intergranular corrosion is an infrequently encountered form of attack that occurs most often in applications involving high-pressure steam. This type of corrosion penetrates the metal along grain boundaries—often to a depth of several grains—which distinguishes it from surface roughening. Mechanical stress is apparently not a factor in intergranular corrosion. The alloys that appear to be the most susceptible to this form of attack are Muntz metal, admiralty metal, aluminum brasses, and silicon bronzes.

Dealloying

Dealloying is a corrosion process in which the more active metal is selectively removed from an alloy, leaving behind a weak deposit of the more noble metal. Copper-zinc alloys containing more than 15% Zn are susceptible to a dealloying process called dezincification. In the dezincification of brass, selective removal of zinc leaves a relatively porous and weak layer of copper and copper oxide. Corrosion of a similar nature continues beneath the primary corrosion layer, resulting in gradual replacement of sound brass by weak, porous copper. Unless arrested, dealloying eventually penetrates the metal, weakening it structurally and allowing liquids or gases to leak through the porous mass in the remaining structure.

The term *plug-type dealloying* refers to the dealloying that occurs in local areas; surrounding areas are usually unaffected or only slightly corroded (Fig. 5 and 6). In *uniform-layer dealloying,* the active component of the alloy is leached out over a broad area of the surface (Fig. 7 and 8). Dezincification is the usual form of corrosion for uninhibited brasses in prolonged contact with waters high in oxygen and carbon dioxide (CO_2). It is frequently encountered with quiescent or slowly moving solutions. Slightly acidic water, low in salt content and at room temperature, is likely to produce uniform attack, but neutral or alkaline water, high in salt content and above room temperature, often produces plug-type attack.

Brasses with copper contents of 85% or more resist dezincification. Dezincification of brasses with two-phase structures is generally more severe, particularly if the second phase is continuous; it usually occurs in two stages: the high-zinc β-phase, followed by the lower-zinc α-phase.

Tin tends to inhibit dealloying, especially in cast alloys. Alloys C46400 (naval brass) and C67500 (manganese bronze), which are α-β brasses containing about 1% Sn, are widely used for naval equipment and have reasonably good resistance to dezincification.Addition of a small amount of phosphorus, arsenic, or antimony to admiralty metal (an all-α 71Cu-28Zn-1Sn brass) inhibits dezincification. Inhibitors are not entirely effective in preventing dezincification of the α-β brasses, because they do not prevent dezincification of the β-phase.

Where dezincification is a problem, red brass, commercial bronze, inhibited admiralty metal, and inhibited aluminum brass can be successfully used. In some cases, the economic penalty of avoiding dealloying by selecting a low-zinc alloy may be unacceptable. Low-zinc alloy tubing requires fittings that are available only as sand castings, but fittings for higher-zinc tube can be die cast or forged much more economically. Where selection of a low-zinc alloy is unacceptable, inhibited yellow brasses are generally preferred.

Dealloying has been observed in other alloys. Dealloying of aluminum occurs in some copper-aluminum alloys, particularly with those having more than 8% Al. It is especially severe in alloys with continuous γ phase and usually occurs as plug-type dealloying. Nickel additions exceeding 3.5% or heat treatment to produce an α + β microstructure prevents dealloying. Dealloying of nickel in C71500 is rare, having been observed at temperatures over 100 °C (212 °F), low flow conditions, and high local heat flux (Fig. 9). Dealloying of tin in cast tin bronzes have been observed as a rare occurrence in hot brine or steam. Cathodic protection generally protects all but the two-phase copper-zinc alloys from dealloying.

Fig. 5 A large plug of dezincified metal beneath a deposit on a brass pipe

Fig. 6 Plug-type dezincification in an α-brass (70Cu-30Zn) exposed for 79 days in 1 *N* NaCl at room temperature. Note porous structure within the plug. The dark line surrounding the plug is an etching artifact. 160×

Fig. 7 Layer-type dezincification of a brass pump component. The dark (red) outer layers are uniformly corroded regions surrounding the uncorroded metal (original yellow) of the brass.

Corrosion Fatigue

The combined action of corrosion (usually pitting corrosion) and cyclic stress may result in corrosion fatigue cracking. Like ordinary fatigue cracks, corrosion fatigue cracks generally propagate at right angles to the maximum tensile stress in the affected region. However, cracks resulting from simultaneous fluctuating stress and corrosion propagate much more rapidly than cracks caused solely by fluctuating stress. Also, corrosion fatigue failure usually involves several parallel cracks, but it is rare for more than one crack to be found in a part that has failed by simple fatigue. The cracks shown in Fig. 10 are characteristic of service failures resulting from corrosion fatigue.

Ordinarily, corrosion fatigue can be readily identified by the presence of several cracks emanating from corrosion pits. Cracks not visible to the unaided eye or at low magnification can be made visible by deep etching or plastic deformation or can be detected by eddy-current inspection. Corrosion fatigue cracking is often transgranular, but there is evidence that certain environments induce intergranular cracking in copper metals.

In addition to effective resistance to corrosion, copper and copper alloys also resist corrosion fatigue in many applications involving repeated stress and corrosion. These applications include such parts as springs, switches, diaphragms, bellows, aircraft and automotive gasoline and oil lines, tubes for condensers and heat exchangers, and fourdrinier wire for the paper industry.

Copper alloys that are high in fatigue limit and resistance to corrosion in the service environment are more likely to have good resistance to corrosion fatigue. Alloys frequently used in applications involving both cyclic stress and corrosion include beryllium coppers, phosphor bronzes, aluminum bronzes, and copper nickels.

Stress-Corrosion Cracking

Stress-corrosion cracking and season cracking describe the same phenomenon—the apparently spontaneous cracking of stressed metal. Stress-corrosion cracking is often intergranular (Fig. 11), but transgranular cracking may occur in some alloys in certain environments. Stress-corrosion cracking occurs only if a susceptible alloy is subjected to the combined effects of sustained stress and certain chemical substances.

Copper alloys crack in a wide variety of electrolytes. In some cases, the crack surfaces have the distinctive brittle appearance that is associated with SCC. In other cases, the threshold stress for cracking may be close to that observed in air, and the fracture surfaces resemble those of samples fractured in air. It is also clear in many systems that cracking occurs at low threshold stresses only when certain environmental conditions exist. Variables that control this threshold stress in a specific environment include:

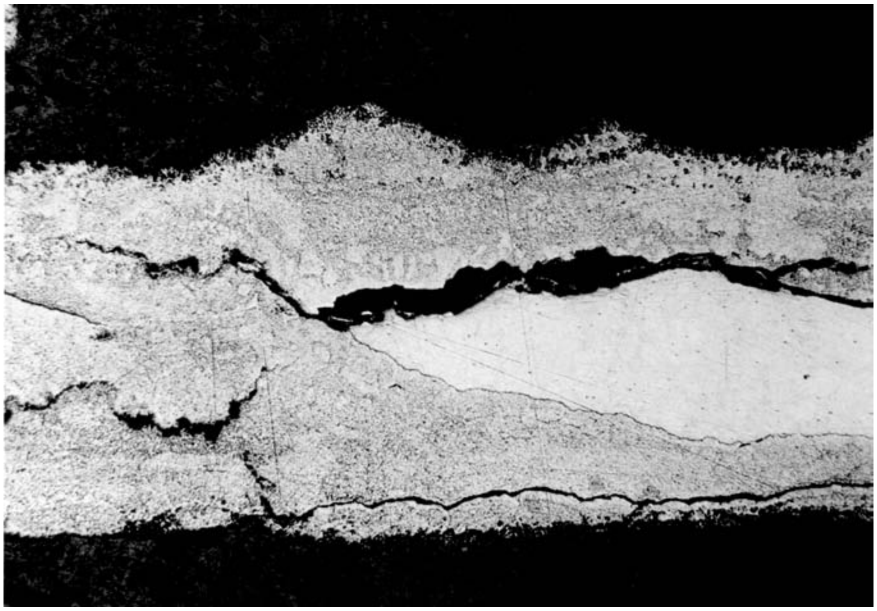

Fig. 8 Layer-type dezincification of a thin brass sheet. The 0.48 mm (0.019 in.) sheet is shown in cross-section. The dezincified layers converge toward the edge (left side) of the sheet. Note the porosity of the dezincified metal.

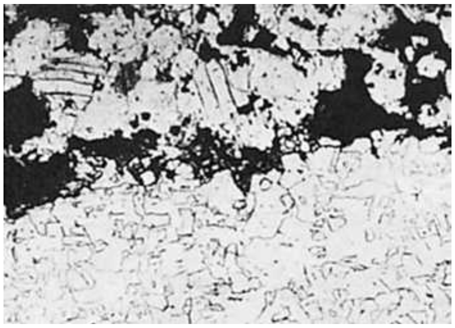

Fig. 9 Residual copper layer from a C71500 feedwater pressure tube that underwent denickelification. The tube was subjected to 205 °C (400 °F) steam on the external surface and boiling water on the internal surface (175 °C, or 350 °F, at pH 8.6 to 9.2).

- Potential, pH, and temperature of the environment
- Minor alloying elements in the copper alloy
- Heat treatment, microstructure, and amount of cold work of the copper alloy

A detailed discussion of these variables can be found in the article "Stress-Corrosion Cracking" which immediately follows in this Handbook and in Ref 1 to 5.

Conditions Leading to SCC. Ammonia and ammonium compounds are the corrosive substances most often associated with SCC of copper alloys. These compounds are sometimes present in the atmosphere; in other cases, they are in cleaning compounds or in chemicals used to treat boiler water. Both oxygen and moisture must be present for NH_3 to be corrosive to copper alloys; other compounds, such as CO_2, are thought to accelerate SCC in NH_3 atmospheres. Moisture films on metal surfaces will dissolve significant quantities of NH_3, even from atmospheres with low NH_3 concentrations.

Fig. 10 Typical corrosion fatigue cracking of a copper alloy. Transgranular cracks originate at the base of corrosion pits on the roughened inner surface of a tube. Etched. About 150×

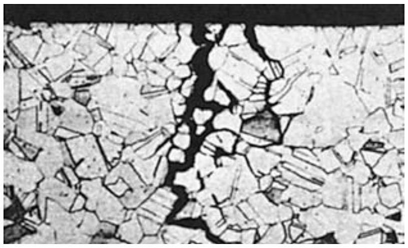

Fig. 11 Typical SCC in a copper alloy. Intergranular cracking in an etched specimen. About 60×

A specific corrosive environment and sustained stress are the primary causes of SCC; microstructure and alloy composition may affect the rate of crack propagation in susceptible alloys. Microstructure and composition can be most effectively controlled by selecting the correct combination of alloy, forming process, thermal treatment, and metal-finishing process. Although test results may indicate that a finished part is not susceptible to SCC, such an indication does not ensure complete freedom from cracking, particularly where service stresses are high.

Applied and residual stresses can both lead to failure by SCC. Susceptibility is largely a function of stress magnitude. Stresses near the yield strength are usually required, but parts have failed under much lower stresses. In general, the higher the stress, the weaker the corroding medium must be to cause SCC. The reverse is also true: the stronger the corroding medium, the lower the required stress.

Sources of Stress. Applied stresses result from ordinary service loading or from fabricating techniques, such as riveting, bolting, shrink fitting, brazing, and welding. Residual stresses are of two types: differential-strain stresses, which result from nonuniform plastic strain during cold forming, and differential-thermal-contraction stresses, which result from nonuniform heating and/or cooling.

Residual stresses induced by nonuniform straining are primarily influenced by the method of fabrication. In some fabricating processes, it is possible to cold work a metal extensively and yet produce only a low level of residual stress. For example, residual stress in a drawn tube is influenced by die angle and amount of reduction. Wide-angle dies (about 32°) produce higher residual stresses than narrow-angle dies (about 8°). Light reductions yield high residual stresses because only the surface of the alloy is stressed; heavy reductions yield low residual stresses because the region of cold working extends deeper into the metal. Most drawing operations can be planned so that residual stresses are low and susceptibility to SCC is negligible.

Residual stresses resulting from upsetting, stretching, or spinning are most difficult to evaluate and to control by varying tooling and process conditions. For these operations, SCC can be prevented more effectively by selecting a resistant alloy or by treating the metal after fabrication.

Alloy Composition. Brasses containing less than 15% Zn are highly resistant to SCC. Phosphorus-deoxidized copper and tough pitch copper rarely exhibit SCC, even under severe conditions. On the other hand, brasses containing 20 to 40% Zn are highly susceptible. Susceptibility increases only slightly as zinc content is increased from 20 to 40%.

There is no indication that the other elements commonly added to brasses increase the probability of SCC. Phosphorus, arsenic, magnesium, tellurium, tin, beryllium, and manganese are thought to decrease susceptibility under some conditions. Addition of 1.5% Si is known to decrease the probability of cracking.

Altering the microstructure cannot make a susceptible alloy totally resistant to SCC. However, the rapidity with which susceptible alloys crack appears to be affected by grain size and structure. All other factors being equal, the rate of cracking increases with grain size. The effects of structure on SCC are not sharply defined, primarily because they are interrelated with effects of both composition and stress.

Relationship between Dezincification and SCC. It was first shown in 1972 that dezincification of 70Cu-30Zn brass occurs in the crack during SCC in an ammonium salt environment (Ref 4). More recently, mechanical strain was found to lead to dezincification of both 85Cu-15Zn and 70Cu-30Zn alloys in an NH_4OH-$(NH_4)_2SO_4$-$CuSO_4$ electrolyte (Ref 6). Unstressed samples of the same alloys did not show dezincification. Strain-induced dealloying was further shown to occur in both intergranular (copper-zinc) and transgranular (copper-zinc-nickel) (Ref 7). These observations indicated that stress corrosion of copper alloys is integrally related to strain-induced dealloying.

Control Measures. Stress-corrosion cracking can be controlled, and sometimes prevented, by selecting copper alloys that have high resistance to cracking (notably those with less than 15% Zn); by reducing residual stress to a safe level by thermal stress relief, which can usually be applied without significantly decreasing strength; or by altering the environment, such as by changing the predominant chemical species present or introducing a corrosion inhibitor.

Residual and assembly stresses can be eliminated by recrystallization annealing after forming or assembly. Recrystallization annealing cannot be used when the integrity of the structure depends on the higher strength of strain-hardened metal, which always contains a certain amount of residual stress. Thermal stress relief (sometimes called relief annealing) can be specified when the higher strength of a cold-worked temper must be retained. Thermal stress relief consists of heating the part for a relatively short time at low temperature. Specific times and temperatures depend on alloy composition, severity of deformation, prevailing stresses, and the size of the load being heated. Usually, time is from 30 min to 1 h and temperature is from 150 to 425 °C (300 to 795 °F). Table 4 lists typical stress-relieving times and temperatures for some of the more common copper alloys.

The exact thermal treatment should be established by examining specific parts for residual stress. If such examination indicates that a thermal treatment is insufficient, temperature and/or time should be adjusted until satisfactory results are obtained. Parts in the center of a furnace load may not reach the desired temperature as soon as parts around the periphery. Therefore, it may be necessary to compensate for furnace loading when setting process controls or to limit the number of parts that can be stress relieved together.

Mechanical methods, such as stretching, flexing, bending, straightening between rollers, peening, and shot blasting, can also be used to reduce residual stresses to a safe level. These methods depend on plastic deformation to decrease dangerous tensile stresses or to convert them to less objectionable compressive stresses.

Factors Influencing Alloy Selection in Specific Environments

Selection of a suitably resistant material requires consideration of the many factors that influence corrosion. Operating records are the most reliable guidelines as long as the data are accurately interpreted. Some of the information in this article has been collected over a period of 20 years or more. Results of short-term laboratory and field testing are also described, but these data may not be as reliable for solving certain problems. Laboratory corrosion tests often do not duplicate such operating factors as stress, velocity, galvanic coupling, concentration cells, initial surface conditions, and contamination of the surrounding medium. If damage occurs by pitting, intergranular corrosion, or dealloying (as in dezincification) or if a thick adherent scale forms, corrosion rates calculated from a change in weight may be misleading. For these forms of corrosion, estimates of reduction in mechanical strength are often more meaningful. Corrosion fatigue and SCC are also potential sources of failure that cannot be predicted from routine measurements of weight loss or dimensional change.

Over the years, experience has been the best criterion for selecting the most suitable alloy for a given environment. The CDA has compiled much field experience in the form of the ratings for wrought alloys shown in Table 5. Similar tabular data for cast alloys are given in the article "Cast Copper and Copper Alloys" in this Handbook. Such tables should be used only as a guide; small changes in the environment conditions sometimes degrade the performance of a given alloy from "suitable" to "not suitable."

Whenever there is a lack of operating experience, whenever reported test conditions do not closely match the conditions for which alloy selection is being made, and whenever there is doubt as to the applicability of published data, it is always best to conduct an independent test. Field tests are the most reliable. Laboratory tests can be equally valuable, but only if operating conditions are precisely defined and then accurately simulated in the laboratory. Long-term tests are generally preferred because the reaction that dominates the initial stages of corrosion may differ significantly from the reaction that dominates later on. If short-term tests must be used as the basis for alloy selection, the test program should be

Table 4 Typical stress-relieving parameters for some common copper alloys

Common name	UNS No.	Temperature		Time, h
		°C	°F	
Commercial bronze	C22000	205	400	1
Cartridge brass	C26000	260	500	1
Muntz metal	C28000	190	375	1/2
Admiralty metal	C44300, C44400, C44500	300	575	1
Phosphor bronze, 5 or 10%	C51000, C52400	190	375	1
Silicon bronze	C65500	370	700	1
Aluminum bronze	C61300, C61400	400	750	1
Copper nickel, 30%	C71500	425	800	1

Table 5 Corrosion ratings of wrought copper alloys in various corrosive media

This table is intended to serve only as a general guide to the behavior of copper and copper alloys in corrosive environments. It is impossible to cover in a simple tabulation the performance of a material for all possible variations of temperature, concentration, velocity, impurity content, degree of aeration, and stress. The ratings are based on general performance; they should be used with caution, and then only for the purpose of screening candidate alloys. The letters E, G, F, and P have the following significance: E, excellent: resists corrosion under almost all conditions of service. G, good: some corrosion will take place, but satisfactory service can be expected under all but the most severe conditions. F, fair: corrosion rates are higher than for the G classification, but the metal can be used if needed for a property other than corrosion resistance and if either the amount of corrosion does not cause excessive maintenance expense or the effects of corrosion can be lessened, such as by use of coatings or inhibitors. P, poor: corrosion rates are high, and service is generally unsatisfactory.

Corrosive medium	Coppers	Low-zinc brasses	High-zinc brasses	Special brasses	Phosphor bronzes	Aluminum bronzes	Silicon bronzes	Copper nickels	Nickel silvers
Acetate solvents	E	E	G	E	E	E	E	E	E
Acetic acid(a)	E	E	P	P	E	E	E	E	G
Acetone	E	E	E	E	E	E	E	E	E
Acetylene(b)	P	P	(b)	P	P	P	P	P	P
Alcohols(a)	E	E	E	E	E	E	E	E	E
Aldehydes	E	E	F	F	E	E	E	E	E
Alkylamines	G	G	G	G	G	G	G	G	G
Alumina	E	E	E	E	E	E	E	E	E
Aluminum chloride	G	G	P	P	G	G	G	G	G
Aluminum hydroxide	E	E	E	E	E	E	E	E	E
Aluminum sulfate and alum	G	G	P	G	G	G	G	E	G
Ammonia, dry	E	E	E	E	E	E	E	E	E
Ammonia, moist(c)	P	P	P	P	P	P	P	F	P
Ammonium chloride(c)	P	P	P	P	P	P	P	F	P
Ammonium hydroxide(c)	P	P	P	P	P	P	P	F	P
Ammonium nitrate(c)	P	P	P	P	P	P	P	F	P
Ammonium sulfate(c)	F	F	P	P	F	F	F	G	F
Aniline and aniline dyes	F	F	F	F	F	F	F	F	F
Asphalt	E	E	E	E	E	E	E	E	E
Atmosphere:									
Industrial(c)	E	E	E	E	E	E	E	E	E
Marine	E	E	E	E	E	E	E	E	E
Rural	E	E	E	E	E	E	E	E	E
Barium carbonate	E	E	E	E	E	E	E	E	E
Barium chloride	G	G	F	F	G	G	G	G	G
Barium hydroxide	E	E	G	E	E	E	E	E	E
Barium sulfate	E	E	E	E	E	E	E	E	E
Beer(a)	E	E	G	E	E	E	E	E	E
Beet-sugar syrup(a)	E	E	G	E	E	E	E	E	E
Benzene, benzine, benzol	E	E	E	E	E	E	E	E	E
Benzoic acid	E	E	E	E	E	E	E	E	E
Black liquor, sulfate process	P	P	P	P	P	P	P	G	P
Bleaching powder (wet)	G	G	P	G	G	G	G	G	G
Borax	E	E	E	E	E	E	E	E	E
Bordeaux mixture	E	E	G	E	E	E	E	E	E
Boric acid	E	E	G	E	E	E	E	E	E
Brines	G	G	P	G	G	G	G	E	E
Bromine, dry	E	E	E	E	E	E	E	E	E
Bromine, moist	G	G	P	F	G	G	G	G	G
Butane(d)	E	E	E	E	E	E	E	E	E
Calcium bisulfate	G	G	P	G	G	G	G	G	G
Calcium chloride	G	G	F	G	G	G	G	G	G
Calcium hydroxide	E	E	G	E	E	E	E	E	E
Calcium hypochlorite	G	G	P	G	G	G	G	G	G
Cane-sugar syrup(a)	E	E	E	E	E	E	E	E	E
Carbolic acid (phenol)	F	G	P	G	G	G	G	G	G
Carbonated beverages(a)(e)	E	E	E	E	E	E	E	E	E
Carbon dioxide, dry		E	E	E	E	E	E	E	E
Carbon dioxide, moist(a)(e)	E	E	E	E	E	E	E	E	E
Carbon tetra-chloride (dry)	E	E	E	E	E	E	E	E	E
Carbon tetra-chloride (moist)	G	G	F	G	E	E	E	E	E
Castor oil	E	E	E	E	E	E	E	E	E
Chlorine, dry(f)	E	E	E	E	E	E	E	E	E
Chlorine, moist	F	F	P	F	F	F	F	G	F
Chloracetic acid	G	F	P	F	G	G	G	G	G
Chloroform, dry	E	E	E	E	E	E	E	E	E
Chromic acid	P	P	P	P	P	P	P	P	P
Citric acid(a)	E	E	F	E	E	E	E	E	E
Copper chloride	F	F	P	F	F	F	F	F	F
Copper nitrate	F	F	P	F	F	F	F	F	F

(continued)

(a) Copper and copper alloys are resistant to corrosion by most food products. Traces of copper may be dissolved and affect taste or color of the products. In such cases, copper alloys are often tin coated. (b) Acetylene forms an explosive compound with copper when moisture or certain impurities are present and the gas is under pressure. Alloys containing less than 65% Cu are satisfactory; when the gas is not under pressure, other copper alloys are satisfactory. (c) Precautions should be taken to avoid SCC. (d) At elevated temperatures, hydrogen will react with tough pitch copper, causing failure by embrittlement. (e) Where air is present, corrosion rate may be increased. (f) Below 150 °C (300 °F), corrosion rate is very low; above this temperature, corrosion is appreciable and increases rapidly with temperature. (g) Aeration and elevated temperature may increase corrosion rate substantially. (h) Excessive oxidation may begin above 120 °C (250 °F). If moisture is present, oxidation may begin at lower temperatures. (j) Use of high-zinc brasses should be avoided in acids because of the likelihood of rapid corrosion by dezincification. Copper, low-zinc brasses, phosphor bronzes, silicon bronzes, aluminum bronzes, and copper nickels offer good resistance to corrosion by hot and cold dilute H_2SO_4 and to corrosion by cold concentrated H_2SO_4. Intermediate concentrations of H_2SO_4 are sometimes more corrosive to copper alloys than either concentrated or dilute acid. Concentrated H_2SO_4 may be corrosive at elevated temperatures due to breakdown of acid and formation of metallic sulfides and sulfur dioxide, which cause localized pitting. Tests indicate that copper alloys may undergo pitting in 90 to 95% H_2SO_4 at about 50 °C (122 °F), in 80% acid at about 70 °C (160 °F), and in 60% acid at about 100 °C (212 °F). (k) Wetting agents may increase corrosion rates of copper and copper alloys slightly to substantially when carbon dioxide or oxygen is present by preventing formation of a film on the metal surface and by combining (in some instances) with the dissolved copper to produce a green, insoluble compound.

Table 5 (continued)

Corrosive medium	Coppers	Low-zinc brasses	High-zinc brasses	Special brasses	Phosphor bronzes	Aluminum bronzes	Silicon bronzes	Copper nickels	Nickel silvers
Copper sulfate	G	G	P	G	G	G	G	E	G
Corn oil(a)	E	E	G	E	E	E	E	E	E
Cottonseed oil(a)	E	E	G	E	E	E	E	E	E
Creosote	E	E	G	E	E	E	E	E	E
Downtherm "A"	E	E	E	E	E	E	E	E	E
Ethanol amine	G	G	G	G	G	G	G	G	G
Ethers	E	E	E	E	E	E	E	E	E
Ethyl acetate (esters)	E	E	G	E	E	E	E	E	E
Ethylene glycol	E	E	G	E	E	E	E	E	E
Ferric chloride	P	P	P	P	P	P	P	P	P
Ferric sulfate	P	P	P	P	P	P	P	P	P
Ferrous chloride	G	G	P	G	G	G	G	G	G
Ferrous sulfate	G	G	P	G	G	G	G	G	G
Formaldehyde (aldehydes)	E	E	G	E	E	E	E	E	E
Formic acid	G	G	P	F	G	G	G	G	G
Freon, dry	E	E		E	E	E	E	E	E
Freon, moist	E	E	E	E	E	E	E	E	E
Fuel oil, light	E	E	E	E	E	E	E	E	E
Fuel oil, heavy	E	E	G	E	E	E	E	E	E
Furfural	E	E	F	E	E	E	E	E	E
Gasoline	E	E	E	E	E	E	E	E	E
Gelatin(a)	E	E	E	E	E	E	E	E	E
Glucose(a)	E	E	E	E	E	E	E	E	E
Glue	E	E	G	E	E	E	E	E	E
Glycerin	E	E	G	E	E	E	E	E	E
Hydrobromic acid	F	F	P	F	F	F	F	F	F
Hydrocarbons	E	E	E	E	E	E	E	E	E
Hydrochloric acid (muriatic)	F	F	P	F	F	F	F	F	F
Hydrocyanic acid, dry	E	E	E	E	E	E	E	E	E
Hydrocyanic acid, moist	P	P	P	P	P	P	P	P	P
Hydrofluoric acid, anhydrous	G	G	P	G	G	G	G	G	G
Hydrofluoric acid, hydrated	F	F	P	F	F	F	F	F	F
Hydrofluosilicic acid	G	G	P	G	G	G	G	G	G
Hydrogen(d)	E	E	E	E	E	E	E	E	E
Hydrogen peroxide up to 10%	G	G	F	G	G	G	G	G	G
Hydrogen peroxide over 10%	P	P	P	P	P	P	P	P	P
Hydrogen sulfide, dry	E	E	E	E	E	E	E	E	E
Hydrogen sulfide, moist	P	P	F	F	P	P	P	F	F
Kerosene	E	E	E	E	E	E	E	E	E
Ketones		E	E	E	E	E	E	E	E
Lacquers	E	E	E	E	E	E	E	E	E
Lacquer thinners (solvents)	E	E	E	E	E	E	E	E	E
Lactic acid(a)	E	E	F	E	E	E	E	E	E
Lime	E	E	E	E	E	E	E	E	E
Lime sulfur	P	P	F	F	P	P	P	F	F
Linseed oil	G	G	G	G	G	G	G	G	G
Lithium compounds	G	G	P	F	G	G	G	E	E
Magnesium chloride	G	G	F	F	G	G	G	G	G
Magnesium hydroxide	E	E	G	E	E	E	E	E	E
Magnesium sulfate	E	E	G	E	E	E	E	E	E
Mercury or mercury salts	P	P	P	P	P	P	P	P	P
Milk(a)	E	E	G	E	E	E	E	E	E
Molasses	E	E	G	E	E	E	E	E	E
Natural gas(d)	E	E	E	E	E	E	E	E	E
Nickel chloride	F	F	P	F	F	F	F	F	F
Nickel sulfate	F	F	P	F	F	F	F	F	F
Nitric acid	P	P	P	P	P	P	P	P	P
Oleic acid	G	G	F	G	G	G	G	G	G
Oxalic acid(g)	E	E	P	P	E	E	E	E	E
Oxygen(h)	E	E	E	E	E	E	E	E	E
Palmitic acid	G	G	F	G	G	G	G	G	G
Paraffin	E	E	E	E	E	E	E	E	E
Phosphoric acid	G	G	P	F	G	G	G	G	G
Picric acid	P	P	P	P	P	P	P	P	P
Potassium carbonate	E	G	E	E	E	E	E	E	E
Potassium chloride	G	G	P	F	G	G	G	E	E
Potassium cyanide	P	P	P	P	P	P	P	P	P
Potassium dichromate (acid)	P	P	P	P	P	P	P	P	P

(continued)

(a) Copper and copper alloys are resistant to corrosion by most food products. Traces of copper may be dissolved and affect taste or color of the products. In such cases, copper alloys are often tin coated. (b) Acetylene forms an explosive compound with copper when moisture or certain impurities are present and the gas is under pressure. Alloys containing less than 65% Cu are satisfactory; when the gas is not under pressure, other copper alloys are satisfactory. (c) Precautions should be taken to avoid SCC. (d) At elevated temperatures, hydrogen will react with tough pitch copper, causing failure by embrittlement. (e) Where air is present, corrosion rate may be increased. (f) Below 150 °C (300 °F), corrosion rate is very low; above this temperature, corrosion is appreciable and increases rapidly with temperature. (g) Aeration and elevated temperature may increase corrosion rate substantially. (h) Excessive oxidation may begin above 120 °C (250 °F). If moisture is present, oxidation may begin at lower temperatures. (j) Use of high-zinc brasses should be avoided in acids because of the likelihood of rapid corrosion by dezincification. Copper, low-zinc brasses, phosphor bronzes, silicon bronzes, aluminum bronzes, and copper nickels offer good resistance to corrosion by hot and cold dilute H_2SO_4 and to corrosion by cold concentrated H_2SO_4. Intermediate concentrations of H_2SO_4 are sometimes more corrosive to copper alloys than either concentrated or dilute acid. Concentrated H_2SO_4 may be corrosive at elevated temperatures due to breakdown of acid and formation of metallic sulfides and sulfur dioxide, which cause localized pitting. Tests indicate that copper alloys may undergo pitting in 90 to 95% H_2SO_4 at about 50 °C (122 °F), in 80% acid at about 70 °C (160 °F), and in 60% acid at about 100 °C (212 °F). (k) Wetting agents may increase corrosion rates of copper and copper alloys slightly to substantially when carbon dioxide or oxygen is present by preventing formation of a film on the metal surface and by combining (in some instances) with the dissolved copper to produce a green, insoluble compound.

Table 5 (continued)

Corrosive medium	Coppers	Low-zinc brasses	High-zinc brasses	Special brasses	Phosphor bronzes	Aluminum bronzes	Silicon bronzes	Copper nickels	Nickel silvers
Potassium hydroxide	G	G	F	G	G	G	G	E	E
Potassium sulfate	E	E	G	E	E	E	E	E	E
Propane(d)	E	E	E	E	E	E	E	E	E
Rosin	E	E	E	E	E	E	E	E	E
Seawater	G	G	F	E	G	E	G	E	E
Sewage	E	E	F	E	E	E	E	E	E
Silver salts	P	P	P	P	P	P	P	P	P
Soap solution	E	E	E	E	E	E	E	E	E
Sodium bicarbonate	E	E	G	E	E	E	E	E	E
Sodium bisulfate	G	G	F	G	G	G	G	E	E
Sodium carbonate	E	E	G	E	E	E	E	E	E
Sodium chloride	G	G	P	F	G	G	G	E	E
Sodium chromate	E	E	E	E	E	E	E	E	E
Sodium cyanide	P	P	P	P	P	P	P	P	P
Sodium dichromate (acid)	P	P	P	P	P	P	P	P	P
Sodium hydroxide	G	G	F	G	G	G	G	E	E
Sodium hypochlorite	G	G	P	G	G	G	G	G	G
Sodium nitrate	G	G	P	F	G	G	G	E	E
Sodium peroxide	F	F	P	F	F	F	F	G	G
Sodium phosphate	E	E	G	E	E	E	E	E	E
Sodium silicate	E	E	G	E	E	E	E	E	E
Sodium sulfate	E	E	G	E	E	E	E	E	E
Sodium sulfide	P	P	F	F	P	P	P	F	F
Sodium thiosulfate	P	P	F	F	P	P	P	F	F
Steam	E	E	F	E	E	E	F	E	E
Stearic acid	E	E	F	E	E	E	E	E	E
Sugar solutions	E	E	G	E	E	E	E	E	E
Sulfur, solid	G	G	E	G	G	G	G	E	G
Sulfur, molten	P	P	P	P	P	P	P	P	P
Sulfur chloride (dry)	E	E	E	E	E	E	E	E	E
Sulfur chloride (moist)	P	P	P	P	P	P	P	P	P
Sulfur dioxide (dry)	E	E	E	E	E	E	E	E	E
Sulfur dioxide (moist)	G	G	P	G	G	G	G	F	F
Sulfur trioxide (dry)	E	E	E	E	E	E	E	E	E
Sulfuric acid 80–95%(j)	G	G	P	F	G	G	G	G	G
Sulfuric acid 40–80%(j)	F	F	F	P	F	F	F	F	F
Sulfuric acid 40%(j)	G	G	P	F	G	G	G	G	G
Sulfurous acid	G	G	P	G	G	G	G	F	F
Tannic acid	E	E	E	E	E	E	E	E	E
Tartaric acid(a)	E	E	G	E	E	E	E	E	E
Toluene	E	E	E	E	E	E	E	E	E
Trichloracetic acid	G	G	P	F	G	G	G	G	G
Trichlorethylene (dry)	E	E	E	E	E	E	E	E	E
Trichlorethylene (moist)	G	G	F	G	E	E	E	E	E
Turpentine	E	E	E	E	E	E	E	E	E
Varnish	E	E	E	E	E	E	E	E	E
Vinegar(a)	E	E	P	F	E	E	E	E	G
Water, acidic mine	F	F	P	F	G	F	F	P	F
Water, potable	E	E	G	E	E	E	E	E	E
Water condensate(c)	E	E	E	E	E	E	E	E	E
Wetting agents(k)	E	E	E	E	E	E	E	E	E
Whiskey(a)	E	E	E	E	E	E	E	E	E
White water	G	G	G	E	E	E	E	E	E
Zinc chloride	G	G	P	G	G	G	G	G	G
Zinc sulfate	E	E	P	E	E	E	E	E	E

(a) Copper and copper alloys are resistant to corrosion by most food products. Traces of copper may be dissolved and affect taste or color of the products. In such cases, copper alloys are often tin coated. (b) Acetylene forms an explosive compound with copper when moisture or certain impurities are present and the gas is under pressure. Alloys containing less than 65% Cu are satisfactory; when the gas is not under pressure, other copper alloys are satisfactory. (c) Precautions should be taken to avoid SCC. (d) At elevated temperatures, hydrogen will react with tough pitch copper, causing failure by embrittlement. (e) Where air is present, corrosion rate may be increased. (f) Below 150 °C (300 °F), corrosion rate is very low; above this temperature, corrosion is appreciable and increases rapidly with temperature. (g) Aeration and elevated temperature may increase corrosion rate substantially. (h) Excessive oxidation may begin above 120 °C (250 °F). If moisture is present, oxidation may begin at lower temperatures. (j) Use of high-zinc brasses should be avoided in acids because of the likelihood of rapid corrosion by dezincification. Copper, low-zinc brasses, phosphor bronzes, silicon bronzes, aluminum bronzes, and copper nickels offer good resistance to corrosion by hot and cold dilute H_2SO_4 and to corrosion by cold concentrated H_2SO_4. Intermediate concentrations of H_2SO_4 are sometimes more corrosive to copper alloys than either concentrated or dilute acid. Concentrated H_2SO_4 may be corrosive at elevated temperatures due to breakdown of acid and formation of metallic sulfides and sulfur dioxide, which cause localized pitting. Tests indicate that copper alloys may undergo pitting in 90 to 95% H_2SO_4 at about 50 °C (122 °F), in 80% acid at about 70 °C (160 °F), and in 60% acid at about 100 °C (212 °F). (k) Wetting agents may increase corrosion rates of copper and copper alloys slightly to substantially when carbon dioxide or oxygen is present by preventing formation of a film on the metal surface and by combining (in some instances) with the dissolved copper to produce a green, insoluble compound.

supplemented with field tests so that the laboratory results can be reevaluated in light of true operating experience.

Erroneous conclusions based on laboratory results can also be reached by measuring corrosion damage inaccurately, especially when corrosion is slight. It is common practice to express test results in terms of penetration or average reduction in metal thickness, even when corrosion was actually measured by weight loss. Weight loss or average-penetration data are valid only when corrosion is uniform. When corrosion occurs predominantly by pitting or some other localized form or when corrosion is intergranular or involves the formation of a thick, adherent scale, direct measurement of the extent of corrosion provides the most reliable information. A common technique is to measure the maximum depth of penetration observed on a metallographic cross section through the region of interest. Statistical averaging of repeated measurements on one or more specimens may or may not be warranted. Despite the deficiencies in laboratory testing, information gained in this manner serves as a useful starting point for alloy selection. Operating experience may later indicate the need for a more discriminating selection.

Atmospheric Corrosion

Comprehensive tests conducted over a 20-year period under the supervision of ASTM as

Table 6 Atmospheric corrosion of selected copper alloys

	Corrosion rates at indicated locations(a)											
	Altoona, PA		New York, NY		Key West, FL		La Jolla, CA		State College, PA		Phoenix, AZ	
Alloy	μm/yr	mils/yr	μm/yr	mils/yr	μm/yr	mils/yr	μm/yr	mils/yr	μm/yr	mils/yr	μm/yr	mils/yr
C11000	1.40	0.055	1.38	0.054	0.56	0.022	1.27	0.050	0.43	0.017	0.13	0.005
C12000	1.32	0.052	1.22	0.048	0.51	0.020	1.42	0.056	0.36	0.014	0.08	0.003
C23000	1.88	0.074	1.88	0.074	0.56	0.022	0.33	0.013	0.46	0.018	0.10	0.004
C26000	3.05	0.120	2.41	0.095	0.20	0.008	0.15	0.006	0.46	0.018	0.10	0.004
C52100	2.24	0.088	2.54	0.100	0.71	0.028	2.31	0.091	0.33	0.013	0.13	0.005
C61000	1.63	0.064	1.60	0.063	0.10	0.004	0.15	0.006	0.25	0.010	0.51	0.002
C65500	1.65	0.065	1.73	0.068	...	...	1.38	0.054	0.51	0.020	0.15	0.006
C44200	2.13	0.084	2.51	0.099	...	...	0.33	0.013	0.53	0.021	0.10	0.004
70Cu-29Ni-1Sn(b)	2.64	0.104	2.13	0.084	0.28	0.011	0.36	0.014	0.48	0.019	0.10	0.004

(a) Derived from 20-year exposure tests. Types of atmospheres: Altoona, industrial; New York City, industrial marine; Key West, tropical rural marine; La Jolla, humid marine; State College, northern rural; Phoenix, dry rural. (b) Although obsolete, this alloy indicates the corrosion resistance expected of C71500.

Table 7 Average atmospheric-corrosion rates of various metals for 10- and 20-year exposure times

Corrosion rates are given in mils/yr (1 mil/yr = 0.025 mm/yr). Values cited are one-half reduction of specimen thickness.

	Atmosphere					
	New York, NY (urban-industrial)		La Jolla, CA (marine)		State College, PA (rural)	
Metal	10 yr	20 yr	10 yr	20 yr	10 yr	20 yr
Aluminum	0.032	0.029	0.028	0.025	0.001	0.003
Copper	0.047	0.054	0.052	0.050	0.023	0.017
Lead	0.017	0.015	0.016	0.021	0.019	0.013
Tin	0.047	0.052	0.091	0.112	0.018	...
Nickel	0.128	0.144	0.004	0.006	0.006	0.009
65% Ni, 32% Cu, 2% Fe, 1% Mn (Monel)	0.053	0.062	0.007	0.006	0.005	0.007
Zinc (99.9%)	0.202	0.226	0.063	0.069	0.034	0.044
Zinc (99.0%)	0.193	0.218	0.069	0.068	0.042	0.043
0.2% C Steel(a) (0.02% P, 0.05% S, 0.05% Cu, 0.02% Ni, 0.02% Cr)	0.48	...	...	...	...	...
Low-alloy steel(a) (0.1% C, 0.2% P, 0.04% S, 0.03% Ni, 1.1% Cr, 0.4%. Cu)	0.09	...	...	...	...	...

(a) Kearney, NJ (near New York City).

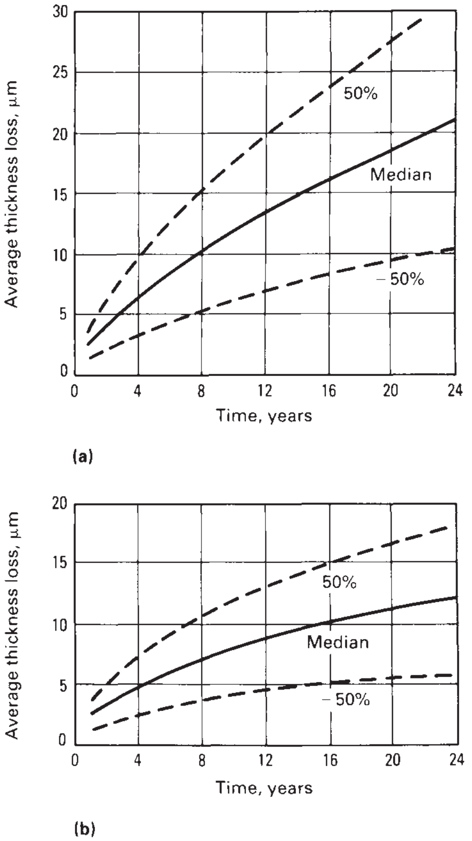

Fig. 12 Typical corrosion rates of representative copper alloys in a marine atmosphere. (a) Average data for copper, silicon bronze, and phosphor bronze. (b) Average data for brass, aluminum bronze, nickel silver, and copper-nickel

well as many service records, have confirmed the suitability of copper and copper alloys for atmospheric exposure (Table 6). Copper and copper alloys resist corrosion by industrial, marine, and rural atmospheres except atmospheres containing NH_3 or certain other agents where SCC has been observed in high-zinc alloys (>20% Zn). The copper metals most widely used in atmospheric exposure are C11000, C22000, C23000, C38500, and C75200. Alloy C11000 is an effective material for roofing, flashings, gutters, and downspouts.

Table 7 compares the atmospheric corrosion rates of copper and various other metals and alloys. Metals that are not particularly resistant to dilute H_2SO_4, such as copper, cadmium, nickel, and iron, show more rapid attack in industrial environments. Metals and alloys that are more resistant to H_2SO_4, such as lead, aluminum, and stainless steels, are less affected in the industrial environments. Copper forms a protective sulfate patina and is therefore more resistant than nickel. As described below, copper also forms a basic copper chloride film in seacoast environments.

The colors of different copper alloys are often important in architectural applications, and color may be the primary criterion for selecting a specific alloy. After surface preparation, such as sanding or polishing, different copper alloys vary in color from silver to yellow to gold to reddish shades. Different alloys having the same initial color may show differences in color after weathering under similar conditions. Therefore, alloys having the same or nearly the same composition are usually used together for consistency of appearance in a specific structure.

Copper alloys are often specified for marine atmosphere exposures because of the attractive and protective patina they form during the exposure. In marine atmospheric exposures, this patina consists of a film of basic copper chloride or carbonate, sometimes with an inner layer of Cu_2O. The severity of the corrosion attack in marine atmospheres is somewhat less than that in industrial atmospheres but greater than that in rural atmospheres. However, these rates decrease with time.

Individual differences in corrosion rates do exist between alloys, but these differences are frequently less than the differences caused by environmental factors. Thus, it becomes possible to classify the corrosion behavior of copper alloys in a marine atmosphere into two general categories: those alloys that corrode at a moderate rate and include high-copper alloys, silicon bronze, and tin bronze and those alloys that corrode at a slower rate and include brass, aluminum bronze, nickel silver, and copper nickel. The average metal loss, d, of the former group can be approximated by $d = 0.1\,t^{2/3}$; the latter group can be approximated by $d = 0.1\,t^{1/3}$. In both equations, t is exposure time. These relationships are shown as solid lines in Fig. 12.

Environmental factors can cause this median thickness loss to vary by as much as 50% or more in a few extreme cases. Figure 12 shows the extent of this variation as a pair of dashed lines forming an envelope around the median. Those environmental factors that tend to accelerate metal loss include high humidity, high temperatures (either ambient or due to solar radiation), proximity to the ocean, long times of wetness, and the presence of pollutants in the atmosphere. The converse of these conditions would tend to retard metal loss.

Metallurgical factors can also affect metal loss. Within a given alloy family, those with a higher alloy content tend to corrode at a lower rate. Surface finish also plays a role in that a highly polished metal will corrode slower than one with a rougher surface. Finally, design details can affect corrosion behavior. For example, designs that allow the collection and stagnation of rainwater will often exhibit wastage rates in the puddle areas that are more typical of those encountered in seawater immersions.

Certain copper alloys are susceptible to various types of localized corrosion that can greatly affect their utility in a marine atmosphere. Brasses and nickel silvers containing more than 15% Zn can suffer from dealloying. The extent of this attack is greater on alloys that contain higher proportions of zinc. In addition, these same alloys are subject to SCC in the presence of small quantities of NH_3 or other gaseous pollutants. Inhibited grades of these alloys are available that resist dealloying but are susceptible to SCC.

Alloys containing large amounts of manganese tend to be somewhat prone to pitting in marine atmospheres, as are the cobalt-containing beryllium-coppers. A tendency toward intergranular corrosion has been observed in silicon bronzes and aluminum brass, but its occurrence is somewhat sporadic.

On the whole, however, even under somewhat adverse conditions, the average thickness losses for copper alloys in a marine atmosphere tend to be very slight, typically under 50 μm (Fig. 12). Thus, copper alloys can be safely specified for applications requiring long-term durability in a marine atmosphere. Design considerations for the atmospheric use of copper alloys include allowance for free drainage of structures, the possibility of staining from runoff water, and the use of smooth or polished surfaces.

Corrosion in Soils and Groundwater

Soils. Copper, zinc, lead, and iron are the metals most commonly used in underground construction. Data compiled by the National Institute of Standards and Technology (NIST), formerly known as the National Bureau of Standards (NBS), compare the behavior of these materials in soils of the following four types: well-aerated acid soils low in soluble salts (Cecil clay loam,) poorly aerated soils (Lake Charles clay), alkaline soils high in soluble salts (Docas clay), and soils high in sulfides (Rifle peat).

Corrosion data as a function of time for copper, iron, lead, and zinc exposed to these four types of soil are given in Fig. 13. Copper exhibits high resistance to corrosion by these soils, which are representative of most soils found in the United States. Where local soil conditions are unusually corrosive, it may be necessary to use some means of protection, such as cathodic protection, neutralizing backfill (limestone, for example), protective coating, or wrapping.

For many years, NIST has conducted studies on the corrosion of underground structures to determine the specific behavior of metals and alloys when exposed for long periods in a wide range of soils. Results indicate that tough pitch coppers, deoxidized coppers, silicon bronzes, and low-zinc brasses behave essentially alike. Soils containing cinders with high concentrations of sulfides, chlorides, or hydrogen ions (H^+) corrode these materials. In this type of contaminated soil, the corrosion rates of copper-zinc alloys containing more than about 22% Zn increase with zinc content. Corrosion generally results from dezincification. In soils that contain only sulfides, corrosion rates of the copper-zinc alloys decrease with increasing zinc content, and no dezincification occurs. Although not included in these tests, inhibited admiralty metals would offer significant resistance to dezincification.

Electric cables that contain copper are often buried underground. One study investigated the corrosion behavior of phosphorus-deoxidized copper (C12200) in four soil types: gravel, salt marsh, swamp, and clay (Ref 8). After three years of exposure, uniform corrosion rates were found to vary between 1.3 and 8.8 μm/yr (0.05 and 0.35 mil/yr). No pitting attack was observed. In general, the corrosion rate was highest for soils of lowest resistivity.

Underground Nuclear Waste Containment. The possibility of disposing of nuclear waste in copper containers buried deep underground has also been investigated. Except for the mining and oil industries, underground construction is usually limited to the first few tens of meters from the surface; an underground waste disposal vault would probably be located at a depth of 500 to 1000 m (1640–3280 ft) in stable bedrock. At these depths, the environment differs in several respects from that nearer the surface. With increasing depth, the natural groundwaters tend to become more saline and less oxidizing. In addition, the pressures exerted by hydrostatic and lithostatic forces become greater. These aspects affect the design and corrosion behavior of any metallic structure buried at such great depths.

A copper nuclear waste disposal container would be surrounded by a compacted claylike material. This serves a dual purpose: first it acts as a physical barrier, reducing the rate of transport of species to and from the container, and second it provides some chemical buffering effects and effectively increases the pH of the environment. Both of these properties are beneficial in terms of the corrosion resistance of copper.

The clay most likely to be used is a montmorillonite clay, such as sodium bentonite. In the compacted form, this clay swells when wet and would effectively seal all cracks in the surrounding rock. The low permeability of the clay ensures that there would be no mass flow of groundwater and that transport of dissolved species would occur by diffusion only. The rate of diffusion in the clay is perhaps 100 times slower than in free solution. This slow rate of diffusion applies not only to the transport of oxidants, such as dissolved oxygen (O^2) or sulfide ions (S^{2-}), to the copper surface but also to the diffusion of soluble corrosion products away from the surface. The net effect is reduction in the corrosion rate of copper compared with that in free solution. One study suggests that under such conditions uniform corrosion of oxygen-free electronic copper (C10100) would only amount to 1.1 mm (43.4 mils) in 10^6 years (Ref 9). Experimental results indicate that the clay may reduce the corrosion rate by about a factor of ten over that in bulk solution, although these results suggest a corrosion rate of about 1 μm/yr (0.04 mils/yr) (Ref 10).

Naturally occurring saline waters are also found deep underground. Although the composition and concentration of these groundwaters vary from site to site, the concentration of dissolved species generally increases with depth (Ref 11). Such groundwaters are encountered in mines, during oil drilling, and in deep bore holes. The waters have a complex composition, often being mixtures of sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^-), sulfate (SO_4^{2-}), and bicarbonate (HCO_3^-) ions as well as

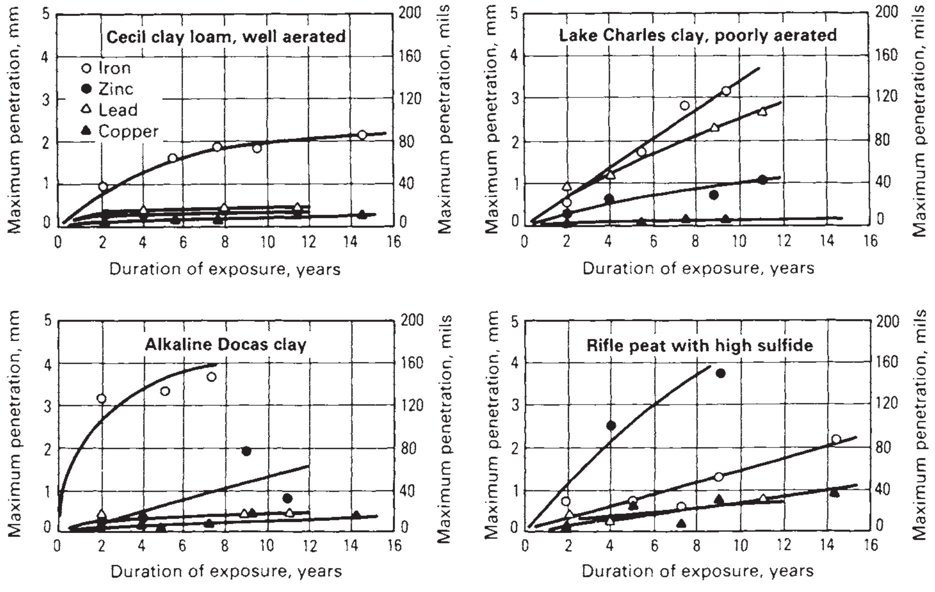

Fig. 13 Corrosion of copper, iron, lead, and zinc in four different soils

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Table 8 Short-term corrosion rates of copper alloys in saline groundwaters

Alloy	Type of groundwater	Oxygen concentration, μg/g	Temperature °C	Temperature °F	Corrosion rate μm/yr	Corrosion rate mils/yr	Ref
C10100	Synthetic 55 g/L TDS(a)	<0.1	150	300	15	0.6	(b)
		6	150	300	340	13.4	
Copper	Brine A 306 g/L TDS	<0.1	250	480	70	2.8	12
		600	250	480	1200	47.2	
	Seawater 35 g/L TDS	<0.1	250	480	50	2	
		1750	250	480	5000	197	
Cu-10Ni (C70600)	Brine A	<0.1	250	480	140	5.5	12
		600	250	480	400	15.7	
	Seawater	<0.1	250	480	70	2.8	
		1750	250	480	700	27.6	

(a) TDS, total dissolved solids. (b) F. King and C.D. Litke, unpublished research, 1985

trace amounts of other ions. Iron minerals in the bedrock react with dissolved oxygen in the groundwater and produce less oxidizing conditions than are found in waters nearer the surface.

Groundwaters. The corrosion rate of copper in quiescent groundwaters tends to decrease with time. This is due to the formation of a protective film, an example of which is shown in Fig. 14. The underlying layer consists of species from the groundwater as well as copper. This layer is brittle and is extensively cracked, permitting continued dissolution of copper ions into solution. In Fig. 14, some of these copper ions have precipitated on the underlying layer in the form of cupric hydroxychloride [$CuCl_2 \cdot 3(Cu(OH)_2)$] and copper oxide crystals. The corrosion layer is not truly passivating, and corrosion will continue, although at a reduced rate.

For both copper and copper alloys, corrosion rate depends strongly on the amount of dissolved oxygen present. The data in Table 8 illustrate this point for both pure copper and Cu-10Ni in various synthetic groundwaters. These data are derived from experiments lasting from 2 to 4 weeks; therefore, they include the high initial rates of corrosion and do not represent long-term corrosion rates. However, they do serve to show that deoxygenation of the solution results in at least an order of magnitude decrease in the short-term corrosion rate. It is also apparent from these data that, in aerated solutions at least, the addition of nickel decreases the uniform corrosion rate of copper. This is due to the formation of a more highly protective surface film.

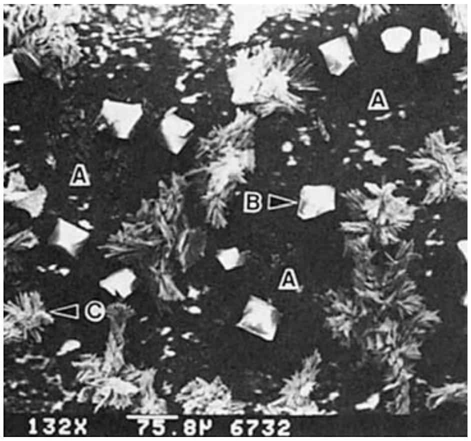

Fig. 14 Scanning electron micrograph of the corrosion product formed on C10100 in complex groundwater at 150 °C (300 °F). A, underlying film containing copper, silicon, calcium, chlorine, and magnesium; B, crystals of $CuCl_2 \cdot 3(Cu(OH)_2)$; C, crystals of CuO or Cu_2O

The effects of salinity and temperature are less well understood. In general, increasing the total salinity of these groundwaters tends to increase their corrosiveness. However, it is not clear whether this is due to the sum effect of all the dissolved ions or of some of the species in particular. In open systems it is difficult to distinguish the effect of temperature from that of dissolved oxygen, because the solubility of oxygen decreases with increasing temperature. The combination of these two opposing effects can lead to an apparent maximum in the corrosion rate at some intermediate temperature. Consequently, it is important that the rates refer to a constant dissolved-oxygen concentration when considering the effects of temperature.

Corrosion in Waters

Freshwater

Copper is used extensively for handling freshwater. Copper tubing in the K-gage range with flared fittings was designed for undergroundwater service and, along with type L tubing, has now become standard for this application. The largest single application of copper tubing is for hot- and cold-water distribution lines in homes and other buildings, although considerable quantities are also used in heating lines (including radiant heating lines for homes), drain tubes, and fire safety systems.

Copper. Minerals in water combine with dissolved CO_2 and oxygen and react with copper to form a protective film. Therefore, the corrosion rate is low (5–25 μm/yr, or 0.2–1.0 mil/yr) in most exposures. In distilled water or very soft water, protective films are less likely to form; therefore, the corrosion rate may vary from less than 2.5 to 125 μm/yr (0.1–5 mils/yr) or more, depending on oxygen and CO_2 contents.

Copper-Zinc Alloys. The corrosion resistance of the brasses is good in unpolluted freshwater—normally 2.5 to 25 μm/yr (0.1–1.0 mil/yr). Corrosion rates are somewhat higher in nonscaling water containing CO_2 and oxygen. Uninhibited brasses of high zinc content (35–40% Zn) are subject to dezincification when used with stagnant or slowly moving brackish or slightly acid waters. One the other hand, inhibited admiralty metals and brasses containing 15% Zn or less are highly resistant to dezincification and are used very successfully in these waters. Inhibited yellow brasses are widely used in Europe and are gaining acceptance in North America. Alloy C68700 (arsenical aluminum brass, an inhibited 77Cu-21Zn-2Al alloy) has been successfully used for condenser and heat-exchanger tubes.

Copper nickels generally have corrosion rates under 25 μm/yr (1 mil/yr) in polluted water. They are sometimes used to resist impingement attack where severe velocity and entrained-air conditions cannot be overcome by changes in operating conditions or equipment design.

Copper-silicon alloys (silicon bronzes) also have excellent corrosion resistance, and for these alloys the amount of dissolved oxygen in the water does not influence corrosion significantly. If CO_2 is also present, the corrosion rate will increase (but not excessively), particularly at temperatures above 60 °C (140 °F). Corrosion rates for silicon bronzes are similar to those for copper.

Copper-Aluminum Alloys. The aluminum bronzes have been used in many waters, from potable water to brackish water to seawater. Softened waters are usually more corrosive to these materials than hard waters. Alloys C61300 and C63200 are used on cooling tower hardware in which the makeup water is sewage effluent. Aluminum bronzes resist oxidation and impingement corrosion because of the aluminum in the surface film.

Steam and Steam Condensate

Steam. Copper and copper alloys resist attack by pure steam, but if much CO_2, oxygen, or NH_3 is present, the condensate is corrosive. Even though wet steam at high velocities can cause severe impingement attack, copper alloys are extensively used in condensers and heat exchangers. Copper alloys are also used for feedwater heaters, although their use in such applications is somewhat limited because of their rapid decline in strength and creep resistance at moderately elevated temperatures. Copper nickels are the preferred copper alloys for the higher temperatures and pressures.

Use of copper in systems handling hot water and steam is limited by the working pressures of tubes and joints. For example, copper tubing of 6.4 to 25 mm ($\frac{1}{4}$–1 in.) nominal diameter joined with 50Sn–50Pb solder can be used at temperatures to 120 °C (250 °F) and pressures to 585 kPa (85 psi). The working pressure at this temperature in tubing of the same size can be increased to 1380 kPa (200 psi) when the system is joined with 95Sn-5Sb solder. When the joining material is a silver-base brazing alloy with a melting point above 540 °C (1000 °F), the working pressure at 120 °C (250 °F) for tubing in this size range can be increased to 2070 kPa (300 psi). A few copper alloys have shown a tendency to fail by SCC when they are highly stressed and exposed to steam. Alpha aluminum bronzes that do not contain tin are among the susceptible alloys.

Steam condensate that has been properly treated so that it is relatively free of noncondensate gases, as in a power-generating station, is relatively noncorrosive to copper and copper alloys. Rates of attack in most such exposures are less than 2.5 μm/yr (0.1 mil/yr). Copper and its alloys are not attacked by condensate that contains a significant amount of oil, such as condensate from a reciprocating steam engine.

Dissolved CO_2, oxygen, or both significantly increase the rate of attack. For example, condensate with 4.6 ppm O, and 14 ppm CO_2, and a pH of 5.5 at 68 °C (155 °F) caused an average penetration of 175 to 350 μm/yr (6.9–13.8 mils/yr) when in contact with C12200 (phosphorus-deoxidized copper), C14200) (arsenical copper), C23000 (red brass), C44300 to C44500 (admiralty metal), and C71000 (copper nickel, 20%). Steel tested under the same conditions was penetrated at about twice the rate given for the copper alloys listed above, but tin-coated copper proved to be much more resistant and was attacked at a rate of less than 25 μm/yr (1 mil/yr). To attain the optimal service life in condensate systems, it is necessary to ensure that the tubes are installed with enough slope to allow proper drainage, to reduce the quantity of corrosive agents (usually CO_2 and oxygen) at the source by mechanical or chemical treatment of the feedwater, or to treat the steam chemically.

Modern utility boiler feedwater treatments commonly include the addition of organic amines to inhibit the corrosion of iron components of the system by scavenging oxygen and increasing the pH of the feedwater. These chemicals, such as morpholine, and hydrazine, decompose in service to yield NH_3, which can be quite corrosive toward some copper alloys. In the main body of well-monitored operating condensers, oxygen and NH_3 levels are quite low, and corrosion is usually mild. More aggressive conditions exist in the air removal section. Abnormal operating conditions, tube leakage, and shutdown-startup cycles may also increase the corrosivity of the steam-side environment by raising the oxygen concentration. The corrosion resistance in laboratory tests of a number of copper alloys and low-carbon steel in both aerated (8–12 ppm O_2) and deaerated (100–200 ppb O_2) NH_3 solutions are illustrated in Fig. 15 and 16. In these tests, NH_3 enhanced the corrosion resistance of the copper-nickel alloys, modifying surface oxides by increasing nickel content. Elevated oxygen levels are generally more deleterious than elevated NH_3 levels. However, C71500 was minimally affected by the elevated oxygen content. These laboratory data correlate well with field corrosion data from operating power plants (Table 9).

Salt Water

An important use of copper alloys is in handling seawater in ships and tidewater power stations. Copper itself, although fairly useful, is usually less resistant to general corrosion than C44300 to C44500, C61300, C68700, C70600, or C71500. The superior performance of these alloys results from the combination of insolubility in seawater, erosion resistance, and biofouling resistance. The corrosion rates of copper and its alloys in relatively quiescent seawater are typically less than 50 μm/yr (2 mils/yr).

In the laboratory and in service, copper-nickel alloys C70600, C71500, C72200, and C71640 exhibit excellent corrosion resistance in seawater. Average corrosion rates for both C70600 and C71500 were shown to range from 2 to 12 μm/yr (0.08–0.5 mils/yr) (Ref 15). The long-term evaluations illustrated in Fig. 17 and 18 revealed corrosion rates under 2.5 μm/yr (0.1 mil/yr) for both alloys after 14 years of exposure to quiescent and low-velocity seawater (Ref 16). Sixteen-year tests confirmed this same low corrosion rate (Ref 17).

Pitting Resistance. Alloys C70600 and C71500 both display excellent resistance to pitting in seawater. The average depth of the 20 deepest pits in C71500 observed at the end of the 16-year tests was less than 127 μm (5 mils) (Ref 17). Chromium-modified copper-nickel alloys, developed for resistance to high-velocity seawater, were evaluated in both low- and high-velocity conditions. The quiescent and low-velocity performances of C72200, C70600, and C71500 were compared (Ref 18, 19); results showed uniform corrosion (5–25 μm/yr, or 0.2–1 mil/yr) on all three alloys. The chromium-containing alloys, however, were slightly more susceptible to localized attack in quiet seawater. Another study reported that the pitting behavior of C72200 is influenced by the presence of iron and chromium in or out of solid solution (Ref 20). The fraction of iron plus chromium in solution in C72200 must be kept higher than 0.7 to avoid pitting corrosion.

Velocity Effects. The corrosion resistance of copper alloys in flowing seawater depends on the

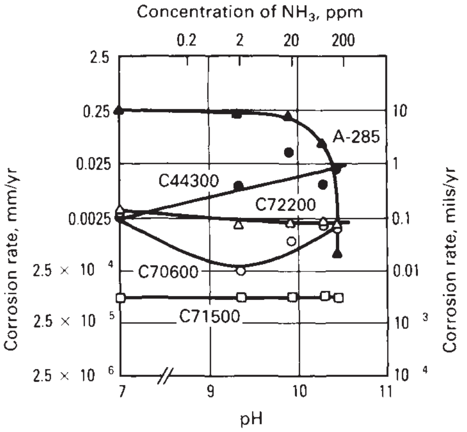

Fig. 15 Corrosion rates of copper alloys in aerated NH_3 solutions. Test duration: 1000 h. Source: Ref 13

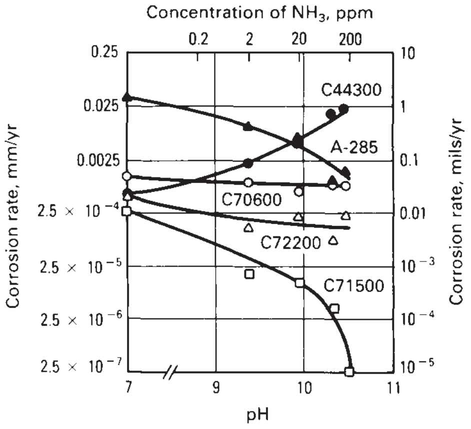

Fig. 16 Corrosion rates of copper alloys in deaerated NH_3 solutions. Test duration: 1000 h. Source: Ref 13

Table 9 Comparison of field and laboratory condensate corrosion of copper alloys

Data are weight loss measured after total exposure time, expressed as penetration rates.

	Corrosion rate, μm/yr (mils/yr)					
	Field tests(a)			Laboratory tests		
Alloy	Plant A	Plant B	Plant C	0 ppm NH_3	2 ppm NH_3	20 ppm NH_3
C71500	0.2 (0.0083)	0.1 (0.004)	0.4 (0.0151)	0.3 (0.012)	0.05 (0.002)	0.025 (0.001)
C72200	0.4 (0.016)	0.4 (0.016)	0.38 (0.015)	0.61 (0.024)	0.2 (0.008)	0.18 (0.007)
C70600	0.48 (0.019)	0.36 (0.014)	0.46 (0.018)	1.3 (0.053)	1.1 (0.043)	0.94 (0.037)
C44300	1.27 (0.05)	0.79 (0.031)	0.61 (0.024)	0.61 (0.024)	2.3 (0.09)	5.6 (0.22)
A-285	6.2 (0.243)	10.4 (0.411)	2.6 (0.103)	38 (1.5)	8.3 (0.325)	4.6 (0.183)

(a) Two-year tests in hot wells at three plant sites (A, B, and C). Plant A, pH range of 8.8–9.7; typical pH of 9.1–9.3. Plant B, pH range of 9–10, typical pH of 9.3–9.6. (b) Laboratory data extrapolated from 10 h tests in deaerated beakers. 0 ppm NH_3 solution, pH 7; 2 ppm NH_3 solution, pH 9.4; 20 ppm NH_3 solution, pH 10. Source: Ref 14

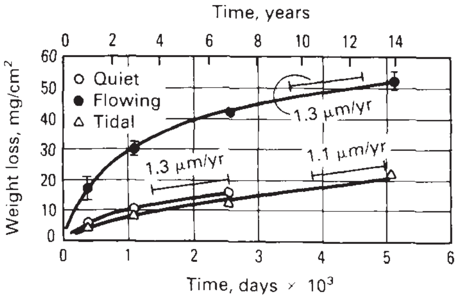

Fig. 17 Chronogravimetric curves for C70600 in quiet, flowing, and tidal seawater. Source: Ref 16

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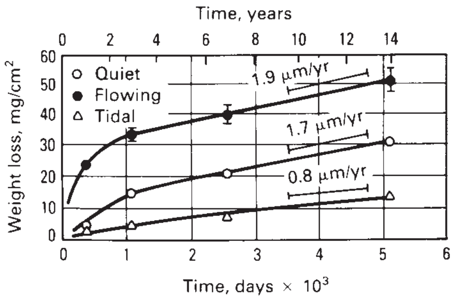

Fig. 18 Chronogravimetric curves for C71500 in quiet, flowing, and tidal seawater. Source: Ref 16

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growth and maintenance of a protective film or corrosion product layers. These alloys typically exhibit velocity-dependent corrosion rates. The more adherent and protective the film on a particular alloy, the higher its breakaway velocity (the velocity at which there is a transition from low to high corrosion rate) and the greater its resistance to impingement attack or erosion-corrosion.

Some of the earliest work on copper-nickel alloys demonstrated the beneficial effects of iron additions on seawater impingement resistance. The graphical summary of the effects of iron shown in Fig. 19 qualitatively illustrates the balance between pitting resistance and impingement resistance that defines the optimal iron content for 90Cu-10Ni and 70Cu-30Ni at 1.5 and 0.5% Fe, respectively. The effects of manganese level in association with iron in copper-nickel alloys are also addressed in Ref 21. The relative beneficial effects of 2% Fe and 2% Mn in a 70Cu-30Ni alloy (C71640) are shown in Fig. 20, which indicates that the C71640 and C72200 alloys are markedly more resistant to erosion-corrosion than C70600 at velocities up to 9 m/s (30 ft/s). The chromium-modified copper-nickel alloys also provide increased resistance to impingement attack compared to Cu-Ni-Fe alloys. In jet impingement tests (Ref 19) on several copper-base alloys at impingement velocities as high as 10 m/s (33 ft/s), no measurable impingement attack was observed on alloys C72200 and C71900 at 4.6 m/s (15 ft/s) (Table 10).

The behaviors of several copper-nickel alloys, including C71640 and C72200, have been characterized under conditions simulating partial blockage of a condenser tube (Ref 22). In the one-year natural seawater tests, enhanced erosion-corrosion resistance was observed for the C71640 and C72200 alloys as compared to C70600 and C71500. Some localized pitting and/or crevice corrosion associated with the nonmetallic blockage device was noted for C71640 and C72200, with no such attack occurring for the C70600 and C71500 alloys. Superior performance of the modified copper-nickel alloys C72200 and C71640 was also observed under severely erosive conditions in seawater containing entrained sand (Ref 23).

The combined results of laboratory impingement studies and service performance have produced maximum acceptable design velocities for condenser tube materials (Table 11). Erosion-corrosion was studied on the basis of fluid dynamics (Ref 24–26). Instead of defining the critical velocity for a material, which is difficult to relate to service conditions and which is specific to tubing diameter, the use of critical surface shear stress was advocated. This shear stress in a dynamic fluid system is a measure of the force applied by the moving fluid to the surface with which it interacts. It takes into account the changes in fluid density and kinematic viscosity with variations in temperature, specific gravity, and hydrodynamic parameters. Values of critical surface shear stress for several copper-base alloys are shown in Table 12.

Galvanic Effects. In general, the copper-base alloys are galvanically compatible with one another in seawater. The copper-nickel alloys are slightly cathodic (noble) to the nickel-free copper-base alloys, but the small differences in corrosion potential generally do not lead to serious galvanic effects unless unusually adverse anodic/cathodic area ratios are involved.

The data given in Table 13 demonstrate the increased attack of less noble carbon steel coupled to copper-nickel alloys, the increased attack

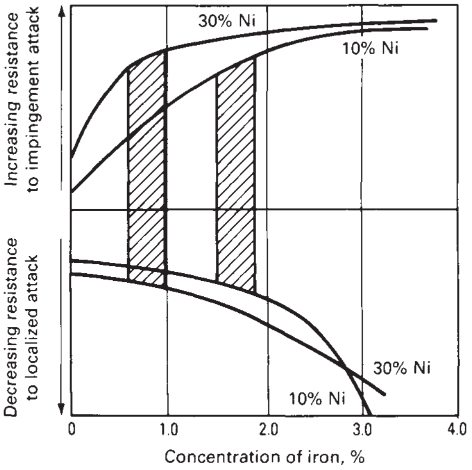

Fig. 19 Corrosion resistance of copper-nickel alloys as a function of iron content. Shaded areas indicate optimal iron contents for good balance between pitting resistance and impingement resistance. Source: Ref 21

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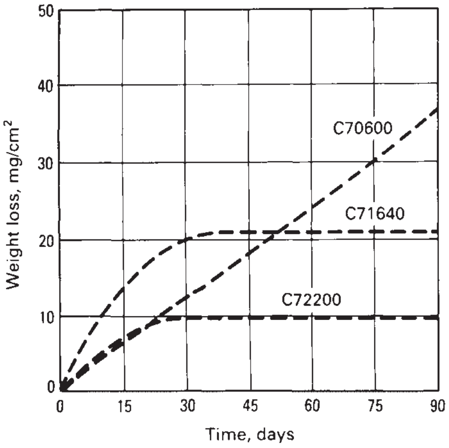

Fig. 20 Weight loss versus time curves for C70600, C71640, and C72200 exposed in seawater at a velocity of 9 m/s (40 ft/s). Source: Ref 21

Table 10 Summary of jet impingement test data for several copper alloys at three velocities

Test duration: 1–2 months; 10 to 26 °C (50 to 80 °F) seawater

	Impingement attack at velocity					
	4.6 m/s (15 ft/s)		6.8 m/s (22 ft/s)		9.8 m/s (32 ft/s)	
Alloy	mm/yr	mils/yr	mm/yr	mils/yr	mm/yr	mils/yr
C44300	1.8–4.8	71–189	(b)	(b)	(b)	(b)
C68700	0.36–3	14.2–118	(b)	(b)	(b)	(b)
C70600	0.12–2.16	4.7–85	0.36–1.56	14.2–61.4	1.56	61.4
C71500	0.12–1.08	4.7–42.5	0.36–6.84	14.2–269	1.68–2.04	66–80.3
C71900	(a)	(a)	0.12–0.36	4.7–14.2	1.08–1.44	42.5–56.7
C72200	(a)	(a)	0.12	4.7	(a)	(a)

(a) No attack. (b) Not tested. Source: Ref 19

Table 11 Accepted maximum tubular design velocities for some copper alloys

	Maximum design velocity	
Alloy	m/s	ft/s
C12200	0.6–0.9	2–3
C44300	1.2–1.8	4–6
C60800, C61300	2.7	9
C68700	2.4	8
C65100, C85500	0.9	3
C70600	3.0–3.6	10–12
C71500	4.5–4.6	14.8–5
C72200	9.0	30

Table 12 Critical surface shear stress for copper-base alloys in seawater

	Critical shear stress	
Alloy	Pa	psi
C12200	9.6	0.0014
C68700	19.2	0.028
C70600	43.1	0.0063
C71500	47.9	0.007
C72200	296.9	0.043

Source: Ref 24

Table 13 Galvanic couple data for C70600 and C71500 with other materials in flowing seawater

Two-year exposures of equal area couples at a velocity of 0.6 m/s (2 ft/s)

	Corrosion rate	
Alloy	μm/yr	mils/yr
Uncoupled		
C70600	31	1.2
C71500	20	0.8
C61400	43	1.7
Carbon steel	330	13
Titanium	2	0.08
Coupled		
C70600	25	1
C61400	43	1.7
C70600	3	0.12
Carbon steel	787	31
C70600	208	8.2
Titanium	2	0.08
C71500	18	0.7
C61400	64	2.5
C71500	3	0.12
Carbon steel	711	28
C71500	107	4.2
Titanium	2	0.08

on the copper-nickel alloys when coupled to more noble titanium, and the general compatibility of copper-nickel alloys with aluminum bronze. Coupling copper-nickel alloys to less noble materials affords protection to the copper-nickel that effectively reduces its corrosion rate, thus inhibiting the natural fouling resistance of the alloy.

Results of short-term galvanic couple tests between C70600 and several cast copper-base and ferrous alloys are listed in Table 14. The corrosion rate of cast 70Cu-30Ni was unaffected by coupling with an equal area of C70600, but some increased corrosion of other cast copper-base alloys was noted. Corrosion rates of cast stainless steels were reduced, with a resultant increase in the corrosion of C70600. Gray iron displayed with largest galvanic effect, while the corrosion rates of Ni-Resist cast irons nominally doubled. Although some caution should be exercised in using absolute values from any short-term tests, the relative degree of acceleration of corrosion from galvanic coupling was shown to be unaffected by extending some tests with Ni-Resist/C70600 couples to 1 year.

Effect of Oxygen, Depth, and Temperature. The corrosion of copper and copper-base alloys in clean seawater is cathodically controlled by oxygen reduction, with H^+ reduction being thermodynamically unfavorable. Dissolved oxygen retards corrosion by the promotion of a protective film on the copper alloy surface, but increases the rate of corrosion by depolarizing cathodic sites and oxidizing Cu^+ ions to more aggressive Cu^{2+} ions. Other factors, such as velocity, temperature, salinity, and ocean depth, affect the dissolved oxygen content of seawater, thus influencing the corrosion rate. In general, oxygen concentration decreases with increasing salinity, temperature, and depth. These factors can vary with depth in a complex manner and also vary from location to location in the oceans of the world (Ref 27).

Although cathodic control by oxygen reduction suggests a strong dependence of corrosion rate on dissolved oxygen concentration, the growth of a protective oxide film on copper-nickel alloys minimizes the influence within the normally observed range of oxygen content found in seawater. Deep-ocean testing indicated that the corrosion rates of copper and copper-nickel alloys do not change significantly for dissolved oxygen contents between 1 and 6 mL/L of seawater and consequently were not significantly affected by variations in depth of exposure (Ref 27).

Short-term laboratory tests indicated only a small increase in corrosion rate with increasing temperature up to 30 °C (85 °F) (Ref 28). Long-term corrosion rate data from tests conducted at a coastal site near Panama (Ref 17) agree very well with long-term data for exposures in Wrightsville Beach, NC (Ref 16), where the seasonal temperature variation is 5 to 30 °C (40–85 °F). Final steady-state corrosion rates at both locations for C71500 ranged from 1 to 3 µm/yr (0.04–0.12 mils/yr).

Studies performed at higher temperatures relative to those in desalination plant environments show considerable disagreement in results (Ref 29–34). From 60 to 107 °C (140–225 °F), temperature may increase, decrease, or have no significant effect on the corrosion rate of copper-nickel alloys. Lower corrosion rates for C70600 over an intermediate temperature range were reported in seawater corrosion tests between 32 and 107 °C (90 and 225 °F) with controlled seawater chemistry; bicarbonate alkalinity, dissolved oxygen, and pH were noted as critical factors controlling corrosion (Ref 33). Other studies confirmed lower average corrosion rates at 40 °C (105 °F) than at lower temperatures (Ref 35). The variation in results reported in the literature can perhaps be explained by variations in seawater chemistry between test sites and/or control of operating conditions in desalination plants.

Effect of Chlorine. Coastal power plants that use seawater as a coolant have long used chlorine to control fouling and slime formation. The effect of chlorination, both continuous and intermittent, on the corrosion of copper-nickel alloys was studied (Ref 36, 37). Continuous chlorine additions increased the corrosion rate of C70600 by a factor of two. Intermittent chlorination at a higher level controlled fouling, yet had no apparent effect on corrosion rates. A net reduction was noted in the corrosion rate of C71500 with continuous and most intermittent chlorine additions.

Seawater impingement tests were conducted on C70600, C71500, and C71640 with continuous additions of chlorine (and iron) (Ref 38). Additions of 0.5 to 4.0 mg/L of chlorine caused increased susceptibility to impingement attack on C70600 at a velocity of 9 m/s (30 ft/s). Addition of chlorine up to 4.0 mg/L had little effect on the impingement resistance of C71500. Figure 21 summarizes the results of these tests.

Polluted Cooling Waters

Polluted cooling waters, particularly in coastal harbors and estuaries, reportedly cause numerous premature failures of power station and shipboard condensers using copper-base alloys, including the copper-nickels. During the early 1950s, polluted waters were identified as the most important contributing factor in the failure of condenser tubes (Ref 39). Although enforcement of strict pollution standards has dramatically reduced pollution in many harbors in recent years, accelerated attack of condenser tubes and seawater piping materials by polluted waters is still reported.

The attack of copper-containing materials by polluted seawater has been addressed in numerous test programs. The primary causes of accelerated attack of copper-base alloys in polluted seawater are (1) the action of sulfate-reducing bacteria, under anaerobic conditions (for example, in bottom muds or sediments), on the natural sulfates present in seawater and (2) the putrefaction of organic sulfur compounds from decaying plant and animal matter within seawater systems during periods of extended shutdown (Ref 40). Partial putrefaction of organic sulfur compounds may

Table 14 Galvanic corrosion data for C70600/cast alloy couples in seawater

32-day tests of equal area couples in seawater at 10 °C (50 °F). Velocity: 1.8 m/s (6 ft/s)

	Galvanic effect(a)	
Alloy	C70600	Other alloy
C70600	1.0	…
Cast 90Cu-10Ni	0.8	1.6
Cast 70Cu-30Ni	0.9	1.0
85-5-5-5 (C83600)	0.9	1.5
M Bronze (C92200)	0.7	1.8
ACI CN7M	1.5	0.6
ACI CF8M	1.2	0.1
Gray iron	0.1	6.0
Ni-Resist type I(b)	0.4	2.1
Ni-Resist type II	0.3	2.6
Ni-Resist type D2	0.3	2.0

(a) Ratio of weight loss in couple to weight loss of an uncoupled control specimen. (b) Ni-Resist couple tests at 29 °C (85 °F)

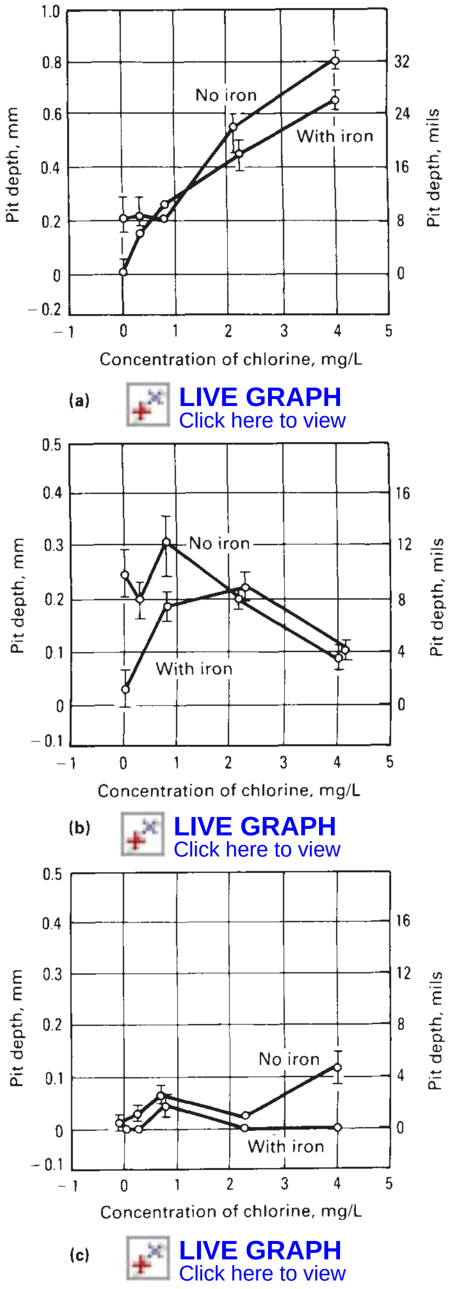

Fig. 21 Impingement attack versus chlorine levels for three copper alloys. (a) C70600. (b) C71500. (c) C71640

also result in the formation of organic sulfides, such as cystine or glutathione, which can cause pitting of copper alloys in seawater (Ref 41).

Alloy C70600 has been found to be susceptible to sulfide-induced attack in aerated seawater containing sulfide concentrations as low as 0.01 mg/L (Ref 42). Another study has demonstrated that, although the presence of 0.01 mg/L sulfide in aerated seawater can accelerate corrosion of copper-nickel alloys, the influence of seawater velocity is more significant (Ref 43). Figure 22 shows the rate of accelerated corrosion for C70600 as a function of sulfide and velocity.

Inhibition of Corrosion. In some applications, the corrosion resistance of copper alloys is further enhanced by adding iron to the seawater. This iron is introduced either through the addition of ferrous sulfate ($FeSO_4$) or by direct oxidation of a sacrificial iron anode either with or without an externally applied current.

The effectiveness of environmental iron additions against sulfide corrosion of copper-nickel alloys was evaluated (Ref 44, 45). Iron added continuously at a level of 0.2 mg/L by a stimulated iron anode was effective against low-level (0.01 mg/L) sulfide corrosion of both C70600 and C71500, although some attack was still observed. Corrosion, already actively proceeding, was significantly reduced, and the effects of additional low-level sulfide exposure were nullified by ferrous ion (Fe^{2+}) treatment. Intermittent injection of $FeSO_4$ for 2 h per day at 1.0 to 5.0 mg/L was not found effective against high sulfide levels (0.2 mg/L), but was effective in reducing corrosion at lower sulfide levels (0.01–0.04 mg/L). Additional work demonstrated that continuous low-level additions of $FeSO_4$ could counteract sulfide-accelerated corrosion of copper-nickel alloys (Fig. 23).

In the use of $FeSO_4$ or stimulated iron anodes to counteract sulfide-induced corrosion, it should also be considered that iron additions affect heat-exchanger efficiency. The continued use of iron additions can result in a significant buildup of scale on the tube surface. At high enough levels of iron addition, sufficient sludge or precipitate may develop to result in complete blockage of the heat-exchanger tubes. At lower levels of iron addition, a bulky deposit will develop on the tube surface that may also interfere with heat transfer. In a study of the increase in deposit formation and loss of heat transfer for aluminum brass in seawater with both intermittent and continuous Fe^{2+} ion dosing, it was recommended that some consideration be given to a gradual reduction in dosing levels after the initial film formation (Ref 47).

Other preventive measures can be taken to minimize the deleterious effects of sulfides (Ref 48–50). Elimination of decaying plant and animal life from inlet pipes and channels can alleviate the effects of sulfate-reducing bacteria. Initial design or operational procedures, such as eliminating stagnant legs in a piping system or careful use of screening and filtration systems, can yield a valuable return on investment. Aeration of the seawater, such as by the use of cooling towers or cascading systems, also helps to displace any dissolved hydrogen sulfide (H_2S). In one study, impingement tests were performed on C71500 in seawater containing 10 mg/L cystine (an organic sulfur compound) and varying amounts of an inhibitor, sodium dimethyldithiocarbamate (Ref 50). The results indicated a reduction in the depth of impingement attack. It was noted, however, that a 0.10% solution would be cost prohibitive on a once-through basis, but would be cost effective if circulated through the shipboard piping system upon first flooding and upon shutting down. It was further noted that inhibitor injection is necessary only when the cooling water source is polluted estuarine seawater.

Biofouling

Copper alloys, particularly the copper-nickels, have long been recognized for their inherent resistance to marine fouling. This fouling resistance is usually associated with macrobiological fouling, such as barnacles, mussels, and marine invertebrates of corresponding size. Service experience with shrimp trawlers and private yachts fabricated with C70600 or C71500 hulls has demonstrated excellent resistance to hard-shell fouling and an accompanying reduction in hull maintenance costs (Ref 49). Copper-nickel alloys have also performed successfully as seawater intake screens by virtue of their mechanical strength, corrosion resistance, and resistance to biofouling (Ref 50).

Research demonstrated that fouling was not observed on copper-nickel alloys containing 80% or more copper and that only incipient fouling was noted on the 70Cu-30Ni alloy (Ref 51, 52). Other evaluations indicated approximately equivalent fouling resistance for C70600 and C71500 in 14- and 5-year exposures, respectively (Ref 16, 53). One investigation concluded that the fouling resistances of pure copper, C70600, and C71500 were virtually identical (Ref 53).

Studies of copper-nickel alloys found that some minimum copper solution rate from the corrosion process is required to prevent fouling (Ref 52). It was not established whether the effect was due to toxicity of copper ions released from the metal surface or to a continual sloughing off of corrosion produces. Fouling was minimal on C71500 exposed for 14 years, during which time the corrosion rate approached 1.0 µm/yr (0.04 mils/yr) (Ref 16). It was further demonstrated that copper ions released from a bare C70600 surface offered no fouling protection to an adjacent painted surface (Ref 53). This work concluded that the duplex nature of corrosion products on copper alloy surfaces is responsible for fouling resistance. The initial film formed on copper alloys exposed to seawater is Cu_2O. This inherently fouling-resistant material subsequently oxidizes to $CuCl_2{\cdot}3(Cu(OH)_2)$, which does not appear to be as toxic to marine organisms. The $CuCl_2{\cdot}3(Cu(OH)_2)$ periodically sloughs off from the material surface, carrying with it many marine organisms that may have attached. This reexposes the adherent, toxic Cu_2O film and renews fouling resistance.

Whatever the mechanism, the resistance to fouling is a result of corrosion of the alloy. If this is suppressed by galvanic effects or impressed cathodic protection, fouling will not be prevented.

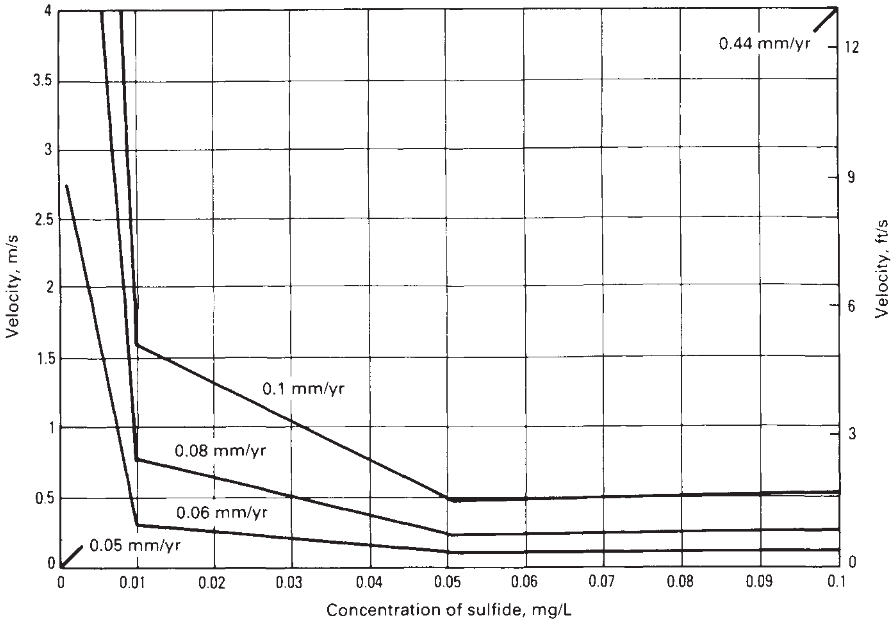

Fig. 22 Corrosion rates of C70600 as a function of seawater velocity and sulfide content

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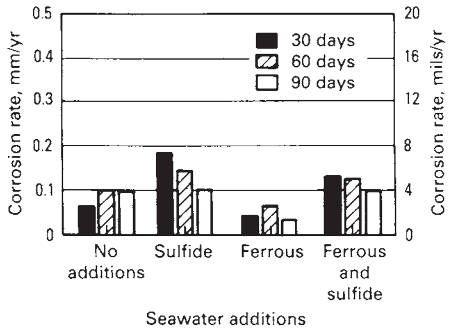

Fig. 23 Corrosion rates for C70600 exposed to seawater with additions of sulfide (0.05 mg/L) and/or Fe^{2+} (0.01 mg/L) ions. Source: Ref 46

Biofouling growth was studied on titanium and C70600 at 27 °C (80 °F) and at various velocities (Ref 54). Results (Fig. 24) indicated that the major fouling problem on titanium in the tests was silt particles bound by organic growths, while C70600 is fouled both by silt and corrosion products. Increasing velocity removes more of the silt and binding organisms, but not the corrosion products. Because titanium does not produce corrosion products, the change in the fouling rate with increasing velocity was more dramatic. The behavior of C70600 suggested the periodic sloughing off of portions of the fouling layer previously noted (Ref 53). At sufficient velocities (1.8 and 2.4 m/s, or 6 and 8 ft/s), macroorganisms did not adhere to the C70600 surface, and heat transfer resistance was due to corrosion products and entrapped particles. Fouling rates decrease by a factor of ten on titanium with an increase in velocity from 0.6 to 2.4 m/s (2–8 ft/s) and decrease by a factor of five on C70600 for the same velocity range.

Other studies demonstrated the excellent resistance to fouling and resulting retention of heat transfer efficiency in natural seawater of the copper alloys (Ref 55, 56). Figure 25 shows corrosion data for C70600 specimens. The relatively infrequent sponge ball mechanical cleaning did not increase corrosion of the C70600 compared to uncleaned controls. Mechanical cleaning was required much more frequently for the titanium in order to maintain a given level of heat transfer efficiency. Intermittent chlorination did increase with initial corrosion rates, although the rates were comparable to uncleaned controls after approximately 90 days. By contrast, in other tests in which excessive mechanical cleaning was used in natural seawater, a significant acceleration of corrosion occurred with daily sponge ball cleaning at a rate of 12 passes/h (Ref 57).

Heat Exchangers and Condensers

The selection of material for condenser and heat-exchanger tubes necessitates a survey of service conditions, an examination of tubes previously used and evaluation of its service life, and a review of the type, form, and location of corrosion experienced in the unit or in similar units. Types of water and operating conditions vary widely, and any estimate of probable tube performance must be based on specific operating factors. The tubes of the various alloys discussed in this section provide satisfactory and economical performance for the services described.

Inhibited admiralty metal (C44300, C44400, and C44500) has good corrosion resistance and is extensively used for tubing in various services, especially steam condensers cooled with fresh, salt, or brackish water. Admiralty metal tubes are also used for heat exchangers in oil refineries, in which corrosion from sulfur compounds and contaminated water may be very severe, and for feedwater heaters and heat-exchanger equipment as well as other industrial processes. Admiralty metal tubes are often used in equipment operating at temperatures of 200 °C (400 °F) or higher. Small amounts of phosphorus (0.02–0.06%) added to admiralty metal markedly increase dezincification resistance.

Inhibited aluminum brass (C68700) resists the action of high-velocity salt and brackish water and is commonly used for condenser tubes. The outstanding characteristic of C68700 is its high resistance to impingement attack. Tubes of this alloy are frequently recommended for use in marine and land power stations, in which cooling water velocities are high and inhibited admiralty metal tubes have failed because of impingement attack.

Aluminum Bronzes. Tube sheets made of C61300 and C63200 have been specified for coastal power station condensers. Alloy C61300 is also used for emergency raw seawater cooling system piping in coastal nuclear power plants. The aluminum bronzes of C61300, C63000, and C63200 in wrought form and C95400, C95500, and C95800 in cast form are extensively used in salt water environments. They are used in Navy seawater systems and submarine systems in pumps, valves, heat exchangers, and structural components for mounting electronic gear and propulsion units and are even more widely used in minesweepers, for which their nonmagnetic characteristics are important. They are used in cast or wrought form for tube sheets and water boxes in saltwater evaporators and in seawater cooling loops in fossil and nuclear power plants. Corrosion rates are of the order of 10 to 50 μm/yr (0.4–2 mils/yr), depending on temperature and velocity, and generally decrease with time. Temper annealing is particularly

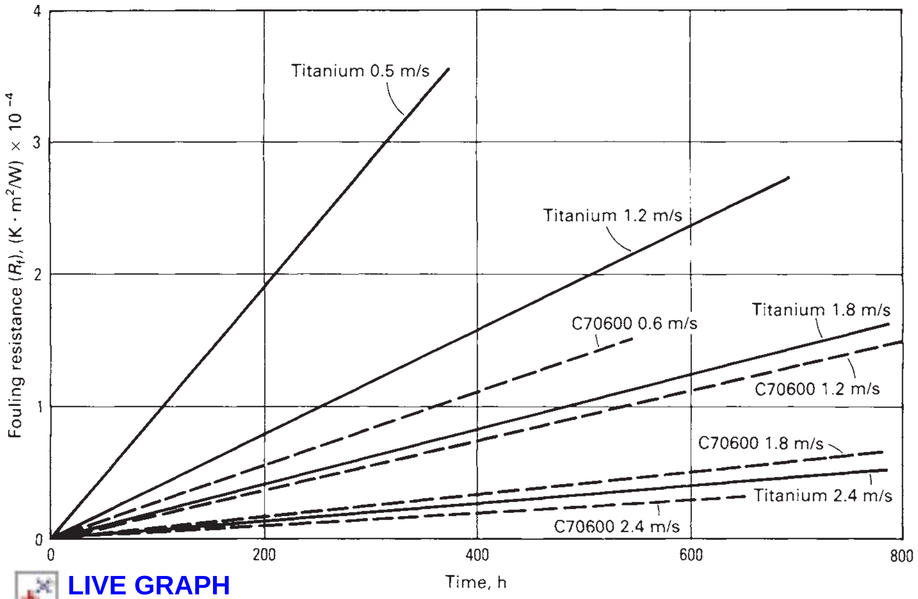

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Fig. 24 Fouling rates of C70600 and titanium as a function of seawater velocity. Source: Ref 54

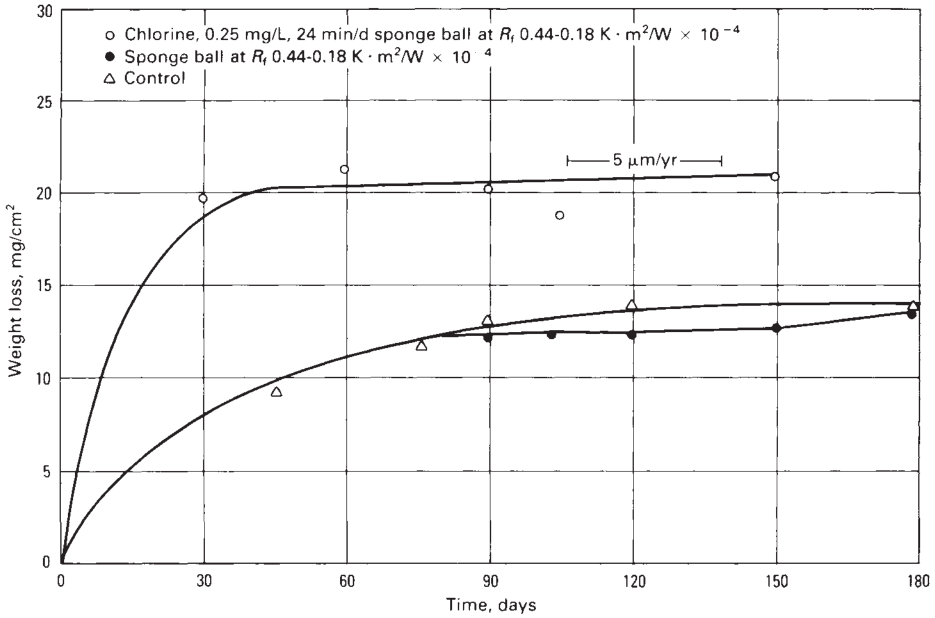

Fig. 25 Weight loss/corrosion data for C70600 cleaned by chlorinated sponge ball and sponge ball without chlorination. R_f, fouling resistance

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important in the cast forms of these alloys when used in seawater.

Copper nickel, 10% (C70600) exhibits excellent resistance to impingement attack; it appears to be inferior only to copper nickel, 30%. It is also highly resistant to SCC. This alloy is suitable for marine condenser tube installations in place of aluminum brass, especially where higher water velocities are encountered.

Copper nickel, 30% (C71500) has, in general, the best resistance of any of the copper alloys to impingement attack and to corrosion by most acids and waters. It is being used in increasing quantities under severely corrosive conditions for which service lives longer than those of other copper alloys are desired. It is used by the U.S. Navy for most shipboard condensers and heat exchangers.

Phosphorus-deoxidized coppers (C12000-C12300) are extensively used in sugar refineries for condensers and evaporators. Deoxidized copper and standard materials in the refrigeration industry and for transferring heat from steam to water or air because of their excellent resistance to corrosion by freshwater and their high thermal conductivities.

Bimetal tubes are sometimes used to meet severe corrosion problems not handled adequately by tubes of a single metal or alloy. Two tubes of different alloys, one inside the other, form one integral tube. Copper may be the inner or outer layer, depending on the application.

Drain Tubes. Copper is used for waste and vent lines in drains. The first such installations were made in the mid-1930s, and since then many municipalities have approved the use of copper drain lines. Development of Sovent fittings now enables construction of a single-stack drain system in high-rise buildings instead of the two-stack system formerly used.

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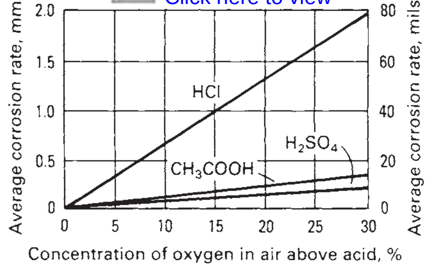

Fig. 26 Effect of oxygen on corrosion rates for copper in 1.2 *N* solutions of nonoxidizing acids. Specimens are immersed for 24 h at 24 °C (75 °F). Oxygen content of the solutions varied from test to test, depending on the concentration of oxygen in the atmosphere above the solutions.

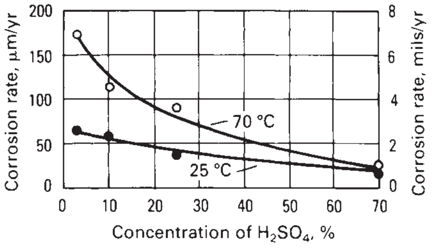

Fig. 27 Corrosion of C65500 in H_2SO_4 solutions. Specimens were immersed for 48 h at the indicated temperatures. The solution was not agitated or intentionally aerated.

LIVE GRAPH
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Corrosion in Acids

Copper is widely employed for industrial equipment used to handle acid solutions. A fairly definite separation exists between those acids that can be handled by copper and those that cannot. In general, copper alloys are successfully used with nonoxidizing acids, such as CH_3COOH, H_2SO^4, HCl, and H_3PO_4, as long as the concentration of oxidizing agents, such as dissolved oxygen (air) and ferric (Fe^{3+}) or dichromate ions, is low. Broadly speaking, a thoroughly agitated or stirred solution or one into which a stream of air has been bubbled approaches air saturation and is therefore not a suitable acid medium for copper. Acids that are oxidizing agents in themselves, such as HNO_3; sulfurous (H_2SO_3); hot, concentrated H_2SO_4; and acids carrying such oxidizing agents at Fe^{3+} salts, dichromate ions, or permanganate (MnO_4^-) ions, cannot be handled in equipment made of copper or its alloys.

The corrosive action of a dilute (up to 1% acid) nonoxidizing acid on copper is relatively low; corrosion rates are usually less than 6 g/m^2/d (equivalent penetration rate: 250 µm/yr, or 10 mils/yr). This is true only of oxidizing acids when the concentration does not exceed 0.01%. At such low acid concentrations, aeration has little effect in either oxidizing or nonoxidizing acids.

Nonoxidizing acids with near-zero aeration have virtually no corrosive effect. Rates in 1.2 *N* H_2SO_4, HCl, and CH_3COOH are less than 0.1 g/m^2/d (4 µm/yr, or 0.15 mils/yr) in the absence of air. Figure 26 shows the general effect of various concentrations of oxygen on the corrosion rate of copper in these acids.

Except for HCl, nonoxidizing acids that contain as much air as is absorbed in quiet contact with the atmosphere are weakly corrosive. Rates generally range from 0.5 to 6 g/m^2/d (approximately 20–250 µm/yr, or 0.8–10 mils/yr).

Air-saturated solutions of nonoxidizing acids are likely to be strongly corrosive, with corrosion rates of 5 to 30 g/m^{2}d (0.2–1.25 mm/yr, or 8–50 mils/yr). This rate is higher for HCl. The actual corrosion in any aerated acid depends on acid concentration, temperature, and other factors that are difficult to classify. Except in very dilute solutions, oxidizing acids corrode copper rapidly—usually at rates above 50 g/m^2/d (2.1 mm/yr, or 85 mils/yr). The reaction is independent of aeration.

The corrosion rates for copper in three common acids are compared below (temperature and aeration are not specified):

Acid	Corrosion rate g/m^2/d	 mm/yr	 mils/yr
32% HNO_3	5700	240	9450
Concentrated HCl	18	0.75	30
17% H_2SO_4	2	0.1	4

Phosphoric, CH_3COOH, tartaric, formic, oxalic, malic, and similar acids normally react comparably to H_2SO_4.

Factors that may accelerate corrosion vary from one plant to another, and it is advisable to conduct preliminary service or field tests under actual operating conditions before purchasing large quantities of an alloy. Corrosion-accelerating factors can then be evaluated. Selection of the most suitable material for use in a chemical process depends not only on corrosion resistance but also on such factors as continuing availability of the alloy in the desired form and size (which should be ensured before any alloy is given serious consideration).

The following corrosion data were obtained in tests made under various conditions for handling different acids and acid solutions. Because of the variety of factors affecting all chemical reactions, the values shown cannot be taken as absolute and should be considered only as trends.

Sulfuric Acid. Copper and copper-base alloys are not widely used in relatively pure H_2SO_4 because of the drastic effect of oxidizing conditions. The resultant Cu^{2+} ions also cause autocatalytic corrosion.

The corrosion rate of C65500 (3% silicon bronze) in H_2SO_4 indicates that this alloy can be successfully used with solutions of 3 to 70% H_2SO_4 (by weight) at temperatures of 25 to 70 °C (75–160 °F). Laboratory test results are shown in Fig. 27.

Rate of attack by H_2SO_4 varies with concentration (Table 15). The presence of copper or iron salts in acid solutions accelerates the corrosion rate of copper (Table 16).

Aluminum bronze C61300 (wrought), as well as C95200 and C95800 (cast), are used extensively in dilute (10–20%) H_2SO_4 service, particularly in steel-pickling acids. Because these alloys have good corrosion resistance and high mechanical properties, thinner sections can withstand the required loads. In general, the copper alloys are quite resistant to the environment, but when in contact with the steel being pickled, they are galvanically protected and in turn accelerate the cleaning action of the acid on the steels. In time, the iron salts are changed from Fe^{2+} to Fe^{3+} (oxidizing) form, and there is increased corrosion; therefore, filtering or elimination of the salts is beneficial. Also, open tanks made of copper for this medium will have a higher corrosion rate at the liquid level line because of higher oxygen concentration. Hydrochloric acid added to H_2SO_4 greatly increases the corrosion rate of copper alloys compared to that in either acid individually.

Phosphoric Acid. Copper and copper alloys are used in heat-exchanger tubes, pipes, and fittings for handling H_3PO_4, although the corrosion rates of some of these alloys may be comparatively high. Laboratory tests were performed on eight groups of copper alloys in aerated and unaerated acid, with specimens at the water line, in quiet immersion and totally submerged. Acid concentrations ranged from 5 to 90%, and temperatures ranged from 20 to 85 °C (70–185 °F) except for the Cu-Al-Si alloy, which was tested only in 6.5% H_3PO_4 at 20 °C

Table 15 Corrosion of copper alloys completely immersed in H_2SO_4 of various strengths

	Average penetration for H_2SO_4 concentration of					
	30%		40%		50%	
Alloy	μm/yr	mils/yr	μm/yr	mils/yr	μm/yr	mils/yr
Exposure time 24–48 h, boiling at a pressure of 13.3 kPa (100 torr)						
C11000	670–700	26.4–27.6	487–700	19.2–27.6	660–792	26.0–31.2
C14200	640–670	25.2–26.4	487–548	19.2–21.6	610	24.0
C51000	640	25.2	395–457	15.6–18.0	915	36.0
C26000	…	…	…	…	…	…
Exposure time: 16–24 h, solution agitated						
C11000	60–245	2.4–9.6	18–60	0.7–2.4	60	2.4
C14200	92–335	3.6–13.2	nil	nil	50–60	2.0–2.4

	Average penetration for H_2SO_4 concentration of					
	60%		70%		80%	
Alloy	μm/yr	mils/yr	μm/yr	mils/yr	μm/yr	mils/yr
Exposure time: 24–48 h, boiling at a pressure of 13.3 kPa (100 torr)						
C11000	2195–2255	86.4–88.8	853–1067	33.6–42.0	39,630–166,420	1560–6552
C14200	2285–2377	90.0–93.6	945	37.2	67,310–527,300	650–20,760
C51000	2957–3385	116.4–133.2	945–1067	37.2–42.0	60,660–62,080	2388–2444
C26000	…	…	580–793	22.8–31.2	72,850–206,050	2868–8112
Exposure time: 16–24 h, solution agitated						
C11000	60–92	2.4–3.6	1830–2745	72.0–108.0	39,370–40,890	1550–1610
C14200	15–60	0.6–2.4	2135	84.0	39,370–50,550	1550–1990

Table 16 Corrosion of copper in boiling 30% H_2SO_4 containing copper and iron salts

	Average penetration			Average penetration			Average penetration	
Copper, ppm	μm/yr	mils/yr	Iron, ppm	μm/yr	mils/yr	Iron and copper, ppm	μm/yr	mils/yr
0	60	2.4	0	122	4.8	0	13	0.5
20	183	7.2	28	122	4.8	20Cu + 28Fe	152	6.0
40	213	8.4	58	245	9.6	40Cu + 56Fe	244	9.6
80	243	9.6	112	427	16.8	80Cu + 112Fe	457	18.0
200	335	13.2	196	782	30.8	200Cu + 196Fe	730	28.8
280	360	14.2	280	975	38.4	280Cu + 280Fe	1005	39.6
360	427	16.8	364	1097	43.2	360Cu + 364Fe	1250	49.2
440	457	18.0	447	1280	50.4	440Cu + 447Fe	1525	60.0

(70 °F) with specimens at the water line and in quiet immersion. Corrosion rates for the eight alloy groups were as follows:

	Corrosion rate	
Alloy type	mm/yr	mils/yr
Copper	0.55–3.7	22–148
Copper-zinc (70% Cu min)	0.13–7.0	5–280
Copper-tin	0.025–1.30	1–52
Copper-nickel	0.025–0.63	1–25
Copper-silicon	0.13–0.93	5–37
Cu-Al-Fe	0.13–0.25	5–10
Cu-Al-Si	0.28–2.4	11–97

Table 17 Corrosion of C65800 totally submerged in HCl

Size of specimens, 50 × 25 × 1.3 mm (2 × 1 × 0.050 in.); surface condition, pickled; velocity of solution, natural convection; aeration, none; duration of test, 48 h

	Corrosion rate		
HCl concentration, wt%	$g/m^2/d$	μm/yr	mils/yr
At 25 °C (75 °F)			
3	2.3	99	3.9
10	2.3	99	3.9
20	1.8	79	3.1
35	12.3	526	20.7
At 70 °C (160 °F)			
3	18.3	780	30.7
10	13.7	508	20.0
20	23.8	102	40.1
35	160.8	6860	270.1

In general, copper and copper alloys provide satisfactory service in handling pure H_3PO_4 solutions in various concentrations. The acid concentration seems to have less effect on the corrosion rate than the amount of impurities. The impure H_3PO_4 produced by H_2SO_4 process may contain a markedly higher concentration of Fe^{3+}, SO_4^{2-}, sulfite (SO_3^{2-}), Cl^-, and fluoride (F^-) ions than acid produced by the electric furnace process. These ions increased the corrosion rate up to 150 times, which limits the service lives of copper alloys.

Pure H_3PO_4 produced by the electric furnace process contains only small quantities of impurities and is therefore only slightly corrosive to copper and its alloys. Inhibited admiralty metals C44300, C44400, and C44500 are suggested for solutions of pure H_3PO_4.

Accumulation of corrosion products on metal surfaces may also increase both the rate of corrosion and the possibility of pitting. Low-copper alloys, such as C46400 (naval brass), appear to form thin, adherent films of corrosion products. Copper, copper-silicon alloys, and other high-copper alloys form more voluminous, porous films or scales beneath which roughened or pitted surfaces are likely to be found.

The H_3PO_4 vapors that condense in electrostatic precipitators at about 120 °C (250 °F) are noticeably more corrosive than solutions of pure H_3PO_4 at the same or lower temperatures. The corrosion rates encountered in precipitators are so high that copper alloy wires will not give satisfactory service as electrodes. The high rate of corrosion is probably caused by an abundant supply of oxygen.

Although the corrosion rates of copper cooling tubes in H_3PO_4 condensation chambers are high (about 10 mm/yr, or 400 mils/yr), the rates are lower than those of some other materials. Therefore, the use of copper tubes is feasible for this application.

The above discussion on the effect of H_3PO_4 on copper and its alloys emphasizes the value of keeping service records. Such records are valuable for anticipating repairs, making changes to minimize the effect of various factors, and selecting materials for replacement parts.

Hydrochloric acid is one of the most corrosive of the nonoxidizing acids when in contact with copper and its alloys and is successfully handled only in dilute concentrations. The rates for C65800 (silicon bronze) in HCl of various concentrations are listed in Table 17. The corrosion rates for two nonstandard silicon bronzes were about the same as those for C65800.

The corrosion rate of copper nickels in 2 *N* HCl at 25 °C (75 °F) may range from 2.3 to 7.6 mm/yr (90–300 mils/yr), depending on the degree of aeration and other factors. Specimens of C71000 (copper nickel, 20%) in stagnant 1% HCl solutions at room temperature corrode at a rate of 305 μm/yr (12 mils/yr); in 10% HCl, 790 μm/yr (31 mils/yr).

Hydrofluoric acid (HF) is less corrosive than HCl and can be successfully handled by C71500 (copper nickel, 30%), which has good resistance to both aqueous and anhydrous HF. Unlike some other copper alloys, C71500 is not sensitive to velocity effects. The data given in Table 18 were generated from laboratory tests in conjunction with the HF alkylation process in anhydrous acid.

Acetic Acid and Acetic Anhydride [$(CH_3CO)_2O$)]. Copper and copper alloys are successfully used in commercial processes involving exposure to CH_3COOH and related

Table 18 Corrosion of wrought copper alloys in anhydrous HF

		Corrosion rate(a)					
Temperature		C51000		C44400		C71500	
°C	°F	μm/yr	mils/yr	μm/yr	mils/yr	μm/yr	mils/yr
16–27	60–80	510	20	255	10	180	7
27–38	80–100	480	18.8	480	18.8	…	…
82–88	180–190	1525	60	510	20	255	10

(a) These values are representative of results on copper alloys having high copper content, such as copper, aluminum bronze, silicon bronze, and inhibited admiralty metal. Corrosion rates for C23000 are between those for C44400 and C51000.

Table 19 Corrosion of copper in CH_3COOH-$(CH_3CO)_2O$ mixtures

Copper alloy	Exposure time, h	Test conditions	Average penetration rate µm/yr	mils/yr
C11000	1115	CH_3COOH-$(CH_3CO)_2O$-acetone mixture, 110 to 140 °C (230 to 285 °F)	483	19.0
	2952	Same as above	66–70	2.6–2.8
C65500	1115	Same as above	213	8.4
	2952	Same as above	70–90	2.7–3.6
C11000	1115	1:1 CH_3COOH-$(CH_3CO)_2O$ mixture, 130 to 145 °C (265 to 295 °F)	120–533	4.7–21.0
C65500	1115	Same as above	166–236	4.6–9.3
C11000	865	95% CH_3COOH-5% $(CH_3CO)_2O$, liquid phase, 120 °C (250 °F)	97–116	3.8–4.4
C11000 coupled to type 316 stainless steel	865	Same as above	102–216	4.0–8.5
C11000	865	95% CH_3COOH-5% $(CH_3CO)_2O$, vapor phase, 120 °C (250 °F)	102–104	4.0–4.1
C11000 coupled to type 316 stainless steel	865	Same as above	94–213	3.7–8.4
C11000	2448	50:50 CH_3COOH-$(CH_3CO)_2O$ 150 °C (300 °F)	84–90	3.3–3.6
C11000	2448	Essentially pure CH_3COOH	5	0.2

Table 21 Corrosion of copper alloys in CH_3COOH

Alloy	Exposure time, h	Average penetration rate µm/yr	mils/yr
$(CH_3CO)_2O$			
C11000	2448(b)	60	2.4
	2448(c)	915–1100	36.0–43.2
C65500	2448(b)	60	2.4
	2448(c)	488–732	19.2–28.8
90% CH_3COOH(d)			
C11000, annealed	672	60	2.4
	816	30	1.2
C11000, cold worked	672	90	3.6
	792	90	3.6
Copper joint(e)	1512	183	7.2
	4000	120	4.8
Copper joint(f)	1512	183	7.2
	4000	120	4.8
45% CH_3COOH(g)			
C11000	1038	30 max	1.2 max
C65500	1038	30 max	1.2 max
Copper joint(f)	1038	30 max	1.2 max
25% CH_3COOH(h)			
C11000	432	274	10.8
	792	152	6.0

(a) Test specimens were exposed in stills separating CH_3COOH from $(CH_3CO)_2O$. (b) Top of column. (c) Kettle. (d) Test specimens were exposed in cycle feed lines at 30–50 °C (85–120 °F). (e) Joint brazed with BCuP-5 filler metal. (f) BAg filler metal. (g) Test specimens were exposed in the CH_3COOH recovery column, in which concentration of the acetic acid was 45% max. (h) Test specimens were exposed to crude by-product CH_3COOH (approximately 25% concentration) in pump suction line from storage tank.

chemical compounds or in the manufacture of this acid. One plant kept records concerning the corrosion rate of C11000 used in two different CH_3COOH still systems. One still operated at 115 to 140 °C (240–285 °F) and handled a solution containing 50% CH_3COOH and about 50% $(CH_3CO)_2O$, with some esters also present. After operating for 663 h, the kettle showed an average penetration rate of 210 µm/yr (8.4 mils/yr). The rate was lower (60 µm/yr, or 2.4 mils/yr) for the bottom column and was lower yet (30 µm/yr or 1.2 mils/yr) for the middle and top columns. A second still operating at 60 to 140 °C (140–285 °F) contained a 70% solution of CH_3COOH, the remainder being anhydride, esters, and ketones. After 1464 h, the kettle showed a corrosion rate of 120 µm/yr (4.8 mils/yr). The rate was only 30 µm/yr (1.2 mils/yr) for the middle and top columns.

Table 22 Corrosion of copper and copper-nickel by HCOOH

Laboratory tests in deaerated acid at atmospheric boiling temperature; test duration: 96 h

Acid concentration, %	Corrosion rate: Copper C10300 mm/yr	mils/yr	Copper-nickel C70600 mm/yr	mils/yr
1.0	0.02	0.8	0.02	0.9
5.0	0.02	0.7	0.02	0.9
10.0	0.02	0.6	0.02	0.7
20.0	0.20	7.8	0.40	15.7
40.0	0.14	5.5	0.34	13.3
50.0	0.26	10.2	0.54	21.1
60.0	0.05	2.0	0.03	1.3
70.0	0.76	30.0	0.76	30.0
80.0	0.20	7.8	0.13	5.0
90.0	0.22	8.7	0.19	7.6

In another field test, C11000 and C65500 coupons were placed in an CH_3COOH storage tank at ambient temperature. The stored solution contained 27% CH_3COOH, 1% butyl acetate, 70% H_2O, and small amounts of acetates, aldehydes, and other acids. During the 3984 h exposure, the specimens were immersed in the liquid phase 80% of the time and were in the vapor phase 20% of the time. The C11000 specimens showed a corrosion rate of 38 to 53 µm/yr (1.5–2.1 mils/yr); the C65500 specimens, 30 to 45 µm/yr (1.2–1.8 mils/yr).

The results of other field tests for C11000 and C65500 exposed in CH_3COOH mixtures are given in Tables 19 to 21. Test conditions involved various temperatures, concentrations, exposure times, and locations in equipment, as well as the presence of other chemicals.

In laboratory tests at room temperature, C61300 and C62300 exhibited typical corrosion rates of 65 to 80 µm/yr (2.5–3.2 mils/yr) in 10 to 40% CH_3COOH. The copper-aluminum alloys are suitable for use in CH_3COOH and the range of aliphatic and aromatic organic acids. The addition of chlorine atoms to the organic molecule will not increase the tendency toward pitting or crevice corrosion. Alloy C61300 is extensively used for pressure and valve castings.

Formic Acid (HCOOH). Copper and copper alloys, except yellow brasses, which dezincify, show fair resistance to HCOOH at any concentration. The resistance to HCOOH depends on the presence or absence of oxygen or other oxidizing agents. If free air or other oxidants are present, high corrosion rates will be encountered; if the acid is free of air and other oxidants, copper will provide usable resistance to HCOOH at all concentrations to the atmospheric boiling point and even at higher temperatures.

Table 20 Corrosion of C11000 in isopropyl ether-CH_3COOH mixtures

Concentration, % Isopropyl ether	CH_3COOH	Average penetration rate µm/yr	mils/yr
Exposed 72 h at 60–65 °C (140–150 °F)			
93	7	40–50	1.6–2.0
85	15	18–20	0.7–0.8
Exposed 328 h at 20 °C (70 °F)			
93	7	100	4.0
85	15	13	0.5

Table 22 shows typical corrosion rates for copper (C10300) and 90Cu-10Ni copper-nickel (C70600) in various concentrations of HCOOH. The anomalies in the data shown in Table 22, such as the higher rate of attack in 50 and 70% HCOOH, are probably caused by incomplete deaeration during laboratory tests, although some increase in the rate of corrosion in intermediate acid strengths is to be expected because of maximum dissociation in these concentrations.

Propionic Acid (CH_3CH_2COOH). Copper and copper alloys are excellent for handling all concentrations of CH_3CH_2COOH. The data shown in Fig. 28 indicate attack on copper in boiling 100% CH_3CH_2COOH, but this is believed to be an anomaly caused by incomplete deaeration of the solution. As with HCOOH and CH_3COOH, copper and its alloys are satisfactory only if the solutions are completely deaerated and do not contain other oxidizing agents.

Other Organic Acids. Although acetic, formic, and propionic are the most common organic acids, there are literally hundreds of organic acids. Table 23 compares the corrosion rates of copper, silicon bronze, plain carbon steel, and austenitic stainless steels in several of the longer-chain aliphatic acids and aromatic acids and dicarboxylic acids. As these data show, copper and copper alloys exhibit good resistance to all of the higher molecular weight acids, even at elevated temperatures in the absence of oxidants.

Hydrocyanic acid (HCN) can be successfully handled by copper and copper alloys. Results of field tests for C11000 and C65500 are given in Tables 24 and 25.

Fatty Acids. Under severe service conditions, fatty acids attack copper alloys at somewhat higher rates than other organic acids, such as CH_3COOH or citric. Tests were conducted for 400 h in a copper-lined wooden splitting tank containing a mixture of about 60% fatty acids, 39% H_2O, and 1.17% H_2SO_4 heated to 100 °C (212 °F) and agitated violently with an open steam jet. Specimens of C71000 (copper nickel, 20%) showed a corrosion rate of 64 µm/yr (2.6 mils/yr); specimens of C71500 (copper nickel, 30%), 59 µm/yr (2.4 mils/yr) when submerged just below the liquid level in the tank. Similar specimens submerged 150 mm (6 in.) from the bottom of the tank showed corrosion rates of 178 and 185 μm/yr (7.0 and 7.3 mils/yr) for C71000 and C71500, respectively.

Oleic Acid. Copper and copper-zinc alloys are highly resistant to attack by pure oleic acid. However, oleic acid will attack these alloys when air and water are present. Temperature also influences the rate of attack. Copper and several copper alloys were tested in oleic acid at 25 °C (75 °F); C51000 and C61300 corroded at less than 50 μm/yr (2 mils/yr) compared with about 500 μm/yr (20 mils/yr) for C26000 and C65500.

Stearic acid, like all other fatty acids, attacks copper and copper alloys when moisture and air are present. Temperature and impurities also influence the rate of attack. Tests made at 25 to 100 °C (75–212 °F) in stearic acid showed corrosion rates of C11000, C26000, and C65500 to be in the range of 500 to 1250 μm/yr (20–50 mils/yr).

Tartaric Acid. Copper and its alloys corrode rather slowly when exposed to various concentrations of tartaric acid, as indicated by the laboratory test data given in Table 26.

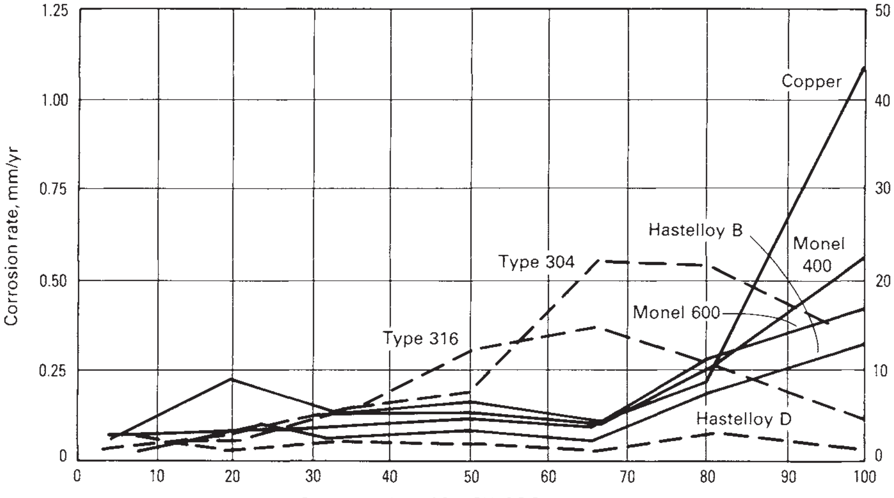
Corrosion in Alkalis

Copper and its alloys resist alkaline solutions, except those containing NH_4OH or compounds that hydrolyze to NH_4OH or cyanides. Ammonium hydroxide reacts with copper to form soluble complex copper cations, but the cyanides react to form soluble complex copper anions. The rate of attack for copper-zinc alloys exposed to alkalies other than those specified above is about 50 to 500 μm/yr (2–20 mils/yr) at room temperature under stagnant conditions, but is about 500 to 1750 μm/yr (20–70 mils/yr) in aerated boiling solutions.

Alloy C71500 corrodes at less than 5 μm/yr (0.2 mil/yr) in 1 to 2 *N* NaOH solutions at room temperature, and the degree of aeration usually has no significant effect. This rate is two to three times as great as the rate in boiling solutions. Copper-tin alloys (phosphor bronzes) corrode at less than 250 μm/yr (10 mils/yr) in 1 to 2 *N* NaOH solutions at room temperature and are apparently unaffected by aeration.

Copper and two grades of silicon bronze were tested in a 50% NaOH solution at 60 °C (140 °F) for 4 weeks. The specimens were bright rolled and degreased sheet measuring about 25 by 50 by 1.3 mm (1 by 2 by 0.05 in.). The solution was exposed to air (no additional aeration), and velocity was limited to natural convection. Alloy C11000 showed a corrosion rate of 1.7 g/m^2/d (70 μm/yr, or 2.8 mils/yr); C65100, 1.5 g/m^2/d (63 μm/yr, or 2.5 mils/yr); and C65500, 1.1 g/m^2/d (47 μm/yr, or 1.85 mils/yr).

Ammonium Hydroxide. Strong NH_4OH solutions attack copper and copper alloys rapidly, as compared with the rates of attack by metallic hydroxides because of the formation of a soluble complex copper-ammonium compound. However, in some applications, the corrosion of copper exposed to dilute solutions of NH_4OH is



LIVE GRAPH
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Fig. 28 Corrosion of metals in CH_3CH_2COOH at boiling temperature

Table 23 Corrosion of metals in refined organic acids

	Corrosion rate									
	Steel		Copper		Silicon-bronze		Type 304 stainless steel		Type 316 stainless steel	
Acid	mm/yr	mils/yr	mm/yr	mils/yr	mm/yr	mils/yr	mm/yr	mils/yr	mm/yr	mils/yr
Butyric										
Room temperature	0.15	6	0.05	2	0.05	2	< 0.02	< 1	< 0.02	< 1
2-ethylbutyric										
Room temperature	0.18	7	0.02	1	0.02	1	< 0.02	< 1	< 0.02	< 1
150 °C (300 °F)	0.86	34	0.41	16	0.23	9	0.53	21	< 0.02	< 1
2-ethylhexoic										
Room temperature	0.02	1	< 0.02	< 1	< 0.02	< 1	< 0.00	< 1	< 0.02	< 1
190 °C (375 °F)	1.27	50	< 0.02	< 1	< 0.02	< 1	0.20	8	< 0.02	< 1
Iso-octanoic										
Room temperature	< 0.02	< 1	< 0.02	< 1	< 0.02	< 1	< 0.02	< 1	< 0.02	<1
190 °C (375 °F)	0.89	35	< 0.02	< 1	< 0.02	< 1	0.20	8	< 0.02	< 1
Iso-decanic										
Room temperature	< 0.02	< 1	< 0.02	< 1	< 0.02	< 1	< 0.02	< 1	< 0.02	< 1
190 °C (375 °F)	0.84	33	< 0.02	< 1	< 0.02	< 1	0.20	8	< 0.02	< 1
2-methylpentanoic										
Room temperature	0.02	1	0.08	3	0.10	4	< 0.02	< 1	< 0.02	< 1
150 °C (300 °F)	0.53	21	0.30	12	0.08	3	< 0.02	< 1	< 0.02	< 1
Pentanoic (valeric)										
Room temperature	0.05	2	0.05	2	0.05	2	< 0.02	< 1	< 0.02	< 1
114 °C (237 °F)	1.37	54	0.68	27	0.13	5	< 0.02	< 1	< 0.02	< 1

Table 24 Corrosion of copper alloys in production of HCN

		Average penetration rate(a)							
		Stripping still		Top of HCN refining still		Base of HCN stripping still		Base of partial condenser	
Alloy	Exposure time, h	μm/yr	mils/yr	μm/yr	mils/yr	μm/yr	mils/yr	μm/yr	mils/yr
C11000	573	173–218	6.8–8.6	54–60	2.1–2.4	1033–1186	40.7–46.7	1534–14 170	60.4–558
	671	155–609	6.1–24.0	18–25	0.7–1.0	nil	nil	478	18.8
C65500	573	229–244	9.06–9.6	18–25	0.7–1.0	777–1145	30.6–45.1	1138–5385	44.8–212
	671	137–503	5.4–19.8	…	…	275	10.8	343	13.5

(a) All data from separate specimens; differences at similar locations imply expected variability.

Table 25 Corrosion of C11000 and C65500 in HCN solutions

			Average penetration rate	
Alloys	Exposure time, h	Test conditions	μm/yr	mils/yr
C11000	3144	Ethylene cyanohydrin residues, 70 °C (160 °F)	5–35	0.2–1.4
C11000	2232	Ethylene cyanohydrin residues, 30–90 °C (85–195 °F)	13	0.5
C65500	2232	Same as above	40	1.6
C11000	1621	Cyanhohydrin stripping still products (kettle)	690	27
C65500	1621	Same as above	35	1.4

low. For example, copper specimens submerged in 0.01 *N* NH_4OH solution at room temperature for 1 week experienced weight loss of 1.5 m/m^2/d (60 μm/yr, or 2.5 mils/yr).

Table 26 Corrosion of copper alloys in contact with tartaric acid at 25 °C (75 °F)

	Corrosion rate	
Acid concentration, %	μm/yr	mils/yr
C26000 and C23000		
10	50 max	2 max
30	500–1250	20–50
50	500–1250	20–50
100	50 max	2 max
C71000		
5	25 max	1 max
C71300		
2	40	1.6

Table 27 Corrosion of copper and brass in anhydrous NH_3

	Average penetration rate(a)			
	Liquid		Vapor	
Alloy	μm/yr	mils/yr	μm/yr	mils/yr
Anhydrous NH_3				
C11000	2.5	0.1	< 2.5	< 0.1
C26000	< 2.5	< 0.1	< 2.5	< 0.1
Anhydrous NH_3 plus 1% H_2O(b)				
C11000	< 2.5	< 0.1	< 2.5	< 0.1
C26000	2.5	0.1	< 2.5	< 0.1
Anhydrous NH_3 plus 2% H_2O(b)				
C11000	2.5	0.1	2.5	0.1
C26000	5.0	0.2	2.5	0.1

(a) Atmospheric temperature and pressure of 345–1035 kPa (50–150 psi) for 1600 h exposure. Specimens were placed at the top and bottom of 2-L bombs that were charged with NH_3. Pressure varied throughout the test, depending on the temperature. Water was added to two of the bombs before charging with NH_3. (b) Any air present was probably depleted rapidly during initial stages of test.

Table 28 Corrosion of C11000 in 30% $CaCl_2$ refrigeration brine

	Corrosion rate	
Inhibitor	μm/yr	mils/yr
None(a)	10	0.4
K_2Cr_2O7(b)	6	0.23
Aluminum foil(c)	119	4.7

(a) Exposed for 325 days at –12 °C (10 °F). (b) Exposed for 372 days, cold. (c) Exposed for 50 days with slight agitation in brine with a pH of 9

Table 29 Corrosion of C11000 in a NaCl brine refrigeration system

Field test; 98 days at –15 °C (4 °F)

	Corrosion rate	
Location in equipment	μm/yr	mils/yr
With $Na_2Cr_2O_7$ inhibitor; pH 6.0 to 6.5		
Brine tank for near main outlet	5	0.2
Top of brine pump, high agitation	10	0.4
Inside cooler tube	15	0.6
Return line to storage tank	2.5	0.1
Brine tank near agitator	2.5	0.1
Without inhibitor; pH 10.5		
Open brine tank	160	6.3
Brine cooler outlet, rapid flow	360	14.2
Cooler inlet	157	6.2
Cooler outlet	250	9.8

Ammonium hydroxide solutions also attack copper-zinc alloys. Alloys containing more than 15% Zn are susceptible to SCC when exposed to NH_4OH. The stress may be due to applied service loads or to unrelieved residual stresses. In quiescent 2 *N* NH_4OH solutions at room temperature, copper-zinc alloys corrode at 1.8 to 6.6 mm/yr (70–260 mils/yr), copper-nickel alloys at 0.25 to 0.50 mm/yr (10–20 mils/yr), copper-tin alloys at 1.3 to 2.5 mm/yr (50–100 mils/yr), and copper silicon alloys at 0.75 to 5 mm/yr (30–200 mils/yr).

Anhydrous NH_3. Copper and its alloys are suitable for handling anhydrous NH_3 if the NH_3 remains anhydrous and is not contaminated with water and oxygen. In one test conducted for 1200 h, C11200 and C26000 each showed an average penetration of 5 μm/yr (0.2 mil/yr) in contact with anhydrous NH_3 at atmospheric temperature and pressure. Tests showed the rates of corrosion to be low in the presence of small amounts of water, but oxygen was probably excluded. Table 27 lists data on exposure for 1600 h. For any new installation, tests simulating the expected conditions are recommended.

Corrosion in Salts

Copper metals are widely used in equipment for handling saline solutions of various kinds, particularly those that are nearly neutral. Among these are the nitrates, sulfates, and chlorides of sodium and potassium. Chlorides are usually more corrosive than the other salts, especially in strongly agitated, aerated solutions.

Table 30 Corrosion of copper alloys in alkaline saline solutions

		Corrosion rate	
Alloy family	Common name	μm/yr	mils/yr
Na_2SiO_3, Na_3PO_4, or Na_2CO_3			
Copper-zinc	Brasses	50–125	2–5
Copper-tin	Phosphor bronzes	< 50	< 2
Copper-nickel	Copper nickels	2.5–40	0.1–1.5
NaCN			
Copper-zinc	Brasses	250–500	10–20
Copper-tin	Phosphor bronzes	875	35
Copper-nickel	Copper nickels	500–2500	20–100

The nonoxidizing acid salts, such as the alums and certain metal chlorides (magnesium and calcium chlorides) that hydrolyze in water to produce an acidic pH, exhibit essentially the same behavior as dilute solutions of the corresponding acids. Corrosion rates generally range from 2.5 to 1500 μm/yr (0.1–60 mils/yr) at room temperature, depending on the degree of aeration and the acidity. Table 28 lists test data for corrosion of copper in 30% calcium chloride ($CaCl_2$) refrigeration brine with and without inhibitors.

Neutral saline solutions can be successfully handled by copper alloys. Consequently, these alloys are used in heat-exchanger and condenser equipment exposed to seawater. Corrosion rates of copper in NaCl brine are given in Table 29. These rates are not necessarily the same as those in seawater.

Such alkaline salts as sodium silicate (Na_2SiO_3), sodium phosphate (Na_3PO_4), and sodium carbonate (Na_2CO_3) attack copper alloys at low but different rates at room temperature. On the other hand, alkali cyanide is aggressive and attacks copper alloys fairly rapidly because it forms a soluble complex copper anion. Table 30 provides specific corrosion rates.

Oxidizing salts corrode copper and copper alloys rapidly; therefore, copper metals should not be used with oxidizing saline solutions except those that are very dilute. Aqueous sodium dichromate ($Na_2Cr_2O_7$) solutions can be safely handled by copper alloys, but the presence of a highly ionized acid, such as H_2CrO_4 or H_2SO_4, may increase the corrosion rate several hundred times, because the dichromate acts as an oxidizing agent in acidic solutions. In one test, a copper-nickel corroded at 2.5 to 250 μm/yr (0.1–10 mils/yr) and a copper-tin alloy (phosphor bronze) at 5 μm (0.2 mil/yr) when handling an aqueous $Na_2Cr_2O_7$ solution. The rate increased 200 to 300 times for both metals when H_2CrO_4 was added to the solution. In solutions containing Fe^{3+}, mercuric (Hg^{2+}), or stannic (Sn^{4+}) ions, a copper-nickel showed a corrosion rate of 27.4 mm/yr (1080 mils/yr), while copper-zinc and copper-tin alloys showed a still greater rate of 228 mm/yr (8980 mils/yr).

Salts of metals more noble than copper, such as the nitrates of mercury and silver, corrode cop-

Table 31 Corrosion of copper alloys in amine system service

			Average penetration rate	
Alloy	Exposure time, h	Test conditions	μm/yr	mils/yr
C11000	1622	Coupons exposed in ethylenediamine refining still	nil–180	nil–7
C11000	1580	Aqueous ethylenediamine	25	1
C71500	1580	Same as above	75	3
C11000	806	Liquid vapor containing NH_3 and mono-, di-, and triethanolamines; 90–156 °C (195–315 °F)	760	30
C65500	806	Same as above	790	31.2
C11000	1437	Liquid vapor containing NH_3 and mono-, di-, and triethanolamines; 180–195 °C (355–385 °F)	28	1.1
C65500	1437	Same as above	48	1.9
C11000	2622	Vapor phase of diethanolamine still containing mono-, di-, and triethanolamines; 180–195 °C (355–385 °F)	28	1.1
C26000	887	Denuded monoethanolamine (20%) CO_2	nil	nil
C26000 coupled to carbon steel	168	20% monoethanolamine (4 mol CO_2 per mol MEA); 60 °C (140 °F)	4550	179
C44200	900	Lean solution of diethanolamine containing impurities	50	2
C26000	1440	Rich solution of monoethanolamine	330	13
C11000	1440	Same as above	Dissolved	Dissolved
C26000	1440	Lean solution of monoethanolamine	3,000	118
C11000	1440	Same as above	11,500	454

per alloys rapidly, simultaneously plating out the noble metal on the copper surface. Temperature and acidity influence the rate of attack. A film of mercury on high-zinc brass (more than 15% Zn) may cause intergranular cracking by liquid metal embrittlement (LME) if the alloy is under tensile stress, either residual or applied.

Corrosion in Organic Compounds

Copper and many of its alloys resist corrosive attack by most organic solvents and by organic compounds, such as amines, alkanolamines, esters, glycols, ethers, ketones, alcohols, aldehydes, naphtha, and gasoline. Although the corrosion rates of copper and copper alloys in pure alkanolamines and amines are low, they can be significantly increased if these compounds are contaminated with water, acids, alkalies, salts, or combinations of these impurities, particularly at high temperatures. Tables 31 to 37 list the results of corrosion testing of copper and a limited but representative variety of copper alloys in contact with various organic compounds under many conditions.

Gasoline, naphtha, and other related hydrocarbons in pure form will not attack copper or any of the copper alloys. However, in the manufacture of hydrocarbon materials, process streams are likely to be contaminated with one or more of such substances as water, sulfides, acids, and various organic compounds. These contaminants attack copper and its alloys. Corrosion rates for C44300 and C71500 exposed to gasoline are low (Table 38), and these two alloys are successfully used in equipment for refining gasoline. Table 39 lists corrosion rates for copper and for alloys exposed to contaminated naphtha in two different environments.

Creosote. Copper and copper alloys are generally suitable for use with creosote, although creosote attacks some high-zinc brasses. Alloys C11000, C23000, C26000, C51000, and C65500 typically corrode at rates less than 500 μm/yr (20 mils/yr) when exposed to creosote at 25 °C (75 °F).

Linseed Oil. Copper and its alloys are fairly resistant to corrosion by linseed oil. All of the alloys show some attack, but none exhibits corrosion severe enough to make it unsuitable for this application. Alloys C11000, C51000, and C65000 showed corrosion rates less than 500 μm/yr (20 mils/yr) in linseed oil at 25 °C (75 °F). Alloy C26000 had a rate of 500 to 1250 μm/yr (20 to 50 mils/yr).

Benzol and Benzene. Alloys C11000, C23000, C26000, C51000, and C65500 tested in these materials at 25 °C (75 °F) had corrosion rates under 500 μm/yr (20 mils/yr).

Sugar. Copper is successfully used for vacuum-pan heating coils, evaporators, and juice extractors in the manufacture of both cane and beet sugar. Inhibited admiralty metals, aluminum brass, aluminum bronzes, and copper nickels are also used for tubes in juice heaters and evaporators. Bimetal tubes of copper and steel have been used by manufacturers of beet sugar to counteract SCC of copper tubes caused by NH_3 from beets grown in fertilized soil. Table 40 lists the results of tests conducted on copper and copper alloys in a beet-sugar refinery.

Beer. Copper is extensively used in the brewing of beer. In one installation, the wall thickness of copper kettles thinned from an original thickness of 16 mm ($\frac{5}{8}$ in.) to 10 mm ($\frac{3}{8}$ in.) in a 30-year period. Brazing with BAg (copper-silver) filler metals eliminates the possibility that the alkaline compounds used for cleaning copper equipment will destroy joints by attacking

Table 32 Corrosion of copper alloys in ester solutions

Alloy	Exposure time, h	Test conditions	Average penetration rate	
			μm/yr	mils/yr
Acetates				
C11000	400	Alkenyl acetate plus H_2SO_4	6100	240
C65500	400	Same as above	3050	120
	257	Allylidene diacetate; 110 °C (230 °F)	183–213	7.2–8.4
C11000	240	Butyl acetate plus 1% H_2SO_4	1625–4090	64–161
C65500	240	Same as above	2870	113
C11000	2328	2-chloroallylidene diacetate	5	0.2
C11000	250	Crude vinyl acetate; 110–150 °C (230–300 °F)	25	1.0
C71500	250	Same as above	7.5–125	0.3–5
C11000	550	Ethyl acetate plus 1.0% H_2SO_4	483	19
C65500	550	Same as above	400	16
C11000	991	Ethyl acetate reaction mixture; liquid; 90 °C (195 °F)	550	21.6
C62300	991	Same as above	395	15.6
C65500	991	Same as above	518	20.4
C11000	991	Ethyl acetate reaction mixture; vapor; 90 °C (195 °F)	5	0.2
C62300	991	Same as above	15	0.6
C65500	991	Same as above	13	0.5
C11000	2976	Ethyl acetoacetate	10	0.4
C65500				
Cold-worked	216	Isopropyl acetate	6700	264
Annealed	216	Isopropyl acetate	6100	240
	480	Isopropyl acetate process; liquid; 120 °C (250 °F)	300	12
C11000	519	Methylamyl acetate process; batch sill coils; 115 °C (240 °F)	500–685	22–27
C65500	519	Same as above	280–300	11–12
C11000	519	Methylamyl acetate process; batch still down pipe; 115 °C (240 °F)	330	13
C65500	51	Same as above	300	12
C11000	1345	Methylamyl acetate process; batch still condenser; 30 °C (85 °F)	840–940	33–37
C65500	1345	Same as above	1400–1575	55–62
C63600	3312	Methylamyl acetate process; batch still coils; 95 °C (205 °F)	483	19
C51000	3312	Same as above	430–483	17–19
C60800	3312	Same as above	330	13
C51000	3312	Methylamyl acetate process; batch still downpipe; 95 °C (205 °F)	380–483	15–19
C63600	3312	Same as above	400–460	16–18
C60800	3312	Same as above	280	11
C11000	217	Refined isopropenylacetate; 98 °C (210 °F)	60	2.4
	2784	Vinyl acetate, inhibited	2.5	0.1
C11000	250	Vinyl acetate, process; 150–190 °C (300–375 °F)	355–400	14–16
C71500	250	Same as above	685–1250	27–49
C11000	768	Vinyl acetate process; batch still kettle	685–1170	27–46
C65500	768	Same as above	150–483	6–19
C11000	864	Same as above	2290–3500	90–138
C65500	864	Same as above	660–2160	26–85
Acrylates				
C11000	240	Acidified sodium acrylate containing 5% H_2SO_4; 49 °C (120 °F)	945	37.2
	254	Ethyl acrylate process; 130–150 °C (265–300 °F)	1220	48
C65500	254	Same as above	430	16.8
C11000	240	Isopropyl ether solution of acrylic acid (18%); 49 °C (120 °F)	18	0.7
	240	Sodium acrylate solution containing 1% NaOH; 49 °C (120 °F)	5	0.2
	240	Washings from isopropyl ether solution of acrylic acid; 49 °C (120 °F)	210	8.3
	240	Wet calcium acrylate	240	9.4
	504	2-ethylhexylacrylate process, 95 °C (205 °F)	230–275	9.0–10.8
C65500	504	Same as above	220–275	8.6–10.8
C11000	566	2-ethylhexyl acrylate process; condensate tank; 30 °C (85 °F)	66–74	2.6–2.9
C51000	566	Same as above	60–86	2.4–3.4
C65500	566	Same as above	114–122	4.5–4.8
C11000	566	2-ethylhexyl acrylate process; 120 °C (250 °F)	236–239	9.3–9.4
C51000	566	Same as above	264	10.4
C65500	566	Same as above	328–360	12.9–14.2
Benzoates				
C11000	1680	Butyl benzoate	nil	nil
	1296	Butyl benzoate process; circulating line; 40 °C (100 °F)	800–1025	31.4–40.4
C60800	1296	Same as above	1060	41.8
C65500	1296	Same as above	843–1090	33.2–42.8
C23000	1296	Same as above	790–1085	31.2–42.7
C22000	1296	Same as above	900–985	35.6–38.8
C11000	1296	Butyl benzoate process; 40 °C (100 °F)	280	11.1
C65500	1296	Same as above	350–400	13.7–15.7
C11000	1296	Butyl benzoate process; batch still kettle; 185 °C (365 °F)	7.5–38	0.3–1.5
C65500	1296	Same as above	7.5–25	0.3–1.0
C11000	1680	Methyl benzoate (refined)	2.5	0.1
C11000	1680	Methyl benzoate (copper-free)	7.5	0.3

tin-lead solders. Steam coils require more frequent replacement than any other component in brewery equipment. They have service lives of 15 to 20 years. The service lives of other copper items exposed to process streams in a brewery range from 30 to 40 years.

Sulfur compounds free to react with copper, such as H_2S, sodium sulfide (Na_2S), or potassium sulfide (K_2S), form CuS. Reaction rates depend on alloy composition; the alloys of highest resistance are those of high zinc content.

Strip tensile specimens of seven copper alloys were exposed in a fractionating tower in which oil containing 1.4% S was being processed. The results of this accelerated test are given in Table 41. These data show the suitability of the higher-zinc alloys for use with sulfur-bearing compounds. Alloy C28000 (60Cu-40Zn) showed good corrosion resistance, but C23000 (85Cu-15Zn) was completely destroyed.

Inhibited admiralty metals are also excellent alloys for use in heat exchangers and condensers that handle sulfur-bearing petroleum products and use water as the coolant. Alloys C44300, C44400, and C44500, which are inhibited toward dezincification by the addition of arsenic, antimony, or phosphorus to the basic 70Cu-29Zn-1Sn composition, offer good resistance to corrosion from sulfur as well as excellent resistance to the water side of the heat exchanger.

Corrosion in Gases

Carbon dioxide and carbon monoxide (CO) in dry forms are usually inert to copper and its alloys, but some corrosion takes place when moisture is present. The rate of reaction depends on the amount of moisture. Because some alloy steels are attacked by CO, the high-pressure equipment used to handle this gas is often lined with copper or copper alloys.

Table 33 Corrosion of copper alloys in ethers

Alloy	Exposure time, h	Test conditions	Average penetration rate	
			μm/yr	mils/yr
C11000	2784	γ-methylbenzyl ether, N_2 atmosphere	2.5 max	0.1 max
C11000	2784	γ-methylbenzyl ether, air atmosphere	2.5 max	0.1 max
C11000	288	Recovered butyl ether	nil	nil
C65500	288	Same as above	2.5	0.1
C11000	94	Dichloro ethyl ether residues, 80 °C (175 °F)	183–915	7.2–36
C65500	94	Same as above	61–245	2.4–9.6
C11000	71	Crude dichloro ethyl ether, 80 °C (175 °F)	2130–3050	84–120
C65500	71	Same as above	1220–3050	48–120
C11000	70	Dichloro ethyl ether, 80 °C (175 °F)	150	6
C65500	70	Same as above	120	4.8
C11000	70	Dichloro ethyl ether, 100 °C (212 °F)	610	24
C65500	70	Same as above	245	9.6
C11000	70	Dichloro ethyl ether, boiling	183	7.2
C65500	70	Same as above	213	8.4

Table 34 Corrosion of copper alloys in ketones

Alloy	Exposure time, h	Test conditions	Average penetration rate	
			μm/yr	mils/yr
C11000	138	Phenylxylol ketone mixture	41–43	1.6–1.7
C65500	138	Same as above	76	3.0
C11000	163	Pentanedione mixture	46–91	1.8–3.6
C65500	163	Same as above	33–84	1.3–3.3
C12000	43	Diethyl ketone, 30 °C (86 °F)	nil	nil
C12000	42	Diethyl ketone, boiling	nil–7.6	nil–0.3
C12000	43	Methyl n-propyl ketone, 30 °C (85 °F)	nil	nil
C12000	42	Methyl n-propyl ketone, boiling	nil	nil
C11000	216	Methylamyl ketone, boiling	2.5	0.1
C11000	353	Methyl ethyl ketone, boiling	12.7	0.5
C11000	409	Phenylxylol ketone containing NaOH	457–518	18–20.4
C65500	409	Same as above	701–823	27.6–32.4
C11000	165	Acetone dispersion of cellulose acetate, 56 °C (135 °F)	10.2	0.4
C26000	165	Same as above	5.1	0.2

Table 35 Corrosion of copper alloys in aldehydes

Alloy	Exposure time, h	Test conditions	Average penetration rate	
			μm/yr	mils/yr
C11000	49	Boiling 2-ethylbutyraldehyde	33	1.3
C11000	112	Boiling butyraldehyde	33	1.3
C11000	1752	2-hydroxyadipaldehyde	20–23	0.8–0.9
C11000	168	Diethyl acetal mixture, 45 °C (115 °F)	60–120	2.4–4.8
C65500	168	Same as above	90–150	3.6–6.0
C26000	168	Same as above	90–150	3.6–6.0
C11000	70	2–ethyl–3–propylacrolein, 98 °C (210 °F)	33	1.3
C11000	168	Diacetoxybutyraldehyde, 160 °C (320 °F)	230–240	9.0–9.4
C65500	168	Same as above	75	3.0
C51000	168	Same as above	18–20	0.7–0.8
C11000	540	Propionaldehyde	1420–1550	56.0–61.0
C11000	216	Propionaldehyde, 190 °C (375 °F)	610–1220	24.0–48.0
C11000	443	Butyladehyde	310	12.2
C51000	443	Same as above	360	14.2
C11000	2374	Same as above	165	6.5
C65500	2374	Same as above	20	0.8
C51000	2374	Same as above	10	0.4

Sulfur Dioxide (SO_2). Gases containing SO_2 attack copper in a manner similar to oxygen. The dry gas does not corrode copper or copper alloys, but the moist gas reacts to produce a mixture of oxide and sulfide scale. Table 42 lists the corrosion rates of some copper alloys in hot paper mill vapor that contains SO_2.

Hydrogen Sulfide. Moist H_2S gas reacts with copper and copper-zinc alloys to form CuS. Alloys containing more than 20% Zn have considerably better resistance than lower-zinc alloys or copper. Hot, wet H_2S vapors corrode C26000, C28000, or C44300 at a rate of only 50 to 75 μm/yr (2–3 mils/yr), but the rate for C11000 and C23000 under the same conditions is 1250 to 1625 μm/yr (50–65 mils/yr).

Halogen Gases. When they are dry, fluorine, chlorine, bromine, and their hydrogen compounds are not corrosive to copper and its alloys. However, they are aggressive when moisture is present. The corrosion rates of copper metals in wet hydrogen compounds are comparable to those given for HF and HCI in Tables 17 and 18.

Hydrogen. Copper and its alloys are not susceptible to attack by hydrogen unless they contain copper oxide. Tough pitch coppers, such as C11000, contain small quantities of Cu_2O. Deoxidized coppers with low residual deoxidizer contents—C12000, for example—may contain Cu_2O, but will contain less than the tough pitch coppers. These deoxidized coppers are not immune to hydrogen embrittlement. Deoxidized coppers with high residual deoxidizer contents, however, are not susceptible to hydrogen embrittlement, because the oxygen is tied up in complex oxides that do not react appreciably with hydrogen.

When oxygen-bearing copper is heated in hydrogen or hydrogen-bearing gases, the hydrogen diffuses into the metal and reacts with the oxide to form water, which is converted to high-pressure steam if the temperature is above 375 °C (705 °F). The steam produces fissures, which decrease the ductility of the metal. This condition is generally known as hydrogen embrittlement. Any degree of embrittlement can lead to catastrophic failure and therefore should be avoided; there is no safe depth of attack.

Figure 29 shows the depth of damage, or embrittlement, of C11000 after it has been heat-

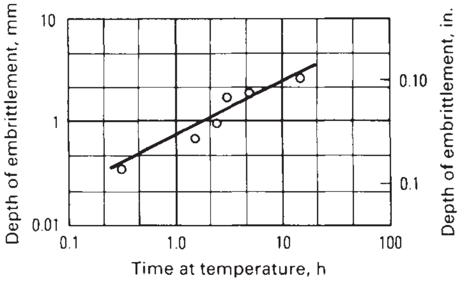

Fig. 29 Hydrogen embrittlement of tough pitch coppers heated in pure hydrogen at 600 °C (1100 °F)

ed in hydrogen at about 600 °C (1100 °F) for varying times. The reaction is especially important when oxygen-containing copper is bright annealed in reducing atmospheres containing relatively small amounts of hydrogen (1–1.5%). Annealing of tough pitch coppers in such atmospheres at temperatures much above 475 °C (900 °F) may lead to severe embrittlement, especially when annealing times are long. In fact, tough pitch coppers should not be exposed to hydrogen at any temperature if they will subsequently be exposed to temperatures above 370 °C (700 °F).

When tough pitch coppers are welded or brazed, the possibility of hydrogen embrittlement must be anticipated, and hydrogen atmospheres must not be used. Where copper must be heated in hydrogen atmospheres, an oxygen-free copper or deoxidized copper with high residual deoxidizer content should be selected. No hydrogen embrittlement problems have been encountered with these materials.

Dry Oxygen. Copper and copper alloy tubing is used to convey oxygen at room temperature, as in hospital oxygen service systems. When heated in air, copper develops a Cu_2O film that exhibits a series of interference tints (temper colors) as it increases in thickness. The colors associated with different oxide film thicknesses are:

Color	Film thickness, nm
Dark brown	37–38
Very dark purple	45–46
Violet	48
Dark blue	50–52
Yellow	94–98
Orange	112–120
Red	124–126

Black cupric oxide (CuO) forms over the Cu_2O layer as the film thickness increases above the interference color range.

Scaling results when copper is used at high temperatures in air or oxygen. At low temperatures (up to 100 °C, or 212 °F), the oxide film increases in thickness logarithmically with time. Scaling rate increases irregularly with further increases in temperature and rises rapidly with pressure up to 1.6 kPa (12 torr). Above 20 kPa (150 torr) the rate of increase is steady. Beyond the interference color range, the growth rate of the oxide film is approximately defined by:

$$W^2 = kt \qquad \text{(Eq 3)}$$

where W is weight gain (or increase in equivalent thickness) per unit area, t is time, and k is a constant of proportionality. Values for k are given in Table 43. Different investigators report different oxidation rates, but those given in Ref 58 appear to be reliable.

Low concentrations of lead, oxygen, zinc, nickel, and phosphorus in copper have little influence on oxidation rate. Silicon, magnesium, beryllium, and aluminum form very thin insulating (nonconductive) oxide films on copper, which protect the metal surface and retard oxidation.

SCC of Copper Alloys in Specific Environments

Properly selected copper alloys possess excellent resistance to SCC in many industrial and chemical environments; nevertheless, cracking has been identified in a significant number of environments. In some cases, the conditions for cracking are very limited and exist only within a narrow range of pH values or a narrow range of potentials. In many cases, the experimental data are limited to a single alloy, and it is not known if the environment is generally deleterious to many copper alloys or to a restricted group of alloys. Data are summarized below for environments in which cracking has been recognized. Additional information is available in the references cited in this section and in the article

Table 36 Corrosion of copper alloys in ethylene glycol solutions

Alloy	Exposure time, h	Test conditions	Average penetration rate μm/yr	mils/yr
C11000	1344	Triethylene glycol solution, aerated; room temperature	nil	nil
C11000	2560	Triethylene glycol air-conditioning system; 175 °C (345 °F)	40	1.6
C26000	2560	Same as above	50	2.0
C11000	3320	Same as above	10	0.4
C26000	3320	Same as above	15	0.6
C11000	8328	Same as above	25	1.0
C26000	8328	Same as above	35	1.4
C11000	2880	Triethylene glycol air-conditioning system(a); 160 °C (320 °F)	7.5	0.3
C26000	2880	Same as above	7.5	0.3
C11000	5760	Same as above	2.5	0.1
C26000	5760	Same as above	2.5	0.1
C51000	2880	Ethylene glycol solution(b) plus 0.03% H_2SO_4; 99 °C (210 °F)	7.5–10	0.3–0.4
C60800	2880	Same as above	2.5–7.5	0.1–0.3
C63000	2880	Same as above	2.5–1	0.1–0.7
C65500	2880	Same as above	20–25	0.8–1.0
C11000	2400	Ethylene glycol solution(b) plus 0.03–0.05% H_2SO_4; second run; 99 °C (210 °F)	580	23
C61800	2400	Same as above	380	15
C70600	2400	Same as above	480	19
C71500	2400	Same as above	460	18
C11000	305	Glycol maleate, 79 °C (175 °F)	20	0.8

(a) 87–95% glycol. (b) 15% glycol, 85% H_2O

Table 37 Corrosion of copper alloys in alcohols

Alloy	Exposure time, h	Test conditions	Average penetration rate μm/yr	mils/yr
C11000	503	Crude C-5 alcohols; 126–140 °C (260–285 °F)	7.5	0.3
C11000	210	Crude decyl alcohol; 175 °C (345 °F)	3–5	0.1–0.2
C11000	288	Primary decyl alcohol; 175 °C	15–45	0.6–1.8
C65500	288	Same as above	20–60	0.8–2.4
C44400	8160	Isopropanol and water; 118–145 °C (245–295 °F)	10–38	0.4–1.5
C23000	8160	Same as above	10–56	0.4–2.2
C11000	8160	Same as above	8–75	0.3–3.0
C65500	8160	Same as above	10–63	0.4–2.5
C11000	264	Allyl alcohol; refluxed at 88 °C (190 °F)	25	1
C11000	94	Methanol; boiling	nil	nil
C11000	46	Denaturing grade ethanol; boiling	25	1
C23000	165	2-ethyl–2-butyl–1,3 propanediol; 45 °C (115 °F)	5	0.2

Table 38 Corrosion of C44300 and C71500 exposed to gasoline in a refinery

Service condition(a)	Temperature °C	°F	Average penetration rate μm/yr	mils/yr
C44300				
Straight-run (untreated)				
Tower liquid(b)	121	250	1270 min	50 min
Storage(c)	4–27	40–80	63	2.5
Distilled tops from straight-run gasoline(d)	35	95	1270	50
Cracked gasoline (top tray in tower)(e)	204	400	15	0.6
Sweet gasoline vapor(f)	177	350	7.5	0.3
C71500				
Straight-run (untreated)				
Tower liquid(b)	121	250	180	7
Storage(c)	4–27	40–80	180	7
Distilled tops from straight-run gasoline(d)	35	95	1140	45
Cracked gasoline (top tray in tower)(e)	204	400	200	8
Sweet gasoline vapor(f)	177	350	10	0.4
Aviation gasoline (top of column)	121	250	2.5	0.1

(a) Gasoline or related hydrocarbons will not attack copper or its alloys. Attack depends on the type and amount of impurities in the gasoline, such as water, sulfides, mercaptans, aliphatic acids, naphthenic acids, phenols, nitrogen bases, and dissolved gases. (b) 100 lb of H_2S present per 1000 bbl of gasoline. (c) 0.02–0.03 g H_2S per liter of gasoline. (d) pH controlled by NH_3 and HCl present. (f) Vacuum operation

"Stress-Corrosion Cracking" in this Handbook; they should be consulted when selecting a copper alloy for a specific application.

Acetate Solution. Pure copper wire stressed beyond the yield strength was observed to crack in 0.05 *N* cupric acetate ($Cu(C_2H_3O_2)_2$) (Ref 59). Alloy C26000 is susceptible to cracking in the same solution, and the cracking rate under slow strain rate conditions is a function of both pH and applied potential (Ref 60).

Amines. Alloy C26000 is susceptible to cracking in solutions of methyl amine, ethyl amine, and butyl amine when dissolved copper is present in the solution (Ref 61). Susceptibility is a maximum at a potential approximately 50 mV anodic from the rest potential. Tubing fabricated from C68700 exhibited cracks from the steam side of a condenser system after 3048 h of service in a desalination plant. The most likely cause of the cracking was an amine used as a water treatment chemical (Ref 62).

Ammonia. All copper-base alloys can be made to crack in NH_3 vapor, NH_3 solutions, ammonium ion (NH_4^+) solutions, and environments in which NH_3 is a reaction product. The rate at which cracks develop is critically dependent on many variables, including stress level, specific alloy, oxygen concentration in the liquid, pH, NH_3 or NH_4^+ concentration, copper ion concentration, and potential.

Early work on the stress corrosion of brass in NH_3 provided the following summary of findings (Ref 63):

- Stress-corrosion cracking occurs in a great variety of brasses that differ widely in composition, degree of purity, and microstructure.
- Cracking occurs only in objects that are subjected to external or internal stresses.
- Visible corrosion is frequently associated with the effect, but the corrosion may often be superficial.
- Lacquer coatings do not offer complete protection against SCC.
- Sufficient and continuous coatings of a metal, such as nickel, confer complete protection.
- Highly stressed articles may be kept for years in a clean air atmosphere without developing cracks.
- Ammonia and ammonium NH_4^+ salts induce cracking.
- Surface defects localize stresses do not appear to contribute to the development of cracks in the absence of an essential corroding agent, such as NH_3.
- Severe corrosion and pitting do not of themselves lead to cracking.
- Cracks often follow an intercrystalline path.
- Traces of NH_3 in the environment are an important agent in inducing SCC in atmospheric exposure.
- Ammonia has a specific and selective action on the material in the grain boundaries of brass.
- Cracking always begins in surface layers that are under tension.
- The behavior of copper alloy subjected to the combined effect of tensile stress and NH_3 is an index of susceptibility to SCC.
- Susceptibility to SCC diminished as the copper content of the brass is increased.
- Protracted heating of 70Cu-30Zn brass at 100 °C (212 °F) does not develop cracks and does not reduce the internal stress appreciably.

Table 44 provides a ranking of various copper alloys according to their relative SCC susceptibility in NH_3 environments.

Atmosphere. Many natural environments contain pollutants that, in the presence of moisture, may cause stress-corrosion problems (Ref 64). Sulfur dioxide, oxides of nitrogen, and NH_3 are known to induce SCC of some copper alloys Chlorides may also cause problems. Atmospheric-exposure test data are summarized in Table 45. In these tests, 150 by 13 mm (6 by $\frac{1}{2}$ in.) U-bend samples were stressed in

Table 39 Corrosion of copper alloys in contaminated naphtha

Alloy	Corrosion rate, μm/yr	Corrosion rate, mils/yr
At 21 °C (70 °F)(a)		
C23000	230	9
C46400	50	2
C28000	75	3
C44200	200	8
C11000	1270	50
At 177 °C (350 °F)(b)		
C23000	2030	80
C46400	10	0.4
C28000	10	0.4
C44200	200	8

(a) The naphtha contained H_2S, H_2O, and HCl. (b) The naphtha contained H_2S, mercaptans, and naphthenic acids.

Table 40 Corrosion of copper alloys in beet-sugar solution

	Decrease in tensile strength, %, for test rack number(a)			
Alloy	1	2	3	4
C11000	0	4.0	3.5	0
C44300	2.0	9.5	11.5	2.5
C44400	0	3.0	6.0	0
C44500	4.5	9.0	12.5	5.5
C71000	1.0	4.5	7.0	0
C71500	0	5.0	8.0	0

(a) Corrosion specimens (0.8 mm, or 0.032 in., thick strips) were exposed in contact with beet-sugar solution for 100 days in normal refinery operations. Test racks 1 and 4 were at the finishing pan containing Steffen's filtrate; rack 2 was in the first-effect thin-juice evaporator; rack 3 was at the third body of the triple-effect evaporator.

Table 41 Corrosion of selected copper alloys in cracked oil containing 1.4% S

			Loss in tensile strength(a),%			
Alloy type	UNS No.	Exposure time, days	360 °C (680 °F)	315 °C (600 °F)	285 °C (545 °F)	255 °C (490 °F)
Red brass, 85%	C23000	27	100(b)	100(c)	100	100
Muntz metal	C28000	27	12(b)	7.5(d)	1	1.5
Naval brass	C46400	24	…	1.5	0	2
Uninhibited admiralty metal	…	27	13(b)	6(c)	3	2
Antimonial admiralty metal	C44400	27	16.5(b)	6(c)	4	2.5
Aluminum brass	…	24	…	7	16	10
Copper nickel, 30%	C71500	24	…	100	100	57
Silicon bronze, 3%	…	34	…	100	100	100

(a) Specimens 0.8 × 13 mm (0.032 × 0.50 in.) in cross section were exposed at different locations within a high-pressure fractionating column, each location having a characteristic average temperature. (b) 115-day exposure. (c) 26-day exposure. (d) Length of exposure unavailable

Table 42 Corrosion of copper alloys in hot paper mill vapor containing SO_2

Temperature 200–220 °C (390–430 °F); atmosphere, 17–18% SO_2 plus 1–2% O_2; test duration, mainly 30 days, but some longer

Alloy type	UNS No.	Weight loss, $g/m^2/d$
Bronze (90Cu-10Sn)	…	22.0
Aluminum bronze	C61800	26.4
Phosphor bronze	C51100	28.6
Nickel silver, 75–20	C73200	35.6
Phosphor bronze, 8% C	C52100	39.4
Silicon bronze	C65800	50.2
Nickel silver, 55–18	C77000	63.8
Nickel silver, 65–18	C75200	67.4
Nickel bronze (88.5 Cu-5Sn-5Ni-1.5Si)	…	70.5

Table 43 Values of rate constant for oxide growth on unalloyed copper

Temperature		Rate constant *k*(a)	
°C	°F	Pure O_2	Air
400	750	4.4×10^{-8}	…
500	950	4.4×10^{-7}	…
600	1100	3.24×10^{-6}	…
700	1300	1.6×10^{-5}	8.03×10^{-6}
800	1475	8.69×10^{-5}	7.97×10^{-5}
900	1650	3.49×10^{-4}	3.36×10^{-4}
950	1750	7.30×10^{-4}	…
1000	1850	1.78×10^{-3}	1.35×10^{-3}

(a) For calculation of weight gain in g/m^2 from Eq 3 when time is measured in seconds

Table 44 Relative susceptibility to SCC of some copper alloys in NH_3

Alloy	Susceptibility index(a)
C26000	1000
C35300	1000
C76200	300
C23000	200
C77000	175
C66400	100
C68800	75
C63800	50
C75200	40
C51000	20
C11000	0
C15100	0
C19400	0
C65400	0
C70600	0
C71500	0
C72200	0

(a) 0, essentially immune to SCC under normal service conditions; 1000, highly susceptible to SCC as typified by C26000 the long-transverse direction. The bend was produced by bending around a 19 mm (3/4 in.) diam mandrel, and the legs of each specimen were held in nonconductive jigs during the test. The stress on the specimens was not determined. The stressed specimens were exposed in two industrial locations in New Haven, CT, and Brooklyn, NY, and in one marine location at Daytona Beach, FL.

Chlorate Solutions. Brass was observed to crack intergranularly and transgranularly when immersed in 0.1 to 5 *M* sodium chlorate ($NaClO_3$) solutions at pHs from 3.5 to 9.5 when subjected to slow straining (Ref 66). Crack velocities in 1 *N* $NaClO_3$ at pH 6.5 were 10^{-7} m/s at a crosshead speed of 10^{-4} cm/min (4×10^{-5} in./min) and 10^{-6} m/s at a crosshead speed of 10^{-3} cm/min (4×10^{-4} in./min).

Chloride Solutions. The service lives of copper alloys under cyclic stress are shorter in chloride solutions than in air. Slow strain rate experiments have also shown that C26000 (Ref 67) and C44300 (Ref 68) have lower fracture stresses in NaCl solutions when the metal is anodically polarized. The changes in fracture stress are insignificant relative to those in air in the absence of an applied potential.

Citrate Solutions. Alloy C72000 is sensitive to cracking in citrate solutions containing dissolved copper in the pH range of 7 to 11. The U-bend test specimens exhibited intergranular cracking (Ref 69).

Formate Solutions. Brass is susceptible to SCC in sodium formate ($NaCHO_2$) solutions at pHs exceeding 11 over a considerable range of applied potentials (Ref 60).

Hydroxide Solutions. Brass exhibits increased crack growth rates under slow strain rate conditions when it is exposed to NaOH at pHs of 12 and 13. The rate of crack growth is a function of the applied potential (Ref 60).

Mercury and Mercury Salt Solutions. Stressed alloys and alloys with internal stress crack readily when exposed to metallic mercury or mercury salt solutions that deposit mercury on the surface of the alloy. This high sensitivity to mercury is the basis of an industry test for the detection of internal stresses in which the alloy is immersed in a solution of mercurous nitrate. Cracking in mercury is the result of LME, not stress corrosion. It does not indicate the SCC susceptibility of an alloy.

Nitrate Solutions. Transgranular cracking was observed on C44300 specimens immersed in naturally aerated 1 *N* sodium nitrate ($NaNO_3$) at pH 8 and a potential of 0.15 V versus standard hydrogen electrode (SHE). The fracture stress relative to air was 0.34 (Ref 68).

Copper alloy (Cu-23Zn-12Ni) wires measuring 0.6 mm (0.023 in.) in diameter and normally under a 6 g load and a positive potential in telephone equipment were observed to undergo SCC within two years (Ref 70). Laboratory tests suggested that nitrate salts were the cause. The phenomenon was duplicated in the laboratory by exposing the wires to such nitrate salts as zinc nitrate ($Zn(NO_3)_2$), ammonium nitrate (NH_4NO_3), calcium nitrate ($Ca(NO_3)_2$), and cupric nitrate ($Cu(NO_3)_2$) at high humidity; a potential was applied such that the wires were anodic to the normal corrosion potential. The wires were tested under a constant load of 386 MPa (56 ksi). Cracking also occurred in the absence of an applied potential when the nitrate concentration of the surface was high. Cracking did not occur in the presence of $(NH_4)_2SO_4$ and ammonium chloride (NH_4Cl) salts. Wires of Cu-20Ni did not crack under similar conditions.

Nitrite Solutions. Copper, 99.9 and 99.996% pure, exhibited transgranular cracking when subjected to a strain rate of 10^{-6} s^{-1} while immersed in 1 *M* sodium nitrite ($NaNO_2$) at a pH of 8.2 (Ref 71). The 99.9% Cu tested in solution showed an ultimate tensile strength of 160 MPa (23 ksi) and 25% elongation, as opposed to the 196 MPa (28.5 ksi) and 55% elongation obtained in air. Cracking in 1 *M* $NaNO_2$ was also observed in C26000, admiralty brasses, and C70600.

Solder. In one investigation of the susceptibility to cracking of copper alloys by various

Table 45 SCC of wrought copper alloys in three atmospheres

		Time to failure, years			Crack morphology(a)		
UNS No.	Temper, % cold rolled	New Haven, CT	Brooklyn, NY	Daytona Beach, FL	New Haven, CT	Brooklyn, NY	Daytona Beach, FL
C11000	37	NF(b) 8.5	NF, 8.5	NF, 8.8	…	…	…
C19400	37	NF, 8.5	NF, 8.5	NF, 8.8	…	…	…
C19500	90	NF, 3.2	NF, 3.1	NF, 3.1	…	…	…
C23000	40	NF, 8.5	NF, 8.5	NF, 8.8	…	…	…
C26000	50	35–47 days	0–23 days	NF, 2.7	I	I	…
C35300	50	51–136 days	70–104 days	NF, 2.7	T+(I)	T+(I)	…
C40500	50	NF, 2.7	NT(c)	NT	…	…	…
C41100	50	NF, 2.7	NT	NT	…	…	…
C42200	37	NF, 8.5	NF, 8.5	NF, 8.8	…	…	…
C42500	50	NF, 2.7	NT	NT	…	…	…
C44300	10	NF, 2.7	NF, 2.7	NF, 2.7	…	…	…
	40	51–95 days	41–70 days	NF, 2.7	T	T	…
	40% + ordered(d)	51–67 days	33–49 days	NF, 2.7	T	T	…
C51000	37	NF, 8.5	NF, 8.5	NF, 8.8	…	…	…
C52100	37	NF, 5.7	NF, 5.7	NF, 5.7	…	…	…
C61900	40%, 9% β phase(e)	NF, 8.5	NF, 8.5	NF, 8.8	…	…	…
	40%, 95% β phase	NF, 8.5	NF, 8.5	NF, 8.8	…	…	…
C63800	50	NF, 5.7	NF, 5.7	NF, 5.7	…	…	…
C67200	annealed	0-30 days	0–134 days	NF, 3.1	I	I	…
	50	0-30 days	0–22 days	18–40 days	I	I	I
C68700	10	517–540 days	2.3–NF 2.7	NF, 2.7	T	T	…
	40	221–495 days	311–362 days	NF, 2.7	T	T	…
	40% + ordered(d)	216–286 days	143–297 days	NF, 2.7	T	T	…
C68800	10	NF, 2.7	NF, 2.7	NF, 2.7	…	…	…
	40	4.7-NF 6.4	2.7-NF 6.4	NF, 6.4	T	T	…
	40% + ordered(d)	NF, 2.7	NF, 2.7	NF, 2.7	…	…	…
C70600	50	NF, 2.2	NF, 2.3	NF, 2.2	…	…	…
C72500	40	NF, 2.2	NF, 2.3	NF, 2.2	…	…	…
C75200	annealed	NF, 3.2	NF, 3.1	NF, 3.1	…	…	…
	25	NF, 3.2	NF, 3.1	NF, 3.1	…	…	…
	50	NF, 3.2	NF, 3.1	NF, 3.1	…	…	…
C76200	annealed	171–NF 3.2	672–NF 3.1	NF, 3.1	T	T	…
	25	142–173 days	236–282 days	NF, 3.1	T	T	…
	50	142–270 days	236–282 days	NF, 3.1	T	T	…
C76600	38	127–966 days	197–216 days	754-NF 8.8	T	T	T
C77000	annealed	731–1003 days	37–515 days	NF, 3.1	T	T	…
	38	137–490 days	196–518 days	596–1234 days	T	T	T
	50	153–337 days	489–540 days	692–970 days	T	T	T
C78200	50	23–48 days	26–216 days	236–300 days	T+(I)	T+(I)	T

(a) I, intergranular; T, transgranular. Parentheses indicate minor mode. (b) NF, no failures in time specified. (c) NT, not tested. (d) Heated at 205 °C (400 ° F) for 30 min. (e) Normal structure for this alloy. Source: Ref 65 solders, a U-shaped tube was coated with solder at 400 °C (750 °F) and then immediately flattened between steel tools in a hand press (Ref 72). The sample was then examined for cracks. The data are given in Table 46.

Sulfur Dioxide. Brass is susceptible to SCC in moist air containing 0.05 to 0.5 vol% SO_2. In addition, pre-exposure of the brass to a solution of benzotriazole inhibits the cracking (Ref 73).

Sulfate Solutions. Stress-corrosion cracking of C26000 was observed in a solution of 1 *N* sodium sulfate (Na_2SO_4) and 0.01 *N* H_2SO_4 when the alloy was polarized at a potential of 0.25 V versus SHE and subjected to a constant strain (Ref 74).

Sulfide Solutions. National Association of Corrosion Engineers (NACE) committee T-1F issued a report on the acceptability of various materials for valves for production and pipeline service (Ref 75). Bronze and other copper-base alloys are generally not acceptable for highly stressed parts in sour service. Some nickel-copper alloys are considered satisfactory.

Tungstate Solutions. Mild transgranular cracking of C44300 was observed in 1 *N* sodium tungstate (Na_2WO_4) at pH 9.4 and a corrosion potential of 0.080 V versus SHE. The fracture stress relative to that in air was 0.89, and the crack growth velocity was 2×10^{-9} m/s when a strain rate of 1.5×10^{-5} s^{-1} was used (Ref 68).

Water. Several cases of the SCC of admiralty brass heat-exchanger tubing are documented in Ref 76. The environments in which such SCC was observed included stagnant water, stagnant water contaminated with NH_3, and water accidentally contaminated with a nitrate. No cases were noted of SCC of the following alloys when used in heat-exchanger service: C70600, C71500, arsenical copper, C19400, and aluminum bronze.

Table 46 Susceptibility of copper alloy tubes to cracking by solder

Solder applied at 400 °C (750 °F); specimens were immediately deformed and examined for cracks.

Solder	Alloy 80Cu-20Ni	97Cu-3Zn	70Cu-30Zn
Lead	Shattered	Cracked	Cracked
97.5Pb–2.5Ag	Shattered	Uncracked	Cracked
95Pb–5Sn	Cracked	Uncracked	Cracked
80Pb–20Sn	Cracked	Uncracked	Uncracked
Grade B solder	Cracked	Uncracked	Uncracked
95Sn–5Sb	Uncracked	Uncracked	Uncracked

Source: Ref 72

Table 47 Experience with copper alloys in condenser tubing service

Medium	Alloy	Susceptibility to SCC
Freshwater	Admiralty brass	Very susceptible
	C70600	Resistant
	Arsenical copper	Resistant
	C19400	Low susceptibility
Seawater	C70600	Resistant
	C71500	Resistant
	Arsenic-aluminum brass bronze	Susceptible

Source: Ref 78

Service data for various copper alloys used as condenser tubing are given in Ref 77. Information on six different alloys used in freshwater and in seawater service is summarized in Table 47.

An instance of the SCC of a Cu-7Al-2Si stud from an extraction pump exposed to wet steam is discussed in Ref 78. Also in Ref 78 are examples of SCC failures of copper alloys in marine service. These include tubing, a lifeboat keel pin, brass bolts and screws, a brass propeller, a flooding valve, and aluminum bronze valve parts. Some of the failures were attributed to bird excreta that provided a source of NH_3.

Protective Coatings

Copper metals resist corrosion in many environments because they react with one or more constituents of the environment upon initial exposure, thus forming an inert surface layer of protective reaction products. In certain applications, the corrosion resistance of copper metals may be increased by applying metallic or organic protective coatings. If the coating material is able to resist corrosion adequately, service life may depend on the impermeability, continuity, and adhesion to the basis metal of the coating. The electropotential relationship of the coating to the basis metal may be important, especially with metallic coatings and at uncoated edges. Tin, lead, and solder, used extensively as coatings, are ordinarily applied by hot dipping. Electroplating is also used.

Tin arrests corrosion caused by sulfur; it is most effective as a coating for copper wire and cable insulated by rubber that contains sulfur. Lead-coated copper is primarily used for roofing applications, in which contact with flue gases or other products that contain dilute H_2SO_4 is likely. Tin or lead coatings are sometimes applied to copper intended for ordinary atmospheric exposure, but this is done primarily for architectural effect; the atmospheric-corrosion resistance of bare copper is excellent in rural, urban, marine, and most industrial locations.

Electroplated chromium is used for decoration, for improvement of wear resistance, or for reflectivity. Because it is somewhat porous, it is not effective for corrosion protection. Where corrosion protection is important, electroplated nickel is most often used as a protective coating under electroplated chromium.

Various organic coatings are applied to copper alloys to preserve a bright metallic appearance. These are discussed in the article "Surface Engineering" in this Handbook.

Corrosion Testing

As with other commonly used metallic materials, tests have been devised for determining the resistance of copper and copper alloys to various aqueous environments, atmospheric exposure, and SCC. Each of these are summarized in the sections that follow. Additional information on test methods can be found in *Corrosion*, Volume 13 of the *ASM Handbook* and in Ref 79 and 80.

Aqueous Corrosion Testing

Static Corrosion Tests. Static tests are used to examine the corrosion behavior of copper alloys in both natural and artificial environments. For example, ASTM standard G 31, "Standard Recommended Practice for Laboratory Immersion Corrosion Testing of Metals," can be used to evaluate general corrosion, dealloying, and galvanic corrosion of copper and copper alloys.

One specific procedure that has been applied to copper alloys in closed-container tests is the determination of the partitioning of the major alloying elements between the corrosion product and the solution (Ref 13, 81). In this procedure, the samples are exposed to the test solution for some time period, after which the sample is removed and the solution filtered to remove any particulate. The collected particulate is dissolved in an acidified solution and quantitatively analyzed for copper and other alloying elements of interest; a similar analysis is performed on the filtered solution. The corrosion product is then stripped from the copper alloy using an inhibited HCl solution and analyzed. The results indicate which alloying elements contribute to film formation and whether the element is more prone to go into solution rather than into the film. In addition, the amount of copper that has entered solution and the amount that is actually particulate that spalled off of the surface can be determined. These data are of significance with regard to heavy-metal ion contamination of water sources.

Dynamic Corrosion Tests. One of the major uses of copper alloy is the transport of aqueous solutions; consequently, a significant number of tests have been designed to examine the effects of dynamic conditions on the corrosion behavior of the materials in these environments. The tests, which range in complexity from simple recirculating loops to jet impingement apparatus, examine the effects of such variables as flow rate, heat transfer conditions, and blockages, as well as various solution conditions. Of the systems developed, the flow loop is probably the most widely used test because it is easily constructed, requiring only a pump, ducting, and valves, and can incorporate a wide variety of test variables. Because of their simplicity, flow loops can be constructed on-site and tapped into process flow systems so that the actual operating environment can be used as the test environment. Descriptions of test loops are available in Ref 24, 43, and 82 to 85.

Tubular samples are the most easily tested in this system because they can be directly incorporated into the loop. As with any other corrosion test, the tube samples must be separated by insulating connectors to avoid galvanic effects; tube union fittings of plastic or flexible plastic hose clamped to the tubes are generally adequate. Flat samples can also be tested in flow loops by using special sample holders, such as those described in ASTM D 2688 (Ref 86) and in Ref 24, 82, 83, and 87.

A major variable that affects the corrosion behavior of copper alloys is solution velocity. The effect of flow rate on copper alloys has been examined by placing various diameters of the same tube material in series within a loop and pumping the solution through the loop at a constant pump speed (Ref 83). Velocity effects have also been studied in a parallel flow system with orifice size and header pressure controlled to produce various velocities simultaneously (Ref 24, 43). The effects of local velocity changes and crevices, conditions that arise in power-plant condenser tubes because of lodged debris, have been examined by introducing artificial blockages into tubes (Ref 82). The blockage reduces the cross section of the tube, increasing local flow rate, and produces crevice corrosion conditions where it contacts the tube.

Heat transfer effects have been studied by running test tubes through small steam condensers to ovens and pumping the test solution through the tubes. It should be noted that the conditions provided by this type of test are unlike those obtained when the bulk solution is heated before pumping it through the tubes. Heating the bulk solution may change the concentration of components throughout the solution, such as decreasing the oxygen concentration or promoting precipitation. Under heat transfer conditions, these changes may only occur locally, resulting in different corrosion behavior. Corrosion behavior can also be affected by the temperature gradient that exists between the tube wall and the solution under heat transfer conditions, which is much larger than that of a heated solution passing through a tube surrounded by ambient air.

Loop tests are generally used to evaluate the corrosion rates of materials based on their weight loss over a period of time. Test duration depends in large measure on the aggressiveness of the solution and the sample thickness. However, for copper alloys in most aqueous solutions, the test duration should be at least 120 days in order to ensure attainment of steady-state corrosion rates.

When evaluating the samples that have been exposed to flowing systems, more than just the weight loss should be considered. Evidence of erosion should be sought, especially at leading edges and obstructions, and the depth of erosion should be monitored with respect to time. Evidence of pitting as a function of time should be determined. Depth of crevice attack should be noted in samples with crevices, for example, at clamp sites. With regard to crevice corrosion in copper alloys, the attack usually occurs adjacent to the contact site; therefore, the contact site will generally be at the original thickness and can be used as a reference point when measuring the depth of attack.

Each alloy should also be examined for evidence of dealloying. This can generally be determined by metallographic examination of the cross section to see of a copper-rich layer at the sample surface is present. The material can also be mechanically tested to determine whether the mechanical properties have deteriorated with respect to a control sample. This type of testing, however, is generally performed only on materials that have not suffered from severe corrosion, which would obviously degrade the properties of the material.

Other dynamic systems, in addition to flow loops, have been developed primarily to evaluate the maximum flow rate that materials can withstand before erosion-corrosion occurs (Ref 88). An example of such a system is the jet impingement test (Ref 89). In this test, a high-velocity stream of solution is sprayed onto the specimen for some period of time, after which the depth of attack and the amount of surface area attacked are determined. Based on this evaluation, the relative erosion-corrosion resistance of various materials can be ranked.

The spinning-disk test is used to define the velocity that causes erosion in a material (Ref 89, 90), In this test, a disk of the material is immersed in the solution and rotated at a specific rate around the disk axis perpendicular to the plane of the disk. At the conclusion of the test, the sample is examined to determine the distance from the center of the disk, and therefore the velocity, at which erosion occurs.

One other test is used to examine the relative resistance of various materials to erosion by entrained particles in solution (Ref 23). In this test, silica sand of controlled size is introduced to the solution in which L-shaped samples are mounted on the periphery of a rotating disk.

Although any solution can be used in these dynamic test systems, most tests are conducted with seawater or freshwater. Natural waters, such as from the sea, rivers, or lakes, are used as test solutions, but their use is generally restricted by the location of the test facility. In addition, the compositions of natural waters vary not only with location but also with time, making a standardized test procedure difficult. To circumvent this problem for seawaters, substitute seawater (Ref 91) and a 3.4% NaCl solution have both been used. In general, these solutions are slightly more aggressive than natural seawaters; as a result, predictions of corrosion lifetimes based on data from these solutions are generally conservative with respect to actual performance.

A significant amount of work has recently been done on the behavior of copper alloys in sulfide-contaminated seawaters. An extensive bibliography is given in Ref 92. Sulfides are added to the seawater by either bubbling H_2S gas through the solution or adding a Na_2S solution. In general, sulfide concentrations of the order of 1 ppm are sufficient to cause accelerated attack. For rapid corrosion to occur, the copper alloy must be exposed to a solution that contains oxygen as well as sulfide or must be alternately exposed to sulfide-bearing deaerated solutions, followed by exposure to sulfide-free aerated solutions.

Because of the transient nature of sulfides in water, it is necessary to monitor the sulfide level in solution with time. Titration techniques are available for measuring the sulfide concentration, but these are generally time consuming and tedious if continual monitoring is required. An alternative is the use of a sulfide-specific ion electrode, which provides accurate sulfide readings in substitute ocean water in much less time.

Another environment of interest is the freshwater cooling tower environment typically found in power plant applications. A simulated cooling tower water environment has been developed based on the analysis of Ohio River water for its major constituents and their concentrations. The solution (Table 48) corresponds to a sixfold concentration of typical river water chemistry, simulating the concentrating effect of the cooling tower. Other cooling water solutions have also been used (Ref 93).

Atmospheric Testing

Laboratory Testing. In a variety of applications, such as electrical and architectural components, the behavior of copper alloys when fully immersed in solution is not relevant with regard to their performance under various atmospheric conditions. Constant humidity and temperature chambers are used to evaluate the relative atmospheric behavior of the materials. The design and typical test environments are described in Ref 94 to 96. As with aqueous tests under artificial conditions, the corrosion behavior determined in these tests generally cannot be used to ensure the behavior of the material in the actual service environment. This is the case primarily because many variables in the service environment cannot be incorporated into the test or are overlooked and because the environment changes constantly. Such tests do, however, provide approximate data and allow ranking of the test materials.

Evaluation of tested specimens involves typical corrosion parameters, such as weight loss, depth of pitting, and crevice corrosion. In addition, patina (oxide film formation) is evaluated with regard to color, continuity, and film tenacity. After the specimen has been cleaned, evidence of dealloying should also be sought by examination of a metallographic cross section or by loss of mechanical properties (as compared to an untested control sample). In the Military Standard 853C Method 1009.4 for electronic materials, materials exposed to the salt fog test are evaluated to determine the amount of corrosion over the surface and to determine whether pitting or corrosion contributed to failure of the bend test. Materials are also evaluated with regard to the effect of the oxide film on solder-

Table 48 Composition of simulated cooling tower water

Component	Concentration, mg/L
CuO	700
$MgSO_4$(anhydrous)	693
NaCl	614
KCl	59
KNO_3	24
Na_2CO_3	167
$SiO_2 \cdot XH_2O$	21
H_2SO_4	0.75 mL/L

ability and the corrosion resistance of the solder base metal.

Other environmental tests are Military Standard 202 Method 2080, in which candidate materials are aged in the steam from boiling distilled water and then solder dipped to evaluate their solderability. Ammonium sulfide $(NH_4)_2S$) is used to determine the effectiveness of tarnish inhibitors in protecting the material. In this test, the specimen is held for a short period of time (usually 30 s) over an open beaker containing $(NH_4)_2S$ solution and then examined. If the surface has become blackened, the protective layer is considered to be inadequate.

Field Testing. Atmospheric testing of copper alloys in natural environments is conducted to evaluate the behavior of the materials in industrial, rural, and marine atmospheres. The procedure most widely used is given in Ref 97, which describes sample preparation, types of test racks, typical locations and orientation. This long-term test may last up to 20 years or more and therefore requires careful record keeping.

Stress-Corrosion Testing

In the past several decades, the study of SCC has been greatly accelerated, and the causes and mechanisms for the behavior have been addressed by materials scientists, physicists, chemists, metallurgists, and mechanical engineers. Laboratory studies under controlled conditions have been expanded, ASTM has developed standardized tests, and laboratories have compared data. As a result, considerable quantitative information is now available in the literature. In some cases, this information is obtained with full knowledge of fracture mechanics principles. The methods of generating SCC data are numerous and, as described below, include both static and dynamic tests. Additional information on tests used to evaluate the susceptibility of copper alloys to SCC can be found in the article "Stress-Corrosion Cracking" in this Handbook.

In the static tests, the sample is put under tension by bending and restraining the sample or by mounting it in a tensile-testing machine. The data thus generated include time to first crack, time to fracture, or time to relax to a certain fraction (for example, 50 or 80%) of the unrestrained distance between the ends of the bent specimen. The data generated in this fashion allow comparison among different alloys, among different pretreatments, and among other experimental variables. The data are comparable within one data set but yield no absolute information.

Various NH_3 environments are widely used to test copper alloys, the most common being Mattsson's solution of pH 4.0, 7.2, and 10. Two other NH_3–base environments that produce very aggressive stress-corrosion conditions are a NH_3–0.5 *M* copper solution of pH 14, and a moist NH_3 test. The pH 14 solution is made by dissolving 3.18 g of copper powder in 1 L of 29.5% NH_4OH solution (typical reagent-strength NH_4OH). The moist NH_3 test requires the construction of a chamber in which 100% relative humidity and a constant NH_3 gas concentration are maintained (Ref 98).

One of the simplest laboratory stress-corrosion tests that provides a significant amount of information is the U-bend test, in which the springback of the sample is measured over time in the test solution. Two sample sets of each material are produced in a manner similar to that described in Ref 99. One is placed in the test solution, and the other remains in the room environment as a control. A variety of test jigs are described in Ref 99; however, the legs of the jig must be compressed the same distance when the sample is removed and then replaced in the jig. A typical example of this jig is given in Ref 99.

The samples are placed in the jig, removed, and the springback between the legs measured; this is also done for the control samples. The samples are reinserted in the test jig and placed in the test solution. At periodic intervals, the samples are removed from the solution, taken from the jig, and the springback distance between the legs remeasured. Similar measurements are made on the air control samples. The test continues until either physical failure occurs—that is, if the sample breaks or if it no longer has enough tension to hold it in the jig—or some predetermined performance criteria are met, for example, 1000 h elapsed time or springback reduction to 80% of its initial value. At the conclusion of the test, the average change in percent springback for each material at each time is determined, taking into account the loss in springback that occurred as a result of stress relaxation based on springback measurements of the air control samples.

A constant percent springback versus time indicates that the material is not susceptible to SCC in the test solution over that time period. A decrease in percent springback with time indicates the SCC has occurred. This should be verified by optical examination for cracking as well as metallographic examination of the sample to determine the mode of cracking. An increase in percent springback indicates that the tension side of the sample dissolved at a faster rate than the compressive side due to stress-assisted dissolution. Examination will reveal that the specimen has thinned and that failure occurred because of overload, not cracking. This result indicates that the solution is too aggressive for SCC to occur and that another solution should be used to compare stress-corrosion behavior.

Dynamic Tests. During the past decade, there has been a major swing toward the use of dynamic tests, which yield values that can be quantitatively applied to the proposed mechanisms of SCC. Primary among these is the slow strain rate technique. The application of this technique to the understanding of SCC began in the early 1960s (Ref 100). Excellent summaries of the slow strain rate technique and its applications to SCC are given in Ref 101 and 102.

This method uses tensile test specimens mounted in stiff-frame machines and strained at the rate of 10^{-7} to 10^{-5} s^{-1} in the presence of a specific environment. Strain rates in this range promote SCC, but the absence of cracking is no assurance of immunity to SCC. Various methods are used to assess the results when SCC is observed. These include the area under the stress-elongation curve, time to failure, crack velocity, and ratio of fracture stress in a medium to fracture stress in air.

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Stress-Corrosion Cracking

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STRESS-CORROSION CRACKING (SCC) was first observed in copper-zinc (brass) alloys more than 90 years ago (Ref 1). The SCC failures were reported in India, where they occurred in brass cartridge cases during the rainy season (and were thus later characterized by the descriptive term "season cracking"). The root cause of the failures was traced to the practice of storing the cartridge cases in horse barns, where they came in contact with ammonia vapors. A further contributing factor was the cold-forming operation used to make the cases, which introduced high residual tensile stresses.

This example of season cracking conveniently identifies the three primary factors associated with SCC failure of copper-base alloys: a specific corrosive medium, a susceptible material, and tensile stresses. These factors are often presented graphically (Fig. 1) to demonstrate that all three must be present simultaneously for SCC to occur.

This article is organized to feature these three primary factors. First, those environments that induce SCC in copper-base alloys are discussed, along with cracking-related environmental factors such as potential, pH, and temperature. The next section identifies SCC-susceptible copper-base alloys and metallurgical factors that affect SCC, such as microstructure, heat treatment, and cold working. Attention is then focused on relevant mechanical factors (for example, stress and stress intensity). Testing methods are discussed, as are techniques for the mitigation of SCC (which generally involve elimination of one or more of the three primary factors). Finally, the fracture mechanisms associated with SCC of copper-base alloys are briefly discussed.

Environmental Effects

Effect of Environment Composition. Aqueous ammonia is the principal environment associated with SCC of copper-base alloys in service applications. Failures of brasses occur most commonly in moist conditions where ammonia, water, and oxygen are present. At one time it was thought that ammonia or its derivatives were the only species responsible for SCC of copper-base alloys. More recently, other such environments have been identified; Table 1 shows that cracking of various copper-base alloys can be caused by a variety of species, including sulfates, nitrates, nitrites, chloride-containing species, and even pure water. Additional data on specific environments that cause SCC of copper alloys can be found in the article "Corrosion Behavior" in this Handbook.

Most research on SCC of copper-base alloys has been carried out in ammonia or variations of this environment. In the 1960s, Pugh and Westwood (Ref 16) demonstrated that SCC of brass would not occur under freely corroding conditions in aqueous ammonia in the absence of dissolved copper, which forms a complex ion in solution. As the copper content of the ammonia increased, cracking became more severe, and at some critical copper concentration an oxide film, or tarnish, formed (Fig. 2). Later work by Pugh and Green (Ref 17) demonstrated that cracking could be produced in copper-free ammonia solutions by anodically polarizing the brass specimen. Thus, the primary role of the cupric complex ion appears to be as an oxidant in solution that provides a cathodic reaction.

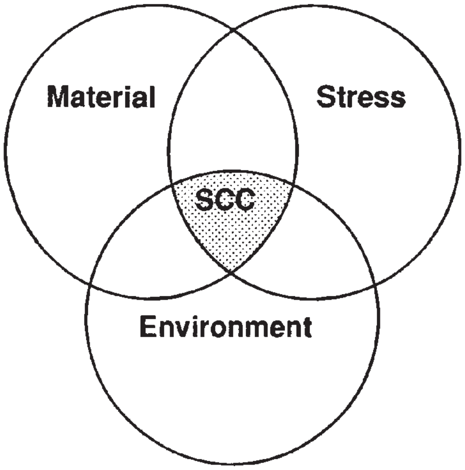

Fig. 1 Schematic representation of the three factors that must be present simultaneously for stress-corrosion cracking to (SCC) occur

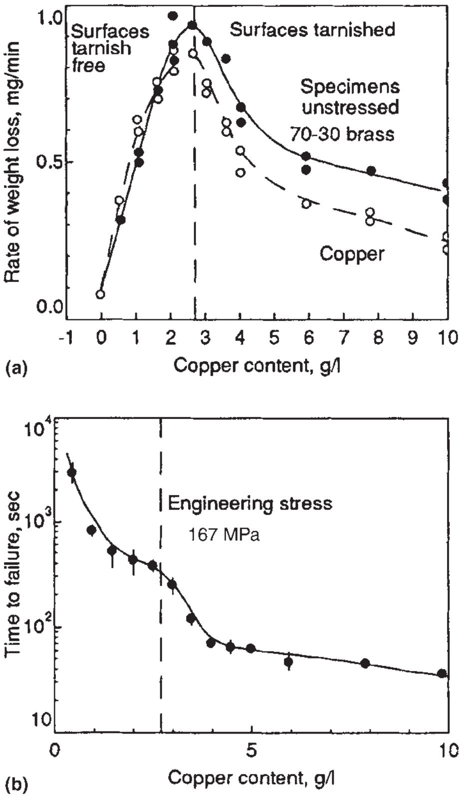

Fig. 2 Relationship between the concentration of dissolved copper in ~ 15 *N* aqueous ammonia and (a) rate of weight loss of unstressed specimens of copper and 70-30 brass and (b) time to failure (t_F) for 70-30 brass. Source: Ref 16

Table 1 Environments reported to cause SCC of copper-base alloys

Alloy	Environment	Ref
β-brass	Deionized water	2
70-30 brass	Sodium chlorate, $NaClO_3$	3
Aluminum brass	Acidic chloride	4
Aluminum bronze	Sodium fluoride, NaF	5
α-brass	Aliphatic amine	6
	Ammonium sulfate, $(NH_4)_2SO_4$	7
Brass	Mercury salts, e.g., $HgNO_3$	8
	Mattsson's solution, $(NH_4)_2SO_4$ + $CuSO_4$	9
	Outdoor environment	10
	Sodium nitrite, $NaNO_2$	11
	Citrates and tartrates	12
	Moist sulfur dioxide, SO_2	13
	Sulfate solution, SO_4^{-2}	14
	Aqueous ammonia	Various
Yellow brass	Sodium sulfate, Na_2SO_4, + borate	15
	Na_2SO_4 + sodium sulfide, Na_2S	15

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The chemistry/electrochemistry of the copper-ammonia system has been studied extensively and is reasonably well understood. It has been reviewed in detail elsewhere (Ref 18, 19) and is summarized below. On a copper surface, the primary reduction reaction in aerated, copper-free aqueous ammonia is oxygen reduction, and the primary oxidation reaction is oxidation of copper to form cuprous complex ions:

$$Cu + 2NH_3 \rightarrow Cu(NH_3)_2^+ + e^-$$

These ions react with oxygen to form cupric complex ions:

$$2\ Cu(NH_3)_2^+ + \tfrac{1}{2}\ O_2 + H_2O + 4\ NH_3 \rightarrow 2\ Cu(NH_3)_4^{+2} + 2\ OH^-$$

In oxygenated solutions, copper in solution exists primarily as the cupric complex ion. The exchange current for cupric ion reduction is much greater than that of oxygen reduction, and thus cupric ion reduction is the dominant reaction in copper-containing solutions. The overall process is autocatalytic in that the corrosion reaction generates more cuprous ions in solution, which subsequently form cupric ions, which in turn accelerate the rate of corrosion. This process does not continue indefinitely, because the onset of tarnishing, which occurs at some critical copper ion content, leads to a decrease in the corrosion rate, as shown in Fig. 2. On the other hand, Fig. 2 also shows that the severity of cracking continues to increase with increasing copper content in the tarnishing range.

Based on research on the chemistry of ammonia solutions, it can be concluded that failures in the field occur under very aggressive conditions in that the condensed layer of moisture can contain very high copper-ion concentrations due to the large ratio of metal surface area to solution volume. Oxygen access to the solution is also facilitated by the thin condensed layer, leading to rapid development of high concentrations of the cupric complex ion.

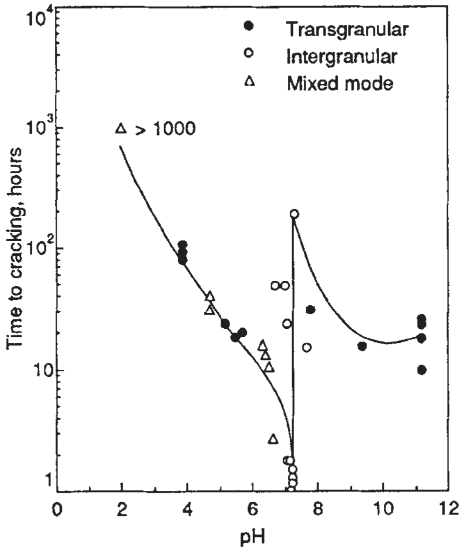

Fig. 3 Time to cracking as a function of the pH for brass in ammoniacal copper sulfate solutions (Mattsson's solutions). Note that the specimen tested at pH of 2 did not fail in 1000 h of testing. Source: Ref 9

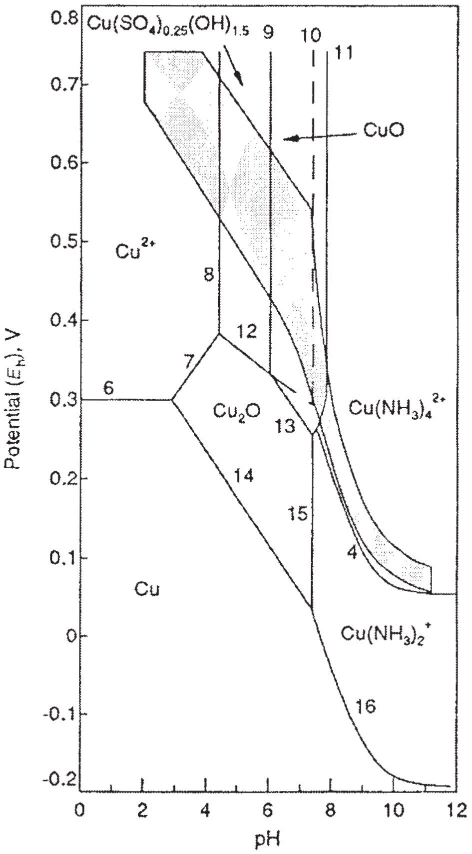

Fig. 4 Potential/pH diagram for a system of copper and a water solution with 1.0 g · mol/L of ammonia partly as ammonium sulfate and 0.05 g · atom/L of dissolved copper added as sulfate at 25 °C (77 °F). Numbers refer to equations from Ref 9. The shaded zone marks solution properties at the beginning of the tests. Source: Ref 9

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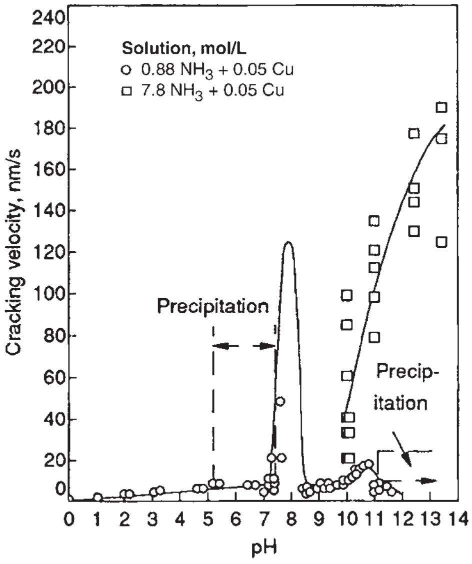

Fig. 5 Effect of pH on average stress-corrosion cracking velocity of brass specimens tested in two ammoniacal solutions. Source: Ref 22

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Effect of Solution pH. The majority of research on pH effects on SCC of copper-base alloys has been performed in ammonia-bearing environments referred to as "Mattsson's solution." Relatively little research has been performed in nonammoniacal environments. In the original milestone work performed by Mattsson (Ref 9), the effect of pH on the SCC and film-forming characteristics of Cu-37Zn was studied in ammoniacal copper sulfate solutions. The pH of the solutions was varied by adding the ammonia partly as ammonium hydroxide (NH_4OH) and partly as ammonium sulfate ($(NH_4)_2SO_4$); sulfuric acid was added to obtain the lowest pH solutions. All solutions had 0.05 M Cu and 1 M NH_3.

The SCC tests were performed on U-bend specimens machined from cold-rolled (half-hard) brass sheet stock. Specimens were exposed in stoppered flasks under freely corroding conditions. Within the flasks was a small air space above the test solutions. Time to failure as a function of pH is shown in Fig. 3, where it can be seen that a minimum existed at a pH of about 7.2. A majority of the cracks were transgranular in the pH ranges of 3.9 to 5.7 and 7.8 to 11.2, whereas cracking was primarily intergranular in the pH range of 6.3 to 7.7. In the latter pH range, a black surface film was found on the specimens. Mattsson measured the redox potential of the solutions with a platinum electrode prior to testing and related the potential and pH of the solutions on a Pourbaix diagram for the copper-ammonia system (Fig. 4). The shaded zone in Fig. 4 indicates the properties of the test solutions. The tarnish films on the specimens in the intermediate-pH range were found to be composed primarily of Cu_2O by Mattsson (Ref 9) and subsequently by Hoar and Booker (Ref 20) and by Johnson and Leja (Ref 12).

Later studies by Lahiri (Ref 21), Bhakta and Lahiri (Ref 7), and Sparks and Scully (Ref 22) confirmed the pH effects on cracking susceptibility of brasses reported by Mattsson (Ref 9). Takemoto and Hori (Ref 23) also reported a similar dependence of cracking on pH for a Cu-4Ti alloy. In the study by Sparks and Scully (Ref 22), the research was extended to consider annealed and cold worked 70-30 brass and higher-pH concentrated ammonia solutions. Testing was performed on single-edge notched cantilever-beam specimens initially loaded to a K value of 35 MPa $\sqrt{m}$ (32 ksi $\sqrt{in.}$).Results, summorized in Fig. 5, show that the high-pH concentrated solutions also produced extensive cracking, with cracking velocity increasing with increasing pH. One difference in the results of the studies of Mattsson (Ref 9) and Sparks and Scully (Ref 22) was in the fracture mode. In the latter study, cracking was primarily intergranular (with some transgranular) at all but the highest pH values tested, whereas Mattsson reported intergranular cracking only at intermediate pH values.

A limited amount of research on the effects of pH on SCC of copper-base alloys has been performed in nonammoniacal environments. Shih et al. (Ref 5) investigated the SCC of aluminum bronze in sodium fluoride solutions with pHs of 8,10, and 12 and found the most severe cracking at pH 8. Torchio (Ref 24) and Torchio and Mazza (Ref 25) investigated the effect of pH on SCC of aluminum brass in acidic chloride and sulfate solutions, respectively. In the former study, cold worked U-bend specimens were exposed in 1 *M* NaCl + 0.25 *M* sodium citrate solutions with 0.5 to 1.5 g/L CuCl and pHs of 1 to 6. Maximum susceptibility to SCC was observed between a pH of 3 and 4 and for the highest copper content.

In the study by Torchio and Mazza (Ref 25), U-bend specimens were exposed to 0.1 *M* Na_2SO_4+0.005 *N* Cl^- with varying $CuSO_4$ concentrations and pHs. Results, summarized in Fig. 6, show that maximum cracking occurred at pH 3 at the highest $CuSO_4$ concentration tested. An interesting aspect of this study is that intergranular SCC, which occurred at pH values below 3, was associated with nontarnishing conditions, while transgranular cracking occurred in tarnishing solutions above pH 3. This behavior is opposite to that observed in Mattsson's and other ammoniacal solutions, where intergranular SCC is normally associated with tarnishing conditions.

Effect of Potential. Researchers have investigated the effect of potential on the SCC of copper-base alloys in ammoniacal environments as well as in other environments that cause cracking. In the former, studies have been performed both in concentrated aqueous ammonia and in Mattsson's solution. Pugh and Green (Ref 17) studied the effect of applied potential on the time to failure of Cu-30Zn in copper-free 15 *M* aqueous ammonia. The data, summarized in Fig. 7, show that cracking susceptibility increased with increasing anodic polarization, as did the dissolution rate of the specimens. No cracking was observed at the free corrosion potential. In these tests, the specimens were tarnish free and the failure mode was transgranular. Based on this work, it was concluded that the role of the cupric complex ion in solution, which promotes SCC, is to anodically polarize the specimen. Tong (Ref 26) observed similar behavior for Cu-30Zn specimens tested under constant-load conditions in a nontarnishing 1 *M* ammonia solution containing added copper. In these tests, the data exhibited maximum cracking susceptibility at an anodic overpotential of about 200mV, with failure times increasing with greater levels of anodic polarization.

Kermani and Scully (Ref 27) studied the effect of potential on the crack velocity of annealed Cu-30Zn in a 15 *N* ammonia solution containing 6 g/L of copper, which is a tarnishing solution. The tests were performed on notched cantilever-beam specimens at three different stress-intensity levels. Results (Fig. 8) are very similar to those reported by Tong (Ref 26) for constant-load specimens, with maximum susceptibility at an anodic overpotential. The rapid decrease in the cracking velocity at more noble potentials was attributed to the onset of nontarnishing conditions. Cracking at all potentials was transgranular.

Several researchers have investigated the effect of applied potential on SCC of copper-base alloys in Mattsson's solution. As previously described, Mattsson's solution is an aqueous 1 *M* $(NH_4)_2SO_4$ solution containing dissolved copper added as $CuSO_4$. The pH of the solution is varied by adding the ammonia partly as NH_3 and partly as $(NH_4)_2SO_4$. Hoar and Booker (Ref 20) investigated the effect of potential on time to failure of α-brass wires in Mattsson's solution of pH 7.2, which is a tarnishing solution at the free corrosion potential (+0.15 to +0.25 V (standard hydrogen electrode, or SHE)). They found that crack propagation was accelerated by some anodic polarization (up to 50 mV) and retarded by greater anodic polarization or by cathodic polarization.

Surcar et al. (Ref 28) performed constant-load tests on annealed Cu-30Zn specimens in Mattsson's solutions of varying copper concentration as a function of applied potential. Results (Fig. 9) show behavior similar to that observed by Hoar and Booker (Ref 20) and that in the ammonia solutions, with maximum susceptibility at an anodic applied potential. A fracture-mode transition from intergranular to transgranular was observed with increasing applied anodic potential. The data in Fig. 9 also suggest that the potential range over which cracking occurred narrowed with decreasing copper content of the solution, although the potential of maximum cracking was unaffected.

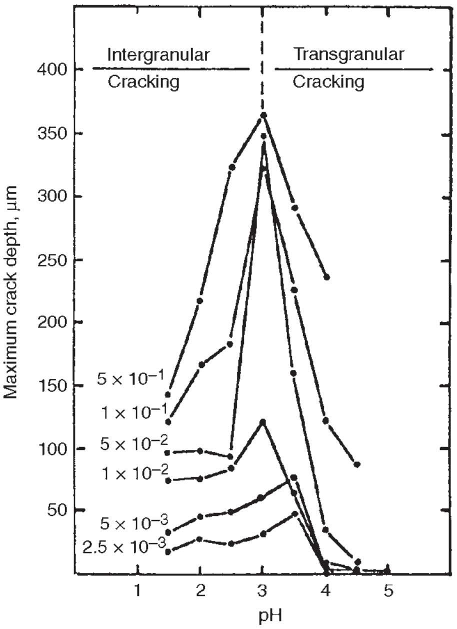

Fig. 6 Maximum crack depth as a function of pH and $CuSO_4$ content measured on U-bend specimens exposed to 0.1 *M* Na_2SO_4 + 0.005 *N* Cl^-. Data to the left of the curves refer to the $CuSO_4$ molar concentration. Test time = 240 h. Source: Ref 25

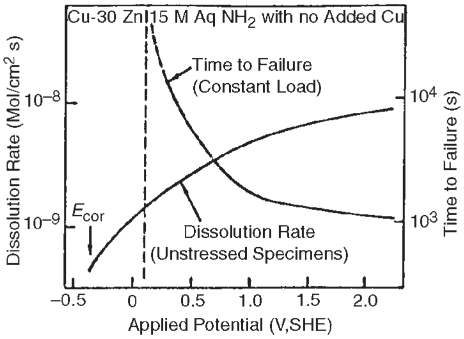

Fig. 7 Effect of applied anodic potentials on the dissolution rate and stress-corrosion life of Cu-30Zn in 15 *M* aqueous ammonia. Specimens were tarnish-free in all cases, and SCC failure was entirely transgranular. Source: Ref 17

Alvarez et al. (Ref 29), Gouda et al. (Ref 30), and Yu and Parkins (Ref 31) investigated the effect of potential on SCC of copper-base alloys in sodium nitrite solutions. All three studies

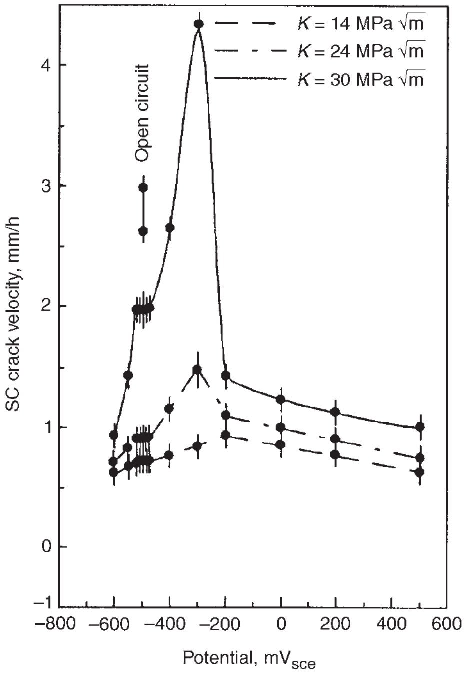

Fig. 8 Effect of potential and stress intensity, *K*, on crack velocity of α-brass in 15 *N* aqueous ammonia containing 6 g/L Cu. Source: Ref 27

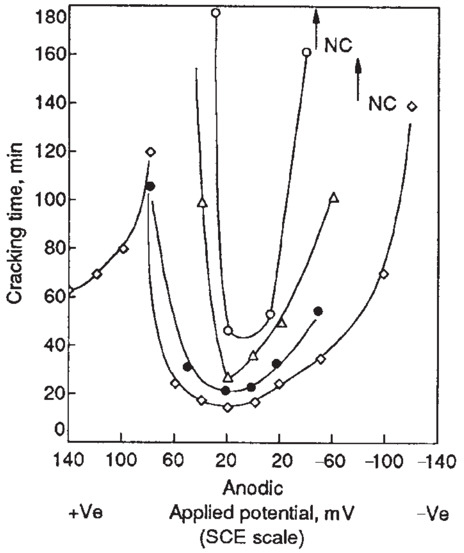

Fig. 9 Effect of applied potential on the time to fracture of α-brass in Mattsson's solutions of pH 7 containing 1 g · mol/L NH_4^+ and different compositions of dissolved copper. Stress = 128 MPa (19 ksi). NC, no cracking. Source: Ref 28

found that anodic polarization from the free corrosion potential accelerated cracking, while cathodic polarization retarded cracking. Both Alvarez et al. (Ref 29) and Yu and Parkins (Ref 31) observed some diminution of cracking at very noble potentials, which was attributed to excessive general corrosion of the specimen. Data by Alvarez et al. for annealed yellow brass tested by a slow-strain-rate technique in 1 *M* $NaNO_2$ are presented in Fig. 10. In the tests, the free corrosion potential was about 0 V (normal hydrogen electrode, or NHE) and the fracture mode was transgranular.

The effect of potential on SCC of α-brass also has been investigated in solutions of sodium chlorate (Ref 3), sodium sulfate (Ref 15), and aliphatic amine (Ref 6). Shih et al. (Ref 5) studied the effect of potential on the SCC of aluminum bronze in sodium fluoride solutions. In all of these environments, anodic polarization of the material promoted cracking, while cathodic polarization retarded cracking. A significant difference among the different alloy/environment systems is in the behavior at the free corrosion potential. For example, α-brass readily cracked at the free corrosion potential in the aliphatic amine solution, while aluminum bronze cracked in the sodium fluoride solution only under anodic polarization. Slight cracking was observed for a brass in aqueous sodium chlorate at the free corrosion potential; cracking was greatly accelerated by anodic polarization.

Effect of Temperature. In general, the temperature dependence of SCC of copper-base alloys appears to follow Arrhenius-type behavior. Data by Suzuki and Hisamatsu (Ref 32) for pure copper and several copper-zinc alloys in a dilute ammonium hydroxide solution over a temperature range of 40 to 70 °C (104 to 158 °F) are given in Fig. 11. The tests were performed under constant load at the free corrosion potential. Yu and Parkins (Ref 31) also observed Arrhenius behavior in slow-strain-rate tests performed on Cu-30Zn in a sodium nitrite solution. The tests were performed at –0.1 V (saturated calomel electrode, or SCE) over a temperature range of 20 to 100 °C (68 to 212 °F) at a strain rate of about 7 × 10^{-4}/s. However, at a slower strain rate, non-Arrhenius-type behavior was observed, with a maximum cracking velocity at an intermediate temperature (see Fig. 12). The behavior observed at the slower strain rate was attributed to a change in the rate-controlling process over the temperature range studied.

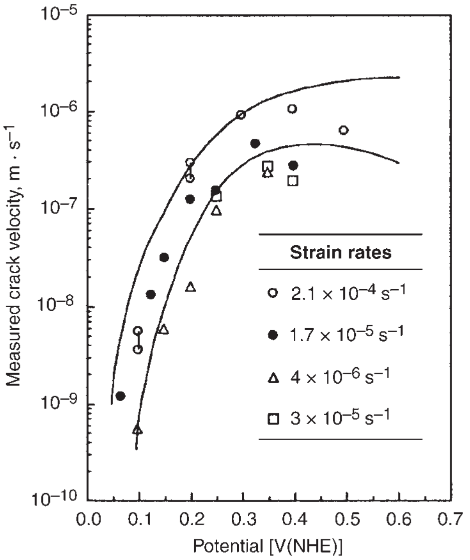

Fig. 10 Effects of potential and strain rate on crack-velocity values measured for yellow brass in deaerated 1 *M* $NaNO_2$ solution. Continuous lines show the crack-velocity values predicted by fast-strain-rate experiments. Source: Ref 29

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Takano (Ref 33) investigated the effects of crosshead speed and temperature on the SCC of Cu-30Zn in Mattsson's solution of pH 7.2. Slow-strain-rate testing was performed over a temperature range of 25 to 50 °C (77 to 122 °F). It was found that at high crosshead speeds (above 10^{-3} mm/min), cracking susceptibility increased with increasing temperature; however, susceptibility decreased with increasing temperature at slower crosshead speeds. This behavior was attributed to the interplay between the corrosion rate and the creep rate at the crack tip. In any case, the findings are qualitatively similar to those of Yu and Parkins (Ref 31).

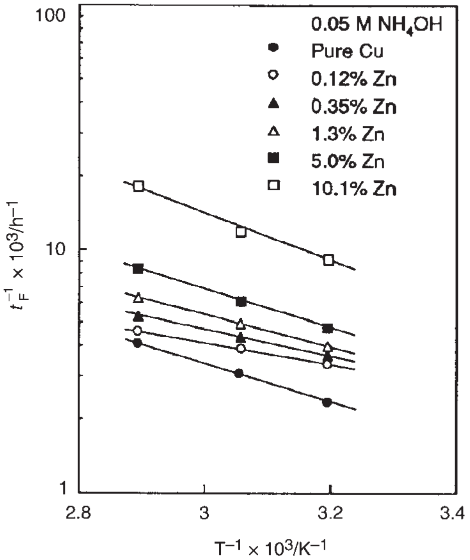

Fig. 11 Arrhenius plot of reciprocal of time-to-failure (t_F^{-1}) for specimens tested under constant load in 0.05 *M* NH_4OH solution. Source: Ref 32

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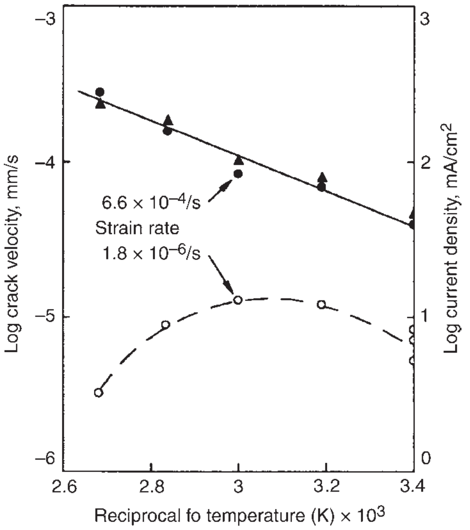

Fig. 12 Effects of temperature and strain rate on cracking velocity of α-brass in 1 *M* $NaNO_2$. Also shown is the maximum current density from rapid straining tests at different temperatures. Source: Ref 31

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Metallurgical Effects

Effects of Alloy Composition. Most of the literature on SCC of copper-base alloys has been concerned with copper-zinc alloys in ammoniacal solutions. However, a number of other copper-base alloys are susceptible to SCC (see Table 2). In general, the susceptible alloys are solid-solution a-phase copper alloys containing other elements such as manganese, aluminum, and even gold. The rate and path of failure (intergranular or transgranular) depend on the nature of the solute and the environment.

Several researchers have investigated the effect of zinc content of binary copper-zinc alloys on SCC susceptibility in ammoniacal solutions (e.g., Ref 43, 44). Data from Ref 44, presented in Fig. 13, show that susceptibility to SCC in constant-load tests increased with increasing zinc content for both tarnishing and nontarnishing solutions. These data also show that the fracture-mode was intergranular for tarnishing solutions, while a fracture-mode transition from intergranular to transgranular occurred at approximately 15% Zn

Table 2 Copper-base alloys that have experienced SCC

Alloy	Environment	Ref
Pure copper	Ammonia	32
	Sodium nitrite	34
DHP copper	Sodium nitrite	35
OFHC copper	Sodium nitrite	35
Cu-Zn alloys	Ammonia	Many authors
Cu-10Mn	Mattsson's solution	Many authors
Cu-5Zn-5Mn	Mattsson's solution	36
Cu-5Zn-10Mn	Mattsson's solution	36
Cu-20Zn-5Ni	Mattsson's solution	36
Aluminum brass	Acidic chloride-citrate	37
Cu-2Be	Ammonia	38
Cu-4Ti	Ammonia	23
Cu-6Mn	Ammonia	39
Cu-12Mn	Ammonia	39
Cu-18Mn	Ammonia	39
Cu-4Al	Ammonia	39
Cu-8Al	Ammonia	39
Cu-Au	Aqua regia	40
	$FeCl_3$	40
	Ammonia	40
Cu-Al	Ammonia	41
Cu-Ga	Ammonia	41
Cu-Ge	Ammonia	41
Cu-Zn	Ammonia	41
	Water	2
Cu-Zn-Sn	Water	2
β-brass	Water	2
Cusil (Cu-72Ag)	Mattsson's solution	42

DHP, phosphorus-deoxidized, high residual phosphorus. OFHC, oxygen-free high conductivity (copper) for the nontarnishing solutions. This transition has been attributed to a change in the dislocation structure as solute addition increases.

While SCC susceptibility of copper-zinc alloys increases monotonically with increasing zinc content, susceptibility appears to reach a maximum with increasing alloy content for other α-phase copper alloys. Data showing the effect of aluminum and nickel on time to failure of binary alloys in moist ammonia are given in Fig. 14. The copper-zinc alloys also are more susceptible to SCC than the other binary alloys, as comparison of the data in Fig. 13 and 14 demonstrates.

The effects on SCC of minor alloy additions to copper-zinc alloys also have been investigated. Syrett and Parkins (Ref 45) studied the effects of tin and arsenic on the SCC of Cu-20Zn alloys in Mattsson's solutions of pH 7.3 and 11.3 and found that additions of both elements increased cracking resistance. These tests, like those described previously, were performed under freely corroding conditions. It also was observed that the alloy additions promoted a fracture-mode transition from intergranular to transgranular. The results were attributed to the effects of the solute on the passivation characteristics of the alloys, as opposed to a change in their stacking-fault energy. On the other hand, Torchio (Ref 24) found that additions of arsenic and phosphorus to aluminum brass decreased the SCC resistance of the alloy in an acidified citrate-chloride solution. The crack path was transgranular in the presence of arsenic, in agreement with the studies of Syrett and Parkins (Ref 45), but was intergranular when only phosphorus was present. Thus, alloying effects in copper-base alloys appear to be environment specific. This conclusion greatly complicates alloy selection for SCC resistance.

A significant finding of of SCC research on copper-base alloys over the past 20 years is that pure copper undergoes SCC (Ref 32, 34) (pure copper was long thought to be immune to cracking). Cracking was transgranular and was observed in sodium nitrite solutions. More recently, Cassagne et al. (Ref 46) have reported transgranular SCC of pure copper in sodium acetate solutions as well.

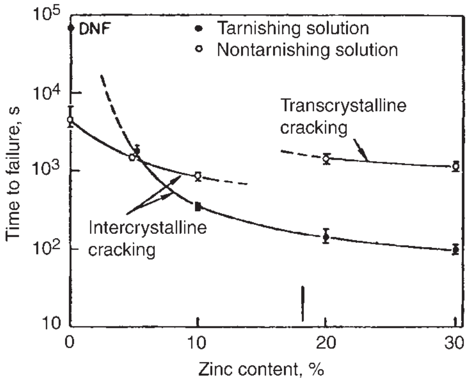

Fig. 13 Effects of zinc content on time to failure for specimens tested at 10% proof stress in tarnishing and nontarnishing ~ 15 *N* ammoniacal solutions containing 8 g/L Cu. DNF, did not fail. Source: Ref 44

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Effects of Microstructure and Heat Treatment. Relatively little research has been devoted to the effects of microstructure and heat treatment on SCC of copper-base alloys. This may reflect the fact that extensive thermomechanical processing is not normally performed on α-phase copper alloys for most engineering applications (in contrast to low-alloy steels and aluminum alloys). Several researchers have studied the effect of grain size on cracking susceptibility. Edmunds (Ref 47) evaluated the effect of grain size on time to failure of 70-30 brass specimens exposed to moist ammonia vapor under constant load. Results, shown in Fig. 15, indicate a monotonic decrease in time to failure with increasing grain size. In a later study by Birley and Tromans (Ref 48), the effect of grain size on the fracture stress of Cu-30Zn was evaluated by slow-strain-rate testing in Mattsson's solutions of pH 5.9 to 8. It was found that the fracture stress followed a Petch relationship:

$$\sigma_f = \sigma_o + KD^{-1/2}$$

where σ_f is fracture stress, σ_o and K are constants, and D is grain size, as shown in Fig. 16. The authors thus concluded that grain-size effects during SCC can be accounted for in terms of their effects on flow stress. In the pH 5.9 and 6.8 solutions, the onset of cracking occurred at plastic strains of about 7 and 4.5%, respectively, which were independent of grain size. In the pH 8 solution, the plastic strain necessary for crack initiation increased with decreasing grain size. This behavior is reflected by the largest slope in Fig. 16, compared to the slopes observed for the lower-pH solutions or for the Petch relationship.

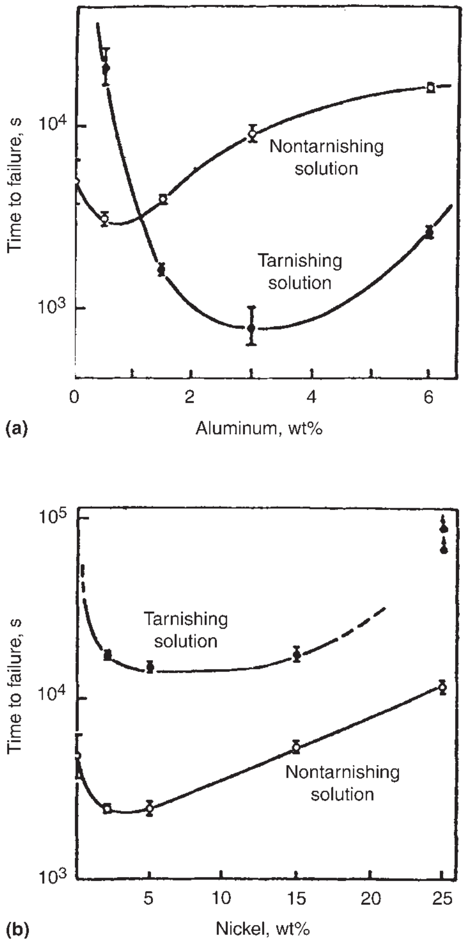

Fig. 14 Effect of aluminum content (a) or nickel content (b) on time to failure of copper-base alloys tested in tarnishing and nontarnishing ~15 *N* aqueous ammonia containing 8 g/L Cu. Source: Ref 44

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More rescently, Yu et al. (Ref 49) evaluated the effect of grain size of 70-30 brass on the initiation of SCC in a sodium nitrate solution by means of the slow-strain-rate technique. The findings were similar to those reported by Birley and Tromans (Ref 48), with the stress for crack initiation following a Petch-type relationship. The plastic strain at crack initiation was about 1% and increased slightly with decreasing grain size.

Popplewell et al. (Ref 50) investigated the effects of postforming heat treatments on the SCC susceptibility of cold-worked specimens of four copper-base alloys (C23000, C61900, C63800, and C68800) in moist ammonia and in Mattsson's solution (pH 7.2). Short-term (30 min) heat treatments were performed over a temperature range of 120 to 315 °C (250 to 600 °F) on preformed U-bend specimens, which were subsequently stressed elastically (under constant deflection) and exposed to the cracking environments. This sequence of forming and heat treating was designed to simulate service conditions where a component is formed and stress-relieved. For red brass alloy C23000 (85Cu-15Zn), the heat treatments reduced cracking susceptibility by reducing the residual stress. For the remaining three alloys, SCC susceptibility of heat-treated specimens was influenced by competing processes: stress relief, which reduced SCC susceptibility, and ordering, which increased susceptibility. For aluminum bronze alloy C63800 (95Cu-2.8Al-1.5Si-0.25Co) and alloy C68800 (73.5Cu-22.7Zn-3.4Al-0.4Co), optimum temperature ranges for heat treating were identified; for aluminum bronze alloy C61900 (86.5Cu-4Fe-9.5Al), cracking susceptibility increased with increasing annealing temperature.

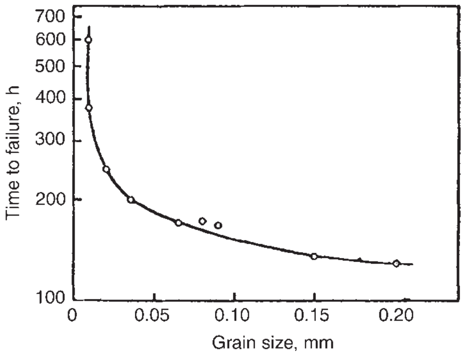

Fig. 15 Effect of grain size on time to failure of 70-30 brass tested in moist ammonia vapor. Source: Ref 47

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Scully (Ref 51) evaluated the effects of annealing and crosshead speed on the SCC of 70Cu-30Zn in an ammoniacal cupric sulfate solution of pH 6.8. The as-received material had a Vickers hardness of 115 and a 0.1% proof stress of 275 MPa (39.9 ksi), while the annealed material had a Vickers hardness of 86 and a proof stress of 205 MPa (29.7 ksi). The cracking velocity of the as-received material was found to be nearly an order of magnitude higher than that of the annealed material over a broad range of crosshead speeds. This effect may not be attributable to residual stresses, because the material is plastically deformed in slow-strain-rate testing.

Mazza and Torchio (Ref 37) evaluated the effects of a sensitization heat treatment and the phosphorus and arsenic content of an aluminum brass on SCC susceptibility in an acidic chloride-citrate solution. The sensitization heat treatment consisted of annealing 50% cold-rolled sheet at 600 °C (1110 °F) for 15 min, then sensitizing the specimens at 350 °C (660 °F) for 30 min. The heat treatment was optimized for sensitization by means of exposure tests performed on unstressed specimens in acidic synthetic seawater, followed by metallographic examination for intergranular attack. The SCC tests were performed under constant load, and time to failure was recorded. It was found that phosphorus and arsenic had a dominant effect on SCC susceptibility but that the sensitization heat treatment increased susceptibility to cracking at a given alloy composition. The authors speculated that the increased susceptibility may have resulted from ordering, as was concluded by Popplewell et al. (Ref 50).

Effect of Cold Work. It is well established that residual stresses introduced into components by cold forming can increase susceptibility to SCC. The SCC failure of brass electrical connectors in an outdoor environment, reported in Ref 10, is a good practical example of this type of failure. The heads on the connectors were formed by cold forging, which led to rapid failure in the field application. Previously, Landgren and Mattsson (Ref 52) had shown that cold-drawn Cu-37Zn cups failed by SCC in a rural environment, whereas annealed cups did not fail in 10 years under similar exposure conditions.

The effect of cold work on residual stresses described in the preceding paragraph should be distinguished from the effect of cold work on the inherent SCC susceptibility of copper-base alloys. Unfortunately, it is very difficult to separate these two factors experimentally, which may be one reason for the contradictory literature on this subject. This problem of contradiction is probably best exhibited by the work of Erzurum and Yeh (Ref 53), who studied SCC of free-cutting brass alloy C36000 (Cu-37Zn-3Pb). This alloy contains some β-phase in addition to lead precipitates. Stress corrosion cracking testing was performed in concentrated ammonia, preconcentrated with copper, using slow-strain-rate and constant-load techniques. In the slow-strain-rate tests, SCC susceptibility increased in the liquid phase but decreased in the vapor phase with increasing cold work. In the constant-load tests, susceptibility to SCC decreased with increasing cold work for both vapor and liquid exposures (see Fig. 17 and 18). With both test techniques, cracking was transgranular and susceptibility was greater in the vapor phase. The authors attributed the cold-work effect in the constant-load tests and in the slow-strain-rate tests in the vapor phase to the preferred orientation imparted during cold working. The contradictory results found for the slow-strain-rate tests performed in the liquid phase were attributed to a change in the rate-limiting step for cracking as a result of the less aggressive nature of the test solution compared to the vapor.

Scully (Ref 51) reported results for slow-strain-rate tests on Cu-30Zn in an ammoniacal solution of pH 6.8 that were similar to those reported by Erzurum and Yeh (Ref 53). Over a broad range of strain rates, the as-received material, which was cold worked, exhibited higher cracking velocities than the annealed material. The cracking mode was transgranular.

Sircar et al. (Ref 6) studied the SCC of Cu-32Zn in methyl amine solution containing dissolved copper over a range of potentials, using a constant-load test technique. Results of the study, summarized in Fig. 19, show that the annealed material was more susceptible to cracking than the cold-worked material, which is qualitatively similar to results obtained by Erzurum and Yeh (Ref 53) for concentrated ammoniacal solutions. Figure 19 also reveals that the potential at maxi-

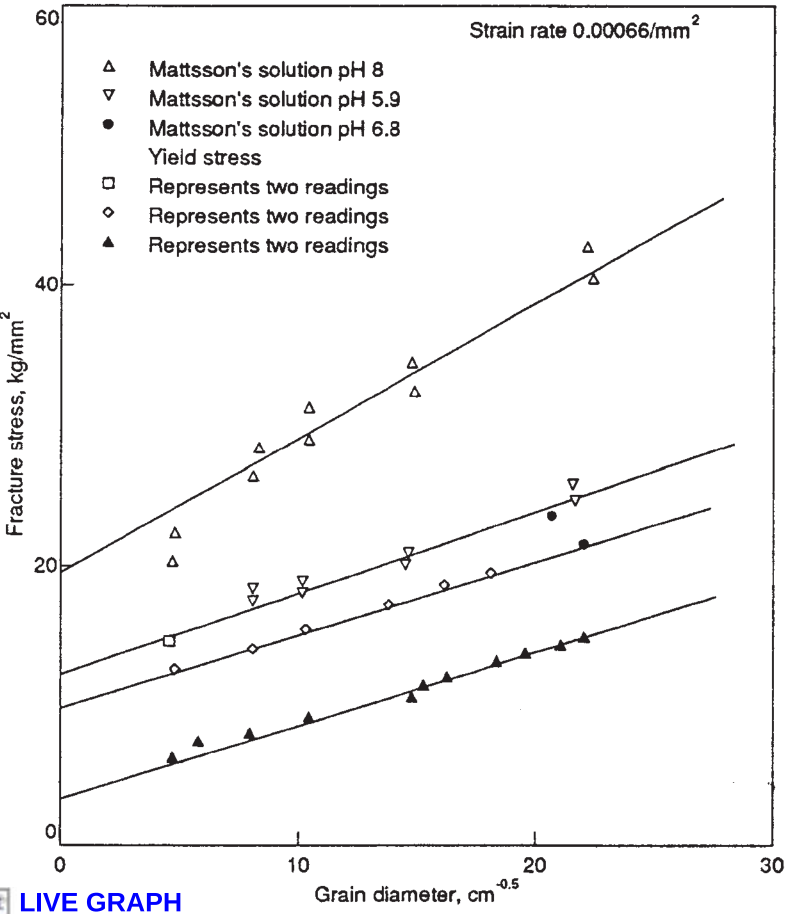

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Fig. 16 Effects of grain diameter and solution pH on the stress required to initiate cracking of α-brass in Mattsson's solution in slow-strain-rate tests. Source: Ref 48

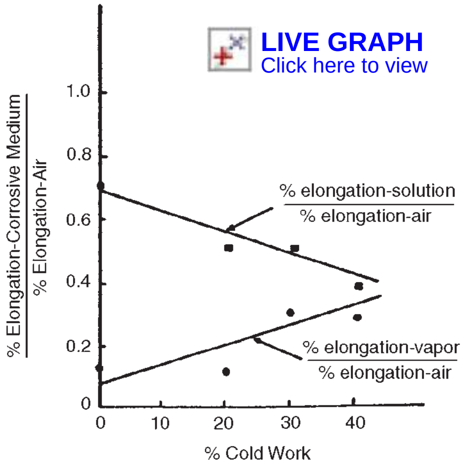

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Fig. 17 Effect of percent of cold work and phase (solution and vapor) on elongation of alloy C36000 in 15 *N* aqueous ammonia containing 6 g/L dissolved copper in slow-strain-rate tests (1.6×10^{-5}/s). Source: Ref 53 mum susceptibility is somewhat more positive for the cold-worked material.

Mechanical and Geometrical Effects

Effects of Stress and Stress Intensity. Several researchers have investigated the relationship between engineering stress and time to failure of copper-zinc alloys in ammoniacal environments. Typical data by Pugh et al. (Ref 44) are presented in Fig. 20. These data suggest that a threshold, below which cracking does not occur, is not present. However, the data do indicate two distinct slopes. Hoar and Booker (Ref 20) have suggested that the change in slope occurs at the flow stress of the material.

The total time to failure of a specimen, represented y the data in Fig. 20, contains both initiation and propagation stages of cracking. McEvily and Bond (Ref 54) studied the crack-propagation stage of cold-rolled Cu-30Zn in Mattsson's tarnishing solution of pH 7.2. Sheet specimens containing center through-notches were tested under various constant loads, and crack growth was measured optically. Results (Fig. 21) indicate a relationship of the form:

$$\frac{dl}{dt} = A\sigma_g^2\, l = B\, K^2$$

Over a wide range of crack velocities, where l is one-half the crack length, σ_g is the maximum applied gross cross-section stress, t is test time, and A and B are constants. This equation is valid for slope 2 in Fig. 21. As indicated by the above equation, the parameter $\sigma_g\sqrt{l}$ is proportional to the stress intensity (K) at the crack tip.

Beavers (Ref 55) studied the effect of stress intensity on crack growth in annealed admiralty brass in a 15 N tarnishing ammoniacal solution. Testing was performed on single-edge notched tensile specimens under constant load.

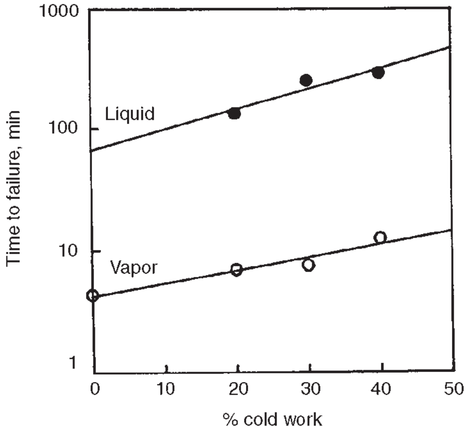

Fig. 18 Effect of percent of cold work and phase (solution and vapor) on time to failure of α-brass in 15 *N* aqueous ammonia containing 6 g/L dissolved copper in constant load tests at 50% of the yield strength. Source: Ref 53

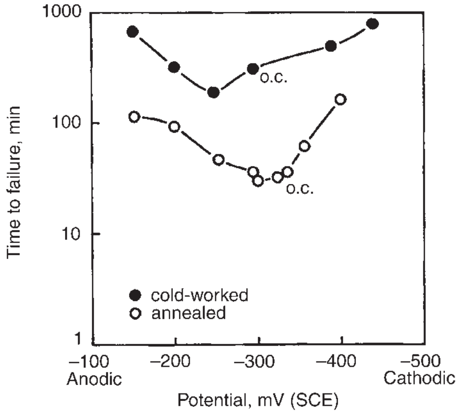

Fig. 19 Effect of potential and cold work on time to failure of α-brass in 2.2 g · mol/L methyl amine at pH 12.5 tested under constant load. o.c., open-circuit condition. Source: Ref 6

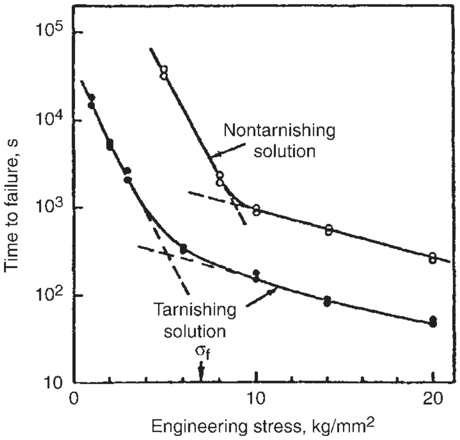

Fig. 20 Influence of engineering stress on time to failure of 70-30 brass tested in tarnishing and nontarnishing ~15 *N* aqueous ammonia containing dissolved copper. Source: Ref 44

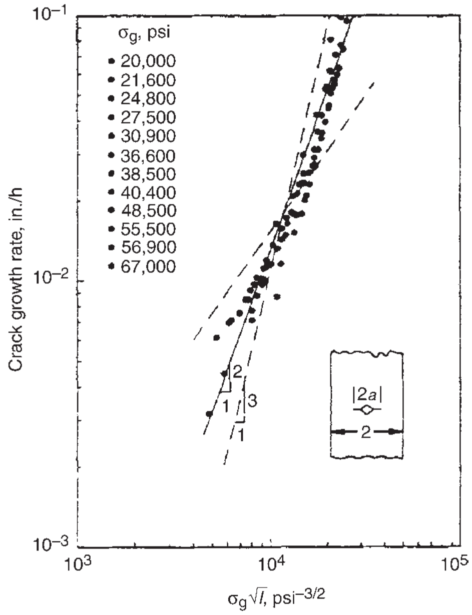

Fig. 21 Rate of stress-corrosion crack propagation in cold-rolled brass exposed to 0.05 *M* $CuSO_4$ + 0.48 *M* $(NH_4)_2SO_4$ (pH 7.25). Source: Ref 54

Results, summarized in Fig. 22, show the classical three stages of cracking: stage 1, at low values of stress intensity (low values of $P\sqrt{l}$), where crack velocity is dependent upon stress intensity; stage 2, where crack velocity is independent of stress intensity; and stage 3, where crack velocity is again stress-intensity dependent. Note that $P\sqrt{l}$ is proportional to K. In such a curve, K_{ISCC} is defined as the highest value of K at which measurable cracking was not observed. In the study by Beavers (Ref 55), crack branching occurred in stage 2. This is typical and is attributed to the fact that the rate-limiting process is independent of stress or stress intensity. The onset of stage 3 cracking is associated with general yielding of the specimen, which was the case in this study. Comparison of these results with those previously reported by McEvily and Bond (Ref 54) suggests that the data in Fig. 21 represent stage 3 cracking.

Kermani and Scully (Ref 27) investigated crack growth in edge-notched cantilever-beam specimens of Cu-30Zn in 15 *N* ammoniacal solutions and observed behavior similar to that reported by Beavers (Ref 55), although their testing did not provide stage 1 data. It was found that the crack-growth rates were a function of solution composition and applied potential. Typical data are presented in Fig. 23.

SCC Test Methods

Standard stress-corrosion test methods are commonly used to study SCC of copper-base alloys. These include constant-strain techniques (employing C-ring, U-bend, and bent-beam specimens), constant-load techniques, slow-strain-rate techniques, and fracture-mechanics techniques (see Table 3). Applicable standards include:

- ASTM G 30, "Standard Practice for Making and Using U-bend Stress-Corrosion Test Specimens"

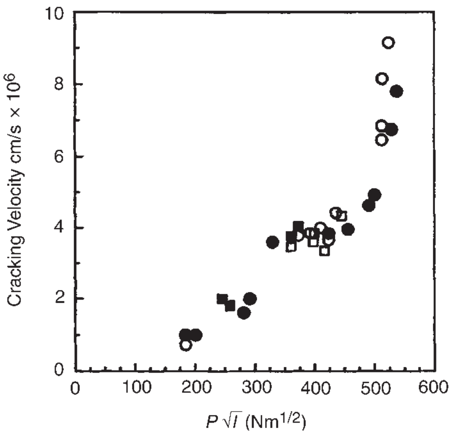

Fig. 22 Cracking velocity as a function of $P\sqrt{l}$, for notched tensile specimens tested in tarnishing 15 *N* aqueous ammonia. *P*, applied load: *l*, crack length. Different symbols indicate different specimens. Source: Ref 55

- ASTM G 38, "Standard Practice for Making and Using C-Ring Stress-Corrosion Test Specimens"
- ASTM G 39, "Standard Practice for Preparing and Using Bent-Beam Stress-Corrosion Test Specimens"
- ASTM G 49, "Standard Practice for Preparation and Use of Direct Tension Stress-Corrosion Test Specimens"
- ASTM G 58, "Standard Practice for Preparation of Stress-Corrosion Test Specimens for Weldments"
- ASTM G 129, "Standard Practice for Slow Strain Rate Testing to Evaluate the Susceptibility of Metallic Materials to Environmentally Assisted Cracking"

Specific standards for fracture-mechanics techniques for SCC testing are not available, but the test techniques used frequently follow the following two standards:

- ASTM E 399, "Standard Test Method for Plane Strain Fracture Toughness of Metallic Materials"
- ASTM E 616, "Standard Terminology Related to Fracture Testing"

Test Environments

A unique aspect of SCC testing of copper-base alloys is the test environment. As described earlier in this article, Mattsson's solution is widely used as a testing medium as are other ammoniacal solutions. These and others are discussed in the following paragraphs.

Testing in Mattsson's Solution. Procedures for the preparation of Mattsson's solution are described in ASTM G 37, "Standard Test Method for Use of Mattsson's Solution of pH 7.2 to Evaluate the Stress-Corrosion Susceptibility of Copper-Zinc Alloys." According to ASTM G 37, a stressed test specimen must be completely and continuously immersed in an aqueous solution containing 0.05 g-atom/L of Cu^{2+} and 1 g-mol/L of ammonium ion (NH_4^+) with a pH of 7.2. The copper is added as hydrated copper sulfate, and the NH_4^+ is added as a mixture of ammonium hydroxide and ammonium sulfate. The ratio of the latter two compounds is adjusted to achieve the desired pH.

Mattsson's pH 7.2 solution is recommended only for brasses (copper-zinc base alloys). This test environment may give erroneous results for other copper alloys and is not recommended. This is particularly true for alloys containing aluminum or nickel.

This test environment is believed to provide an accelerated ranking of the relative or absolute degree of susceptibility to SCC for different brasses. The test environment correlates well with the corresponding service ranking in environments that cause SCC, which may be due to the combined presence of traces of moisture and ammonia vapor. The extent to which the accelerated ranking correlates with the ranking obtained after long-term exposure to environments containing corrodents other than ammonia is not known. Such environments may be severe marine atmospheres (chloride), severe industrial atmospheres (predominantly sulfur dioxide), or superheated ammonia-free steam.

It is currently not possible to specify a time to failure in Mattsson's pH 7.2 solution that corresponds to a distinction between acceptable and unacceptable SCC behavior in brass alloys. Such correlations must be determined on an individual basis.

Mattsson's pH 7.2 solution may also cause some stress-independent general and intergranular corrosion of brasses. Therefore, SCC failure may possibly be confused with mechanical failure induced by corrosion-reduced net cross section. This is most likely with small cross-sectional specimens, high applied stress levels, long exposure times, and SCC-resistant alloys. Careful metallographic examination is recommended for accurate determination of the cause of failure. Alternatively, unstressed control specimens can be exposed to corrosive environments in order to determine the extent to which stress-independent corrosion degrades mechanical properties.

Other Testing Media (Ref 66). The most widely used SCC agent for copper and copper alloys is ammonia (NH_3). The NH_4^+ ion does not appear to cause cracking in a stable salt, such as ammonium sulfate. Cracking will occur in a salt that dissociates (such as ammonium carbonate) to form ammonia.

The $Cu(NH_3)_x^{2+}$ ion (x is usually 4 to 5) is thought to be necessary to induce SCC in copper metals. Amine groups also cause cracking or are easily converted to ammonia. Amines and sulfamic acid also cause cracking. Dry ammonia does not cause SCC of brass, as demonstrated by the successful use of brass valves and gages on tanks of anhydrous ammonia.

Stress-corrosion cracking of copper metals in ammonia will not occur in the absence of oxygen or an oxidizing agent. Carbon dioxide is also a requisite. Therefore, air rather than pure oxygen is necessary, and, as a practical matter, moisture is essential. When other factors are favorable, a very small amount of NH_3 is sufficient to cause cracking. The controlling factor may, therefore, be moisture, because cracking may appear to be caused by the presence of a condensed moisture film.

Other than ammonia, the most effective agents for causing cracking are the fumes from nitric acid or moist nitrogen dioxide. Sulfur dioxide will also crack brass, but both maximum and minimum concentration limits exist. The

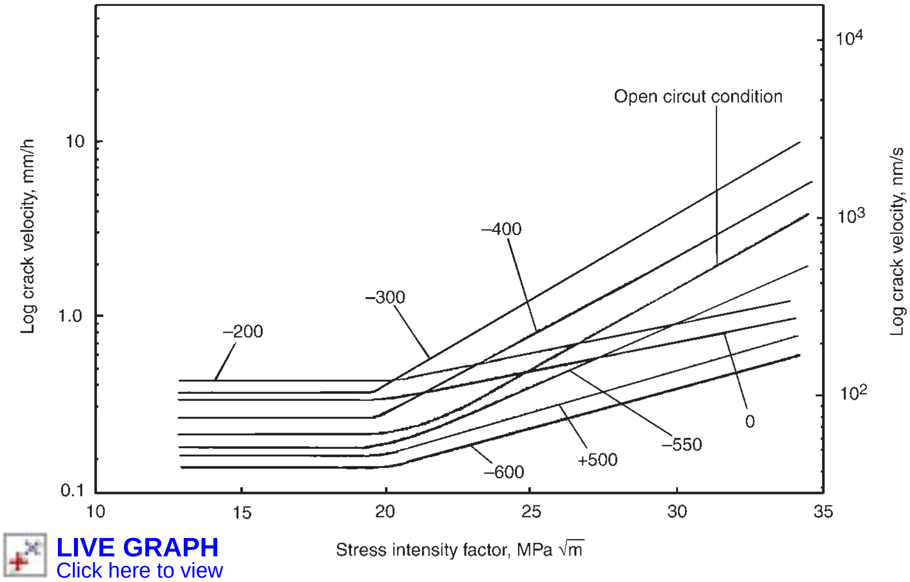

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Fig. 23 Effect of stress intensity *(K)* and potential on crack velocity of α-brass in aqueous 15 *N* ammonia containing 6 g/L Cu. Source: Ref 27

Table 3 Various techniques that have been used for the study of SCC of copper-base alloys

Technique	Alloy	Ref
Three-point bend	α-brass	56
	Aluminum bronze	57
C-rings	α-brass	58
	Aluminum brass	4
Constant load	C36000 brass	53
	α-brass	6,20,28,59
	Cu-Mn	39
	Cu-Al alloys	39
	70-30 brass	16,60
	Cu, Cu-Zn alloys	32
Constant strain	Cu-Zn-Sn alloys	45
Fracture mechanics	α-brass	54,61
	70-30 brass	22
Slow strain rate	70-30 brass and copper	31
	Brass	8
	C36000 brass	53
	70-30 brass	51,62
	Cu-30Zn	63
	Admiralty brass	64
	α-brass	14
	72-28 brass	3
	Yellow brass	15
	Cu-Ag eutectic	42
	Cu-Zn-Sn alloys	45
	Aluminum bronze	5
U-bend	α-brass	12
	Cu-Zn	36
	Cu-Zn-Mn	36
	Cu-Zn-Ni alloys	36
	Aluminum brass	4
	70-30 brass	65
	63-37 brass	9

reaction is slow. Alloy development studies have been conducted with a moist ammoniacal test atmosphere containing 80% air, 16% NH_3, and 4% water vapor at 35 °C (95 °F). However, none of these corrodents has received the attention that ammonia has garnered.

Historically, immersion of a copper alloy product in a mercurous nitrate solution has been used to test for residual stresses. Because these residual stresses are possible sources of failure by SCC in other environments, some have regarded this test as a stress-corrosion test. However, it is only an indirect method of identifying SCC tendencies and does not correlate to the presence of SCC as well as test methods based on specific attack by ammonia. It does indicate, however, that mercury and other low-melting liquid metals can cause embrittlement and failure due to cracking; that is, liquid metal embrittlement (LME).

Mitigation of SCC

Successful mitigation of SCC of copper-base alloys generally involves modifying one or more of the three primary factors associated with SCC: material susceptibility, the specific corrosive environment, and tensile stresses. These factors are shown graphically in Fig. 1. Elimination of any one of these factors will mitigate SCC. In the example of the season cracking of brass cartridge cases described in the introductory section of this article, it was found that the source of the cracking environment (ammonia) was the horses in the barns where the cartridge cases were stored. Storing them elsewhere mitigated the problem. Another example where elimination of a cracking environment helped to mitigate SCC involves copper refrigeration tubing. Occasional SCC failures occurred in insulated copper tubing used in commercial refrigeration systems. The root cause of the failure was found to be ammonia, which was a byproduct of the manufacturing process for the insulation. Limits were established for the acceptable level of ammonia in the insulation, and this appears to have lessened the problem.

In the example of season cracking, it was also found that the cold-forming operation used to make the cartridge cases introduced high residual tensile stresses and that annealing the cases after forming also eliminated the problem. Another example of reducing residual stresses to mitigate SCC is described by Han et al. (Ref 10). In this study, it was found that cold-worked brass electrical connectors failed in an outdoor environment unless properly stress-relieved. A mercurous nitrate solution is often used in industry as a quality-control test of copper-alloy articles for residual stresses. This environment promotes LME (from the mercury) if residual tensile stresses are present.

The third primary option for mitigating SCC is to change the alloy to one that is less susceptible to SCC in a given environment. An example of the application of this option is the SCC of brass condenser tubes in power plants. As reported by Beavers et al. (Ref 67), a measurable percentage of the failures of copper-alloy condenser tubes in the 1960s and 1970s occurred as a result of SCC. The air-removal section of the condenser is particularly prone to SCC as a result of the concentration of oxygen and ammonia on the steam side of the condenser. The most common method for lessening the SCC is to use a more cracking-resistant alloy, such as alloy C70600 (Cu-10Ni), for this section of the condenser.

It should be cautioned that mitigation of SCC of copper-base alloys by means of modifying one of the three primary factors may not always be as straightforward as the preceding discussion implies. For example, Fig. 20 suggests that there is no threshold stress below which SCC will not occur for 70–30 brass in aqueous ammonia. Thus, reducing the stress on a component may prolong its life but may not prevent SCC from ultimately causing failure. Changing to an alternate copper-base alloy may not be fully effective in mitigating SCC in some very aggressive cracking environments, since even pure copper may be susceptible to cracking. For these situations, a "belt and suspenders" approach may be prudent, modifying two or more of the primary factors simultaneously.

Cracking Mechanisms

Much of the research into SCC of copper-base alloys has focused on the mechanism of cracking, and a detailed discussion of this subject is beyond the scope of this article. Several balanced reviews on the topic have been written by Pugh et al. (Ref 19, 44, 68) and are summarized here. The reader is referred to these articles for further details.

The ammonia-brass system has dominated mechanistic studies of SCC of copper-base alloys (e.g., Ref 69). Such studies generally have been divided according to fracture mode: intergranular and transgranular. There is no consensus as to whether these modes correspond to two different mechanisms or whether there is a common mechanism; Pugh and his coworkers favor the former theory.

Intergranular SCC. The characteristics of intergranular SCC are generally considered to be consistent with the film-rupture mechanism proposed by Champion (Ref 70) and Logan (Ref 71). According to this mechanism, the crack initiates by film rupture as a result of plastic deformation at the crack tip. The crack propagates by localized anodic dissolution as repassivation is inhibited by further plastic deformation at the crack tip. The mechanism, as originally proposed, is essentially continuous, with the key elements being the repassivation behavior and the deformation behavior of the alloy/environment system. Characteristics of intergranular SCC of copper-zinc alloys that are consistent with the film-rupture mechanism include the association of cracking with a thin passive layer at the crack tip, the smooth nature of the intergranular fracture surfaces, and the absence of acoustic emission during crack propagation. In addition, based on Faraday's law, the observed cracking velocities are consistent with a dissolution process.

On the other hand, the originally proposed film-rupture mechanism was a transgranular mechanism, and the issue of crack mode has not been fully explained. It has been postulated that the grain-boundary repassivation is slow because of segregation, but the nature of the segregation has not been established. Moreover, intergranular SCC of brass has been observed in nontarnishing solutions, where the presence of a passive film has not been confirmed.

Transgranular SCC. Over the past 25 years, the mechanism of transgranular SCC in the ammonia-brass system has received considerable attention. Characteristics of this cracking mode that must be accounted for in the mechanism include its discontinuous nature, the cleavagelike appearance of the fracture surfaces, and the observation that cracking can occur in the absence of anodic dissolution. Beavers and Pugh (Ref 72) demonstrated that cracking in admiralty brass occurs on parallel 110 planes and that discrete pulses of acoustic emission are emitted during the cracking process. Several researchers have confirmed the presence of crack-arrest markings on the fracture surfaces, and Newman and Sieradzki (Ref 73) have observed discontinuous current transients during cracking. Bertocci et al. (Ref 62) first reported that cracking could occur in the absence of anodic dissolution, and this was later confirmed by others.

The dissolution models such as the film-rupture mechanism described previously are not consistent with the above characteristics and are not considered applicable to transgranular SCC. Similarly, models based on adsorption of a specific chemical species at the crack tip are generally thought to be continuous models and thus are not applicable. Other mechanisms that have been proposed include hydrogen embrittlement, cleavage of a thick tarnish (tarnish rupture) or a dealloyed layer, and film-induced cleavage (FIC). The tarnish-rupture model was discredited in the 1970s when it was shown that the thick tarnish does not extend to the crack tip. A model based on rupture of a dealloyed layer does not adequately explain transgranular SCC of pure copper. More recently, the hydrogen-embrittlement mechanism has been shown to be improbable based on thermodynamic considerations.

The FIC mechanism was first proposed by Sieradzki and Newman (Ref 74). According to this mechanism, the crack initiates and propagates in a brittle film on the metal surface. Traveling at a high velocity and on an orientation favorable for cleavage, the crack propagates some distance into the ductile metal prior to blunting. The major difference between this model and the tarnish-rupture model (or rupture of a dealloyed layer) is the propagation of the crack into the ductile matrix. For the brass-ammonia system, the brittle film is thought to be a copper-rich dealloyed layer. Newman et al. (Ref 75) demonstrated a key aspect of the model when they showed that the presence of a dealloyed layer on a Cu-30Zn sample could induce significant crack propagation (approximately 12 mm) in the bulk alloy. On the other hand, dealloying of copper-base alloys occurs in systems where cracking has not been observed, such as chlorides. Thus, the film apparently must possess other characteristics for SCC to occur. Moreover, SCC of pure copper suggests, at the least, that other types of films also may promote crack propagation in the ductile matrix, assuming the model is correct. Clearly, further research is needed to resolve these issues.

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Effect of Temperature on Properties

THE EFFECTS OF TEMPERATURE on mechanical properties are addressed in this article. Both low- and elevated-temperature property data are given. Information on the influence of temperature on the physical properties of coppers and copper alloys can be found in the final three articles of this Handbook covering properties of pure copper, wrought copper and copper alloys, and cast copper alloys.

Low-Temperature Properties

Copper and copper alloys retain a high degree of ductility and toughness at subzero temperatures (Ref 1–5). In fact, copper alloys become stronger and more ductile as the temperature goes down, and they retain excellent impact resistance to 20 K (–253 °C, or –424 °F). These properties, combined with good thermal conductivity, led to the widespread use of copper and copper alloys for heat exchangers and other components in cryogenic plants and in low-temperature processing and storage equipment. A shortage of the skilled welders required for fabricating copper equipment and the development of brazed aluminum equipment were factors that caused copper to be replaced by aluminum for many of these applications.

Current interest in the cryogenic properties of copper stems from its use as a thermal and electrical stabilizer in superconducting multifilament wires (see the article "Shape Memory Alloys and Composite Materials" in this Handbook). Copper's high thermal and electrical conductivities, combined with its excellent formability and reasonable cost, make it the best practical material for superconducting magnet applications. Corresponding interest in the cryogenic properties of copper-tin alloys is based on a manufacturing process for niobium-tin-based superconductors (Ref 6). Continuous filaments of superconducting Nb_3Sn are formed in situ by encapsulating pure niobium wires in a copper-tin bronze, then heating the composite to diffuse the tin from the bronze and react it with niobium.

Superconducting magnets operate under high mechanical stresses, and superconducting wire assemblies must resist these stresses to avoid distortion. Pure copper and copper-tin alloys can be strengthened by cold work or combinations of cold work and solid solution strengthening, respectively, but there are practical limits to the degree of strengthening obtainable. Very high strengths can be gained through combinations of cold work and age-hardening, and beryllium coppers, in which this strengthening method is especially efficient, have also been specified for use in high-field magnets. Regardless of the strengthening mechanism, high strength and high conductivity are difficult to achieve simultaneously, and a compromise between strength and conductivity is usually necessary.

Cryogenic properties of copper-base materials of interest to superconducting magnet designers have been extensively analyzed under a program sponsored jointly by the U.S. National Institute of Standards and Technology (NIST) and the International Copper Association, Ltd. (ICA). This study (Ref 7) also provides data on the effects of cryogenic temperatures on physical properties, including electrical resistivity, thermal conductivity, thermal expansion, specific heat, and magnetic susceptibility.

Tensile Properties. Data on the tensile properties of copper and copper alloys at subzero temperatures are summarized in Table 1. Supplementary data on values of Young's modulus for copper and two copper-nickel alloys, obtained by ultrasonic testing, are plotted in Fig. 1.

Many copper alloys have good strength, ductility, and notch toughness, even at liquid-helium temperature. Some have been used for valves and tubular fittings in cryogenic equipment. Both spring cold drawn alloy C51000 (phosphor bronze A) and the beryllium copper alloy C17200 in the HT condition are spring alloys. These alloys exhibit increases in yield strength and Young's modulus at very low temperatures, and thus their spring properties are better at cryogenic temperatures than at room temperature.

Impact Strength. The impact energy for the fracturing of notched specimens (Table 2) also remains at high levels for many copper-base materials at temperatures as low as 20 K (–253 °C, or –423 °F). These data represent average values from two or more tests on longitudinal specimens of the wrought product. Selected impact data are plotted in Fig. 2.

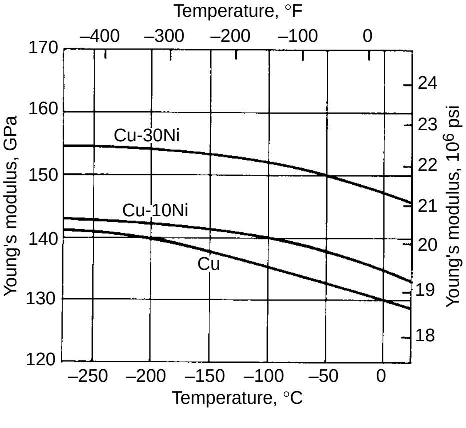

Fig. 1 Young's modulus for copper and two copper-nickel alloys as determined ultrasonically. Source: Ref 8

LIVE GRAPH
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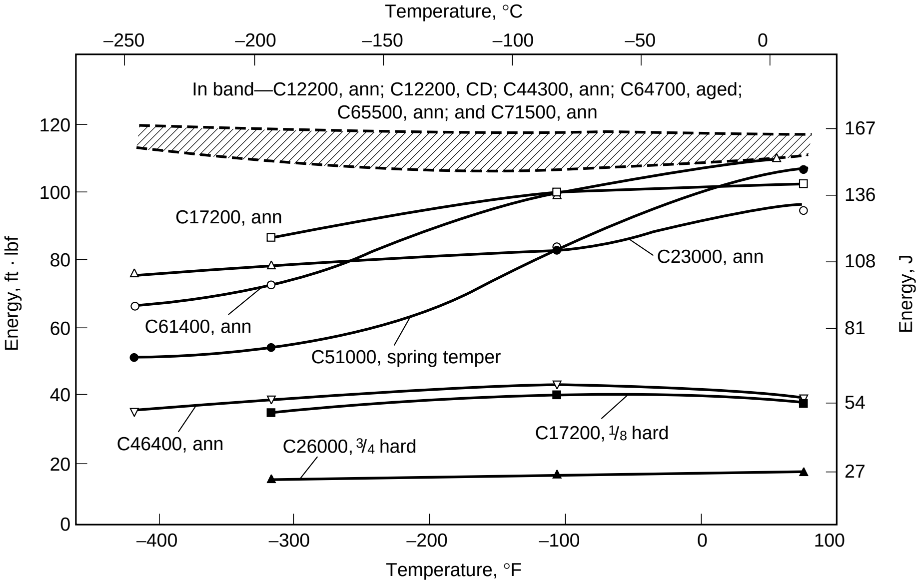

Fig. 2 Impact energy for Charpy specimens from bar stock. All specimens were V-notch, except for alloy C17200, which was U-notch. See also Table 2. Source: Ref 9

LIVE GRAPH
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The fatigue properties of copper and copper alloys also increase as the testing temperature is reduced to 20 K (–253 °C, or –423 °F) or 4 K (–269 °C, or –452 °F). Data for small axial-loaded round-bar specimens are plotted in Fig. 3. Data for fatigue tests on flexure sheet specimens are presented in Fig. 4.

High-Temperature Properties

Copper and copper alloys are generally not suitable for carrying sustained stresses for lengthy periods of time at high temperatures (i.e., they do not exhibit high creep strengths or stress-rupture strengths). For example, as shown in Fig. 5, the tensile strength of phosphorus deoxidized copper decreases by ~25% between room temperature and 240 °C (464 °F). Similarly, the stress required for 1% creep deformation falls from ~70 MPa (10 ksi) at 100 °C (212 °F) to 55 MPa (8 ksi) at 210 °C (410 °F), while the stress for rupture in 105 h decreases from 155 MPa (22 ksi) at 90 °C (194 °F) to 100 MPa (14.5 ksi) at 160 °C (320 °F) (Ref 10). Copper alloys, including high-copper alloys—such as beryllium copper, oxide dispersion strengthened copper, and chromium copper—aluminum bronzes, and copper-nickels have considerably higher elevated-temperature properties (see, for example, Fig. 5–7), but they cannot compete with heat-resistant alloys such as alloy steels, stainless steels, and nickel-base alloys.

Copper and copper alloys are used, however, in some applications involving moderate tem-

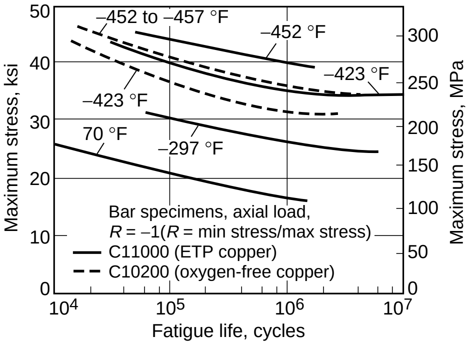

Fig. 3 Fatigue properties of annealed copper at low temperatures. Source: Ref 9

Table 1 Typical low-temperature tensile properties of copper and copper alloys

Temperature		Tensile strength		Yield strength		Elongation, %	Reduction in area, %	Notch tensile strength(a)		Young's modulus	
°C	°F	MPa	ksi	MPa	ksi			MPa	ksi	GPa	10^6 psi
C10200, bar, O61 temper(b)											
24	75	220	32.2	75	10.9	54	86	…	…	…	…
–78	–108	270	39.0	80	11.6	53	84	…	…	…	…
–196	–320	360	52.2	88	12.8	60	84	…	…	…	…
–253	–423	420	60.7	90	13.1	69	83	…	…	…	…
C12200, bar, O61 temper(b)											
24	75	215	31.3	46	6.7	45	76	300	43.3	105	15.1
–78	–108	265	38.3	46	6.6	56	87	345	50.4	110	16.0
–196	–320	350	50.6	51	7.4	62	84	430	62.3	110	16.2
–253	–423	440	63.8	58	8.4	68	83	495	72.0	110	16.3
–269	–452	415	60.4	54	7.9	65	81	515	74.7	115	16.4
C22000, bar, O61 temper(b)											
24	75	265	38.5	66	9.6	56	84	345	49.9	105	15.1
–78	–108	290	41.8	70	10.2	57	80	385	55.6	115	16.4
–196	–320	380	55.2	91	13.2	86	78	475	69.2	120	17.7
–253	–423	505	73.2	110	15.6	95	73	525	76.3	125	18.0
–269	–451	470	68.2	105	15.0	91	73	545	78.9	125	18.1
C26000, bar, H03 temper(c)											
24	75	655	95.2	420	60.9	14	58	…	…	…	…
–78	–108	695	101	445	64.3	17	62	…	…	…	…
–196	–320	805	117	475	68.6	28	63	…	…	…	…
–253	–423	910	132	505	73.4	32	58	…	…	…	…
C70600, bar, O61 temper(b)											
24	75	340	49.6	150	21.4	38	79	450	65.0	120	17.7
–78	–108	375	54.7	170	24.7	42	77	505	73.1	…	…
–196	–320	495	72.0	170	24.8	50	77	600	87.2	135	19.5
–253	–423	570	82.5	210	30.2	50	73	670	97.1	…	…
–269	–452	555	80.6	170	24.9	53	73	690	100	140	20.5
C71500, bar, O61 temper(b)											
24	75	400	57.8	130	18.7	47	68	545	79.4	145	20.9
–78	–108	470	68.0	155	22.2	48	70	625	90.5	150	22.1
–196	–320	620	89.8	220	31.6	52	70	780	113	130	18.8
–253	–423	710	103	265	38.1	51	66	885	128	150	21.7
–269	–452	725	105	275	40.1	48	65	895	130	135	19.5
C51000, bar, H08 temper(d)											
24	75	535	77.4	495	72.0	18	78	940	136	110	15.6
–78	–108	590	85.6	545	78.7	30	78	1010	147	115	16.5
–196	–320	725	105	615	89.2	34	67	1150	167	115	16.7
–253	–423	905	131	725	105	39	62	1280	185	115	16.5
–269	–452	800	116	690	100	34	58	1280	185	115	16.4
C17200 sheet, TD02 temper(e)											
24	75	620	90	550	80	15	…	…	…	120	17.5
–78	–108	655	95	600	87	20	…	…	…	120	17.6
–196	–320	805	117	690	100	37	…	…	…	130	18.8
–253	–423	945	137	750	109	45	…	…	…	135	19.5
C17200 sheet, TH02 temper(f)											
24	75	1320	191	1140	166	2.8	…	…	…	130	19
–253	–423	1640	238	1230	178	3.5	…	…	…	145	21

All alloys have a longitudinal base-metal orientation. (a) $K_t = 5$. (b) Annealed. (c) 3/4 hard. (d) Spring temper. (e) Solution treated, cold worked to 1/2 hard. (f) Aged 2 h at 350 °C (600 °F). Source: Ref 1–5 peratures where high conductivity or good heat transfer characteristics are needed. The elevated-temperature properties of importance for these applications include resistance to stress relaxation and thermal softening. Both of these characteristics are discussed subsequently. Additional short-time elevated-temperature data, creep strength data, and stress-rupture data for copper alloys can be found in the article "Powder Metallurgy Copper and Copper Alloys" (see the discussion on oxide dispersion strengthened alloys) and in the data sheets found in the articles "Properties of Wrought Copper and Copper Alloys" and "Properties of Cast Copper and Copper Alloys" in this Handbook. Reference 10 also reviews high-temperature mechanical property data for copper and copper alloys.

Stress Relaxation in Copper and Copper Alloys

As mentioned previously, copper and copper alloys are used extensively in structural applications in which they are subject to moderately elevated temperatures. Examples include automotive radiators, solar heating panels, communications cable, and electrical connectors. At relatively low operating temperatures, these alloys can undergo stress relaxation (decrease in stress resulting from transformation of elastic strain into plastic strain in a constrained solid), which can lead to service failures. Because of the wide variations in composition and processing among commercial copper alloys, resistance to stress relaxation varies considerably. Of course, selection of an alloy for a given application is based not only on stress-time-temperature response but also on such factors as cost, basic mechanical and physical properties, operating temperature, service environment, and formability. For many applications, electrical conductivity is a primary consideration.

Stress Relaxation Data. Unalloyed copper C11000 (electrolytic tough pitch) is probably the most inexpensive high-conductivity copper and is used extensively because of its ease of fabrica-

Table 2 Impact properties of copper and copper alloys at low temperatures

Copper or copper alloy number	Common name	Condition	Type of specimen	Test temperature		Energy absorbed		Fracture area(a), %
				°C	°F	J	ft · lbf	
C10200	Oxygen-free copper	Annealed bar, 19 mm (0.75 in.) diam (HRH 86)	½ thickness, V-notch Charpy	24	75	71.2	52.5	25
				–78	–108	77.3	57.0	25
				–196	–320	88.8	65.5	25
				–253	–423	86.1	63.5	25
C12200	Phosphorus deoxidized copper, high residual phosphorus	Annealed bar, 19 mm (0.75 in.) diam	V-notch Charpy	24	75	150.5	111	20
				–78	–108	151.8	112	20
				–196	–320	151.8	112	20
				–250	–418	161.3	119	50
C12200	Phosphorus deoxidized copper, high residual phosphorus	Cold-drawn bar, 19 mm (0.75 in.) diam	V-notch Charpy	24	75	151.8	112	10
				–78	–108	151.8	112	10
				–196	–320	151.8	112	10
				–250	–418	161.3	119	40
C17200	Beryllium copper	Annealed bar, 19 mm (0.75 in.) diam (HRB 95)	U-notch Charpy	24	75	138.3	102	50
				–78	–108	133.5	98.5	50
				–196	–320	117.3	86.5	75
C17200	Beryllium copper	½ hard-drawn bar, 19 mm (0.75 in.) diam (HRB 95)	U-notch Charpy	24	75	50.8	37.5	75
				–78	–108	54.2	40.0	75
				–196	–320	46.8	34.5	100
C17200	Beryllium copper	Annealed and tempered bar, 13 mm (0.50 in.) diam	½ thickness, V-notch Charpy	24	75	7.5	5.5	100
				–196	–320	6.4	4.7	100
				–253	–423	6.8	5.0	100
C23000	Red brass 85%	Annealed bar, 19 mm (0.75 in.) diam	V-notch Charpy	24	75	130.2	96.0	95
				–78	–108	112.0	82.6	95
				–196	–320	106.4	78.5	95
				–250	–418	102.4	75.5	95
C26000	Cartridge brass 70% (70-30 brass)	¾ hard bar, 19 mm (0.75 in.) diam (HRB 88)	V-notch Charpy	24	75	21.0	15.5	100
				–78	–108	21.0	15.5	100
				–196	–320	21.0	15.5	100
C44300	Admiralty arsenical	Annealed bar, 19 mm (0.75 in.) diam	V-notch Charpy	24	75	151.8	112	10
				–78	–108	153.2	113	10
				–196	–320	154.6	114	10
				–250	–418	154.6	114	10
C46400	Naval brass	Annealed bar, 19 mm (0.75 in.) diam	V-notch Charpy	24	75	52.6	38.8	100
				–78	–108	56.0	41.3	100
				–196	–320	50.7	37.4	100
				–250	–418	47.7	35.2	100
C51000	Phosphor bronze, 5% A	Spring temper bar, 19 mm (0.75 in.) diam	V-notch Charpy	24	75	143.7	106	95
				–78	–108	111.4	82.2	95
				–196	–320	73.9	54.5	95
				–250	–418	69.3	51.1	95
C61400	Aluminum bronze D	Annealed bar, 19 mm (0.75 in.) diam	V-notch Charpy	24	75	149.1	110	95
				–78	–108	134.6	99.3	95
				–196	–320	96.9	71.5	95
				–250	–418	90.2	66.5	95
C64700	Copper nickel silicon	Aged bar, 19 mm (0.75 in.) diam	V-notch Charpy	24	75	149.1	110	90
				–78	–108	145.1	107	90
				–196	–320	147.8	109	50
				–250	–418	157.3	116	25
C65500	High-silicon bronze A	Annealed bar, 19 mm (0.75 in.) diam	V-notch Charpy	24	75	151.8	112	5
				–78	–108	151.8	112	5
				–196	–320	154.6	114	5
				–250	–418	157.3	116	5
C71500	Copper-nickel, 30%	Annealed bar, 19 mm (0.75 in.) diam	V-notch Charpy	24	75	155.9	115	60
				–78	–108	154.6	114	60
				–196	–320	154.6	114	60
				–250	–418	154.6	114	60

(a) If specimen did not separate into two pieces, the fracture area was less than 100%. Source: Ref 9 tion. The stress-relaxation behavior of this material is rather poor, as demonstrated in Fig. 8, in which relaxed stress is plotted as a function of time and temperature for 0.25 mm (0.010 in.) C11000 wire initially stressed in tension to 89 MPa (13 ksi). Comparison of stress values at a given time for different temperatures illustrated the very sharp dependence of stress relaxation on temperature for this copper. At 93 °C (200 °F), for example, no tension remains after 10^5 h (11.4 years), whereas 40% of the initial stress remains after 40 years at room temperature. For C11000 and for many other copper metals, stress relaxation in a given time period is inversely proportional to absolute temperature (Ref 11).

The stress-relaxation behavior of C10200 (oxygen-free copper) is somewhat better than that of C11000, as shown in Table 3, which also presents stress-relaxation data for many other high-conductivity copper metals. (For compositions of these metals, see Table 4; basic mechanical properties are given in Table 5.) A more extensive comparison of the mechanical behavior of C10200 and C11000 has been presented in Ref 12.

Among the high-conductivity coppers, relaxation is greatest in very-high-purity copper (99.999+%)—a material used mainly in research. Improvement in the stress-relaxation behavior of high-conductivity copper can be achieved by adding alloying elements that cause solid-solution strengthening, age hardening, or dispersion hardening (Ref 13). For example, minute additions of silver significantly reduce stress relaxation in copper (Ref 14, 15).

Besides the strengthened high-conductivity coppers for which stress-relaxation data are given in Table 3, proprietary coppers strengthened with small amounts of cadmium, chromium, zirconium, or a combination of one or more of these elements have been found to have good to superior stress-relaxation resistance (Ref 11). Processing variations that strengthen copper metals, even including internal oxidation, are almost always beneficial.

Lower-conductivity alloys, which are strengthened by alloy additions or precipitation hardening, exhibit improved resistance to stress relaxation, compared to pure copper. The performance of any particular material will be dependent on its chemical composition, condition, and temperature at which it is tested. For materials that are strengthened by cold rolling, several general comments can be made. First, the amount of relaxation that will occur during a given time at a certain temperature will increase with increasing amounts of prior cold work.

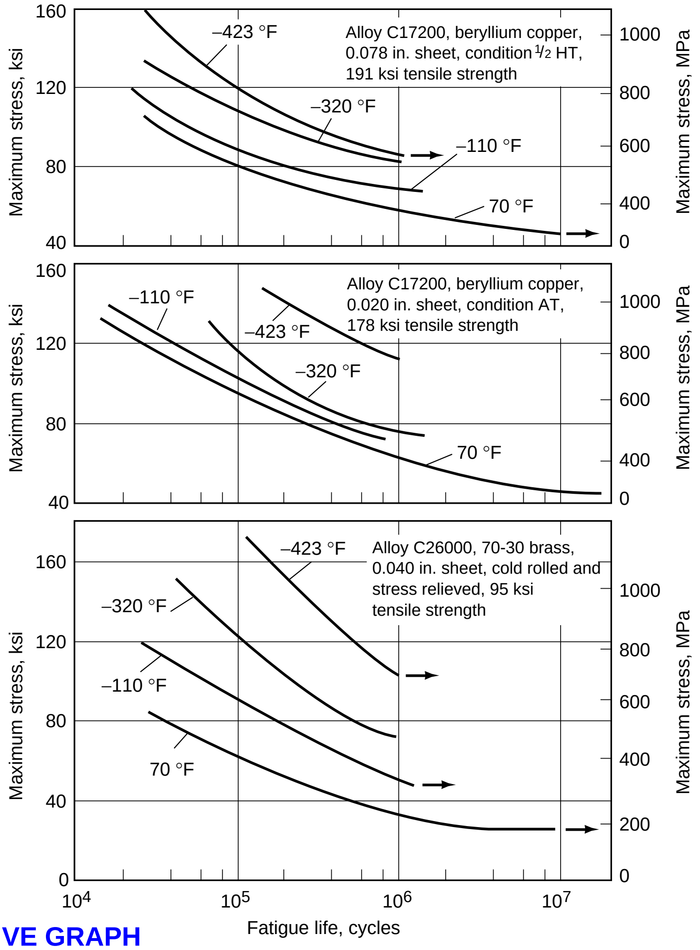

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Fig. 4 Low-temperature fatigue properties of copper alloy sheet specimens. $R = -1$. Fatigue rate: 1800 cycles per minute at 70, –110, and –320 °F; 3450 and 5175 cycles per minute at –423 °F. Source: Ref 9

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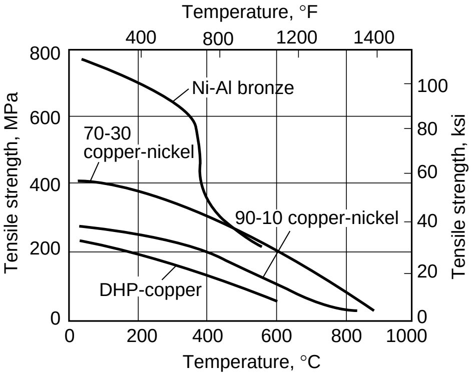

Fig. 5 Tensile strengths of copper alloys over a range of elevated temperatures. Source: Ref 10

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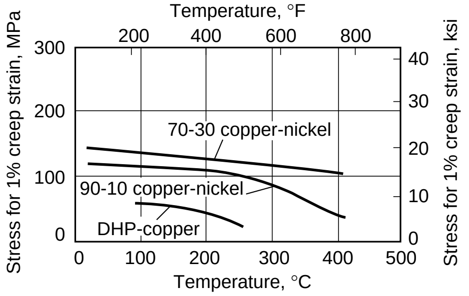

Fig. 6 Stress for 1% creep in 10^5 h for selected copper alloys. Source: Ref 10

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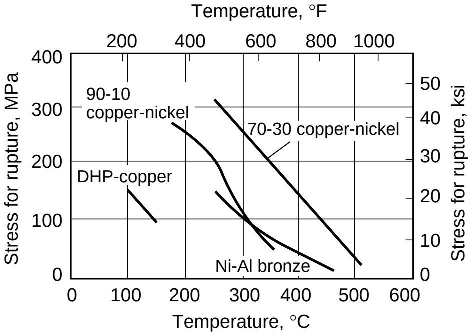

Fig. 7 Stress for rupture in 10^5 h for selected copper alloys. Source: Ref 10

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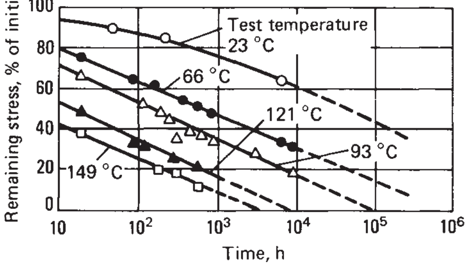

Fig. 8 Tensile-stress-relaxation characteristics of C11000. Data are for tinned 30 AWG (0.25 mm diam) annealed ETP copper wire; initial elastic stress, 89 MPa (13 ksi).

Table 3 Tensile-stress-relaxation data for selected types of copper wire

Material	Temper	Length of test, h	Temperature		Initial stress		Percent of initial stress remaining after:	
			°C	°F	MPa	ksi	10,000 h	40 years
0.25 mm (0.01 in.) diameter wire								
C10200, tinned	O61	10,000	27	80	41.0	5.95	72	55
		10,000	27	80	61.5	8.92	70	53
		10,000	27	80	82.0	11.9	69	50
		2,850	121	250	82.0	11.9	15	0
		2,850	149	300	82.0	11.9	6	0
C10200, tinned	H04	10,000	27	80	79.9	11.6	82	68
		8,600	66	150	88.9	12.9	78	68
		9,300	93	200	88.9	12.9	67	42
		2,850	121	250	88.9	12.9	55	37
		2,850	149	300	88.9	12.9	42	18
		10,000	27	80	160	23.2	80	68
		8,600	66	150	160	23.2	69	57
		9,300	93	200	160	23.2	59	43
		2,850	121	250	160	23.2	40	14
		2,850	149	300	160	23.2	22	0
C11000, tinned	O61	10,000	23	73	44.8	6.5	60	41
		9,300	66	150	44.8	6.5	47	22
		9,700	93	200	44.8	6.5	32	3
		2,850	121	250	44.8	6.5	12	0
		2,850	149	300	44.8	6.5	12	0
		10,000	23	73	88.9	12.9	60	38
		9,300	66	150	88.9	12.9	30	6
		9,700	93	200	88.9	12.9	20	0
		2,850	121	250	88.9	12.9	8	0
		2,850	149	300	88.9	12.9	8	0
C12000, tinned	O61	10,000	27	80	52.4	7.6	86	80
		10,000	27	80	77.9	11.3	85	79
		10,000	27	80	104	15.1	84	78
C13400, tinned(a)	H00	2,833	93	200	88.9	12.9	50	27
		2,833	93	200	101	14.7	49	28
		2,833	93	200	152	22.1	45	25
		2,833	93	200	203	29.5	42	19
C13700, tinned(b)	H00	9,700	23	73	88.9	12.9	88	83
		9,300	66	150	88.9	12.9	78	67
		9,700	93	200	88.9	12.9	70	52
		2,850	121	250	88.9	12.9	51	27
		2,760	149	300	88.9	12.9	41	8
		9,700	23	73	136	19.7	86	81
		9,300	66	150	136	19.7	77	64
		9,700	93	200	136	19.7	67	48
		2,850	121	250	136	19.7	42	19
		2,760	149	300	136	19.7	28	0
C15000, tinned	H04(c)	9,700	23	73	88.9	12.9	93	92
		9,300	66	150	88.9	12.9	93	89
		9,700	93	200	88.9	12.9	92	82
		2,850	121	250	88.9	12.9	82	78
		2,850	149	300	88.9	12.9	80	76
		9,700	23	73	203	29.5	93	92
		9,800	66	150	203	29.5	93	87
		9,700	93	200	203	29.5	92	82
		2,850	121	250	203	29.5	80	76
		2,850	149	300	203	29.5	78	74
C15000, bare	H04(c)	9,700	23	73	88.9	12.9	96	95
		9,600	66	150	88.9	12.9	96	95
		9,700	93	200	88.9	12.9	96	95
		9,700	23	73	203	29.5	96	95
		9,600	66	150	203	29.5	96	95
		9,700	93	200	203	29.5	86	79
C15000, tinned	H00	2,800	93	200	88.9	12.9	96	91
		2,800	93	200	128	18.6	95	90
		2,800	93	200	192	27.9	94	89
		2,800	93	200	256	37.2	93	89
C15000, silver plated	(d)	9,800	27	80	74.4	10.8	97.9	95
		9,800	27	80	112	16.2	98.8	94
		9,800	27	80	149	21.6	96.7	93
C16200, tinned	H04(e)	9,700	23	73	88.9	12.9	97	94
		9,700	66	150	88.9	12.9	93	92
		9,700	93	200	88.9	12.9	92	87
		2,800	121	250	88.9	12.9	79	71
		2,800	149	300	88.9	12.9	62	40
		9,700	23	73	226	32.8	95	92
		9,700	66	150	226	32.8	91	88

(continued)

(a) Boron-deoxidized copper containing 0.027% Ag. (b) Boron-deoxidized copper containing 0.085% Ag. (c) In-process strand annealed. (d) Proprietary mill processing. (e) Batch annealed

Table 3 (continued)

Material	Temper	Length of test, h	Temperature		Initial stress		Percent of initial stress remaining after:	
			°C	°F	MPa	ksi	10,000 h	40 years
		9,700	93	200	226	32.8	88	84
		2,800	121	250	226	32.8	77	64
		2,800	149	300	226	32.8	60	34
C16200, tinned	H00	2,800	93	200	88.9	12.9	91	85
		2,800	93	200	114	16.6	91	84
		2,800	93	200	172	24.9	91	84
		2,800	93	200	229	33.2	91	84
0.5 mm (0.02 in.) diameter wire								
C10200	O61	22,600	27	80	58.6	8.5	81	71
		22,600	27	80	75.8	11.0	81	71
		22,600	27	80	86.2	12.5	81	71
		22,600	27	80	103	15.0	79	70
		22,600	27	80	110	16.0	78	67
C10200	H00	4,060	93	200	68.9	10.0	48	9
		4,060	93	200	142	20.6	42	0
C11000	O61	35,000	27	80	34.5	5.0	60	43
		35,000	27	80	68.9	10.0	55	39
C11000	O61	24,500	27	80	34.5	5.0	60	38
		24,500	27	80	41.2	6.0	60	38
		24,500	27	80	51.7	7.5	59	38
		24,500	27	80	68.9	10.0	57	38
		24,500	27	80	82.7	12.0	56	38
		24,500	27	80	96.5	14.0	55	37
C11000	H00	4,100	93	200	68.9	10.0	35	6
		4,100	93	200	121	17.5	23	0
C11600	H00	4,100	93	200	68.9	10.0	50	20
		4,100	93	200	143	20.7	43	18
C13400	H00	4,100	93	200	68.9	10.0	53	27
		4,100	93	200	148	21.4	38	14
C15500, bare	H00	4,060	93	200	68.9	10.0	78	62
		4,060	93	200	164	23.8	74	60
C16200	H00	4,100	93	200	68.9	10.0	88	82
		4,100	93	200	158	22.9	80	69

(a) Boron-deoxidized copper containing 0.027% Ag. (b) Boron-deoxidized copper containing 0.085% Ag. (c) In-process strand annealed. (d) Proprietary mill processing. (e) Batch annealed

Table 4 Chemical composition of copper wire tested for stress relaxation

Material	Composition, %				
	Ag	Pb	Fe	Ni	Others
0.25 mm (0.01 in.) diam					
C10200	0.002	…	…	…	…
C11000	0.002	0.001	0.002	0.001	…
C12000	0.002	…	…	…	…
C13400	0.031	…	0.003	…	0.02 B, 0.001 Si
C13700	0.090	0.001	0.004	…	0.01 B, 0.001 Si
C15000	0.003	0.001	0.002	…	0.001 Mg, 0.15 Zr
C16200	0.005	0.01	0.015	0.005	0.75 Cd, 0.01 Sn
0.05 mm (0.02 in.) diam					
C10200	0.002	…	…	…	…
C11000	0.001	…	…	…	0.0355 O
C13000	0.083	…	0.0029	0.0079	0.0310 O
C13400	0.031	…	0.003	…	0.02 B, 0.001 Si
C15500	0.037	…	…	…	0.10 Mg, 0.063 P
C16200	0.003	0.005	…	0.005	0.97 Cd, 0.007 Sn, 0.07 Zn

Table 5 Typical room-temperature mechanical properties of copper wire tested for stress relaxation

Material	Temper	Tensile strength		Yield strength(a)		Elongation(b), %	Conductivity, %IACS
		MPa	ksi	MPa	ksi		
0.25 mm (0.01 in.) diam							
C10200, tinned	O61	250	36.3	160	23.2	24.6	99
C10200, tinned	H04	271	39.3	228	33.1	2.3	99
C11000, tinned	O61	254	36.9	147	21.3	30.0	99
C12000, tinned	O61	276	40.0	198	28.7	18.1	98
C13400, tinned	H00	365	53.0	359	52.1	0.82	98
C13700, tinned	H00	242	35.1	221	32.1	10.5	99
C15000, tinned	H04	414	60.0	365	53.0	3.7	90
C15000, bare	H04	…	…	…	…	…	…
C15000, tinned	H00	393	57.0	388	56.3	0.82	93
C15000, silver plated	…	347	50.3	298	43.3	13.5	…
C16200, tinned	H04	473	68.6	404	58.6	6.6	85
C16200, tinned	H00	403	58.5	395	57.3	0.91	85
0.05 mm (0.02 in.) diam							
C10200, tinned	O61	249	36.1	138	20.0	34.7	101
C10200, bare	H00	278	40.3	261	37.8	11.1	101
C11000, tinned	O61	239	34.7	…	…	28.8	101
C11000, silver plated	O61	233	33.8	…	…	24.6	101
C11000, bare	H00	280	40.6	245	35.5	11.7	101
C11600	H00	295	42.8	274	39.8	9.5	98
C13400	H00	258	37.5	240	34.8	9.4	98
C15500, bare	H00	367	53.2	332	48.1	1.9	93.8
C16200	H00	312	45.3	276	40.1	10.9	85

(a) 0.2% offset. (b) In 254 mm (10 in.)

Second, the performance of these materials may vary, depending on the orientation of the test sample to the rolling direction. Finally, the performance of heavily cold-rolled materials can be improved by stress-relief annealing (Ref 16, 17). Figures 9 and 10 illustrate these effects for alloys C51000 and C72500.

Since copper alloys are commonly used in electrical and electronic connectors, some manufacturers have published data to assist in the design of these items (Ref 18). A compilation of stress-relaxation data from these sources for some of the more common alloys is given in Table 6. It is important to realize that the data from relaxation tests, such as in Table 6, serves as only a comparative ranking of alloy performance because these tests are usually performed on flat samples cut from strip, rather than on finished parts. Other factors that might influence part performance include part geometry, deformation introduced during fabrication, and performance of other materials used

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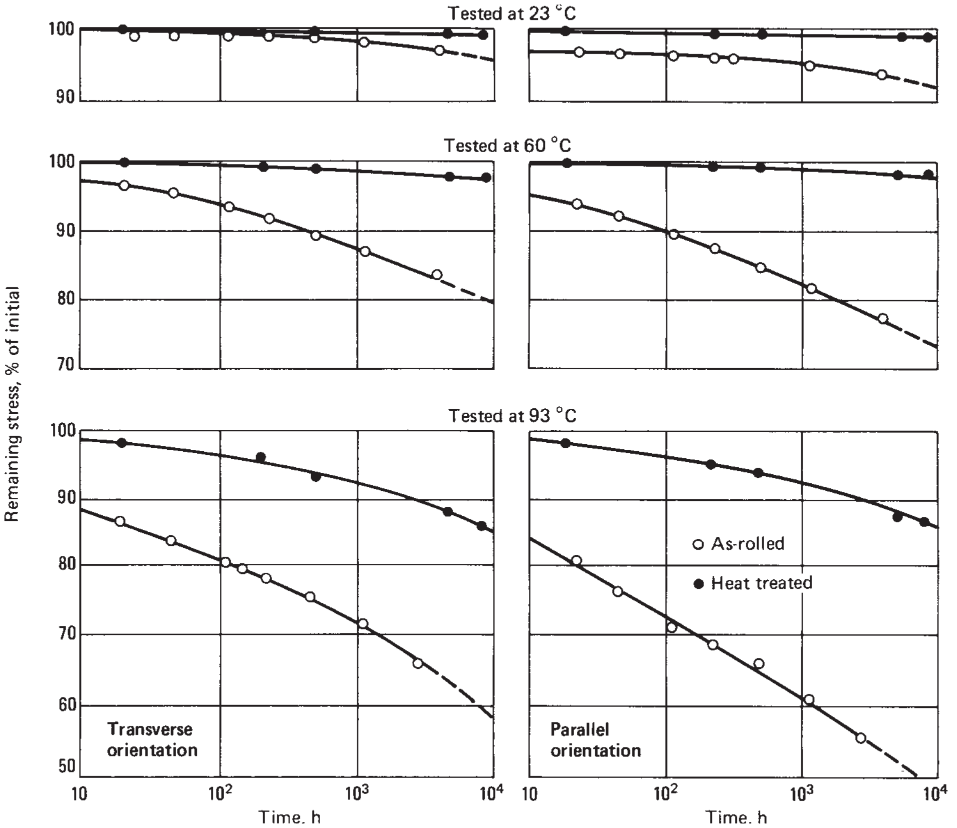

Fig. 9 Anisotropic stress-relaxation behavior in bending for highly cold-worked C51000 strip. Data are for 5% Sn phosphor bronze cold rolled 93% (reduction in area) to 0.25 mm (0.01 in.) and heat treated 2 h at 260 °C (500 °F). Graphs at left are for stress relaxation transverse to the rolling direction; graphs at right, for stress relaxation parallel to the rolling direction. Initial stresses: as rolled, parallel orientation, 607 MPa (88 ksi); as rolled, transverse orientation, 634 MPa (92 ksi); heat treated, parallel orientation, 641 MPa (93 ksi); heat treated, transverse orientation, 738 MPa (107 ksi)

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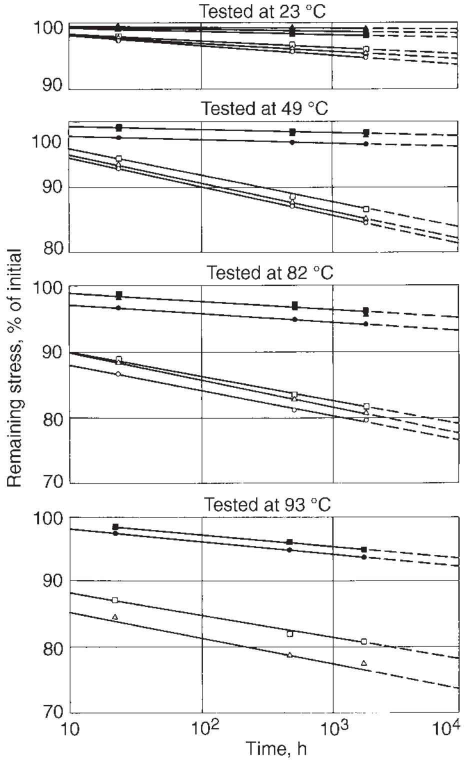

Fig. 10 Anisotropic stress-relaxation behavior in bending for highly cold-worked C72500 strip. Data are for 89Cu-9Ni-2Sn alloy cold rolled 98.7% (reduction in area) to 0.25 mm (0.01 in.) and heat treated 2 h at 357 °C (675 °F). Points represented by circles are for stress relaxation parallel to the rolling direction; triangles, for relaxation at 45° to the rolling direction; squares, for relaxation transverse to the rolling direction. Open points are for as-rolled stock; solid points, for heat-treated stock. Initial stresses: as-rolled, parallel orientation, 524 MPa (76 ksi); as rolled, 45° orientation, 510 MPa (74 ksi); as-rolled, transverse orientation, 586 MPa (85 ksi); heat treated, parallel orientation, 669 MPa (97 ksi); heat treated, 45° orientation, 552 MPa (80 ksi); heat treated, transverse orientation, 710 MPa (103 ksi)

Table 6 Typical stress-relaxation values for selected copper alloys

		Percent of initial stress remaining after specified time at:									
		Room temperature		75 °C (170 °F)		105 °C (220 °F)		150 °C (300 °F)		200 °C (390 °F)	
Alloy	Temper	10^3 h	10^5 h	10^3 h	10^5 h	10^3 h	10^5 h	10^3 h	10^5 h	10^3 h	10^5 h
C15100	H02	97	95	…	…	86	81	84	80	…	…
	H04	93	89	…	…	80	76	…	…	…	…
	H06	94	92	…	…	78	71	…	…	…	…
C17200	AM	…	…	…	…	97(a)	…	…	…	67	…
	¼ HM	…	…	…	…	97(a)	…	…	…	67	…
	½ HM	…	…	…	…	97(a)	…	…	…	67	…
	HM	…	…	…	…	98(a)	…	…	…	68	…
	SHM	…	…	…	…	98(a)	…	…	…	68	…
	XHM	…	…	…	…	98(a)	…	…	…	69	…
	XHMS	…	…	…	…	98(a)	…	…	…	69	…
C17410	½ HT	…	…	…	…	85(a)	…	…	…	…	…
	HT	…	…	…	…	80(a)	…	76	…	…	…
C19400	H02	95	93	…	…	78	71	…	…	…	…
C26000	H04	95	92	74	63	…	…	…	…	…	…
	H08	87	84	68	53	…	…	36	…	…	…
C51000	H02	94	94	…	…	89	81	…	…	…	…
	H08	95	93	90	81	75	62	44	…	…	…
C52100	H02	97	96	92	89	88	83	…	…	…	…
	H04	99	98	89	84	81	71	…	…	…	…
	H08	98	98	91	87	82	74	45	…	…	…
C63800	H03	89	84	75	66	…	…	…	…	…	…
	H06	87	81	69	56	…	…	…	…	…	…
C65400	H02	…	…	…	…	81	78	…	…	…	…
	H04	…	…	…	…	76	69	…	…	…	…
	H08	…	…	…	…	71	63	…	…	…	…
C68800	H02	97	95	78	67	…	…	…	…	…	…
	H08	95	90	73	61	…	…	…	…	…	…
C70250	TM00	98	98	97	96	91	83	80	65	…	…
C72500	H02	…	…	…	…	86	82	…	…	…	…
	H08	97	96	…	…	83	76	74	…	61	…

(a) Data for C17200 and C17410 in the 105 °C (220 °F) column are actually for tests at 100 °C (212 °F). Source: Ref 18, 19 in the part (for example, plastic housings used in electrical connectors). Testing of prototype parts is the best way to assess overall performance.

Stress Relaxation in Mechanical Components. A solderless wrapped connection such as the one shown in Fig. 11, in which electrical contact is made by wrapping a wire around a terminal, is a typical application for high-conductivity copper metals where stress relaxation is of concern. Typical operating temperatures can be as high as 85 °C (185 °F); generally, conductivities higher than 98% IACS at 20 °C (68 °F) are desirable. After the connection is made, it is maintained by elastic stresses in the two members. If the wire undergoes stress relaxation, electrical contact between the wire and the terminal may be lost.

The spring in the alarm fuse shown in Fig. 12 is a typical application for copper alloys with room-temperature conductivities of 55 to 85% IACS. This spring conducts relatively high electrical currents and also triggers an alarm circuit if the fuse blows. To perform the latter function reliably, the spring must retain spring force for extended periods of time. But if the spring material undergoes stress relaxation, the device may fail to trigger the alarm when the fuse blows. C16200 (Cu-1Cd) has been used successfully in spring-loaded alarm fuses operating at temperatures below 95 °C (200 °F). (This alloy has an electrical conductivity of 80 to 85% IACS at 20 °C, or 68 °F.) For higher operating temperatures up to 165 °C (330 °F), C19000 (Cu-Ni-P alloy) springs have performed adequately, provided the ratio of nickel to phosphorus is at least 5 to 1 (Ref 20). (The nominal ratio for this alloy is about 3.5:1.) For applications where lower electrical conductivity can be tolerated, C17500 (Cu-2.5Co-0.6Be) conductivity, 45% IACS at 20 °C (68 °F), is a satisfactory alternative for temperatures up to 165 °C (330 °F). Both C19000 and C17500 must be age hardened after forming.

A typical application of the lower-conductivity, high-strength copper alloys is the pressure-type, split-beam connector shown in Fig 13. The knife edges of the connector first cut through the insulation on the conductor and then must maintain electrical contact with it. Materials used for connectors of this type, depending on operating stress and temperature, include some of the phosphor bronzes, nickel silvers, copper-nickels, beryllium-coppers, and some of the copper-nickel-tin alloys strengthened by spinodal decomposition (Ref 21).

Stress relaxation can produce mechanical or thermal ratcheting, which sometimes occurs in multilayer circuit boards, such as the one illustrated in Fig. 14. A multilayer board usually consists of an epoxy-glass composite substrate with several lands of electroplated copper and including a plated-through hole. When a lead-wire is soldered into the plated-through hole, differential thermal expansion causes the hole to expand more than the substrate, and a tensile stress is applied to the copper barrel. While at temperature, the stressed electroplated copper relaxes according to behavior that varies with the plating system and bath used (Ref 22). If the board is repeatedly heated and cooled, the electroplated copper alternately expands and relaxes during each heating cycle, and permanent strain accumulates in the copper barrel until the assembly fails by buckling or by low-cycle fatigue.

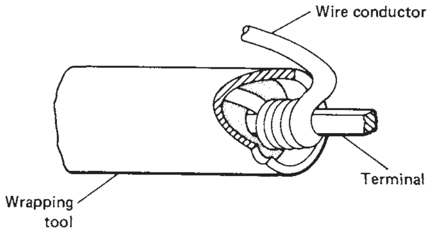

Fig. 11 Typical solderless wrapped connection. Wrapping tool is removed after connection is made.

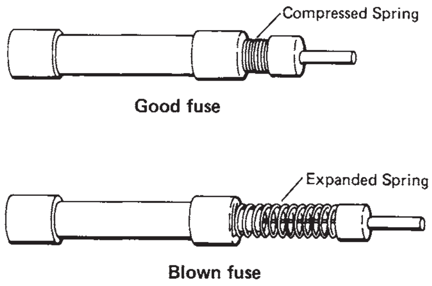

Fig. 12 Typical spring-type alarm fuse

Thermal Softening in Electrical Coppers

The term *thermal softening* refers to a degradation of strength and/or hardness after exposure to elevated temperatures. It is of primary concern when using annealed high-conductivity coppers, which are soft and ductile materials.

Thermal Softening Data. At temperatures lower than those inducing recrystallization in commercial heat treatments, thermal softening can occur over extended periods. If resistance to softening at slightly elevated temperature is required, C11100 is often specified. This copper contains a small amount of cadmium, which raises the temperature at which recovery and recrystallization occur. Oxygen-free copper, electrolytic tough pitch copper, and fire-refined tough pitch copper are available as silver-bearing coppers having specific minimum silver contents. The silver, which may be present as an impurity in anode copper or may be intentionally alloyed to molten cathode copper, also imparts resistance to softening to cold-worked metal. Silver-bearing coppers and cadmium-bearing coppers are used for applications such as automotive radiators and electrical conductors that must operate at temperatures above approximately 200 °C (400 °F).

Adding small amounts of elements such as silver, cadmium, iron, cobalt, and zirconium to deoxidized copper imparts resistance to softening at the times and temperatures encountered in soldering operations, such as those used to join components of automobile and truck radiators, and those used in semiconductor packaging operations. Thermal and electrical conductivities and room-temperature mechanical properties are unaffected by small additions of these elements.

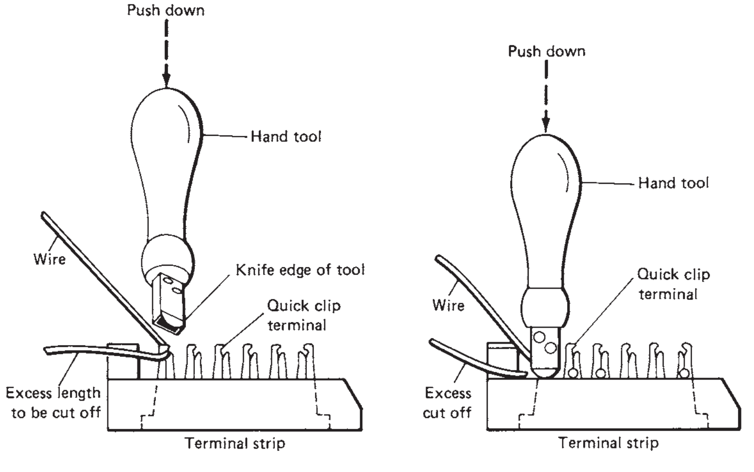

Fig. 13 Typical quick clip connection

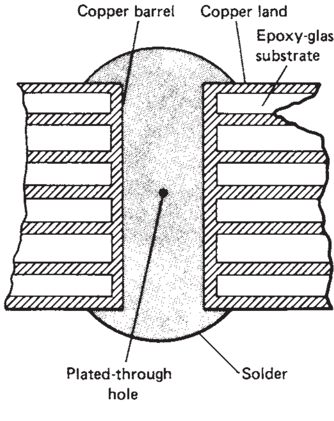

Fig. 14 Cutaway view through a typical multilayer circuit board showing barrel-land construction and a plated-through hole

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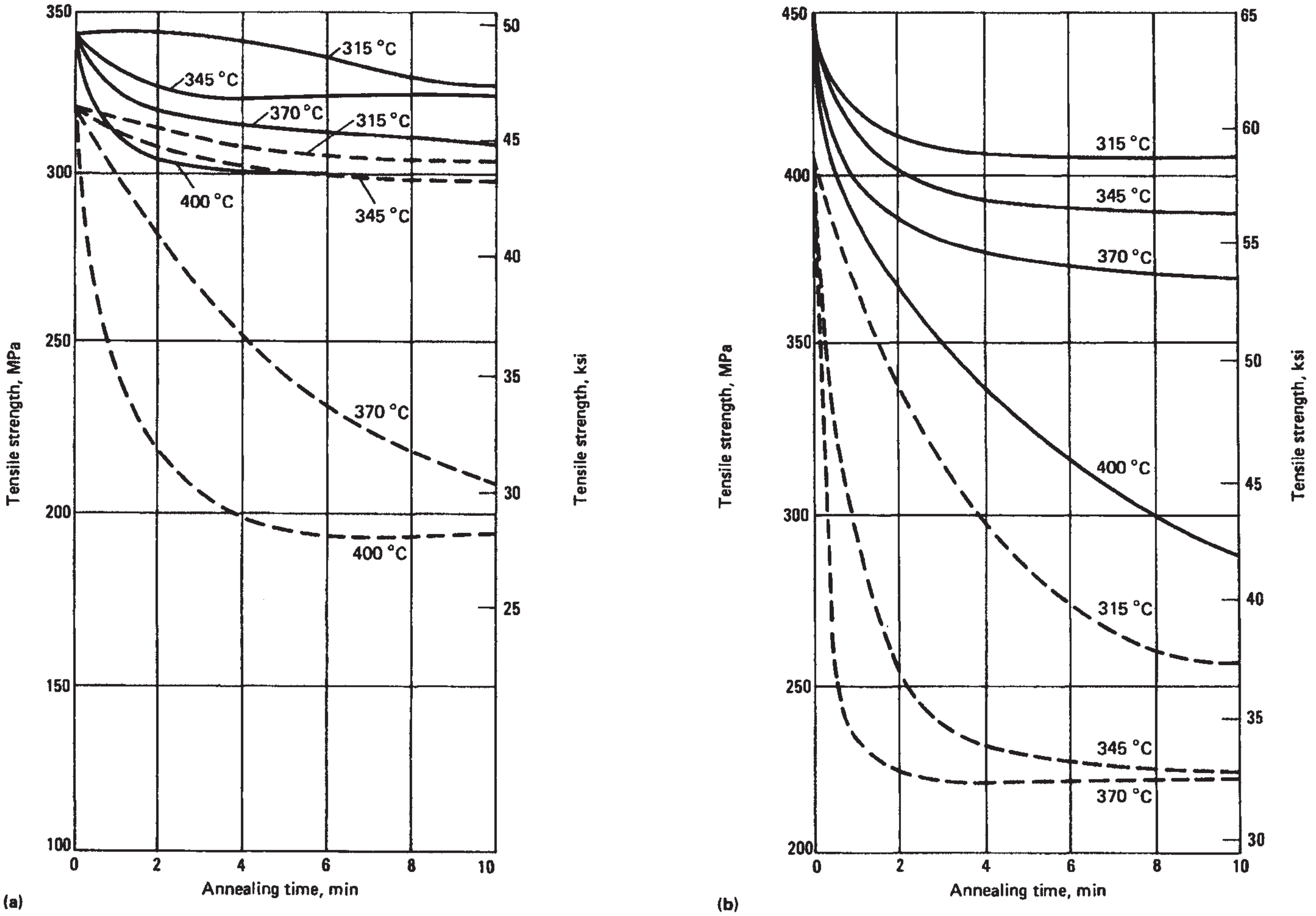

Fig. 15 Softening characteristics of cadmium-bearing copper (C14300, represented by solid curves) and silver-bearing tough pitch copper (C11400, represented by dashed curves). (a) Softening curves for material cold reduced 21% in area, from 0.1 to 0.075 mm (0.0038 to 0.0030 in.) in thickness. (b) Softening curves for material cold reduced 90% in area, from 0.75 to 0.075 mm (0.0300 to 0.0030 in.) in thickness

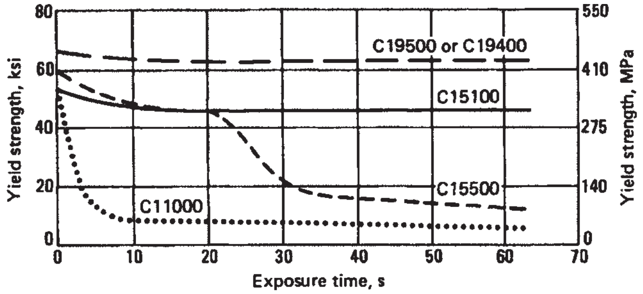

Fig. 16 Softening resistance of lead frame materials at the upper temperature limit (500 °C, or 930 °F)

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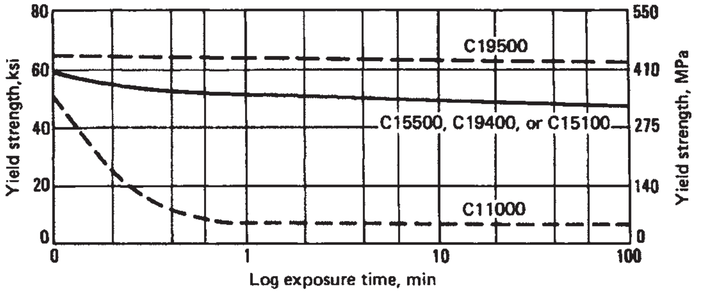

Fig. 17 Softening resistance of lead frame materials at an intermediate temperature level (350 °C, or 660 °F)

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However, cadmium-copper and zirconium-copper work harden at higher rates than either silver-bearing copper or electrolytic tough pitch copper.

Cold-rolled silver-bearing copper is used extensively for automobile radiator fins. Usually such strip is only moderately cold rolled because heavy cold rolling makes silver-bearing copper more likely to soften during soldering or baking operations. Some manufacturers prefer cadmium-copper C14300 because it can be severely cold rolled without making it susceptible to softening during soldering.

Figure 15 illustrates the softening characteristics of C14300 and C11400 as measured for several temperatures and two tempers. As shown in Fig. 15(b), C14300 cold rolled to a tensile strength of 400 MPa (64 ksi) retains 91% strength after a typical core bake of 3 min at 345 °C (650 °F). Silver-bearing copper C11400 given the same cold reduction retains only 60% tensile strength after the same baking schedule.

Another application in which softening resistance is of paramount importance is lead frames for electronic devices, such as plastic dual-in-line packages. During packaging and assembly, lead frames may be subjected to temperatures up to 350 °C (660 °F) for several minutes and up to 500 °C (930 °F) for several seconds. The leads must maintain good strength because they are pressed into socket connectors, often by automated assembly machines; softened leads collapse, causing spoilage. Copper alloys developed for lead frames are discussed in the article "Applications" in this Handbook.

Alloy C15100 (copper-zirconium), alloy C15500 (copper-silver-magnesium-phosphorus), alloy C19400 (copper-iron-phosphorus-zinc), and alloy C19500 (copper-iron-cobalt-tin-phosphorus) are popular for these applications because they have good conductivity, good strength, and good softening resistance. Figures 16 and 17 compare the softening resistance of these alloys with electrolytic copper C11000.

ACKNOWLEDGMENTS

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- D.E. Tyler and W.T. Black, Introduction to Copper and Copper Alloys, *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials*, Vol 2, *ASM Handbook*, ASM International, 1990, p 216–240
- Stress-Relaxation Characteristics of Copper and Copper Alloys, *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials*, Vol 2, *ASM Handbook*, ASM International, 1990, p 258–264

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Fatigue Properties

COPPER AND ITS ALLOYS, when compared to other structural alloys, are not used extensively in applications involving cyclic stressing. The most common use of copper or copper alloys under dynamic loading is in rotating electrical machinery used for power generation. This application involves commercially pure copper and very dilute copper alloys, which are not covered in this article. The reader is referred to Ref 1 to 3 for information on fatigue of copper.

One application of copper alloys requiring resistance to fracture after two or three highly stressed reverse bend cycles relates to the use of lead frame in insertion mounted microelectronic devices. The "leadbend fatigue" test involves repeated 90 degree bending and straightening of the lead frame leads. The test was designed to ensure that materials used for lead frames would not be susceptible to fracture if leads were straightened after inadvertent deformation during handling. This subject is covered in Ref 4 and 5, which describe the test method, list many of the alloys used for lead frames, and provide comparative leadbend fatigue data. With the increasing use of surface-mounted devices, the leadbend fatigue test and this property have become less important. Copper alloys whose fatigue characteristics are covered in this article are used in applications involving repeated flexing: springs used for contacts and connectors, bellows, and Bourdon tubes. Alloys used for these applications include the brasses, bronzes (tin-, silicon-, aluminum-, and combinations thereof), and beryllium coppers. Copper-nickel-tin spinodally hardened alloys are also used in connectors and contacts. Flexural fatigue properties of all these classes of alloys in strip form are presented in this article. Heavier copper alloy sections subjected to cyclic loading are largely confined to the beryllium coppers for applications such as aircraft landing gear bushings, races and rollers for rolling-element bearings, and oil and gas downhole hardware such as antigalling thread-saver subs and instrument housings. Rotating-beam fatigue results are reported for beryllium copper alloy C17200.

The wrought alloy designations and nominal compositions of alloys covered in this article are given in Table 1. Copper alloys are classified by the Unified Numbering System (UNS) designations, which identify alloy groups by major alloying element. More detailed information on alloy designations can be found in the article "Standard Designations for Wrought and Cast Copper and Copper Alloys" in this Handbook.

The brasses, nickel silvers, and bronzes covered in this article are strengthened by cold work, the exception being C70250, the copper-nickel-silicon-magnesium alloy, which is strengthened by combinations of cold work and precipitation hardening. The beryllium coppers are strengthened by cold work and/or precipitation hardening. The spinodally strengthened copper-nickel-tin alloy is cold worked and aged. The temper designations used for the materials tested are listed in Table 2. These designations are used throughout the text and figures. Because of their ability to be precipitation hardened, C70250 and beryllium copper alloys can be tailored across a wide range of strength and conductivity combinations. Additional fatigue data can be found in the articles "Properties of Wrought Copper and Copper Alloys" and "Properties of Cast Copper and Copper Alloys" in this Handbook.

Alloy Metallurgy and General Mechanical Properties

Brasses. Both the standard cartridge brass (C26000, 70Cu-30Zn) and the higher-strength aluminum brass (C68800) offer excellent combinations of strength and formability and are widely used as spring materials. The microstructure of C26000 is an all-α solid solution. In addition to a copper-zinc-aluminum solid solution, C68800 contains a second-phase cobalt aluminide that acts as a grain refiner.

Nickel-Silvers. The copper-nickel-zinc alloy C76200 is a nickel-modified brass. The nickel modification offers improved strength over conventional brasses. This family of alloys is used in springs of all types.

Bronzes. Tin bronze (C51000) is one of the most widely used alloys for springs that require strength higher than standard brass. It is also used for bellows and Bourdon tubes. It is essentially a single-phase alloy.

The silicon-aluminum-bronze alloy (C63800) and the silicon-tin-bronze alloy (C65400) both are used in a broad range of electronic and electrical springs. The microstructure is a single-phase solid solution, with a coarse second-phase particulate (cobalt silicide in the case of C63800).

The nickel-silicon alloy C70250 has wide application in electrical and electronic springs. It combines moderately high conductivity and formability with high strength. The alloy microstructure consists of an a solid solution and a second-phase nickel silicide that provides precipitation hardening.

Beryllium Coppers. Commercial wrought beryllium copper alloys contain from 0.2 to 2.0 wt% Be and 0.2 to 2.7 wt% Co (or up to 2.2 wt% Ni), with the balance primarily copper. Within this compositional band, two distinct classes of commercial materials have been developed: high-strength alloys and moderate-conductivity alloys.

Wrought high-strength alloys (C17000 and C17200) contain 1.6 to 2.0 wt% Be and nominal 0.25 wt% Co. Wrought moderate-conductivity alloys (C17500 and C17510) contain 0.2 to 0.7 wt% Be and nominal 2.5% Co (or 2 wt% Ni).

Table 1 Alloy designations and compositions discussed in this article

UNS designation	Nominal composition, %
C17200	1.9 Be, 0.25 Co
C17410	0.3 Be, 0.4 Co
C17510	0.4 Be, 1.8 Ni
C26000	30 Zn
C51000	5.0 Sn, 0.2 P
C63800	2.8 Al, 1.8 Si, 0.4 Co
C65400	3.1 Si, 1.6 Sn, 0.05 Cr
C68800	23 Zn, 3.4 Al, 0.4 Co
C72050	3.2 Ni, 0.75 Si, 0.2 Mg
C72900	15 Ni, 8 Sn
C76200	29 Zn, 12 Ni, 0.5 Mn

Table 2 Copper alloy temper designations discussed in this article

ASTM B 601 temper designation(a)	Process(b)
O60	Soft annealed
H01	CW to quarter-hard
H02	CW to half-hard
H03	CW to three-quarter hard
H04	CW to hard
H06	CW to extra hard
H08	CW to spring
H10	CW to extra spring
H14	CW to super spring
TB00	ST
TF00	ST + age
TD01	ST + CW
TD02	ST + CW
TD04	ST + CW
TH01	ST + CW + age
TH02	ST + CW + age
TH04	ST + CW + age
TM00	CW + age (mill hardened)
TM02	CW + age (mill hardened)
TM03	CW + age (mill hardened)
TM04	CW + age (mill hardened)
TM06	CW + age (mill hardened)
TM08	CW + age (mill hardened)

(a) TD, TH, and TM tempers increase in number with increasing cold work. (b) CW, cold work; ST, solution treat

The leanest alloy is C17410, which contains less than 0.4 wt% Be and 0.6 wt% Co.

Additional detailed information on the composition, physical metallurgy, mechanical properties, and thermal treatments of beryllium copper alloys, including casting alloys and special tempers and alloys, can be found in Ref 6.

Spinodal Alloys. The family of copper-nickel-tin alloys spinodally strengthened during aging is represented here by the highest-strength version, the 15Ni-8Sn alloy C72900 used for connectors. Optimal strength and formability are obtained by a combination of cold working followed by aging.

Fatigue Testing

Strip. Bend fatigue testing of strip was performed in conformance with the ASTM B 593 standard method for copper alloy spring materials. This method employs a fixed-cantilever, constant-deflection machine. The tapered test sample is held as a cantilever beam in a clamp at one end and deflected near the opposite end of the apex of the tapered section. Testing was done in a Krouse machine, with the force applied to the sample by a cam and rod linkage. A wide range of bending load ratios can be applied with this method. Typically, load ratios are chosen between $R = -1$ and 0 to simulate reverse bending and unidirectional bending, respectively. The test frequency is approximately 20 Hz.

Test samples were made from commercial materials. Gages covered 0.20 to 0.38 mm (0.008 to 0.015 in.) for the beryllium coppers and spinodal alloys and 0.25 to 1.5 mm (0.010 to 0.60 in.) for the remaining alloys. Samples of the as-rolled strip were milled to the required test specimen geometry. The rolled surface was left intact and the milled edges deburred.

The required deflection is determined by using either the cantilever simple beam equation or measured with strain-gaged samples under dynamic conditions. The maximum outer fiber bending stress is calculated by:

$$S = \frac{6PL}{bd^2}$$

where S is the desired bending stress, P is the applied load at the connecting pin (apex of the sample triangle), L is the distance between the connecting pin and the point of stress, b is the specimen width at length L from the point of load application, and d is the specimen thickness.

A load cell at the fixed end of the sample is used to detect change in the sample loading resulting from a macroscopic crack initiation. The load cell information is relayed to a monitoring circuit that determines the test completion based on the failure criteria required.

Rotating Beam. Fatigue tests of materials representing heavy section products made from rod, bar, and plate were conducted by the rotating-beam method following ASTM E 647 guidelines.

Fatigue Data

Strip

Nonaging Alloys. All flexural fatigue data are reported as *S-N* curves, where *S* is the maximum stress in flexure and *N* is the number of cycles to failure. Failure is defined as complete specimen fracture. Fatigue strength is defined here as the maximum stress without failure after 100 million cycles of reversed bending. Figures 1 to 6 present *S-N* curves for the solid-solution (nonaging) strengthened alloys (with or without a second-phase grain refiner). In general, fatigue strength follows tensile strength monotonically, but there are exceptions where fatigue strength is relatively insensitive to temper and a few cases, most notably C51000 but also C65400, where crossovers occur. This behavior has been observed before in tin-bronze alloys (Ref 7, 8).

For many copper alloy systems, transverse tensile and yield strengths are substantially higher than longitudinal strengths, and this characteristic is reflected normally by higher transverse fatigue strengths, as show in Fig. 6. Although transverse data are not shown for the other alloys, similar behavior is observed. In

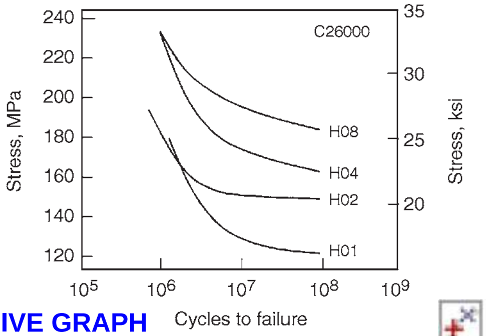

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Fig. 1 *S-N* curves for C26000. Longitudinal loading, $R = -1$

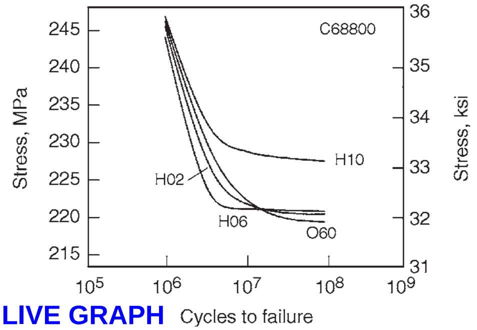

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Fig. 2 *S-N* curves for C68800. Longitudinal loading, $R = -1$

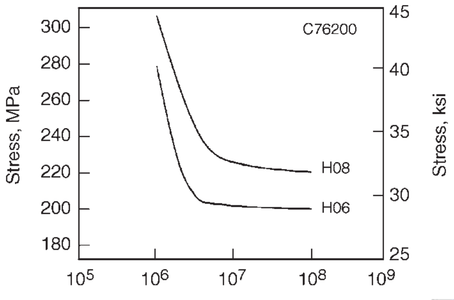

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Fig. 3 *S-N* curves for C76200. Longitudinal loading, $R = -1$

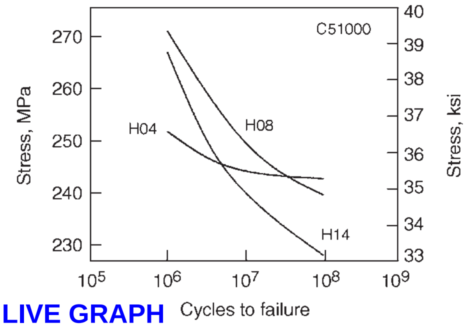

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Fig. 4 *S-N* curves for C51000. Longitudinal loading, $R = -1$

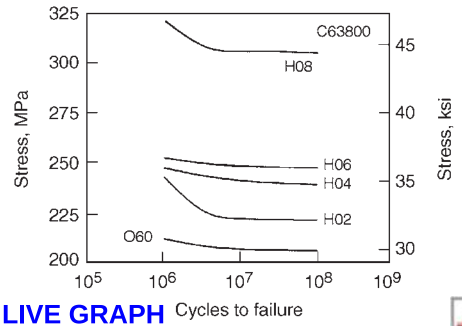

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Fig. 5 *S-N* curves for C63800. Longitudinal loading, $R = -1$

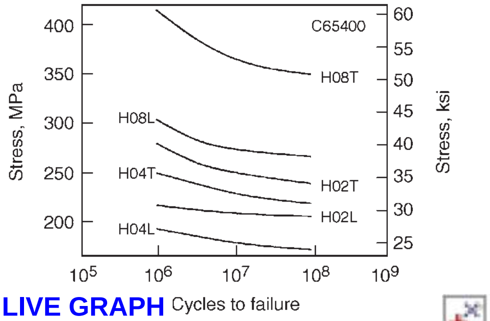

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Fig. 6 *S-N* curves for C65400. Longitudinal and transverse loading, $R = -1$

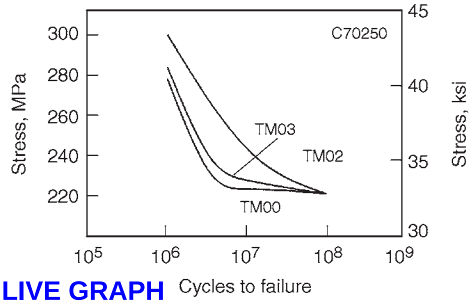

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Fig. 7 *S-N* curves for C70250. Longitudinal loading, $R = -1$

general, low-stacking-fault-energy (SFE) alloys such as C68800 and C63800, as well as C65400, exhibit greater directionality, more so than the beryllium coppers or C70250.

The C70250 alloy data are shown in Fig. 7 for three tempers. At higher cycles, the temper effect is minimal; at lower cycles, there is some temper dependence.

All of the curves shown in Fig. 1 to 7 represent fatigue stresses at which 50% of the samples would be expected to fail. The data should therefore be treated as representative and not be used for design purposes. Table 3 lists tensile properties and fatigue strengths for the alloys shown in Fig. 1 to 7.

Beryllium Coppers: Heat-Treatable and Heat-Treated Alloys. Fatigue data shown here for beryllium copper alloys are represented by a band, the lower bound determined by the lowest stress to cause failure and the upper bound determined by regression analysis of failure data from four or more commercial lots of materials. These upper bound curves are equivalent to the 50% failure curves shown in Fig. 1–7.

Beryllium copper in the solution-annealed or cold-rolled condition prior to age hardening is referred to as being in the heat-treatable temper. Examples of the bending fatigue behavior of C17200 strip heat-treatable tempers are shown in Fig. 8. The effect of cold reduction, up to 37% for the TD04 temper, has only a small effect on the fatigue response.

Figure 9 demonstrates the effect of age hardening to peak strength after cold work on fatigue behavior—about a 70 MPa (10 ksi) increase in fatigue strength. The differences due to prior cold work become pronounced at $R = 0$ (unidirectional) stressing (Fig. 10). The benefit available for unidirectional stressing is useful for switch designs that operate in unidirectional bending.

The fatigue response for age hardened C17510 (TH04), the higher-conductivity alloy with lower strength (Fig. 11), demonstrates that fatigue strengths achievable at this higher conductivity level are comparable to the higher-strength beryllium copper C17200 in the solution-treated and cold-worked, unaged condition (see Fig. 8).

Beryllium Coppers: Mill-Hardened Strip. Mill hardening consists of age hardening to a specific strength level as part of the manufacturing process. This process can reduce or eliminate the need for age hardening after component forming that is required for the age-hardenable tempers. The data in Fig. 12 represent two mill-hardened tempers of C17200 strip. The TM04 temper is a medium-strength product (760 to 930 MPa, or 110 to 135 ksi, yield strength); the TM08 temper offers the greatest strength available (1035 to 1240 MPa, or 150 to 180 ksi, yield strength). The TM08 temper shows greater stress to failure at high cycles than the TM04 temper. Both tempers show very little directionality at either load ratio, as illustrated by comparing Fig. 12 and 13. Compared to the heat-treated tempers in Fig. 9, the TM08 temper displays the greater fatigue strength in reverse bending; however, in contrast, the TH04 temper displays the greatest fatigue strength in unidirectional bending (Fig. 10).

C17410 is manufactured in two mill-hardened strip tempers, designated by their manufacturer as TH02 and TH04. Typical mill-hardened tempers are designated TM*x*. These alloys do not require additional aging by the customer. Figures 14 and 15 show the fatigue curves for these alloys. The lower-strength (TH02) temper generally shows greater fatigue strength in reverse bending than the higher-strength temper. This is in contrast to the tensile strength/fatigue trend seen in C17200 alloys. The difference between the two tempers is diminished in unidirectional bending. Fatigue strengths around 550 MPa (80 ksi) are achieved for unidirectional bending. In general, the reverse bending fatigue response of this alloy compares to the fatigue strength of the C17200 mill-hardened strip, but shows slightly reduced response unidirectionally.

Edge condition can severely affect the fatigue response of strip products, particularly high-strength alloys. Electrical and electronic spring contacts are usually manufactured by stamping, slitting, electrodischarge machining, or chemically etching. Each of these operations can impart some degree of damage to the affected edge. The effect of slit edges, simulating stamped conditions, on fatigue response were addressed in Ref 9, which studied stamped versus milled edge samples. The results confirmed that high-cycle fatigue is surface dependent in strip and that careful application of fatigue data to a design is critical.

Table 4 lists tensile and fatigue strengths of the beryllium copper alloys shown in Fig. 8 to 15.

Example 1: Strip Applications Requiring High Fatigue Strength and Resilience. The combination of high fatigue strength and resilience (the ratio of yield strength to elastic modulus as shown in Fig. 16) of beryllium copper in strip form has resulted in the use of these alloys as blades in many different types of switches, thermostatic controls, and electromechanical relays. A switch, for example a snap-acting type, undergoes a high flexural load with each cycle. The lifetime of the device is ultimately limited by the fatigue life of the switch or relay contact blade. The *S-N* curves shown in Fig. 17 illustrate the fatigue behavior of beryllium-copper for two different values of the stress ratio *R*. Switch action almost always involves unidirectional bending ($R = 0$), and therefore a very large number of cycles can be sustained by even a miniaturized switch or relay configuration. Switch designers often specify beryllium copper in the heat treated condition to achieve the highest strength possible. If mill-hardened alloys are used, it is common to choose the highest-strength tempers (TM05 through TM08) when forming requirements are not severe. Relay and thermostatic control users typically select the high-conductivity alloys such as C17510 or C17410 because their current levels are higher, and thermal management is critical in these applications.

Other types of devices also use the spring resilience and fatigue strength of beryllium copper to advantage. Detectors for seismic, ultrasonic, or other types of vibratory energy, for example, must have very high sensitivity to small signals. Springs for these devices are produced in foil thicknesses and are usually designed to have very high stiffness to vibration modes other than those in the direction of greatest interest.

Spinodal Alloy. *S-N* data for alloy C72900 are shown in Fig. 18 for TM02, 04, and 06 tempers. Fatigue strengths at 100 million cycles in reversed bending are in the range of 220 to 275 MPa (32 to 40 ksi) for all three tempers. These curves represent averaged data comparable to *S-N* curves in Fig. 1–7.

Table 3 Tensile and fatigue strengths of the copper alloys in Fig. 1 to 7

Alloy	Temper	0.2% yield strength		Ultimate tensile strength		Elongation, %	Fatigue strength (10^8 cycles)
		MPa	ksi	MPa	ksi		
C26000	H01	310	45	421	61.1	33	18
	H02	427	62	476	69	17	22
	H04	538	78	572	83	5	24
	H08	641	93	676	98	2	26
C51000	H04	581	84	597	86	8	35
	H08	712	103	732	106	3	34
	H14	745	108	788	114	3	33
C63800	O60	290	42	517	75	42	30
	H02	614	89	696	101	13	32
	H04	696	101	772	112	7	35
	H06	765	111	834	121	4	36
	H08	793	115	869	126	3	44
C65400	H02L	568	82	657	95	18	29
	H02T	593	86	701	101	10	34
	H04L	746	108	832	120	4	24
	H04T	731	106	866	125	3	31
	H08L	846	122	934	135	3	37
	H08T	859	124	991	143	2	50
C68800	O60	331	48	538	78	37	32
	H02	621	90	676	98	7	32
	H06	731	106	814	118	2	32
	H10	758	110	862	125	1	33
C70250	TM00	568	82	712	103	15	33
	TM02	643	93	718	104	12	33
C76200	H06	724	105	737	107	4	29
	H08	772	112	786	114	3	32

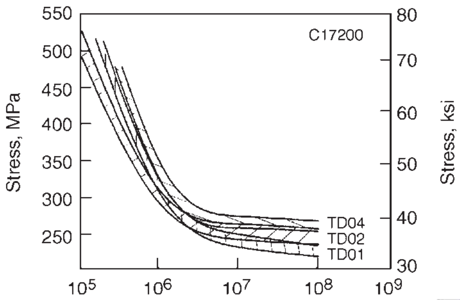

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Fig. 8 Bending fatigue curves for beryllium copper C17200 strip in the heat-treatable condition. Longitudinal loading, *R* = –1

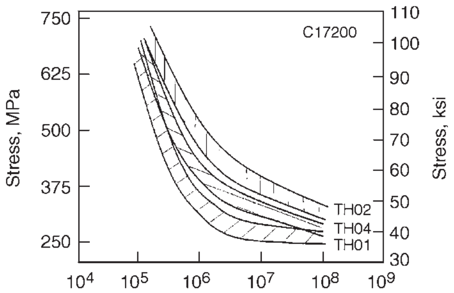

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Fig. 9 Bending fatigue curves for heat-treated (peak-aged) C17200 strip. Longitudinal loading, *R* = –1

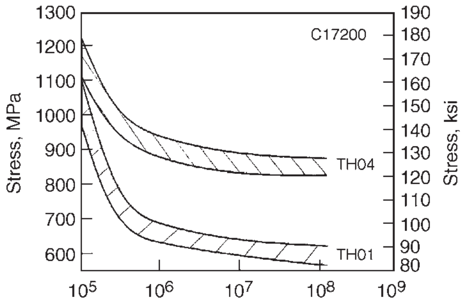

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Fig. 10 Bending fatigue curves for heat-treated (peak-aged) C17200 strip. Longitudinal loading, *R* = 0

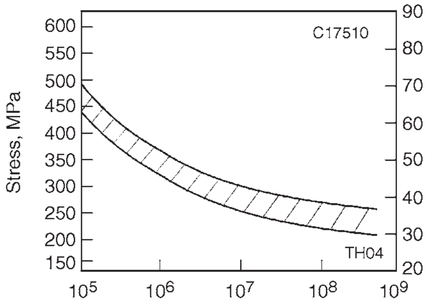

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Fig. 11 Bending fatigue curves for C17510 TH04 strip. Longitudinal and transverse loading, *R* = –1

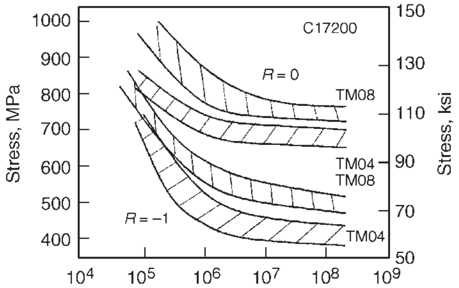

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Fig. 12 Bending fatigue curves for C17200 TM04 and TM08 strip tempers. Longitudinal loading, R = 0 and –1

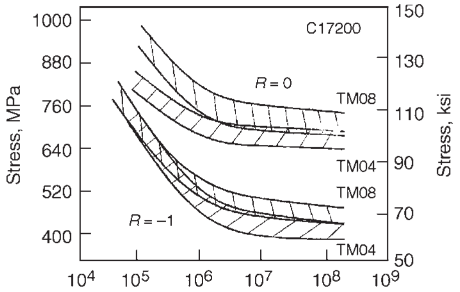

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Fig. 13 Bending fatigue curves for C17200 TM04 and TM08 strip tempers. Transverse loading, *R* = 0 and –1

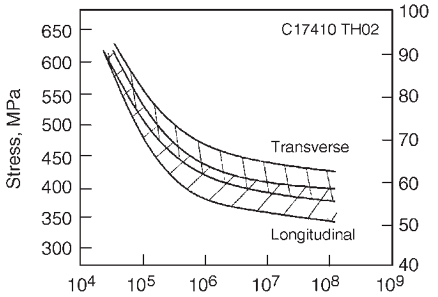

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Fig. 14 Bending fatigue curves for C17410 TH02 strip. Longitudinal and transverse loading, R = –1

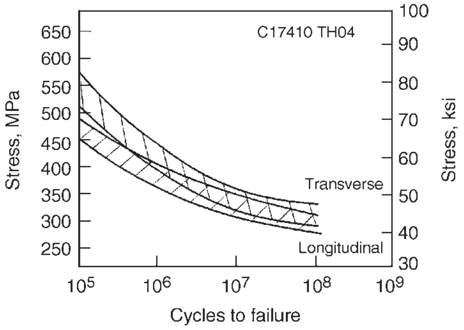

Fig. 15 Bending fatigue curves for C17410 TH04 strip. Longitudinal and transverse loading, *R* = –1

Table 4 Tensile and fatigue strengths of selected tempers of the beryllium copper alloys in Fig. 8 to 15

		0.2% yield strength		Ultimate tensile strength			
Alloy	**Temper**	**MPa**	**ksi**	**MPa**	**ksi**	**Elongation, %**	**Fatigue strength (10^8 cycles, R = –1)**
C17200	TD01	415–550	60–80	515–605	75–88	30–45	31–36
	TD02	515–655	75–95	585–690	85–100	12–30	32–38
	TD04	620–795	90–115	690–825	100–120	2–18	35–39
	TH01	1035–1275	150–185	1205–1415	175–205	3–10	40–45
	TH02	1105–1345	160–195	1275–1480	185–215	1–8	42–47
	TH04	1140–1415	165–205	1310–1515	190–220	1–6	45–50
	TM04	760–930	110–135	930–1035	135–150	9–20	45–52
	TM08	1035–1240	150–180	1205–1310	175–190	3–12	50–60
C17510	TH04	655–825	95–120	760–930	110–135	8–20	42–47
C17410	TH02	550–690	80–100	655–790	95–115	10 (min)	45
	TH04	690–825	100–120	760–895	110–130	7 (min)	45

Heavy-Section Beryllium Copper

Rotating-beam *S-N* curves are shown in Fig. 19 for C17200 in age-hardened tempers TF00 and TH04. Generally speaking, the smaller the diameter or size, the greater the fatigue strength. This behavior is linked directly to the microstructure, which will be discussed in the following section.

Structure, Processing, and Property Relationships

As noted earlier, fatigue strength for copper alloys is usually defined as the stress sustainable without failure for 100 million cycles. (For the average (50% failure) curves, this actually means 50% will fail at this stress level.) For this high-cycle condition, most of the life is spent in crack nucleation, assuming the component in question does not have mechanical defects or other notches in the high-stress area.

High SFE alloys exhibit fatigue crack nucleation within persistent slip bands—markings produced by cyclic microplastic deformation. This is not an apparent mode of crack nucleation for low-SFE alloys. In general, cold work has a more beneficial effect on fatigue strength of low-SFE alloys versus copper and high-SFE copper alloys. Reducing grain size generally increases fatigue strength. This effect diminishes with increasing cold work.

Resistance to microplastic deformation and enhancement of fatigue life can be produced by precipitation hardening if the precipitate phase is stable under cyclic loading. This is the case for beryllium copper and copper-nickel-tin precipitates.

Beryllium Coppers. Microstructure plays an important role in the fatigue performance of beryllium copper alloys. Age-hardened structures contain a mixture of metastable precipitates within a copper alloy matrix. The metastable precipitates dominate the deformation behavior of these alloys because of the small size, high volume fraction, homogeneous distribution, and high elastic strain contribution within the copper matrix. Aging, therefore, significantly affects fatigue behavior.

The high-strength C17200 alloys and C17410 contain a stable cobalt beryllide intermetallic, and C17510 contains a nickel beryllide. These beryllides are considerably larger than the precipitates and spaced sufficiently apart (i.e., long mean free path) so they do not contribute significantly to the fatigue performance.

An overaged structure will generally result in improved bending or rotating fatigue performance. Even though overaging results in some-

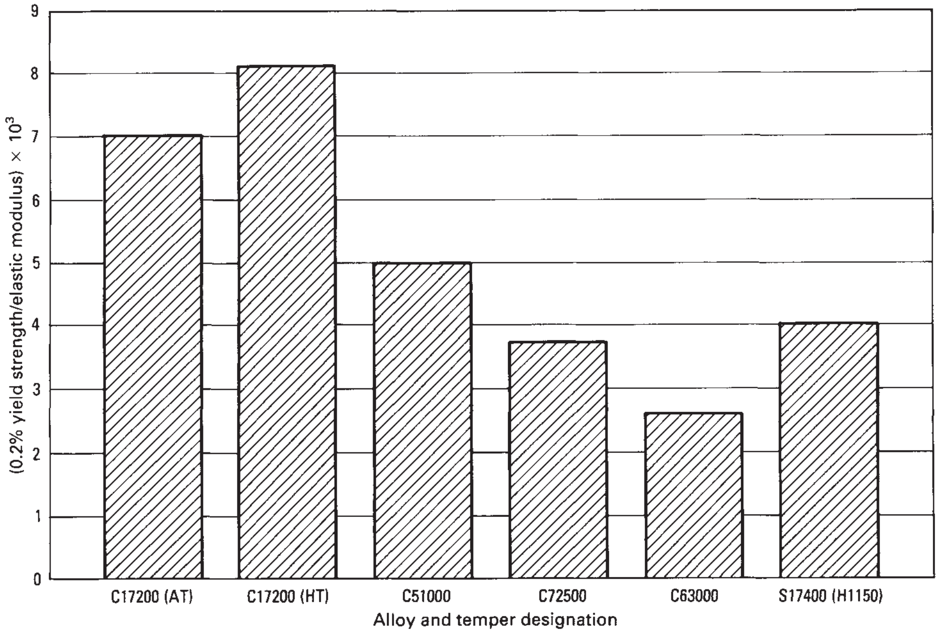

Fig. 16 The resilience (ratio of yield strength to elastic modulus) for two tempers of beryllium copper, several other electronic component copper alloys, and one steel (precipitation hardening stainless steel S17400). This property measures the ability of a spring to apply a high force from a relatively large deflection without taking a permanent set. The high ratio displayed by beryllium copper tempers means that they can grip the edge of a printed circuit board or a mating pin member with positive action, and this action will be retained through repeated insertion cycles. Source: Ref 6

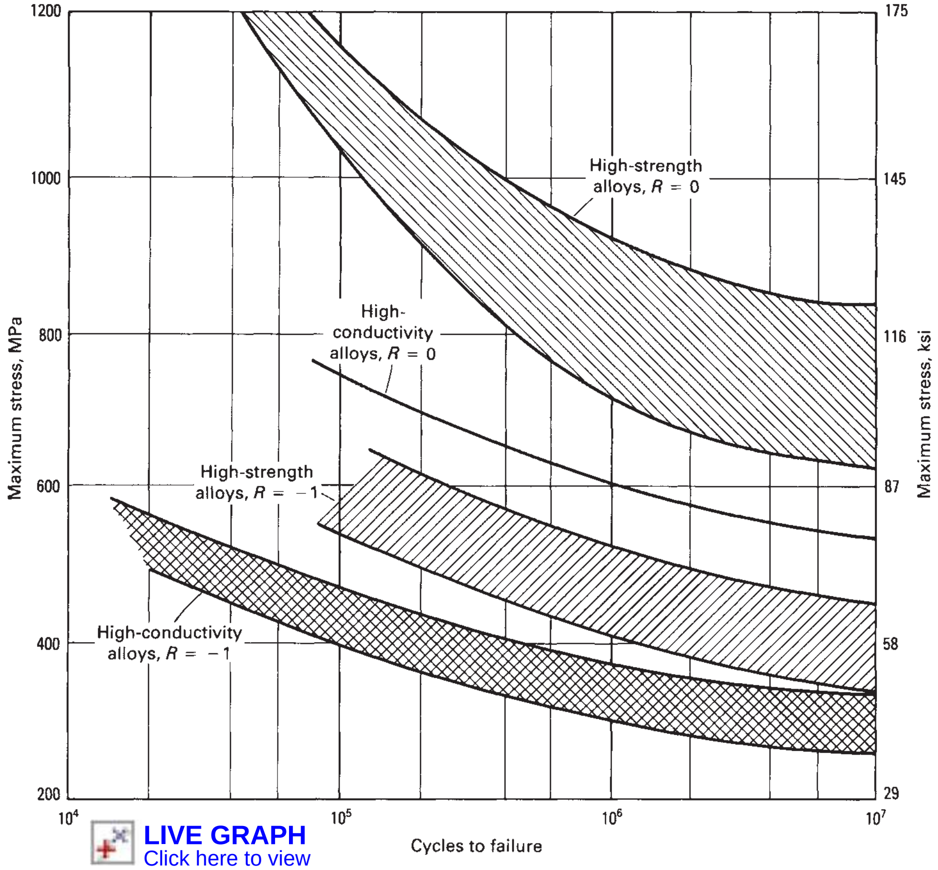

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Fig. 17 Fatigue behavior of beryllium copper strip according to the stress ratio R in unidirectional ($R = 0$) and fully reversed ($R = -1$) bending. Source: Ref 6

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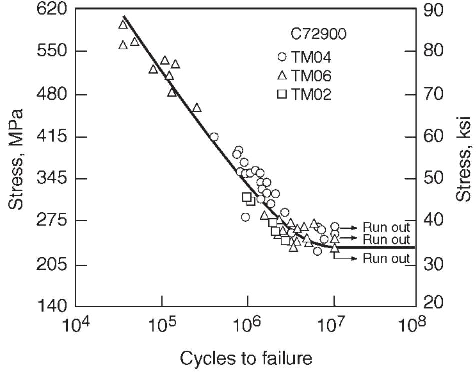

Fig. 18 *S-N* curve for C72900 in TM02, TM04, and TM06 tempers. Longitudinal loading, $R = -1$

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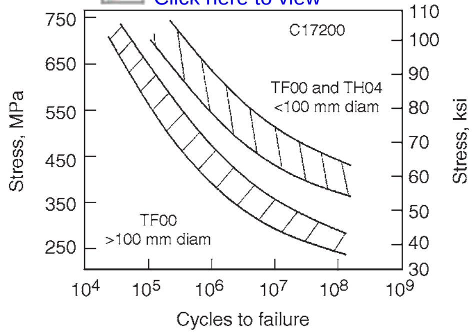

Fig. 19 Rotating-beam fatigue curves for C17200 TF00 and TH04 rod as a function of diameter

what lower strength, the net result is an improvement in fatigue life because overaging prolongs the crack nucleation stage. Overaging causes the precipitate/matrix orientation relationship to progress to form incoherent γ phase from the metastable coherent Guinier-Preston zones.

Conversely, the fatigue crack propagation behavior worsens as the alloys are overaged (Fig. 20). Deformation becomes highly localized at the grain boundaries as a result of the heterogeneous cellular reaction forming the equilibrium γ phase while creating adjacent regions within the grain boundaries of solute-depleted copper. Dislocation pileups at the grain boundaries are not adequately blunted and propagate easily into the boundaries, resulting in a crack path "short circuit." Nonetheless, the increase in crack propagation rate for overaged versus peak-aged material does not alter the overall improved life associated with the overaged condition.

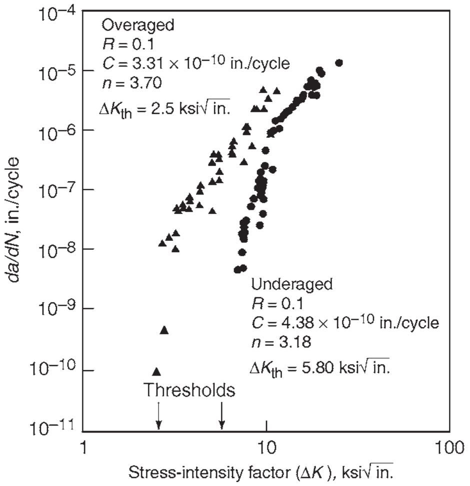

Fig. 20 Fatigue crack propagation rate of C17200 in the overaged and underaged conditions. Material aged to 760 MPa (110 ksi) yield strength

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ACKNOWLEDGMENTS

This article was adapted from J. Crane, J.O. Ratka, and J.F. Breedis, Fatigue Properties of Copper Alloys, *Fatigue and Fracture,* Vol 19, *ASM Handbook,* ASM International, 1996, p 869–873. Example 1 was taken from Ref 6.

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Properties of Pure Copper

THE PROPERTY DATA presented in this article were measured on various coppers of purity equal to or exceeding those of electrolytic copper (99.90% Cu min) up to 99.999+% Cu (a total impurity content of less than 10 ppm). The original references cited should be consulted if more detailed information regarding purity levels or the method of characterizing purity is needed.

Atomic and Electron Structures

Atomic Structure. Copper, with atomic number 29 and atomic weight 63.546, occupies the first position of subgroup IB in the periodic chart of the elements (Fig. 1). Subgroup IB also includes silver and gold, and in fact, copper shares many characteristics with these other noble metals as a result of its atomic and electron structure.

Electron Structure. The copper atom is composed of a positively charged nucleus containing 29 protons and 34 to 36 neutrons surrounded by 29 electrons. The electrons are arranged in a structure described by the notation $1s^22s^22p^63s^23p^63d^{10}4s^1$, which implies that the 1s and 2s energy states contain two electrons each, and the 3s state contains two electrons; the 2p states contain six electrons, and so forth. The structure is essentially that of an argon atom core plus the filled 3d state and the one 4s electron; it is sometimes written as $Ar3d^{10}4s^1$. The single "outer shell" 4s electron is responsible for many important physical properties of copper, including its high electrical conductivity, its chemical stability, and its reddish color. In metallic crystalline copper, as with other metals, the 4s electron does not remain associated with any particular atom but becomes part of the electron cloud that pervades the crystal lattice (Ref 1).

The ionization potential of the 4s electron, 7.724 eV, is relatively low, and the "cuprous" ion, Cu^+, is easily formed. The ionization potential of the 3d state is only slightly higher, and copper, therefore, also displays a "cupric" valence state, Cu^{2+} (Ref 1–3).

Crystal Structure

Copper exhibits the face-centered cubic (fcc) structure at all temperatures below the melting point (structure symbol: *A*1; space group: *Fm*3*m*; Pearson symbol: c*F*4). Reported values for the lattice parameter include $a = 0.3615090 \pm 0.000004$ nm at 25 °C (77 °F) (Ref 2), and $a =$ 0.36147 nm at 293 K (20 °C, or 68 °F) (Ref 4). Based on the value reported by Weast (Ref 2), the distance of nearest approach, or Burgers vector, in the [110] direction at 293 K is 0.255625 nm.

Slip Systems. In fcc metals such as copper, the {111} octahedral planes and the ⟨110⟩ directions contain closest atomic packing and, therefore, constitute the most active slip systems. There are four independent (111) slip planes in the fcc unit cell. Each (111) plane contains three [110] directions; therefore, the copper lattice has 12 possible slip systems. Slip occurs when the shear stress in a slip direction in the slip plane reaches a critical value, τ_{cr}. Room-temperature values of τ_{cr} for copper single crystals of two degrees of purity are as follows (Ref 5):

Purity, %	τ_{cr}
99.999+	65
98.98	94

Twinning. Face-centered metals such as copper undergo twinning; for example, they deform by forming mirror-image orientations, across {111} planes in the [112] direction. Twinning is a less important deformation mechanism in fcc metals than it is in body-centered cubic (bcc) or hexagonal close packed (hcp) metals, which have less favorable slip systems; however, copper does form annealing twins to accommodate deformation arising from recrystallization following cold work. Thus, the presence of annealing twins in the microstructure is evidence that the metal has been mechanically deformed prior to annealing.

Stacking Faults. The stacking fault energy of copper, that is, the energy associated with imperfectly positioned adjacent lattice planes, is approximately 40 erg/cm^2. Stacking fault energy is related to such deformation-related properties as flow stress and strain hardening. It has been shown by x-ray diffraction that the stacking fault energy of brass decreases with zinc content, and this is in agreement with the observation that alpha brass forms a greater number of mechanical twins than copper.

Density and Volume Change on Freezing

The density of copper varies from 8.90 to 8.95 g/cm^3, depending on the metal's thermomechanical history (Table 1). Density initially decreases with increasing degrees of cold work owing to the generation of vacancies and dislocations. It then increases to a value higher than that of recrystallized copper. This has been explained by the presence of persistent subgrain boundaries. The accepted value for the density of copper is 8.94 g/cm^3 at 298 K (25 °C, or 77 °F). This density is slightly different from that used in electrical standards, as described subsequently. Temperature also affects density values (Ref 2):

°C	g/cm^3
20	8.93
Melting point	7.940
1100	7.924
1200	7.846
1300	7.764

See also Fig. 2.

The volume change on freezing for pure copper equals 4.92% contraction.

Electrical Properties

Electrical Conductivity. In 1913, the standard conductivity of pure annealed copper was fixed by the International Electrotechnical Commission (IEC) as that of an annealed copper wire 1 m long, weighing 1 g and having a density of 8.89 g/cm^3. The wire exhibited a resistance of exactly 0.15328 Ω. This value was assigned a volume conductivity of 100% of the International Annealed Copper Standard, written 100% IACS (Ref 8).

Conductivity depends strongly on purity. Purity levels and processing techniques have improved considerably since the IACS was established, and a more precise value for density has also been measured. However, the standard value continues to be used in engineering practice. Currently, the highest measured room-temperature (20 °C, or 68 °F) volume

Table 1 Effect of processing on the densities of pure copper at 20 °C (68 °F)

State	Density (ρ), g/cm^3
Single crystal	8.95285
Melted and solidified in vacuum	8.94153
Commercial soft-drawn wire, annealed at 970 °C (1778 °F) in vacuum for 12 h	8.92426
Sample reduced 67.90% in cross section by drawing	8.90526
Diameter reduced 96.81%	8.91187
Sample annealed at 880 °C (1616 °F) in vacuum for 12 h	8.93003
Sample annealed at 1035 °C (1895 °F) in vacuum for 12 h	8.92763

Source: Ref 6

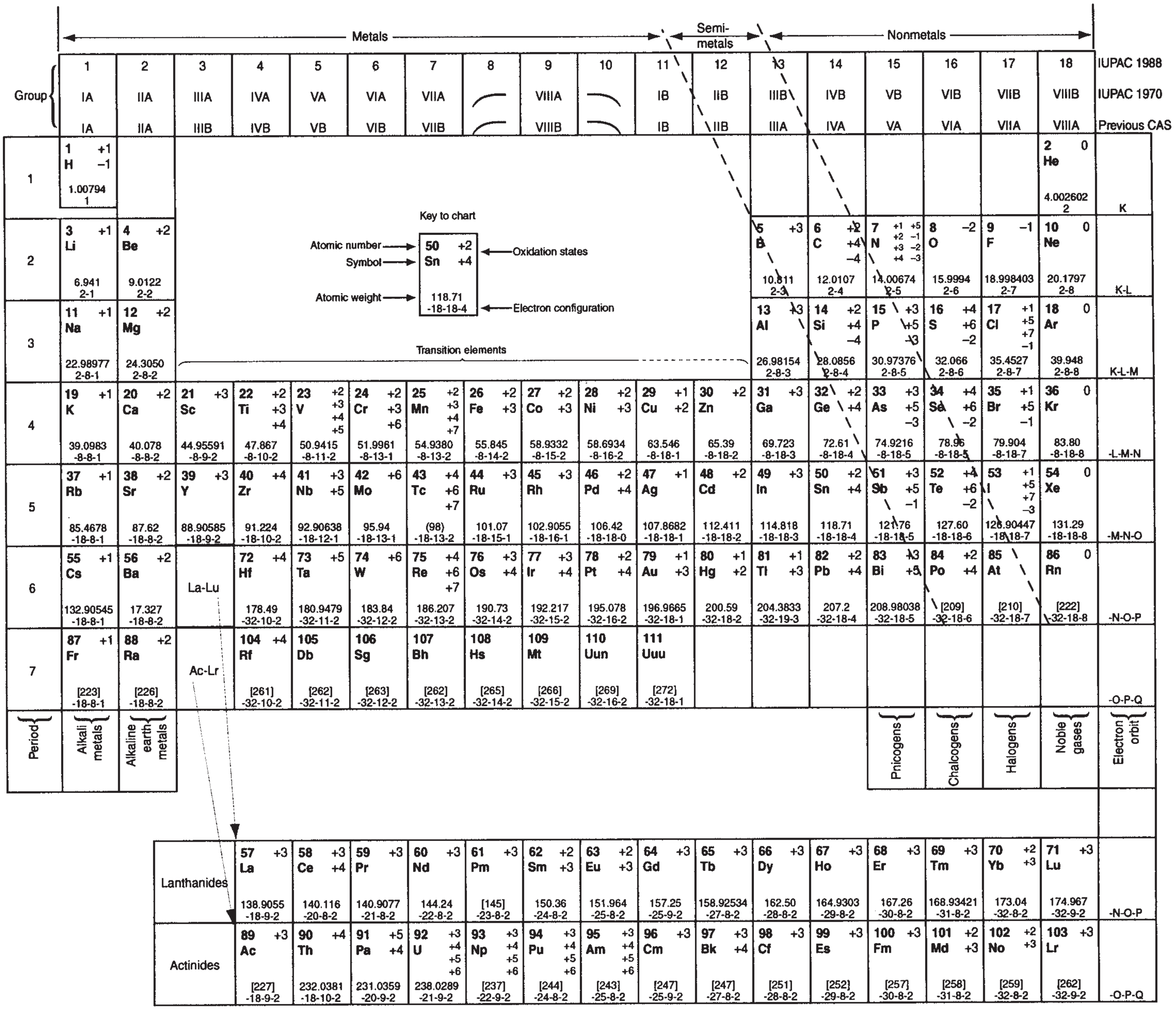

Fig. 1 Periodic table of the elements. Values in brackets indicate the mass number of the longest-lived isotope of the radioactive element. Copper occupies the first position of subgroup IB·

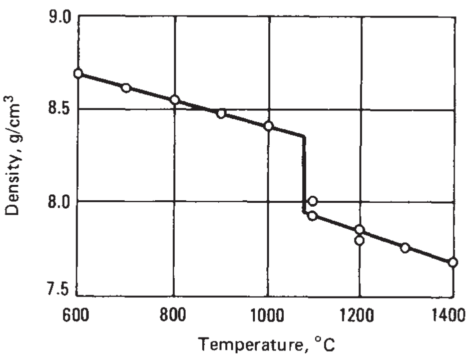

Fig. 2 Variation of density with temperature for pure copper. Source: Ref 7

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conductivity for very pure copper is about 103.6% IACS.

Current practically attainable conductivity values for electrolytic tough pitch and deoxidized low residual phosphorus coppers stand at about 101% IACS. Oxygen-free (OF) copper is certified under ASTM B 170 to meet this as a minimum value.

Figures 3 and 4 show the effects of annealing and cold reduction on the electrical conductivity of pure copper, respectively. Additional conductivity data for copper and its alloys can be found in various articles in this Handbook covering wrought and cast copper products. The decrease in electrical conductivity brought about by impurities or secondary elements in solid solution is discussed in the articles "Introduction and Overview" and "Physical Metallurgy: Heat Treatment, Structure, and Properties" in this Handbook.

The electrical resistivity of pure copper at 20 °C (68 °F) is 16.730 nΩ · m. The temperature coefficient at 20 °C (68 °F) is 0.068 nΩ · m. The pressure coefficient is –20.228 aΩ · m/Pa for the pressure range of 100 kPa to 9.8 GPa. The increase in resistivity brought about by impurities or secondary elements in solid solution is discussed in the articles "Introduction and Overview" and "Physical Metallurgy: Heat Treatment, Structure, and Properties" in this Handbook. The effect of high temperature (in degrees Kelvin) on resistivity is shown in Fig. 5. Electrical resistivities for low temperatures measured in degrees Kelvin are:

K	nΩ · m
250	14.0
220	12.0
200	10.6
180	9.2
160	7.75
140	6.35
120	4.90
100	3.50
90	2.80
80	2.15
70	1.53
60	0.95
50	0.50
40	0.22
30	0.063
25	0.025
20	0.008
15	0.001

Other electrical properties of interest for pure copper include:

- *Thermoelectric potential versus platinum* (Ref 2, 9):

°C	mV
–200	–0.19
–100	0.37
0	0
100	0.76
200	1.83
300	3.15
400	4.68
500	6.41
600	8.34
700	10.47
800	12.81
900	15.37
1000	18.16

- *Electrochemical equivalent:* 0.3294 mg/C for Cu^{2+}; 0.6588 mg/C for Cu^{+}
- *Electrolytic solution potential:* All versus standard hydrogen electrode (Ref 2): $Cu^{2+} + e^{-} \leftrightarrow Cu^{+}$, 0.158 V; $Cu^{2+} + 2e^{-} \leftrightarrow Cu$, 0.3402 V; $Cu^{+} + e^{-} \leftrightarrow Cu^{+}$, 0.522 V
- *Ionization potential:* Cu(I), 7.724 eV; Cu(II), 20.29 eV; Cu(III), 36.83 eV (Ref 2)
- *Hydrogen overvoltage:* In 1 N H_2SO_4 $\eta = a + b (\log i)$, where η is overvoltage in V, i is current density in A/cm^2, constant a is 0.80 V, and constant b is 0.115 V (Ref 10)
- *Hall effect:* Hall voltage, -5.24×10^{-4} V at 0.30 to 0.8116 T; Hall coefficient, –5.5 mV · m/A · T (Ref 9)
- *Electron emission:* Secondary electron emission: 1.3 max secondary electron yield; 600 eV primary electron energy for max yield; 200 eV for E(I) crossover; 1500 eV for E(II) crossover
- *Work function:*

Work function, eV	Conditions	Method of determination
4.5	1160–1200 K	Thermionic
4.6	1350 K	Thermionic
4.4	1100–1300 K	Thermionic
4.76	$\langle 111 \rangle$	Photoelectric
4.86	$\langle 111 \rangle$	Photoelectric
5.61	$\langle 110 \rangle$	Photoelectric
4.60	…	Contact potential
4.51	…	Contact potential

Source: Ref 9

Thermal Properties

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The thermal conductivity of pure copper at 27 °C (81 °F) is 398 W/m · K. The effect of temperature on thermal conductivity of pure copper is shown in Table 2 and Fig. 6. As with electrical conductivity, a decrease in the thermal conductivity of pure copper is brought on by the presence of impurities or secondary alloying elements in solid solution.

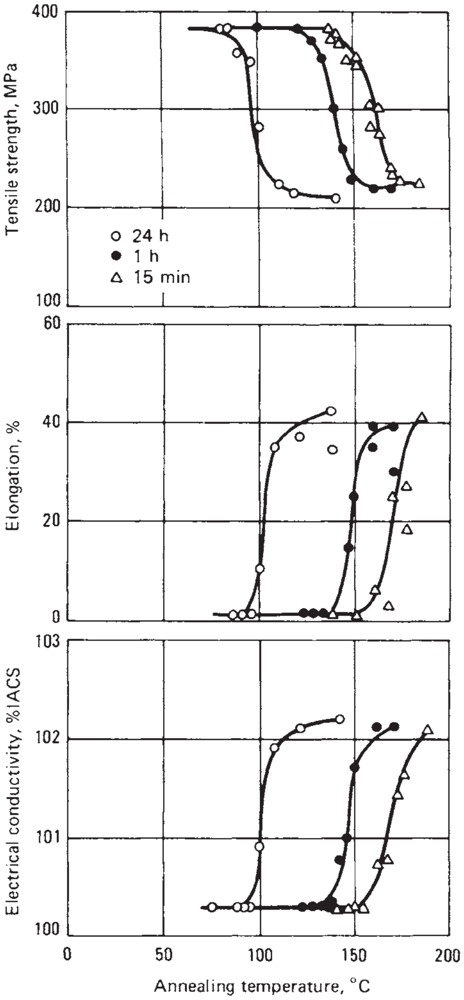

Fig. 3 Effect of annealing on the tensile strength, elongation, and electrical conductivity of pure copper.

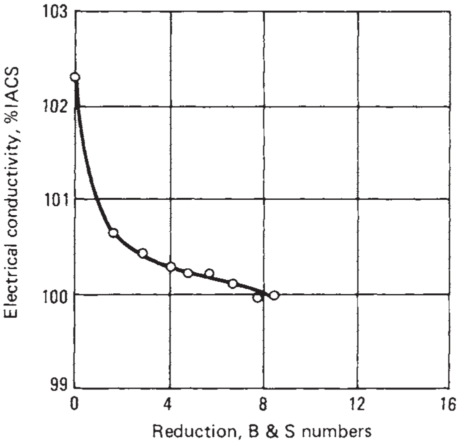

Fig. 4 Effect of cold reduction on the electrical conductivity of pure copper wire. B & S, Brown and Sharpe (wire gage numbers)

LIVE GRAPH
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Other thermal properties of interest for pure copper include:

- *Melting point:* 1084.88 °C (Ref 11)
- *Boiling point:* 2595 °C (Ref 12); 2567 °C (Ref 2)
- *Coefficient of thermal expansion:* Linear, 16.5 µm/m · K at 20 °C (Ref 2). See also Table 3. Volumetric, 49.5×10^{-6}/K (Ref 9)
- *Specific heat:* 0.494 kJ/kg · K at 2000 K; 0.386 kJ/kg · K at 293 K; 0.255 kJ/kg · K at 100 K (Ref 2). See also Fig. 6 and Table 4.
- *Enthalpy, entropy:* See Table 4.
- *Latent heat of fusion:* 205 kJ/kg (Ref 2); 204.9 kJ/kg (Ref 11); 206.8 kJ/kg (Ref 9)
- *Latent heat of vaporization:* 4729 kJ/kg (Ref 1); 4726 kJ/kg (Ref 9); 4793 kJ/kg (Ref 10)

Table 2 Thermal conductivity of pure copper

Temperature, K	Conductivity, W/m · K
0	0
1	2870
2	5730
3	8550
4	11300
5	13800
6	15400
7	17700
8	18900
9	19500
10	19600
11	19300
12	18500
13	17600
14	16600
15	15600
16	14500
18	12400
20	10500
25	6800
30	4300
35	2900
40	2050
45	1530
50	1220
60	850
70	670
80	570
90	514
100	483
150	428
200	413
250	404
273	401
300	398
350	394
400	392
500	388
600	383
700	377
800	371
900	364
1000	357
1100	350
1200	342
1300	334(a)
1373	160
1773	172
1973	176
2273	177

(a) Extrapolated value. Source: Ref 2, 9

- *Recrystallization temperature:* Depends on several variables, including the time at annealing temperature, chemical composition, and the amount and type of plastic deformation (Ref 13). The inflection points of the curves shown in Fig. 3 indicate the recrystallization temperature for the annealing times/temperatures given. More detailed information can be found in the article "Heat Treating" in this Handbook.
- *Vapor pressure:* From Ref 2:

°C	Pa
946	1.3×10^{-3}
1035	1.3×10^{-2}
1141	1.3×10^{-1}
1273	1.3
1432	13
1628	130
1879	1330
2067	5.33×10^{3}
2207	1.33×10^{4}
2465	5.33×10^{4}
2595	1.01×10^{5}
2760	2.02×10^{5}
3010	5.07×10^{5}
3500	1.01×10^{6}
3640	2.02×10^{6}
3740	4.05×10^{6}

Magnetic Properties

Magnetic susceptibility (χ) is defined as the ratio of induced magnetization to applied magnetic field, for example, $\chi = M/H$, where H is the applied magnetic field, and M is the magnetization. Each material has a characteristic magnetic susceptibility, although the property varies somewhat with thermomechanical history. Copper is diamagnetic because its magnetic susceptibility is negative. Data from several sources are listed in Table 5.

In commercial coppers and copper alloys, magnetic susceptibility is determined largely by the iron contained as an impurity. In OF copper, the small amount of iron present in solid solution has only a small effect on magnetic properties. In electrolytic-tough-pitch (ETP) copper containing about 200 ppm oxygen, the iron is present as Fe_3O_4, which has a much greater effect on the magnetic properties than iron in solid solution.

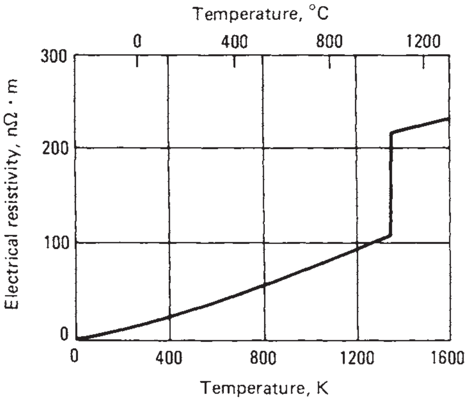

Fig. 5 Effect of high temperatures on the electrical resistivity of pure copper

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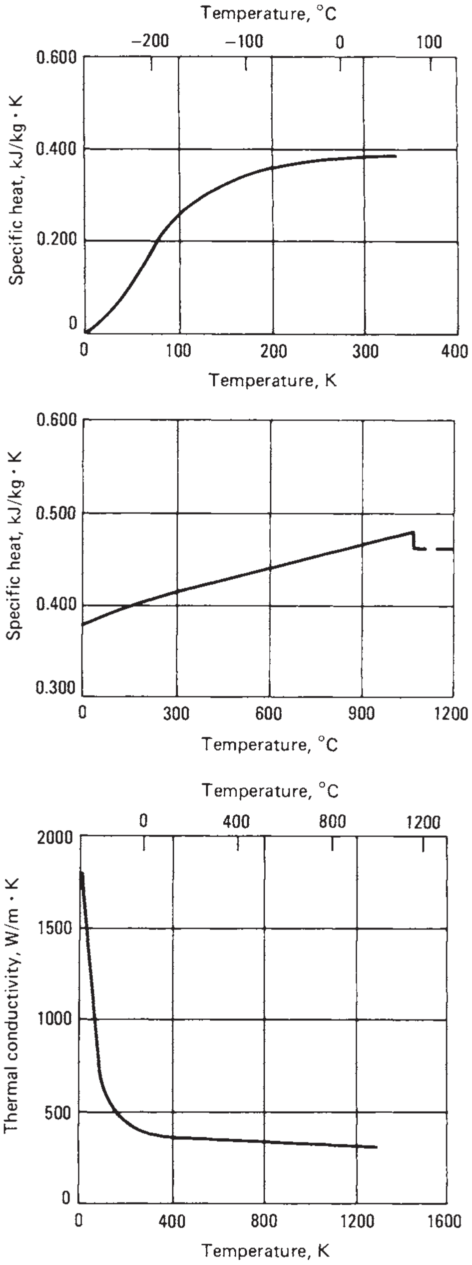

Fig. 6 Effect of temperature on the specific heat and thermal conductivity of pure copper

Magnetic permeability (μ) is defined as the magnetic opacity of a material in a given magnetic field. It is expressed as $\mu = B/H$, where B is the flux density and H is the applied magnetic field or magnetizing force. It is the instantaneous slope of the magnetization. For pure copper, μ is very low. This is very useful because low permeability in the presence of magnetic fields avoids energy losses in applications such as electric motors and generators.

Table 3 Mean coefficient of linear thermal expansion for pure copper

Temperature, K	Mean coefficient, μm/m · K
2	0.0006
4	0.0025
6	0.0074
8	0.016
10	0.030
12	0.052
14	0.083
16	0.128
18	0.186
20	0.26
25	0.6
50	3.8
75	7.6
100	10.5
150	13.6
200	15.2
250	16.1
293	16.7
350	17.3
400	17.6
500	18.3
600	18.9
700	19.6
800	20.4
1000	22.4
1200	24.8

Source: Ref 2

Optical Properties

Color. Copper is the only metallic element except gold to have a natural color other than silvery gray. The distinctive reddish color of copper corresponds to the sharp onset in frequency of strong interband optical transitions between filled states at the upper part of the 3d band and empty conduction-band 4s-like states. Copper alloys range in color from the reddish pink of pure copper to golden yellow and silvery white, depending on alloy composition. The color of brasses ranges from reddish to pale yellow, depending on their zinc content. Thus, low zinc casting alloys are categorized as "red" or "semired" brasses, while high-zinc brasses are called yellow brasses. Beryllium coppers change from red to gold with increasing beryllium content, while copper-nickels are pink at low nickel concentrations and distinctly silvery at higher nickel contents.

Reflectivity and Emissivity. The reflectivity of copper decreases continuously with wavelength from the infrared through ultraviolet regions. For incandescent light, the spectral reflection coefficient of copper is 0.63. Tables 6 and 7 list indices of refraction, extinction coefficients, and reflectance values (measured and calculated) for several types of copper surfaces. Reflectance data for polished or electroplated surfaces are as follows:

Wavelength, μm	Reflectance(a), %
0.25	25.9
0.30	25.3
0.35	27.5
0.40	30.0
0.50	43.7
0.60	71.8
0.70	83.1
0.80	88.6
1.0	90.1
2.0	95.5
4.0	97.3
6.0	98.0
8.0	98.3
10.0	98.4
12.0	98.4

(a) Data are for polished surfaces at close-to-normal incidence

Table 4 Thermodynamic properties of copper

Temperature, K	C_p^0 • J/kg • K	$H_T^0 - H_0^0$, J/kg	$(H_T^0 - H_0^0)/T$, J/kg • K	S_T^0, J/kg • K	$-(G_T^0 - H_0^0)$, J/kg	$G_T^0 - H_0^0)/T$, J/kg • K
1	0.0117	0.00565	0.00565	0.0112	0.00552	0.0052
2	0.0278	0.0249	0.0124	0.0239	0.0228	0.0114
3	0.0530	0.0644	0.0214	0.0395	0.0543	0.0181
4	0.0916	0.0135	0.0338	0.0596	0.103	0.0258
5	0.148	0.253	0.0507	0.0859	0.176	0.0351
6	0.228	0.439	0.0733	0.120	0.277	0.0463
7	0.335	0.717	0.103	0.162	0.417	0.0596
8	0.474	1.120	0.140	0.216	0.606	0.0757
9	0.651	1.684	0.187	0.282	0.853	0.0947
10	0.873	2.439	0.244	0.360	1.174	0.117
11	1.14	3.446	0.313	0.456	1.57	0.144
12	1.47	4.752	0.395	0.570	2.09	0.175
13	1.87	6.405	0.493	0.703	3.51	0.209
14	2.34	8.513	0.607	0.858	2.72	0.250
15	2.89	11.11	0.741	1.039	4.45	0.297
16	3.54	14.32	0.895	1.245	5.59	0.349
17	4.30	18.22	1.072	1.481	6.96	0.409
18	5.16	22.94	1.275	1.747	8.56	0.475
19	6.14	28.58	1.504	2.061	10.46	0.551
20	7.27	35.28	1.763	2.392	12.68	0.634
25	15.15	89.75	3.59	4.80	30.17	1.21
30	26.64	192.8	6.42	8.51	62.87	2.09
35	41.51	361.8	10.34	13.71	117.8	3.37
40	58.86	612.0	15.30	20.36	202.4	5.07
45	77.55	952.7	21.17	28.36	323.7	7.19
50	96.84	1388	27.78	37.53	488.0	9.757
60	135.3	2549	42.50	58.60	965.9	16.10
70	170.9	4084	58.35	82.18	1668	23.83
80	202.2	5955	74.42	107.1	2614	32.67
90	229.1	8115	90.17	132.5	3811	42.35
100	251.9	10520	105.2	157.8	5264	52.64
110	271.0	13140	119.5	182.9	6968	63.34
120	287.2	15940	132.8	207.1	8918	74.32
130	300.9	18870	145.2	230.7	11110	85.43
140	312.7	21950	156.7	253.4	13530	96.62
150	322.7	25130	167.4	275.2	16180	107.8
160	331.3	28390	177.5	296.5	19030	118.9
180	345.3	35170	195.5	336.3	25370	140.9
200	356.1	41290	210.9	373.3	32460	162.2
220	364.6	49400	224.6	407.6	40270	183.1
240	371.4	56760	236.5	439.7	48750	203.2
260	376.7	64240	247.1	469.6	57850	222.5
273.15	379.7	69210	253.4	488.2	64140	234.8
280	381.1	71820	256.5	497.6	67530	241.1
298.15	384.6	78760	264.2	521.7	76780	257.5
300	384.9	79490	265.0	524.0	77740	259.2

Notes: C_p^0 is the specific heat at constant pressure conditions; H_T^0 is the enthalpy at absolute temperature; H_0^0 is enthalpy at 0 K and 1 atm; S_T^0 is the entropy at absolute temperature; G_T^0 is the free energy at absolute temperature; T is degrees Kelvin. Source: Ref 2

Table 5 Magnetic susceptibility of pure copper

Temperature, °C	$\chi \times 10^6$, cgs	Temperature, °C	$\chi \times 10^6$, cgs
–267	–0.0836(c)	18	–1.08(b)
–259 to –253	–1.22(b)	19	–0.0855(c)
–250	–0.0856(c)	20	–0.086(a)
–242	–0.0863(c)	300	–0.085(a)
–233	–0.0879(c)	600	–0.082(a)
–211	–0.0873(c)	900	–0.079(a)
–174	–0.0869(c)	1080 (solid)	–0.077(a)
–171	–0.0867(c)	1080	–0.97(b)
–65	–0.0863(c)	1090	–0.68(b)
–26	–0.0859(c)	1090 (liquid)	–0.054(a)

(a) Ref 14. (b) Ref 15. (c) Ref 16. Source: Ref 17

Other optical properties of interest for pure copper include:

- *Nominal spectral emittance:* 0.15 for polished Cu at λ = 655 nm and 1080 K
- *Absorptive index:* Coefficient of absorption of solar radiation, 0.25 (Ref 2)

Nuclear Properties

Isotopes. Copper has two stable isotopes:

Isotope	Atomic weight	Natural abundance, %
^{63}Cu	62.9298	69.09
^{65}Cu	64.9278	30.91

The unstable isotopes of copper include:

Isotope	Half-life	Modes of decay(a)	Mean decay energy, MeV
^{58}Cu	3.20 s	β^+	8.569
^{59}Cu	82.0 ± 0.4 s	β^+, EC	4.8
^{60}Cu	23.0 ± 0.3 min	β^+, EC	6.12
^{61}Cu	3.41 h	β^+, EC	2.242
^{62}Cu	9.8 min	β^+, EC	3.939
^{64}Cu	12.9 h	β^-	0.573
		β^+, EC	1.677
^{66}Cu	5.10 ± 0.02 min	β^-	2.633
^{67}Cu	61.88 ± 0.11 h	β^-	0.576
^{68}Cu	30 s	β^-	4.6

(a) EC, electron capture

Nuclear Absorption Cross Section. The absorption cross section of copper, σ, with respect to low energy proton bombardment is 10^{-27} barns (1 barn = 1 cm^2). For high energy (134 ± 4 MeV) protons, $\sigma = 725 \pm 68$ barns. The absorption cross section for fast neutrons is 10^{-24} barns, while for thermal neutrons, values of 3.63 and 3.8 barns have been reported (Ref 2).

Chemical Properties

Corrosion Resistance. Copper is insoluble in both hot and cold water, slightly soluble in hydrochloric acid and ammonium hydroxide, and soluble in nitric acid and hot sulfuric acid (Ref 2). A more detailed account of the corrosion resistance of coppers in a variety of environments can be found in the article "Corrosion Behavior" in this Handbook.

Mechanical Properties

Tensile Properties. Copper, particularly when in the annealed state, is considered a soft and ductile metal. Tensile properties for both annealed and cold-drawn copper are listed in Table 8. Figure 3 shows the effects of annealing times and temperatures on the tensile strength and elongation of pure copper. The variation in tensile properties of copper wire due to cold reduction is illustrated in Fig. 7. Additional information on the tensile properties of commercially pure coppers can be found throughout this Handbook.

Other mechanical properties of interest for pure copper include:

- *Hardness:* Cold drawn, 37 HRB
- *Poisson's ratio:* 0.308 calculated from elastic modulus; annealed, 0.343 (Ref 11); cold drawn, 0.364 (Ref 9)
- *Strain-hardening exponent:* Annealed, 0.54 (Ref 18)
- *Elastic modulus:*

Tension, GPa	Ref
128	9
112 (cold drawn)	9
125 (annealed)	18
129.8	11
Shear, GPa	**Ref**
46.8	9
46.4 (annealed)	18
48.3	11
Bulk, GPa	**Ref**
140	9
137.8	11

- *Elastic modulus along crystal axes:* Tension: ⟨100⟩, 68 GPa; ⟨111⟩, 21 GPa. Shear: ⟨100⟩, 77 GPa (Ref 18)
- *Specific damping capacity:* Log decrement: 3.2×10^{-3} (Ref 9)
- *Dynamic liquid viscosity:* (Ref 2)

°C	mPa · s
1085	3.36
1100	3.33
1150	3.22
1200	3.12

- *Liquid surface tension:* 99.99999% purity, in vacuum: 1.300 N/m at the melting point. 99.999% purity, in N_2: 1.341 N/m at 1100 °C; 1.338 N/m at 1150 °C; 1.335 N/m at 1200 °C. 99.997% purity, at the melting point: 1.355 N/m in He or H_2; 1.358 N/m in Ar; 1.352 N/m in vacuum
- *Coefficient of friction:* See Table 9
- *Velocity of sound:* 4759 m/s for longitudinal bulk waves; 3813 m/s for irrotational rod waves; 2325 m/s for shear waves; 2171 m/s for Rayleigh waves

Table 6 Normal-incidence reflectance of freshly evaporated mirror-coating copper

Wavelength, μm	Reflectance, %
0.220	40.1
0.240	39.0
0.260	35.5
0.280	33.0
0.300	33.6
0.315	35.5
0.320	36.3
0.340	38.5
0.360	41.5
0.380	41.5
0.400	47.5
0.450	55.2
0.500	60.0
0.550	66.9
0.600	93.3
0.650	96.6
0.700	97.5
0.750	97.9
0.800	98.1
0.850	98.3
0.900	98.4
0.950	98.4
1.0	98.5
1.5	98.5
2.0	98.6
3.0	98.6
4.0	98.7
5.0	98.7
6.0	98.7
7.0	98.7
8.0	98.8
9.0	98.8
10.0	98.9
15.0	99.0

Source: Ref 9

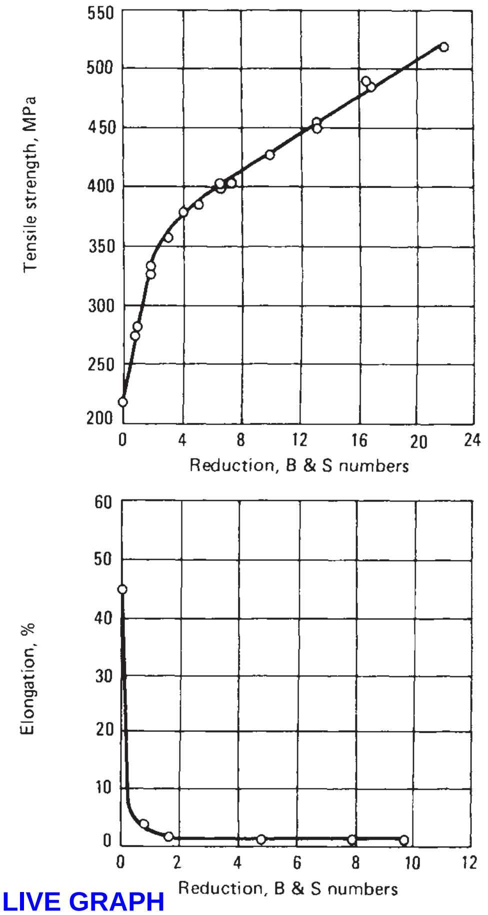

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Fig. 7 Variation of tensile properties with amount of cold reduction for pure copper wire

Table 7 Optical properties of copper

Wavelength, μm	Index of refraction	Extinction coefficient	Reflectance (calculated)
Bulk copper			
0.3650	1.0719	2.0710	0.5004
0.4050	1.0769	2.2890	0.5491
0.4360	1.0707	2.4610	0.5860
0.5000	1.0308	2.7843	0.6528
0.5500	0.7911	2.7177	0.7013
0.5780	0.3250	2.8923	0.8716
0.6000	0.1491	3.2867	0.9508
0.6500	0.1074	3.9104	0.9740
0.7500	0.1034	4.8847	0.9835
1.0000	0.1471	6.9334	0.9881
Single-crystal copper			
0.4400	1.1070	2.5565	0.5965
0.4600	1.0942	2.6320	0.6131
0.4800	1.0618	2.7124	0.6341
0.5000	1.0836	2.7684	0.6390
0.5200	1.0438	2.7784	0.6490
0.5400	0.9324	2.7348	0.6674
0.5600	0.6470	2.7200	0.7440
0.5800	0.2805	2.9764	0.8931
0.6000	0.1360	3.3464	0.9565
0.6200	0.1040	3.6525	0.9714
0.6400	0.0972	4.0692	0.9798
0.6600	0.0897	4.0692	0.9798
Evaporated copper			
0.1025	1.05	0.70	0.098
0.1113	0.95	0.73	0.115
0.1215	0.95	0.78	0.137
0.1306	0.96	0.83	0.148
0.1392	1.00	0.91	0.165
0.1500	1.02	1.02	0.192
0.1603	0.98	1.04	0.219
0.1700	0.94	1.12	0.254
0.1800	0.90	1.21	0.296
0.1900	0.88	1.36	0.335
0.2000	0.94	1.51	0.378
0.500	0.88	2.42	0.625
0.600	0.186	2.980	0.928
0.700	0.150	4.049	0.966
0.800	0.170	4.840	0.973
0.900	0.190	5.569	0.977
1.000	0.197	6.272	0.981
1.35	0.45	7.81	0.971
1.69	0.58	9.96	0.977
2.28	0.82	13.0	0.981
3.00	1.22	17.1	0.984
3.4	1.53	20.3	0.985
3.97	1.94	23.1	0.986
4.87	2.86	28.9	0.987
5.0	2.92	27.45	0.985
5.8	3.71	34.6	0.988
7.00	5.25	40.7	0.988
7.3	5.79	43.2	0.988
8.35	7.28	49.2	0.988
9.6	9.76	57.2	0.988
10.25	11.0	60.6	0.988
10.8	12.6	64.3	0.988
12.25	15.5	71.9	0.989

Source: Ref 9

Table 8 Tensile properties of pure copper

Tensile strength		Yield strength at 0.5% extension, under load			
MPa	ksi	MPa	ksi	Elongation, %	Reduction in area, %
Annealed condition					
209	30	33	4.8	60	92
Cold-drawn condition					
344	50	333.4	48.4	14	88

Source: Ref 9

Table 9 Friction coefficient data for copper

Specimens tested in air at room temperature

Material			Friction coefficient	
Fixed specimen	Moving specimen	Test geometry(a)	Static	Kinetic
Cu	Co	IS	0.44	…
	Cr	IS	0.46	…
	Cu	IS	0.55	…
	Fe	IS	0.50	…
	Ni	IS	0.49	…
	Zn	IS	0.56	…
	Alumina	RPOF	…	0.43
	Zirconia	RPOF	…	0.40
Cu, OFHC	Steel, 4619	BOR	…	0.82
Ag	Cu	IS	0.48	…
Al, 6061-T6	Cu	FOF	0.28	0.23
Steel, 1032	Cu	FOF	0.32	0.25
Steel, stainless, type 304	Cu	FOF	0.23	0.21
Teflon	Cu	FOF	0.13	0.11
W	Cu	IS	0.41	…
Zn	Cu	IS	0.56	…

(a) Test geometry codes: BOR, flat block pressed against the cylindrical surface of a rotating ring; FOF, flat surface sliding on another flat surface; IS, sliding down an inclined surface; RPOF, reciprocating pin on flat. Source: Ref 19

ACKNOWLEDGMENTS

Portions of this article were adapted from:

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Properties of Wrought Copper and Copper Alloys*

C10100, C10200

Commercial Names

Previous trade names. C10100: Oxygen-free electronic copper. C10200: Oxygen-free copper
Common name. Oxygen-free copper
Designations. C10100: OFE. C10200: OF

Specifications

ASTM specifications for C10100. Flat products: B 48, B 133, B 152, B 187, B 272, B 432, F 68. Pipe: B 42, B 188, F 68. Rod: B 12, B 49, B 133, B 187, F 68. Shapes: B 133, B 187, F 68. Tubing: B 372, B 68, B 75, B 188, B 280, F 68. Wire: B 1, B 2, B 3, F 68
ASTM specifications for C10200. Flat products: B 48, B 133, B 152, B 187, B 272, B 370, B 432. Pipe: B 42, B 188. Rod: B 12, B 49, B 124, B 133, B 187. Tubing: B 68, B 75, B 88, B 111, B 188, B 280, B 359, B 372, B 395, B 447. Wire: B 1, B 2, B 3, B 33, B 47, B 116, B 189, B 246, B 286, B 298, B 355. Shapes: B 124, B 133, B 187
Government specifications for C10100. Rod: QQ-C-502
Government specifications for C10200. Flat products: QQ-C-576. Rod and shapes: QQ-C-502. Tubing: WW-T-775. Wire: QQ-C-502, QQ-W-343, MIL-W-3318

Chemical Composition

Composition limits. C10100: 99.99 Cu min (there are specific limits in ppm for 17 named elements; refer to ASTM B 170 or the Copper Development Association *Standards Handbook*). C10200: 99.95 Cu + Ag min
Consequence of exceeding impurity limits. C10100 and C10200 are high-conductivity electrolytic coppers produced without use of metal or metalloid deoxidizers. Excessive amounts of impurities reduce conductivity. Excessive oxygen causes the metal to fail the ASTM B 170 bend test after being heated 30 min at 850 °C (1560 °F) in pure hydrogen.

Applications

Typical uses. Busbars, waveguides, lead-in-wire, anodes, vacuum seals, transistor components, glass-to-metal seals, coaxial cables, klystrons, microwave tubes
Precautions in use. Avoid heating in oxidizing atmospheres.

Mechanical Properties

Tensile properties. See Table 1, Fig. 1, and Fig. 2.
Shear strength. See Table 1.
Hardness. See Table 1.
Elastic modulus. Tension, 115 GPa (17×10^6 psi); shear, 44 GPa (6.4×10^6 psi)
Impact resistance. See Fig. 2.
Fatigue strength. See Table 1.
Creep-rupture characteristics. See Tables 2 and 3.

Mass Characteristics

Density. 8.94 g/cm^3 (0.323 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Melting point. 1083 °C (1981 °F)
Coefficient of linear thermal expansion. 17.0 μm/m · K (9.4 μin./in. · °F) at 20 to 100 °C (68 to 212 °F); 17.3 μm/m · K (9.6 μin./in. · °F) at 20 to 200 °C (68 to 392 °F); 17.7 μm/m · K (9.8 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 385 J/kg · K (0.092 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 391 W/m · K (226 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Annealed: volumetric, 101% IACS min at 20 °C (68 °F)
Electrical resistivity. 17.1 nΩ · m at 20 °C (68 °F)

Chemical Properties

General corrosion behavior. Copper is cathodic to hydrogen in the electromotive series and therefore is the cathode in galvanic couples with other base metals such as iron, aluminum, magnesium, lead, tin, and zinc. C10100 and C10200 have excellent resistance to atmospheric corrosion and to corrosion by most waters, including brackish water and seawater. They have good resistance to nonoxidizing acids but poor resistance to oxidizing acids, moist ammonia, moist halogens, sulfides, and solutions containing ammonium ions.

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Forgeability. 65% of C37700 (forging brass)
Formability. Readily formed by a wide variety of hot and cold methods. Can be easily stamped, bent, coined, sheared, spun, upset, swaged, forged, roll threaded, and knurled
Weldability. Can be readily soldered, brazed, gas tungsten arc welded, gas metal arc welded, or upset welded. Its capacity for being oxyfuel gas welded is fair. Shielded metal arc welding and most resistance welding methods are not recommended.
Annealing temperature. 375 to 650 °C (700 to 1200 °F)
Hot-working temperature. 750 to 875 °C (1400 to 1600 °F)

C10300

Commercial Names

Common name. Oxygen-free extra-low-phosphorus copper
Designation. OFXLP

Specifications

ASTM. Flat products: B 133, B 152, B 187, B 272, B 432. Pipe: B 42, B 188, B 302. Rod: B 12, B 133, B 187. Shapes: B 133, B 187. Tubing: B 68, B 75, B 88, B 111, B 188, B 251, B 280, B 306, B 359, B 372, B 395, B 447

Chemical Composition

Composition limits. 99.95 Cu + Ag + P min, 0.001 to 0.005 P, 0.05 max other (total)

Applications

Typical uses. Busbars, electrical conductors and terminals, commutators, tubular busbars, clad products, waveguide tubing, thermostatic control tubing

Mechanical Properties

Tensile properties. See Table 4.
Shear strength. See Table 4.
Hardness. See Table 4.

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*Reprinted from *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials,* Vol 2, *ASM Handbook,* 1990, p 265–345. The article was prepared for that Volume by Peter Robinson, Olin Corporation.

Table 1 Typical mechanical properties of C10100 and C10200

	Tensile strength		Yield strength(a)			Hardness			Shear strength		Fatigue strength(b)	
Temper	MPa	ksi	MPa	ksi	Elongation in 50 mm (2 in.), %	HRF	HRB	HR30T	MPa	ksi	MPa	ksi
Flat products, 1 mm (0.04 in.) thick												
M20	235	34	69	10	45	45	…	…	160	23	…	…
OS025	235	34	76	11	45	45	…	…	160	23	76	11
OS050	220	32	69	10	45	40	…	…	150	22	…	…
H00	250	36	195	28	30	60	10	25	170	25	…	…
H01	260	38	205	30	25	70	25	36	170	25	…	…
H02	240	42	250	36	14	84	40	50	180	26	90	13
H04	345	50	310	45	6	90	50	57	195	28	90	13
H08	380	55	345	50	4	94	60	63	200	29	95	14
H10	395	57	360	53	4	95	62	64	200	29	…	…
Flat products, 6 mm (0.25 in.) thick												
M20	220	32	69	10	50	40	…	…	150	22	…	…
OS050	220	32	69	10	50	40	…	…	150	22	…	…
H00	250	36	195	28	40	60	10	…	170	25	…	…
H01	260	38	205	30	35	70	25	…	170	25	…	…
H04	345	50	310	45	12	90	50	…	195	28	…	…
Flat products, 25 mm (1 in.) thick												
H04	310	45	275	40	20	85	45	…	180	26	…	…
Rod, 6 mm (0.25 in.) in diameter												
H80 (40%)	380	55	345	50	10	94	80	…	200	29	…	…
Rod, 25 mm (1 in.) in diameter												
M20	220	32	69	10	55(c)	40	…	…	150	22	…	…
OS050	220	32	69	10	55(c)	40	…	…	150	22	…	…
H80 (35%)	330	48	305	44	16(d)	87	47	…	185	27	115	17
Rod, 50 mm (2 in.) in diameter												
H80 (16%)	310	45	275	40	20	85	45	…	180	26	…	…
Wire, 2 mm (0.08 in.) in diameter												
OS050	240	35	…	…	35(e)	45	…	…	165	24	…	…
H04	380	55	…	…	1.5(f)	…	…	…	200	29	…	…
H08	455	66	…	…	1.5(f)	…	…	…	230	33	…	…
Tubing, 25 mm (1 in.) outside diameter × 1.65 mm (0.065 in.) wall thickness												
OS025	235	34	76	11	45	45	…	…	160	23	…	…
OS050	220	32	69	10	45	40	…	…	150	22	…	…
H55 (15%)	275	40	220	32	25	77	35	45	180	26	…	…
H80 (40%)	380	55	345	50	8	95	60	63	200	29	…	…
Shapes, 13 mm (0.50 in.) in diameter												
M20	220	32	69	10	50	45	…	…	150	22	…	…
M30	220	32	69	10	50	45	…	…	150	22	…	…
OS050	220	32	69	10	50	45	…	…	150	22	…	…
H80 (15%)	275	40	220	32	30	…	35	…	180	26	…	…

(a) At 0.5% extension under load. (b) At 10^8 cycles. (c) 70% reduction in area. (d) 55% reduction in area. (e) Elongation in 254 mm (10 in.). (f) Elongation in 1500 mm (60 in.)

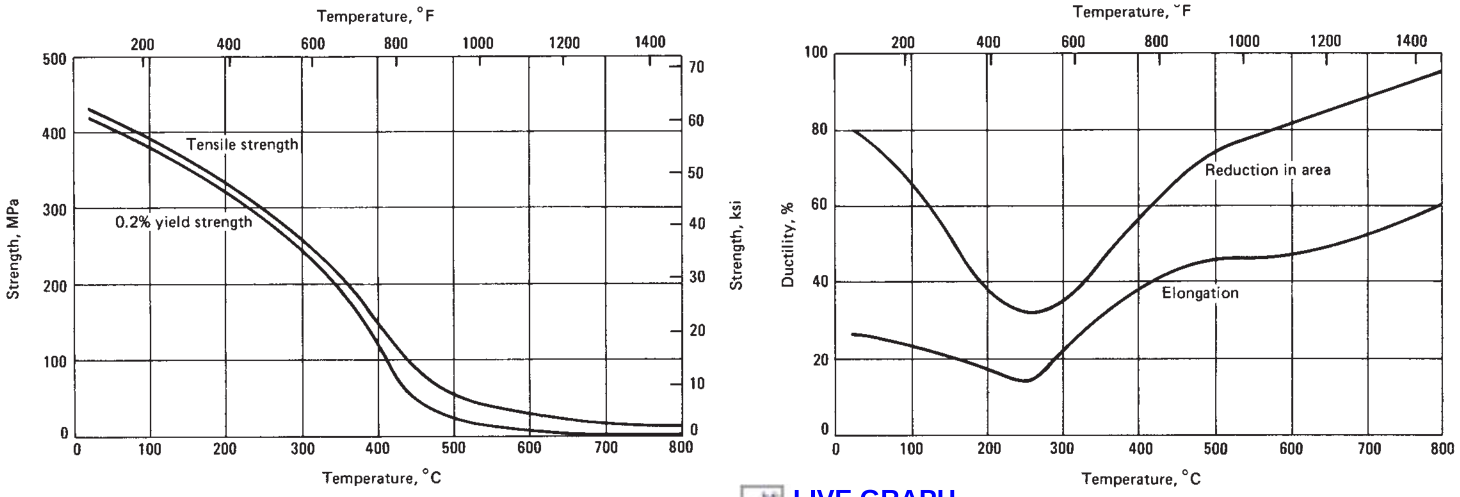

Fig. 1 Elevated-temperature tensile properties of C10100 or C10200 rod, H80 temper

LIVE GRAPH
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Table 2 Creep properties of C10100 and C10200

Condition and grain size	Test temperature		Stress(a) for creep rate of											
			10^{-6}%/h		10^{-5}%/h		10^{-4}%/h		10^{-3}%/h		10^{-2}%/h		10^{-1}%/h	
	°C	°F	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi
OS025(b)	43	110	…	…	…	…	…	…	170	25	185	27	200	29
	120	250	…	…	…	…	…	…	125	18	150	22	165	24
	150	300	11	1.6	25	3.6	55	8.0	110	16	130	19	150	22
	205	400	3	0.5	10	1.5	33	4.8	…	…	…	…	…	…
	260	500	0.7	0.1	3	0.4	12	1.x7	…	…	…	…	…	…
	370	700	…	…	…	…	…	…	…	…	21	3.1	(40)	(5.8)
	480	900	…	…	…	…	…	…	…	…	9.9	1.45	(23)	(3.3)
Cold drawn 40%(c)	43	110	…	…	…	…	…	…	310	45	330	48	…	…
	120	250	…	…	…	…	…	…	240	35	270	39	(295)	(43)
	150	300	…	…	…	…	…	…	200	29	235	34	250	36
	370	700	…	…	…	…	…	…	11	1.6	26	3.8	(39)	(5.6)
	480	900	…	…	…	…	…	…	…	…	8.3	1.2	(17)	(2.4)
	650	1200	…	…	…	…	…	…	…	…	3	0.5	6	0.9
Cold drawn 84%(d)	150	300	…	…	55	8.0	89.6	13.0	…	…	…	…	…	…
	205	400	(4.5)	(0.65)	12	1.7	35	5.0	…	…	…	…	…	…

(a) Parentheses indicate extrapolated values. (b) Tensile strength, 220 MPa (31.9 ksi) at 21 °C (70 °F). (c) Tensile strength, 352 MPa (51.1 ksi) at 21 °C (70 °F). (d) Tensile strength, 376 MPa (54.5 ksi) at 21 °C (70 °F)

Table 3 Stress-rupture properties of C10100 and C10200

Temper or condition	Test temperature		Stress(a) for rupture in					
			10 h		100 h		1000 h	
	°C	°F	MPa	ksi	MPa	ksi	MPa	ksi
OS025(b)	150	300	…	…	161	23.4	147	21.3
	200	380	…	…	130	18.9	106	15.3
Cold drawn 40%(c)	120	250	…	…	272	39.4	(245)	(35.6)
	150	300	…	…	241	35.0	(215)	(31.2)
H80(d)	450	840	33	4.8	17	2.4	…	…
	650	1200	9.7	1.4	5.2	0.75	…	…

(a) Parentheses indicate extrapolated values. (b) Tensile strength, 238 MPa (34.5 ksi) at 21 °C (70 °F). (c) Tensile strength, 352 MPa (51.1 ksi) at 21 °C (70 °F). (d) Tensile strength, 426 MPa (61.8 ksi) at 21 °C (70 °F)

Table 4 Typical mechanical properties of C10300

Temper	Tensile strength		Yield strength(a)		Elongation in 50 mm (2 in.), %	Hardness			Shear strength	
	MPa	ksi	MPa	ksi		HRF	HRB	HR30T	MPa	ksi
Flat products, 1 mm (0.04 in.) thick										
OS050	220	32	69	10	45	40	…	…	150	22
OS025	235	34	76	11	45	45	…	…	160	23
H00	250	36	195	28	30	60	10	25	170	25
H01	260	38	205	30	25	70	25	36	170	25
H02	290	42	250	36	14	84	40	50	180	26
H04	345	50	310	45	6	90	50	57	195	28
Flat products, 6 mm (0.25 in.) thick										
OS050	220	32	69	10	50	40	…	…	150	22
H00	250	36	195	28	40	60	10	…	170	25
H04	345	50	310	45	12	90	50	…	195	28
M20	220	32	69	10	50	40	…	…	150	22
Flat products, 25 mm (1 in.) thick										
H04	310	45	275	40	20	85	45	…	180	26
Rod, 6 mm (0.25 in.) in diameter										
H80 (40%)	380	55	345	50	20	94	60	…	200	29
H80 (35%)	330	48	305	44	16	87	47	…	185	27
H80 (16%)	310	45	275	40	20	85	45	…	180	26
Tubing, 25 mm (1 in.) outside diameter × 1.65 mm (0.65 in.) wall thickness										
OS050	220	32	69	10	45	40	…	…	150	22
OS025	235	34	76	11	45	45	…	…	160	23
H80 (15%)	275	40	220	32	25	77	35	45	180	26
H80 (40%)	380	55	345	50	8	95	60	63	200	29
Pipe, 3/4 SPS										
H80 (30%)	345	50	310	45	10	90	50	…	195	28
Shapes, 13 mm (0.50 in.) section size										
OS050	220	32	69	10	50	40	…	…	150	22
H80 (15%)	275	40	220	32	30	…	35	…	180	26

(a) At 0.5% extension under load

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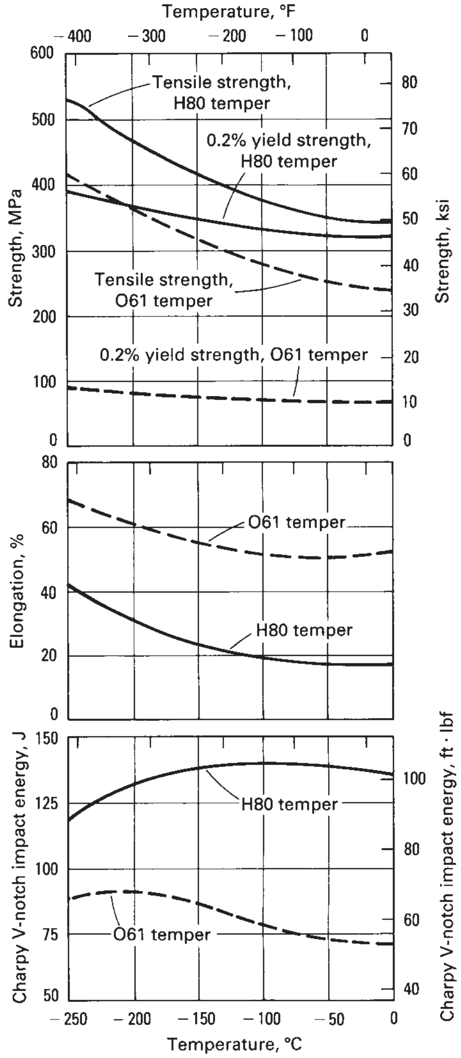

Fig. 2 Low-temperature mechanical properties of C10100 or C10200 bar

Elastic modulus. Tension, 115 GPa (17×10^6 psi); shear, 44 GPa (6.4×10^6 psi)
Fatigue strength. 1 mm (0.04 in.) thick strip: OS025 temper, 76 MPa (11 ksi); H02 or H04 temper, 90 MPa (13 ksi)

Mass Characteristics

Density. 8.94 g/cm^3 (0.323 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1083 °C (1981 °F)
Solidus temperature. 1083 °C (1981 °F)
Coefficient of linear thermal expansion. 17.0 µm/m · K (9.4 µin./in. · °F) at 20 to 100 °C (68 to 212 °F); 17.3 µm/m · K (9.6 µin./in. · °F) at 20 to 200 °C (68 to 392 °F); 17.7 µm/m · K (9.8 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 385 J/kg · K (0.092 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 386 W/m · K (223 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. O61 temper: volumetric, 99% IACS at 20 °C (68 °F)
Electrical resistivity. 17.4 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Annealing temperature. 375 to 650 °C (700 to 1200 °F)
Hot-working temperature. 750 to 875 °C (1400 to 1600 °F)

C10400, C10500, C10700

Commercial Names

Trade name. AMSIL copper
Common name. Oxygen-free silver-copper

Specifications

ASTM. See Table 5.

Chemical Composition

Composition limits. C10400: 99.95 Cu + Ag min, 0.027 Ag min. C10500: 99.95 Cu + Ag min, 0.034 Ag min. C10700: 99.95 Cu + Ag min, 0.085 Ag min

Applications

Typical uses. Busbars, conductivity wire, contacts, radio parts, windings, switches, commutator segments, automotive gaskets and radiators, chemical plant equipment, printing rolls, printed-circuit foil. Many uses are based on the good creep strength at elevated temperatures and the high softening temperature of these alloys.

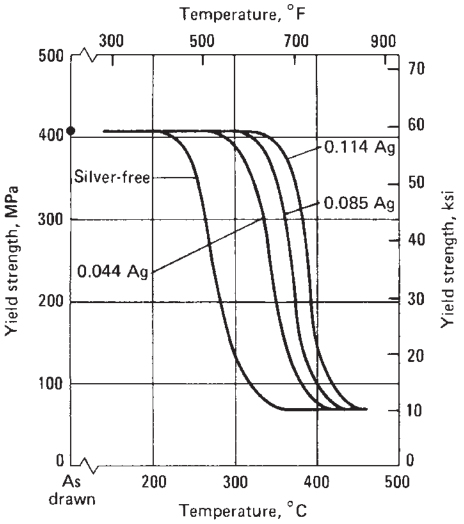

Fig. 3 Softening characteristics of oxygen-free copper containing various amounts of silver. Data are for copper wire cold worked 90% to a diameter of 2 mm (0.08 in.) and then annealed $\frac{1}{2}$ h at various temperatures.

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Table 5 Summary of ASTM and government specifications for C10400, C10500, and C10700

Mill product	C10400	C10500	C10700
ASTM numbers			
Flat products	B 48, B 133, B 152, B 187, B 272	B 152, B 187, B 272	B 152, B 187, B 272
Pipe	B 42, B 188	B 188	B 188
Rod	B 12, B 49, B 133, B 187	B 12, B 49, B 133, B 187	B 12, B 49, B 133, B 187
Shapes	B 133, B 187	B 187	B 187
Tube	B 188	B 188	B 188
Wire	B 1, B 2, B 3	B 1, B 2, B 3	B 1, B 2, B 3
Government numbers			
Flat products	QQ-C-502, QQ-C-576	QQ-C-502, QQ-C-576	QQ-C-576
Rod	QQ-C-502	QQ-C-502	QQ-C-502
Shapes	QQ-C-502, QQ-B-825	QQ-C-502	QQ-B-825, MIL-B-19231
Tube	QQ-B-825	QQ-B-825	QQ-B-825
Wire	QQ-W-343, MIL-W-3318	QQ-W-343, MIL-W-3318	QQ-W-343, MIL-W-3318

Table 6 Typical mechanical properties of C10400, C10500, and C10700

	Tensile strength		Yield strength(a)			Hardness			Shear strength	
Temper	MPa	ksi	MPa	ksi	Elongation in 50 mm (2 in.), %	HRF	HRB	HR30T	MPa	ksi
Flat products, 1 mm (0.04 in.) thick										
OS025	235	34	76	11	45	45	…	…	160	23
H00	250	36	195	28	30	60	10	25	170	25
H01	260	38	205	30	25	70	25	36	170	25
H02	290	42	250	36	14	84	40	50	180	26
H04	345	50	310	45	6	90	50	57	195	28
H08	380	55	345	50	4	94	60	63	200	29
H10	395	57	365	53	4	95	62	64	200	29
M20	235	34	69	10	45	45	…	…	160	23
Flat products, 6 mm (0.25 in.) thick										
OS050	220	32	69	10	50	40	…	…	150	22
H00	250	36	195	28	40	60	10	…	170	25
H01	260	38	205	30	35	70	25	…	170	25
H04	345	50	310	45	12	90	50	…	195	28
M20	220	32	69	10	50	40	…	…	150	22
Flat products, 25 mm (1 in.) thick										
H04	310	45	275	40	20	85	45	…	180	26
Rod, 6 mm (0.25 in.) in diameter										
H80 (40%)	380	55	345	50	10	94	60	…	200	29
Rod, 25 mm (1 in.) in diameter										
OS050	220	32	69	10	55	40	…	…	150	22
H80 (35%)	330	48	305	44	16	87	47	…	185	27
M20	220	32	69	10	55	40	…	…	150	22
Rod, 50 mm (2 in.) in diameter										
H80 (16%)	310	45	275	40	20	85	45	…	180	26
Wire, 2 mm (0.08 in.) in diameter										
OS050	240	35	…	…	35(b)	…	…	…	165	24
H04	380	55	…	…	1.5(c)	…	…	…	200	29
H08	455	66	…	…	1.5(c)	…	…	…	230	33
Shapes, 13 mm (0.50 in.) section size										
OS050	220	32	69	10	50	40	…	…	150	22
H80 (15%)	275	40	220	32	30	…	35	…	180	26
M20	220	32	69	10	50	40	…	…	150	22
M30	220	32	69	10	50	40	…	…	150	22
Tubing, 25 mm (1.0 in.) diameter × 1.65 mm (0.065 in.) wall thickness										
OS050	220	32	69	10	45	40	…	…	150	22
OS025	235	34	76	11	45	45	…	…	160	23
H80 (15%)	275	40	220	32	25	77	35	45	180	26
H80 (50%)	380	55	345	50	8	95	60	62	200	29

(a) At 0.5% extension under load. (b) Elongation in 25 mm (10 in.). (c) Elongation in 1500 mm (60 in.)

Mechanical Properties

Tensile properties. See Table 6 and Fig. 3.
Shear strength. See Table 6.
Hardness. See Table 6.
Elastic modulus. Tension, 115 GPa (17×10^6 psi); shear, 44 GPa (6.4×10^6 psi)

Mass Characteristics

Density. 8.94 g/cm^3 (0.323 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1083 °C (1981 °F)
Solidus temperature. 1083 °C (1981 °F)
Coefficient of linear thermal expansion. 17.0 μm/m · K (9.4 μin./in. · °F) at 20 to 100 °C (68 to 212 °F); 17.3 μm/m · K (9.6 μin./in. · °F) at 20 to 200 °C (68 to 392 °F); 17.7 μm/m · K (9.8 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 385 J/kg · K (0.092 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 388 W/m · K (224 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. O61 temper: volumetric, 100% IACS at 20 °C (68 °F)
Electrical resistivity. 17.2 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Annealing temperature. 475 to 750 °C (900 to 1400 °F). See also Fig. 3.
Hot-working temperature. 750 to 875 °C (1400 to 1600 °F)

C10800

Commercial Names

Trade name. AMAX-LP copper
Common name. Oxygen-free low-phosphorus copper

Specifications

ASTM. Flat products: B 113, B 152, B 187, B 432. Pipe: B42, B 302. Rod: B 12, B 133. Shapes: B 133. Tubing: B 68, B 75, B 88, B 111, B 188, B 251, B 280, B 306, B 357, B 360, B 372, B 395, B 447, B 543

Chemical Composition

Composition limits. 99.95 Cu + Ag + P min, 0.005 to 0.012 P

Applications

Typical uses. Refrigerator and air conditioner tubing and terminals, commutators, clad products, gas and burner lines and units, oil burner tubes, condenser and heat exchanger tubes, pulp and paper lines, steam and water lines, tank gage lines, plumbing pipe and tubing, thermostatic control tubing, plate for welded continuous casting molds, tanks, kettles, rotating bands, and similar uses

Mechanical Properties

Tensile properties. See Table 7.
Shear strength. See Table 7.
Hardness. See Table 7
Elastic modulus. Tension, 115 GPa (17×10^6 psi); shear, 44 GPa (6.4×10^6 psi)
Fatigue strength. See Table 7.

Table 7 Typical mechanical properties of C10800

	Tensile strength		Yield strength(a)		Elongation in 50 mm (2 in.), %	Hardness			Shear strength		Fatigue strength(b)	
Temper	MPa	ksi	MPa	ksi		HRF	HRB	HR30T	MPa	ksi	MPa	ksi
Flat products, 1 mm (0.04 in.) thick												
OS025	235	34	76	11	45	45	…	…	160	23	76	11
H00	250	36	195	28	30	60	10	25	170	25	…	…
H01	260	38	205	30	25	70	25	36	170	25	…	…
H02	290	42	250	36	14	84	40	50	180	26	90	13
H04	345	50	310	45	6	90	50	57	195	28	90	13
H08	380	55	345	50	4	94	60	63	200	29	97	14
Flat products, 6 mm (0.25 in.) thick												
OS050	220	32	69	10	50	40	…	…	150	22	…	…
H00	250	36	195	28	40	60	10	…	170	25	…	…
H04	345	50	310	45	12	90	50	…	195	28	…	…
M20	220	32	69	10	50	40	…	…	150	22	…	…
Flat products, 25 mm (1 in.) thick												
H04	310	45	275	40	20	85	45	…	180	26	…	…
Rod, 6 mm (0.25 in.) in diameter												
H80 (40%)	380	55	345	50	20	94	60	…	200	29	…	…
Rod, 25 mm (1 in.) in diameter												
H80 (35%)	330	48	305	44	16	87	47	…	185	27	115	17
Rod, 50 mm (2 in.) in diameter												
H80 (16%)	310	45	275	40	20	85	45	…	180	26	…	…
Tubing, 25 mm (1 in.) outside diameter × 1.65 mm (0.065 in.) wall thickness												
OS050	220	32	69	10	45	40	…	…	150	22	…	…
OS025	235	34	76	11	45	45	…	…	160	23	…	…
H55 (15%)	275	40	220	32	25	77	35	45	180	26	…	…
H80 (40%)	380	55	345	50	8	95	60	63	200	29	…	…
Pipe, 3/4 SPS												
H80 (30%)	345	50	310	45	10	90	50	…	195	28	…	…

(a) At 0.5% extension under load. (b) At 10^8 cycles

Mass Characteristics

Density. 8.94 g/cm^3 (0.323 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1083 °C (1981 °F)
Solidus temperature. 1083 °C (1981 °F)
Coefficient of linear thermal expansion. 17.0 μm/m · K (9.4 μin./in. · °F) at 20 to 100 °C (68 to 212 °F); 17.3 μm/m · K (9.6 μin./in. · °F) at 20 to 200 °C (68 to 392 °F); 17.7 μm/m · K (9.8 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 385 J/kg · K (0.092 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 350 W/m · K (202 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. O61 temper: volumetric, 92% IACS at 20 °C (68 °F)
Electrical resistivity. 18.7 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Annealing temperature. 375 to 650 °C (700 to 1200 °F)
Hot-working temperature. 750 to 875 °C (1400 to 1600 °F)

C11000
99.95Cu-0.04O

Commercial Names

Common name. Electrolytic tough pitch copper
Designation. ETP

Specifications

AMS. Sheet and strip: 4500. Wire: 4701
ASME. Plate for locomotive fireboxes: SB11. Rod for locomotive staybolts: SB12
ASTM: See Table 8.
SAE. J463
Government. Federal specifications: See Table 8. Military specifications: Rod, MIL-C-12166; wire, MIL-W-3318, MIL-W-6712

Chemical Composition

Composition limits. 99.90 Cu min (silver counted as copper)
Silver has little effect on mechanical and electrical properties, but does raise the recrystallization temperature and tends to produce a fine-grain copper.
Iron, as present in commercial copper, has no effect on mechanical properties, but even traces of iron can cause C11000 to be slightly ferromagnetic.
Sulfur causes spewing and unsoundness, and is kept below 0.003% in ordinary refinery practice.
Selenium and tellurium are usually considered undesirable impurities but may be added to improve machinability.
Bismuth creates brittleness in amounts greater than 0.001%.
Lead should not be present in amounts greater than 0.005% if the copper is to be hot rolled.

Cadmium is rarely present; its effect is to toughen copper without much loss in conductivity.

Arsenic decreases the conductivity of copper noticeably, although it is often added intentionally to copper not used in electrical service because it increases the toughness and heat resistance of the metal.

Antimony is sometimes added to the copper when a high recrystallization temperature is desired.

Applications

Typical uses. Produced in all forms except pipe, and used for building fronts, downspouts, flashing, gutters, roofing, screening, spouting, gaskets, radiators, busbars, electrical wire, stranded conductors, contacts, radio parts, switches, terminals, ball floats, butts, cotter pins, nails, rivets, soldering copper, tacks, chemical process equipment, kettles, pans, printing rolls, rotating bands, roadbed expansion plates, vats

Precautions in use. C11000 is subject to embrittlement when heated to 370 °C (700 °F) or above in a reducing atmosphere, as in annealing, brazing, or welding. If hydrogen or carbon monoxide is present in the reducing atmosphere, embrittlement can be rapid.

Mechanical Properties

Tensile properties. See Table 9 and Fig. 4 to 8.

Shear strength. See Table 9.

Hardness. See Table 9 and Fig. 9.

Poisson's ratio. 0.33

Elastic modulus. O60 temper: tension, 115 GPa (17×10^6 psi); shear, 44 GPa (6.4×10^6 psi). Cold-worked (H) tempers: tension, 115 to 130 GPa (17×10^6 to 19×10^6 psi); shear, 44 to 49 GPa (6.4×10^6 to 7.1×10^6 psi)

Impact strength. See Table 10.

Fatigue strength. See Table 9; values shown there are typical of all tough pitch, oxygen-free, phosphorus-deoxidized and arsenical coppers. Copper does not exhibit an endurance limit under fatigue loading and, on the average, will fracture in fatigue at the stated number of cycles when subjected to an alternating stress equal to the corresponding fatigue strength (see Fig. 10).

Creep-rupture characteristics. See Table 11.

Specific damping capacity. The damping capacity of coppers and brasses depends on the amplitude and, in some instances, on the frequency of vibration; it is also affected by the condition of the metal. Up to a point, damping capacity increases with increasing cold work; for example, the damping capacity of 70-30 brass has been reported to increase for reductions up to 60%. When subjected to the same conditions, coppers have about three times the damping capacity of C21000 or C22000. A specific damping capacity of 5×10^{-5} has been recorded for single-crystal annealed copper. Log decrement: O60 temper, 3.2; cold rolled (H) tempers, 5.0

Table 8 ASTM and federal specifications for C11000

Product and condition	Specification number ASTM	 Federal
Flat products		
General requirements for copper and copper alloy plate, sheet, strip, and rolled bar	B 248	…
Sheet, strip, plate, and rolled bar	B 152	QQ-C-576
Sheet, lead coated	B 101	…
Sheet and strip for building construction	B 370	…
Strip and flat wire	B 272	QQ-C-502
Foil, strip, and sheet for printed circuits	B 451	…
Rod, bar, and shapes		
General requirements for copper and copper alloy rod, bar, and shapes	B 249	…
Rod, bar, and shapes	B 133	QQ-C-502, QQ-C-576
Rod, hot rolled	B 49	…
Rod, bar, and shapes for forging	B 124	QQ-C-502
Busbars, rods, and shapes	B 187	QQ-B-825
Wire		
General requirements for copper and copper alloy wire	B 250	…
Hard drawn	B 1	QQ-W-343
Tinned	B 246	…
Medium-hard drawn	B 2	QQ-W-343
Tinned	B 246	…
Soft	B 3	QQ-W-343
Lead alloy coated	B 189	…
Nickel coated	B 355	…
Rectangular and square	B 48, B 272	…
Tinned	B 33	…
Silver coated	B 298	…
Trolley	B 47, B 116	…
Conductors		
Bunch stranded	B 174	…
Concentric-lay stranded	B 8, B 226, B496	…
Conductors for electronic equipment	B 286, B 470	…
Rope-lay stranded	B 172, B 173	…
Composite conductors (copper plus copper-clad steel)	B 229	…
Tubular products		
Bus pipe and tube	B 188	QQ-B-825
Pipe	…	WW-P-377
Welded copper tube	B 477	…
Miscellaneous		
Standard classification of coppers	B 224	…
Electrolytic Cu wirebars, cakes, slabs, billets, ingots, and ingot bars	B 5	…
Anodes	…	QQ-A-673
Die forgings	B 283	…

Coefficient of friction. Values given below apply to any of the unalloyed coppers in contact with the indicated materials without lubrication of any kind between the contacting surfaces:

Opposing material	Coefficient of friction Static	 Sliding
Carbon steel	0.53	0.36
Cast iron	1.05	0.29
Glass	0.68	0.53

Mass Characteristics

Density. Solid: 8.89 g/cm^3 (0.321 lb/in.^{3}) at 20 °C (68 °F); 8.32 g/cm^3 (0.301 lb/in.^{3}) at 1083 °C (1981 °F); see also Fig. 11. Liquid: 7.93 g/cm^3 (0.286 lb/in.^{3}) at 1083 °C (1981 °F)

Thermal Properties

Liquidus temperature. 1083 °C (1981 °F)

Solidus temperature. Eutectic point, 1065 °C (1950 °F)

Coefficient of linear thermal expansion. 17 µm/m · K (9.4 µin./in. · °F) at 20 to 100 °C (68 to 212 °F); 17.3 µm/m · K (9.6 µin./in. · °F) at 20 to 200 °C (68 to 392 °F); 17.7 µm/m · K (9.8 µin./in. · °F) at 20 to 300 °C (68 to 572 °F). See also Fig. 12.

Specific heat. 385 J/kg · K (0.092 Btu/lb · °F) at 20 °C (68 °F)

Enthalpy. See Fig. 12.

Latent heat of fusion. 205 kJ/kg

Thermal conductivity. 388 W/m · K (224 Btu/ft · h · °F) at 20 °C (68 °F). For high conductivity coppers, a values of 387 W/m · K (223 Btu/ft · h · °F) is an adjusted value corresponding to an electrical conductivity of 101% IACS:

Temperature K	 °C	Thermal conductivity W/m · K	 Btu/ft · h · °F
4.2	–268.8	300	170
20	–253	1300	750
77	–196	550	318
194	–79	400	230
273	0	390	225
373	100	380	220
573	300	370	215
973	700	300	170

Electrical Properties

Electrical conductivity. Volumetric: O60 temper: 100 to 101.5% IACS; H14 temper, 97% IACS. See also Fig. 13.

Electrical resistivity. O60 temper: 17.00 to 17.24 nΩ · m; temperature coefficient, 0.00393/K at –100 to 200 °C (–148 to 392 °F) for 100% IACS material, 0.00397/K at –100 to 200 °C for 101% IACS material. H14 temper: 1.78 nΩ · m; temper-

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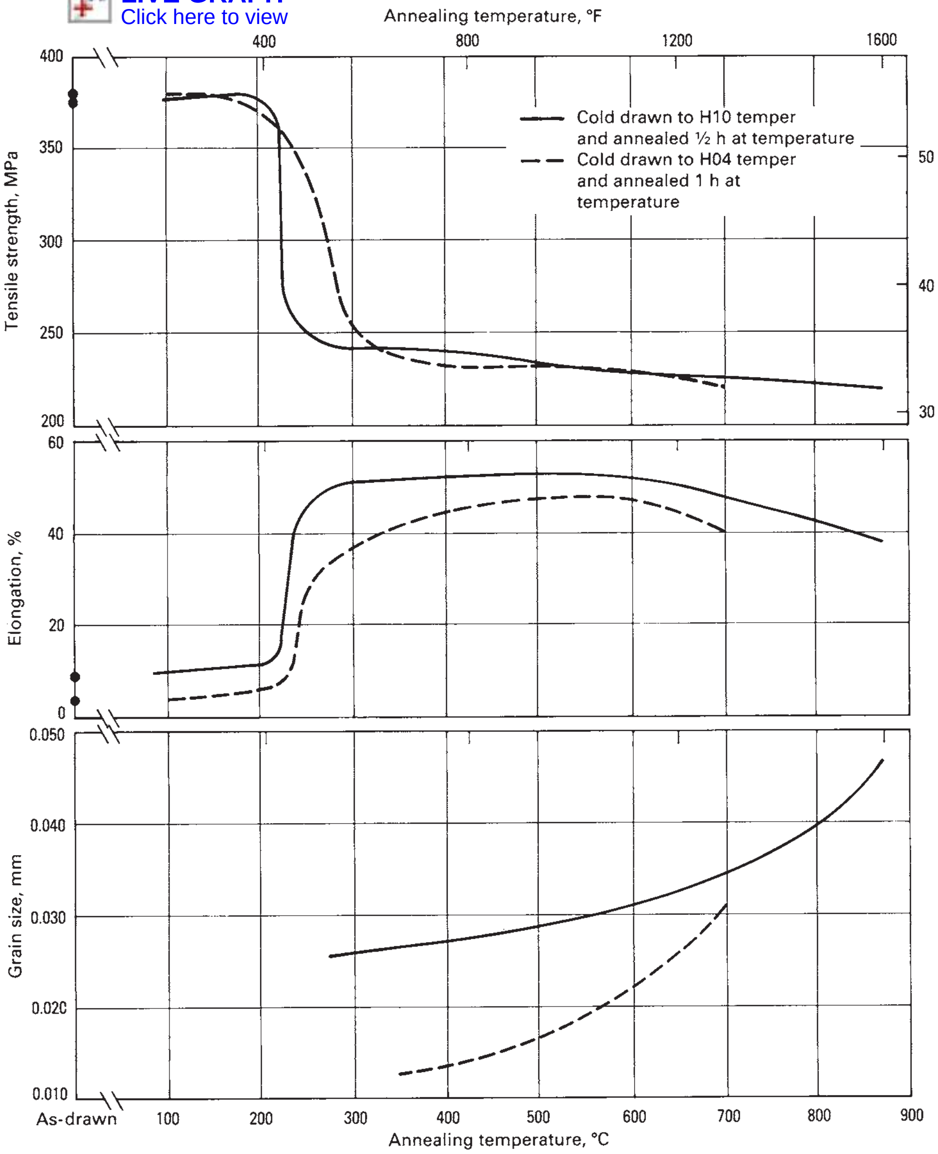

Fig. 4 Variation of tensile properties and grain size of electrolytic tough pitch copper (C11000) and similar coppers

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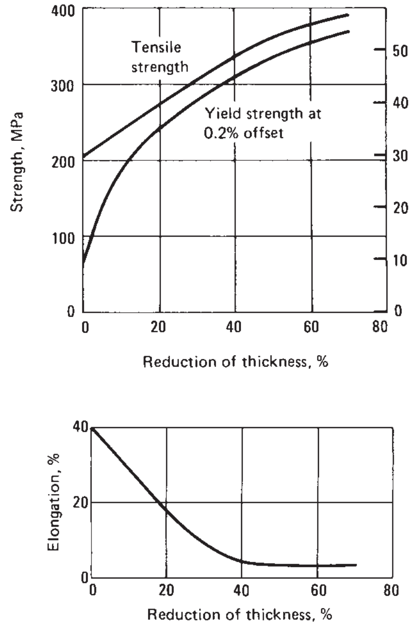

Fig. 5 Variation of tensile properties with amount of cold reduction by rolling for C11000 and similar coppers

ature coefficient, 0.00381/K at 0 to 100 °C (32 to 212 °F) for 97% IACS material. See also Fig. 13.

Thermoelectrical potential. See Fig. 14.

Electrochemical equivalent. Cu^{2+}, 0.329 mg/C; Cu^{+}, 0.659 mg/C

Electrolytic solution potential. Cu^{2+}, –0.344 V versus standard hydrogen electrode; Cu^{+}, –0.470 V versus standard hydrogen electrode; temperature coefficient, –0.01 mV/K at 20 to 50 °C (68 to 122 °F)

Hydrogen overvoltage. Approximately 0.23 V in dilute sulfuric acid; specific value varies with current density.

Hall effect. Hall coefficient, –52 pV · m/A · T

Optical Properties

Color. Reddish metallic

Spectral reflectivity. 32.7% for λ of 420 nm; 43.7% for λ of 500 nm; 71.8% for λ of 600 nm; 83.4% for λ of 700 nm. See also Fig. 15 and 16.

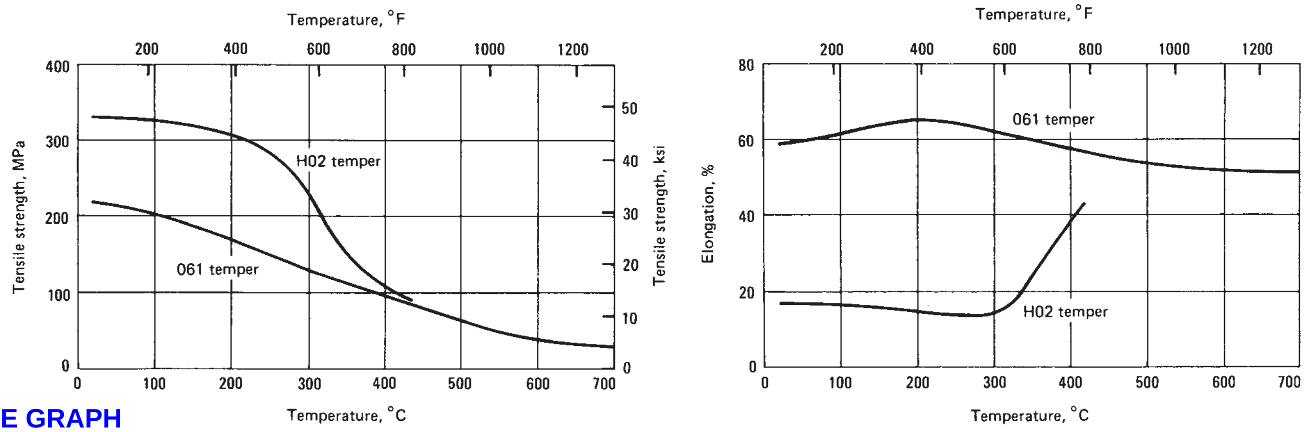

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Fig. 6 Short-time elevated-temperature tensile properties of C11000 and similar coppers

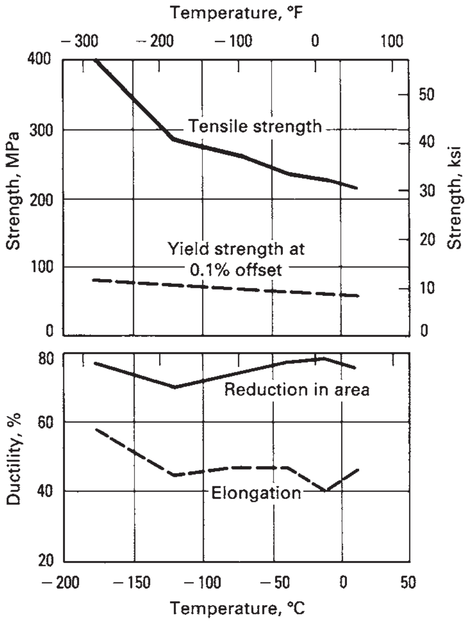

Fig. 7 Low-temperature tensile properties of C11000 and similar coppers

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Chemical Properties

General corrosion behavior. Although many factors influence the corrosion resistance of copper under specific conditions of service, copper is generally less subject to corrosion than other engineering metals. Copper often is used where resistance to corrosion is of prime importance. Sometimes, it is better to use a copper alloy rather than an unalloyed copper.

In general, copper resists nonoxidizing mineral and organic acids, caustic solutions, saline solutions, and various natural waters or process waters. It is suitable for underground service because it resists soil corrosion. Copper is not suitable for service in oxidizing acids such as nitric acid, and it is not recommended for use with ammonia, nitric acid, acid chromate solutions, ferric chloride, mercury salts, perchlorates, or persulfates. Also, copper may corrode in aerated nonoxidizing acids such as sulfuric or acetic acids, even though it is practically immune to these acids in the complete absence of air.

Tough pitch copper is considered to be immune to stress-corrosion cracking in ammonia and the other agents that induce season cracking of brasses. However, tough pitch copper is susceptible to embrittlement in reducing atmosphere, especially those containing hydrogen.

Resistance to specific corroding agents. Depending on concentration and specific conditions of exposure, copper generally resists the following agents.

Acids: mineral acids such as hydrochloric and sulfuric acids; organic acids such as acetic acid (including vinegar and acetates), carbolic acid, citric acid, formic acid, oxalic acid, and tartaric acid; fatty acids; and acidic solutions containing sulfur, such as the sulfurous acid and sulfite solutions used in pulp mills

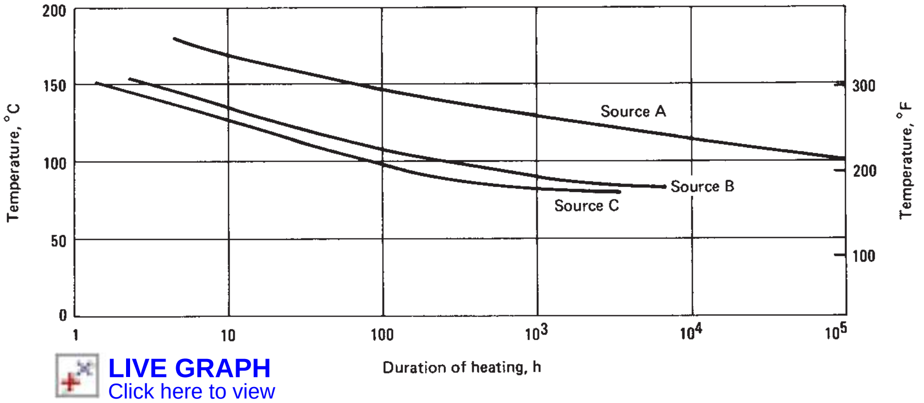

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Fig. 8 Stress relaxation curves for C11000 and similar coppers. Data are for H80 temper wire, 2 mm (0.08 in.) in diameter, and represent the time-temperature combination necessary to produce a 5% reduction in tensile strength.

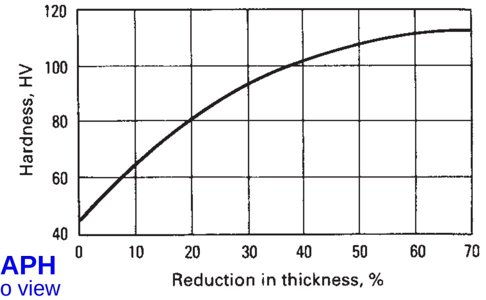

Fig. 9 Variation of hardness with amount of cold reduction by rolling for C11000 and similar coppers

Alkalies: fused sodium or potassium hydroxide; concentrated or dilute caustic solutions

Salt solutions: aluminum chloride, aluminum sulfate, calcium chloride, copper sulfate, sodium carbonate, sodium nitrate, sodium sulfate, and zinc sulfate

Waters: all types of potable water, many industrial and mine waters, seawater, and brackish water

Fabrication Characteristics

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Machinability. 20% of C36000 (free-cutting brass)

Forgeability. 65% of C37700 (forging brass)

Formability. Excellent for cold working and hot forming

Weldability. Soldering: excellent. Brazing and resistance butt welding: good. Gas-shielded arc welding: fair. Oxyfuel gas, shielded metal-arc, resistance spot, and resistance seam welding: not recommended

Annealing temperature. 475 to 750 °C (900 to 1400 °F). See also Fig. 4 and 17.

Hot-working temperature. 750 to 875 °C (1400 to 1600 °F)

Typical softening temperature. 360 °C (675 °F)

C11100
99.95Cu-0.04O-0.01Cd

Commercial Names

Previous trade name. Electrolytic tough pitch copper, anneal resistant

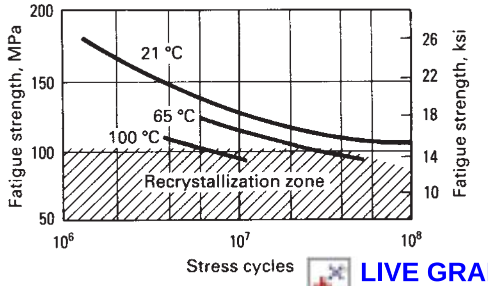

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Fig. 10 Rotating-beam fatigue strength of C11000 wire, 2 mm (0.08 in.) in diameter, H80 temper

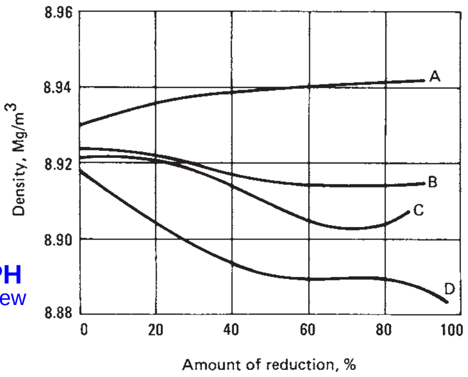


Fig. 11 Variation of density with amount of cold reduction by rolling for C11000 and similar coppers. A, vacuum annealed 12 h at 880 °C (1615 °F) and cold drawn. B, vacuum annealed 12 h at 970 °C (1780 °F) and flat rolled. C, vacuum annealed 12 h at 995 °C (1825 °F) and cold drawn. D, hot rolled, vacuum annealed 4 h at 600 °C (1110 °F), and drawn

Common name. Anneal-resistant electrolytic copper

Specifications

ASTM. See Table 12.

SAE. Bar, plate, sheet, strip: J461, J463

Government: See Table 12.

Chemical Composition

Composition limits. 99.90 Cu min. Limits on O and Cd or other elements present to make this copper anneal resistant are established by conductivity tests and/or stress relaxation tests rather than by chemical analysis.

Table 9 Typical mechanical properties of C11000

Temper	Tensile strength		Yield strength(a)		Elongation in 50 mm (2 in.), %	Hardness			Shear strength		Fatigue strength(b)	
	MPa	ksi	MPa	ksi		HRF	HRB	HR30T	MPa	ksi	MPa	ksi
Flat products, 1 mm (0.04 in.) thick												
OS050	220	32	69	10	45	40	…	…	150	22	…	…
OS025	235	34	76	11	45	45	…	…	160	23	76	11
H00	250	36	195	28	30	60	10	25	170	25	…	…
H01	260	38	205	30	25	70	25	36	170	25	…	…
H02	290	42	250	36	14	84	40	50	180	26	90	13
H04	345	50	310	45	6	90	50	57	195	28	90	13
H08	380	55	345	50	4	94	60	63	200	29	97	14
H10	395	57	365	53	4	95	62	64	200	29	…	…
M20	235	34	69	10	45	45	…	…	160	23	…	…
Flat products, 6 mm (0.25 in.) thick												
OS050	220	32	69	10	50	40	…	…	150	22	…	…
H00	250	36	195	28	40	60	10	…	170	25	…	…
H01	260	38	205	30	35	70	25	…	170	25	…	…
H04	345	50	310	45	12	90	50	…	195	28	…	…
M20	220	32	69	10	50	40	…	…	150	22	…	…
Flat products, 25 mm (1.0 in.) thick												
H04	310	45	275	40	20	85	45	…	180	26	…	…
Rod, 6 mm (0.25 in.) diameter												
H80 (40%)	380	55	345	50	10	94	60	…	200	29	…	…
Rod, 25 mm (1.0 in.) diameter												
OS050	220	32	69	10	55	40	…	…	150	22	…	…
H80 (35%)	330	48	305	44	16	87	47	…	185	27	115(c)	17(c)
M20	220	32	69	10	55	40	…	…	150	22	…	…
Rod, 50 mm (2.0 in.) diameter												
H80 (16%)	310	45	275	40	20	85	45	…	180	26	…	…
Wire, 2 mm (0.08 in.) diameter												
OS050	240	35	…	…	35(d)	…	…	…	165	24	…	…
H04	380	55	…	…	1.5(e)	…	…	…	200	29	…	…
H08	455	66	…	…	1.5(e)	…	…	…	230	33	…	…
Tube, 25 mm (1.0 in.) diameter 3 1.65 mm (0.065 in.) wall thickness												
OS050	220	32	69	10	45	40	…	…	150	22	…	…
OS025	235	34	76	11	45	45	…	…	160	23	…	…
H55 (15%)	275	40	220	32	25	77	35	45	180	26		
H80 (40%)	380	55	345	50	8	95	60	63	200	29	…	…
Shapes, 13 mm (0.50 in.) section size												
OS050	220	32	69	10	50	40	…	…	150	22	…	…
H80 (15%)	275	40	220	32	30	…	35	…	180	26	…	…
M20	220	32	69	10	50	40	…	…	150	22	…	…
M30	220	32	69	10	50	40	…	…	150	22	…	…

(a) At 0.5% extension under load. (b) At 10^8 cycles in a reversed bending test. (c) At 3×10^8 cycles in a rotating beam test. (d) Elongation in 250 mm (10 in.). (e) Elongation in 1500 mm (60 in.)

Applications

Typical uses. Produced mainly as wire for electrical power transmission where resistance to softening under overloads is desired

Mechanical Properties

Typical tensile properties. Tensile strength, 455 MPa (66 ksi); elongation, 1.5% in 150 cm (60 in.)
Elastic modulus. Tension, 115 GPa (17×10^6 psi); shear, 44 GPa (6.4×10^6 psi)

Mass Characteristics

Density. 8.89 to 8.94 g/cm^3 (0.321 to 0.323 lb/in.^{3}) at 20 °C (68 °F)

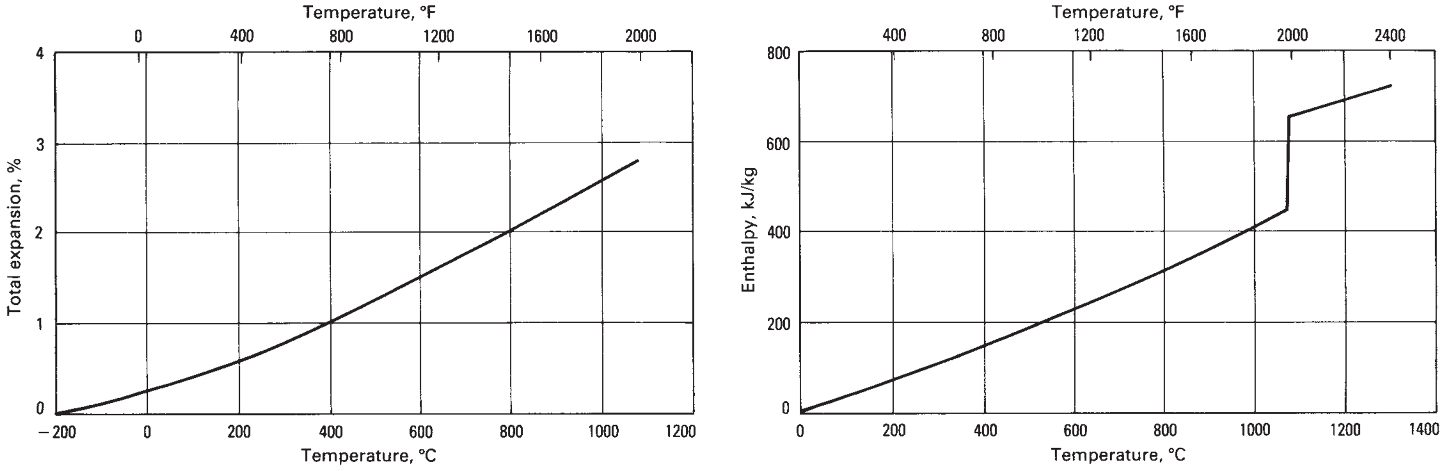
Thermal Properties

Liquidus temperature. 1085 °C (1980 °F)
Solidus temperature. 1065 °C (1950 °F)

Table 10 Typical impact strength of C11000

Product and condition	Impact strength	
	J	ft · lbf
Charpy V-notch		
Hot rolled, annealed	96	71
Charpy keyhole-notch		
As-cast	11	8
As-hot rolled	43	32
Rod		
Annealed	52	38
Commercial temper	35	26
Izod		
Rod		
Annealed and drawn 30%	54	40
Drawn 30%	45	33
Plate		
As-hot rolled	52	38
Annealed	53(a)	39(a)
	39(b)	29(b)
Cold rolled 50%	26(a)	19(a)
	12(b)	9(b)

(a) Parallel to rolling direction. (b) Transverse to rolling direction



(a) LIVE GRAPH Click here to view

(b)

Fig. 12 Thermal expansion and enthalpy of C11000. (a) Total thermal expansion from –190 °C (–310 °F). (b) Enthalpy (heat content) above 0 °C (32 °F)

Coefficient of linear thermal expansion. 17.0 µm/m · K (9.4 µin./in. · °F) at 20 to 100 °C (68 to 212 °F); 17.3 µm/m · K (9.6 µin./in. · °F) at 20 to 200 °C (68 to 392 °F); 17.7 µm/m · K (9.8 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 385 J/kg · K (0.092 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 388 W/m · K (224 Btu/ft · h · °F)

Electrical Properties

Electrical conductivity. Volumetric: 100% IACS at 20 °C (68 °F)
Electrical resistivity. 17.2 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Forgeability. 65% of C37700 (forging brass)
Formability. Excellent for cold working and hot forming. Common processes include drawing, stranding, and stamping.
Weldability. Soldering: excellent. Brazing and resistance butt welding: good. Gas-shielded arc welding: fair. Oxyacetylene coated metal-arc and resistance spot and seam welding: not recommended
Annealing temperature. 475 to 750 °C (900 to 1400 °F)
Hot-working temperature. 750 to 875 °C (1400 to 1600 °F)
Typical softening temperature. 355 °C (675 °F)

C11300, C11400, C11500, C11600
99.96Cu + Ag-0.4O

Commercial Names

Previous trade name. Tough pitch copper with silver
Common name. Silver-bearing tough pitch copper
Designation. STP

Specifications

AMS. Soft wire (all alloys) and trolley wire (C11300 only): 4701
ASME. Strip (C11300 only): SB152
ASTM. See Table 13.
SAE. Bar, sheet, strip (C11300, C11400, and C11600) and plate (C11300 and C11400): J463
Federal. See Table 13.
Military. Soft wire (all alloys) and trolley wire (C11300 only): MIL-W-3318. Commutator bar (11600 only): MIL-B-19231

Chemical Composition

Copper limits. 99.0 to 99.9 Cu
Oxygen limit. 0.04% O max
Silver limits. C11300, 0.027 Ag max; C11400, 0.034 Ag max; C11500, 0.054 Ag max; C11600, 0.085 Ag max. These coppers may be low-resistance lake copper or electrolytic copper to which Ag has been intentionally added.

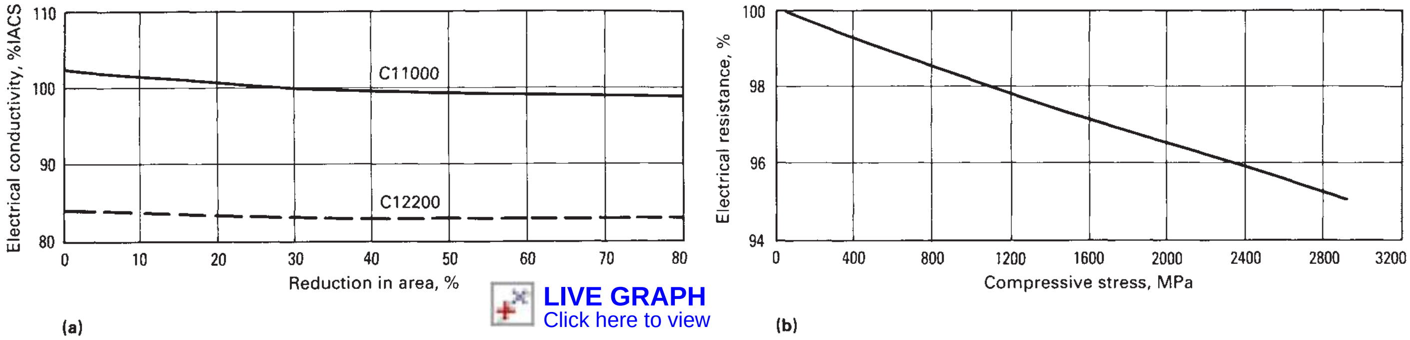


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Fig. 13 Electrical properties of copper. (a) Electrical conductivity as a function of amount of cold reduction by drawing. (b) Variation of electrical resistance with applied compressive stress at 30 and 75 °C (86 and 167 °F). Resistance expressed as percent of no load value

Table 11 Creep properties of copper

Temper	Testing temperature °C	Testing temperature °F	Stress MPa	Stress ksi	Duration of test, h	Total extension(a),%	Intercept, %	Minimum creep rate, % per 1000 h
Strip, 2.5 mm (0.10 in.) thick								
OS030	130	265	55	8	2500	2.6	2.0	0.15
			100	14.5	2600	10.0	7.6	1.2
			140	20	170	29.8(b)	…	39
	175	345	55	8	2000	3.3	2.3	0.65
			100	14.5	350	15(b)	8.0	6.3
H01	130	265	55	8	8250	0.20	0.15	0.01
			100	14.5	8600	0.67	0.26	0.042
			140	20	1750	2.4(b)	0.32	0.45
	175	345	55	8	6850	1.14	0.14	0.088
			100	14.5	1100	2.0	0.22	0.66
H02	130	265	55	8	7200	0.24	0.13	0.01
			100	14.5	8600	1.02	0.25	0.054
			140	20	4680	3.4(b)	0.36	0.27
	175	345	55	8	1050	3.3(b)	…	0.6
H06	130	265	55	8	8250	1.58	0.08	0.035
			100	14.5	8700	7.31	0.16	0.055
			140	20	4030	11(b)	0.24	0.17
Rod, 3.2 mm (0.13 in.) diameter								
OS025	260	500	2.5	0.36	6000	0.08	0.016	0.011
			4.1	0.60	6000	0.19	0.010	0.030
			7.2	1.05	6500	0.64	0.113	0.080
			13.8	2.0	6500	2.88	0.87	0.306
H08	205	400	7.2	1.05	6500	0.06	0.045	0.011
			14.5	2.1	6500	0.20	0.112	0.012
			28	4.05	6500	1.08	0.41	0.097
			50	7.25	6500	5.42	2.47	0.44

Note: Values shown are typical for the tough pitch grades of copper. Oxygen-free, phosphorus-deoxidized, and arsenical coppers have marginally greater resistance to creep deformation. (a) Total extension is initial extension (not given in table) plus intercept (column 8) plus the product of minimum creep rate (column 9) and duration (column 6). (b) Rupture test

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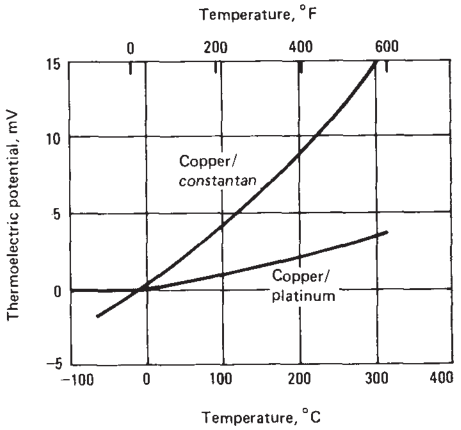

Fig. 14 Thermoelectric properties of copper with cold junctions at 0 °C (32 °F)

Applications

Typical uses. All forms except pipe and tubing: gaskets, radiators, busbars, conductivity wire, contacts, radio parts, windings, switches, terminals, commutator segments, chemical process equipment, printing rolls, clad metals, printed circuit foil

Mechanical Properties

Tensile properties. See Table 14.
Shear strength. See Table 14.
Hardness. See Table 14.
Elastic modulus. Tension, 115 GPa (17 × 10^6 psi); shear, 44 GPa (6.4 × 10^6 psi)

Mass Characteristics

Density. 8.89 to 8.94 g/cm^3 (0.321 to 0.323 lb/$in.^3$) at 20 °C (68 °F)

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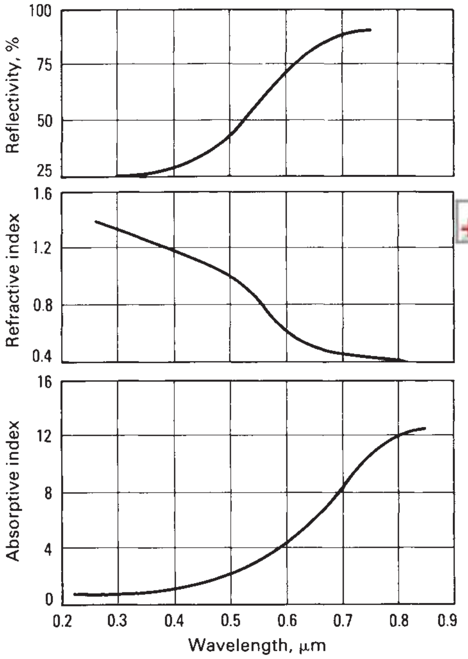

Fig. 15 Optical properties of C11000 and similar coppers at 21 °C (70 °F)

Thermal Properties

Liquidus temperature. 1080 °C (1980 °F)
Coefficient of linear thermal expansion. 17.7 µm/m · K (9.8 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 385 J/kg · K (0.092 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 388 W/m · K (224 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric: 100% IACS at 20 °C (68 °F)
Electrical resistivity. 17.2 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Forgeability. 65% of C37700 (forging brass)
Formability. Excellent for cold working and hot forming
Weldability. Soldering: excellent. Brazing and resistance butt welding: good. Gas-shielded arc welding: fair. Oxyacetylene coated metal-arc and resistance spot and seam welding: not recommended
Annealing temperature. 475 to 750 °C (900 to 1400 °F)

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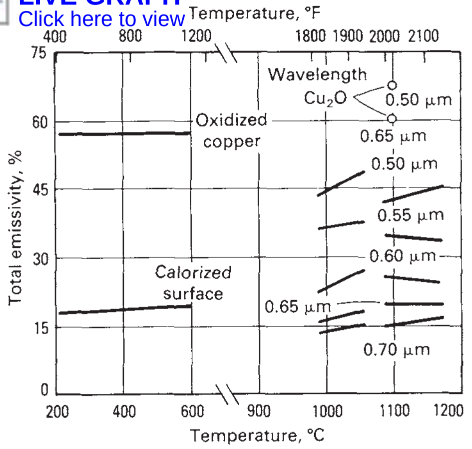

Fig. 16 Emissivity of commercial coppers

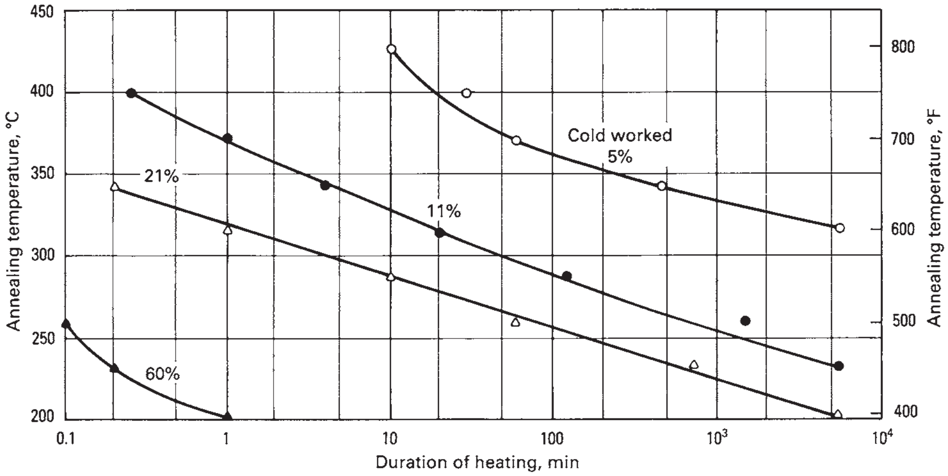

Fig. 17 Time-temperature relationships for annealing C11000 and similar coppers

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Hot-working temperature. 750 to 875 °C (1400 to 1600 °F)

C12500, C12700, C12800, C12900, C13000

Commercial Names

Previous trade name. Fire-refined tough pitch copper (C12500); fire-refined tough pitch copper with silver (C12700, C12800, C12900, C13000)
Common name. Fire-refined copper
Designation. C12500; FRTP. Others: FRTSP

Specifications

ASTM. Flat products: B 11, B 124, B 133, B 152, B 272. Rod: B 12, B 124, B 133. Shapes: B 124, B 133, B 216. Lake copper wirebar, cake, slab, billet, and ingot: B 4
Government. MIL-W-3318

Chemical Composition

Composition limits in ASTM B 216: 99.88 Cu + Ag min (minimum Ag content may be specified by agreement), 0.012 As max, 0.003 Sb max, 0.025 Se + Te max, 0.05 Ni max, 0.003 Bi max, 0.004 Pb max
Consequence of exceeding impurity limits. Bi and Pb can cause hot workability problems if composition limits are exceeded. Se and Te greatly affect recrystallization and grain growth.

Applications

Typical uses. Architectural: Building fronts, downspouts, flashing, gutters, roofing, screening, spouting. Automotive: gaskets, radiators. Electrical: busbars, contacts, radio parts, commutator segments, switches, terminals. Miscellaneous: anodes, chemical process equipment, kettles, pans, printing rolls, rotating bands, roadbed expansion

Table 12 Specifications for C11100

Product	Federal	ASTM
Bar	QQ-C-502, QQ-C-576	…
Bar, bus	QQ-B-865	…
Pipe, bus	QQ-B-825	…
Plate	QQ-C-576	…
Rod	QQ-B-502	B 49, B 133
Rod, bus	QQ-B-825	…
Shapes	QQ-C-502	…
Shapes, bus	QQ-B-825	…
Sheet	QQ-C-576	…
Strip	QQ-C-502, QQ-C-576	…
Tubing, bus	QQ-B-825	…
Wire, coated	…	B 246
With tin	…	B 334
With lead alloy	…	B 189
With nickel	…	B 355
With silver	…	B 298
Wire, flat	QQ-C-502	…
Wire, hard drawn	QQ-W-343	B 1
Wire, medium-hard drawn	…	B 2
Wire, stranded	…	B 8, B 172, B 173, B 174, B 226, B 228, B 229, B 286
Wire, rod	…	B 47
Wire, trolley	…	B 116

plates, vats. This copper is suitable for use where the high conductivity and low annealing temperature of electrolytic tough pitch copper are not required.
Precautions in use. This copper is subject to embrittlement when heated in a reducing atmosphere, as in annealing, brazing, or welding at temperatures of 370 °C (700 °F) or above. If hydrogen or carbon monoxide is present, embrittlement can be rapid.

Mechanical Properties

Tensile properties. See Table 15.
Shear strength. See Table 15.
Hardness. See Table 15.
Fatigue strength. Strip, OS025 temper, 76 MPa (11 ksi)

Mass Characteristics

Density. 8.89 g/cm^3 (0.321 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1085 °C (1980 °F)
Coefficient of linear thermal expansion. 16.8 μm/m · K (9.3 μin./in. · °F) at 20 to 100 °C (68 to 212 °F); 17.4 μm/m · K (9.7 μin./in. · °F) at 20 to 200 °C (68 to 392 °F); 17.7 μm/m · K (9.8 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 385 J/kg · K (0.092 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 377 W/m · K (218 Btu/ft · h · °F) at 20 °C (68 °F)

Table 13 Specifications for C11300, C11400, C11500, and C11600

Product	ASTM	Federal
Bar	B 152(a)	QQ-C-576(a), QQ-C-502(b)
Bar, bus	B 187(a)	QQ-B-825(a)
Pipe, bus	B 188(a)	QQ-B-825(c)
Plate	B 152(a)	QQ-B-825(a)
Rod	B 49(e)	QQ-C-502(f)
Rod, bus	B 187(a)	QQ-B-825(f)
Shapes	…	QQ-C-502(f)
Shapes, bus	B 187(a)	QQ-B-825(f)
Sheet	B 152(a)	QQ-C-576(f)
Sheet, clad	B 506(a)	QQ-C-502(c)
Strip	B 152(a), B 272(e)	QQ-C-502(b), QQ-C-576(f)
Strip clad	B 506(a)	…
Tube, bus	B 188(a)	QQ-B-825(f)
Wire, coated with		
Tin	B 246, B 334(e)	…
Lead alloy	B 189(e)	…
Nickel	B 355(e)	…
Silver	B 298(e)	…
Wire, flat	B 272(e)	QQ-C-502(a)
Wire, hard drawn	B 1(e)	QQ-W-343(e)
Wire, medium-hard drawn	B 2(e)	QQ-W-343(e)
Wire, rod	B 49(e)	…
Wire, soft	B 3(a), B 48(e)	QQ-W-343(e)
Wire, stranded	B 8, B 172, B 173, B 174, B 226, B 228, B 229, B 286(e)	…
Wire, trolley	B 47, B 116(e)	QQ-W-343(g)

(a) C11300, C11400, and C11600. (b) C11600 only. (c) C11400 only. (d) C11300 and C11400. (e) C11300, C11400, C11500, and C11600. (f) C11400 and C11600. (g) C11300 only

Electrical Properties

Electrical conductivity. Volumetric, 98% IACS at 20 °C (68 °F), annealed
Electrical resistivity. 17.6 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Formability. Excellent for hot or cold forming but should not be heated for forming or annealed in a reducing atmosphere
Joining. Riveting: use copper rivets. Pressure welding: use Koldweld proprietary method. Soft solder with all grades of solder, commercial solder fluxes, or rosin. Silver braze with all types of flame using copper-phosphorus, silver, or copper-zinc (see ASTM B 260). Satisfactory fluxes are commercially available. Use gas-shielded arc welding processes with recommended filler metals, depending on application. Other welding methods generally are not recommended.
Annealing temperature. 400 to 650 °C (750 to 1200 °F)
Hot-working temperature. 750 to 950 °C (1400 to 1750 °F)

C14300, C14310
99.9Cu-0.1Cd; 99.8Cu-0.2Cd

Commercial Names

Previous trade names. C14300: cadmium-copper, deoxidized

Chemical Composition

Copper. 99.8 to 99.9 Cu
Cadmium. C14300, 0.05 to 0.15 Cd; C14310, 0.1 to 0.3 Cd

Applications

Typical uses. Rolled strip for anneal-resistant electrical applications: applications requiring thermal softening and embrittlement resistance, such as lead frames, contacts, terminals, solder-coated and solder-fabricated parts. Furnace brazed assemblies and welded components such as tube or cable wrap

Mechanical Properties

Tensile properties. See Table 16.
Shear strength. See Table 16.
Hardness. See Table 16.
Elastic modulus. Tension, 115 GPa (17 × 10^6 psi); shear, 44 GPa (6.4 × 10^6 psi)

Table 14 Typical mechanical properties of C11300, C11400, C11500, and C11600

	Tensile strength		Yield strength(a)			Hardness			Shear strength	
Temper	MPa	ksi	MPa	ksi	Elongation in 50 mm (2 in.), %	HRF	HRB	HR30T	MPa	ksi
Flat products, 1 mm (0.04 in.) thick										
OS025	235	34	75	11	45	45	…	…	160	23
H00	250	36	195	28	30	60	10	25	170	25
H01	260	38	205	30	25	70	25	36	170	25
H02	290	42	250	36	14	84	40	50	180	26
H04	345	50	310	45	6	90	50	57	195	28
H08	380	55	345	50	4	94	60	63	200	29
H10	395	57	365	53	4	95	62	64	200	29
M20	235	34	69	10	45	45	…	…	160	23
Flat products, 6 mm (0.25 in.) thick										
OS050	220	32	69	10	50	40	…	…	150	22
H00	250	36	195	28	40	60	10	…	170	25
H01	260	38	205	30	35	70	25	…	170	25
H04	345	50	310	45	12	90	50	…	195	28
M20	220	32	69	10	50	40	…	…	150	22
Flat products, 25 mm (1.0 in.) thick										
H04	310	45	275	40	20	85	45	…	180	26
Rod, 6 mm (0.25 in.) diameter										
H80 (40%)	380	55	345	50	10	94	60	…	200	29
Rod, 25 mm (1.0 in.) diameter										
OS050	220	32	69	10	55	40	…	…	150	22
H80 (35%)	330	48	305	44	16	87	47	…	185	27
M20	220	32	69	10	55	40	…	…	150	22
Rod, 51 mm (2.0 in.) diameter										
H80 (16%)	310	45	275	40	20	85	45	…	180	26
Wire, 2 mm (0.08 in.) diameter										
OS050	240	35	…	…	35(b)	…	…	…	165	24
H04	380	55	…	…	1.5(c)	…	…	…	200	29
H08	455	66	…	…	1.5(c)	…	…	…	230	33
Shapes, 13 mm (0.50 in.) diameter										
OS050	220	32	69	10	50	40	…	…	150	22
H80 (15%)	275	40	220	32	30	…	35	…	180	26
M20	220	32	69	10	50	40	…	…	150	22
M30	220	32	69	10	50	40	…	…	150	22

(a) At 0.5% extension under load. (b) Elongation in 250 mm (10 in.). (c) Elongation in 1500 mm (60 in.)

Mass Characteristics

Density. 8.94 g/cm^3 (0.323 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1080 °C (1976 °F)
Solidus temperature. 1052 °C (1926 °F)
Coefficient of linear thermal expansion. 17.0 µm/m · K (9.4 µin./in. · °F) at 20 to 100 °C (68 to 212 °F); 17.3 µm/m · K (9.6 µin./in. · °F) at 20 to 200 °C (68 to 392 °F); 17.7 µm/m · K (9.8 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 385 J/kg · K (0.092 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. C14300, 377 W/m · K (218 Btu/ft · h · °F) at 20 °C (68 °F); C14310, 343 W/m · K (198 Btu/ft · h · °F)

Electrical Properties

Electrical conductivity. Volumetric: C14300, 96% IACS at 20 °C (68 °F); C14310, 85% IACS at 20 °C (68 °F)
Electrical resistivity. C14300, 18 nΩ · m at 20 °C (68 °F); C14310, 20.3 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Forgeability. 65% of C37700 (forging brass)
Formability. Excellent capacity for cold working and hot forming
Weldability. Soldering, brazing, and gas-shielded arc welding: excellent. Oxyacetylene welding and resistance butt welding: good. Coated metal arc and resistance seam and spot welding: not recommended
Annealing temperature. 535 to 750 °C (1000 to 1400 °F)
Hot-working temperature. 750 to 875 °C (1400 to 1600 °F)

C14500
99.5Cu-0.5Te

Commercial Names

Previous trade name. Phosphorus-deoxidized tellurium-bearing copper
Common name. Free-machining copper
Designation. DPTE

Specifications

ASTM. Flat products and rod: B 124, B 301, Shapes: B 124, B 283

Chemical Composition

Composition limits. 99.90 Cu + Ag + Te min, 0.004 to 0.012 P, 0.40 to 0.60 Te

Applications

Typical uses. Forgings and screw machine products requiring high conductivity, extensive machining, corrosion resistance, copper color, or a combination of these qualities; typical parts include electrical connectors, motor parts, switch parts, plumbing fixtures, soldering tips, welding-torch tips, transistor bases, and parts that are assembled by furnace brazing
Precautions in use. Carbide-tipped tools should be used for machining C14500.

Mechanical Properties

Tensile properties. See Table 17.
Shear strength. See Table 17.
Hardness. See Table 17.
Elastic modulus. Tension, 115 GPa (17 × 10^6 psi); shear, 44 GPa (6.4 × 10^6 psi)

Mass Characteristics

Density. 8.94 g/cm^3 (0.323 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1075 °C (1967 °F)
Solidus temperature. 1051 °C (1924 °F)
Coefficient of linear thermal expansion. 17.1 µm/m · K (9.5 µin./in. · °F) at 20 to 100 °C (68 to 212 °F); 17.4 µm/m · K (9.7 in./in. · °F) at 20 to 200 °C (68 to 392 °F); 17.8 µm/m · K (9.9 in./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 385 J/kg · K (0.092 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 355 W/m · K (205 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric: 93% IACS at 20 °C (68 °F)
Electrical resistivity. 18.6 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 85% of C36000 (free-cutting brass)
Formability. Good capacity for being cold worked, usually by drawing, rolling, or swaging. Excellent capacity for being hot formed, most often by extrusion, forging, or rolling
Weldability. Soldering or brazing: excellent. Arc welding, oxyfuel gas welding, and most resistance welding processes are not recommended.
Annealing temperature. 425 to 650 °C (800 to 1200 °F)
Hot-working temperature. 750 to 875 °C (1400 to 1600 °F)

C14700
99.6Cu-0.4S

Commercial Names

Previous trade name. Sulfur-bearing copper
Common name. Free-machining copper, sulfur copper

Table 15 Typical mechanical properties of C12500, C12700, C12800, C12900, and C13000

			Yield strength									
	Tensile strength		At 0.5% extension under load		At 0.2% offset		Elongation in 50 mm (2 in.), %	Hardness			Shear strength	
Temper	MPa	ksi	MPa	ksi	MPa	ksi		HRF	HRB	H30T	MPa	ksi
Flat products, 1 mm (0.04 in.) thick												
OS025	235	34	76	11	…	…	45	45	…	…	160	23
H00	250	36	195	28	235	34	30	60	10	25	170	25
H02	290	42	250	36	270	39	14	84	40	50	180	26
H04	345	50	310	45	327	47.5	6	90	50	57	195	28
H08	380	55	345	50	360	52	4	94	60	63	200	29
H10	395	57	365	53	370	54	4	95	62	64	200	29
M20	235	34	69	10	…	…	45	45	…	…	160	23
Rod, 25 mm (1 in.) diameter												
OS050	220	32	69	10	…	…	55	40	…	…	150	22
H80 (35%)	330	48	305	44	…	…	16	87	47	…	185	27
M20	220	32	69	10	…	…	55	40	…	…	150	22
Wire, 2 mm (0.08 in.) diameter												
OS050	240	35	…	…	…	…	35(a)	…	…	…	165	24
H04	380	55	…	…	…	…	1.5(b)	…	…	…	200	29
H08	455	66	…	…	…	…	1.5(b)	…	…	…	230	33
Shapes, 13 mm (0.50 in.) diameter												
OS050	220	32	69	10	…	…	50	40	…	…	150	22
H80 (15%)	275	40	220	32	…	…	30	…	35	…	180	26
M20	220	32	69	10	…	…	50	40	…	…	150	22
M30	220	32	69	10	…	…	50	40	…	…	150	22

(a) Elongation in 250 mm (10 in.). (b) Elongation in 1500 mm (60 in.)

Specifications

ASTM. Flat products and rod: B 301

Chemical Composition

Composition limits. 0.20 to 0.50 S, 0.10 max other (total), bal Cu + Ag

Applications

Typical uses. Screw machine products and parts requiring high conductivity, extensive machining, corrosion resistance, copper color, or a combination of these properties; electrical connectors, motors, and switch components; plumbing fittings; furnace-brazed articles; screws; soldering coppers; rivets; and welding-torch tips

Mechanical Properties

Tensile properties. See Table 17, C14500.
Hardness. See Table 17, C14500.
Elastic modulus. Tension, 115 GPa (17 × 10^6 psi); shear, 44 GPa (6.4 × 10^6 psi)

Mass Characteristics

Density. 8.94 g/cm^3 (0.323 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1076 °C (1969 °F)
Solidus temperature. 1067 °C (1953 °F)
Coefficient of linear thermal expansion. 17.0 μm/m · K (9.4 μin./in. · °F) at 20 to 100 °C (68 to 212 °F); 17.3 μm/m · K (9.6 μin./in. · °F) at 20 to 200 °C (68 to 392 °F); 17.7 μm/m · K (9.8 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 385 J/kg · K (0.092 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 374 W/m · K (216 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric: O61 temper, 95% IACS at 20 °C (68 °F)
Electrical resistivity. 18.1 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 85% of C36000 (free-cutting brass)
Annealing temperature. 425 to 650 °C (800 to 1200 °F)
Hot-working temperature. 750 to 875 °C (1400 to 1600 °F)

C15000
99.85Cu-0.15Zr

Commercial Names

Trade name. Amzirc Brand copper; N-4 alloy
Common name. Zirconium-copper

Chemical Composition

Composition limits. 99.95 Cu + Ag + Zr min, 0.13 to 0.20 Zr

Applications

Typical uses. Stud bases for power transmitters and rectifiers, switches and circuit breakers for high-temperature service, commutators, resistance welding tips and wheels, solderless wrapped connectors. Zirconium-copper is heat treatable and retains much of its room-temperature strength up to 450 °C (840 °F).
Precautions in use. During hot working, forging should be discontinued if the temperature falls below 800 °C (1470 °F). The part must be reheated to at least 900 °C (1650 °F) before forging can be resumed.

Mechanical Properties

Tensile properties. See Tables 18 and 19, and Fig. 18.
Hardness. Rod, up to 16 mm (0.62 in.) in diameter, TB04 or TH04 temper: 72 HRB. Wire: 6 mm (0.25 in.) in diameter, OS025 temper, 40 HRB; 13 mm (0.50 in.) in diameter, H01 temper, 90 HRF
Elastic modulus. Tension, 129 GPa (18.7 × 10^6 psi)
Fatigue strength. TH04 temper: 180 MPa (26 ksi) at 10^8 cycles

Table 16 Typical mechanical properties of C14300 and C14310

	Tensile strength		Yield strength at 0.2% offset		Elongation in 50 mm (2 in.), %
Temper	MPa	ksi	MPa	ksi	
OS025	220	32	75	11	42
H04	310	45	275	40	14
H08	350	51	330	48	7
H10	400	58	385	56	3

Note: Values for strip, 0.3 to 1 mm (0.01 to 0.04 in.) diameter

Impact strength. See Table 19.
Creep-rupture characteristics. See Table 20 and Fig. 19.

Mass Characteristics

Density. 8.89 g/cm^3 (0.321 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1080 °C (1976 °F)
Solidus temperature. 980 °C (1796 °F)
Coefficient of linear thermal expansion. 16.9 μm/m · K (9.4 μin./in. · °F) at 20 to 100 °C (68 to 212 °F); 17.6 μm/m · K (9.8 μin./in. · °F) at 20 to 300 °C (68 to 572 °F); 20.2 μm/m · K (11.2 μin./in. · °F) at 20 to 650 °C (68 to 1200 °F)
Specific heat. 385 J/kg · K (0.092 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. Solution-treated, cold-worked 84%, and aged material, 367 W/m · K (212 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric: 93% IACS at 20 °C (68 °F)

LIVE GRAPH
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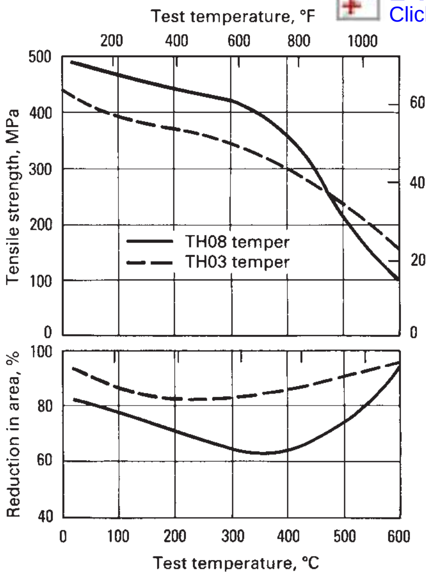
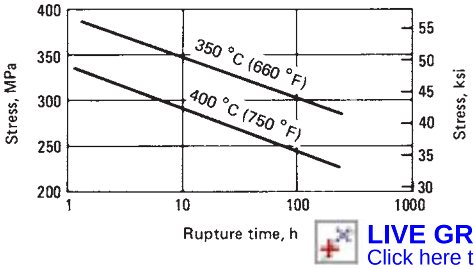


Fig. 18 Short-time elevated-temperature tensile properties of C15000. Material was solution treated 15 min at 900 °C (1650 °F), quenched, cold worked, and aged. The TH03 temper material was cold worked 54%, then aged 1 h at 400 °C (750 °F); the TH08 temper material was cold worked 84%, then aged 1 h at 375 °C (705 °F).



LIVE GRAPH
Click here to view

Fig. 19 Stress-rupture properties of C15000, TH08 temper. Material was solution treated 1 h at 950 °C (1740 °F), quenched, cold worked 85%, and aged 1 h at 425 °C (795 °F).

Table 17 Typical mechanical properties of C14500, C14700, and C18700 rod

	Tensile strength		Yield strength(a)		Elongation in 50 mm (2 in.), %	Hardness, HRB	Shear strength	
Temper	MPa	ksi	MPa	ksi			MPa	ksi
6 mm (0.25 in.) diameter								
H02	295	43	275	40	18	43	180	26
H04	365	53	340	49	10	54	200	29
13 mm (0.50 in.) diameter								
OS015	230	33	76	11	46	43 HRF	150	22
H02	295	43	275	40	20	43	180	26
H04	330	48	305	44	15	48	185	27
25 mm (1 in.) diameter								
OS050	220	32	69	10	50	40 HRF	150	22
H02	290	42	275	40	25	42	170	25
H04	330	48	305	44	20	48	185	27
50 mm (2 in.) diameter								
H02	290	42	270	39	35	42	170	25

(a) At 0.5% extension under load

Electrical resistivity. Solution-treated, cold-worked 84%, and aged material, 18.6 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Formability. Excellent capacity for being cold worked or hot formed. Most often fabricated by swaging, bending, heading, or forging
Weldability. Soldering: excellent. Brazing or resistance butt welding: good. Other welding processes are not recommended.
Heat treating. Solution treat 5 to 30 min at temperature, then age 1 to 4 h. Aging time and temperature depend on section size and amount of previous cold work.
Annealing temperature. 600 to 700 °C (1110 to 1300 °F)
Solution temperature. 900 to 925 °C (1650 to 1700 °F)
Aging temperature. Aged only, 500 to 550 °C (930 to 1020 °F); cold worked and aged, 375 to 475 °C (705 to 885 °F)
Hot-working temperature. 900 to 950 °C (1650 to 1740 °F)

Table 18 Typical mechanical properties of C15000

Section size		Cold work, % after		Tensile strength		Yield strength(c)		Elongation in 50 mm (2 in.), %
mm	in.	Solution treating(a)	Aging(b)	MPa	ksi	MPa	ksi	
Rod								
5	0.20	…	76	430	62	385	56	8
6	0.25	10(d)	…	285	41	250	36	34
9.5	0.37	80	44	470	68	440	64	11
13	0.50	56	47	460	67	435	63	15
16	0.62	61	31	440	64	430	62	15
19	0.75	50	34	435	63	420	61	15
22	0.87	48	52	430	62	415	60	15
25	1.0	48	47	430	62	415	60	15
32	1.25	32	17	413	60	400	58	18
Wire								
1	0.04	…	98(e)	525	76	495	72	1.5
2.3	0.09	…	62(e)	495	72	470	68	3
		0	…	200	29	40	6	54
		…	0	205	30	90	13	49
6	0.25	0(d)(f)	…	255	37	75	11	50
13	0.50	30(d)	…	365	53	340	49	23

(a) At 900 to 925 °C (1650 to 1695 °F). (b) For 1 h or more at 400 to 425 °C (750 to 795 °F). (c) At 0.5% extension under load. (d) Mill annealed. (e) Solution treated, cold worked the stated amount, then aged. (f) OS025 temper

Table 19 Typical low-temperature mechanical properties of C15000

Test temperature		Tensile strength		Notched tensile strength(a)		Yield strength(b)		Elongation(c), %	Reduction in area, %	Impact strength(d)	
°C	°F	MPa	ksi	MPa	ksi	MPa	ksi			J	ft · lbf
22	72	445	64.5	673	97.6	411	59.6	16	62	121	89
–78	–108	463	67.2	711	103.1	423	61.3	20	66	142	105
–197	–323	534	77.4	775	112.4	453	65.7	26	71	155	114
–253	–423	587	85.2	820	119.0	458	66.4	37	72	155	114
–269	–452	591	85.7	838	121.6	446	64.7	36	69	…	…

Note: Data are for TH04 temper materials solution treated at 950 °C (1740 °F), cold worked 85 to 90%, and aged 1 h at 450 °C (840 °F). (a) For K_t of 5.0. (b) At 0.2% offset. (c) In 2 diameters. (d) Charpy V-notch, standard 10 mm (0.39 in.) square specimen

Table 20 Typical creep strength of C15000

Test temperature		Stress for 1% creep in					
		1000 h		10,000 h		100,000 h	
°C	°F	MPa	ksi	MPa	ksi	MPa	ksi
TH01 temper (17% cold work)							
300	570	277	40.2	241	35.0	208	30.2
350	660	217	31.5	166	24.0	185	26.8
400	750	150	21.7	123	17.9	102	14.8
450	840	98	14.2	70	10.2	51	7.4
500	930	88	12.7	39	5.6	16	2.3
600	1110	28	4.1	15	2.2	7.5	1.1
TH02 temper (43% cold work)							
250	480	343	49.7	330	47.8	317	46.0
300	570	325	47.2	297	43.1	272	39.5
350	660	247	35.8	212	30.7	181	26.2
400	750	176	25.6	142	20.6	114	16.5
450	840	100	14.5	74	10.7	51	7.4
500	930	74	10.7	53	7.7	39	5.6
600	1110	18	2.6	12	1.8	8.3	1.2
TH04 temper (82% cold work)							
250	480	321	46.5	312	45.2	303	44.0
300	570	305	44.2	271	39.3	240	34.8
350	660	257	37.3	238	34.5	219	31.8
400	750	201	29.2	161	23.4	139	20.2
450	840	77	11.1	53	7.7	44	6.4
500	930	63	9.2	41	6.0	28	4.0
600	1100	5.2	0.75	2.8	0.41	1.5	0.22
650	1200	3.0	0.44	1.7	0.25	1.0	0.14

Note: Data are for materials solution treated, cold worked the indicated amount, then aged 1 h at 425 °C (795 °F).

C15100
99.9Cu-0.1Zr

Commercial Names

Trade name. ZHC Copper

Chemical Composition

Composition limits. 0.05 to 0.15 Zr, 0.005 Al max, 0.005 Mn max, 0.005 Fe max, 0.01 Al + Mn + Fe max, bal Cu

Applications

Typical uses. Lead frames for high-power electronic circuits, connectors, and switchblade jaws. Applications requiring high conductivity, moderate strength, good bend formability, and good stress relaxation resistance.

Mechanical Properties

Tensile properties. See Table 21.
Hardness. See Table 21.
Elastic modulus. 121 GPa (17.5 × 10^6 psi)
Fatigue strength. See Table 21.

Mass Characteristics

Density. 8.94 g/cm^3 (0.323 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1080 °C (1976 °F)
Solidus temperature. 1065 °C (1949 °F) at 0.05 Zr; 966 °C (1771 °F) at 0.15 Zr
Coefficient of linear thermal expansion. 17.7 μm/m · K (9.8 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Thermal conductivity. 360 W/m · K (208 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric at 20 °C (68 °F): annealed, 95% IACS; rolled, 90% IACS

Electrical resistivity. At 20 °C (68 °F): annealed, 18.1 nΩ · m; rolled, 19.2 nΩ · m

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Formability. Excellent capacity for both cold and hot forming.
Weldability. Solderability: excellent. Brazing or resistance butt welding: good. All other welding processes are not recommended.
Annealing temperature. 450 to 550 °C (840 to 1025 °F)
Hot-working temperature. 750 to 875 °C (1400 to 1600 °F).

C15500
99.75Cu-0.11Mg-0.06P

Chemical Composition

Composition limits. 99.75 Cu min, 0.027–0.10 Ag, 0.04–0.080 P, 0.08–0.13 Mg

Applications

Typical uses. High-conductivity light-duty springs, electrical contacts, resistance welding electrodes, electrical fittings, clamps, connectors, diaphragms, electronic components

Mechanical Properties

Tensile properties. See Table 22.
Hardness. See Table 22.
Elastic modulus. 115 GPa (17×10^6 psi)
Modulus of rigidity. 44 GPa (6.4×10^6 psi)
Fatigue strength. See Table 22.

Mass Characteristics

Density. 8.9 g/cm^3 (0.322 lb/in.^{3})

Thermal Properties

Liquidus temperature. 1080 °C (1980 °F)
Solidus temperature. 1078 °C (1972 °F)
Coefficient of linear thermal expansion. 17.7 μm/m · K (9.8 μin./in. · °F) from 20 to 300 °C (68 to 570 °F)
Thermal conductivity. 345 W/m · K (200 Btu/ft · h · °F)
Specific heat. 385 J/kg · K (0.092 Btu/lb · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Annealed condition: 90% IACS at 20 °C (68 °F)
Electrical resistivity. Annealed condition after precipitation heat treatment: 1.92 μΩ · cm at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Formability. Excellent capacity for cold working and hot forming
Hot Forgeability. 65% of C37700 (forging brass)
Annealing temperature. 485 to 540 °C (900 to 1000 °F)
Hot-working temperature. 750 to 875 °C (1400 to 1600 °F)

Joining

Weldability. Welding not recommended except for resistance spot welding
Solderability. Excellent
Brazing. Excellent

C15710
99.8Cu-0.2Al_2O_3

Chemical Composition

Composition limits. 99.69 to 99.85 Cu, 0.15 to 0.25 Al_2O_3, 0.01 Fe max, 0.01 Pb max, 0.04 O max

Applications

Typical uses. Rolled strip, rolled flat wire, rod and wire for electrical connectors, light-duty current-carrying springs, inorganic insulated wire, thermocouple wire, lead wire, resistance welding electrodes for aluminum, heat sinks

Mechanical Properties

Tensile properties. See Table 23.
Hardness. See Table 23.
Elastic modulus. Tension, 105 GPa (15×10^6 psi)

Mass Characteristics

Density. 8.82 g/cm^3 (0.319 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1080 °C (1980 °F)
Coefficient of linear thermal expansion. 19.5 μm/m · K (10.8 μin/in. · °F) from 20 to 300 °C (68 to 572 °F)

Table 21 Nominal mechanical properties of C15100 rolled strip

Temper	Tensile strength MPa	Tensile strength ksi	Yield strength MPa	Yield strength ksi	Elongation in 50 mm (2 in.), %	Hardness, HRB	Fatigue strength(a) MPa	Fatigue strength(a) ksi
H01	295	43	240	35	22	32	…	…
H02	325	47	295	43	10	38	…	…
H03	360	52	345	50	5	48	…	…
J04	400	58	385	56	3	57	95	14
H06	430	62	415	60	2	60	…	…
H08	470	68	455	66	2	62	…	…

(a) At 10^8 cycles

Table 22 Mechanical properties of C15500 flat products

	Tensile strength		Yield strength At 0.5% extension under load		Yield strength At 0.2% offset			Hardness		Fatigue strength	
Temper	MPa	ksi	MPa	ksi	MPa	ksi	Elongation in 50 mm (2 in.), %	HRF	HRB	MPa	ksi
Section size, 1.0 mm (0.040 in.) thick											
Light anneal (O50)	275	40	125	18	123	17.8	34	70	…	103	15.0
Quarter hard (H01)	310	45	250	36	247	35.8	25	89	…	…	…
Half hard (H02)	365	53	325	47	324	47.0	13	92	…	…	…
Hard (H04)	425	62	393	57	394	57.2	5	97	…	162	23.5
Spring (H08)	460	67	450	65	462	67.0	4	100	…	155	22.5
Extra spring (H10)	495	72	470	68	490	71.0	3	…	80	…	…
Super spring	515	75	480	70	503	73.0	3	…	82	…	…
Special spring	550	80	495	72	517	75.0	3	…	84	…	…
Section size, 5.0 mm (0.200 in.) thick											
Light anneal	275	40	125	18	122	17.7	40	70	…	…	…
Quarter hard	310	45	248	36	246	35.7	28	89	…	…	…

Table 23 Typical mechanical properties of C15710

Diameter mm	Diameter in.	Amount of cold working or temper designation	Tensile strength(a) MPa	Tensile strength(a) ksi	Yield strength at 0.2% offset(a) MPa	Yield strength at 0.2% offset(a) ksi	Elongation in 50 mm (2 in.), %	Hardness, HRB
Rod								
24	0.94	0%	325	47	270	39	20	60
22	0.88	13%	345	50	330	48	18	65
19	0.75	39%	415	60	400	58	16	70
16	0.63	56%	450	65	425	62	12	70
10	0.38	82%	510	74	470	68	10	72
6	0.25	93%	530	77	485	70	10	74
		O61	325	47	275	40	20	60
Wire								
2	0.09	98.5%	565	82	540	78	…	…
1	0.05	99.5%	650	94	620	90	…	…
		O61	325	47	275	40	…	…
0.8	0.03	99.8%	685	99	650	94	…	…
		65%	455	66	420	61	…	…
0.5	0.02	99.9%	725	105	690	100	…	…
		85%	475	69	450	65	…	…
		O61	345	50	290	42	…	…

(a) Properties will vary, depending on extrusion ratio and temperature.

Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 360 W/m · K (208 Btu/ft · h · °F)

Electrical Properties

Electrical conductivity. Volumetric, 90% IACS at 20 °C (68 °F)
Electrical resistivity. 19.2 nΩ · m at 20 °C (68 °F); temperature coefficient, 5.22 nΩ · m per K at 20 °C (68 °F)

Fabrication Characteristics

Formability. Excellent for cold working; poor for hot forming
Weldability. Soldering: excellent. Brazing: good. Resistance butt welding: fair. Resistance spot and seam welding: poor. Oxyacetylene, gas shielded arc, and coated metal arc welding are not recommended.
Annealing temperature. 650 to 875 °C (1200 to 1600 °F)

C15720
99.6Cu-0.4Al$_2$O$_3$

Chemical Composition

Composition limits. 99.49 to 99.6 Cu, 0.35 to 0.45 Al$_2$O$_3$, 0.01 Pb max, 0.01 Fe max, 0.04 O max

Applications

Typical uses. Rolled and drawn strip, rolled flat wire, drawn bar, rod, wire, and shapes for relay and switch springs, lead frames, contact supports, heat sinks, circuit breaker parts, rotor bars, resistance welding electrodes and wheels, and connectors. Parts requiring a combination of high strength and conductivity, particularly after exposure to high manufacturing or operating temperatures

Mechanical Properties

Tensile properties. See Table 24.
Hardness. See Table 24.
Elastic modulus. Tension, 113 GPa (16.4 × 10^6 psi)

Mass Characteristics

Density. 8.81 g/cm^3 (0.319 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1080 °C (1980 °F)
Coefficient of linear thermal expansion. 19.6 μm/m · K (10.9 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 353 W/m · K (204 Btu/ft · h · °F)

Electrical Properties

Electrical conductivity. Volumetric, 89% IACS at 20 °C (68 °F)
Electrical resistivity. 19.4 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Formability. Excellent for cold working; poor for hot forming
Weldability. Soldering: excellent. Brazing: good. Resistance butt welding: fair. Resistance spot and seam welding: poor. Oxyacetylene, gas-shielded arc, and coated metal arc welding are not recommended.
Annealing temperature. 650 to 925 °C (1200 to 1700 °F)

Table 24 Typical mechanical properties of C15720

Size	Amount of cold working or temper designation	Tensile strength(a) MPa	Tensile strength(a) ksi	Yield strength at 0.2% offset(a) MPa	Yield strength at 0.2% offset(a) ksi	Elongation in 50 mm (2 in.), %	Hardness, HRB
Flat products							
0.76mm (0.03 in.) thick	91%	570	83	545	79	7	…
0.51 mm (0.02 in.) thick	95%	585	85	565	82	6	…
0.25 mm (0.01 in.) thick	97%	605	88	580	84	5	…
0.152 mm (0.006 in.) thick	98%	615	89	585	85	3.5	…
	O61	485	70	380	55	13	…
Rod							
24 mm (0.94 in.) diameter	0%	470	68	365	53	19	74
21 mm (0.81 in.) diameter	26%	495	72	470	68	16	77
18 mm (0.72 in.) diameter	42%	510	74	485	70	14	78
16 mm (0.63 in.) diameter	56%	530	77	495	72	13	79
13 mm (0.50 in.) diameter	72%	540	78	505	73	11	79
10 mm (0.38 in.) diameter	82%	550	80	510	74	10	80
76 mm (3.0 in.) diameter	M30	525	76	510	74	13	78
102 mm (4.0 in.) diameter	M30	460	67	395	57	20	68

(a) Properties will vary, depending on extrusion ratio and temperature.

Table 25 Typical mechanical properties of C15735 rod

Diameter mm	Diameter in.	Amount of cold working or temper designation	Tensile strength(a) MPa	Tensile strength(a) ksi	Yield strength at 0.2% offset(a) MPa	Yield strength at 0.2% offset(a) ksi	Elongation in 50 mm (2 in.), %	Hardness, HRB
24	0.94	0%	485	70	420	61	16	77
19	0.75	39%	550	80	540	78	13	80
16	0.63	56%	585	85	565	82	10	83
64	2.5	M30	490	71	415	60	16	76
76	3.0	M30	565	82	540	78	11	78
102	4.0	M30	515	75	485	70	13	75

(a) Properties will vary, depending on extrusion ratio and temperature.

C15735
99.3Cu-0.7Al$_2$O$_3$

Chemical Composition

Composition limits. 99.19 to 99.35 Cu, 0.65 to 0.75 Al$_2$O$_3$, 0.01 Fe max, 0.01 Pb max, 0.04 O max

Applications

Typical uses. Rod for resistance welding electrodes, circuit breakers, feed-through conductors, heat sinks, motor parts; parts requiring retention of high strength and conductivity after high-temperature exposure

Mechanical Properties

Tensile properties. See Table 25.
Hardness. See Table 25.
Elastic modulus. Tension, 123 GPa (17.8 × 10^6 psi)

Mass Characteristics

Density. 8.80 g/cm^3 (0.318 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1080 °C (1980 °F)
Coefficient of linear thermal expansion. 20 μm/m · K (11.1 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 420 J/kg · K (0.10 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 339 W/m · K (196 Btu/ft · h · °F)

Electrical Properties

Electrical conductivity. Volumetric, 85% IACS at 20 °C (68 °F)
Electrical resistivity. 20.3 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Formability. Excellent for cold working; poor for hot forming
Weldability. Soldering: excellent. Brazing: good. Resistance butt welding: fair. Resistance spot and seam welding: poor. Oxyacetylene, gas-shielded arc, and coated metal arc welding are not recommended.
Annealing temperature. 650 to 925 °C (1200 to 1700 °F)

C16200
99Cu-1Cd

Commercial Names

Previous Trade name. Cadmium-copper

Specifications

ASTM. Wire: B 9, B 105
SAE. J463

Chemical Composition

Composition limits. 98.78 to 99.3 Cu, 0.7 to 1.2 Cd, 0.02 Fe max

Applications

Typical uses. Rolled strip, rod, and wire for trolley wire, heating pad and electric blanket elements, spring contacts, rail bands, high-strength transmission lines, connectors, cable wrap, switch gear components, waveguide cavities

Mechanical Properties

Tensile properties. See Table 26.
Shear strength. Rod, 13 mm (0.50 in.) in diameter: OS050 temper, 185 MPa (27 ksi); H04 temper, 385 MPa (56 ksi)
Hardness. See Table 26.
Elastic modulus. Tension, 115 GPa (17 × 10^6 psi); shear, 44 GPa (6.4 × 10^6 psi)
Fatigue strength. At 10^8 cycles for rod 13 mm (0.50 in.) in diameter: OS050 temper, 100 MPa (14.5 ksi); H04 temper, 205 MPa (30 ksi)

Mass Characteristics

Density. 8.89 g/cm^3 (0.321 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1076 °C (1969 °F)
Solidus temperature. 1030 °C (1886 °F)
Coefficient of linear thermal expansion. 17.0 µm/m · K (9.4 µin./in. · °F) at 20 to 100 °C (68 to 212 °F); 17.3 µm/m · K (9.6 µin./in. · °F) at 20 to 200 °C (68 to 392 °F); 17.7 µm/m · K (9.8 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 360 W/m · K (208 Btu/ft · h · °F)

Electrical Properties

Electrical conductivity. Volumetric, 90% IACS at 20 °C (68 °F)
Electrical resistivity. 19.2 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Formability. Excellent for cold working; good for hot forming
Weldability. Soldering and brazing: excellent. Oxyfuel gas, gas shielded arc, and resistance butt welding: good. Shielded metal arc, resistance spot, and resistance seam welding are not recommended.
Annealing temperature. 425 to 750 °C (800 to 1400 °F)
Hot-working temperature. 750 to 875 °C (1400 to 1600 °F)

C17000
98Cu-1.7Be-0.3Co

Commercial Names

Trade name. Berylco 165
Common name. Beryllium-copper; 165 alloy

Specifications

ASTM. Flat products: B 194. Rod, bars: B 196. Forgings and extrusions: B 570
SAE: J463
Government: QQ-C-533
Resistance Welding Manufacturers' Association. Class IV

Chemical Composition

Composition limits. 1.60 to 1.79 Be, 0.20 Ni + Co min, 0.6 Ni + Fe + Co max, bal Cu

Applications

Typical uses. Bellows, Bourdon tubing; diaphragms, fuse clips, fasteners, lock washers, springs, switch and relay parts, electrical and electronic components, retaining rings, roll pins, valves, pumps, spline shafts, rolling mill parts, welding equipment, nonsparking safety tools
Precautions in use. This material is a potential health hazard. Because it contains beryllium, ventilation must be provided for dry sectioning and grinding, machining, melting, welding, and any other process that produces metal dust or fumes.

Mechanical Properties

Tensile properties. See Tables 27 and 28.
Hardness. See Tables 28 and 29.
Poisson's ratio. 0.30
Elastic modulus. Tension, 115 GPa (17 × 10^6 psi); shear, 50 GPa (7.3 × 10^6 psi)
Fatigue strength. See Table 27.

Mass Characteristics

Density. 8.26 g/cm^3 (0.298 lb/in.^{3}) at 20 °C (68 °F)
Volume change on phase transformation. During age hardening: 0.2% maximum decrease in length; 0.6% maximum increase in density

Thermal Properties

Liquidus temperature. 980 °C (1800 °F)
Solidus temperature. 865 °C (1590 °F)
Coefficient of linear thermal expansion. 16.7 µm/m · K (9.3 µin./in. · °F) at 20 to 100 °C (68 to 212 °F); 17.0 µm/m · K (9.4 µin./in. · °F) at 20 to 200 °C (68 to 392 °F); 17.8 µm/m · K (9.9 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 420 J/kg · K (0.10 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 118 W/m · K (69 Btu/ft · h · °F) at 20 °C (68 °F); 145 W/m ·K (84 Btu/ft · h · °F) at 200 °C (392 °F)

Table 26 Typical mechanical properties of C16200

	Tensile strength		Yield strength(a)			
Temper	MPa	ksi	MPa	ksi	Elongation in 50 mm (2 in.), %	Hardness
Flat products, 1 mm (0.04 in.) thick						
OS025 anneal (0.025 mm grain size)	240	35	76	11	52	54 HRF
Hard	415	60	310	45	5	64 HRB
Spring	440	64	…	…	3	73 HRB
Extra spring	495	72	405	59	1	75 HRB
Rod, 13 mm (0.50 in.) diameter						
OS050 anneal (0.050 mm grain size)	240	35	48	7	56	46 HRF
OS025 anneal (0.025 mm grain size)	250	36	83	12	57	46 HRF
Half hard (25%)	400	58	310	45	12	65 HRB
Hard	505	73	474	68.7	9	73 HRB
Wire, 0.25 mm (0.01 in.) diameter						
Drawn (>99%)	690	100	…	…	1.0(b)	…
Wire, 2 mm (0.08 in.) diameter						
OS025 anneal (0.025 mm grain size)	260	38	83	12	50	…
Hard	485	70	380	55	6	…
Spring	550	80	455	66	2	…
Drawn (>96%)	605	88	…	…	1.5(b)	…

(a) At 0.5% extension under load. (b) In 1.5 m (60 in.)

Table 27 Typical mechanical properties and electrical conductivity of C17000 strip

	Tensile strength		Proportional limit at 0.002% offset		Yield strength at 0.2% offset				Fatigue strength(a)	
Temper	MPa	ksi	MPa	ksi	MPa	ksi	Elongation in 50 mm (2 in.), %	Electrical conductivity, %IACS	MPa	ksi
TB00	410–540	60–78	100–140	15–20	190–370	28–53	35–60	17–19	190–230	28–33
TD01	520–610	75–88	280–410	40–60	310–520	45–75	10–35	16–18	200–235	29–34
TD02	590–690	85–100	380–480	55–70	450–620	65–90	5–25	15–17	220–260	32–38
TD04	690–825	100–120	480–590	70–85	550–760	80–110	2–8	15–17	240–270	35–39
TF00(b)	1030–1240	150–180	550–760	80–110	895–1140	130–165	4–10	22–25	240–270	35–39
TH01(c)	1100–1280	160–185	620–795	90–115	930–1170	135–170	3–6	22–25	250–280	36–41
TH02(c)	1170–1340	170–195	660–860	95–125	1000–1210	145–175	2–5	22–25	250–290	36–42
TH04(c)	1240–1380	180–200	690–930	100–135	1070–1240	155–180	1–4	22–25	260–310	38–45
TM00(d)	690–760	100–110	480–590	70–85	520–620	75–90	18–22	20–33	230–255	33–37
TM01(d)	760–825	110–120	520–660	75–95	620–760	90–110	15–19	20–33	230–260	34–38
TM02(d)	825–930	120–135	550–690	80–100	690–860	100–125	12–16	20–33	240–270	35–39
TM04(d)	930–1030	135–150	590–725	85–105	760–930	110–135	9–13	20–33	250–280	36–40
TM06(d)	1030–1100	150–160	590–760	85–110	860–965	125–140	9–12	20–33	255–290	37–42
TM08(d)	1100–1210	160–795	620–175	90–115	965–1140	140–165	3–7	20–33	230–310	33–45

(a) Rotating beam at 108 cycles. (b) Aged 3 h at 315 °C (1600 °F). (c) Aged 2 h at 315 °C (600 °F). (d) Proprietary mill heat treatment intended to produce the stated tensile properties

Electrical Properties

Electrical conductivity. Volumetric, 15 to 33% IACS at 20 °C (68 °F), depending on heat treatment. See also Tables 27 and 28.
Electrical resistivity. Typical, 76.8 n$\Omega \cdot$ m at 20 °C (68 °F), but varies with heat treatment

Chemical Properties

General corrosion behavior. Similar to that of other high-copper alloys and basically the same as that of pure copper
Resistance to specific corroding agents. Essentially the same as that of C17200. See also Table 30.

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Formability. This alloy can be formed, drawn, blanked, pierced, and machined in the unhardened condition.
Weldability. Soldering, brazing, gas-shielded arc welding, shielded metal arc welding, and resistance spot welding: good. Resistance seam and resistance butt welding: fair. Oxyfuel gas welding is not recommended.
Recrystallization temperature. 730 °C (1350 °F)
Annealing temperature. Strip, thin rod, wire: 775 to 800 °C (1425 to 1475 °F) for 10 min, water quench. Larger sections: 1 h for each 25 mm (1 in.) of thickness
Solution temperature. 760 to 790 °C (1400 to 1450 °F). All annealing of this material is a solution treatment.
Aging temperature. 260 to 425 °C (500 to 800 °F). Maximum strength is obtained by aging 1 to 3 h at 315 to 345 °C (600 to 650 °F), depending on amount of cold work preceding the aging treatment.
Hot-working temperature. 650 to 825 °C (1200 to 1500 °F)
Hot-shortness temperature. 845 °C (1550 °F)

C17200, C17300

Commercial Names

Previous trade names. C17200: 25 alloy, alloy 25. C17300: alloy M25
Common name. Beryllium-copper

Specifications

AMS. Flat products: 4530, 4532, Rod, bar, and forgings: 4650. Wire: 4725
ASTM. Flat products: B 194 (C17200 only), B 196. Rod and bar: B 196. Wire: B 197 (C17200 only). Forgings and extrusions: B 570 (C17200 only)
SAE. J463 (C17200)
Government. Strip: QQ-C-533 (C17200 only). Rod and bar: MIL-C-21657, QQ-C-530. Wire: QQ-C-530
Resistance Welding Manufacturers' Association. Class IV

Chemical Composition

Composition limits. 1.80 to 2.00 Be, 0.20 Ni + Co min, 0.6 Ni + Co + Fe max, 0.10 Pb max (C17200) or 0.20 to 0.6 Pb (C17300), 0.5 max other (total), bal Cu
Consequences of exceeding impurity limits. Excessive P and Si decrease electrical conductivity. Excessive Sn and Pb cause hot shortness.

Applications

Typical uses. C17200 and C17300 are used in parts that are subject to severe forming conditions but require high strength, anelasticity, and fatigue and creep resistance (a wide variety of springs, flexible metal hose, Bourdon tubing, bellows, clips, washers, retaining rings); in parts that require high strength or wear resistance along with good electrical conductivity and/or magnetic characteristics (navigational instruments, nonsparking safety tools, firing pins, bushings, valves, pumps, shafts, rolling mill parts); and in parts requiring high strength and good corrosion resistance and electrical conductivity (electrochemical springs, diaphragms, contact bridges, bolts, screws).
Precautions in use. Because this alloy contains beryllium, it is a potential health hazard. Adequate ventilation should be provided for dry sectioning, melting, grinding, machining, welding, and any other fabrication or testing process that produces dust or fumes.

Mechanical Properties

Tensile properties. See Tables 31 and 32.
Hardness. See Tables 31 and 32.
Poisson's ratio. 0.30
Elastic modulus. Tension, 125 to 130 GPa (18 to 19 $\times$ 10^6 psi); shear, 50 GPa (7.3 $\times$ 10^6 psi)
Fatigue strength. Rotating beam: 380 to 480 MPa (55 to 70 ksi) at 10^7 cycles for both TF00 temper rod having a tensile strength of 1140 to 1310 MPa (165 to 190 ksi) and TH04 temper rod having a tensile strength of 1280 to 1480 MPa (185 to 215 ksi). Reversed torsion: 170 to 275 MPa (25 to 40 ksi). See also Table 33.

Structure

Crystal structure. Alpha copper solid solution is face-centered cubic, disordered. At 20 °C (68 °F), the lattice parameter of the parent phase with about 1.8% Be, homogenized at 815 °C (1500 °F), and quenched in water, is 0.3570 nm. The lattice parameter decreases sharply with increasing beryllium content. Age hardening begins with the formation of coherent Guinier-Preston (G-P) zones on {100} planes. The intermediate precipitate γ' may be nucleated either from the G-P zones or discontinuously at the grain boundaries. In either case, it has a B2 superlattice structure, a lattice parameter of 0.270 nm, and the orientation $(\bar{1}\,13)\big|_{\alpha} \| (130)_{\gamma'}$, $[110]_{\alpha} \| [001]_{\gamma'}$. The equilibrium precipitate γ', which requires longer aging times than are normally used commercially, is body-centered cubic of the CsCl type with a B2 superlattice structure, a lattice parameter of 0.270 nm, and the orientation $(\bar{1}\,11)_{\alpha} \| (110)_{\gamma}$,$[110]_{\alpha} \| [001]_{\gamma}$.
Microstructure. Small, mainly spheroidal, uniformly dispersed (Cu,Co)Be beryllides (bluish gray) in a matrix of equiaxed a copper. (Typical grain size is 0.012 to 0.030 nm in wrought product.) There is a strong tendency to form mechanical and annealing twins. In the age-hardened condition, the matrix shows pronounced striations (the so-called tweed structure) caused by G-P zone formation on {110} planes. At long aging times (>8 h), or high aging temperatures (>315 °C, or >600 °F), there is a strong tendency to form continuous bands of cellular precipitate at the grain boundaries and along twin boundaries.
Conventional metallographic techniques may be used. Dry sectioning and grinding should be done in a ventilated area.

Table 28 Typical mechanical properties and electrical conductivities of C17000 rod, bar, plate, tubing, billets, and forgings

Product form	Temper	Tensile strength		Yield strength at 0.2% offset		Elongation in 50 mm (2 in.), %	Hardness	Electrical conductivity, %IACS
		MPa	ksi	MPa	ksi			
Rod, bar, plate, tubing								
All sizes								
	TB00	415–585	60–85	140–205	20–30	35–60	45–85 HRB	17–19
	TF00(a)	1035–1240	150–180	860–1070	125–155	4–10	32–39 HRC	22–25
< 10 mm (< 3/8 in.)	TD04	655–895	95–130	515–725	75–105	10–20	92–103 HRB	15–17
	TH04(b)	1205–1380	175–200	930–1140	135–165	2–5	36–41 HRC	22–25
10–25 mm (–1 in.)	TD04	620–825	90–120	515–725	75–105	10–20	91–102 HRB	15–17
	TH04(b)	1170–1345	170–195	930–1140	135–165	2–5	35–40 HRC	22–25
> 25 mm (> 1 in.)	TD04	585–795	85–115	515–725	75–105	10–20	88–101 HRB	15–17
	TH04(b)	1140–1310	165–190	930–1140	135–165	2–5	34–39 HRC	22–25
Billet	As-cast	515–585	75–85	275–345	40–50	15–30	80–85 HRB	16–22
	Cast and aged(a)	655–690	95–100	485–515	70–75	10–25	18–25 HRC	18–23
	TB00	415–515	60–75	170–205	25–30	25–45	65–75 HRB	13–18
	TF00(a)	965–1170	140–170	725–930	105–135	1–4	30–38 HRC	18–25
Forgings	TB00	415–585	60–85	140–205	20–30	35–60	45–85 HRB	17–19
	TF00(a)	1035–1240	150–180	860–1070	125–155	4–10	32–39 HRC	22–25

(a) Aged 3 h at 350 °C (625 °F). (b) Aged 2 to 3 h at 330 °C (625 °F)

Table 29 Typical hardnesses of C17000 strip

Temper	HV	Standard Rockwell	Superficial Rockwell
TB00	90–160	45–78 HRB	45–67 HR30T
TD01	150–190	68–90 HRB	62–75 HR30T
TD02	185–225	88–96 HRB	74–79 HR30T
TD04	200–260	96–102 HRB	79–83 HR30T
TF00	320 min	33–38 HRC	55–58 HR30N
TH01	343 min	35–39 HRC	55–59 HR30N
TH02	360 min	37–40 HRC	56–80 HR30N
TH04	370 min	39–41 HRC	58–61 HR30N
TM00	200–235	18–23 HRC	37–42 HR30N
TM01	230–265	21–26 HRC	42–46 HR30N
TM02	260–295	25–30 HRC	46–50 HR30N
TM04	290–325	30–35 HRC	50–54 HR30N
TM06	320–350	31–37 HRC	52–56 HR30N
TM08	434–375	32–38 HRC	55–58 HR30N

One of the common etchants for immersion etching is ammonium persulfate: 3 parts concentrated NH_4OH, 1 part 3% H_2O_2, 2 parts 10% $(NH_4)_2S_2O_3$, and 7 to 10 parts H_2O. This etchant reveals general details of the microstructure. The matrix is stained blue to deep lavender, depending on the state of heat treatment, etchant concentration, and etching time. The etchant should be freshly made.

A common etchant for swabbing is potassium dichromate: $K_2Cr_2O_7$, 1.5 g NaCl, 8 mL H_2SO_4, and 100 mL H_2O. This etchant emphasizes grain boundaries, particularly when heavily decorated with discontinuous precipitate. A very effective procedure for studying grain boundaries and discontinuous precipitation is to first etch with ammonium persulfate, then remove the stain with a single wipe of the dichromate etchant.

Mass Characteristics

Density. 8.25 g/cm^3 (0.298 lb/in.^{3}) at 20 °C (68 °F)

Volume change on phase transformation. During age hardening, there is a maximum decrease in length of 0.2% and a maximum increase in density of 0.6%.

Thermal Properties

Liquidus temperature. 980 °C (1800 °F)

Solidus temperature. 865 °C (1590 °F)

Coefficient of linear thermal expansion. 16.7 μm/m · K (9.3 μin./in. · °F) at 20 to 100 °C (68 to 212 °F); 17.0 μm/m · K (9.4 μin./in. · °F) at 20 to 200 °C (68 to 392 °F); 17.8 μm/m · K (9.9 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)

Specific heat. 420 J/kg · K (0.10 Btu/lb · °F) at 20 to 100 °C (68 to 212 °F)

Thermal conductivity. 105 to 130 W/m · K (60 to 75 Btu/ft · h · °F) at 20 °C (68 °F); 130 to 133 W/m · K (75 to 77 Btu/ft · h · °F) at 200 °C (392 °F)

Electrical Properties

Electrical conductivity. Volumetric, 15 to 30% IACS at 20 °C (68 °F), depending on heat treatment. See also Tables 32 and 33.

Electrical resistivity. 57 to 115 nΩ · m at 20 °C (68 °F), depending on heat treatment

Table 30 Approximate corrosion resistance of C17000

Good resistance(a)

- Acetate solvents
- Acetic acid, cold, unaerated
- Alcohols
- Ammonia, dry
- Atmosphere, rural, industrial, marine
- Benzene
- Borax
- Boric acid
- Brine
- Butane
- Carbon dioxide
- Carbon tetrachloride
- Chlorine, dry
- Freon
- Gasoline
- Hydrogen
- Nitrogen
- Oxalic acid
- Potassium chloride
- Potassium sulfate
- Propane
- Rosin
- Sodium bicarbonate
- Sodium chloride
- Sodium sulfate
- Sulfur dioxide
- Sulfur trioxide
- Water, fresh or salt

Fair resistance(b)

- Acetic acid, cold, aerated
- Acetic anhydride
- Acetylene
- Ammonium chloride
- Ammonium sulfate
- Aniline
- Bromine, dry
- Carbonic acid
- Copper nitrate
- Ferrous chloride
- Ferrous sulfate
- Fluorine, dry
- Hydrochloric acid, up to 0.1%
- Hydrofluoric acid, dilute

Fair resistance(b)

- Hydrofluosilicic acid
- Hydrogen peroxide
- Nitric acid, up to 0.1%
- Phenol
- Phosphoric acid, unaerated
- Potassium hydroxide
- Sodium hydroxide
- Sodium hypochlorite
- Sodium peroxide
- Sodium sulfide
- Sulfur
- Sulfur chloride
- Sulfuric acid, unaerated
- Zinc chloride

Poor resistance(c)

- Acetic acid, hot
- Ammonia, moist
- Ammonium hydroxide
- Ammonium nitrate
- Bromine, aerated or hot
- Chlorine, moist or warm
- Chromic acid
- Ferric chloride
- Ferric sulfate
- Fluorine, moist or warm
- Hydrochloric acid, over 0.1%
- Hydrocyanic acid
- Hydrofluoric acid, concentrated
- Hydrogen sulfide, moist
- Lactic acid, hot or aerated
- Mercuric chloride
- Mercury
- Mercury salts
- Nitric acid, over 0.1%
- Phosphoric acid, aerated
- Picric acid
- Potassium cyanide
- Silver chloride
- Sodium cyanide
- Stannic chloride
- Sulfuric acid, aerated
- Sulfurous acid
- Tartaric acid, hot or aerated

(a) < 0.25 mm/year (0.01 in./year) penetration. (b) 0.025–2.5 mm/year (0.001–0.10 in./year) penetration. (c) > 0.25 mm/year (0.01 in./year) penetration

Table 31 Tensile property ranges for C17200 and C17300 strip of various tempers

	Tensile strength		Proportional limit at 0.002% offset		Yield strength at 0.2% offset		
Temper	MPa	ksi	MPa	ksi	MPa	ksi	Elongation in 50 mm (2 in.), %
TB00	415–540	60–78	105–140	15–20	195–380	28–55	35–60
TD01	515–605	75–88	275–415	40–60	415–605	60–88	10–36
TD02	585–690	85–100	380–485	55–70	515–655	75–95	5–25
TD04	690–825	100–120	485–585	70–85	620–770	90–112	2–8
TF00(a)	1140–1310	165–190	690–860	100–125	965–1205	140–175	4–10
TH01(b)	1205–1380	175–200	760–930	110–135	1035–1275	150–185	3–6
TH02(b)	1275–1450	185–210	825–1000	120–145	1105–1345	160–195	2–5
TH04(b)	1310–1480	190–215	860–1070	125–155	1140–1415	165–205	1–4
TM00(c)	690–760	100–110	450–585	65–85	515–620	75–90	18–23
TM01(c)	760–825	110–120	515–655	75–95	620–760	90–110	15–20
TM02(c)	825–930	120–135	585–725	85–105	690–860	100–125	12–18
TM04(c)	930–1035	135–150	655–795	95–115	795–930	115–135	9–15
(c)	1035–1105	150–160	725–825	105–120	860–965	125–140	9–14
TM06(c)	1105–1205	160–175	760–860	110–125	1000–1170	145–170	4–10
TM08(c)	1205–1310	175–190	795–895	115–130	1070–1240	155–180	3–9

(a) Solution treated and aged 3 h at 315 °C (600 °F). (b) Cold rolled and aged 2 h at 315 °C (600 °F). (c) Proprietary mill treatment to produce the indicated tensile properties

Chemical Properties

General corrosion behavior. Similar to that of other high-copper alloys; basically the same as that of pure copper

Resistance to specific corroding agents. See Table 34.

Fabrication Characteristics

Machinability. C17200: 20% of C36000 (free-cutting brass). C17300: 50% of C36000. Both alloys can be readily machined by all conventional methods. Specific machining parameters

depend on shapes, machining method, and temper or condition of the metal. The leaded version of this alloy, C17300, is especially intended for machined parts. Other properties are unchanged by the addition of lead to enhance machinability.
Recrystallization temperature. Approximately 730 °C (1350 °F)
Annealing temperature. Strip, thin rod, and wire: 760 to 790 °C (1400 to 1450 °F)/10 min/water quench. Larger sections: 1 h per inch or fraction of an inch of cross section
Solution temperature. 760 to 790 °C (1400 to 1450 °F). All annealing of this material is a solution treatment.
Aging temperature. 260 to 425 °C (500 to 800 °F). Maximum strength is obtained by aging material 1 to 3 h at 315 to 345 °C (600 to 650 °F), depending on the amount of cold work.
Hot-working temperature. 650 to 800 °C (1200 to 1475 °F). C17300 cannot be hot rolled or forged, but it can be hot extruded.
Hot-shortness temperature. 845 °C (1550 °F)

C17410
99.2Cu-0.3Be-0.5Co

Chemical Composition

Composition limits. 0.15 to 0.5 Be, 0.35 to 0.6 Co, 0.2 Al max, 0.2 Si max, 0.2 Fe max, 99.5 min Cu + Ag + named elements

Applications

Typical uses. Strip and wire: fuse clips, fasteners, springs, diaphragms, lead frames, switch parts, and electrical connectors. Rod and plate: resistance spot welding tips, die casting plunger tips, tooling for plastic molding
Precautions in use. Because this alloy contains beryllium, it is a potential health hazard. Adequate safety precautions are mandatory for all melting, welding, grinding, and machining operations.

Mechanical Properties

Tensile properties. See Table 35.
Hardness. See Table 35.
Elastic modulus. 138 GPa (20.0 × 10^6 psi)
Fatigue strength. See Table 35.

Mass Characteristics

Density. 8.80 g/cm^3 (0.318 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1065 °C (1950 °F)
Solidus temperature. 1025 °C (1875 °F)
Thermal conductivity. 233 W/m · K (135 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 45% IACS at 20 °C (68 °F)
Electrical resistivity. 38.2 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 25% of C36000 (free-cutting brass)
Formability. Excellent capacity for both cold and hot forming
Weldability. Solderability, brazing, or resistance spot welding: good. Oxyacetylene welding is not recommended. Other welding processes: fair
Heat-treating temperature. 450 to 550 °C (840 to 1025 °F)
Hot-working temperature. 650 to 925 °C (1200 to 1700 °F)

C17500
97Cu-0.5Be-2.5Co

Commercial Names

Trade names. 10 alloy, alloy 10, Berylco 10
Common name. Low-beryllium copper

Specifications

ASTM. Flat products: B 534. Rod, bar: B 441
SAE. J463
Government. Rod, bar: MIL-C-46087. Strip: MIL-C-81021
Resistance Welding Manufacturers' Association. Class III

Chemical Composition

Composition limits. 0.40 to 0.7 Be, 2.4 to 2.7 Co, 0.10 Fe max, 0.5 max other (total), bal Cu

Applications

Typical uses. Strip, wire: fuse clips, fasteners, springs, switch parts, electrical connectors, and conductors. Rod, plate: resistance spot welding tips, seam welding discs, die casting plunger tips, tooling for plastic molding
Precautions in use. Because this alloy contains beryllium, it is a potential health hazard. Adequate safety precautions are mandatory for all melting, welding, grinding, and machining operations.

Mechanical Properties

Tensile properties. See Table 36 and Fig. 20.
Hardness. See Table 36.
Elastic modulus. Tension, 125 to 130 GPa (18 to 19 × 10^6 psi)
Fatigue strength. Rod, TF00 temper (rotating-beam tests): 275 to 310 MPa (40 to 45 ksi) at 10^7 cycles. Strip: see Table 36.

Table 32 Property ranges for various mill products of C17200 and C17300

Temper	Thickness or diameter	Tensile strength		Yield strength at 0.2% offset		Elongation in 50 mm (2 in.), %	Hardness	Electrical conductivity, %IACS
		MPa	ksi	MPa	ksi			
Rod, bar, plate, and tubing								
TB00	All sizes	415–585	60–85	140–205	20–30	35–60	45–85 HRB	17–19
TD04	< 9.5 mm (3/8 in.)	655–900	95–130	515–725	75–105	10–20	92–103 HRB	15–17
	9.5–25 mm (3/8–1 in.)	620–825	90–120	515–725	75–105	10–20	91–102 HRB	15–17
	> 25 mm (1 in.)	585–790	85–115	515–725	75–105	10–20	88–102 HRB	15–17
TF00(a)	All sizes	1140–1310	165–190	1000–1210	145–175	3–10	36–40 HRC	22–25
TH04(b)	< 9.5 mm (3/8 in.)	1280–1480	185–215	1140–1380	165–200	2–5	39–45 HRC	22–25
	9.5–25 mm (3/8–1 in.)	1240–1450	180–210	1140–1380	165–200	2–5	38–44 HRC	22–25
	> 25 mm (1 in.)	1210–1410	175–205	1030–1340	150–194	2–5	37–43 HRC	22–25
Wire								
TB00	All sizes	400–540	58–78	140–240	20–35	35–55	…	17–19
TD04	< 2 mm (0.08 in.)	895–1070	130–155	760–930	110–135	2–8	…	15–17
	2–9.5 mm (0.08–0.38 in.)	655–900	95–130	515–725	75–105	10–35	…	15–17
	> 9.5 mm (0.38 in.)	620–825	90–120	515–725	75–105	10–35	…	15–17
TF00(a)	All sizes	1140–1310	165–190	1000–1210	145–175	3–8	…	22–25
TH04(c)	< 2 mm (0.08 in.)	1310–1590	190–230	1240–1410	180–205	1–3	…	22–25
TH04(d)	2–9.5 mm (0.08–0.38 in.)	1280–1480	185–215	1210–1380	175–200	2–5	…	22–25
	> 9.5 mm (0.38 in.)	1240–1450	180–210	1140–1380	165–200	2–5	…	22–25
Billets								
As cast	…	515–585	75–85	275–345	40–50	15–30	80–85 HRB	16–22
Cast and aged(a)	…	725–760	105–110	515–550	75–80	10–20	20–25 HRC	18–23
TB00	…	415–515	60–75	170–205	25–30	25–45	65–75 HRB	13–18
TF00(a)	…	1070–1210	155–175	860–1030	125–150	1–3	36–42 HRC	18–25
Forgings								
TB00	…	415–585	60–85	140–205	20–30	35–60	45–85 HRB	17–19
TF00(a)	…	1140–1310	165–190	1000–1210	145–175	3–10	36–41 HRC	22–25

(a) Aged 3 h at 330 °C (625 °F). (b) Aged 2 to 3 h at 330 °C (625 °F). (c) Aged 1 h at 330 °C (625 °F). (d) Aged 1½ to 3 h at 330 °C (625 °F)

Table 33 Hardness, conductivity, and fatigue strength for C17200 and C17300 strip of various tempers

	Hardness			Electrical conductivity, %IACS	Fatigue strength(a)	
Temper	HV	HRC	HR30N		MPa	ksi
TB00	90–160	45–78 HRB	45–67 HR30T	17–19	205–240	30–35
TD01	150–190	68–90 HRB	62–75 HR30T	16–18	215–250	31–36
TD02	185–225	88–96 HRB	74–79 HR30T	15–17	220–260	32–38
TD04	200–260	96–102 HRB	79–83 HR30T	15–17	240–270	35–39
TF00	343 min	31–41	56–61	22–25	240–260	35–38
TH01	370 min	38–42	58–63	22–25	240–270	35–39
TH02	380 min	39–44	59–65	22–25	270–295	39–43
TH04	385 min	40–45	60–65	22–25	285–315	41–46
TM00	200–235	18–23	37–42	20–28	230–255	33–37
TM01	230–265	21–26	42–47	20–28	235–260	34–38
TM02	260–295	25–30	45–51	20–28	240–295	35–43
TM04	290–325	30–35	50–55	20–28	260–310	38–45
(b)	320–350	31–37	52–56	20–28	260–310	38–45
TM06	343–375	32–38	55–58	20–28	260–310	38–45
TM08	370–400	33–42	56–63	20–28	275–330	40–48

(a) Proprietary mill heat treatment to produce tensile strength of 1030–1100 MPa (150 to 160 ksi). (b) In reversed bending at 10^8 cycles.

Table 34 Approximate corrosion resistance of C17200 and C17300

Good resistance(a)

Acetate solvents
Acetic acid, cold, unaerated
Alcohols
Ammonia, dry
Atmosphere, rural, industrial, marine
Benzene
Borax
Boric acid
Brine
Butane
Carbon dioxide
Carbon tetrachloride
Chlorine, dry
Freon
Gasoline
Hydrogen
Nitrogen
Oxalic acid
Potassium chloride
Potassium sulfate
Propane
Rosin
Sodium bicarbonate
Sodium chloride
Sodium sulfate
Sulfur dioxide
Sulfur trioxide
Water, fresh or salt

Fair resistance(b)

Acetic acid, cold, aerated
Acetic anhydride
Acetylene
Ammonium chloride
Ammonium sulfate
Aniline
Bromine, dry
Carbonic acid
Copper nitrate
Ferrous chloride
Ferrous sulfate
Fluorine, dry
Hydrochloric acid, up to 0.1%
Hydrofluoric acid, dilute

Fair resistance(b)

Hydrofluosilicic acid
Hydrogen peroxide
Nitric acid, up to 0.1%
Phenol
Phosphoric acid, unaerated
Potassium hydroxide
Sodium hydroxide
Sodium hypochlorite
Sodium peroxide
Sodium sulfide
Sulfur
Sulfur chloride
Sulfuric acid, unaerated
Zinc chloride

Poor resistance(c)

Acetic acid, hot
Ammonia, moist
Ammonium hydroxide
Ammonium nitrate
Bromine, aerated or hot
Chlorine, moist or warm
Chromic acid
Ferric chloride
Ferric sulfate
Fluorine, moist or warm
Hydrochloric acid, over 0.1%
Hydrocyanic acid
Hydrofluoric acid, concentrated
Hydrogen sulfide, moist
Lactic acid, hot or aerated
Mercuric chloride
Mercury
Mercury salts
Nitric acid, over 0.1%
Phosphoric acid, aerated
Picric acid
Potassium cyanide
Silver chloride
Sodium cyanide
Stannic chloride
Sulfuric acid, aerated
Sulfurous acid

(a) < 0.25 mm/year (0.01 in./year) attack. (b) 0.025–2.54 mm/year (0.001–0.10 in./year) attack. (c) > 0.25 mm/year (0.01 in./year) attack

Table 35 Nominal mechanical properties of mill-hardened C17410 strip

	Tensile strength		Yield strength		Elongation in 50 mm (2 in.), %	Hardness, HRB	Fatigue strength	
Temper	MPa	ksi	MPa	ksi			MPa	ksi
½ HT	725	105	620	90	15	95	…	…
HT	830	120	760	110	12	95 min	300	43

Structure

Crystal structure. The α Cu solid solution is face-centered cubic. The beryllide, (Cu,Co)Be, is ordered body-centered cubic of the CsCl (B2) type.

Microstructure. Alpha copper with beryllium in solid solution and with (Cu,Co)Be beryllide inclusions. The appearance of the matrix of the beryllides depends on the extent of deformation and the state of heat treatment.

In the cast condition, the matrix is essentially like pure copper; the beryllides, which are blue-gray, are large and sharply angular in the grain boundaries and small with Widmanstätten orientation within the grains. When such cast shapes are annealed, the cored appearance is reduced slightly, and the matrix becomes slightly cleaner as small amounts of the beryllides are dissolved.

As the cast product is reduced by either hot or cold working, the beryllides are broken up and uniformly distributed.

For such products as strip or rod, the microstructure is fine-grain equiaxed a copper with small, mainly spherical, uniformly dispersed beryllides. For all products types, there is little difference in microstructure between the annealed and the aged conditions.

Metallography is by ordinary metallographic techniques, except that grinding must be performed in a vented area, and all other appropriate OSHA requirements should be strictly observed.

Mass Characteristics

Density. 8.75 g/cm^3 (0.316 lb/in.^{3}) at 20 °C (68 °F)

Volume change on phase transformation. Slight contraction during age hardening; exact amount depends on starting condition of material and on time and temperature of aging.

Thermal Properties

Liquidus temperature. 1070 °C (1955 °F)

Solidus temperature. 1030 °C (1885 °F)

Coefficient of linear thermal expansion. 17.6 μm/m · K (9.8 μin./in. · °F) at 20 to 200 °C (68 to 392 °F)

Specific heat. 420 J/kg · K (0.10 Btu/lb · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. See Table 36.

Electrical resistivity. 29 to 86 nΩ · m at 20 °C (68 °F), depending on heat treatment

Chemical Properties

General corrosion behavior. Comparable to that of other high-copper alloys. May tarnish in humid or sulfur-bearing atmospheres

Fabrication Characteristics

Machinability. Readily machinable by all common methods. Recommended machining conditions depend greatly on the shape of the part, on the heat treatment of material, and on the type of machining operation.

Because this alloy contains beryllium, OSHA requirements must be strictly observed. Normally, these requirements include flooding and/or special ventilation to prevent personnel from inhaling or ingesting metal dust.

Annealing temperature. All annealing of this alloy is a solution treatment.

Solution temperature. Strip, rod, bar, tubing, wire: 10 min at 900 to 955 °C (1650 to 1750 °F), water quench. Large sections: 1 h per inch or fraction of an inch at 900 to 925 °C (1650 to 1700 °F), water quench

Aging temperature. For maximum strength: 3 to 6 h at 425 °C (800 °F), depending on the degree of cold work. Commercial practice: 2 to 3 h at 470 to 495 °C (875 to 925 °F) to provide a combination of high strength and electrical conductivity. Cooling rate after aging is not critical. See also Fig. 20.

Hot-working temperature. 700 to 925 °C (1300 to 1700 °F)

Hot-shortness temperature. 980 °C (1800 °F)

C17600

Commercial Names

Previous Trade name. 50 alloy, alloy 50

Common name. Beryllium-copper

Specifications

SAE. J463 (CA176)

Resistance Welding Manufacturers' Association. Class III

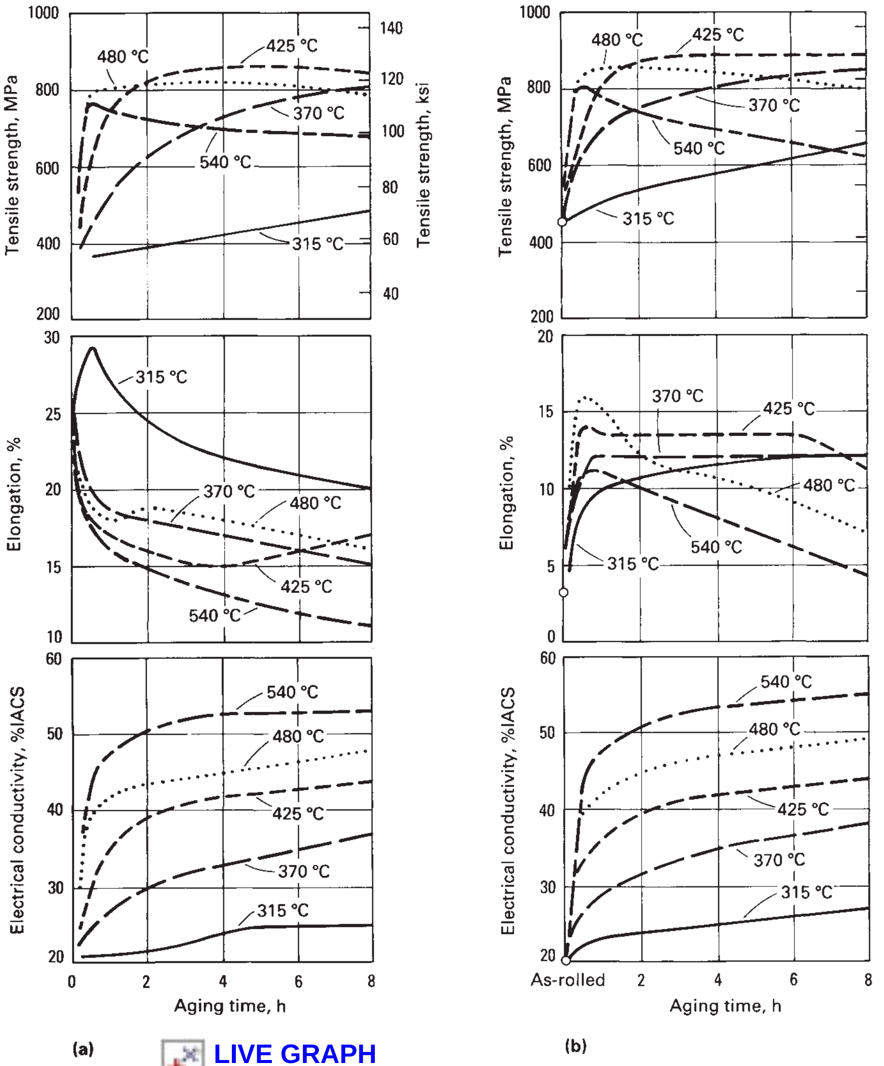
Chemical Composition

Composition limits. 99.5 Cu + Be + additives min, 0.25 to 0.50 Be, 1.40 to 1.70 Co, 0.90 to 1.10 Ag, 1.40 Co + Ni min, 1.90 Co + Ni + Fe max

Applications

Typical uses. A high-conductivity alloy designed especially for resistance welding electrodes for spot, seam, flash, and projection welding methods; electrical connectors, clips

Precautions in use. Ventilation should be used during melting, welding, grinding, and all machining operations.



LIVE GRAPH
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Fig. 20 Aging curves for C17500. (a) TB00 temper. (b) TD02 temper

Table 36 Typical mechanical properties and electrical conductivity of C17500

Temper	Tensile strength MPa	Tensile strength ksi	Proportional limit at 0.002% offset MPa	Proportional limit at 0.002% offset ksi	Yield strength at 0.2% offset MPa	Yield strength at 0.2% offset ksi	Elongation in 50 mm (2 in.), %	Hardness, HRB	Electrical conductivity, %IACS	Fatigue strength(a) MPa	Fatigue strength(a) ksi
Strip											
TB00	240–380	35–55	69–140	10–20	140–205	20–30	20–35	28–50	20–30	…	…
H04	485–585	70–85	240–450	35–65	380–550	55–80	3–10	70–80	20–30	205	30
TF00	690–825	100–120	380–515	55–75	550–690	80–100	10–20	92–100	45–60	205	30
TH04	760–895	110–130	485–655	70–95	690–825	100–120	8–15	98–102	50–60	240	35
HTR(b)	825–1035	120–150	550–760	80–110	760–965	110–140	1–4	98–103	45–60	240–260	35–38
HTC(c)	515–585	75–85	205–415	30–60	345–515	50–75	8–15	79–88	60 min	205–240	30–35
Rod, bar, plate, tubing											
TB00	240–380	35–55	…	…	140–205	20–30	20–35	20–50	20–30	…	…
H04	450–550	65–80	…	…	380–515	55–75	10–15	60–80	20–30	…	…
TF00	690–825	100–120	…	…	550–690	80–100	10–25	92–100	45–60	…	…
TH04	760–895	110–130	…	…	690–825	100–120	10–20	95–102	50–60	…	…
Forged products											
TB00	240–380	35–55	…	…	140–205	20–30	20–35	20–50	20–30	…	…
TF00	690–825	100–120	…	…	550–690	80–100	10–25	92–100	45–60	…	…

(a) Reversed bending at 108 cycles. (b) Proprietary mill hardening for maximum strength. (c) Proprietary mill hardening for maximum electrical conductivity

Mechanical Properties

Tensile properties. See Table 37.
Hardness. See Table 37.
Elastic modulus. Tension, 125 to 130 GPa (18 to 19 × 10^6 psi); shear, 44 GPa (6.4 × 10^6 psi)

Structure

Crystal structure. Alpha copper solid solution is face-centered cubic; the beryllide, (Cu,Co)Be, is ordered body-centered cubic of the CsCl (B2) type.
Microstructure. Matrix of α copper; large and sharply angular blue-gray beryllide inclusions in grain boundaries of cast product, smaller Widmanstätten beryllides within the grain. In wrought products with large amounts of deformation, the beryllides are small, mainly spherical, and uniformly distributed.
Metallography is by conventional techniques. For dry grinding, ventilation should be provided. Some common etchants for immersion etching are 3 parts concentrated NH_4OH, 1 part 3% H_2O_2, 2 parts 10% $(NH_4)_2S_2O_3$, and 7 to 10 parts H_2O. Common etchants for swabbing are 3 g $K_2Cr_2O_7$, 1.5 g NaCl, 8 mL H_2SO_4, and 100 mL H_2O.

Mass Characteristics

Density. 8.75 g/cm^3 (0.316 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1068 °C (1955 °F)
Solidus temperature. 1031 °C (1855 °F)
Coefficient of linear thermal expansion. 16.7 μm/m · K (9.3 μin./in. · °F) at 20 to 200 °C (68 to 392 °F)
Specific heat. 420 J/kg · K (0.10 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 215 to 245 W/m · K (125 to 140 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical properties

Electrical conductivity. See Table 37.
Electrical resistivity. 28.7 to 86.2 nΩ · m at 20 °C (68 °F), depending strongly on heat treatment

Fabrication Characteristics

Machinability. Readily machinable by all conventional methods
Annealing temperature. For strip, wire, rod, and bar, 900 to 950 °C (1650 to 1750 °F)/10 min/water quench. For larger sections, anneal 1 h per inch or fraction of an inch at 900 to 925 °C (1650 to 1700 °F) and water quench.
Solution temperature. All annealing for this alloy is solution treatment.
Aging temperature. Maximum strength is obtained by 3 to 6 h at 425 °C (800 °F). Commercial practice is to age material 2 to 3 h at 480 °C (900 °F) to obtain a combination of high strength and electrical conductivity.
Hot-working temperature. 750 to 925 °C (1400 to 1700 °F)
Hot-shortness temperature. 975 °C (1800 °F)

C18100
99Cu-0.8Cr-0.16Zr-0.04Mg

Chemical Composition

Composition limits. 0.4 to 1.2 Cr, 0.05 to 0.3 Zr, 0.03 to 0.6 Mg

Applications

Typical uses. Resistance welding electrodes and wheels, switches, circuit breakers, high-temperature wire, semiconductor bases, heat sinks, and continuous castings molds

Mechanical Properties

Tensile properties. See Table 38.
Hardness. See Table 38.
Elastic modulus. 125 GPa (18.2 × 10^6 psi)

Mass Characteristics

Density. 8.88 g/cm^3 (0.319 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1075 °C (1967 °F)
Thermal conductivity. 324 W/m · K (187 Btu/ft · h · °F) at 20 °C (68 °F)
Coefficient of linear thermal expansion. 16.7 μm/m · K (9.3 μin./in. · °F) at 20 to 100 °C (68 to 212 °F); 18.4 μm/m · K (10.2 μin./in. · °F) at 20 to 200 °C (68 to 392 °F); 19.3 μm/m · K (10.7 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)

Electrical Properties

Electrical conductivity. Volumetric, 80% IACS at 20 °C (68 °F), annealed
Electrical resistivity. 21.7 nΩ · m at 20 °C (68 °F), annealed

Fabrication Characteristics

Formability. Excellent capacity for both cold and hot forming
Weldability. Solderability, excellent; brazing and gas-shielded arc welding, good; butt resistance welding, fair. Oxyacetylene, spot, and seam resistance welding are not recommended.
Annealing temperature. 600 to 700 °C (1110 to 1300 °F)
Heat-treating temperatures. Solution treatment: 900 to 975 °C (1650 to 1790 °F) for 1 h. Aging treatment: 400 to 500 °C (750 to 930 °F) for 1 h
Hot-working temperature. 790 to 925 °C (1450 to 1700 °F)

C18200, C18400, C18500
99Cu-1Cr

Commercial Names

Previous Trade name. CA182, CA184, CA185; Chrome Copper 999 (C18200)
Common name. Chromium-copper

Specifications

ASTM. Wire: F 9
SAE. J463 (C18400 only)

Table 37 Typical mechanical properties and electrical conductivity of C17600 heat treated to various tempers

Temper(a)	Tensile strength, MPa	Tensile strength, ksi	Yield strength at 0.2% offset, MPa	Yield strength at 0.2% offset, ksi	Elongation in 50 mm (2 in.), %	Hardness, HRB	Electrical conductivity, %IACS
Rod, bar, wire, tubing, plate							
TB00	240–380	35–55	140–205	20–30	20–35	20–50	20–30
H04	450–550	65–80	380–515	55–75	10–15	60–80	20–30
TF00	690–825	100–120	550–690	80–100	10–25	92–100	45–60
TH04	760–900	110–130	690–825	100–120	10–20	95–102	50–60
Billet							
As–cast	310–415	45–60	105–240	15–35	15–25	60–65	32–37
Cast and aged	415–515	60–75	205–380	30–55	10–20	65–90	40–50
TB00	275–345	40–50	69–115	10–17	20–40	10–45	22–28
TF00	655–760	95–110	515–550	75–80	3–15	92–100	50–60
Forged products							
TB00	240–380	35–55	140–205	20–30	20–35	25–45	20–30
TF00	690–825	100–120	550–690	80–100	10–25	92–100	50–60

(a) For TB00 temper: solution treat strip, bar, rod, and tubing 10 min at 900 to 955 °C (1650 to 1750 °F) and water quench; solution treat thicker products such as billet 1 h for each 25 mm (1 in.) of thickness or fraction thereof at 900 to 925 °C (1650 to 1700 °F) and water quench. For aging cast billets or producing TF00 temper, age 3 h at 470 to 500 °C (875 to 925 °F). For producing TH04 temper, age 2 h at 470 to 500 °C (875 to 925 °F).

Table 38 Nominal mechanical properties of C18100 strip and wire

Temper	Tensile strength, MPa	Tensile strength, ksi	Yield strength, MPa	Yield strength, ksi	Elongation in 50 mm (2 in.), %	Hardness, HRB
Strip						
Cold worked (40% reduction)	460	67	430	62	6	…
Cold worked (40% reduction), aged	495	72	455	66	10	…
Wire						
Cold worked (60% reduction)	480	70	435	63	6	…
Cold worked (60% reduction), aged	515	75	470	68	11	80
Cold worked (75% reduction)	495	72	455	66	5	…
Cold worked (75% reduction), aged	550	80	475	69	12	…
Cold worked (90% reduction)	500	73	455	66	4	…
Cold worked (90% reduction), aged	585	85	515	75	13	…

Government. Bar, forgings, rod, strip: MIL-C-19311 (C18400, C18500)

Chemical Composition

Composition limits of C18200. 0.6 to 1.2 Cr, 0.10 Fe max, 0.10 Si max, 0.05 Pb max, 0.5 max other (total), bal Cu + Ag
Composition limits of C18400. 0.40 to 1.2 Cr, 0.7 Zn max, 0.15 Fe max, 0.10 Si max, 0.05 P max, 0.05 Li max, 0.005 As max, 0.005 Ca max, 0.2 max other (total), bal Cu + Ag
Composition limits of C18500. 0.40 to 1.0 Cr, 0.08 to 0.12 Ag, 0.04 P max, 0.04 Li max, 0.015 Pb max, bal Cu + Ag

Applications

Typical uses. Applications requiring excellent cold workability and good hot workability coupled with medium-to-high conductivity. Uses include resistance welding electrodes, seam welding wheels, switch gears, electrode holder jaws, cable connectors, current-carrying arms and shafts, circuit breaker parts, molds, spot welding tips, flash welding electrodes, electrical and thermal conductors requiring more strength than that provided by unalloyed coppers, and switch contacts.

Mechanical Properties

Tensile properties. See Table 39.
Hardness. See Table 39.
Elastic modulus. Tension, 130 GPa (19 × 10^6 psi); shear, 50 GPa (7.2 × 10^6 psi)

Mass Characteristics

Density. 8.89 g/cm^3 (0.321 lb/$in.^3$) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1075 °C (1965 °F)
Solidus temperature. 1070 °C (1960 °F)
Coefficient of linear thermal expansion. 17.6 μm/m · K (9.8 μin./in. · °F) at 20 to 100 °C (68 to 212 °F)
Specific heat. 385 J/kg · K (0.092 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. TB00 temper: 171 W/m · K (99 Btu/ft · h · °F) at 20 °C (68 °F). TH04 temper: 324 W/m · K (187 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric. TB00 temper: 40% IACS at 20 °C (68 °F). TH04 temper: 80% IACS at 20 °C (68 °F)
Electrical resistivity. TH04 temper: 21.6 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Formability. Suited for hot working by extrusion, rolling, and forging (subsequent solution treatment required) and for cold working (in soft, solution-annealed, or suitable drawn temper) by drawing, rolling, impacting, heading, bending, or swaging
Weldability. Welding and brazing temperatures lower the properties developed by heat treatment; such processes normally are applied to material in the soft condition, followed by necessary heat treatment. Soldering: good. Oxyfuel gas, shielded metal arc, resistance spot, and resistance seam welding are not recommended.
Solution treatment. 980 to 1000 °C (1800 to 1850 °F) for 10 to 30 min, water quench
Aging temperature. 425 to 500 °C (800 to 930 °F) for 2 to 4 h
Hot-working temperature. 800 to 925 °C (1500 to 1700 °F)

Table 39 Typical mechanical properties of C18200, C18400, and C18500

Temper	Tensile strength		Yield strength		Elongation in 50 mm (2 in.), %	Hardness, HRB
	MPa	ksi	MPa	ksi		
Flat products, 1 mm (0.04 in.) thick						
TB00	235	34	130	19	40	16
TF00(b)	350	51	250	36	22	59
TD04	365	53	350	51	6	66
TH04(c)	460	67	405	59	14	79
Plate, 50 mm (2.0 in.) thick						
TF00	400	58	290	42	25	70
Plate, 75 mm (3.0 in.) thick						
TF00	385	56	275	40	30	68
Rod: 4 mm (0.156 in.) diameter						
TD08	510	74	505	73	5	…
TH08	595	86	530	77	14	…
Rod, 13 mm (0.50 in.) diameter						
TB00	310	45	97	14	40	…
TF00(b)	485	70	380	55	21	70
TD04	395	57	385	56	11	65
TH04(c)	530	77	450	65	16	82
TH03, cold worked 6%	530	77	460	67	19	83
Rod, 25 mm (1.0 in.) diameter						
TF00	495	72	450	65	18	80
Rod, 50 mm (2.0 in.) diameter						
TF00	485	70	450	65	18	75
Rod, 75 mm (3.0 in.) diameter						
TF00	450	65	380	55	18	70
Rod, 100 mm (4.0 in.) diameter						
TF00	380	55	295	43	25	68
Tube, 9.5 mm (3/8 in.) outside diameter × 2.4 mm (0.094 in.) wall thickness						
O60	275	40	105	15	50	59 HRF
Tube, 31.8 mm (1 1/4 in.) outside diameter × 5.4 mm (0.212 in.) wall thickness						
TD04	405	59	395	57	21	67
TH04, cold-worked 28%	475	69	435	63	26	84

(a) At 0.5% extension under load. (b) Aged 3 h at 500 °C (930 °F). (c) Aged 3 h at 450 °C (840 °F)

C18700
99Cu-1Pb

Commercial Names

Previous Trade name. Leaded copper
Common name. Free-machining copper

Specifications

ASTM. Flat products, rod: B 301
SAE. Rod: J463

Chemical Composition

Composition limits. 0.8 to 1.5 Pb, 0.10 max other (total), bal Cu. Oxygen-free grades or grades containing deoxidizers such as P, B, or Li may be specified.

Applications

Typical uses. Electrical connectors, motor parts, switch parts, and screw machine parts requiring high conductivity
Precautions in use. Unless specifically deoxidized, this copper is subject to embrittlement when heated in a reducing atmosphere (as in annealing or brazing) at temperatures of 350 °C (660 °F) or higher. If hydrogen or carbon monoxide is present, embrittlement can be rapid.

Mechanical Properties

Tensile properties. See Tables 17 and 40.
Shear strength. See Tables 17 and 40.
Hardness. See Tables 17 and 40.
Elastic modulus. Tension, 115 GPa (17 × 10^6 psi); shear, 44 GPa (6.4 × 10^6 psi)

Mass Characteristics

Density. 8.94 g/cm^3 (0.323 lb/$in.^3$) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1080 °C (1975 °F)
Solidus temperature. 950 °C (1750 °F)

Coefficient of linear thermal expansion. 17.6 µm/m · K (9.8 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 385 J/kg · K (0.092 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 377 W/m · K (218 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 96% IACS at 20 °C (68 °F)
Electrical resistivity. 17.9 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 85% of C36000 (free-cutting brass)
Formability. Good for cold working; poor for hot forming
Weldability. Soldering: excellent. Brazing: good. Most arc, gas, and resistance welding processes are not recommended.
Annealing temperature. 425 to 650 °C (800 to 1200 °F)
Hot-working temperature. 750 to 875 °C (1400 to 1600 °F)

C19200
98.97Cu-1.0Fe-0.03P

Specifications

ASTM. Tubing: B 111, B 359, B 395, B 469

Chemical Composition

Composition limits. 98.7 to 99.19 Cu, 0.8 to 1.2 Fe, 0.01 to 0.04 P

Applications

Typical uses. Rolled strip and tubing for air conditioning and heat exchanger tubing, applications requiring resistance to softening and stress corrosion, automotive hydraulic brake lines, cable wrap, circuit breaker components, contact springs, electrical connectors and terminals, eyelets, flexible hose, fuse clips, gaskets, gift hollowware, lead frames

Mechanical Properties

Tensile properties. See Table 41.
Hardness. See Table 41.
Elastic modulus. Tension, 115 GPa (17 × 10^6 psi); shear, 44 GPa (6.4 × 10^6 psi)

Mass Characteristics

Density. 8.87 g/cm^3 (0.320 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1084 °C (1983 °F)
Solidus temperature. 1078 °C (1973 °F)
Coefficient of linear thermal expansion. 16.2 µm/m · K (9.0 µin./in. · °F) at 20 to 100 °C (68 to 212 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. Strip, 251 W/m · K (145 Btu/ft · h · °F) at 20 °C (68 °F); tubing, 216 W/m · K (125 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Strip, 60% IACS at 20 °C (68 °F); tubing, 50% IACS at 20 °C (68 °F)
Electrical resistivity. Strip, 28.8 nΩ · m at 20 °C (68 °F); tubing, 34.5 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Forgeability. 65% of C37700 (forging brass)
Weldability. Soldering, brazing, and gas-shielded arc welding: excellent. Oxyacetylene welding: good. Coated metal arc and resistance seam, spot, and butt welding are not recommended.
Annealing temperature. 700 to 815 °C (1300 to 1500 °F)
Hot-working temperature. 825 to 950 °C (1500 to 1750 °F)

C19210
99.87Cu-0.1Fe-0.03P

Chemical Composition

Composition limits. 0.05 to 0.15 Fe, 0.025 to 0.04 P, bal Cu

Applications

Typical uses. Air conditioner and heat exchanger tubing, lead frames, electrical connectors and terminals

Mechanical Properties

Tensile properties. See Table 42.
Elastic modulus. 125 GPa (18.2 × 10^6 psi)

Mass Characteristics

Density. 8.94 g/cm^3 (0.323 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1082 °C (1980 °F)
Coefficient of linear thermal expansion. 16.9 µm/m · K (9.4 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)

Electrical Properties

Electrical conductivity. Volumetric, 80% IACS at 20 °C (68 °F), annealed
Electrical resistivity. 21.6 nΩ · m at 20 °C (68 °F), annealed

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Formability. Excellent capacity for both cold and hot forming
Weldability. Soldering, brazing, and coated metal arc welding: excellent. Butt, resistance and oxyacetylene welding: good. Gas-shielded arc, spot, and seam resistance welding are not recommended.
Annealing temperature. 450 to 550 °C (840 to 1020 °F)
Hot-working temperature. 700 to 900 °C (1300 to 1650 °F)
Hot forgeability rating. 65% of C37700 (forging brass)

C19400
Cu-2.35Fe-0.03P-0.12Zn

Commercial Names

Previous trade name. High-strength modified copper, HSM copper

Specifications

ASME. Welded tubing: SB543

Table 40 Typical mechanical properties of C18700 rod, H04 temper

Diameter		Tensile strength		Yield strength		Elongation in 50 mm (2 in.), %	Hardness, HRB	Shear strength	
mm	in.	MPa	ksi	MPa	ksi			MPa	ksi
6	0.25	415	60	380	55	10	55	200	32
13	0.50	380	55	345	50	11	50	205	30
19	0.75	365	53	330	48	12	50	200	29
25	1.0	350	51	315	46	14	50	195	28

Table 41 Typical mechanical properties of C19200

			Yield strength					
	Tensile strength		At 0.5% extension under load		At 0.2% offset			
Temper	MPa	ksi	MPa	ksi	MPa	ksi	Elongation in 50 mm (2 in.), %	Hardness, HRB
Strip, 1 mm (0.04 in.) diameter								
O60	310	45	…	…	140 min	20 min	25 min	38
O82	395	57	…	…	305	44	20	55
H02	395	57	…	…	305	44	9	55
H04	450	65	…	…	415	60	7	72
H06	485	70	…	…	460	67	3	75
H08	510	74	…	…	490	71	2 min	76
H10	530	77	…	…	510	74	2 min	77
Tubing, 48 mm (1.88 in.) outside diameter × 3 mm (0.12 in.) wall thickness								
O50	290	42	160	23	150	22	30	…
O60	255	37	83	12	76	11	40	…
H80 (40%)	385	56	360	52	360	52	7	…
Tubing, 5 mm (0.19 in.) outside diameter × 0.8 mm (0.03 in.) wall thickness								
H55	290	42	215	31	205	30	35	…

ASTM. Flat products: B 465. Welded tubing: B 543, B 586

Chemical Composition

Composition limits. 2.1 to 2.6 Fe, 0.05 to 0.20 Zn, 0.015 to 0.15 P, 0.03 Pb max, 0.03 Sn max, 0.15 max other (total), bal Cu

Applications

Typical uses. Applications requiring excellent hot and cold workability as well as high strength and conductivity. Specific uses include circuit breaker components; contact springs; electrical clamps, springs, and terminals; flexible hose; fuse clips; gaskets; gift hollowware; plug contacts; rivets; welded condenser tubes; semiconductor lead frames, and cable shielding

Table 42 Nominal tensile properties of C19210 sheet

Temper	Tensile strength		Yield strength		Elongation in 50 mm (2 in.), %
	MPa	ksi	MPa	ksi	
H01	345	50	330	48	13
H02	390	57	385	56	6
H04	440	64	435	63	4
H08	490	71	480	70	2

Mechanical Properties

Tensile properties. See Tables 43, 44, 45, and 46.
Hardness. See Table 43.
Elastic modulus. Tension, 121 GPa (17.5 × 10^6 psi); shear, 45.5 GPa (6.6 × 10^6 psi)
Charpy impact strength. Plate, O61 temper: longitudinal, 144 J (106 ft · lbf) at –196 °C (–320 °F); transverse, 99 J (73 ft · lbf) at –196 °C (–320 °F)
Fatigue strength. See Table 43.
Creep and stress-rupture properties. See Table 45.

Mass Characteristics

Density. 8.78 g/cm^3 (0.317 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1090 °C (1990 °F)
Solidus temperature. 1080 °C (1980 °F)
Coefficient of linear thermal expansion. 16.3 μm/m · K (9.0 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 385 J/kg · K (0.092 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 260 W/m · K (150 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, at 20 °C (68 °F). O60 temper: 40% IACS nominal. H14 temper: 50% IACS min. All other tempers: 65% IACS nominal, 60% IACS min. In O50, O80, and H02 tempers, 75% IACS min conductivity may be available depending on mill processing restrictions.
Electrical resistivity. At 20 °C (68 °F). O60 temper: 43.1 nΩ · m nominal. H14 temper: 34.5 nΩ · m max. All other tempers: 26.6 nΩ · m nominal; may be only 23.0 nΩ · m max under certain circumstances

Magnetic Properties

Magnetic permeability. 1.1

Chemical Properties

General corrosion behavior. Very corrosion resistant and essentially immune to stress-corrosion cracking

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Formability. Suited to forming by blanking, coining, coppersmithing, drawing, bending, heading and upsetting, hot forging and pressing, piercing and punching, roll threading and knurling, shearing, spinning, squeezing, and stamping
Weldability. Joining by soldering, brazing, and gas tungsten arc welding: excellent
Annealing temperature. See Table 46.

C19500
97Cu-1.5Fe-0.1P-0.8Co-0.6Sn

Commercial Names

Trade name. Strescon

Chemical Composition

Composition limits. 1.3 to 1.7 Fe, 0.6 to 1.0 Co, 0.08 to 0.12 P, 0.40 to 0.7 Sn, 0.20 Zn max, 0.02 Al max, 0.02 Pb max, 0.05 max other (each), 0.10 max other (total), bal Cu

Table 43 Typical mechanical properties of C19400

Temper	Tensile strength		Yield strength at 0.2% offset		Elongation in 50 mm (2 in.), %	Hardness		Fatigue strength(a)	
	MPa	ksi	MPa	ksi		HRB	HR30T	MPa	ksi
Flat products, 0.64 mm (0.025 in.) thick									
O60	310	45	150 max	22 max	29 min	38	…	110	16
O50	345	50	160	23	28	45	…	…	…
O82	400	58	255	37	15	…	…	…	…
Flat products, 1 mm (0.04 in.) thick									
H02	400	58	315(b)	46(b)	18	68	66	…	…
H04	450	65	380	55	7	73	69	145	21
H06	485	70	465	67.5	3	74	71	…	…
H08	505	73	486	70.5	3	75	72	148	21.5
H10	530	77	507	73.5	2 max	77	74	141	20.5
H14	550 min	80 min	530 min	77 min	2 max	…	>73	…	…
Tubing, 25 mm (1 in.) outside diameter × 0.9 mm (0.035 in.) wall thickness									
O60	310	45	165	24	28	38	…	…	…
O50	345	50	205	30	16	45	…	…	…
WM02	400	58	365	53	9	61	60	…	…
WM04	450	65	435	63	4	73	66	…	…
WM06	485	70	465	67.5	3	74	68	…	…
WM08	505	73	486	70.5	2	75	69	…	…
WM10	525	76	505	73	1	76	69	…	…
H55 (15%)	400	58	380	55	9	61	60	…	…
H80 (35%)	470	68	455	66	2	73	66	…	…

(a) At 10^8 cycles as determined by the rotating-beam test. (b) At 0.5% extension under load

Table 44 Typical room-temperature and low-temperature (cryogenic) properties of C19400

Temper	Tensile strength		Yield strength at 0.2% offset		Elongation in 50 mm (2 in.), %
	MPa	ksi	MPa	ksi	
Room-temperature properties					
O61	325	47	170	25	28
H02	405	59	360	52	15
H04	455	66	405	59	10
Cryogenic properties: –196 ˚C (–320 ˚F)					
O61	475	69	195	28	38
H02	570	83	425	62	30
H04	615	89	485	70	23

Table 45 Typical elevated-temperature properties of annealed C19400 strip

Test temperature		Tensile strength, min		Yield strength at 0.2% offset, min		Creep strength, min(a)		Stress-rupture stress, min(b)	
˚C	˚F	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi
Ambient		341	49.5	150	22.0	…	…	…	…
65	150	324	47.0	144	20.9	…	…	…	…
95	200	313	45.4	144	20.9	…	…	…	…
120	250	300	43.5	144	20.9	190	27.6	…	…
150	300	289	41.9	139	20.2	171	24.8	171	24.9
175	350	276	40.1	135	19.6	143	20.8	148	21.4
205	400	266	38.6	131	19.0	124	18.0	125	18.1
230	450	253	36.8	131	19.0	110	16.0	105	15.2
260	500	235	34.1	127	18.4	96	13.9	82	11.9
290	550	219	31.8	123	17.8	84	12.2	65	9.4
315	600	203	29.5	116	16.8	74	10.8	47	6.8

(a) Stress causing secondary creep of 0.01% per 1000 h in a 10,000-h test. (b) Stress causing rupture in 100,000 h (extrapolated from 10,000 h)

Applications

Typical uses. Electrical springs, sockets, terminals, connectors, clips, and other current-carrying parts requiring strength and exceptional softening resistance. Applications requiring excellent hot and cold workability, high strength, and high conductivity

Mechanical Properties

Tensile properties. See Table 47.
Hardness. See Table 47.
Elastic modulus. Tension, 119 GPa (17.3 × 10^6 psi)

Mass Characteristics

Density. 8.92 g/cm^3 (0.322 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1090 °C (1995 °F)
Solidus temperature. 1085 °C (1985 °F)
Coefficient of linear thermal expansion. 16.9 µm/m · K (9.4 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Thermal conductivity. 199 W/m · K (115 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 50% IACS at 20 °C (68 °F), annealed
Electrical resistivity. 34.4 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Formability. Suited to forming by bending, coining, drawing, and stamping

Table 46 Annealing response of C19400 strip

Annealing temperature		Tensile strength		Yield strength at 0.2% offset		Elongation in 50 mm (2 in.), %	Electrical conductivity, %IACS
°C	°F	MPa	ksi	MPa	ksi		
H04 temper							
100	212	460	67	450	65	3	66
205	400	450	65	435	63	5	67
315	600	440	64	415	60	9	68
370	700	415	60	385	56	12	68
425	800	415	60	360	52	14	72
480	900	400	59	345	50	16	71
540	1000	385	56	310	45	17	64(a)
595	1100	350	51	220	32	23	52
650	1200	315	46	140	20	33	51
705	1300	310	45	115	17	34	49
760	1400	305	44	110	16	36	48
815	1500	305	44	110	16	36	48
H10 temper							
100	212	510	74	490	71	3	65
205	400	495	72	460	67	5	66
315	600	485	70	415	60	8	67
370	700	330	48	170	25	25	71
425	800	325	47	145	21	27	74
480	900	315	46	140	20	28	69
540	1000	315	46	140	20	31	64(a)
595	1100	310	45	130	19	33	58
650	1200	305	44	130	19	34	52
705	1300	295	43	115	17	34	49
760	1400	290	42	110	16	35	48
815	1500	285	41	105	15	35	48

(a) Conductivity may be restored to about 70% IACS by holding at 500 °C (925 °F) for 1 h.

Table 47 Typical mechanical properties of C19500

Temper	Tensile strength		Yield strength at 0.2% offset		Elongation in 50 mm (2 in.), %	Hardness, HRB
	MPa	ksi	MPa	ksi		
O61	360 min	52 min	170 min	25 min	25 min	…
O50	520–590	75–85	395–530	57–77	11–17	81–89
H02	565–620	82–90	505–605	73–88	3–13	85–88
H08	605–670	88–97	585–650	85–94	2–5	87–90
H10	670 min	97 min	650 min	94 min	2 max	90 min

C19520
97.97Cu-0.75Fe-1.25Sn-0.03P

Chemical Composition

Composition limits. 0.5 to 1.5 Fe, 0.5 to 1.5 Sn, 0.01 to 0.35 P, 96.6 Cu min

Applications

Typical uses. Lead frames

Mechanical Properties

Tensile properties. See Table 48.
Hardness. See Table 48.
Elastic modulus. 117 GPa (17 × 10^6 psi)

Mass Characteristics

Density. 8.8 g/cm^3 (0.318 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Coefficient of linear thermal expansion. 16.7 µm/m · K (9.3 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Thermal conductivity. 173 W/m · K (100 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 40% IACS at 20 °C (68 °F)
Electrical resistivity. 49.3 nΩ · m at 20 °C (68 °F)

Table 48 Nominal mechanical properties of C19520 strip

Temper	Tensile strength		Elongation in 50 mm (2 in.), %	Hardness, HV
	MPa	ksi		
H01	415	60	20	125
H02	440	64	10	140
H04	460	67	4	150
H06	515	75	2	160
H08	585	85	…	170
H10	640	93	…	180
H12	660	96 min	…	190 min

C19700
99.15Cu-0.6Fe-0.2P-0.05Mg

Chemical Composition

Composition limits. 0.3 to 1.2 Fe, 0.1 to 0.4 P, 0.01 to 0.2 Mg, 0.2 max each Sn and Zn, 0.05 max each Co, Mn, Ni, and Pb, 99.8 min Cu + named elements

Applications

Typical uses. Electrical and electronic connectors, circuit breaker components, fuse clips, cable shielding, and lead frames. Generally suited to applications requiring excellent formability combined with high strength and conductivity

Mechanical Properties

Tensile properties. See Table 49.
Hardness. See Table 49.
Elastic modulus. 121 GPa (17.5 × 10^6 psi)

Mass Characteristics

Density. 8.83 g/cm^3 (0.319 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1086 °C (1987 °F)
Solidus temperature. 1069 °C (1956 °F)
Coefficient of linear thermal expansion. 15.8 µm/m · K (8.8 µin./in. · °F) at 20 to 100 °C (68 to 212 °F); 16.8 µm/m · K (9.3 µin./in. · °F) at 20 to 200 °C (68 to 392 °F); 17.3 µm/m · K (9.6 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Thermal conductivity. 320 W/m · K (185 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 80% IACS at 20 °C (68 °F)
Electrical resistivity. 21.6 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Formability. Excellent capacity for both cold and hot forming
Weldability. Soldering and brazing: excellent

Annealing temperature. 450 to 600 °C (840 to 1110 °F)
Hot-working temperature. 750 to 950 °C (1400 to 1740 °F)

C21000
95Cu-5Zn

Commercial Names

Previous trade name. Gilding metal, 95%; CA210

Specifications

ASTM. Rolled bar, plate, sheet, and strip: B 36. Wire: B 134
SAE. J463
Government. Wire: QQ-W-321. Sheet and strip: MIL-C-21768

Chemical Composition

Composition limits. 94.0 to 96.0 Cu, 0.05 Pb max, 0.05 Fe max, bal Zn

Effect of zinc content on properties. See Fig. 21.

Applications

Typical uses. Coins, medals, tokens, bullet jackets, firing-pin supports, shells, fuse caps and primers, emblems, jewelry plaques, base for gold plate, base for vitreous enamel

Mechanical Properties

Tensile properties. See Table 50 and Fig. 22.
Shear strength. See Table 50.
Hardness. See Table 50.
Elastic modulus. Tension, 115 GPa (17 × 10^6 psi); shear, 44 GPa (6.4 × 10^6 psi)
Velocity of sound. 3.78 km/s at 20 °C (68 °F)

Structure

Crystal structure. Face-centered cubic alpha; lattice parameter, 0.3627 nm

Table 49 Nominal mechanical properties of C19700 strip

Temper	Tensile strength MPa	Tensile strength ksi	Yield strength MPa	Yield strength ksi	Elongation in 50 mm (2 in.), %	Hardness, HRB
H02	380	55	315	46	10	68
H04	450	65	415	60	6	70
H06	480	70	470	68	3	73
H08	500	73	490	71	2	75

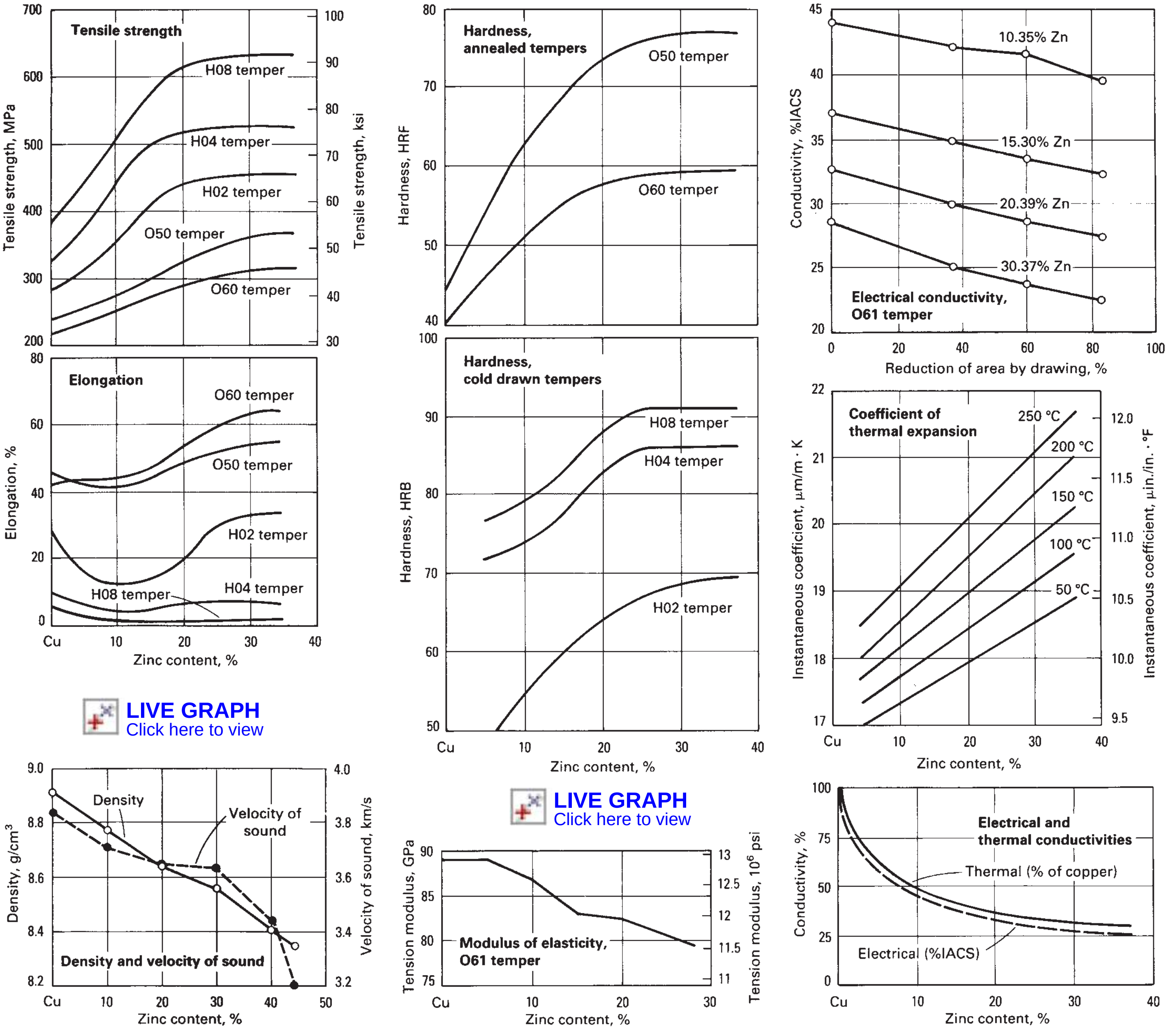

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Fig. 21 Variation of properties with zinc content for wrought copper-zinc alloys

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Minimum interatomic distance. 0.2564 nm

Mass Characteristics

Density. 8.86 g/cm^3 (0.320 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1065 °C (1950 °F)
Solidus temperature. 1050 °C (1920 °F)
Coefficient of linear thermal expansion. 18 μm/m · K (10 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 234 W/m · K (135 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 56% IACS at 20 °C (68 °F), annealed
Electrical resistivity. 31 nΩ · m at 20 °C (68 °F), annealed; temperature coefficient, 0.0231 nΩ · m per K at 20 °C (68 °F). Liquid phase: 244 nΩ · m at 1100 °C (2010 °F), 266 nΩ · m at 1300 °C (2370 °F)

Magnetic Properties

Magnetic susceptibility. -1.0×10^{-6} to -12.5×10^{-6} (SI units)

Optical Properties

Spectral reflectance. 90% for $\lambda = 578$ nm

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Recrystallization temperature. 370 °C (700 °F) for 50% reduction and 0.015 to 0.070 mm initial grain size. See Fig. 22.
Annealing temperature. 425 to 800 °C (800 to 1450 °F)
Hot-working temperature. 750 to 875 °C (1400 to 1600 °F)

C22000
90Cu-10Zn

Commercial Names

Previous Trade name. Commercial bronze, 90%; CA220

Specifications

ASTM. Rolled bar, plate, and sheet: B 36. Strip: B 36 and B 130. Cups, bullet jacket: B 131. Tube, rectangular waveguide: B 372. Seamless tube: B 135. Wire: B 134
SAE. Rolled bar, plate, sheet, strip, and seamless tube: J463 (CA220)
Government. Wire: QQ-W-321; MIL-W-6712. Bands, projectile rotating: MIL-B-18907. Blanks, rotating band for projectiles: MIL-B-20292. Cups, bullet jacket: MIL-C-3383. Sheet and strip: MIL-C-21768. Tube, rectangular waveguide: MIL-W-85. Seamless tube for microwave use: MIL-T-52069

Chemical Composition

Composition limits. 89.0 to 91.0 Cu, 0.05 Pb max, 0.05 Fe max, bal Zn
Consequence of exceeding impurity limits. See general statement for brasses under C26000.
Effect of zinc content on properties. See Fig. 21.

Applications

Typical uses. Architectural: etching bronze, grillwork, screen cloth, weather stripping. Hardware: escutcheons, kickplates, line clamps, marine hardware, rivets, screws, screw shells. Munitions: primer caps, rotating bands. Miscellaneous: compacts, lipstick cases, costume jewelry, ornamental trim, screen wire, base for vitreous enamel, waveguides

Mechanical Properties

Tensile properties. See Table 51 and Fig. 23
Shear strength. See Table 51.
Hardness. See Table 51.
Elastic modulus. Tension, 115 GPa (17×10^6 psi); shear, 44 GPa (6.4×10^6 psi)
Fatigue strength. Spring temper flat product 1.0 mm (0.40 in.) thick: 145 MPa (21 ksi) at 15×10^6 cycles; hard wire 2.0 mm (0.080 in.) in diameter: 160 MPa (23 ksi) at 10^8 cycles
Velocity of sound. 3720 m/s (12,200 ft/s) at 20 °C (68 °F)

Structure

Crystal structure. Face-centered cubic α; lattice parameter, 0.364 nm
Minimum interatomic distance. 0.257 nm

Mass Characteristics

Density. 8.80 g/cm^3 (0.318 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1045 °C (1910 °F)
Solidus temperature. 1020 °C (1870 °F)
Boiling point. About 1400 °C (2550 °F) at 101 kPa (1 atm)
Coefficient of linear thermal expansion. 18.4 μm/m · K (10.2 μin./in. · °F) at 20 to 300 °C (68 to 572 °F), cold rolled
Specific heat. 376 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 189 W/m · K (109 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 44% IACS at 20 °C (68 °F), annealed
Electrical resistivity. 39.1 nΩ · m at 20 °C (68 °F). Liquid phase, 272 nΩ · m at 1100 °C (2012 °F). Temperature coefficient, 0.00186 nΩ · m per K at 20 °C (68 °F)

Magnetic Properties

Magnetic susceptibility. -0.086×10^{-6} to -1.00×10^{-6} (cgs units)

Table 50 Typical mechanical properties of C21000

	Tensile strength		Yield strength(a)		Elongation in 50 mm (2 in.), %	Hardness		Shear strength	
Temper	MPa	ksi	MPa	ksi		HRB	HR30T	MPa	ksi
OS050 anneal (0.050 mm grain size)	235	34	69	10	45	46 HRF	…	…	…
OS035 anneal (0.035 mm grain size)	240	35	76	11	45	52 HRF	4	195	28
OS015 anneal (0.015 mm grain size)	260	38	97	14	42	60 HRF	15	205	30
Quarter hard	290	42	220	32	25	38	44	220	32
Half hard	330	48	275	40	12	52	54	235	34
Hard	385	56	345	50	5	64	60	255	37
Extra hard	420	61	380	55	4	70	64	270	39
Spring	440	64	400	58	4	73	66	275	40

Note: Values for flat products, 1 mm (0.04 in.) thick. At 0.5% extension under load

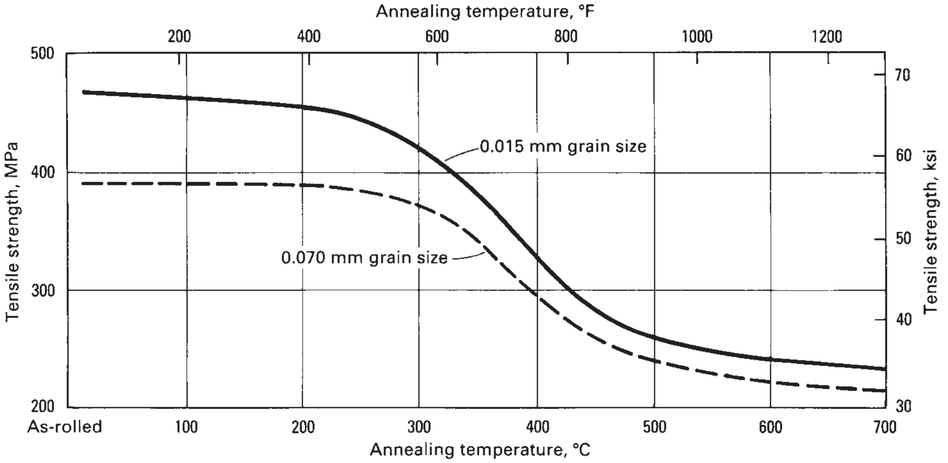

Fig. 22 Variation of tensile strength with annealing temperature for C21000. Data are for 1 mm (0.04 in.) thick ready-to-finish strip that was cold rolled 50% then annealed 1 h at the indicated temperature. Recrystallization temperature, 370 °C (700 °F) for initial grain sizes of 0.015 to 0.070 mm

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Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Recrystallization temperature. 370 °C (700 °F) for 37% reduction and 0.050 mm (0.002 in.) initial grain size. See Fig. 23.
Annealing temperature. 425 to 800 °C (800 to 1450 °F)
Hot-working temperature. 750 to 875 °C (1400 to 1600 °F)

C22600
87.5Cu-12.5Zn

Commercial Names

Previous trade name. Jewelry bronze, 87½ %; CA226
Common name. Jewelry bronze

Chemical Composition

Composition limits. 86.0 to 89.0 Cu, 0.05 Pb max, 0.005 Fe max, bal Zn

Table 51 Typical mechanical properties of C22000

	Tensile strength		Yield strength(a)		Elongation in 50 mm (2 in.), %	Hardness		Shear strength	
Temper	MPa	ksi	MPa	ksi		HRF	HR30T	MPa	ksi
Flat products, 1 mm (0.040 in.) thick									
OS050	255	37	69	10	45	53	6	195	28
OS035	260	38	83	12	45	57	12	205	30
OS025	270	39	97	14	44	60	16	215	31
OS015	280	41	105	15	42	65	26	220	32
H01	310	45	240	35	25	42 HRB	44	230	33
H02	360	52	310	45	11	58 HRB	56	240	35
H04	420	61	370	54	5	70 HRB	63	260	38
H06	460	67	400	58	4	75 HRB	67	275	40
H08	495	72	425	62	3	78 HRB	69	290	42
M20	270	39	97	14	44	60	…	215	31
Flat products, 6 mm (0.250 in.) thick									
OS035	260	38	83	12	50	57	…	205	30
H02	360	52	310	45	15	58 HRB	…	240	35
M20	255	37	69	10	45	53	…	195	28
Wire, 2 mm (0.080 in.) diameter									
OS035	275	40	…	…	50	…	…	205	30
OS015	290	42	…	…	48	…	…	220	32
H00	305	44	…	…	27	…	…	230	33
H01	345	50	…	…	13	…	…	235	34
H02	415	60	…	…	6	…	…	255	37
H04	510	74	…	…	4	…	…	290	42
H06	570	83	…	…	3	…	…	…	…
H08	620	90	…	…	3	…	…	…	…
Tubing, 25 mm (1 in.) outside diameter × 1.65 mm (0.065 in.) wall thickness									
OS025	260	38	83	12	50	57	12	…	…
H80(b)	415	60	365	53	6	69 HRB	62	…	…
Rod, 12.7 mm (0.500 in.) diameter									
OS035	275	40	…	…	50	55	…	220	32
H00	310	45	…	…	25	42 HRB	…	230	33

(a) At 0.5% extension under load. (b) Drawn 35%

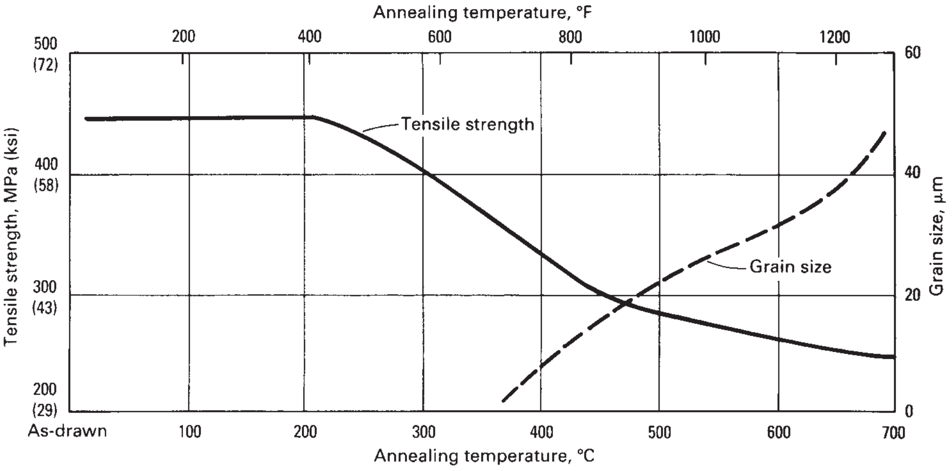

Fig. 23 Variation of tensile strength and grain size with annealing temperature for C22000. Data are for rod less than 25 mm (1 in.) in diameter that was cold drawn to a 37% reduction in area and then annealed 1 h at the indicated temperature. Grain size before annealing was 0.050 mm.

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Applications

Typical uses. Architectural: angles, channels. Hardware: chain, eyelets, fasteners, slide fasteners. Novelties: compacts, costume jewelry, emblems, etched articles, lipstick containers, plaques, base for gold plate

Mechanical Properties

Tensile properties. See Table 52 and Fig. 24.
Shear strength. See Table 52.
Elastic modulus. Tension, 115 GPa (17 × 10^6 psi); shear, 44 GPa (6.4 × 10^6 psi)

Mass Characteristics

Density. 8.78 g/cm^3 (0.317 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1035 °C (1895 °F)
Solidus temperature. 1005 °C (1840 °F)
Coefficient of linear thermal expansion. 18.6 µm/m · K (10.3 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 173 W/m · K (100 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 40% IACS at 20 °C (68 °F), annealed
Electrical resistivity. 43 nΩ · m at 20 °C (68 °F), annealed

Fabrication Characteristics

Machinability. 30% of C36000 (free-cutting brass)
Recrystallization temperature. About 330 °C (625 °F) for 1 mm (0.04 in.) strip rolled six Brown and Sharpe numbers hard from a 0.035 mm (0.001 in.) grain size. See also Fig. 24.
Annealing temperature. 425 to 750 °C (800 to 1400 °F)
Hot-working temperature. 750 to 900 °C (1400 to 1650 °F)

C23000
85Cu-15Zn

Commercial Names

Previous trade name. Red brass, 85%; CA230
Common name. Red brass

Specifications

ASME. Pipe: SB43. Condenser tubing: SB111. Finned tubing: SB359. U-bend tubing: SB395
ASTM. Plate, sheet, strip, hot-rolled bar: B 36. Pipe: B 43. Condenser tubing: B 111. Finned tubing: B 359. Seamless tubing: B 135. U-bend tubing: B 395. Wire: B 134
SAE. Sheet, strip, seamless tube: J463 (CA230)
Government. Bar, forgings, rod, shapes, strip: QQ-B-626. Plate, sheet, strip, hot-rolled bar: QQ-B-613. Pipe: WW-P-351. Seamless tubing: WW-T-791; MIL-T-20168. Wire: QQ-W-321

Chemical Composition

Composition limits. 84.0 to 86.0 Cu, 0.06 Pb max, 0.05 Fe max, bal Zn

Consequence of exceeding impurity limits. See general statement for cartridge brass (C26000).
Effect of zinc on properties. See Fig. 21.

Applications

Typical uses. Architectural: etching parts, trim, weather strip. Electrical: conduit, screw shells, sockets. Hardware: eyelets, fasteners, fire extinguishers. Industrial: condenser and heat exchanger tubes, flexible hose, pickling crates, pump lines, radiator cores. Plumbing: plumbing pipe, J-bends, service lines, traps. Miscellaneous: badges, compacts, costume jewelry, dials, etched articles, lipstick containers, nameplates, tags

Mechanical Properties

Tensile properties. See Table 53 and Fig. 25.
Shear strength. See Table 53.
Hardness. See Table 53.
Impact strength. Izod: cast, 45 J (33 ft · lbf); cast and annealed, 43 J (32 ft · lbf). Charpy keyhole: annealed rod, 69 J (51 ft · lbf). See also Fig. 26.
Elastic modulus. Tension, 115 GPa (17 × 10^6 psi); shear, 44 GPa (6.4 × 10^6 psi)
Fatigue strength. Rod, H00 temper, 140 MPa (20 ksi) at 300 × 10^6 cycles
Creep-rupture characteristics. See Fig. 27.
Velocity of sound. 3660 m/s (12,000 ft/s) at 20 °C (68 °F)

Mass Characteristics

Density. 8.75 g/cm^3 (0.316 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1025 °C (1880 °F)
Solidus temperature. 990 °C (1810 °F)

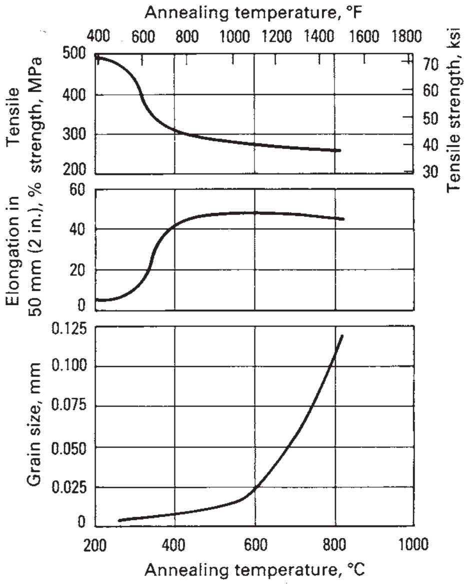

Fig. 24 Annealing characteristics of C22600. Data are for jewelry bronze strip with an initial grain size of 0.035 mm that was cold rolled 50% to a thickness of 1 mm (0.04 in.) and annealed 1 h at various temperatures.

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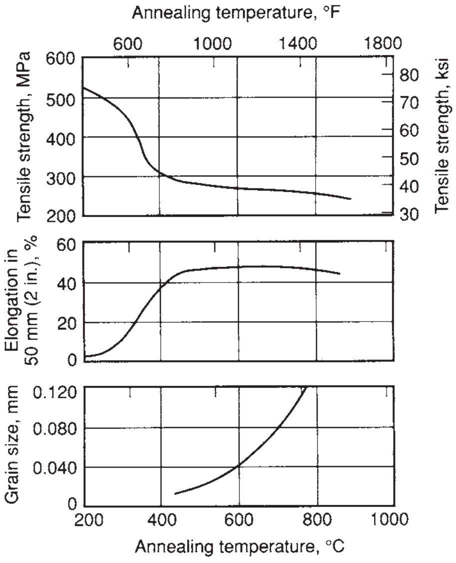

Fig. 25 Annealing characteristics of C23000. Data are for 1 mm (0.04 in.) thick red brass sheet, H06 temper, annealed 1 h at various temperatures.

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Table 52 Typical mechanical properties of C22600

	Tensile strength		Yield strength(a)		Elongation in 50 mm (2 in.), %		Shear strength	
Temper	MPa	ksi	MPa	ksi		Hardness	MPa	ksi
Flat products, 1 mm (0.04 in.) thick								
OS050	270	39	76	11	46	55 HRF	200	29
OS035	275	40	90	13	45	59 HRF	205	30
OS025	290	42	105	15	44	64 HRF	215	31
OS015	305	44	110	16	42	68 HRF	220	32
H01	325	47	255	37	25	47 HRB	235	34
H02	370	54	325	47	12	61 HRB	250	36
H04	455	66	385	56	5	73 HRB	275	40
H06	495	72	415	60	4	78 HRB	290	42
H08	545	79	425	62	4	82 HRB	305	44
Wire, 2 mm (0.08 in.) diameter								
OS050	275	40	90	13	44	…	200	29
OS035	285	41	105	15	42	…	205	30
OS025	295	43	115	17	40	…	215	31
OS015	310	45	125	18	38	…	220	32
H00	325	47	240	35	26	…	235	34
H01	385	56	360	52	12	…	250	36
H02	470	68	415	60	7	70 HRB	275	40
H04	570	83	440	64	5	…	…	…
H06	615	89	450	65	4	…	…	…
H08	670	97	455	66	3	…	…	…

(a) At 0.5% extension under load

Table 53 Typical mechanical properties of C23000

	Tensile strength		Yield strength(a)		Elongation in 50 mm (2 in.), %	Hardness		Shear strength	
Temper	MPa	ksi	MPa	ksi		HRF	HR30T	MPa	ksi
Flat products, 1 mm (0.04 in.) thick									
OS070	270	39	69	10	48	56	10	215	31
OS050	275	40	83	12	47	59	14	215	31
OS035	285	41	97	14	46	63	22	215	31
OS025	295	43	110	16	44	66	28	220	32
OS015	310	45	125	18	42	71	38	230	33
H01	345	50	270	39	25	55 HRB	54	240	35
H02	395	57	340	49	12	65 HRB	60	255	37
H04	485	70	395	57	5	77 HRB	68	290	42
H06	540	78	420	61	4	83 HRB	72	305	44
H08	580	84	435	63	3	86 HRB	74	315	46
Wire, 2 mm (0.08 in.) diameter									
OS035	285	41	…	…	48	…	…	215	31
OS025	295	43	…	…	…	…	…	220	32
OS015	310	45	…	…	…	…	…	230	33
H00	345	50	…	…	25	…	…	240	35
H01	405	59	…	…	11	…	…	260	38
H02	495	72	…	…	8	…	…	295	43
H04	605	88	…	…	6	…	…	330	48
H08	725	105	…	…	…	…	…	370	54
Tubing, 25 mm (1.0 in.) outside diameter × 1.65 mm (0.065 in.) wall thickness									
OS050	275	40	83	12	55	60	15	…	…
OS015	305	44	125	18	45	71	38	…	…
H55 (15%)	345	50	275	40	30	55 HRB	54	…	…
H80 (35%)	485	70	365	53	8	77 HRB	68	…	…
Pipe, 19 mm (0.75 in.) SPS									
OS015	305	44	125	18	45	71	…	…	…

(a) At 0.5% extension under load

Coefficient of linear thermal expansion. 18.7 µm/m · K (10.4 µin./in. · °F) at 20 to 300 °C (68 to 572 °F), cold rolled
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 159 W/m · K (92 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 37% IACS at 20 °C (68 °F), annealed
Electrical resistivity. 47 nΩ · m at 20 °C (68 °F), annealed. Liquid: 299 nΩ · m at 1100 °C (2012 °F); 304 nΩ · m at 1200 °C (2192 °F). Temperature coefficient, 0.0016/°C at 20 °C (68 °F)

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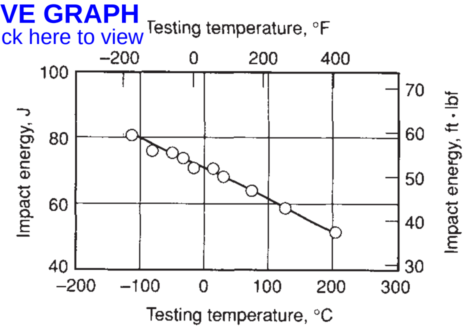

Fig. 26 Impact strength of C23000. Charpy keyhole specimens were machined from O61 temper material, then tested at the indicated temperatures. Impact strengths represent energy absorbed without fracture.

Magnetic Properties

Magnetic susceptibility. Approximately –1.00 × 10^{-6} (cgs units)

Fabrication Characteristics

Machinability. 30% of C26000 (free-cutting brass)
Recrystallization temperature. About 350 °C (660 °F) for 1 mm (0.04 in.) sheet rolled six Brown and Sharpe numbers hard with a 50% reduction and 0.035 mm (0.001 in.) initial grain size
Annealing temperature. 425 to 725 °C (800 to 1350 °F). See also Fig. 25.
Hot-working temperature. 800 to 900 °C (1450 to 1650 °F)

C24000
80Cu-20Zn

Commercial Names

Trade name. Low brass, 80%; CA240
Common name. Low brass

Specifications

ASTM. Flat products: B 36. Wire: B 134
SAE. Sheet, strip: J463 (CA240)
Government. Finished-edge bar and strip, forgings, rod, shapes: QQ-B-626. Rolled bar, plate, sheet, strip: QQ-B-613. Wire: QQ-W-321. Brazing alloy wire: QQ-B-650

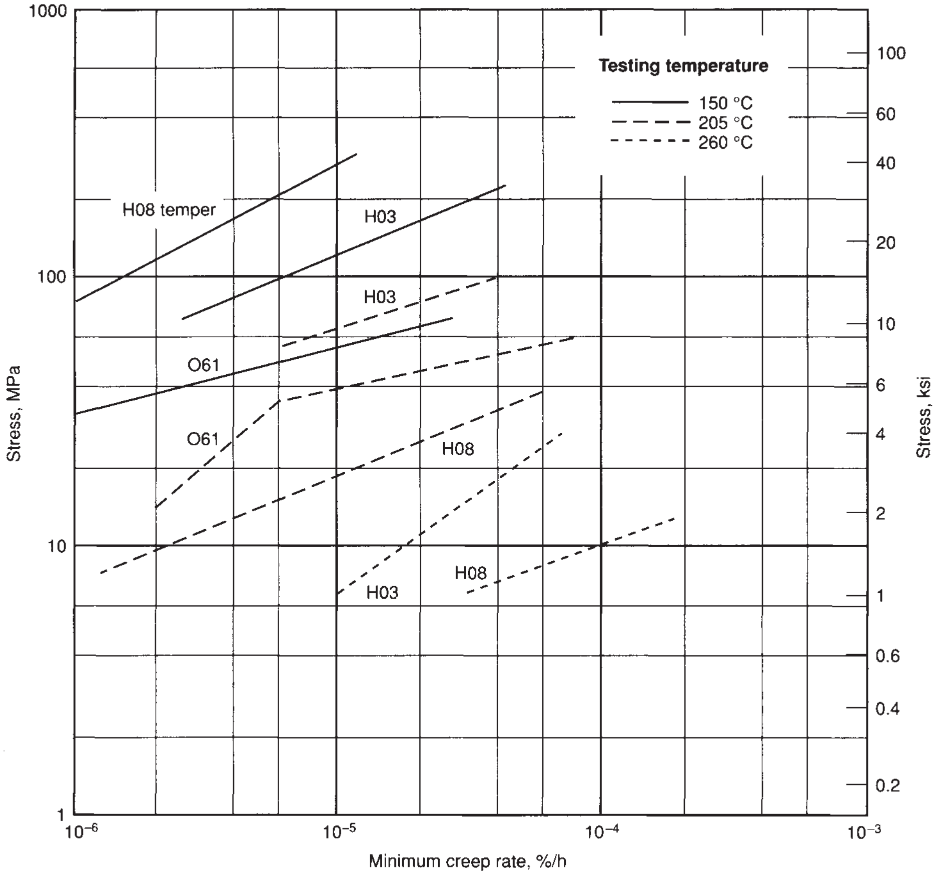

Fig. 27 Minimum creep rates for C23000 wire. Data are for red brass wire, 3.2 mm (0.125 in.) in diameter, that was cold drawn to size, then tested in the as-drawn or annealed condition.

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Chemical Composition

Composition limits. 78.5 to 81.5 Cu, 0.05 Pb max, 0.05 Fe max, bal Zn
Effect of zinc content on properties. See Fig. 21.

Applications

Typical uses. Ornamental metal work, medallions, spandrels, electrical battery caps, bellows and musical instruments, clock dials, flexible hose, pump lines, tokens

Mechanical Properties

Tensile properties. See Table 54 and Fig. 28.
Shear strength. See Table 54.
Hardness. See Table 54.
Elastic modulus. Tension, 110 GPa (16 × 10^6 psi); shear, 40 GPa (6 × 10^6 psi)
Fatigue strength. 1 mm (0.04 in.) thick strip, H08 temper: 165 MPa (24 ksi) at 20 × 10^6 cycles

Structure

Crystal structure. Face-centered cubic α′; lattice parameter, 0.366 nm
Minimum interatomic distance. 0.259 nm

Mass Characteristics

Density. 8.67 g/cm^3 (0.313 lb/$in.^3$) at 20 °C (68 °F)
Solidification shrinkage. 5 to 6%

Thermal Properties

Liquidus temperature. 1000 °C (1830 °F)
Solidus temperature. 965 °C (1770 °F)
Coefficient of linear thermal expansion. 19.1 µm/m · K (10.6 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 140 W/m · K (81 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, O61 temper: 32% IACS at 20 °C (68 °F)
Electrical resistivity. O61 temper: 54 nΩ · m at 20 °C (68 °F). Liquid: 330 nΩ · m at 1000 °C (1830 °F); 338 nΩ · m at 1200 °C (2190 °F). Temperature coefficient, 0.00154/°C at 20 °C (68 °F)

Magnetic Properties

Magnetic susceptibility. Approximately –1.00 × 10^{-6} (cgs units)

Fabrication Characteristics

Machinability. 30% of C36000 (free-cutting brass)
Recrystallization temperature. About 400 °C (750 °F) for 37% reduction and 0.060 mm initial grain size
Annealing temperature. 425 to 700 °C (800 to 1300 °F). See also Fig. 28.
Hot-working temperature. 825 to 900 °C (1500 to 1650 °F)

C26000
70Cu-30Zn

Commercial Names

Previous trade name. Cartridge brass, 70%; CA260

Common name. Cartridge brass, 70-30 brass, spinning brass, spring brass, extra-quality brass

Specifications

AMS. Flat products: 4505, 4507. Tube: 4555
ASTM. Flat products: B 19, B 36, B 569. Cups for cartridge cases: B 129. Tube: B 135, B 587. Wire: B 134
SAE. J463
Government. Flat products: QQ-B-613, QQ-B-626, MIL-C-50. Rod, bar, shapes, forgings: QQ-B-626. Tube: MIL-T-6945, MIL-T-20219. Wire: QQ-W-321, QQ-B-650. Shim stock, laminated: MIL-S-22499. Cups for cartridge cases: MIL-C-10375

Chemical Composition

Composition limits. 68.5 to 71.5 Cu, 0.07 Pb max, 0.05 Fe max, 0.15 max other (total), bal Zn
Effect of zinc on properties. See Fig. 21.
Lead should be kept under 0.01% for hot rolling, although additions of lead up to 4% improve machinability in material processed by extrusion and cold working. Lead lowers room-temperature ductility in brass and leads to hot shortness at temperatures above 315 °C (600 °F).
Aluminum at levels as high as 2% has no adverse effect on hot or cold working. However, annealing and grain size are affected.
Arsenic does not affect hot or cold working, but it tends to refine the grain size, thereby lowering ductility.
Cadmium. The effects of cadmium are not universally agreed upon; some claim as much as 0.10% has little effect, others maintain that it should be kept below 0.05%.
Chromium affects temperature of anneal and grain size. This condition is aggravated when iron is present.
Iron chiefly affects annealing and magnetic properties.
Nickel restrains grain growth.
Phosphorus has no adverse effect up to 0.04%; it does, however, restrain grain growth, increase tensile strength, and lower ductility to some extent.

Applications

Typical uses. Architectural: grillwork. Automotive: radiator cores and tanks. Electrical: bead chain, flashlight shells, reflectors, lamp fixtures, socket shells, screw shells. Hardware: eyelets, fasteners, pins, hinges, kickplates, locks, rivets, springs, stampings, tubes, etched articles. Munitions: ammunition components, particularly cartridge cases. Plumbing: accessories, fittings. Industrial: pump and power cylinders, cylinder liners
Precautions in use. Highly susceptible season cracking in ammoniacal environments

Mechanical Properties

Tensile properties. See Tables 55 and 56 and Fig. 29, 30, and 31.
Hardness. See Table 55 and Fig. 31.
Elastic modulus. Tension, 110 GPa (16 × 10^6 psi); shear, 40 GPa (6 × 10^6 psi)
Fatigue strength. See Table 55.
Impact strength. Charpy V-notch: O61 temper, 60 J (44 ft · lbf); M20 temper, 19 J (14 ft · lbf); Izod: O61 temper, 89 J (66 ft · lbf) for notched round specimen
Creep-rupture properties. See Fig. 32.
Velocity of sound. 3660 m/s (12,000 ft/s) at 20 °C (68 °F)

Structure

Crystal structure. Face-centered cubic; lattice parameter, 0.3684 nm
Minimum interatomic distance. 0.2605 nm
Microstructure. Single-phase α usually with extensive pattern of annealing twins
Damping capacity. See Fig. 33.

Mass Characteristics

Density. 8.53 g/cm^3 (0.308 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 955 °C (1750 °F)
Solidus temperature. 915 °C (1680 °F)
Coefficient of linear thermal expansion. Cold-rolled stock: 19.9 μm/m · K (11.1 μin./in. · °F) at 20 to 300 °C (68 to 572 °F). Equation for 20 to 300 °C: $L_t = L_0[1 + (17.75t + 0.00653t^2) \times 10^{-6}]$, where t is temperature difference from 20 °C
Specific heat. 375 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 120 W/m · K (70 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, O61 temper, 28% IACS at 20 °C (68 °F)

Table 54 Typical mechanical properties of C24000

	Tensile strength		Yield strength(a)		Elongation in 50 mm (2 in.), %	Hardness		Shear strength	
Temper	MPa	ksi	MPa	ksi		HRF	HR30T	MPa	ksi
Flat products, 1 mm (0.04 in.) thick									
OS070	290	42	83	12	52	57	8	…	…
OS050	305	44	97	14	50	61	16	220	32
OS035	315	46	105	15	48	66	28	…	…
OS025	330	48	115	17	47	69	32	…	…
OS015	345	50	140	20	46	75	42	230	33
H01	365	53	275	40	30	55 HRB	54	250	36
H02	420	61	345	50	18	70 HRB	64	270	39
H04	510	74	405	59	7	82 HRB	71	295	43
H08	625	91	450	65	3	91 HRB	77	330	48
Wire, 2 mm (0.08 in.) diameter									
OS050	305	44	…	…	55	…	…	220	32
OS035	315	46	…	…	50	…	…	…	…
OS015	345	50	…	…	47	…	…	230	33
H00	385	56	…	…	27	…	…	255	37
H01	470	68	…	…	12	…	…	290	42
H02	565	82	…	…	8	…	…	325	47
H04	740	107	…	…	5	…	…	365	53
H06	800	116	…	…	4	…	…	…	…
H08	860	125	…	…	3	…	…	415	60

(a) At 0.5% extension under load

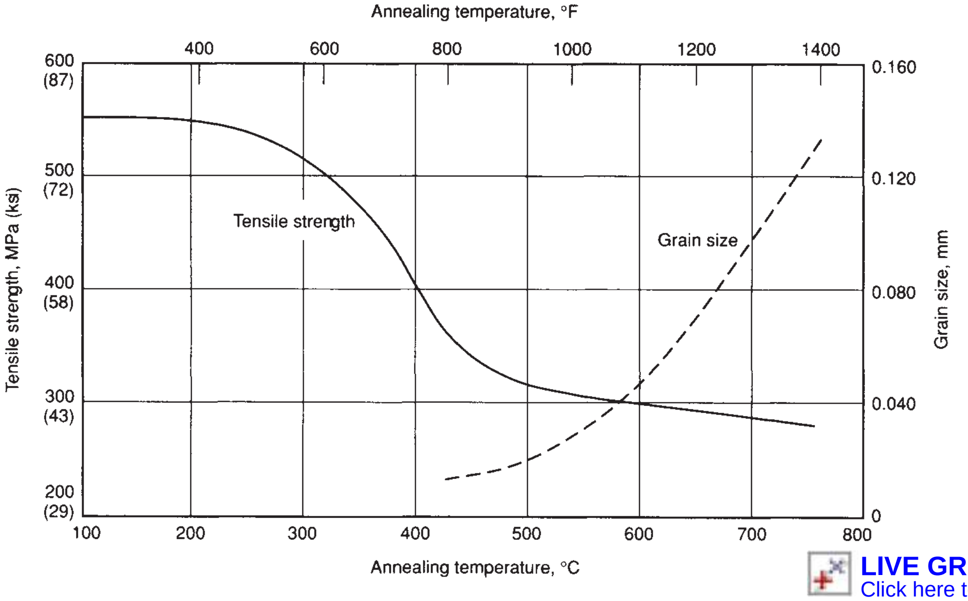

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Fig. 28 Tensile strength and grain size versus annealing temperature for C24000, annealed from H02 temper. Data are for low brass with an initial grain size of 0.060 mm that was cold drawn 37% to a diameter of less than 25 mm (1 in.) and annealed 1 h at the indicated temperature.

Table 55 Typical mechanical properties of C26000

Temper	Tensile strength		Yield strength(a)		Elongation in 50 mm (2 in.), %	Hardness		Shear strength		Fatigue strength(b)	
	MPa	ksi	MPa	ksi		HRF	HR30T	MPa	ksi	MPa	ksi
Flat products, 1 mm (0.04 in.) thick											
OS100	300	44	75	11	68	54	11	215	31	90	13
OS070	315	46	95	14	65	58	15	220	32	90	13
OS050	325	47	105	15	62	64	26	230	33	…	…
OS035	340	49	115	17	57	68	31	235	34	95	14
OS025	350	51	130	19	55	72	36	235	34	…	…
OS015	365	53	150	22	54	78	43	240	35	105	15
H01	370	54	275	40	43	55 HRB	54	250	36	…	…
H02	425	62	360	52	23	70 HRB	65	275	40	125	18
H04	525	76	435	63	8	82 HRB	73	305	44	145	21
H06	595	86	450	65	5	83 HRB	76	315	46	…	…
H08	650	94	…	…	3	91 HRB	77	330	48	160	23
H10	680	99	…	…	3	93 HRB	78	…	…	…	…
Wire, 2 mm (0.08 in.) diameter											
OS050	330	48	110	16	64	…	…	230	33	…	…
OS035	345	50	125	18	60	…	…	235	34	…	…
OS025	360	52	145	21	58	…	…	240	35	…	…
OS015	370	54	160	23	58	…	…	250	36	…	…
H00	400	58	315	46	35	…	…	260	38	…	…
H01	485	70	395	57	20	…	…	290	42	…	…
H06	855	124	…	…	4	…	…	…	…	…	…
H08	895	130	…	…	3	…	…	415	60	150	22
Tube, 25 mm (1 in.) outside diameter × 1.6 mm (0.065 in.) wall thickness											
OS050	325	47	105	15	65	64	26	…	…	…	…
OS025	360	52	140	20	55	75	40	…	…	…	…
H80	540	78	440	64	8	82 HRB	73	…	…	…	…
Rod, 25 mm (1.0 in.) diameter											
OS050	330	48	110	16	65	65	…	235	34	…	…
H00	380	55	275	40	48	60 HRB	…	260	38	…	…
H02	480	70	360	52	30	80 HRB	…	290	42	22(c)	150(c)

(a) At 0.5% extension under load. (b) Reverse bending, at 10^8 cycles. (c) Reverse bending, at 5×10^7 cycles

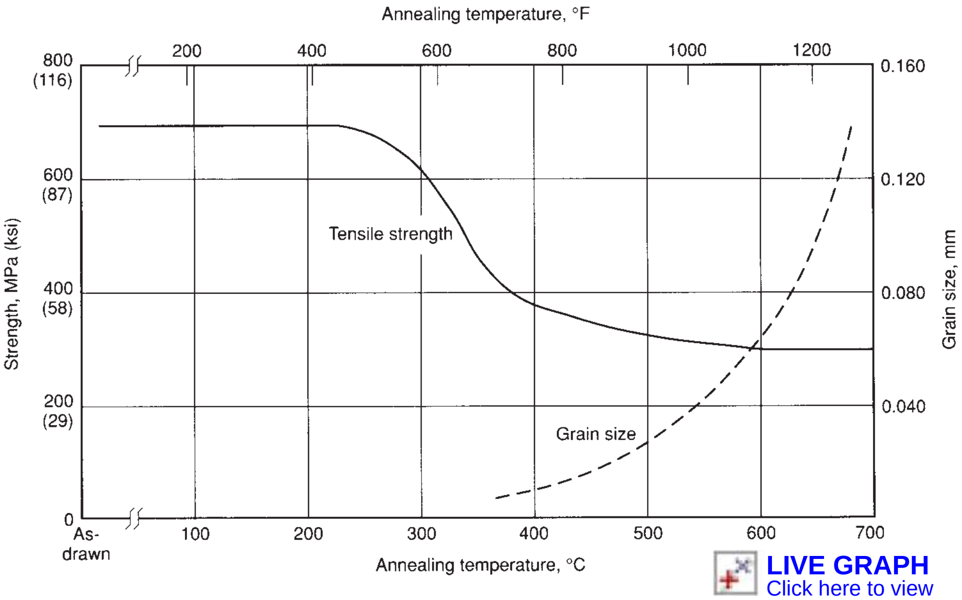

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Fig. 29 Tensile strength and grain size as a function of annealing temperature for C26000 rod. Data are for cartridge brass rod less than 25 mm (1 in.) in diameter that was cold drawn 50% (from starting material having a grain size of 0.045 mm), then annealed 1 h at the indicated temperature.

Table 56 Typical tensile properties of cold-rolled and annealed C26000 sheet

Direction in sheet	Tensile strength		Elongation, %
	MPa	ksi	
Parallel to RD	330	48	59
40° to RD	305	44	66
90° to RD	325	47	61

Note: Approximate values for material given a ready-to-finish anneal at 400 °C (750 °F), then cold rolled 70% and annealed 1 h at 575 °C (1070 °F). RD, rolling direction

Electrical resistivity. O61 temper, 62 nΩ · m at 20 °C (68 °F), temperature coefficient, 0.092 nΩ · m per K at 20 °C (68 °F)
Hall coefficient. 25 pV · m/A · T

Magnetic Properties

Iron in excess of 0.03% can precipitate from C26000 during suitable low-temperature anneals. Precipitation is slow and occurs chiefly in a nonmagnetic form, which is converted to a ferromagnetic structure on subsequent cold working.
Magnetic susceptibility. -8×10^{-8} to -16×10^{-8} (mks units); susceptibility in a brasses decreases with increasing zinc content.

Chemical Properties

General corrosion behavior. Resists corrosion in a wide variety of waters and chemical solutions; may undergo dezincification in stagnant or slowly moving salt solutions, brackish water, or mildly acidic solutions. Susceptible to stress-corrosion cracking (season cracking), especially in ammoniacal environments

Fabrication Characteristics

Machinability. 30% of C36000 (free-cutting brass)
Formability. Excellent for cold working and forming; fair for hot forming. Directionality in brass is more readily developed with high zinc content, such as in C26000 and higher-zinc brasses. Earing usually occurs 45° to the direction of rolling and is aggravated by heavy final reductions, low ready-to-finish annealing temperatures, and high finish annealing temperatures.
Weldability. Soldering and brazing: excellent. Oxyfuel gas, resistance spot, and resistance butt welding: good. Gas metal arc welding: fair. Other welding processes are not recommended.
Recrystallization temperature. About 300 °C (575 °F) for 0.045 mm initial grain size and a cold reduction of 50%

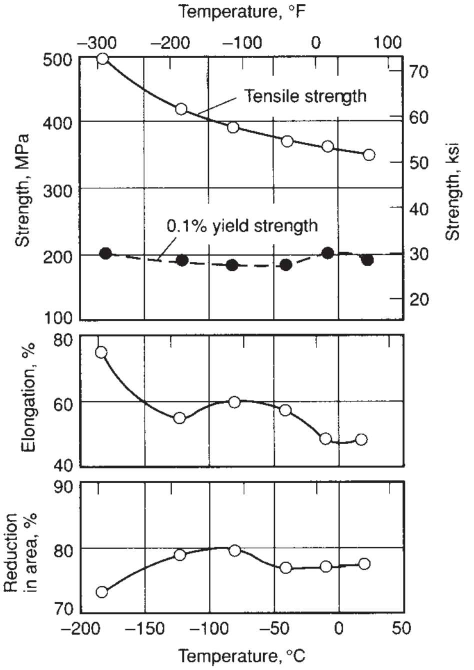

Fig. 30 Low-temperature tensile properties of C26000 rod, O61 temper

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Annealing temperature. 425 to 750 °C (800 to 1400 °F)
Hot-working temperature. 725 to 850 °C (1350 to 1550 °F)

C26800, C27000
65Cu-35Zn

Commercial Names

Previous Trade name. C26800: Yellow brass, 66%. C27000: Yellow brass, 65%
Common name. Yellow brass

Specifications

AMS. Wire: 4710, 4712
ASTM. Flat products: B 36 (C26800). Tube: B 135 (C27000), B 587 (C26800 and C27000). Wire: B 134
SAE. J463
Government. Flat products: QQ-B-613, Bar, rod, forgings, shapes: QQ-B-626. Wire: QQ-W-321, MIL-W-6712

Chemical Composition

Composition limits of C26800. 64.0 to 68.5 Cu, 0.15 Pb max, 0.05 Fe max, bal Zn
Composition limits of C27000. 63.0 to 68.5 Cu, 0.10 Pb max, 0.07 Fe max, bal Zn
Effect of zinc on properties. See Fig. 21.

Applications

Typical uses. Architectural grillwork, radiator cores and tanks, reflectors, flashlight shells, lamp fixtures, screw shells, socket shells, bead chain, chain, eyelets, fasteners, grommets, kickplates, push plates, stencils, plumbing accessories, sink strainers, wire, pins, rivets, screws, springs

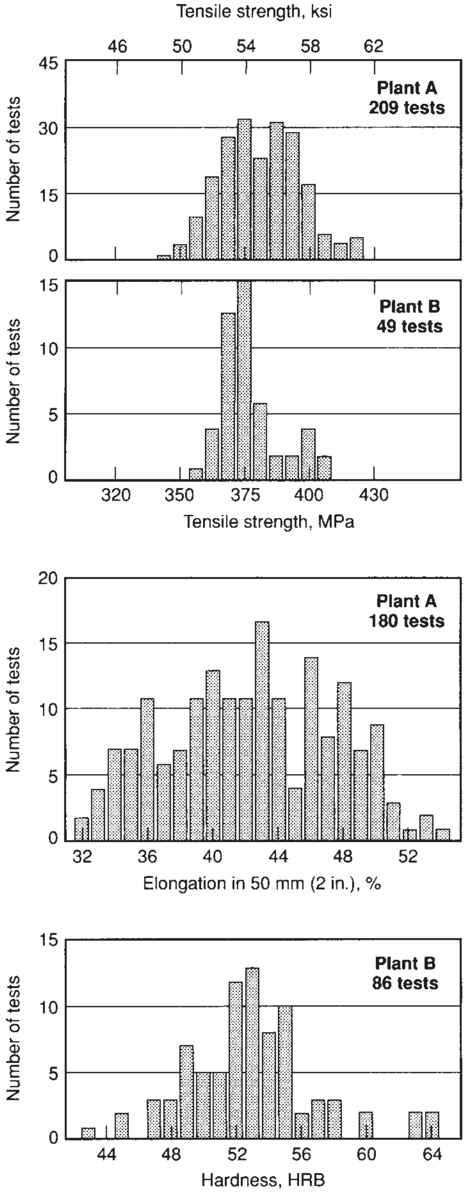

Fig. 31 Typical distribution of tensile properties and hardness for C26000 strip, H01 temper. Data are for cartridge brass strip 0.5 to 1 mm (0.020 to 0.040 in.) thick.

Mechanical Properties

Tensile properties. See Table 57.
Shear strength. See Table 57.
Hardness. See Table 57.
Elastic modulus. Tension, 105 GPa (15 × 10^6 psi); shear, 35 GPa (5 × 10^6 psi)
Fatigue strength. Rotating beam tests. At 10^8 cycles, for strip 1 mm (0.04 in.) thick: OS070 temper, 83 MPa (12 ksi); H04 temper, 97 MPa (14 ksi); H08 temper, 140 MPa (20 ksi)

Mass Characteristics

Density. 8.47 g/cm^3 (0.306 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 930 °C (1710 °F)
Solidus temperature. 905 °C (1660 °F)

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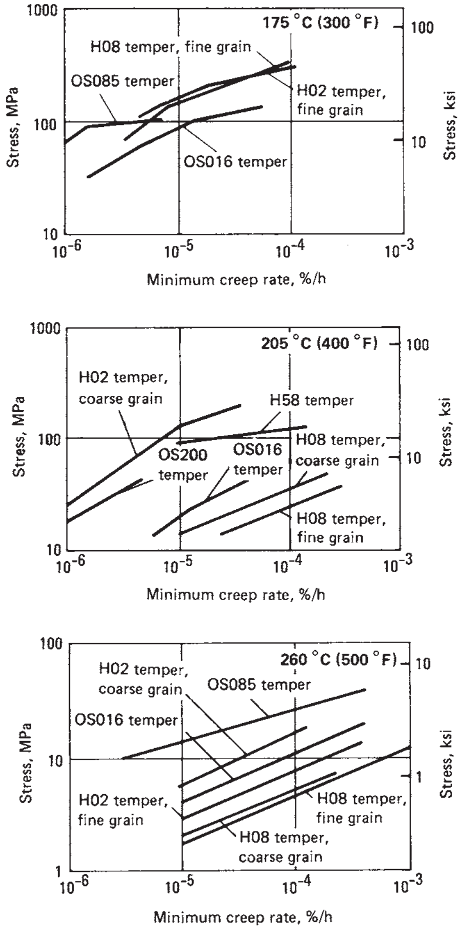

Fig. 32 Minimum creep rates for C26000

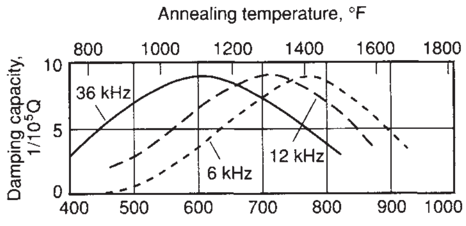

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Fig. 33 Damping capacity of annealed C26000

Coefficient of linear thermal expansion. 20.3 μm/m · K (11.3 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 116 W/m · K (67 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 27% IACS at 20 °C (68 °F), annealed
Electrical resistivity. 64 nΩ · m at 20 °C (68 °F), annealed

Structure

Crystal structure. Face-centered cubic α
Microstructure. Single-phase α

Fabrication Characteristics

Machinability. 30% of C36000 (free-cutting brass)
Recrystallization temperature. About 290 °C (550 °F) for strip cold rolled 50% to 1 mm (0.04 in.) thickness and having an initial grain size of 0.035 mm
Maximum cold reduction between anneals. 90%
Annealing temperature. 425 to 700 °C (800 to 1300 °F)
Hot-working temperature. 700 to 820 °C (1300 to 1500 °F)

C28000
60Cu-40Zn

Commercial Names

Previous Trade name. Muntz metal, 60%; CA280
Common name. Muntz metal

Specifications

ASME. Condenser tubing: SB111
ASTM. Tubing: B 111, B 135
Government. Flat products: QQ-B-613. Bar, rod, forgings, shapes: QQ-B-626. Seamless tubing: WW-T-791

Chemical Composition

Composition limits. 59.0 to 63.0 Cu, 0.30 Pb max, 0.07 Fe max, bal Zn
Effect of zinc on properties. See Fig. 21.

Applications

Typical uses. Decoration, as architectural panel sheets; structural, as heavy plates; bolting and valve stems; tubing for heat exchangers; brazing rod (for copper alloys and cast iron); hot forgings
Precautions in use. C28000 has poor cold-drawing and forming properties in comparison with those of higher-copper alloys, but it has excellent hot-working properties. It is the strongest of the copper-zinc alloys but is less ductile than higher-copper alloys. It is subject to dezincification and stress-corrosion cracking under certain conditions.

Mechanical Properties

Tensile properties. See Table 58 and Fig. 34 and 35.
Shear strength. See Table 58.
Hardness. See Table 58.
Elastic modulus. Tension, 105 GPa (15 × 10^6 psi); shear, 39 GPa (5.6 × 10^6 psi)

Mass Characteristics

Density. 8.39 g/cm^3 (0.303 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 905 °C (1660 °F)
Solidus temperature. 900 °C (1650 °F)
Coefficient of linear thermal expansion. 20.8 μm/m · K (11.6 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 375 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 123 W/m · K (71 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 28% IACS at 20 °C (68 °F)
Electrical resistivity. 61.6 nΩ · m at 20 °C (68 °F)

Structure

Microstructure. Two phase: face-centered cubic α plus body-centered cubic β. Beta phase

Table 57 Typical mechanical properties of C26800 and C27000

Temper	Tensile strength		Yield strength(a)		Elongation in 50 mm (2 in.), %	Hardness		Shear strength	
	MPa	ksi	MPa	ksi		HRF	HR30T	MPa	ksi
Flat products, 1 mm (0.04 in.) thick									
OS070	315	46	97	14	65	58	15	220	32
OS050	325	47	105	15	62	64	26	230	33
OS035	340	49	115	17	57	68	31	235	34
OS025	350	51	130	19	55	72	36	240	35
OS015	365	53	150	22	54	78	43	250	36
H01	370	54	275	40	43	55 HRB	54	250	36
H02	420	61	345	50	23	70 HRB	65	275	40
H04	510	74	415	60	8	80 HRB	70	295	43
H06	585	85	425	62	5	87 HRB	74	310	45
H08	625	91	425	62	3	90 HRB	76	325	47
H10	675	98	435	63	3	91 HRB	77	…	…
Rod, 25 mm (1.0 in.) diameter									
OS050	330	48	110	16	65(b)	65	…	235	34
H00 (6%)	380	55	275	40	48(c)	…	55	…	36
Wire, 2 mm (0.08 in.) diameter									
OS050	330	48	110	16	64	…	…	230	33
OS035	345	50	125	18	60	…	…	235	34
OS025	360	52	145	21	58	…	…	240	35
OS015	370	54	160	23	55	…	…	250	36
H00	400	58	315	46	35	…	…	260	38
H01	485	70	395	57	20	…	…	290	42
H02	605	88	420	61	15	…	…	…	…
H04	760	110	…	…	8	…	…	380	55
H06	825	120	…	…	4	…	…	…	…
H08	885	128	…	…	3	…	…	415	60

(a) At 0.5% extension under load. (b) 75% reduction in area

Table 58 Typical mechanical properties of C28000

Temper	Tensile strength		Yield strength(a)		Elongation in 50 mm (2 in.), %	Hardness, HRF	Shear strength	
	MPa	ksi	MPa	ksi			MPa	ksi
Flat products, 1 mm (0.04 in.) thick								
M20	370	54	145	21	45	85	275	40
O61	370	54	145	21	45	80	275	40
H00	415	60	240	35	30	55 HRB	290	42
H02	485	70	345	50	10	75 HRB	305	44
Rod, 25 mm (1 in.) diameter								
M30	360	52	140	20	52	78	270	39
O61	370	54	145	21	50	80	275	40
H01	495	72	345	50	25	78	310	45

(a) 0.5% extension under load

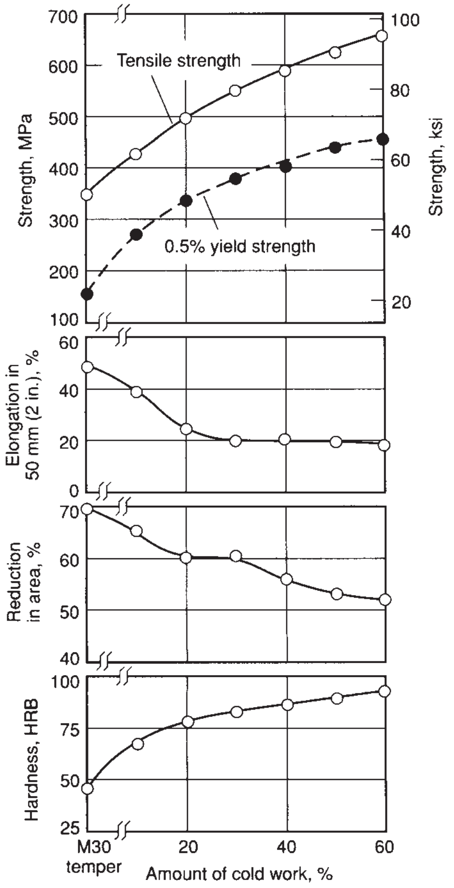

Fig. 34 Typical mechanical properties of extruded and drawn C28000. Data are for Muntz metal rod less than 25 mm (1 in.) in diameter that was extruded and then cold drawn to various percentages of reduction in area.

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appears lemon yellow when etched with ammonia peroxide; it is dark when etched with ferric chloride. In grain size determination, the beta phase should be ignored.

Optical Properties

Color. Reddish compared to C26000 (70-30 cartridge brass). C28000 is used as a good match to the color of C23000 (85-15 red brass).

Chemical Properties

General corrosion behavior. Generally good; similar to copper except as noted below
Resistance to specific corroding agents. Better resistance to sulfur-bearing compounds than that of higher-copper alloys

Fabrication Characteristics

Machinability. 40% of C36000 (free-cutting brass)
Forgeability. 90% of C37700 (forging brass)
Formability. Fair capacity for cold working; excellent capacity for hot forming
Weldability. Soldering or brazing: excellent. Oxyfuel gas welding, resistance spot welding, or resistance butt welding: good. Gas-shielded arc welding: fair
Annealing temperature. 425 to 600 °C (800 to 1100 °F). See also Fig. 35.
Hot-working temperature. 625 to 800 °C (1150 to 1450 °F)

C31400
89Cu-9.1Zn-1.9Pb

Commercial Names

Previous trade name. Leaded commercial bronze; CA314

Specifications

ASTM. B 140

Chemical Composition

Composition limits. 87.5 to 90.5 Cu, 1.3 to 2.5 Pb, 0.10 Fe max, 0.7 Ni max, 0.5 max other (total), bal Zn

Applications

Typical uses. Screws, screw machine parts, pickling racks and fixtures, electrical plug-type connectors, builders' hardware

Mechanical Properties

Tensile properties. Rod, typical. O61 temper: tensile strength, 255 MPa (37 ksi); yield strength, 83 MPa (12 ksi) at 0.5% extension under load; elongation, 45% in 50 mm (2 in.); reduction in area, 70%. H02 temper: tensile strength, 360 MPa (52 ksi); yield strength, 310 MPa (45 ksi); elongation, 18%; reduction in area, 60%
Shear strength. Rod, typical: O61 temper, 165 MPa (24 ksi); H02 temper, 205 MPa (30 ksi)
Hardness. O61 temper, 55 HRF; H02 temper, 58 HRB; H04 temper, 61 to 65 HRB
Elastic modulus. Tension, 115 GPa (17 × 10^6 psi); shear, 45 GPa (6.4 × 10^6 psi)

Mass Characteristics

Density. 8.83 g/cm^3 (0.319 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1040 °C (1900 °F)
Solidus temperature. 1010 °C (1850 °F)
Coefficient of linear thermal expansion. 18.4 μm/m · K (10.2 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 375 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 180 W/m · K (104 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 42% IACS at 20 °C (68 °F)
Electrical resistivity. 41 nΩ · m at 20 °C (68 °F)

Optical Properties

Color. Rich bronze

Fabrication Characteristics

Machinability. 80% of C36000 (free-cutting brass)
Formability. Cold working, good; hot forming, poor
Weldability. Soldering: excellent. Brazing: good. Resistance butt welding: fair. All other welding processes are not recommended.
Annealing temperature. 425 to 650 °C (800 to 1200 °F)

C31600
89Cu-8.1Zn-1.9Pb-1Ni

Commercial Names

Previous trade name. Leaded commercial bronze-nickel bearing; CA316

Specifications

ASTM. B 140

Chemical Composition

Composition limits. 87.5 to 90.5 Cu, 1.3 to 2.5 Pb, 0.7 to 1.2 Ni, 0.1 Fe max, 0.04 to 0.10 P, 0.5 max other (total), bal Zn

Applications

Typical uses. Electrical connectors, fasteners, hardware, nuts, screws, screw machine parts. Most commonly used as rod or drawn bar

Mechanical Properties

Tensile properties. See Table 59.

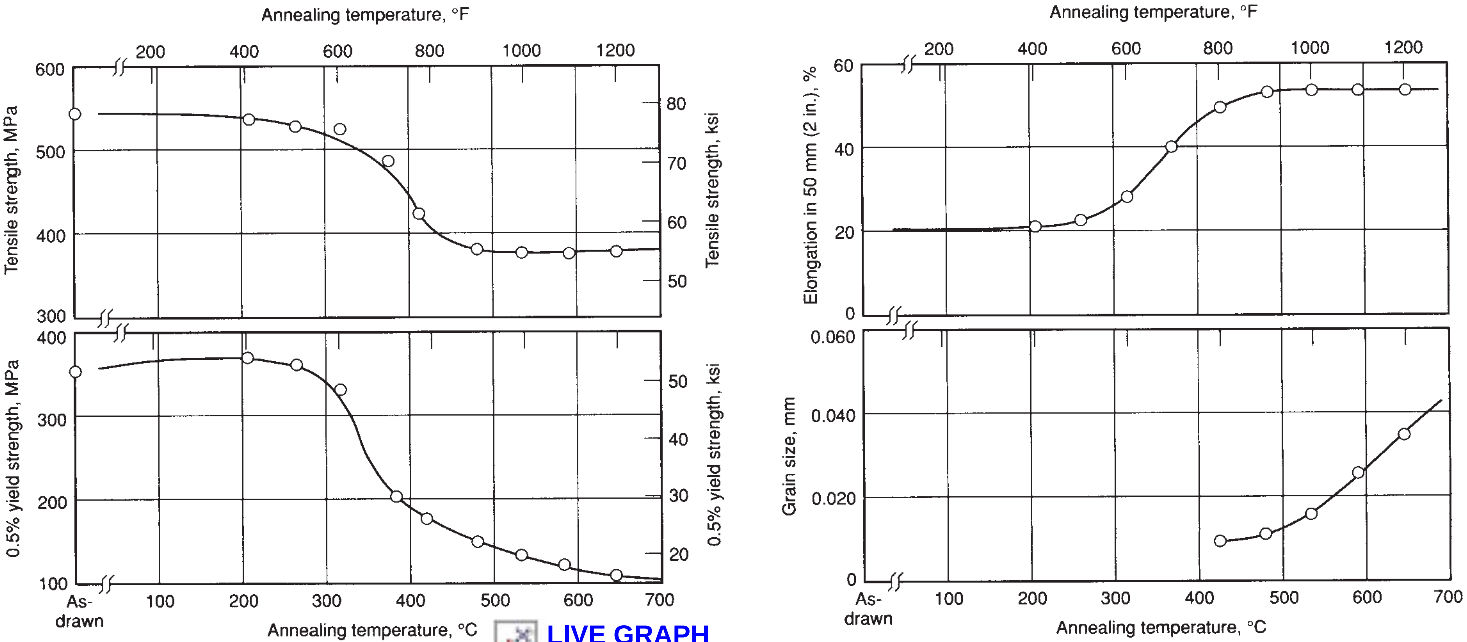

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Fig. 35 Annealing curves for C28000. Data are for Muntz metal rod less than 25 mm (1 in.) in diameter that was extruded, cold drawn 30%, and annealed 1 h at various temperatures.

Hardness. See Table 59.
Elastic modulus. Tension, 115 GPa (17 × 10^6 psi)

Mass Characteristics

Density. 8.86 g/cm^3 (0.320 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1040 °C (1900 °F)
Solidus temperature. 1010 °C (1850 °F)
Coefficient of linear thermal expansion. 18.4 µm/m · K (10.2 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 140 W/m · K (81 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 32% IACS at 20 °C (68 °F)
Electrical resistivity. 54 nΩ · m at 20 °C (68 °F)

Optical Properties

Color. Rich bronze

Fabrication Characteristics

Machinability. 80% of C36000 (free-cutting brass)
Formability. Cold working: good. Hot forming: poor
Weldability. Soldering: excellent. Brazing: good. Resistance butt welding: fair. All other welding processes are not recommended.
Annealing temperature. 425 to 650 °C (800 to 1200 °F)

C33000
66Cu-33.5Zn-0.5Pb

Commercial Names

Previous trade name. Low-leaded brass (tube)
Common name. High brass; yellow brass

Specifications

AMS. 4555
ASTM. B 135
SAE. J463
Government. WW-T-791, MIL-T-46072

Chemical Composition

Composition limits. 65 to 68 Cu, 0.2 to 0.8 Pb, 0.07 Fe max, 0.5 max other (total), bal Zn. For tubing with an outside diameter greater than 125 mm (5 in.), Pb content may be less than 0.2%.

Applications

Typical uses. General-purpose use where some degree of machinability is required together with moderate cold-working properties; for example, primers for munitions. Plumbing: J-bends, pump lines, trap lines

Mechanical Properties

Tensile properties. See Table 60.
Hardness. See Table 60.
Elastic modulus. Tension, 105 GPa (15 × 10^6 psi); shear, 39 GPa (5.6 × 10^6 psi)

Mass Characteristics

Density. 8.50 g/cm^3 (0.31 lb/in.^{3}) at 20 °C (68 °F)

Table 59 Typical mechanical properties of C31600

Temper	Tensile strength MPa	Tensile strength ksi	Yield strength(a) MPa	Yield strength(a) ksi	Elongation in 50 mm (2 in.), %	Hardness, HRB	Shear strength MPa	Shear strength ksi
Drawn bar, 6 mm (0.25 in.) diameter								
H04	435	63	385	56	12	70	…	…
Rod, 13 mm (0.50 in.) diameter								
H04	460	67	405	59	13	72	275	40
Rod, 25 mm (1 in.) diameter								
OS050	255	37	83	12	45	55 HRF	165	24
H04	450	65	395	57	15	70	270	39

(a) 0.5% extension under load

Table 60 Typical mechanical properties of C33000 tubing

Temper	Tensile strength MPa	Tensile strength ksi	Yield strength(a) MPa	Yield strength(a) ksi	Elongation in 50 mm (2 in.), %	Hardness HRF	Hardness HRB	Hardness HR30T
OS050	325	47	105	15	60	64	…	26
OS025	360	52	135	20	50	75	…	36
H58	450	65	345	50	32	100	70	66
H80	515	75	415	60	7	…	85	76

Note: Values for tubing, 25 mm (1.0 in.) outside diameter × 1.65 mm (0.065 in.) wall thickness. (a) 0.5% extension under load

Table 61 Typical mechanical properties of C33200 tubing

Temper	Tensile strength MPa	Tensile strength ksi	Yield strength(a) MPa	Yield strength(a) ksi	Elongation in 50 mm (2 in.), %	Hardness HRF	Hardness HRB	Hardness HR30T
OS050	325	47	105	15	60	64	…	26
OS025	360	52	135	20	50	75	…	36
H58	450	65	345	50	32	100	70	66
H80	515	75	415	60	7	…	85	76

Note: Values for tubing, 25 mm (1.0 in.) outside diameter×; 1.65 mm (0.065 in.) wall thickness. (a) 0.5% extension under load

Thermal Properties

Liquidus temperature. 940 °C (1720 °F)
Solidus temperature. 905 °C (1660 °F)
Coefficient of linear thermal expansion. 20.2 µm/m · K (11.2 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 115 W/m · K (67 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, O61 temper, 26% IACS at 20 °C (68 °F)
Electrical resistivity. 66 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 60% of C36000 (free-cutting brass)
Formability. Cold working, excellent; hot forming, poor
Weldability. Soldering: excellent. Brazing: good. Oxyfuel gas, gas-shielded arc, resistance spot, and resistance butt welding: fair. All other welding processes are not recommended.
Recrystallization temperature. 290 °C (550 °F)
Annealing temperature. 425 to 650 °C (800 to 1200 °F)

C33200
66Cu-32.4Zn-1.6Pb

Commercial Names

Previous trade name. High-leaded brass (tube)
Common name. Free-cutting tube brass

Specifications

AMS. 4558
ASTM. B 135
Government. MIL-T-46072

Chemical Composition

Composition limits. 65.0 to 68.0 Cu, 1.3 to 2.0 Pb, 0.07 Fe max, 0.5 max other (total), bal Zn

Applications

Typical uses. General-purpose screw machine products

Mechanical Properties

Tensile properties. See Table 61 and Fig. 36.
Hardness. See Table 61 and Fig. 36.
Elastic modulus. Tension, 105 GPa (15 × 10^6 psi); shear, 39 GPa (5.6 × 10^6 psi)

Mass Characteristics

Density. 8.53 g/cm^3 (0.31 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 930 °C (1710 °F)
Solidus temperature. 900 °C (1650 °F)
Coefficient of linear thermal expansion. 20.3 µm/m · K (11.3 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 115 W/m · K (67 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric. O61 temper, 26% IACS at 20 °C (68 °F)
Electrical resistivity. 66 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 80% of C36000 (free-cutting brass)
Formability. Cold working, fair; hot forming, poor
Weldability. Soldering: excellent. Brazing: good. Resistance butt welding: fair. All other welding processes are not recommended.
Recrystallization temperature. 288 °C (550 °F)
Annealing temperature. 425 to 650 °C (800 to 1200 °F)

C33500
65Cu-34.5Zn-0.5Pb

Commercial Names

Previous trade name. Low-leaded brass

Specifications

ASTM. Flat products: B 121. Rod: B 453
Government. Flat products: QQ-B-613. Bar, forgings, rod, shapes, strip: QQ-B-626

Chemical Composition

Composition limits. 62.5 to 66.5 Cu, 0.3 to 0.8 Pb, 0.1 Fe max, 0.5 max other (total), bal Zn

Applications

Typical uses. Hardware such as butts and hinges; watch backs

Mechanical Properties

Tensile properties. See Table 62.
Shear strength. See Table 62.
Hardness. See Table 62.
Elastic modulus. Tension, 105 GPa (15 × 10^6 psi); shear, 39 GPa (5.6 × 10^6 psi)

Mass Characteristics

Density. 8.47 g/cm^3 (0.306 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 925 °C (1700 °F)
Solidus temperature. 900 °C (1650 °F)
Coefficient of linear thermal expansion. 20.3 µm/m · K (11.3 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 115 W/m · K (67 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 26% IACS at 20 °C (68 °F)
Electrical resistivity. 66 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 60% of C36000 (free-cutting brass)
Formability. Cold working, good; hot forming, poor. Commonly fabricated by blanking, drawing, machining, piercing, punching, and stamping
Weldability. Soldering: excellent. Brazing: good. Oxyfuel gas, gas-shielded arc, resistance spot, and resistance butt welding: fair. Shielded metal arc and resistance seam welding are not recommended.
Annealing temperature. 425 to 700 °C (800 to 1300 °F)

C34000
65Cu-34Zn-1Pb

Commercial Names

Previous trade name. Medium-leaded brass, 64.5%

Specifications

ASTM. Flat products: B 121. Rod: B 453
Government. Flat products: QQ-B-613. Bar, forgings, rod, shapes, strip: QQ-B-626

Chemical Composition

Composition limits. 62.5 to 66.5 Cu, 0.8 to 1.4 Pb, 0.10 Fe max, 0.5 max other (total), bal Zn

Applications

Typical uses. Flat products: butts, dials, engravings, gears, instrument plates, nuts, or drawn shells, all involving piercing, threading, or machining. Rod, bar, and wire: couplings, free-machining screws and rivets, gears, nuts, tire valve stems, screw machine products involving severe knurling and roll threading or moderate cold heading, flaring, spinning, or swaging

Mechanical Properties

Tensile properties. See Table 63.
Shear strength. See Table 63.
Hardness. See Table 63.
Elastic modulus. Tension, 105 GPa (15 × 10^6 psi); shear, 39 GPa (5.6 × 10^6 psi)

Mass Characteristics

Density. 8.47 g/cm^3 (0.306 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 925 °C (1700 °F)
Solidus temperature. 885 °C (1630 °F)
Coefficient of linear thermal expansion. 20.3 µm/m · K (11.3 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 115 W/m · K (67 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric. O61 temper, 26% IACS at 20 °C (68 °F)
Electrical resistivity. 66 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 60% of C36000 (free-cutting brass)
Formability. Cold working, good; hot forming, poor
Weldability. Soldering: excellent. Brazing: good. Resistance butt welding: fair. All other welding processes are not recommended.
Recrystallization temperature. 288 °C (550 °F)
Annealing temperature. 425 to 650 °C (800 to 1200 °F)

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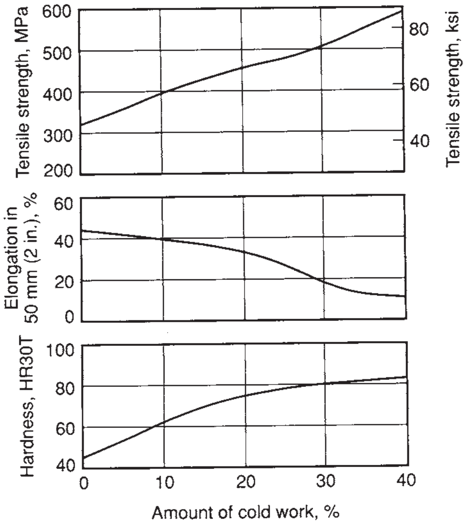

Fig. 36 Typical mechanical properties of cold drawn C33200 copper alloy tubing

Table 62 Typical mechanical properties of C33500

Temper	Tensile strength		Yield strength(a)		Elongation in 50 mm (2 in.), %	Hardness		Shear strength	
	MPa	ksi	MPa	ksi		HRF	HR30T	MPa	ksi
OS070	315	46	97	14	65	58	15	220	32
OS050	325	47	105	15	62	64	26	…	…
OS035	340	49	115	17	57	68	31	235	34
OS025	350	51	130	19	55	72	36	…	…
H01	370	54	275	40	43	55 HRB	54	250	36
H02	420	61	345	50	23	70 HRB	65	275	40
H04	510	74	415	60	8	80 HRB	69	295	43
H06	580	84	…	…	…	86 HRB	74	…	…

Note: Values for flat products, 1 mm (0.04 in.) thick. (a) 0.5% extension under load

C34200
64.5Cu-33.5Zn-2Pb
C35300
62Cu-36.2Zn-1.8Pb

Commercial Names

Previous trade name. High-leaded brass
Common name. Clock brass, engraver's brass, heavy-leaded brass

Specifications

ASTM. Flat products: B 121. Rod: B 453
SAE. J463
UNS number. C34200, C35300
Government. Flat products: QQ-B-613. Bar, forgings, rod, shapes, strip: QQ-B-626

Chemical Composition

Composition limits of C34200. 62.5 to 66.5 Cu, 1.5 to 2.5 Pb, 0.1 Fe max, 0.5 max other (total), bal Zn
Composition limits of C35300. 59.0 to 64.5 Cu, 1.3 to 2.3 Pb, 0.1 Fe max, 0.5 max other (total), bal Zn

Applications

Typical uses. Flat products: gears, wheels, nuts, plates for clocks, keys, bearing cages, engraver's plates. Rod: gears, pinions, valve stems, automatic screw machine parts that need more severe cold working than can be tolerated with free-cutting brass (for example, processes such as knurling and moderate staking)

Mechanical Properties

Tensile properties. See Table 64.
Hardness. See Table 64.
Elastic modulus. Tension, 105 GPa (15×10^6 psi); shear, 39 GPa (5.6×10^6 psi)

Structure

Crystal structure. Face-centered cubic α
Microstructure. Two phase, α and lead

Mass Characteristics

Density. 8.5 g/cm^3 (0.307 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 910 °C (1670 °F)
Solidus temperature. 885 °C (1630 °F)
Coefficient of linear thermal expansion. 20.3 μm/m · K (11.3 min./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 115 W/m · K (67 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, O61 temper, 26% IACS at 20 °C (68 °F)
Electrical resistivity. 66 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 90% of C36000 (free-cutting brass)
Formability. Cold working, fair; hot forming, poor
Weldability. Soldering: excellent. Brazing: good. Resistance butt welding: fair. All other welding processes are not recommended.
Recrystallization temperature. 320 °C (600 °F)
Annealing temperature. 425 to 600 °C (800 to 1100 °F). See also Fig. 37.
Hot-working temperature. 785 to 815 °C (1445 to 1500 °F)

C34900
62Cu-37.5Zn-0.3Pb

Chemical Composition

Composition limits. 61.0 to 64.0 Cu, 0.1 to 0.5 Pb, 0.1 Fe max, 0.5 max other (total), bal Zn

Applications

Typical uses. Building hardware, drilled and tapped rivets, plumbing goods, saw nuts, and

Table 63 Typical mechanical properties of C34000

	Tensile strength		Yield strength(a)			Hardness		Shear strength	
Temper	MPa	ksi	MPa	ksi	Elongation in 50 mm (2 in.), %	HRB	HR30T	MPa	ksi
Flat products, 1 mm (0.04 in.) thick									
OS035	340	49	115	17	54	68 HRF	31	225	33
OS025	350	51	130	19	53	72 HRF	36	235	34
H01	370	54	275	40	41	55	54	250	36
H02	420	61	345	50	21	70	63	275	40
H04	510	74	415	60	7	80	70	295	43
H06	585	85	425	62	5	87	73	310	45
Rod, 25 mm (1.0 in.) diameter									
OS025	345	50	135	20	60	70 HRF	…	235	34
H03	380	55	290	42	40	60	…	250	36
H02	435	63	330	48	30	68	…	275	40
Wire, 2 mm (0.08 in.) diameter									
OS025	345	50	…	…	50	…	…	235	34
H00	400	58	…	…	30	…	…	260	38
H01	485	70	…	…	13	…	…	290	42
H02	605	88	…	…	7	…	…	315	46

(a) 0.5% extension under load

Table 64 Typical mechanical properties of C34200

	Tensile strength		Yield strength(a)			Hardness		Shear strength	
Temper	MPa	ksi	MPa	ksi	Elongation in 50 mm (2 in.), %	HRB	HR30T	MPa	ksi
Flat products, 1 mm (0.04 in.) thick									
OS015	370	54	165	24	45	78 HRF	41	255	37
OS025	360	52	140	20	48	76 HRF	37	250	36
OS035	340	49	115	17	52	68 HRF	32	235	34
OS050	325	47	105	15	55	66 HRF	28	225	33
H01	370	54	275	40	38	55	54	250	36
H02	420	61	345	50	20	70	63	275	40
H04	510	74	415	60	7	80	71	295	43
H06	585	85	425	62	5	87	75	310	45
Rod, 25 mm (1.0 in.) diameter									
O50	325	47	125	18	59(b)	66 HRF	…	…	…
H55	400	58	270	39	28(c)	65	…	…	…
H02	450	65	310	45	23(d)	72	…	…	…

(a) 0.5% extension under load. (b) Reduction in area 65%. (c) Reduction in area 50%. (d) Reduction in area 35%

parts requiring moderate cold working combined with some machining

Mechanical Properties

Tensile properties. See Table 65.
Shear strength. See Table 65.
Hardness. See Table 65.
Elastic modulus. Tension, 105 GPa (15 × 10^6 psi); shear, 39 GPa (5.6 × 10^6 psi)

Mass Characteristics

Density. 8.44 g/cm^3 (0.305 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 910 °C (1670 °F)
Solidus temperature. 895 °C (1640 °F)
Coefficient of linear thermal expansion. 20.3 μm/m · K (11.3 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 115 W/m · K (67 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 26% IACS at 20 °C (68 °F)
Electrical resistivity. 66 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 50% of C36000 (free-cutting brass)
Formability. Cold working, good; hot forming, poor
Weldability. Soldering: excellent. Brazing: good. Oxyfuel gas, gas-shielded arc, and resistance spot and butt welding: fair. Shielded metal arc and resistance seam welding are not recommended.
Annealing temperature. 425 to 650 °C (800 to 1200 °F)
Hot-working temperature. 675 to 800 °C (1250 to 1450 °F)

C35000
62.5Cu-36.4Zn-1.1Pb

Commercial Names

Previous trade name. Medium-leaded brass, 62%

Specifications

ASTM. Flat products: B 121. Rod: B 453
SAE. J463
Government. Flat products: QQ-B-613. Bar, forgings, rod, shapes, strip: QQ-B-626

Chemical Composition

Composition limits. 59.0 to 64.0 Cu, 0.8 to 1.4 Pb, 0.1 Fe max, 0.5 max other (total), bal Zn

Applications

Typical uses. Bearing cages, book dies, clock plates, engraving plates, gears, hinges, hose couplings, keys, lock parts, lock tumblers, meter parts, sink strainers, strike plates, templates, nuts, type characters, washers, wear plates

Mechanical Properties

Tensile properties. See Table 66.
Shear strength. See Table 66.
Hardness. See Table 66.
Elastic modulus. Tension, 105 GPa (15 × 10^6 psi); shear, 39 GPa (5.6 × 10^6 psi)

Mass Characteristics

Density. 8.47 g/cm^3 (0.306 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 915 °C (1680 °F)
Solidus temperature. 895 °C (1640 °F)
Coefficient of linear thermal expansion. 20.3 μm/m · K (11.3 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)

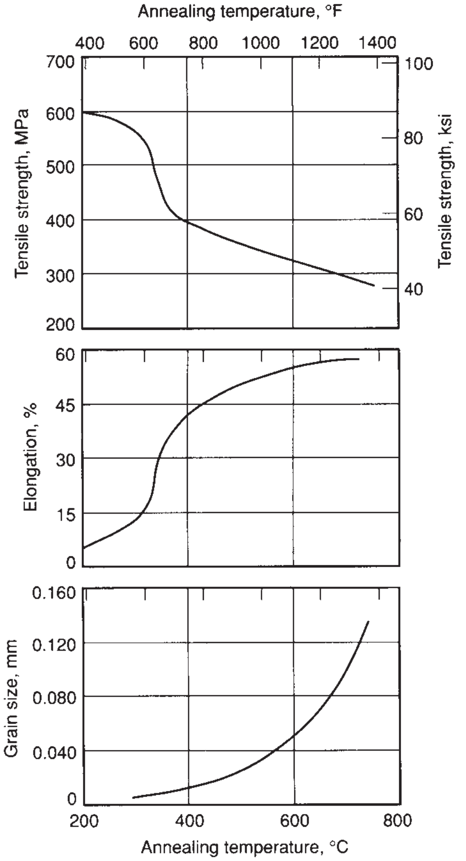

Fig. 37 Annealing behavior of C34200. Curves are for 1 mm (0.04 in.) thick strip cold rolled from OS035 temper starting stock.

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Table 65 Typical mechanical properties of C34900

	Tensile strength		Yield strength(a)				Shear strength	
Temper	MPa	ksi	MPa	ksi	Elongation in 50 mm (2 in.), %	Hardness	MPa	ksi
Rod, 6 mm (0.25 in.) diameter								
OS035	365	53	165	24	50	75 HRF	235	34
Rod, 25 mm (1.0 in.) diameter								
H01	385	56	290	42	42	70 HRB	250	36
Wire, 6 mm (0.25 in.) diameter								
OS015	380	55	150	22	48	70 HRF	240	35
H01	470	68	380	55	19	72 HRB	285	410
Wire, 19 mm (0.75 in.) diameter								
OS050	330	48	110	16	72	67 HRF	220	32

(a) At 0.5% extension under load

Table 66 Typical mechanical properties of C35000

			Yield strength								
	Tensile strength		0.5% extension under load		0.2% offset			Hardness		Shear strength	
Temper	MPa	ksi	MPa	ksi	MPa	ksi	Elongation in 50 mm (2 in.), %	HRB	HR30T	MPa	ksi
Flat products, 1 mm (0.04 in.) thick											
OS050	310	45	90	13	90	13	57	61 HRF	…	…	…
OS035	325	47	110	16	110	16	54	67 HRF	…	…	…
OS025	330	48	135	20	135	20	50	70 HRF	…	…	…
OS015	350	51	170	25	170	25	46	74 HRF	52	…	…
H01	370	54	220	32	235	34	43	66	60	…	…
H02	415	60	310	45	310	45	29	75	68	…	…
H03	460	67	365	53	380	55	17	80	71	…	…
H04	505	73	415	60	415	60	10	86	75	…	…
H06	580	84	450	65	475	69	5				
Rod, 12 mm (0.5 in.) diameter											
OS050	330	48	110	16	…	…	56	65 HRF	25	235	34
OS015	380	55	170	25	…	…	46	85 HRF	50	250	36
H01	400	58	305	44	…	…	42	60	57	260	38
H02	485	70	360	52	…	…	22	80	70	290	42

Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 115 W/m · K (67 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 26% IACS at 20 °C (68 °F)
Electrical resistivity. 66 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 70% of C36000 (free-cutting brass)
Forgeability. 50% of C37700 (forging brass)
Formability. Fair for cold working and hot forming
Weldability. Soldering: excellent. Brazing: good. Resistance butt welding: fair. All other welding processes are not recommended.
Annealing temperature. 425 to 600 °C (800 to 1100 °F)
Hot-working temperature. 760 to 800 °C (1400 to 1500 °F)

C35600
62Cu-35.5Zn-2.5Pb

Commercial Names

Previous trade name. Extra-high-leaded brass

Specifications

ASTM. Flat products: B 121. Rod: B 453
Government. Flat products: QQ-B-613. Bar, rod, shapes, strip: QQ-B-626

Chemical Composition

Composition limits. 59.0 to 64.5 Cu, 2.0 to 3.0 Pb, 0.1 Fe max, 0.5 max other (total), bal Zn

Applications

Typical uses. Hardware: clock plates and nuts, clock and watch backs, clock gears and wheels. Industrial: channel plate

Mechanical Properties

Tensile properties. See Table 67.
Hardness. See Table 67.
Elastic modulus. Tension, 97 GPa (14 × 10^6 psi); shear, 37 GPa (5.3 × 10^6 psi)

Mass Characteristics

Density. 8.5 g/cm^3 (0.307 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 905 °C (1660 °F)
Solidus temperature. 885 °C (1630 °F)
Coefficient of linear thermal expansion. 20.5 μm/m · K (11.4 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 115 W/m · K (67 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, O61 temper, 26% IACS at 20 °C (68 °F)
Electrical resistivity. 66 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 100% of C36000 (free-cutting brass)
Formability. Cold working, poor; hot forming, fair
Weldability. Soldering: excellent. Brazing: good. Resistance butt welding: fair. All other welding processes are not recommended.
Annealing temperature. 425 to 600 °C (800 to 1100 °F)
Hot-working temperature. 700 to 800 °C (1300 to 1450 °F)

C36000
61.5Cu-35.5Zn-3Pb

Commercial Names

Previous trade name. Free-cutting brass
Common name. Free-turning brass, free-cutting yellow brass, high-leaded brass

Specifications

AMS. 4610
ASTM. B 16
SAE. J463
Government. Flat products: QQ-B-613. Bar, forgings, rod, shapes, strip: QQ-B-626

Chemical Composition

Composition limits. 60.0 to 63.0 Cu, 2.5 to 3.7 Pb, 0.35 Fe max, 0.5 max other (total), bal Zn

Applications

Typical uses. Hardware: gears, pinions. Industrial: automatic high-speed screw machine parts

Mechanical Properties

Tensile properties. See Table 68 and Fig. 38.
Hardness. See Table 68.
Elastic modulus. Tension, 97 GPa (14 × 10^6 psi); shear, 37 GPa (5.3 × 10^6 psi)
Fatigue strength. Rotating-beam tests on 90 mm (0.350 in.) diam specimens taken from 50 mm (2 in.) diam rod. H02 temper (cold drawn 15%): 140 MPa (20 ksi) at 10^8 cycles; 97 MPa (14 ksi) at 3 × 10^8 cycles

Structure

Microstructure. Generally three phase: α, β, and lead

Mass Characteristics

Density. 8.5 g/cm^3 (0.307 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 900 °C (1660 °F)
Solidus temperature. 885 °C (1630 °F)
Coefficient of linear thermal expansion. 20.5 μm/m · K (11.4 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 115 W/m · K (67 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, O61 temper, 26% IACS at 20 °C (68 °F)
Electrical resistivity. 66 nΩ · m at 20 °C (68 °F)

Table 67 Typical mechanical properties of 1 mm (0.04 in.) thick C35600 sheet and strip

	Tensile strength		Yield strength(a)		Elongation in 50 mm (2 in.), %	Hardness	
Temper	MPa	ksi	MPa	ksi		HRB	HR30T
OS035	340	49	115	17	50	68 HRF	31
H01	370	54	275	40	35	55	54
H02	420	61	345	50	20	70	65
H04	510	74	415	60	7	80	69

(a) At 0.5% extension under load

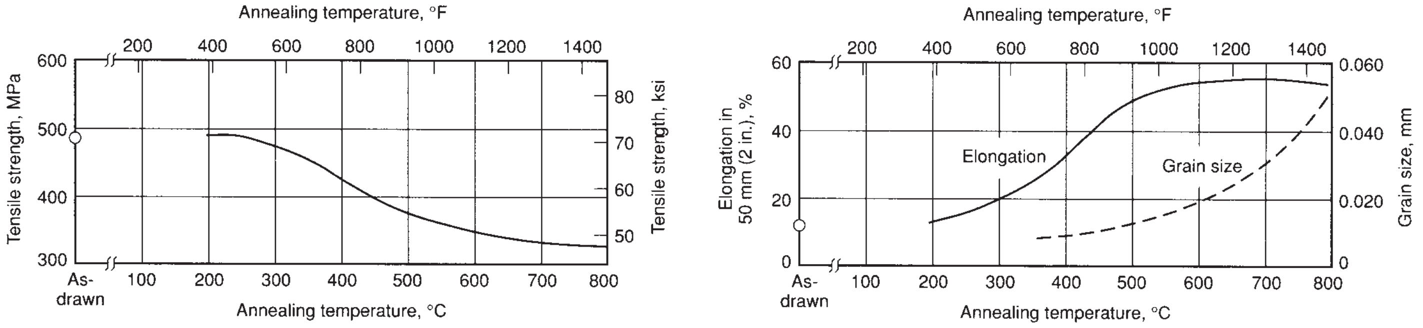

Fig. 38 Annealing curves for C36000. Data are for free-cutting brass rod, cold drawn 30% to 19 mm (0.75 in.) in diameter from M30 temper (as-extruded) starting stock, then annealed 1 h at temperature

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Fabrication Characteristics

Machinability. 100%. This is the standard material against which the machining qualities of all other copper alloys are judged.
Formability. Cold working, poor; hot forming, fair
Weldability. Soldering: excellent. Brazing: good. Resistance butt welding: fair. All other welding processes are not recommended.
Recrystallization temperature. 330 °C (625 °F)
Annealing temperature. 425 to 600 °C (800 to 1100 °F). See also Fig. 38.
Hot-working temperature. 700 to 800 °C (1300 to 1450 °F)

C36500, C36600, C36700, C36800
60Cu-39.4Zn-0.6Pb

Commercial Names

Previous trade name. C36500, uninhibited leaded Muntz metal; C36600, arsenical leaded Muntz metal; C36700, antimonial leaded Muntz metal; C36800, phosphorized leaded Muntz metal
Common name. Leaded Muntz metal; inhibited leaded Muntz metal

Specifications

ASME. Plate, condenser tube: SB171
ASTM. Plate, condenser tube: B 171. Plate, clad: B 432

Chemical Composition

Composition limits. 58.0 to 61.0 Cu, 0.4 to 0.9 Pb, 0.15 Fe max, 0.25 Sn max; As, Sb, or P (see below); 0.1 max other (total), bal Zn
Antimony or phosphorus limits. C36500, none specified; C36600, 0.02 to 0.1 As; C36700, 0.02 to 0.1 Sb; C36800, 0.02 to 0.1 P

Applications

Typical uses. Main tube sheets for condensers and heat exchangers; support sheets; baffles

Mechanical Properties

Tensile properties. 25 mm (1 in.) plate, M20 temper: tensile strength, 370 MPa (54 ksi); yield strength (0.5% extension), 140 MPa (20 ksi); elongation, 45% in 50 mm (2 in.)
Shear strength. M20 temper: 275 MPa (40 ksi)
Hardness. M20 temper: 80 HRF
Elastic modulus. Tension, 105 GPa (15×10^6 psi); shear, 39 GPa (5.6×10^6 psi)

Structure

Crystal structure. Face-centered cubic
Microstructure. Alpha and β with undissolved lead. Beta phase appears lemon yellow with ammonia peroxide etch; it may be darkened with ferric chloride etch. Lead appears as insoluble gray particles randomly distributed throughout the structure.

Mass Characteristics

Density. 8.41 g/cm^3 (0.304 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 900 °C (1650 °F)
Solidus temperature. 885 °C (1630 °F)
Coefficient of linear thermal expansion. 20.8 μm/m · K (11.6 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 123 W/m · K (71 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, O61 temper: 28% IACS at 20 °C (68 °F)
Electrical resistivity. 62 nΩ · m at 20 °C (68 °F)

Chemical Properties

General corrosion behavior. Good resistance to corrosion in both fresh and salt water. C36500 is the uninhibited alloy and is subject to dezincification; the inhibited alloys each contain 0.02 to 0.10% of an inhibitor element (As, Sb, or P), which imparts high resistance to dezincification.

Fabrication Characteristics

Machinability. 60% of C36000 (free-cutting brass)
Formability. Cold working, fair; hot working, excellent
Weldability. Soldering: excellent. Brazing: good. Oxyfuel gas, gas-shielded arc, and resistance butt welding: fair. All other welding processes are not recommended.
Annealing temperature. 425 to 600 °C (800 to 1100 °F)
Hot-working temperature. 625 to 800 °C (1150 to 1450 °F)

C37000
60Cu-39Zn-1Pb

Commercial Names

Previous trade name. Free-cutting Muntz metal

Specifications

ASTM. Tube: B 135
Government. Flat products: QQ-B-613. Bar, forgings, rod, strip: QQ-B-626. Tube: MIL-T-46072

Chemical Composition

Composition limits. 59.0 to 62.0 Cu, 0.9 to 1.4 Pb, 0.15 Fe max, 0.5 max other (total), bal Zn

Applications

Typical uses. Automatic screw machine parts

Mechanical Properties

Tensile properties. See Table 69.
Hardness. See Table 69.
Elastic modulus. Tension, 105 GPa (15×10^6 psi); shear, 39 GPa (5.6×10^6 psi)

Mass Characteristics

Density. 8.41 g/cm^3 (0.304 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 900 °C (1650 °F)
Solidus temperature. 885 °C (1630 °F)
Coefficient of linear thermal expansion. 20.8 μm/m · K (11.6 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 375 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 120 W/m · K (69 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, O61 temper: 27% IACS at 20 °C (68 °F)
Electrical resistivity. 63.9 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 70% of C36000 (free-cutting brass)

Table 68 Typical mechanical properties of C36000

	Tensile strength		Yield strength(a)		Elongation in 50 mm (2 in.), %	Reduction in area, %	Hardness, HRB	Shear strength	
Temper	MPa	ksi	MPa	ksi				MPa	ksi
Rod, 6 mm, (0.25 in.) diameter									
H02(b)	470	68	360	52	18	48	80	260	38
Rod, 25 mm (1 in.) diameter									
O61	340	49	125	18	53	58	68 HRF	205	30
H02(c)	400	58	310	45	25	50	78	235	34
Rod, 50 mm (2 in.) diameter									
H02(d)	380	55	305	44	32	52	75	220	32
Shapes									
M30	340	49	125	18	50	…	68 HRF	205	30
H01(e)	385	56	310	45	20	…	62	230	33

(a) 0.5% extension under load. (b) Cold drawn 25%. (c) Cold drawn 20%. (d) Cold drawn 18%. (e) Cold drawn 15%

Table 69 Typical mechanical properties of C37000

	Tensile strength		Yield strength(a)		Elongation in 50 mm (2 in.), %	Hardness	
Temper	MPa	ksi	MPa	ksi		HRB	HR30T
Tube, 38 mm (1.5 in.) outside diameter × 3 mm (0.125 in.) wall thickness							
O50	370	54	140	20	40	80 HRF	43
H80(b)	550	80	415	60	6	85	74
Tube, 50 mm (2 in.) outside diameter × 6 mm (0.25 in.) wall thickness							
H80(c)	485	70	310	45	10	75	67

(a) At 0.5% extension under load. (b) Cold drawn 35%. (c) Cold drawn 25%

Weldability. Soldering: excellent. Brazing: good. Resistance butt welding: fair. All other welding processes are not recommended.
Annealing temperature. 425 to 600 °C (800 to 1100 °F)
Hot-working temperature. 625 to 800 °C (1150 to 1450 °F)

C37700
60Cu-38Zn-2Pb

Commercial Names

Previous trade name. Forging brass

Specifications

AMS. Die forgings, forging rod: 4614
ASME. Die forgings: SB283
ASTM. Bar, forging, rod, shapes: B 124. Die forgings: B 283
SAE. Die forgings: J463
Government. QQ-B-626. Die forgings: MIL-C-13351

Chemical Composition

Composition limits. 58.0 to 62.0 Cu, 1.5 to 2.5 Pb, 0.3 Fe max, 0.5 max other (total), bal Zn

Applications

Typical uses. Forgings and pressings of all kinds

Mechanical Properties

Tensile properties. M30 temper: tensile strength, 360 MPa (52 ksi); yield strength (0.5% extension), 140 MPa (20 ksi); elongation, 45% in 50 mm (2 in.). See Fig. 39 and 40.
Hardness. M30 temper: 78 HRF. See also Fig. 39 and 40.

LIVE GRAPH
Click here to view

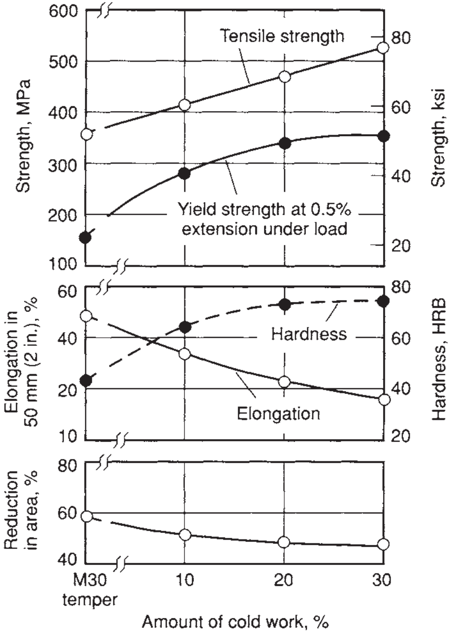

Fig. 39 Typical mechanical properties of extruded and drawn C37700. Data are for forging brass rod less than 25 mm (1 in.) in diameter that was extruded, then cold drawn to various percentages of reduction in area.

Elastic modulus. Tension, 105 GPa (15 × 10^6 psi); shear, 39 GPa (5.6 × 10^6psi)

Structure

Crystal structure. Face-centered cubic
Microstructure. Two phase: α and β, with undissolved lead. Beta phase appears lemon yellow with ammonia peroxide etch. Ferric chloride darkens β phase. Lead appears as gray particles.

Mass Characteristics

Density. 8.44 g/cm^3 (0.305 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 895 °C (1640 °F)
Solidus temperature. 880 °C (1620 °F)
Coefficient of linear thermal expansion. 20.7 μm/m · K (11.5 μin./in · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 120 W/m · K (69 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 27% IACS at 20 °C (68 °F)
Electrical resistivity. 64 nΩ · m at 20 °C (68 °F)

Magnetic Properties

Magnetic susceptibility. Nonmagnetic

Optical Properties

Color. Golden hue compared to yellow of C26000 (cartridge brass)

Fabrication Characteristics

Machinability. 80% of C36000 (free-cutting brass)

LIVE GRAPH
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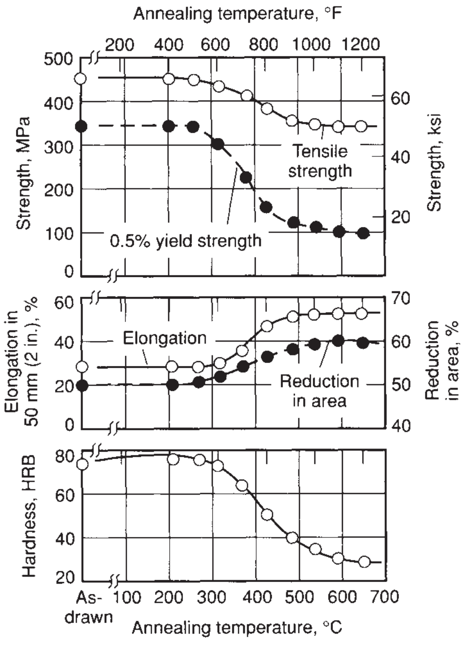

Fig. 40 Annealing curves for C37700. Typical data are for forging brass rod less than 25 mm (1 in.) in diameter that was extruded, cold drawn 18%, and annealed 1 h at various temperatures.

Forgeability. 100%. This is the standard material against which the forging qualities of all other copper alloys are judged.
Formability. Cold working, poor; hot forming, excellent
Weldability. Soldering: excellent. Brazing: good. Resistance butt welding: fair. All other welding processes are not recommended.
Annealing temperature. 425 to 600 °C (800 to 1100 °F). See also Fig. 40.
Hot-working temperature. 650 to 825 °C (1200 to 1500 °F)

C38500
57Cu-40Zn-3Pb

Commercial Names

Previous trade name. Architectural bronze

Specifications

ASTM. Shapes: B 455

Chemical Composition

Composition limits. 55.0 to 60.0 Cu, 2.0 to 3.8 Pb, 0.35 Fe max, 0.5 max other (total), bal Zn

Applications

Typical uses. Architectural: extrusions, storefronts, thresholds, and trim. Hardware: butts, hinges, and lock bodies. Industrial: forgings

Mechanical Properties

Tensile properties. M30 temper: tensile strength, 415 MPa (60 ksi); yield strength (0.5% extension), 140 MPa (20 ksi); elongation, 30% in 50 mm (2 in.)
Shear strength. M30 temper: 240 MPa (35 ksi)
Hardness. M30 temper: 65 HRB
Elastic modulus. Tension, 97 GPa (14 × 10^6 psi); shear, 37 GPa (5.3 × 10^6 psi)

Mass Characteristics

Density. 8.47 g/cm^3 (0.306 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 890 °C (1630 °F)
Solidus temperature. 875 °C (1610 °F)
Coefficient of linear thermal expansion. 20.9 μm/m · K (11.6 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 123 W/m · K (71 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, O61 temper: 28% IACS at 20 °C (68 °F)
Electric resistivity. 62 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 90% of C36000 (free-cutting brass)
Formability. Cold working, poor; hot forming, excellent
Weldability. Soldering: excellent. Brazing: good. Resistance butt welding: fair. All other welding processes are not recommended.

Annealing temperature. 425 to 600 °C (800 to 1100 °F)
Hot-working temperature. 625 to 725 °C (1150 to 1350 °F)

C40500
95Cu-4Zn-1Sn

Commercial Names

Trade name. High-conductivity bronze
Common name. Penny bronze

Specifications

ASTM. B 591

Chemical Composition

Composition limits. 94 to 96 Cu, 0.7 to 1.3 Sn, 0.05 Pb max, 0.05 Fe max, bal Zn

Applications

Typical uses. Meter clips, terminals, fuse clips, contact springs, relay springs, washers from rolled strip, rolled bar, sheet

Mechanical Properties

Tensile properties. See Table 70.
Shear strength. See Table 70.
Hardness. See Table 70.
Elastic modulus. Tension: hard, 110 GPa (16 × 10^6 psi); annealed, 125 GPa (18 × 10^6 psi)

Mass Characteristics

Density. 8.83 g/cm^3 (0.319 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1060 °C (1940 °F)
Solidus temperature. 1025 °C (1875 °F)
Thermal conductivity. 165 W/m · K (95 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 41% IACS at 20 °C (68 °F)
Electrical resistivity. 42 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Formability. Excellent for cold working; good for hot forming
Weldability. Soldering and brazing: excellent. Gas-shielded arc and resistance spot and butt welding: good. Oxyacetylene and resistance seam welding: fair. Coated metal arc welding is not recommended.
Annealing temperature. 510 to 670 °C (950 to 1240 °F)
Hot-working temperature. 830 to 890 °C (1525 to 1635 °F)

C40800
95Cu-2Sn-3Zn

Specifications

ASTM. Flat products: B 591

Chemical Composition

Composition limits. 94 to 96 Cu, 1.8 to 2.2 Sn, 0.05 Pb max, 0.05 Fe max, bal Zn

Applications

Typical uses. Rolled strip for electrical connectors

Mechanical Properties

Tensile properties. See Table 71.
Shear strength. See Table 71.
Hardness. See Table 71.
Elastic modulus. Tension: hard, 110 GPa (16 × 10^6 psi); shear, 41 GPa (6 × 10^6 psi)

Mass Characteristics

Density. 8.86 g/cm^3 (0.320 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1054 °C (1930 °F)
Solidus temperature. 1038 °C (1900 °F)
Coefficient of linear thermal expansion. 18.2 μm/m · K (10.1 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 160 W/m · K (92 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 37% IACS at 20 °C (68 °F)
Electrical resistivity. 46.6 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Formability. Excellent for cold working; fair for hot forming
Weldability. Soldering and brazing: excellent. Oxyacetylene, gas-shielded arc, and resistance butt welding: good. Resistance spot and seam welding are not recommended.
Annealing temperature. 450 to 675 °C (850 to 1250 °F)
Hot-working temperature. 830 to 890 °C (1525 to 1635 °F)

Table 70 Typical mechanical properties of C40500

			Yield strength								
	Tensile strength		At 0.5% extension under load		At 0.2% offset		Elongation in 50 mm (2 in.), %	Hardness		Shear strength	
Temper	MPa	ksi	MPa	ksi	MPa	ksi		HRB	HR30T	MPa	ksi
Flat products, 1 mm (0.04 in.) thick											
OS035	270	39	83	12	69	10	49	55 HRF	10	215	31
OS025	280	41	83	12	76	11	48	58 HRF	13	230	33
OS015	290	42	90	13	97	14	47	64 HRF	24	230	33
H01	325	47	250	36	250	36	30	46	47	240	35
H02	360	52	295	43	345	50	15	60	56	255	37
H03	400	58	340	49	385	56	12	67	62	260	38
H04	440	64	380	55	425	62	10	72	65	270	39
H06	475	69	415	60	460	67	7	76	69	280	41
H08	510	74	435	63	495	72	4	79	71	295	43
H10	540	78	485	70	525	76	3	82	72	310	45

Table 71 Typical mechanical properties of C40800

			Yield strength								
	Tensile strength		At 0.5% extension under load		At 0.2% offset		Elongation in 50 mm (2 in.), %	Hardness		Shear strength	
Temper	MPa	ksi	MPa	ksi	MPa	ksi		HRB	HR30T	MPa	ksi
OS035	290	42	90	13	…	…	43	60 HRF	22	230	33
OS025	305	44	97	14	…	…	43	65 HRF	26	235	34
OS015	310	45	105	15	…	…	42	69 HRF	31	235	34
H01	345	50	270	39	310	45	24	50	54	250	36
H02	370	54	315	46	380	55	12	65	62	260	38
H03	425	62	360	52	415	60	6	72	67	280	41
H04	460	67	395	57	485	70	5	76	70	295	43
H06	505	73	420	61	540	78	4	82	73	310	45
H08	545	79	455	66	565	82	3	85	77	330	48
H10	545 min	79 min	515	75	580	84	3	84 min	75 min	340	49

Note: Values for flat products, 1 mm (0.04 in.) thick

C41100
91Cu-8.5Zn-0.5Sn

Commercial Names

Previous trade name. Lubaloy

Specifications

ASTM. Flat products: B 508, B 591. Wire: B 105

Chemical Composition

Composition limits. 89 to 93 Cu, 0.3 to 0.7 Sn, 0.1 Pb max, 0.05 Fe max, bal Zn

Applications

Typical uses. Rolled strip; rolled bar, rod, and sheet for bushings, bearing sleeves, thrust washers, terminals, connectors, flexible metal hose, and electrical conductors

Mechanical Properties

Tensile properties. See Table 72.
Hardness. See Table 72.
Elastic modulus. Tension: hard, 115 GPa (16.7 × 10^6 psi); annealed, 125 GPa (18 × 10^6 psi). Shear, 46 GPa (6.7 × 10^6 psi)

Mass Characteristics

Density. 8.80 g/cm^3 (0.318 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1040 °C (1905 °F)
Solidus temperature. 1020 °C (1870 °F)
Coefficient of linear thermal expansion. 18 μm/m · K (10 μin./in. · °F) at 20 to 100 °C (68 to 212 °F)
Thermal conductivity. 130 W/m · K (75 Btu/ft · h · °F) at 20 °C (68 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 32% IACS at 20 °C (68 °F)
Electrical resistivity. 54 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Formability. Excellent for cold working; good for hot forming
Weldability. Soldering: excellent. Gas-shielded arc welding and resistance butt welding: good. Brazing, oxyacetylene, and resistance spot welding: fair. Coated metal arc and resistance seam welding are not recommended.
Annealing temperature. 500 to 700 °C (930 to 1290 °F)
Hot-working temperature. 830 to 890 °C (1525 to 1635 °F)

C41500
91Cu-7.2Zn-1.8Sn

Specifications

ASTM. B 591

Chemical Composition

Composition limits. 89 to 93 Cu, 1.5 to 2.2 Sn, 0.1 Pb max, 0.05 Fe max, bal Zn

Applications

Typical uses. Rolled strip for spring applications for electrical switches

Mechanical Properties

Tensile properties. See Table 73.
Hardness. See Table 73.
Elastic modulus. Tension: hard, 110 GPa (16 × 10^6 psi); annealed, 125 GPa (18 × 10^6 psi). Shear, 46 GPa (6.7 × 10^6 psi)

Mass Characteristics

Density. 8.80 g/cm^3 (0.318 lb/in.^{3}) at 20 °C (68 °F)

Table 72 Typical mechanical properties of C41100

			Yield strength								
	Tensile strength		At 0.5% extension under load		At 0.2% offset		Elongation in 50 mm (2 in.), %	Hardness		Shear strength	
Temper	MPa	ksi	MPa	ksi	MPa	ksi		HRB	HR30T	MPa	ksi
Flat products, 1 mm (0.04 in.) thick											
OS050	260	38	76	11	62	9	44	58 HRF	…	220	32
OS035	270	39	76	11	83	12	43	60 HRF	…	230	33
OS025	280	41	83	12	97	14	41	68 HRF	…	…	…
OS015	290	42	83	12	105	15	40	71 HRF	…	235	34
H01	330	48	260	38	280	41	23	52	58	…	…
H02	380	55	325	47	365	53	14	62	60	250	36
H03	415	60	360	52	400	58	6	70	66	…	…
H04	455	66	380	55	440	64	5	76	69	275	40
H06	495	72	415	60	485	70	4	78	71	…	…
H08	540	78	485	70	515	75	3	81	72	…	…
H10	550	80	495	72	525	76	2	83	73	…	…
Wire, 6 mm (0.25 in.) diameter											
H80 (70%)	560	81	…	…	…	…	2(a)	…	…	…	…
Wire, 3 mm (0.10 in.) diameter											
H80 (95%)	705	102	…	…	…	…	1(b)	…	…	…	…
Wire, 1 mm (0.05 in.) diameter											
H80 (98.7%)	730	106	…	…	…	…	0.9(b)	…	…	…	…

(a) Elongation in 254 mm (10 in.). (b) Elongation in 1500 mm (60 in.)

Table 73 Typical mechanical properties of C41500

			Yield strength								
	Tensile strength		At 0.5% extension under load		At 0.2% offset		Elongation in 50 mm (2 in.), %	Hardness		Fatigue strength	
Temper	MPa	ksi	MPa	ksi	MPa	ksi		HRB	HR30T	MPa	ksi
OS035	315	46	115	17	125	18	44	64 HRF	24	240	35
OS025	…	…	…	…	…	…	…	68 HRF	29	…	…
OS015	345	50	180	26	185	27	42	74 HRF	36	250	36
H01	345	50	280	41	…	…	28	62	58	…	…
H02	385	56	365	53	370	54	16	74	65	280	41
H03	435	63	…	…	…	…	…	78	68	290	42
H04	485	70	450	65	455	66	5	83	72	305	44
H06	525	76	490	71	515	75	4	86	73	305	44
H08	560	81	505	73	570	83	3	90	75	345	50
H10	560 min	81 min	515	75	605	88	2	89 min	74 min	360	52

Note: Values for flat products, 1 mm (0.04 in.) thick

Thermal Properties

Liquidus temperature. 1032 °C (1890 °F)
Solidus temperature. 1010 °C (1850 °F)
Coefficient of linear thermal expansion. 18.6 µm/m · K (10.3 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 123 W/m · K (71 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 28% IACS at 20 °C (68 °F)
Electrical resistivity. 62 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 30% of C36000 (free-cutting brass)
Formability. Excellent for cold working; fair for hot forming
Weldability. Soldering and brazing: excellent. Oxyacetylene, gas-shielded arc, and resistance butt welding: good. Resistance spot welding: fair. Coated metal arc and resistance seam welding are not recommended.
Annealing temperature. 400 to 705 °C (750 to 1300 °F)
Hot-working temperature. 730 to 845 °C (1350 to 1550 °F)

C41900
90.5Cu-4.35Zn-5.15Sn

Commercial Names

Previous trade name. CA419
Common name. Tin brass

Chemical Composition

Composition limits. 89 to 92 Cu, 4.8 to 5.5 Sn, 0.10 Pb max, 0.05 Fe max, bal Zn

Applications

Typical uses. Electrical connectors

Mechanical Properties

Tensile properties. See Table 74.
Hardness. See Table 74.
Elastic modulus. Tension, 125 GPa (18 × 10^6 psi)

Mass Characteristics

Density. 8.80 g/cm^3 (0.318 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1025 °C (1880 °F)
Solidus temperature. 1000 °C (1830 °F)
Coefficient of linear thermal expansion. 18.7 µm/m · K (10.4 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Thermal conductivity. 100 W/m · K (58 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 22% IACS at 20 °C (68 °F)
Electrical resistivity. 78 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Annealing temperature. 480 to 680 °C (900 to 1250 °F)

C42200
87.5Cu-11.4Zn-1.1Sn

Commercial Names

Previous trade name. Lubronze

Specifications

ASTM. B 591

Chemical Composition

Composition limits. 86.0 to 89.0 Cu, 0.8 to 1.4 Sn, 0.35 P max, 0.05 Pb max, 0.05 Fe max, bal Zn

Applications

Typical uses. Rolled strip, rolled bar and sheet for sash chains, terminals, fuse clips, spring washers, contact springs, and electrical connectors

Mechanical Properties

Tensile properties. See Table 75.
Hardness. See Table 75.
Elastic modulus. Tension: hard, 110 GPa (16 × 10^6 psi); annealed, 125 GPa (18 × 10^6 psi)

Mass Characteristic

Density. 8.80 g/cm^3 (0.318 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1040 °C (1905 °F)
Solidus temperature. 1020 °C (1870 °F)
Thermal conductivity. 130 W/m · K (75 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 31% IACS at 20 °C (68 °F)
Electrical resistivity. 55 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 30% of C36000 (free-cutting brass)
Formability. Excellent for cold working, good for hot forming
Weldability. Soldering and gas-shielded arc welding: excellent. Resistance spot and butt welding: good. Resistance seam welding and brazing: fair. Oxyacetylene welding is not recommended.
Annealing temperature. 500 to 675 °C (930 to 1250 °F)
Hot-working temperature. 830 to 890 °C (1525 to 1635 °F)

C42500
88.5Cu-9.5Zn-2Sn

Specifications

ASTM. B 591

Chemical Composition

Composition limits. 87 to 90 Cu, 1.5 to 3.0 Sn, 0.35 P max, 0.05 Pb max, 0.05 Fe max, bal Zn

Applications

Typical uses. Rolled strip, rolled bar and sheet for electrical switch springs, terminals, connectors, fuse clips, pen clips, and weather stripping

Table 74 Typical mechanical properties of C41900 strip

	Tensile strength		Yield strength at 0.2% offset			
Temper	MPa	ksi	MPa	ksi	Elongation in 50 mm (2 in.), %	Hardness, HRB
O61	340	49	130	19	42	67 HRF
H01	400	58	315	46	25	64
H02	470	68	395	57	14	73
H03	515	75	450	65	5	78
H04	565	82	510	74	4	87
H06	640	93	530	77	3	92
H08	705	102	550	80	2	95

Table 75 Typical mechanical properties of C42200

			Yield strength						
	Tensile strength		At 0.5% extension under load		At 0.2% offset			Hardness	
Temper	MPa	ksi	MPa	ksi	MPa	ksi	Elongation in 50 mm (2 in.), %	HRB	HR30T
OS035	295	43	105	15	97	14	46	65 HRF	27
OS025	305	44	110	16	105	15	45	70 HRF	31
OS015	315	46	115	17	130	19	44	75 HRF	40
H01	360	52	275	40	270	39	30	56	54
H02	415	60	350	51	395	57	12	70	64
H03	455	66	380	55	440	64	6	77	68
H04	505	73	450	65	485	70	4	81	70
H06	550	80	470	68	525	76	3	84	72
H08	600	87	505	73	560	81	2	87	73
H10	605 min	88 min	515	75	580	84	2	86 min	74 min

Note: Values for flat products, 1 mm (0.04 in.) thick

Mechanical Properties

Tensile properties. See Table 76.
Hardness. See Table 76.
Elastic modulus. Tension: hard, 110 GPa (16 × 10^6 psi); annealed, 125 GPa (18 × 10^6 psi)

Mass Characteristics

Density. 8.78 g/cm^3 (0.317 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1030 °C (1890 °F)
Solidus temperature. 1010 °C (1850 °F)
Coefficient of linear thermal expansion. 18.4 μm/m · K (10.2 μin./in. · °F) at 20 to 100 °C (68 to 212 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 120 W/m · K (69 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 28% IACS at 20 °C (68 °F)
Electrical resistivity. 62 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 30% of C36000 (free-cutting brass)
Formability. Excellent for cold working; fair for hot forming
Weldability. Soldering and brazing: excellent. Oxyacetylene, gas-shielded arc and resistance butt welding: good. Coated metal arc and resistance spot and seam welding are not recommended.
Annealing temperature. 425 to 700 °C (800 to 1300 °F)
Hot-working temperature. 790 to 840 °C (1455 to 1545 °F)

C43000
87Cu-10.8Zn-2.2Sn

Specifications

ASTM. Flat products: B 591

Chemical Composition

Composition limits. 84 to 87 Cu, 1.7 to 2.7 Sn, 0.10 Pb max, 0.05 Fe max, bal Zn

Applications

Typical uses. Rolled strip and sheet for electrical switches, springs, fuse and pen clips, and weather stripping

Mechanical Properties

Tensile properties. See Table 77.
Hardness. See Table 77.
Elastic modulus. Tension, 110 GPa (16 × 10^6 psi); shear, 119 GPa (17.3 × 10^6 psi)

Mass Characteristics

Density. 8.75 g/cm^3 (0.316 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1025 °C (1877 °F)
Solidus temperature. 1000 °C (1832 °F)
Coefficient of linear thermal expansion. 18.4 μm/m · K (10.2 μin./in. · °F) at 20 to 100 °C (68 to 212 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 119 W/m · K (69 Btu/ft · h · °F)

Electrical Properties

Electrical conductivity. Volumetric, 27% IACS at 20 °C (68 °F)
Electrical resistivity. 64 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 30% of C36000 (free-cutting brass)
Formability. Excellent for cold working; good for hot forming
Weldability. Soldering and brazing: excellent. Oxyacetylene, gas-shielded arc, and resistance butt welding: good. Resistance spot welding: fair. Coated metal arc and resistance seam welding are not recommended.
Annealing temperature. 425 to 700 °C (800 to 1300 °F)
Hot-working temperature. 790 to 840 °C (1455 to 1545 °F)

C43400
85Cu-14.3Zn-0.7Sn

Specifications

ASTM. Flat products: B 591

Chemical Composition

Composition limits. 84 to 87 Cu, 0.4 to 1.0 Sn, 0.05 Pb max, 0.05 Fe max, bal Zn

Applications

Typical uses. Rolled strip for electrical uses: switch parts, blades, relay springs, contacts

Mechanical Properties

Tensile properties. See Table 78.
Shear strength. See Table 78.
Hardness. See Table 78.
Elastic modulus. Tension: hard, 110 GPa (16 × 10^6 psi); annealed, 40 GPa (6 × 10^6 psi)

Mass Characteristics

Density. 8.75 g/cm^3 (0.316 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1020 °C (1870 °F)
Solidus temperature. 990 °C (1810 °F)
Coefficient of linear thermal expansion. 18.9 μm/m · K (10.5 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · h · °F) at 20 °C (68 °F)
Thermal conductivity. 137 W/m · K (79 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 31% IACS at 20 °C (68 °F)
Electrical resistivity. 56 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 30% of C36000 (free-cutting brass)
Formability. Excellent for cold working; fair for hot forming
Weldability. Soldering and brazing: excellent. Oxyacetylene, gas-shielded arc, and resistance spot and butt welding: good. Resistance seam welding is not recommended.
Annealing temperature. 425 to 675 °C (800 to 1250 °F)
Hot-working temperature. 815 to 870 °C (1500 to 1600 °F)

Table 76 Typical mechanical properties of C42500

			Yield strength						
	Tensile strength		At 0.5% extension under load		At 0.2% offset			Hardness	
Temper	MPa	ksi	MPa	ksi	MPa	ksi	Elongation in 50 mm (2 in.), %	HRB	HR30T
OS035	310	45	125	18	105	15	49	70 HRF	32
OS025	315	46	125	18	125	18	48	72 HRF	36
OS015	325	47	135	20	130	19	47	79 HRF	45
H01	370	54	310	45	315	46	35	60	56
H02	435	63	345	50	405	59	20	75	68
H03	470	68	395	57	450	65	15	80	70
H04	525	76	435	63	505	73	9	86	73
H06	565	82	485	70	545	79	7	90	74
H08	615	89	515	75	585	85	4	92	76
H10	635 min	92 min	525	76	615	89	2	92 min	76 min

Note: Values for flat products, 1 mm (0.04 in.) thick

C43500
81Cu-18.1Zn-0.9Sn

Chemical Composition

Composition limits. 79 to 83 Cu, 0.6 to 1.2 Sn, 0.1 Pb max, 0.05 Fe max, 0.15 max other (total), bal Zn

Applications

Typical uses. Rolled strip and tubing for Bourdon tubing and musical instruments

Mechanical Properties

Tensile properties. See Table 79.
Shear strength. See Table 79.
Elastic modulus. Tension, 110 GPa (16 × 10^6 psi); shear, 40 GPa (6 × 10^6 psi)

Mass Characteristics

Density. 8.66 g/cm^3 (0.313 lb/$in.^3$) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1005 °C (1840 °F)
Solidus temperature. 965 °C (1770 °F)
Coefficient of linear thermal expansion. 19.4 µm/m · K (10.8 µin./in. · °F) at 20 °C (68 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 28% IACS at 20 °C (68 °F)
Electrical resistivity. 62 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 30% of C36000 (free-cutting brass)
Formability. Excellent for cold working; good for hot forming
Weldability. Soldering and brazing: excellent. Oxyacetylene and resistance spot and butt welding: good. Gas-shielded metal arc welding: fair. Coated metal arc and resistance seam welding are not recommended.

C44300, C44400, C44500
71Cu-28Zn-1Sn

Commercial Names

Previous trade names. C44300, arsenical admiralty metal; C44400, antimonial admiralty metal; C44500, phosphorized admiralty metal
Common names. Inhibited admiralty metal; admiralty brass

Specifications

ASME. Condenser plate: SB171. Tubing: SB111, SB359, SB395, SB543
ASTM. Condenser plate: B 171. Tubing: B 111, B 359, B 395, B 543

Chemical Composition

Composition limits. 70.0 to 73.0 Cu, 0.07 Pb max, 0.06 Fe max, 0.9 to 1.2 Sn (or 0.8 to 1.2 Sn for flat-rolled products); As, Sb, or P (see below); bal Zn
Arsenic, antimony, or phosphorus limits. C44300, 0.02 to 0.10 As; C44400, 0.02 to 0.10 Sb, C44500, 0.02 to 0.10 P

Applications

Typical uses. Condenser, distiller, and heat exchanger tubes, ferrules, strainers, condenser tube plates
Precautions in use. These three alloys are susceptible to stress-corrosion cracking. Whenever possible, they should be used in the annealed condition. Where fabrication results in residual stresses, a suitable stress-relieving heat treatment should be applied.

Mechanical Properties

Tensile properties. See Table 80 and Fig. 41.
Hardness. See Table 80.

Table 77 Typical mechanical properties of C43000

	Tensile strength		Yield strength(a)		Elongation in 50 mm (2 in.), %	Hardness		
Temper	MPa	ksi	MPa	ksi		HRF	HRB	HR30T
OS035	315	46	125	18	55	69	30	…
OS025	…	…	…	…	…	72	34	…
OS015	…	…	…	…	…	77	39	…
H01	365	53	275	40	44	…	57	57
H02	425	62	380	55	25	…	73	65
H03	495	72	450	65	13	…	79	69
H04	540	78	460	67	10	…	84	73
H06	605	88	485	70	5	…	81	75
H08	650	94	495	72	4	…	91	77
H10	620 min	90 min	505	73	3	…	90 min	75 min

Note: Values for flat products, 1 mm (0.04 in.) thick. (a) At 0.5% extension under load

Table 78 Typical mechanical properties of C43400

	Tensile strength		Yield strength(a)		Elongation in 50 mm (2 in.), %	Hardness		Shear strength	
Temper	MPa	ksi	MPa	ksi		HRB	HR30T	MPa	ksi
OS035	310	45	105	15	49	64 HRF	22	250	36
OS025	315	46	110	16	48	65 HRF	26	255	37
OS015	330	48	115	17	47	70 HRF	30	255	37
H01	360	52	280	41	28	54	55	275	40
H02	405	59	350	51	18	66	63	290	42
H03	470	68	405	59	10	73	68	310	45
H04	510	74	460	67	7	80	71	340	49
H06	580	84	490	71	5	83	74	360	52
H08	620	90	510	74	4	86	76	370	54
H10	605 min	88 min	515	75	3	84 min	74 min	385	56

(a) At 0.5% extension under load

Table 79 Typical mechanical properties of C43500

	Tensile strength		Yield strength(a)		Elongation in 50 mm (2 in.), %	Hardness		Shear strength	
Temper	MPa	ksi	MPa	ksi		HRF	HR30T	MPa	ksi
Flat products, 1 mm (0.04 in.) thick									
OS025	340	49	125	18	46	70	31	250	36
H02	450	65	370	54	16	72 HRB	…	286	41.5
H04	550	80	470	68	7	85 HRB	…	310	45
Tubing, 25 mm (1.0 in.) outside diameter × 1.65 mm (0.065 in.) wall thickness									
OS035	315	46	110	16	46	69	40	…	…
H80 (35%)	515	75	415	60	10	…	…	…	…

(a) At 0.5% extension under load

Elastic modulus. Tension, 110 GPa (16 × 10^6 psi); shear, 40 GPa (6 × 10^6 psi)
Impact strength. See Table 81.
Fatigue strength. 115 to 125 MPa (17 to 18 ksi) at 10^7 cycles
Creep-rupture characteristics. See Table 82.

Mass Characteristics

Density. 8.53 g/cm^3 (0.308 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 935 °C (1720 °F)
Solidus temperature. 900 °C (1650 °F)
Coefficient of linear thermal expansion. 20.2 μm/m · K (11.2 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/ft · °F) at 20 °C (68 °F)
Thermal conductivity. 110 W/m · K (64 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 25% IACS at 20 °C (68 °F)
Electrical resistivity. 69 nΩ · m at 20 °C (68 °F)

Chemical Properties

General corrosion behavior. Good resistance to salt and fresh waters at low velocities. Water velocities above 1.8 m/s (6 ft/s) give rise to impingement attack. A different inhibitor is added to each alloy to protect against dezincification.

Fabrication Characteristics

Machinability. 30% of C36000 (free-cutting brass)
Formability. Excellent for cold working; fair for hot forming
Weldability. Soft soldering: excellent. Silver alloy brazing, oxyfuel gas welding, resistance spot welding, and flash welding: good. Gas-shielded arc welding: fair. Shielded metal arc welding and resistance seam welding are not recommended.
Recrystallization temperature. 300 °C (572 °F) for 1 mm (0.04 in.) strip cold rolled hard (50% reduction) from a grain size of 0.015 mm. See also Fig. 41.
Annealing temperature. 425 to 600 °C (800 to 1100 °F)
Hot-working temperature. 650 to 800 °C (1200 to 1450 °F)

Table 80 Typical mechanical properties of C44300, C44400, and C44500

	Tensile strength		Yield strength(a)		Elongation in 50 mm (2 in.), %	Hardness		
Temper	MPa	ksi	MPa	ksi		HRF	HR15T	HR30T
Tubing, 25 mm (1 in.) outside diameter × 1.65 (0.065 in.) wall thickness								
OS025	365	53	152	22	65	75	…	37
H01	434	63	…	…	45	…	86.5	…
H02	503	73	…	…	29	…	90	78
H03	565	82	…	…	15	…	90	81
H04	669	97	…	…	4	…	93	84
Plate, 25 mm (1 in.) diameter								
M20	330	48	124	18	65	70	…	…
Strip, 1 mm (0.04 in.) diameter								
O60 (0.080 mm)	310	45	90	13	69	59	9	20
O60 (0.015 mm)	330	48	97	14	62	60	9	20
H04	607	88	496	72	4	109	90	76

(a) At 0.5% extension under load. Apparent elastic limit (tubing), 125 MPa (18 ksi)

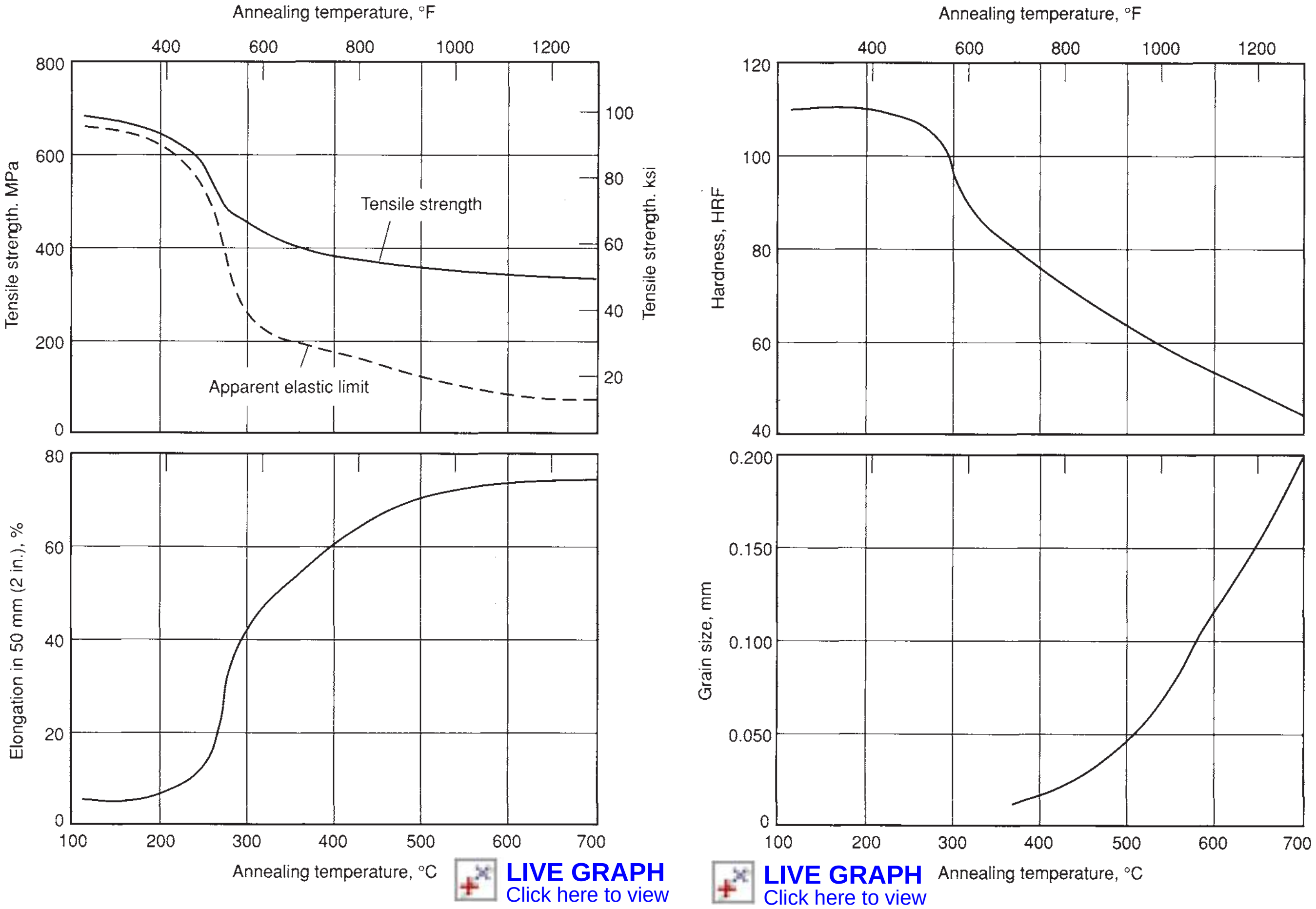

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Fig. 41 Variation of properties and grain size with annealing temperature for C44300, C44400, or C44500. Data for inhibited admiralty metal tubing (71Cu-28Zn–1Sn), cold drawn 50% and annealed 1 h at temperature

Table 81 Typical Charpy impact strength data for C44300, C44400, or C44500

Test temperature		Impact strength	
°C	°F	J	ft · lbf
20	68	82.4	60.8
3	38	82.2	60.6
–18	0	79.7	58.8
–30	–25	82.4	60.8
–50	–60	79.9	58.9
–80	–110	83.4	61.5
–115	–175	80.3	59.2

Note: Annealed specimens, cut from 19 mm (0.75 in.) diam rod into keyhole-notch bars. Values are averages of data from three tests (specimens did not fracture). Tensile strength at 20 °C (68 °F), 320 MPa (46.5 ksi); yield strength, 92 MPa (13.3 ksi); elongation, 83.5%; hardness, 64 HRF

Table 82 Typical creep data for C44300, C44400, or C44500

Temperature		Stress required to produce designated creep in 1000 h							
		Nil(a)		0.01%		0.10%		1.00%	
°C	°F	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi
205	400	69	10	90	13	117	17	130	19
315	600	(b)	(b)	6.9	1.0	13.4	1.95	26	3.8
425	800	(b)	(b)	0.37	0.054	1.1	0.16	3.4	0.5

Note: Values for rod, hot rolled to 22.2 mm (0.875 in.), then cold drawn to 19.0 mm (0.750 in.). (a) No measurable flow. (b) Nearly zero

Table 83 Typical mechanical properties of C46400, C46500, C46600, or C46700

Temper	Tensile strength		Yield strength(a)		Elongation in 50 mm (2 in.), %	Reduction in area, %	Hardness, HRB	Shear strength	
	MPa	ksi	MPa	ksi				MPa	ksi
Flat products, 1 mm (0.04 in.) thick									
O50	427	62	207	30	40	…	60	283	41
H01	483	70	400	58	17	…	75	296	43
Flat products, 6 mm (0.25 in.) thick									
O60	400	58	172	25	49	…	56	275	40
O50	414	60	193	28	45	…	58	283	41
Flat products, 25 mm (1.0 in.) thick									
M20	379	55	172	25	50	…	55	275	40
Rod and bar, 6 mm (0.25 in.) diameter									
O60	400	58	186	27	45	60	56	275	40
O50	434	63	207	30	40	55	60	290	42
H01 (10%)	482	70	331	48	25	50	80	296	43
H02 (20%)	552	80	393	57	20	45	85	310	45
Rod and bar, 25 mm (1.0 in.) diameter									
O60	393	57	172	25	47	60	55	275	40
O50	434	63	207	30	40	55	60	290	42
H01 (8%)	476	69	317	46	27	50	78	296	43
H02 (20%)	517	75	365	53	20	45	82	303	44
Rod and bar, 51 mm (2.0 in.) diameter									
O60	386	56	172	25	47	60	55	275	40
O50	427	62	193	28	43	55	60	290	42
H01 (8%)	462	67	276	40	35	50	75	296	43
Tubing, 9 mm (0.375 in.) outside diameter × 2.5 mm (0.097 in.) wall thickness									
H80 (35%)	607	88	455	66	18	40	95	…	…
O61	427	62	207	30	45	…	25	…	…
Extruded shapes									
M30	400	58	170	25	40	…	…	275	40

(a) At 0.5% extension under load

C46400, C46500, C46600, C46700
60Cu-39.2Zn-0.8Sn

Commercial Names

Previous trade names. C46400, uninhibited naval brass; C46500, arsenical naval brass; C46600, antimonial naval brass; C46700, phosphorized naval brass
Common names. Naval brass; inhibited naval brass

Specifications

AMS. Bar and rod (C46400 only): 4611, 4612
ASME. Condenser plate: SB171
ASTM. Bar, rod, and shapes (C46400 only): B 21, B 124, Forgings (C46400 only): B 283. Condenser plate: B 171
SAE. Bar, rod, and shapes (C46400 only): J461, J463
Government. QQ-B-626. Bar, rod, shapes, forgings, and wire (C46400 only): QQ-B-637. Bar and flat products (C46400 only): QQ-B-639. Tubing (C46400 only): MIL-T-6945

Chemical Composition

Composition limits. 59.0 to 62.0 Cu; 0.50 to 1.0 Sn; 0.20 Pb max; 0.10 Fe max; As, Sb, or P (see below); bal Zn
Arsenic, antimony, or phosphorus limits. C46400, none specified; C46500, 0.02 to 0.10 As; C46600, 0.02 to 0.10 Sb; C46700, 0.02 to 0.10 P

Applications

Typical uses. Condenser plates, welding rod, marine hardware, propeller shafts, valve stems, airplane turnbuckle barrels, balls, nuts, bolts, rivets, fittings

Mechanical Properties

Tensile properties. See Table 83 and Fig. 42.
Shear strength. See Table 83.
Hardness. See Table 83.
Elastic modulus. Tension, 100 GPa (15×10^6 psi); shear, 39 GPa (5.6×10^6 psi)
Impact strength. 43 J (32 ft · lbf) at 21 °C (70 °F) for Charpy keyhole specimens 10 mm (0.4 in.) square machined from annealed plate 13 mm (0.5 in.) thick; plate hardness, 96 HRF
Fatigue strength. 100 MPa (15 ksi) at 3×10^8 cycles

Structure

Crystal structure. Face-centered-cubic α and body-centered-cubic β
Microstructure. Generally two phases: α and β

Mass Characteristics

Density. 8.41 g/cm^3 (0.304 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 900 °C (1650 °F)
Solidus temperature. 885 °C (1630 °F)
Coefficient of linear thermal expansion. 21.2 μm/m · K (11.8 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 116 W/m · K (67 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 26% IACS at 20 °C (68 °F), annealed
Electrical resistivity. 66.3 nΩ · m at 20 °C (68 °F), annealed

Chemical Properties

General corrosion behavior. Good resistance to corrosion in both fresh and salt water; different inhibitor elements are added to C46500, C46600, and C46700 to protect against dezincification.

Fabrication Characteristics

Machinability. 30% of C36000 (free-cutting brass)
Forgeability. 90% of C37700 (forging brass)
Formability. Excellent for hot forming; fair for cold forming
Weldability. Soft soldering and silver alloy brazing: excellent. Oxyfuel gas welding, resistance spot welding, and flash welding: good. Gas-shielded arc welding and resistance seam welding: fair. Shielded arc welding is not recommended.
Recrystallization temperature. About 350 °C (660 °F) for 19 mm (0.75 in.) diam rod cold drawn 30%. See also Fig. 42.
Annealing temperature. 425 to 600 °C (800 to 1100 °F)
Maximum cold reduction between anneals. 30%
Hot-working temperature. 650 to 825 °C (1200 to 1500 °F)

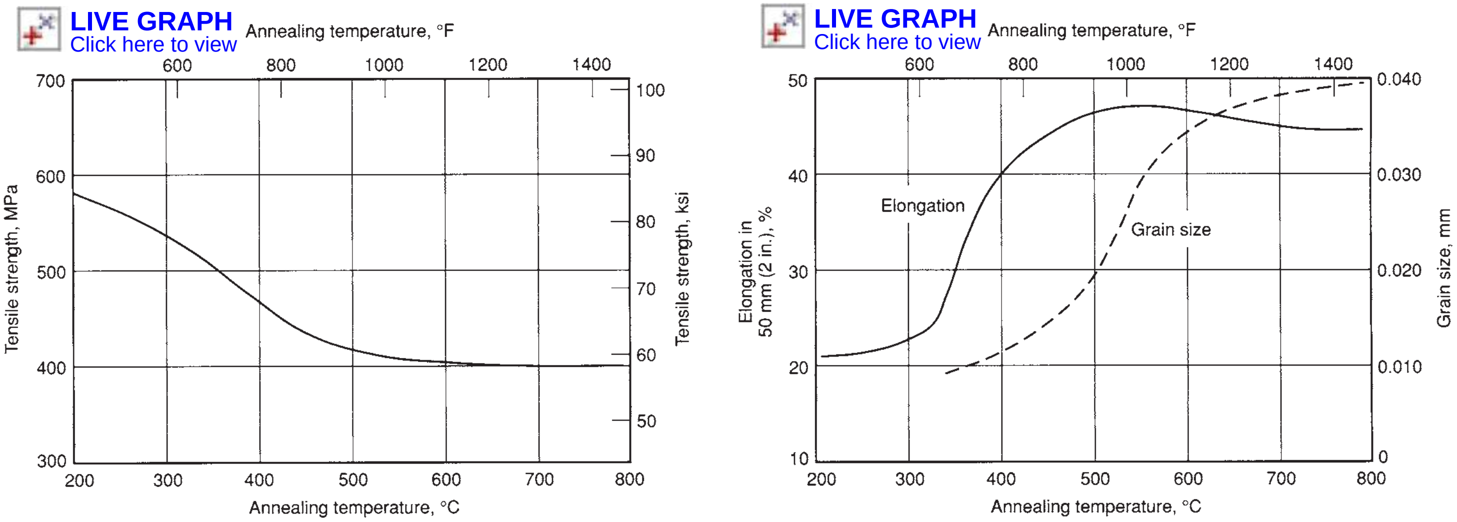

Fig. 42 Variation of strength, ductility, and grain size with annealing temperature for C46400, C46500, C46600, or C46700. Data for 19 mm (0.75 in.) diam naval brass rod (60Cu-39.2Zn–0.8Sn), cold drawn 30% and annealed 1 h at temperature. Grain size before cold drawing, 0.025 mm

C48200
60.5Cu-38Zn-0.8Sn-0.7Pb

Table 84 Typical mechanical properties of C48200

Temper	Tensile strength MPa	Tensile strength ksi	Yield strength(a) MPa	Yield strength(a) ksi	Elongation in 50 mm (2 in.), %	Hardness, HRB	Shear strength MPa	Shear strength ksi
Rod, 25 mm (1.0 in.) diameter								
O60	395	57	170	25	40	55	260	38
O50	435	63	205	30	35	60	270	39
H01 (8%)	475	69	315	46	20	78	275	40
H02 (20%)	515	75	365	53	15	82	285	41
Rod, 51 mm (2.0 in.) diameter								
O60	385	56	170	25	40	55	260	38
O50	425	62	195	28	37	60	270	39
H01 (8%)	460	67	275	40	30	75	275	40
H02 (15%)	485	70	360	52	17	78	285	41
Rod, 76 mm (3.0 in.) diameter								
H01 (4%)	435	63	230	33	43	78	275	40
Bar, 10 mm (0.38 in.) diameter								
M30	435	63	230	33	34	60	270	39
Bar, 38 mm (1.5 in.) diameter								
H01	455	66	275	40	32	75	275	40

(a) At 0.5% extension under load

Commercial Names

Previous trade names. Naval brass, medium leaded; CA482
Common name. Leaded naval brass

Specifications

ASTM. Rod, bar, and shapes: B 21 (CA482), B 124 (C48200)
Government. QQ-B-626. Bar, rod, shapes, forgings, and wire: QQ-B-637. Bar and plate: QQ-B-639

Chemical Composition

Composition limits. 59.0 to 62.0 Cu, 0.40 to 1.0 Pb; 0.10 Fe max, 0.50 to 1.0 Sn, bal Zn

Applications

Typical uses. Marine hardware, screw machine products, valve stems

Mechanical Properties

Tensile properties. See Table 84.
Shear strength. See Table 84.
Hardness. See Table 84.
Elastic modulus. Tension, 100 GPa (15 × 10^6 psi); shear, 39 GPa (5.6 × 10^6 psi)

Structure

Microstructure. Generally three phases: α, β, and lead

Mass Characteristics

Density. 8.44 g/cm^3 (0.305 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 900 °C (1650 °F)
Solidus temperature. 885 °C (1625 °F)
Coefficient of linear thermal expansion. 21.2 μm/m · K (11.8 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 116 W/m · K (67 Btu/ft · h · °F)

Electrical Properties

Electrical conductivity. Volumetric, 26% IACS at 20 °C (68 °F)
Electrical resistivity. 66.3 nΩ · m at 20 °C (68 °F), annealed

Chemical Properties

General corrosion behavior. Good resistance to seawater and marine atmospheres

Fabrication Characteristics

Machinability. 50% of C36000 (free-cutting brass)
Forgeability. 90% of C37700 (forging brass)
Formability. Good for hot working; poor for cold working
Weldability. Soft soldering: excellent. Silver alloy brazing: good. Flash welding: fair. Oxyfuel gas welding, arc welding, and most resistance welding processes are not recommended.
Recrystallization temperature. About 360 °C (680 °F) for 19 mm (0.75 in.) diam rod cold drawn 30%
Annealing temperature. 425 to 600 °C (800 to 1100 °F)
Hot-working temperature. 650 to 760 °C (1200 to 1400 °F)

C48500
60Cu-37.5Zn-1.8Pb-0.7Sn

Commercial Names

Previous trade names. High-leaded naval brass; CA485
Common name. Leaded naval brass

Specifications

ASTM. Rod, bar, and shapes: B 21 (CA482), B 124 (C48500). Forgings: B 283 (CA485)
Government. QQ-B-626. Bar, rod, shapes, forgings, and wire: QQ-B-637. Bar and plate products: QQ-B-639

Chemical Composition

Composition limits. 59.0 to 62.0 Cu, 1.3 to 2.2 Pb; 0.10 Fe max, 0.50 to 1.0 Sn, bal Zn

Applications

Typical uses. Marine hardware, screw-machine products, valve stems

Mechanical Properties

Tensile properties. See Table 85.
Shear strength. See Table 85.
Hardness. See Table 85.
Elastic modulus. Tension, 100 GPa (15 × 10^6 psi); shear, 39 GPa (5.6 × 10^6 psi)

Structure

Microstructure. Generally three phases: α, β, and lead

Mass Characteristics

Density. 8.44 g/cm^3 (0.305 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 900 °C (1650 °F)
Solidus temperature. 885 °C (1625 °F)
Coefficient of linear thermal expansion. 21.2 μm/m · K (11.8 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 116 W/m · K (67 Btu/ft · h · °F)

Electrical Properties

Electrical conductivity. Volumetric, 26% IACS at 20 °C (68 °F)
Electrical resistivity. 66.3 nΩ · m at 20 °C (68 °F)

Chemical Properties

General corrosion behavior. Good resistance to seawater and marine atmospheres

Fabrication Characteristics

Machinability. 70% of C36000 (free-cutting brass)
Forgeability. 90% of C37700 (forging brass)
Formability. Good for hot working; poor for cold working
Weldability. Soft soldering: excellent. Silver alloy brazing: good. Flash welding: fair. Oxyfuel gas welding, arc welding, and most resistance welding processes are not recommended.
Recrystallization temperature. About 360 °C (680 °F) for 19 mm (0.75 in.) diam rod cold drawn 30%. See also Fig. 43.
Annealing temperature. 425 to 600 °C (800 to 1100 °F)
Maximum cold reduction between anneals. 20%
Hot working temperature. 650 to 760 °C (1200 to 1400 °F)

C50500
98.7Cu-1.3Sn

Commercial Names

Previous names. Phosphor bronze, 1.25% E; CA505
Common name. Phosphor bronze (1.25% Sn)

Specifications

ASTM. Strip: B 105. Wire: B 105

Chemical Composition

Composition limits. 1.0 to 1.7 Sn; 0.05 Pb max; 0.10 Fe max; 0.30 Zn max; 0.35 P max; bal Cu; 99.5 Cu + Sn + P min

Applications

Typical uses. Electrical contacts, flexible hose, pole line hardware

Mechanical Properties

Tensile properties. See Table 86.
Hardness. See Table 86.
Elastic modulus. Tension, 117 GPa (17 × 10^6 psi); shear, 44 GPa (6.4 × 10^6 psi)
Fatigue strength. See Table 86.

Mass Characteristics

Density. 8.89 g/cm^3 (0.321 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1075 °C (1970 °F)

Table 85 Typical mechanical properties of C48500

Temper	Tensile strength		Yield strength(a)		Elongation in 50 mm (2 in.), %	Hardness, HRB	Shear strength	
	MPa	ksi	MPa	ksi			MPa	ksi
O60	393	57	172	25	40	55	248	36
H01 (8%)	476	69	317	46	20	78	269	39
H02 (20%)	517	75	365	53	15	82	276	40

Note: Values for rod, 25 mm (1.0 in.) diameter. (a) At 0.5% extension under load.

Table 86 Typical mechanical properties of C50500

Temper	Grain size, mm	Tensile strength		Yield strength(a)		Elongation in 50 mm (2 in.), %	Hardness, HRB	Fatigue strength(b)	
		MPa	ksi	MPa	ksi			MPa	ksi
OS035	0.035	276	40	76	11	47.0	…	114	16.5
OS075	0.015	290	42	90	13	47.0	…	121	17.5
H02	0.035	365	53	352	51	12.0	59.0	162	23.5
	0.015	372	54	359	52	13.0	60.0	172	25
H04	0.035	421	61	414	60	5.0	67.0	179	26
	0.015	441	64	434	63	5.0	69.0	190	27.5
H06	0.035	462	67	455	66	3.0	73.0	172	25
	0.015	483	70	476	69	3.0	75.0	193	28
H08	0.035	483	70	476	69	3.0	76.0	197	28.5
	0.015	510	74	503	73	3.0	78.0	203	29
H10	0.035	510	74	503	73	3.0	79.0	197	28.5
	0.015	524	76	517	75	3.0	80.0	210	30.5

Note: Values for flat products 1 mm (0.040 in.) thick. Data in this table were interpolated from ASTM STP 1. (a) At 0.2% offset. (b) At 10^8 cycles of fully reversed stress

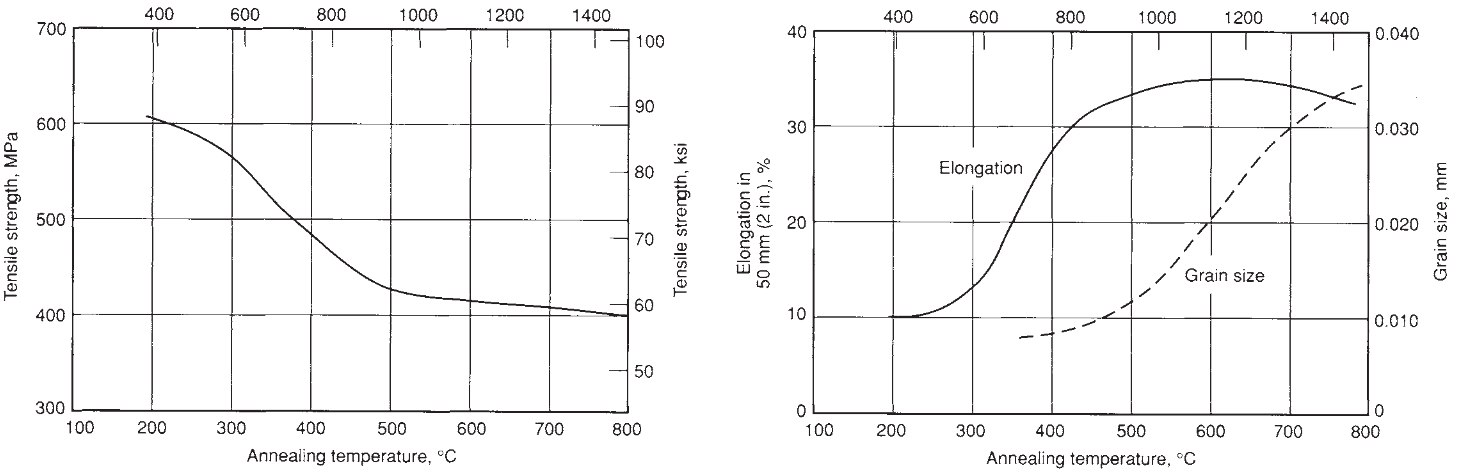

Fig. 43 Variation of strength, ductility, and grain size with annealing temperature for C48500. Data for 19 mm (0.75 in.) diam high-leaded naval brass (60Cu-37.5Zn–1.8Pb–0.7Sn) rod that was cold drawn 30% and annealed 1 h at temperature. Grain size before cold drawing, 0.025 mm

LIVE GRAPH
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Solidus temperature. 1035 °C (1900 °F)
Coefficient of linear thermal expansion. 17.8 µm/m · K (9.9 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 208 W/m · K (120 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 48% IACS at 20 °C (68 °F)
Electrical resistivity. 36 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Formability. Cold: excellent. Hot: good. Commonly fabricated by blanking, forming, bending, heading, upsetting, shearing, squeezing, and swaging
Weldability. Flash welding, soldering, and brazing: excellent. Gas metal arc welding: good. Oxyfuel gas welding and shielded metal arc welding: fair. Other processes are not recommended.
Annealing temperature. 475 to 650 °C (900 to 1200 °F)
Hot-working temperature. 800 to 875 °C (1450 to 1600 °F)

C50710
97.7Cu-2.0Sn-0.3Ni

Chemical Composition

Composition limits. 1.7 to 2.3 Sn, 0.1 to 0.4 Ni, 0.35 P max

Applications

Typical uses. Lead frames

Mechanical Properties

Tensile properties. See Table 87.
Hardness. See Table 87.
Elastic modulus. 113 GPa (16.4 × 10^6 psi)

Mass Characteristics

Density. 8.88 g/cm^3 (0.321 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1065 °C (1950 °F)
Solidus temperature. 995 °C (1820 °F)
Coefficient of linear thermal expansion. 17.0 µm/m · K (9.4 µin./in. · °F) from 20 to 550 °C (68 to 1025 °F)
Thermal conductivity. 154 W/m · K (89 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 30% IACS at 20 °C (68 °F)
Electrical resistivity. 57.4 nΩ · m at 20 °C (68 °F)

Table 87 Nominal mechanical properties of C50710 strip

Temper	Tensile strength		Elongation in 50 mm (2 in.), %	Hardness, HV
	MPa	ksi		
H02	455	66	25	150
H04	540	78	11	168
H06	585	85	9	185

C51000
94.8Cu-5Sn-0.2P

Commercial Names

Previous trade names. Phosphor bronze, 5% A

Specifications

AMS. Flat products: 4510. Bar, rod, tubing: 4625. Wire: 4720
ASTM. Flat products: B 100, B 103. Bar: B 103, B 139. Rod, shapes: B 139. Wire: B 159
SAE. J463
Government. Flat products, bar, shapes: QQ-B-750. Rod: QQ-B-750, MIL-B-13501.Bearings: MIL-B-13501. Wire: QQ-B-750, QQ-W-321, MIL-W-6712

Chemical Composition

Composition limits. 93.6 to 95.6 Cu, 4.2 to 5.8 Sn, 0.03 to 0.35 P, 0.05 Pb max, 0.1 Fe max, 0.3 Zn max

Applications

Typical uses. Architectural: bridge bearing plates. Hardware: beater bars, bellows, Bourdon tubing, clutch disks, cotter pins, diaphragms, fuse clips, fasteners, lock washers, sleeve bushings, springs, switch parts, truss wire, wire brushes. Industrial: chemical hardware, perforated sheets, textile machinery, welding rods

Mechanical Properties

Tensile properties. See Table 88.
Hardness. See Table 88.
Elastic modulus. Tension, 110 GPa (16 × 10^6 psi); shear, 41 GPa (6 × 10^6 psi)
Fatigue structure. At 10^8 cycles. Flat products: H04 temper, 170 MPa (25 ksi); H08 temper, 150 MPa (22 ksi). Wire: H04 temper, 185 MPa (27 ksi); H06 temper, 205 MPa (30 ksi)

Mass Characteristics

Density. 8.86 g/cm^3 (0.320 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1060 °C (1945 °F)
Solidus temperature. 975 °C (1785 °F)
Coefficient of linear thermal expansion. 17.8 µm/m · K (9.9 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F)
Thermal conductivity. 84 W/m · K (48.4 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 20% IACS at 20 °C (68 °F)
Electrical resistivity. 87 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Formability. Excellent capacity for cold working by blanking, drawing, forming, bending, roll threading, knurling, shearing, and stamping. Poor capacity for hot forming
Weldability. Soldering, brazing, and resistance butt welding: excellent. Gas metal arc and resistance spot welding: good. Oxyfuel gas, shielded metal arc, and resistance seam welding: fair
Annealing temperature. 475 to 675 °C (900 to 1250 °F)

C51100
95.6Cu-4.2Sn-0.2P

Specifications

ASTM. Flat products: B 100, B 103

Chemical Composition

Composition limits. 94.5 to 96.3 Cu, 3.5 to 4.9 Sn, 0.003 to 0.35 P, 0.05 Pb max, 0.1 Fe max, 0.3 Zn max

Applications

Typical uses. Architectural: bridge bearing plates. Hardware: beater bars, bellows, clutch

Table 88 Typical mechanical properties of C51000

Temper	Tensile strength		Yield strength(a)		Elongation in 50 mm (2 in.), %	Hardness, HRB
	MPa	ksi	MPa	ksi		
Flat products, 1 mm (0.04 in.) thick						
OS050	325	47	130	19	64	26
OS035	340	49	140	20	58	28
OS025	345	50	145	21	52	30
OS015	365	53	150	22	50	34
H02	470	68	380	55	28	78
H04	560	81	515	75	10	87
H06	535	92	550	80	6	93
H08	690	100	…	…	4	95
H10	740	107	…	…	3	97
Rod, 13 mm (0.05 in.) diameter						
H02	515	75	450	65	25	80
Rod, 25 mm (1 in.) diameter						
H02	480	70	400	58	25	78
Wire, 2 mm (0.08 in.) diameter						
OS035	345	50	140	20	58	…
H01	470	68	415	60	24	…
H02	585	85	550	80	8	…
H04	760	110	…	…	5	…
H06	895	130	…	…	3	…
H08	965	140	…	…	2	…

(a) At 0.5% extension under load

disks, connectors, diaphragms, fuse clips, fasteners, lock washers, sleeve bushings, springs, switch parts, terminals. Industrial: chemical hardware, perforated sheets, textile machinery

Mechanical Properties

Tensile properties. See Table 89.
Hardness. See Table 89.
Elastic modulus. Tension, 110 GPa (16 × 10^6 psi); shear, 41 GPa (6 × 10^6 psi)

Mass Characteristics

Density. 8.86 g/cm^3 (0.32 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1060 °C (1945 °F)
Solidus temperature. 975 °C (1785 °F)
Coefficient of linear thermal expansion. 17.8 µm/m · K (9.9 µin./in · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 84 W/m · K (48.4 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 20% IACS at 20 °C (68 °F)
Electrical resistivity. 87 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Formability. Excellent capacity for cold working by blanking, drawing, forming, bending, roll threading, knurling, shearing, and stamping. Poor capacity for hot forming
Weldability. Soldering, brazing, and resistance butt welding: excellent. Gas metal arc and resistance spot welding: good. Oxyfuel gas, shielded metal arc, and resistance seam welding: fair
Annealing temperature. 475 to 675 °C (900 to 1250 °F)

C52100
92Cu-8Sn

Commercial Names

Previous trade names. Phosphor bronze, 8% C

Specifications

ASTM. Flat products: B 103. Bar: B 103, B 139. Rod, shapes: B 139. Wire: B 159
SAE. J463
Government. MIL-E-23765

Chemical Composition

Composition limits. 90.5 to 92.8 Cu, 7.0 to 9.0 Sn, 0.03 to 0.35 P, 0.05 Pb max, 0.1 Fe max, 0.2 Zn max

Applications

Typical uses. For more severe service conditions than C51000. Architectural: bridge bearing plates. Hardware: beater bars, bellows. Bourdon tubing, clutch disks, cotter pins, diaphragms, fuse clips, fasteners, lock washers, sleeve bushings, springs, switch parts, truss wire, wire brushes. Industrial: chemical hardware, perforated sheets, textile machinery, welding rods

Mechanical Properties

Tensile properties. See Table 90.
Hardness. See Table 90.
Elastic modulus. Tension, 110 GPa (16 × 10^6 psi); shear, 41 GPa (6 × 10^6 psi)
Fatigue strength. Strip, 1 mm (0.04 in.) thick, H04 temper: 150 MPa (22 ksi) at 10^8 cycles

Mass Characteristics

Density. 8.8 g/cm^3 (0.318 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1025 °C (1880 °F)
Solidus temperature. 880 °C (1620 °F)
Coefficient of linear thermal expansion. 18.2 µm/m · K (10.1 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 62 W/m · K (36 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 13% IACS at 20 °C (68 °F)
Electrical resistivity. 133 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Formability. Good capacity for cold working by blanking, drawing, forming, bending, shearing, and stamping. Poor capacity for hot forming
Weldability. Soldering, brazing, and resistance butt welding: excellent. Gas metal arc and resistance spot welding: good. Oxyfuel gas, shielded metal arc, and resistance seam welding: fair
Annealing temperature. 475 to 675 °C (900 to 1250 °F)

C52400
90Cu-10Sn

Commercial Names

Previous trade name. Phosphor bronze, 10% D

Specifications

ASTM. Flat products: B 103. Bar: B 103, B 139. Rod, shapes: B 139. Wire: B 159
Government. Flat products, wire: QQ-B-750

Chemical Composition

Composition limits. 88.3 to 90.07 Cu, 9.0 to 11.0 Sn, 0.03 to 0.35 P, 0.05 Pb max, 0.1 Fe max, 0.2 Zn max

Applications

Typical uses. Heavy bars and plates for severe

Table 89 Typical mechanical properties of 1 mm (0.04 in.) thick C51100 strip

Temper	Tensile strength MPa	Tensile strength ksi	Yield strength at 0.2% offset MPa	Yield strength at 0.2% offset ksi	Elongation in 50 mm (2 in.), %	Hardness HRB	Hardness HR30T
OS050	315	46	110	16	48	70 HRF	…
OS035	330	48	130	19	47	73 HRF	…
OS025	345	50	145	21	46	75 HRF	…
OS015	350	51	160	23	46	76 HRF	…
H01	380	55	295	43	36	48	45
H02	425	62	385	56	19	70	65
H03	510	74	495	72	11	84	72
H04	550	80	530	77	7	86	74
H06	635	92	615	89	4	91	78
H08	675	98	655	95	3	93	79
H10	710	103	675	98	2	95	80

Table 90 Typical mechanical properties of C52100

Temper	Tensile strength MPa	Tensile strength ksi	Yield strength(a) MPa	Yield strength(a) ksi	Elongation in 50 mm (2 in.), %	Hardness HRF	Hardness HRB	Hardness HR30T
Flat products, 1 mm (0.04 in.) thick								
OS050	380	55	…	…	70	75	…	…
OS035	400	58	…	…	65	80	…	…
OS025	415	60	165	24	63	82	50	…
OS015	425	62	…	…	60	85	…	…
H02	525	76	380	55	32	…	84	73
H04	640	93	495	72	10	…	93	78
H06	730	106	550	80	4	…	96	80
H08	770	112	…	…	3	…	98	81
H10	825	120	…	…	2	…	100	82
Rod, 13 mm (0.5 in.) diameter								
H02	550	80	450	65	33	…	85	…
Wire, 2 mm (0.08 in.) diameter								
OS035	415	60	165	24	65	…	…	…
H01	560	81	…	…	…	…	…	…
H02	725	105	…	…	…	…	…	…
H04	895	130	…	…	…	…	…	…
H06	965	140	…	…	…	…	…	…

(a) At 0.5% extension under load.

compression requiring good wear and corrosion resistance; bridge and expansion plates and fittings; and articles requiring extra spring qualities and optimum resiliency, particularly in fatigue

Mechanical Properties

Tensile properties. Tensile strength and elongation, See Table 91. Yield strength, typical, OS035 temper: 195 MPa (28 ksi) at 0.5% extension under load
Hardness. See Table 91.
Elastic modulus. Tension, 110 GPa (16 × 10^6 psi); shear, 41 GPa (6 × 10^6 psi)

Mass Characteristics

Density. 8.78 g/cm^3 (0.317 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1000 °C (1830 °F)
Solidus temperature. 845 °C (1550 °F)
Coefficient of linear thermal expansion. 18.4 μm/m · K (10.2 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 50 W/m · K (29 Btu/ft · h · °F) at 20 °C (68 °F)

Table 91 Typical mechanical properties of C52400

Temper	Tensile strength MPa	Tensile strength ksi	Elongation in 50 mm (2 in.), %	Hardness, HRB
Flat products, 1 mm (0.04 in.) thick				
OS035	455	66	68	55
H02	570	83	32	92
H04	690	100	13	97
H06	795	115	7	100
H08	840	122	4	101
H10	885	128	3	103
Wire, 2 mm (0.08 in.) diameter				
OS035	455	66	70	…
H01	640	93	…	…
H02	815	118	…	…
H04	1013	147	…	…

Electrical Properties

Electrical conductivity. Volumetric, 11% IACS at 20 °C (68 °F)
Electrical resistivity. 157 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Formability. Good capacity for cold working by blanking, forming, bending, and shearing. Poor capacity for hot forming
Weldability. Soldering, brazing, and resistance butt welding: excellent. Gas metal arc and resistance spot welding: good. Oxyfuel gas, shielded metal arc, and resistance seam welding: fair
Annealing temperature. 475 to 675 °C (900 to 1250 °F)

C54400
88Cu-4Pb-4Sn-4Zn

Commercial Names

Previous trade name. Phosphor bronze B-2
Common names. Free-cutting phosphor bronze; 444 bronze; bearing bronze

Specifications

AMS. Strip 4520
ASTM. B 103, B 139
SAE. J463. Bearing alloy: J460 (791)
Government. Bar and rod: QQ-B-750

Chemical Composition

Composition limits. 3.5 to 4.5 Pb, 3.5 to 4.5 Sn, 1.5 to 4.5 Zn, 0.10 Fe max, 0.01 to 0.50 P, bal Cu; 99.5 Cu + Pb + Sn + Zn + P min

Applications

Typical uses. Bearings (sleeve and thrust), bushings, gears, pinions, screw machine products, shafts, thrust washers, valve parts

Mechanical Properties

Tensile properties. See Table 92.

Table 92 Typical mechanical properties of C54400

Temper	Tensile strength MPa	Tensile strength ksi	Yield strength(a) MPa	Yield strength(a) ksi	Elongation in 50 mm (2 in.), %	Hardness, HRB
Sheet and strip, 1 mm (0.04 in.) thick						
OS050	315	46	…	…	48	70 HRF
OS035	330	48	…	…	47	73 HRF
OS025	345	50	…	…	46	75 HRF
OS015	350	51	…	…	46	76 HRF
H02	425	62	370	54	19	70
H04	550	80	510	74	7	86
H06	635	92	…	…	4	91
H08	675	98	550	80	3	93
H10	710	103	…	…	2	95
Flat products, 8 mm (0.38 in.) thick						
H04	415	60	310	45	20	70
Flat products, 19 mm (0.75 in.) thick						
H04	380	55	240	35	25	…
Rod, 13 mm (0.50 in.) diameter						
H04	515	75	435	63	15	83
Rod, 25 mm (1.0 in.) diameter						
H04	470	68	395	57	20	80

(a) At 0.5% extension under load

Hardness. See Table 92.
Elastic modulus. Tension, 103 GPa (15 × 10^6 psi); shear, 39 GPa (5.6 × 10^6 psi)

Mass Characteristics

Density. 8.89 g/cm^3 (0.321 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1000 °C (1830 °F)
Solidus temperature. 930 °C (1700 °F)
Coefficient of linear thermal expansion. 17.3 μm/m · K (9.6 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 87 W/m · K (50 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical properties

Electrical conductivity. Volumetric, 19% IACS at 20 °C (68 °F)
Electrical resistivity. 91 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 80% of C36000 (free-cutting brass)
Formability. Good cold working characteristics; commonly fabricated by machining, shearing, blanking, drawing, forming, bending. Hot working and hot forming are not recommended.
Weldability. Soldering: excellent. Brazing: good. Flash welding: fair. Other welding processes are not recommended.

C60600
95Cu-5Al

Commercial Names

Previous trade name. Aluminum bronze A; CA606
Common names. Aluminum bronze, 5%

Specifications

ASTM. Flat products: B 169
Government. Bar, rod, forgings, shapes: QQ-C-645. Sheet and plate: QQ-C-450. Strip: QQ-C-450, QQ-C-465

Chemical Composition

Composition limits. 92.0 to 96.0 Cu, 4.0 to 7.0 Al, 0.50 Fe max, 0.50 max other (total)
Consequence of exceeding impurity limits. Excessive amounts of Pb, Zn, and P will cause hot shortness and difficulties in welding.

Applications

Typical uses. Produced as sheet, strip, and rolled bar; used to make fasteners, deep drawn "gold" decoration, and parts requiring corrosion resistance
Precautions in use. Not suitable for use in oxidizing acids

Mechanical Properties

Tensile properties. Typical data for 13 mm (0.5 in.) thick plate. Tensile strength: O61 temper, 310 MPa (45 ksi); H04 temper, 415 MPa (60 ksi). Yield strength: O60 temper, 115 MPa (17 ksi); H04 temper, 165 MPa (24 ksi). Elongation:

O60 temper, 40% in 50 mm (2 in.); H04 temper, 25% in 50 mm (2 in.)
Hardness. O60 temper, 42 HRB; H04 temper, 55 HRB
Poisson's ratio. 0.326
Elastic modulus. Tension, 121 GPa (17.5 × 10^6 psi); shear, 46 GPa (6.6 × 10^6 psi)
Fatigue strength. Rotating beam, 169 MPa (24.5 ksi) at 10^8 cycles

Structure

Microstructure. Alpha structure, face-centered cubic

Mass Characteristics

Density. 8.17 g/cm^3 (0.295 lb/in.^{3}) at 20 °C (68 °F)
Volume change on freezing. Approximately 1.6% contraction

Thermal Properties

Liquidus temperature. 1065 °C (1945 °F)
Solidus temperature. 1050 °C (1920 °F)
Coefficient of linear thermal expansion. 18 μm/m · K (10 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 375 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 79.5 W/m · K (45.9 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 17% IACS at 20 °C (68 °F)
Electrical resistivity. 100 nΩ · m at 20 °C (68 °F)

Magnetic Properties

Magnetic permeability. 1.01

Chemical Properties

General corrosion resistance. See C61400.
Resistance to specific agents. Has been used in sulfuric acid pickling applications where oxygen content is low. Has been used for anhydrous NH_4OH, but the presence of moisture leads to season cracking. Not suitable for use with nitric acid. Oxidizing salts such as chromates and metal salts such as ferric chloride are generally corrosive to C60600.

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass). Tends to form tough, stringy chips. Good lubrication and cooling essential for good finish. Carbide or tool steel cutters may be used.
Recrystallization temperature. 350 °C (660 °F) at 44% reduction and 0.075 mm (0.003 in.) initial grain size
Annealing temperature. 550 to 650 °C (1020 to 1200 °F)
Hot-working temperature. 815 to 870 °C (1500 to 1600 °F)

C60800
95Cu-5Al

Commercial Names

Previous trade name. 5% aluminum bronze
Common name. Aluminum bronze, 5%

Specifications

ASME. Tubing: SB111, SB359, SB395
ASTM. Tubing: B 111, B 359, B 395

Chemical Composition

Composition limits. 92.5 to 94.8 Cu, 5.0 to 6.5 Al, 0.02 to 0.35 As, 0.10 Pb max, 0.10 Fe max
Consequence of exceeding impurity limits. Excessive amounts of Pb, Zn, and P will cause difficulties in welding and hot working.

Applications

Typical uses. Produced as seamless tubing and ferrule stock for heat exchanger tubes, condenser tubes, and other applications requiring corrosion-resistant seamless tubing
Precautions in use. Not suitable for use in oxidizing acids.

Mechanical Properties

Tensile properties. Typical for OS025 temper tubing, 25 mm (1.0 in.) outside diameter × 1.65 mm (0.065 in.) wall thickness: tensile strength, 415 MPa (60 ksi); yield strength (0.5% extension under load), 185 MPa (27 ksi); elongation, 55% in 50 mm (2 in.)
Hardness. OS025 temper: 77 HRF
Poisson's ratio. 0.325
Elastic modulus. Tension, 121 GPa (17.5 × 10^6 psi); shear, 46 GPa (6.6 × 10^6 psi)

Structure

Microstructure. Alpha structure, face-centered cubic

Mass Characteristics

Density. 8.17 g/cm^3 (0.295 lb/in.^{3}) at 20 °C (68 °F)
Volume change on freezing. Approximately 1.6% contraction

Thermal Properties

Liquidus temperature. 1065 °C (1945 °F)
Solidus temperature. 1050 °C (1920 °F)
Coefficient of linear thermal expansion. 18 μm/m · K (10 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 79.5 W/m · K (45.9 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 17% IACS at 20 °C (68 °F)
Electrical resistivity. 100 nΩ · m at 20 °C (68 °F)

Magnetic Properties

Magnetic permeability. 1.01

Chemical Properties

General corrosion resistance. See C61400.
Resistance to specific agents. Has been used in sulfuric acid pickling applications where oxygen content is low. Has been used for anhydrous NH_4OH, but the presence of moisture leads to season cracking. Not suitable for use with nitric acid. Oxidizing salts such as chromates and metal salts such as ferric chloride are generally corrosive to C60800.

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass). Tends to form tough, stringy chips. Good lubrication and cooling essential for good finishes. Carbide or tool steel cutters may be used.
Formability. Good for cold working; fair for hot forming.
Weldability. Arc and resistance welding: good. Brazing: fair. Soldering and oxyfuel gas welding are not recommended.
Recrystallization temperature. 350 °C (660 °F) at 44% reduction and 0.075 mm (0.003 in.) initial grain size
Annealing temperature. 550 to 650 °C (1020 to 1200 °F)
Hot-working temperature. 800 to 875 °C (1470 to 1610 °F)

C61000
92Cu-8Al

Commercial Names

Common name. 8% aluminum bronze

Specifications

ASME. SB169
ASTM. B 169
Government. QQ-C-450; MIL-E-23765

Chemical Composition

Composition limits. 6.0 to 8.5 Al, 0.50 Fe max, 0.02 Pb max, 0.20 Zn max, 0.10 Si max, 0.50 max other (total), bal Cu

Applications

Typical uses. Produced as rod or wire and used to make bolts, shafts, tire rods, and pump parts. Also used as a welded overlay on steel to improve surface wear resistance

Mechanical Properties

Tensile properties. Typical data for rod, 25 mm (1 in.) in diameter. O60 temper: tensile strength 480 MPa (70 ksi); yield strength (0.5% extension under load), 205 MPa (30 ksi); elongation, 65% in 50 mm (2 in.). H04 temper: tensile strength, 550 MPa (80 ksi); yield strength, 380 MPa (55 ksi); elongation, 25%
Hardness. O60 temper: 60 HRB. H04 temper: 85 HRB
Elastic modulus. Tension, 117 GPa (17 × 10^6 psi); shear, 44 GPa (6.4 × 10^6 psi)

Mass Characteristics

Density. 7.78 g/cm^3 (0.281 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1040 °C (1905 °F)
Coefficient of linear thermal expansion. 17.9 μm/m · K (9.9 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 375 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 69 W/m · K (40 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 15% IACS at 20 °C (68 °F)
Electrical resistivity. 115 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Forgeability. 70% of C37700 (forging brass)
Formability. Good capacity for being hot formed or cold worked. Common fabrication processes include blanking, drawing, forming, bending, cold heading, and roll threading.
Weldability. Arc welding, resistance spot welding, and resistance butt welding: good. Soldering and resistance seam welding: fair. Brazing and oxyfuel gas welding are not recommended.
Annealing temperature. 600 to 675 °C (1100 to 1250 °F)
Hot-working temperature. 760 to 875 °C (1400 to 1600 °F)

C61300
90Cu-7Al-2.7Fe-0.3Sn

Commercial Names

Common name. Aluminum bronze, 7%

Specifications

Government. Flat products: QQ-C-450

Chemical Composition

Composition limits. 88.5 to 91.5 Cu, 6.0 to 7.5 Al, 0.02 to 0.50 Sn, 2.0 to 3.0 Fe, 0.10 Mn max, 0.15 Ni (+ Co) max, 0.01 Pb max, 0.05 Zn max, 0.05 max other
Consequence of exceeding impurity limits. Excessive amounts of Pb, Zn, P, or Si will cause hot shortness, which can lead to problems during hot working or welding.

Applications

Typical uses. Produced as rod, bar, sheet, plate, seamless tubing and pipe, welded pipe, fasteners, tube sheets, heat exchanger tubes, acid-resistant piping, columns, water boxes, and corrosion-resistant vessels
Precautions in use. Not suitable for use in oxidizing acids

Mechanical Properties

Tensile properties. Typical data for 13 mm (0.50 in.) thick plate. Tensile strength: O60 temper, 540 MPa (78 ksi); H04 temper, 585 MPa (85 ksi). Yield strength (0.5% extension): O60 temper, 240 MPa (35 ksi); H04 temper, 400 MPa (58 ksi). Elongation: O60 temper, 42% in 50 mm (2 in.); H04 temper, 35% in 50 mm (2 in.). Reduction in area: O60 temper, 32%; H04 temper, 25%. See also Table 93.
Compressive properties. Typical data for 13 mm (0.50 in.) thick plate. Compressive strength, ultimate: O60 temper, 825 MPa (120 ksi); H04 temper, 860 MPa (125 ksi)
Hardness. O60 temper, 82 HRB; H04 temper, 91 HRB. See also Table 93.
Poisson's ratio. 0.312
Elastic modulus. Tension, 115 GPa (17 × 10^6 psi); shear, 44 GPa (6.4 × 10^6 psi). See also Table 93.
Impact strength. Charpy keyhole, 81 to 88 J (60 to 65 ft · lbf) at –30 to 150 °C (–20 to 300 °F); Izod, 54 to 66 J (40 to 49 ft · lbf) at –30 to 150 °C (–20 to 300 °F). See also Fig. 44.
Fatigue strength. Reverse bending, 180 MPa (26 ksi) at 10^8 cycles

Structure

Microstructure. Alpha structure, single phase, with iron-rich precipitates

Mass Characteristics

Density. 7.89 g/cm^3 (0.285 lb/in.^{3}) at 20 °C (68 °F)
Volume change on freezing. Approximately 1.8% contraction

Thermal Properties

Liquidus temperature. 1045 °C (1915 °F)
Solidus temperature. 1040 °C (1905 °F)
Coefficient of linear thermal expansion. 16.2 μm/m · K (9.0 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 375 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 56.5 W/m · K (32.7 Btu/ft · h · °F) at 20 °C (68 °F); temperature coefficient, 0.12 W/m · K per K at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 12% IACS at 20 °C (68 °F)
Electrical resistivity. 144 nΩ · m at 20 °C (68 °F)

Magnetic Properties

Magnetic permeability. 1.16

Chemical Properties

General corrosion resistance. See C61400.
Resistance to specific agents. C61300 is very resistant to neutral and nonoxidizing salts. It has given extended service in potash solutions of potassium chloride, sodium chloride, magnesium chloride, and calcium chloride. The alloy resists nonoxidizing mineral acids and has been used successfully for tanks containing hydrofluoric acid in glass-etching applications. In organic acid service, it has been used to make acetic acid distillation columns.

C61300 is highly resistant to dealloying and to season cracking in steam and in hot oxidizing aqueous solutions and vapors. The presence of tin in 7% aluminum bronze (C61300 contains 0.3% Sn, C61400 does not contain Sn) evidently renders the alloy immune to stress-corrosion cracking in these environments. Like many copper alloys, C61300 is susceptible to season cracking in moist ammonia and mercurous nitrate solutions. However, it is highly resistant to season cracking in anhydrous ammonia, especially when the moisture content is below 500 ppm and the temperature is below 85 °C (180 °F).

Because of its high resistance to corrosion in salt water, C61300 has been specified for a wide variety of components for marine and desalting plant service. Typical uses of C61300 include tube sheets for condensers in both nuclear and fossil fuel power stations, cooling tower transfer piping, seawater piping for secondary cooling systems in nuclear power plants, and piping for geothermal heat transfer systems.

Fabrication Characteristics

Machinability. Fair to poor, with chips tending to be stringy and gummy. Good lubrication and cooling are essential. Tool steel cutters: roughing speed, 90 m/min (300 ft/min) with a feed of 0.3 mm/rev (0.011 in./rev); finishing speed, 350 m/min (1150 ft/min) with a feed of 0.3 mm/rev (0.011 in./rev)
Forgeability. 50% of C37700 (forging brass)
Formability. Good for cold working and hot forming
Weldability. Arc and resistance welding: good. Brazing: fair. Soldering and oxyfuel gas welding are not recommended.

Table 93 Typical mechanical properties of C61300 and C61400 rod at various temperatures

Temperature		Tensile strength		Yield strength(a)		Elongation in 50 mm (2 in.), %	Reduction in area, %	Modulus of elasticity		Hardness, HB(b)
°C	°F	MPa	ksi	MPa	ksi			GPa	10^6 psi	
Cold finished										
–182	–295	718	104.1	397	57.6	50	49	156	22.7	186
–60	–75	611	88.6	335	48.7	45	55	149	21.6	170
–29	–20	606	87.9	339	49.2	44	58	172	25.0	162
20	70	590	85.5	318	46.1	42	59	126	18.3	157
204	400	532	77.2	298	43.3	35	32	128	18.5	144
316	600	432	62.6	271	39.3	22	24	88	12.8	137
427	800	170	24.6	105	15.2	52	41	48	6.9	83
538	1000	88	12.8	71	10.3	27	26	45	6.6	49
Annealed										
–182	–295	707	102.6	347	50.3	52	51	139	20.2	185
–60	–75	610	88.4	305	44.3	47	57	176.5	25.6	162
–29	–20	600	87.1	303	43.9	44	56	172	24.9	161
20	70	583	84.6	288	41.8	45	56	136.5	19.8	155
204	400	522	75.7	276	40.1	34	32	130	18.8	142
316	600	427	62.0	256	37.1	30	27	81	11.7	134
427	800	174	25.3	123	17.8	60	55	67	9.7	84
538	1000	92	13.3	68	9.9	36	33	45	6.5	50

(a) At 0.5% extension under load. (b) 3000 kg (6615 lb) load

Recrystallization temperature. 785 to 870 °C (1450 to 1600 °F)
Annealing temperature. 600 to 875 °C (1125 to 1600 °F)
Hot-working temperature. 800 to 925 °C (1450 to 1700 °F)
Hot-shortness temperature. 1010 °C (1850 °F)

C61400
91Cu-7Al-2Fe

Commercial Names

Previous trade name. Aluminum bronze D
Common name. Aluminum bronze, 7%

Specifications

ASME. Flat products: SB169, SB171. Bar, rod, shapes: SB150
ASTM. Flat products: B 169, B 171. Bar, rod, shapes: B 150
SAE. J463
Government. Flat products: QQ-C-450, QQ-C-465. Bar, rod, shapes, forgings: QQ-C-465. Flat wire: QQ-C-465

Chemical Composition

Composition limits. 88.0 to 92.5 Cu, 6.0 to 8.0 Al, 1.5 to 3.5 Fe, 1.0 Mn max, 0.20 Zn max, 0.01 Pb max, 0.015 P max, 0.5 max other (total)
Consequence of exceeding impurity limits. Excessive amounts of Pb, Zn, Si, or P will cause hot shortness and cracking during hot working and welding.

Applications

Typical uses. Produced as seamless tubing, welded and seamless pipe, sheet, plate, rod, and bar for condenser and heat exchanger tubes, fasteners, tube sheets, and corrosion-resistant vessels
Precautions in use. Not suitable for use in oxidizing acids. Susceptible to stress-corrosion cracking in moist ammonia or in steam environments, especially when stress levels are high

Mechanical Properties

Tensile properties. See Tables 93 and 94.
Shear strength. See Table 94.
Compressive properties. Compressive strength, ultimate: O60 temper, 825 MPa (120 ksi); H04 temper, 860 MPa (125 ksi)
Hardness. O60 temper, 80 to 84 HRB; H04 temper, 84 to 91 HRB. See also Table 94.
Poisson's ratio. 0.312
Elastic modulus. Tension, 115 GPa (17 × 10^6 psi); shear, 44 GPa (6.4 × 10^6 psi). See also Table 94.
Impact strength. Charpy keyhole, 81 to 88 J (60 to 65 ft · lbf); Izod, 54 to 61 J (40 to 45 ft · lbf). See also Fig. 44.
Fatigue strength. Reverse bending, 180 MPa (26 ksi) at 10^8 cycles

Structure

Microstructure. Alpha solid solution with precipitates of iron-rich phase

Mass Characteristics

Density. 7.89 g/cm^3 (0.285 lb/in.^{3}) at 20 °C (68 °F)
Volume change on freezing. Approximately 1.8% expansion

Thermal Properties

Liquidus temperature. 1045 °C (1915 °F)
Solidus temperature. 1040 °C (1905 °F)
Coefficient of linear thermal expansion. 16.2 µm/m · K (9.0 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 375 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 56.5 W/m · K (32.6 Btu/ft · h · °F) at 20 °C (68 °F); temperature coefficient, 0.12 W/m · K per K at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 14% IACS at 20 °C (68 °F)
Electrical resistivity. 123 nΩ · m at 20 °C (68 °F)

Magnetic Properties

Magnetic permeability. 1.16

Chemical Properties

General corrosion behavior. The aluminum bronzes resist nonoxidizing mineral acids such as sulfuric, hydrochloric, and phosphoric acid. Resistance tends to decrease with increasing concentration of dissolved oxygen or oxidizing agents, particularly as temperatures increase above 55 °C (130 °F). Aluminum bronzes are generally suited for service in alkalies, neutral salts, nonoxidizing acid salts, and many organic acids and compounds. Oxidizing acids, oxidizing salts, and heavy-metal salts are corrosive. Aluminum bronzes resist waters, whether potable water, brackish water, or seawater. Softened water tends to be more corrosive than hard water. Aluminum bronzes resist dealloying, but to different degrees depending on alloy composition. In general, corrosion resistance is influenced most by solution concentration, aeration, temperature, velocity, and the type and amount of any impurities in the solution.
Like many other copper alloys, the aluminum bronzes are susceptible to stress-corrosion cracking in moist ammonia and mercury compounds. When stress levels are high, they may also be susceptible to stress-corrosion cracking in purified steam or in steam containing acidic or salt vapors.
Resistance to specific agents. C61400 has been used successfully to contain mineral acids, alkalies such as sodium or potassium hydroxide, neutral salts such as sodium chloride, and organic acids such as acetic, lactic, or oxalic acid. C61400 resists anhydrous ammonia, but precautions must be taken to exclude moisture and thus avoid season cracking. Similarly, this alloy resists anhydrous chlorinated hydrocarbons such as carbon tetrachloride, but the presence of moisture makes those chemicals corrosive.

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass). Tendency to form continuous, stringy chips. Good lubrication and cooling essential. Tool steel or carbide cutters may be used. Typical conditions, using tool steel cutters: roughing speed, 90 m/min (300 ft/min) with a feed of 0.3 mm/rev (0.011 in./rev); finishing speed, 350 m/min (1150 ft/min) with a feed of 0.3 mm/rev (0.011 in./rev)

Table 94 Typical mechanical properties of C61400

	Tensile strength		Yield strength(a)		Elongation in 50 mm (2 in.), %	Shear strength	
Size	MPa	ksi	MPa	ksi		MPa	ksi
Flat products, O60 temper							
3 mm (0.12 in.) thick	565	82	310	45	40	310	45
8 mm (0.31 in.) thick	550	80	275	40	40	290	42
13 mm (0.50 in.) thick	535	78	240	35	42	275	40
25 mm (1.00 in.) thick	525	76	230	33	45	275	40
Flat products, H04 temper							
3 mm (0.12 in.) thick	615	89	415	60	32	…	…
8 mm (0.31 in.) thick	585	85	400	58	35	…	…
13 mm (0.50 in.) thick	550	80	370	54	38	…	…
25 mm (1.00 in.) thick	535	78	310	45	40	…	…
Rod, H04 temper							
13 mm (0.50 in.) diameter	585	85	310	45	35	330	48
25 mm (1.00 in.) diameter	565	82	275	40	35	310	45
51 mm (2.00 in.) diameter	550	80	240	35	35	275	40

(a) At 0.5% extension under load

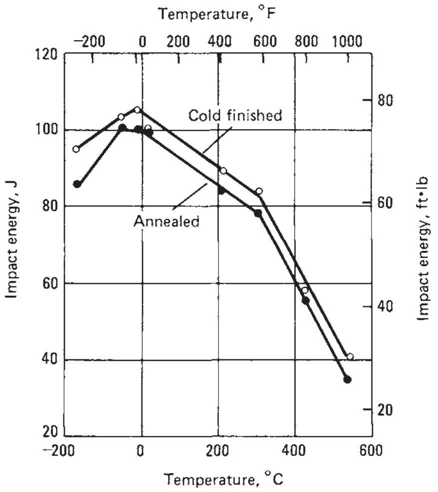

Fig. 44 Variation in Charpy V-notch impact strength with temperature for C61300 and C61400

LIVE GRAPH
Click here to view

Formability. Fair for cold working; good for hot forming
Weldability. Gas-shielded arc, coated metal arc, and resistance welding: good. Brazing: fair. Soldering, oxyacetylene, and carbon arc welding are not recommended.
Recrystallization temperature. 785 to 870 °C (1450 to 1600 °F)
Annealing temperature. 600 to 900 °C (1125 to 1650 °F)
Hot-working temperature. 800 to 925 °C (1450 to 1700 °F)
Hot-shortness temperature. 1010 °C (1850 °F)

C61500
90Cu-8Al-2Ni

Commercial Names

Previous trade name. Lusterloy

Chemical Composition

Composition limits. 89.0 to 90.5 Cu, 7.7 to 8.3 Al, 1.8 to 2.2 Ni, 0.015 Pb max

Applications

Typical uses. Hardware, decorative metal trim, interior furnishings, giftware, springs, fasteners architectural panels and structural sections, deep drawn articles, tarnish-resistant articles

Mechanical Properties

Tensile properties. See Table 95.
Hardness. See Table 95.
Elastic modulus. Tension, 112 GPa (16.6 × 10^6 psi)
Fatigue strength. See Table 95.

Mass Characteristics

Density. 7.65 g/cm^3 (0.278 $lb/in.^3$) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1040 °C (1904 °F)
Solidus temperature. 1030 °C (1890 °F)
Coefficient of linear thermal expansion. 16.8 µm/m · K (9.3 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 58 W/m · K (33.6 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 12.6% IACS at 20 °C (68 °F)
Electrical resistivity. 137 nΩ · m at 20 °C (68 °F)

Optical Properties

Color. Gold

Chemical Properties

General corrosion behavior. Excellent; similar to that of other aluminum bronzes

Table 95 Typical mechanical properties of 1 mm (0.04 in.) thick C61500 sheet and strip

	Tensile strength		Yield strength at 0.2% offset				Fatigue strength at 10^8 cycles	
Temper	MPa	ksi	MPa	ksi	Elongation in 50 mm (2 in.), %	Hardness, HR30T	MPa	ksi
O60	485	70	150	22	55	42	…	…
O50	585	85	345	50	36	70	260	38
H02	725	105	515	75	15	81	…	…
H04	860	125	620	90	5	83	…	…
H06	930	135	690	100	4	84	270	39
H08	965	140	725	105	3	84.5	…	…
HR06(a)	1000	145	965	140	1	86.5	275	40

(a) Cold worked 50%, then stress relieved for 1 h at 300 °C (570 °F)

Table 96 Typical mechanical properties of C62300 rod at various temperatures

Temperature		Tensile strength		Yield strength(a)				Modulus of elasticity in tension		
°C	°F	MPa	ksi	MPa	ksi	Elongation in 50 mm (2 in.), %	Reduction in area, %	GPa	10^6 psi	Hardness, HB(b)
Cold finished										
–182	–295	778	112.8	390	56.5	37	41	127	18.4	193
–60	–75	682	98.9	340	49.3	34	41	108	15.7	170
–29	–20	663	96.2	326	47.3	34	44	114	16.5	168
20	70	652	94.5	320	46.4	34	44	111	16.1	165
204	400	550	79.8	296	43.0	22	22	114	16.5	152
316	600	465	67.5	296	43.0	10	13	85	12.4	148
427	800	196	28.5	138	20.0	32	33	54	7.9	98
538	1000	103	15.0	92	13.3	18	29	41	5.9	54
Annealed										
–182	–295	762	110.5	377	54.7	35	38	125	18.1	195
–60	–75	664	96.3	330	47.9	33	39	121	17.5	171
–29	–20	647	93.8	323	46.9	31	38	124	18.0	168
20	70	620	90.0	294	42.6	32	39	120	17.4	161
204	400	534	77.5	302	43.8	20	21	138	20.0	151
316	600	448	65.0	288	41.8	10	13	79	11.5	146
427	800	210	30.5	153	22.2	46	39	73	10.6	97
538	1000	94	13.6	84	12.2	27	32	51	7.4	46

(a) At 0.5% extension under load. (b) 3000 kg (6615 lb) load

Fabrication Characteristics

Machinability. 30% of C36000 (free-cutting brass)
Forgeability. 50% of C37700 (forging brass)
Formability. Suitable for forming by bending, drawing, deep drawing, forging, extrusion, blanking, and stamping; only slight directionality in bending. Good for cold working and hot forming
Weldability. Gas-shielded arc welding, shielded metal arc welding, and resistance welding: excellent. Soldering and brazing: easily done using mildly aggressive fluxes. Oxyfuel gas welding is not recommended.
Annealing temperature. 620 to 675 °C (1150 to 1250 °F)
Aging temperature. Order strengthening, 300 °C (575 °F) for 1 h
Hot-working temperature. 815 to 870 °C (1500 to 1600 °F)

C62300
87Cu-10Al-3Fe

Commercial Names

Common name. Aluminum bronze, 9%

Specifications

ASME. Bar, rod, shapes: SB150
ASTM. Bar, rod, shapes: B 150. Forgings: B 283
SAE. J463
Government. Forgings: MIL-B-16166

Chemical Composition

Composition limits. 82.2 to 89.5 Cu, 8.5 to 11.0 Al, 2.0 to 4.0 Fe, 1.0 Ni (+ Co) max, 0.6 Sn max, 0.50 Mn max, 0.25 Si max, 0.5 max other (total)
Consequence of exceeding impurity limits. An excessive amount of Pb will cause hot shortness, and excessive Si will cause the alloy to lose ductility. Excessive Al will reduce ductility and corrosion resistance.

Applications

Typical uses. Produced as rod and bar for bearings, bushings, bolts, nuts, gears, valve guides, pump rods, cams, and applications requiring corrosion resistance
Precautions in use. Not suitable for use in oxidizing acids

Mechanical Properties

Tensile properties. Typical. Tensile strength, 605 MPa (88 ksi); yield strength, 305 MPa (44 ksi); elongation, 15% in 50 mm (2 in.); reduction in area, 15%. See Table 96.
Compressive properties. See Table 97.
Hardness. 89 HRB. See Table 96.
Poisson's ratio. 0.328
Elastic modulus. Tension, 115 GPa (17 × 10^6 psi); shear, 44 GPa (6.4 × 10^6 psi). See also Table 96.
Impact strength. Charpy V-notch, 25 to 40 J (18 to 30 ft · lbf); Izod, 43 to 47 J (32 to 35 ft · lbf). See also Fig. 45.
Fatigue strength. Reverse bending, 200 MPa (29 ksi) at 10^8 cycles

Structure

Microstructure. Duplex structure of face-centered-cubic α plus metastable body-centered-cubic β with iron-rich precipitates

Mass Characteristics

Density. 7.65 g/cm^3 (0.276 lb/in.^{3}) at 20 °C (68 °F)
Volume change on freezing. Approximately 2% expansion

Thermal Properties

Liquidus temperature. 1045 °C (1915 °F)
Solidus temperature. 1040 °C (1905 °F)
Phase transformation temperature. Eutectoid transformation, 563 to 570 °C (1045 to 1055 °F)
Coefficient of linear thermal expansion. 16.2 µm/m · K (9.0 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 375 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 54.4 W/m · K (31.4 Btu/ft · h · °F) at 20 °C (68 °F); temperature coefficient, 0.12 W/m · K per K at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 12% IACS at 20 °C (68 °F)
Electrical resistivity. 144 nΩ · m at 20 °C (68 °F)

Magnetic Properties

Magnetic permeability. 1.17

Chemical Properties

General corrosion behavior. See C61400.
Resistance to specific agents. C62300 resists nonoxidizing mineral acids, but hydrochloric acid is more corrosive than other nonoxidizing mineral acids. C62300 resists dealloying, but to a lesser extent than C61300 or C61400. Like other aluminum bronzes, C62300 is not suitable for use in an oxidizing acid such as nitric acid.

Fabrication Characteristics

Machinability. Fair, with good surface finish possible. Carbide or tool steel cutters may be used. Typical conditions using tool steel cutters: roughing speed, 107 m/min (350 ft/min) with a feed of 0.3 mm/rev (0.011 in./rev); finishing speed, 350 m/min (1150 ft/min) with a feed of 0.15 mm/rev (0.006 in./rev)
Forgeability. 75% of C37700 (forging brass)
Formability. Good for cold working and hot forming
Weldability. Gas-shielded arc, shielded metal arc, and all types of resistance welding: good. Brazing: fair. Soldering and oxyfuel gas welding are not recommended.
Annealing temperature. 600 to 650 °C (1110 to 1200 °F)
Hot-working temperature. 700 to 875 °C (1290 to 1600 °F)
Hot shortness temperature. 1010 °C (1850 °F)

C62400
86Cu-11Al-3Fe

Commercial Names

Common name. Aluminum bronze, 11%

Specifications

SAE. J463

Chemical Composition

Composition limits. 82.8 to 88.0 Cu, 10.0 to 11.5 Al, 2.0 to 4.5 Fe, 0.30 Mn max, 0.25 Si max, 0.20 Sn max, 0.5 max other (total)
Consequence of exceeding impurity limits. Excessive amounts of Si and Al decrease ductility

Applications

Typical uses. Produced as rod and bar for gears, wear plates, cams, bushings, nuts, drift pins, and tie rods
Precautions in use. May lose ductility upon prolonged heating in range from 370 to 565 °C (700 to 1050 °F). Not suitable for use in oxidizing acids

Mechanical Properties

Tensile properties. Typical data for 50 mm (2 in.) diam round rod (half hard). Tensile strength, 655 MPa (95 ksi); yield strength (0.5% extension), 330 MPa (48 ksi); elongation, 14% in 50 mm (2 in.); reduction in area, 11%
Compressive properties. See Table 98.
Hardness. 92 HRB
Poisson's ratio. 0.318
Elastic modulus. Tension, 115 GPa (17 × 10^6 psi); shear, 44 GPa (6.4 × 10^6 psi)
Impact strength. Charpy keyhole, 15 J (11 ft · lbf) at –23 to 27 °C (–10 to 80 °F); Izod, 23 J (17 ft · lbf) at –23 to 27 °C (–10 to 80 °F)
Fatigue strength. Reverse bending, 235 MPa (34 ksi) at 108 cycles

Structure

Microstructure. Duplex-structure α plus metastable β phases and iron-rich precipitates

Mass Characteristics

Density. 7.45 g/cm^3 (0.269 lb/in.^{3}) at 20 °C (68 °F)
Volume change on freezing. Approximately 2% contraction

Thermal Properties

Liquidus temperature. 1040 °C (1900 °F)
Solidus temperature. 1025 °C (1880 °F)
Phase transformation temperature. Eutectoid, 560 to 570 °C (1045 to 1055 °F)
Coefficient of linear thermal expansion. 16.5 µm/m · K (9.2 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 375 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 58.6 W/m · K (33.9 Btu/ft · h · °F) at 20 °C (68 °F); temperature coefficient, 0.12 W/m · K per K at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 12% IACS at 20 °C (68 °F)
Electrical resistivity. 144 nΩ · m at 20 °C (68 °F)

Magnetic Properties

Magnetic permeability. 1.34

Chemical Properties

General corrosion behavior. See C61400.
Resistance to specific agents. C62400 resists nonoxidizing mineral acids, but hydrochloric acid is more corrosive than other nonoxidizing mineral acids. C62400 is susceptible to dealloying, but proper heat treatment increases resistance to this type of corrosion. Like other aluminum bronzes, C62400 is not suitable for use in an oxidizing acid such as nitric acid.

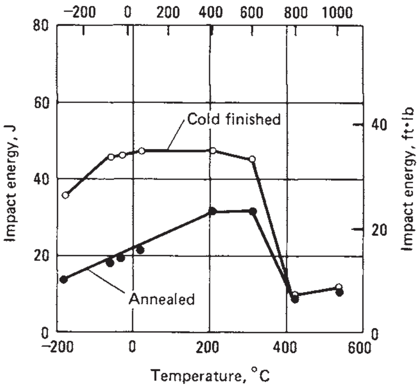

Fig. 45 Variation in Charpy V-notch impact strength with temperature for C62300

LIVE GRAPH
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Table 97 Typical compressive properties for C62300 rod, H50 temper

	Compressive strength at permanent set of							
	0.1%		1%		10%		20%	
Rod diameter	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi
≤ 25 mm (≤ 1 in.)	360	52	485	70	825	120	965	140
25–50 mm (1–2 in.)	345	50	450	65	675	98	930	135
50–75 mm (2–3 in.)	315	46	415	60	620	90	895	130

Table 98 Typical compressive properties for C62400 rod, H50 temper

	Compressive strength at permanent set of						Ultimate compressive strength	
	0.1%		1%		10%			
Rod diameter	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi
≤ 25 mm (≤ 1 in.)	290	42	470	68	885	128	1140	165
25–50 mm (1–2 in.)	220	32	400	58	825	120	1090	158
50–75 mm (2–3 in.)	175	25	330	48	795	115	1090	158

Fabrication Characteristics

Machinability. 50% of C36000 (free-cutting brass); chips break readily. Carbide or tool steel cutters may be used. Typical conditions using tool steel cutters: roughing speed, 90 m/min (300 ft/min) with a feed of 0.3 mm/rev (0.011 in./rev); finishing speed, 290 m/min (950 ft/min) with a feed of 0.1 mm/rev (0.004 in./rev). Using carbide cutters with 2.3 to 6.4 mm (0.09 to 0.25 in.) cut: roughing speed, 53 m/min (175 ft/min) with a feed of 0.3 mm/rev (0.011 in./rev); finishing speed, 38 to 45 m/min (125 to 150 ft/min) with a feed of 0.3 mm/rev (0.011 in./rev)
Weldability. Similar to that of C62300
Annealing temperature. 600 to 700 °C (1110 to 1300 °F)
Hot-working temperature. 760 to 925 °C (1400 to 1700 °F)

C62500
82.7Cu-4.3Fe-13Al

Commercial Names

Trade name. Ampco 21, Wearite 4-13

Chemical Composition

Compositions limits. 12.5 to 13.5 Al, 3.5 to 5.0 Fe, 2.0 Mn max, 0.5 max other (total), bal Cu
Consequence of exceeding impurity limits. Possibility of hot shortness, reduced wear resistance, increased spalling tendency, and lower strength when elements such as Pb, Zn, P, and Si are present in more than trace quantities

Applications

Typical uses. Guide bushings, wear strips, cams, sheet metal forming dies, forming rolls
Precautions in use. Low ductility and impact resistance make it advisable to provide adequate structural support for components made of C62500 that will be subjected to shock loads or high stress. Corrosion resistance is inferior to that of aluminum bronzes containing less aluminum.

Mechanical Properties

Tensile properties. Typical M30 and O61 tempers: tensile strength, 690 MPa (100 ksi); yield strength (0.5% extension), 380 MPa (55 ksi); elongation, 1% in 50 mm (2 in.); reduction in area, 1%
Compressive properties. Compressive strength, 450 MPa (65 ksi) at a permanent set of 0.1%; 880 MPa (128 ksi) at a permanent set of 1%
Hardness. 27 HRC
Poisson's ratio. 0.312
Elastic modulus. Tension, 110 GPa (16×10^6 psi); shear, 42.3 GPa (6.13×10^6 psi)
Impact strength. Izod or Charpy keyhole, 3 J (2 ft · lbf) at –18 to 100 °C (0 to 212 °F)
Fatigue strength. Rod, M30 temper: 460 MPa (67 ksi) at 10^8 cycles

Structure

Microstructure. Primarily body-centered-cubic metastable β phase with small crystals of ordered close-packed hexagonal γ phase

Magnetic Properties

Magnetic permeability. 1.2

Mass Characteristics

Density. 7.21 g/cm^3 (0.260 $lb/in.^3$) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1052 °C (1925 °F)
Solidus temperature. 1047 °C (1917 °F)
Coefficient of linear thermal expansion. 16.2 µm/m · K (9.0 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 38.9 W/m · K (22.5 Btu/ft · h · °F) at 20 °C (68 °F); temperature coefficient, 0.093 W/m · K per K at –100 to 150 °C (–150 to 300 °F)

Electrical Properties

Electrical conductivity. Volumetric, 10% IACS at 20 °C (68 °F)
Electrical resistivity. 172 nΩ · m at 20 °C (68 °F)

Table 99 Typical mechanical properties of C63000 rod at various temperatures

Temperature		Tensile strength		Yield strength(a)		Elongation in 50 mm (2 in.), %	Reduction in area, %	Modulus of elasticity		Hardness, HB(b)
°C	°F	MPa	ksi	MPa	ksi			GPa	10^6 psi	
Cold finished										
–182	–295	845	122.5	469	68.1	8	10	128	18.5	238
–60	–75	774	112.3	443	64.3	26	28	131	19.0	216
–29	–20	784	113.7	463	67.1	24	29	132	19.1	209
20	70	776	112.5	407	59.1	20	21	117	16.9	200
204	400	694	100.7	403	58.5	13	15	136	19.7	188
316	600	582	84.4	373	54.1	8	9	85	12.3	181
427	800	245	35.5	166	24.1	51	56	57	8.2	98
538	1000	107	15.5	88	12.8	41	59	44	6.4	47
Annealed										
–182	–295	867	125.8	431	62.5	12	12	130	18.8	235
–60	–75	784	113.7	379	54.9	24	26	123	17.9	212
–29	–20	781	113.3	384	55.7	23	23	139	20.1	209
20	70	766	111.1	370	53.6	21	21	125	18.1	200
204	400	706	102.4	348	50.4	16	15	107	15.5	189
316	600	605	87.7	337	48.9	10	11	110	15.9	176
427	800	232	33.7	158	22.9	41	46	64	9.3	101
538	1000	95	13.7	78	11.3	39	46	48	7.0	50

(a) At 0.5% extension under load. (b) 3000 kg (6615 lb) load

Chemical Properties

General corrosion behavior. Adequate corrosion resistance to ambient moisture and industrial atmospheres. C62500 is rarely used for its corrosion characteristics in strongly corrosive environments. General corrosion characteristics are inferior to those of C62400 and C62300.

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Formability. Not recommended for cold working; excellent for hot forming
Weldability. Gas-shielded arc and shielded metal arc welding: good. Brazing and resistance welding: fair. Oxyfuel gas welding and soldering are not recommended.
Annealing temperature. 600 to 650 °C (1100 to 1200 °F)
Hot-working temperature. 745 to 850 °C (1375 to 1550 °F)

C63000
82Cu-10Al-5Ni-3Fe

Commercial Names

Previous trade name. Aluminum bronze E
Common name. Nickel-aluminum bronze

Specifications

AMS. Bar, shapes: 4640
ASME. Bar, rod, shapes: SB150. Condenser tube plate: SB171
ASTM. Bar, rod, shapes: B 124, B 150. Condenser tube plate: B 171. Forgings: B 283
SAE. J463
Government. Flat products, rod, shapes: QQ-C-465. Forgings: QQ-C-465, MIL-B-16166

Chemical Composition

Composition limits. 78.0 to 85.0 Cu, 9.0 to 11.0 Al, 2.0 to 4.0 Fe, 4.0 to 5.5 Ni (+ Co), 1.5 Mn max, 0.30 Zn max, 0.25 Si max, 0.20 Sn max, 0.5 max other (total)
Consequence of exceeding impurity limits. Excessive amounts of Zn, Sn, and Pb will cause cracking during hot working and joining. Excessive Si will result in machining difficulties.

Applications

Typical uses. Produced as rod, bar, and forgings for nuts, bolts, shafting, pump parts, valve seats, faucet balls, gears, cams, structural members, and tube sheets for condensers in power stations and desalting units
Precautions in use. Not suitable for use in oxidizing acids

Mechanical Properties

Tensile properties. Typical data for 25 mm (1 in.) diam round rod, HR50 temper: tensile strength, 760 MPa (110 ksi); yield strength, 470 MPa (68 ksi); elongation, 10% in 50 mm (2 in.); reduction in area, 10%. See also Table 99.
Compressive properties. HR50 temper. Compressive strength, ultimate: 1035 MPa (150 ksi)
Hardness. HR50 temper: 94 HRB. See also Table 99.

Poisson's ratio. 0.328
Elastic modulus. Tension, 115 GPa (17×10^6 psi); shear, 44 GPa (6.4×10^6 psi). See also Table 99.
Impact strength. Charpy V-notch, 16 to 21 J (12 to 15 ft · lbf) at 20 °C (68 °F). See also Fig. 46.
Fatigue strength. Reverse bending, 255 MPa (37 ksi) at 10^8 cycles

Structure

Microstructure. Features α, κ, and metastable β phases in various structures, depending on heat treatment and/or thermal history and composition. Normally, α plus α-κ lamellar structure with areas of β

Mass Characteristics

Density. 7.58 g/cm^3 (0.274 lb/in.^{3}) at 20 °C (68 °F)
Volume change on freezing. Approximately 2% contraction

Thermal Properties

Liquidus temperature. 1055 °C (1930 °F)
Solidus temperature. 1035 °C (1895 °F)
Coefficient of linear thermal expansion. 16.2 μm/m · K (9.0 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 375 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 37.7 W/m · K (21.8 Btu/ft · h · °F) at 20 °C (68 °F); temperature coefficient, 0.09 W/m · K per K at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 9% IACS at 20 °C (68 °F)
Electrical resistivity. 192 nΩ · m at 20 °C (68 °F)

Magnetic Properties

Magnetic permeability. 1.05

Chemical Properties

General corrosion behavior. See C61400.

Fabrication Characteristics

Machinability. 30% of C36000 (free-cutting brass), with breaking to slightly stringy chips. Carbide or tool steel cutters may be used, and good lubrication and cooling are essential. Typical conditions using tool steel cutters: roughing speed, 75 m/min (250 ft/min) with a feed of 0.3 mm/rev (0.011 in./rev); finishing speed, 290 m/min (950 ft/min) with a feed of 0.1 mm/rev (0.004 in./rev). Using carbide cutters: roughing speed, 53 m/min (175 ft/min) with a feed of 0.3 mm/rev (0.011 in./rev); finishing speed, 38 m/min (125 ft/min) with a feed of 0.3 mm/rev (0.011 in./rev)

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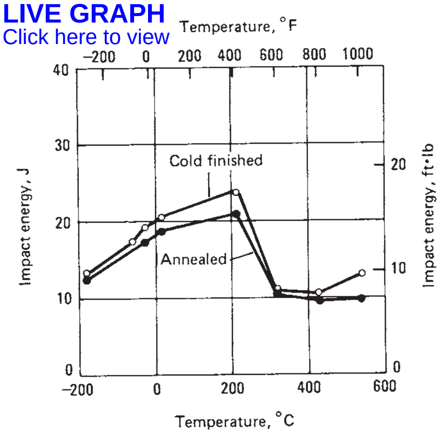

Fig. 46 Variation in Charpy V-notch impact strength with temperature for C63000

Forgeability. 75% of C37700 (forging brass)
Formability. Poor for cold working; good for hot forming
Weldability. Gas-shielded arc, coated metal arc and spot, seam, and butt resistance welding: good. Brazing: fair. Soldering and oxyacetylene welding are not recommended.
Annealing temperature. 600 to 700 °C (1100 to 1300 °F)
Hot-working temperature. 800 to 925 °C (1450 to 1700 °F)

C63200
82Cu-9Al-5Ni-4Fe

Commercial Names

Common name. Nickel-aluminum bronze

Chemical Composition

Composition limits. 75.9 to 84.5 Cu, 8.5 to 9.5 Al, 3.0 to 5.0 Fe, 4.0 to 5.5 Ni (+ Co), 3.5 Mn max, 0.10 Si max, 0.02 Pb max, 0.5 max other (total)
Iron content shall not exceed Ni content.
Consequence of exceeding impurity limits. Excessive Pb and Si will cause hot shortness in weld joints. Excessive Mn will reduce corrosion resistance.

Applications

Typical uses. Produced as rod, bar, and forgings for nuts, bolting, shafts, pump parts, propellers, and miscellaneous uses for corrosion- and spark-resistant parts for industrial, marine, and submarine applications
Precautions in use. Not suitable for use in oxidizing acids

Mechanical Properties

Tensile properties. Depending on amount of cold work or heat treatment. Tensile strength, 640 to 725 MPa (93 to 105 ksi); yield strength, 330 to 380 MPa (48 to 55 ksi); elongation, 18% in 50 mm (2 in.); reduction in area, 18%
Compressive properties. Compressive strength, ultimate: 760 MPa (110 ksi)
Hardness. 92 to 97 HRB
Poisson's ratio. 0.320
Elastic modulus. Tension, 115 GPa (17×10^6 psi); shear, 44 GPa (6.4×10^6 psi)
Impact strength. Charpy V-notch, 23 to 27 J (17 to 20 ft · lbf) at –29 to 20 °C (–20 to 78 °F); Charpy keyhole, 13 to 16 J (10 to 12 ft · lbf) at –29 to 20 °C (–20 to 78 °F)

Structure

Microstructure. Features α, κ, and metastable β phases in various structures, depending on heat treatment and/or thermal history and composition. Normally, α plus α-κ lamellar structure with or without areas of β phase

Mass Characteristics

Density. 7.64 g/cm^3 (0.276 lb/in.^{3}) at 20 °C (68 °F)
Volume change on freezing. Approximately 2% contraction

Thermal Properties

Liquidus temperature. 1060 °C (1940 °F)
Solidus temperature. 1040 °C (1905 °F)
Coefficient of linear thermal expansion. 16.2 μm/m · K (9.0 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 439 J/kg · K (0.105 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 36 W/m · K (21 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 7% IACS at 20 °C (68 °F)
Electrical resistivity. 246 nΩ · m at 20 °C (68 °F)

Magnetic Properties

Magnetic permeability. 1.04

Fabrication Characteristics

Machinability. Fair. Tendency to form stringy chips and to gall makes good lubrication and cooling essential. Tool steel or carbide cutters may be used. Good finish and fine thread tapping possible. Typical conditions using tool steel cutters: roughing speed, 75 m/min (250 ft/min) with a feed of 0.3 mm/rev (0.011 in./rev); finishing speed, 290 m/min (950 ft/min) with a feed of 0.1 mm/rev (0.004 in./rev). Using carbide cutters: roughing speed, 53 m/min (175 ft/min) with a feed of 0.3 mm/rev (0.011 in./rev); finishing speed, 38 m/min (125 ft/min) with a feed of 0.3 mm/rev (0.011 in./rev)
Annealing temperature. 705 to 880 °C (1300 to 1615 °F)
Hot-working temperature. 705 to 925 °C (1300 to 1700 °F)

C63600
95.5Cu-3.5Al-1.0Si

Chemical Composition

Composition limits. 93.5 to 96.3 Cu, 3.0 to 4.0 Al, 0.7 to 1.3 Si, 0.50 Zn max, 0.20 Sn max, 0.15 Ni max, 0.15 Fe max, 0.05 Pb max

Applications

Typical uses. Rod and wire for components for pole line hardware; cold-headed nuts for wire and cable connectors; bolts; screw machine products

Mechanical Properties

Tensile properties. See Table 100.
Hardness. See Table 100.
Elastic modulus. Tension, 110 GPa (16 × 10^6 psi)

Mass Characteristics

Density. 8.33 g/cm^3 (0.301 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1035 °C (1890 °F)
Coefficient of linear thermal expansion. 17.2 µm/m · K (9.4 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Thermal conductivity. 57 W/m · K (33 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 12% IACS at 20 °C (68 °F)
Electrical resistivity. 143 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 40% of C36000 (free-cutting brass)
Formability. Excellent for cold working; fair for hot forming
Weldability. Gas-shielded arc, shielded metal arc, and resistance welding: fair. Soldering, brazing, and oxyfuel gas welding are not recommended.
Hot-working temperature. 760 to 875 °C (1400 to 1600 °F)

Table 100 **Typical mechanical properties of C63600**

Diameter			Tensile strength		Elongation in 50 mm (2 in.), %	Hardness, HRB
mm	in.	Temper	MPa	ksi		
Rod						
16	0.63	O61	415	60	64	…
14	0.56	H01	510	74	31	…
Wire						
10	0.40	O61	415	60	67	…
11	0.42	H00 (7%)	470	68	52	71
12	0.49	H01 (21%)	580	84	29	84

Table 101 **Typical mechanical properties of C63800 sheet and strip**

	Tensile strength		Yield strength at 0.2% offset		Elongation in 50 mm (2 in.), %	Hardness	
Temper	MPa	ksi	MPa	ksi		HRB	HR30T
O61	565	82	385	56	33	…	74
H01	660	96	565	82	17	94	78
H02	730	106	640	93	10	97	80
H03	765	111	680	99	8	98	81
H04	825	120	750	109	5	99	82
H06	855	124	780	113	4	100	82
H08	895	130	800	116	3	100	83
H10	895 min	130 min	820 min	119 min	2 max	100 min	83 min

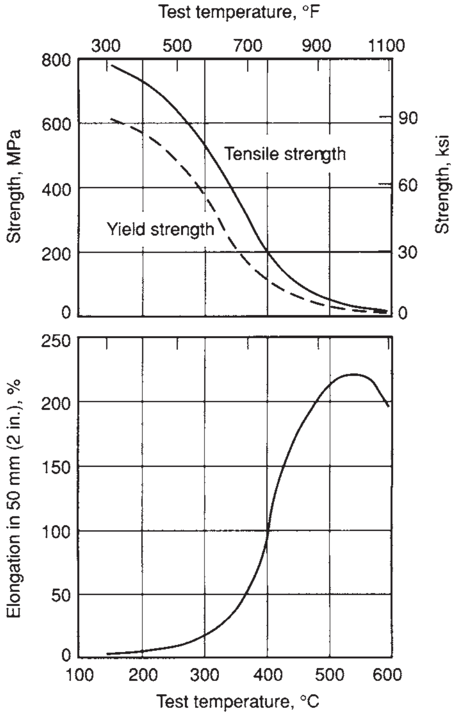

Fig. 47 Typical short-time tensile properties of C63800, H02 temper

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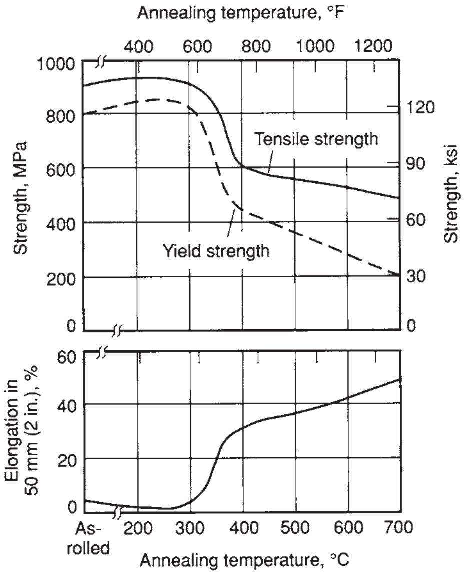

Fig. 48 Anneal resistance of C63800 strip, H08 temper. Typical room-temperature tensile properties for material annealed 1 h at various temperatures

LIVE GRAPH
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C63800
95Cu-2.8Al-1.8Si-0.40Co

Commercial Names

Trade name. Coronze

Chemical Composition

Composition limits. 2.5 to 3.1 Al, 1.5 to 2.1 Si, 0.25 to 0.55 Co, 0.80 Zn max, 0.10 Ni max, 0.05 Pb max, 0.10 Fe max, 0.10 Mn max, bal Cu

Applications

Typical uses. Springs, switch parts, contacts, relay springs, glass sealing, and porcelain enameling

Mechanical Properties

Tensile properties. See Table 101 and Fig. 47 and 48.
Hardness. See Table 101.
Poisson's ratio. 0.312
Elastic modulus. Tension, 117 GPa (16.7 × 10^6 psi)

Mass Characteristics

Density. 8.28 g/cm^3 (0.299 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1030 °C (1885 °F)
Solidus temperature. 1000 °C (1830 °F)
Coefficient of linear thermal expansion. 17.1 µm/m · K (9.5 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 375 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 42 W/m · K (24 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 10% IACS at 20 °C (68 °F), annealed
Electrical resistivity. 174 nΩ · m at 20 °C (68 °F), annealed

Chemical Properties

General corrosion behavior. C63800 is more resistant to stress corrosion than the nickel silvers, approaching the performance of the highly resistant phosphor bronzes. This alloy is far superior to most other copper alloys in resistance to crevice corrosion. At elevated temperature, the oxidation resistance of C63800 is excellent. For example, after heating in air for 2 h, the film thickness on C83800 was 7 nm (0.26 µin.) at 450 °C (840 °F), 12 nm (0.47 µin.) at 600 °C (1100 °F), and 24 nm (0.94 µin.) at 700 °C (1300 °F). On the basis of weight gain after heating 2 to 24 h in air at temperatures of 600 to 800 °C (1100 to 1300 °F), C63800 was consistently superior to Nickel 270, Nichrome (80Ni-20Cr), type 301 stainless steel, Incoloy 800 (ASTM B 408), and C60600. The superiority of C63800 was especially evident at 800 °C (1300 °F).

Fabrication Characteristics

Formability. Suitable for blanking, drawing, bending, shearing, and stamping. Excellent for cold working and hot forming

Weldability. Soft soldering utilizing standard fluxes is normally employed. Brazing, gas-shielded arc welding, and all forms of resistance welding are also commonly used.
Annealing temperature. 400 to 600 °C (750 to 1100 °F). See also Fig. 48.

C65100
98.5Cu-1.5Si

Commercial Names

Previous trade name. Low-silicon bronze B
Common name. Low-silicon bronze

Specifications

ASME. Bar, rod, shapes: SB98. Tubular products: SB315
ASTM. Flat products: B 97. Bar, rod, shapes: B 98. Tubular products: B 315. Wire: B 99
Government. QQ-C-591

Chemical Composition

Composition limits. 0.8 to 2.0 Si, 0.05 Pb max, 0.8 Fe max, 1.5 Zn max, 0.7 Mn max, bal Cu

Applications

Typical uses. Aircraft: hydraulic pressure lines. Hardware: anchor screws, bolts, cable clamps, cap screws, machine screws, marine hardware, nuts, pole line hardware, rivets, U-bolts. Industrial: electrical conduits, heat exchanger tubes, welding rod

Mechanical Properties

Tensile properties. See Table 102.
Shear strength. See Table 102.
Hardness. See Table 102.
Elastic modulus. Tension, 115 GPa (17 × 10^6 psi); shear, 44 GPa (6.4 × 10^6 psi)
Fatigue strength. Reverse bending, H04 temper, 170 MPa (25 ksi) at 10^8 cycles; H06 temper, 195 MPa (28 ksi) at 10^8 cycles

Mass Characteristics

Density. 8.75 g/cm^3 (0.316 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1060 °C (1940 °F)
Solidus temperature. 1030 °C (1890 °F)
Coefficient of linear thermal expansion. 18 µm/m · K (9.9 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 57 W/m · K (33 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 12% IACS at 20 °C (68 °F)
Electrical resistivity. 144 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 30% of C36000 (free-cutting brass)
Formability. Excellent for cold working and hot forming
Weldability. Soldering, brazing, gas-shielded arc, resistance spot, and resistance butt welding: excellent. Oxyfuel gas and resistance seam welding: good. Shielded metal arc welding: fair
Annealing temperature. 475 to 675 °C (900 to 1250 °F)
Hot-working temperature. 700 to 875 °C (1300 to 1600 °F)

C65400
95.4Cu-3.0Si-1.5Sn-0.1Cr

Chemical Composition

Composition limits. 2.7 to 3.4 Si, 1.2 to 1.9 Sn, 0.01 to 0.12 Cr, 0.5 Zn max, 0.05 Pb max, bal Cu

Applications

Typical uses. Applications where high strength and good formability combined with good stress relaxation resistance is required. Specific uses include contact springs, connectors, and wiring devices.

Mechanical Properties

Tensile properties. See Table 103.
Hardness. See Table 103.
Elastic modulus. 117 GPa (17.0 × 10^6 psi)
Fatigue strength. See Table 103.

Mass Characteristics

Density. 8.55 g/cm^3 (0.309 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1020 °C (1865 °F)
Solidus temperature. 955 °C (1755 °F)
Coefficient of linear thermal expansion. 17.5 µm/m · K (9.7 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Thermal conductivity. 36 W/m · K (21 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 7% IACS at 20 °C (68 °F)
Electrical resistivity. 246 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 30% of C36000 (free-cutting brass)
Formability. Excellent capacity for both cold working and hot forming
Weldability. Soldering and brazing: good. All forms of resistance welding and gas-shielded arc welding: excellent. Coated metal arc welding: fair
Annealing temperature. 400 to 600 °C (750 to 1100 °F)

C65500
97Cu-3Si

Commercial Names

Previous trade name. High-silicon bronze A
Common name. High-silicon bronze

Specifications

AMS. Bar, rod: 4615. Tubing: 4665
ASME. Flat products: SB96. Bar, rod, shapes: SB98. Tubular products: SB315

Table 102 Typical mechanical properties of C65100

Temper	Tensile strength MPa	Tensile strength ksi	Yield strength(a) MPa	Yield strength(a) ksi	Elongation in 50 mm (2 in.), %	Hardness	Shear strength MPa	Shear strength ksi
Rod, 25 mm (1 in.) thick								
OS035	275	40	105	15	50	55 HRF	…	…
H04 (36%)	485	70	380	55	15	80 HRB	310	45
H06 (50%)	620	90	460	67	12	90 HRB	345	50
Wire, 2 mm (0.08 in.) diameter								
H00	380	55	275	40	40	…	250	36
H01	450	65	345	50	25	…	275	40
H02	550	80	435	63	15	…	310	45
H04	690	100	485	70	11	…	345	50
H06	725	105	490	71	10	…	365	53
Wire, 11 mm (0.44 in.) diameter								
H00 (21%)	435	63	…	…	30	…	…	…
H02 (37%)	550	80	…	…	20	…	…	…
H04 (60%)	655	95	…	…	12	…	…	…
Tubing, 25 mm (1.0 in.) outside diameter × 1.65 mm (0.065 in.) wall thickness								
OS015	310	45	140	20	55	68 HRF	…	…
H80 (35%)	450	65	275	40	20	75 HRB	…	…

(a) At 0.5% extension under load

Table 103 Nominal mechanical properties of C65400 strip

Temper	Tensile strength MPa	Tensile strength ksi	Yield strength MPa	Yield strength ksi	Elongation in 50 mm (2 in.), %	Hardness, HRB	Fatigue strength at 10^8 cycles MPa	Fatigue strength at 10^8 cycles ksi
H01	570	83	415	60	30	82	…	…
H02	655	95	585	85	20	92	…	…
H03	725	105	635	92	13	95	…	…
H04	790	115	700	102	6	97	235	34
H06	825	120	760	110	5	99	…	…
H08	890	129	815	118	3	100	255	37
H10	930	135	860	125	2	101	…	…

ASTM. Flat products: B 96, B 97, B 100. Bar, rod, shapes: B 98, B 124. Forgings: B 283. Tubular products: B 315. Wire: B 99
SAE. J463
Government. QQ-C-591. Tubing: MIL-T-8231

Chemical Composition

Composition limits. 2.8 to 3.8 Si, 0.5 Pb max, 0.8 Fe max, 1.5 Zn max, 1.5 Mn max, 0.6 Ni max, bal Cu

Applications

Typical uses. Aircraft: hydraulic pressure lines. Hardware: bolts, burrs, butts, clamps, cotter pins, hinges, marine hardware, nails, nuts, pole line hardware, screws. Industrial: bearing plates, bushings, cable, channels, chemical equipment, heat exchanger tubes, kettles, piston rings, tanks, rivets, screen cloth and wire, screen plates, shafting. Marine: propeller shafts

Mechanical Properties

Tensile properties. See Table 104.
Shear strength. See Table 104.
Hardness. See Table 104.
Elastic modulus. Tension, 105 GPa (15 × 10^6 psi); shear, 39 GPa (5.6 × 10^6 psi)
Fatigue strength. Reverse bending, H04 temper, 200 MPa (29 ksi) at 10^8 cycles; H08 temper, 205 MPa (30 ksi) at 10^8 cycles

Mass Characteristics

Density. 8.53 g/cm^3 (0.308 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1025 °C (1880 °F)
Solidus temperature. 970 °C (1780 °F)
Coefficient of linear thermal expansion. 18 μm/m · K (10 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 36 W/m · K (21 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 7% IACS at 20 °C (68 °F)
Electrical resistivity. 246 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 30% of C36000 (free-cutting brass)
Forgeability. 40% of C37700 (forging brass)
Formability. Excellent for cold working and hot forming
Weldability. Brazing, gas-shielded arc, and all forms of resistance welding: excellent. Soldering and oxyfuel gas welding: good. Shielded metal arc welding: fair
Annealing temperature. 475 to 700 °C (900 to 1300 °F)
Hot-working temperature. 700 to 875 °C (1300 to 1600 °F)

C66400
86.5Cu-1.5Fe-0.5Co-11.5Zn

Commercial Names

Previous trade name. Cobron

Chemical Composition

Composition limits. 1.3 to 1.7 Fe, 0.30 to 0.70 Co, 11.0 to 12.0 Zn, 0.05 Sn max, 0.05 Ni max, 0.05 Al max, 0.05 Mn max, 0.05 Si max, 0.05 Ag max, 0.02 P max, 0.015 Pb max, bal Cu. Note: The Fe + Co content shall be 1.8 to 2.0 (total).

Applications

Typical uses. Spring washers, switchblades, fuse clips, contact springs, socket contacts, connectors, terminals, and similar parts for electronic and electromechanical assemblies

Table 104 Typical mechanical properties of C65500

Temper	Tensile strength MPa	Tensile strength ksi	Yield strength(a) MPa	Yield strength(a) ksi	Elongation in 50 mm (2 in.), %	Hardness, HRB	Shear strength MPa	Shear strength ksi
Flat products, 1 mm (0.04 in.) thick								
OS070	385	56	145	21	63	40	290	42
OS035	415	60	170	25	60	62	295	43
OS015	435	63	205	30	55	66	310	45
H01	470	68	240	35	30	75	325	47
H02	540	78	310	45	17	87	345	50
H04	650	94	400	58	8	93	390	57
H06	715	104	415	60	6	96	415	60
H08	760	110	427	62	4	97	435	63
Rod, 25 mm (1.0 in.) diameter								
OS050	400	58	150	22	60	60	295	43
H02 (20%)	540	78	310	45	35	85	360	52
H04 (36%)	635	92	380	55	22	90	400	58
H06 (50%)	745	108	415	60	13	95	425	62
Wire, 2 mm (0.08 in.) diameter								
OS035	415	60	170	25	60	…	295	43
H00	485	70	275	40	35	…	330	48
H01	550	80	330	48	20	…	360	52
H02	675	98	395	57	8	…	400	58
H04	860	125	450	65	5	…	450	65
H08 (80%)	1000	145	485	70	3	…	485	70
Tubing, 25 mm (1.0 in.) outside diameter × 1.65 mm (0.065 in.) wall thickness								
OS050	395	57	…	…	70	45	…	…
H80 (35%)	640	93	…	…	22	92	…	…

(a) At 0.5% extension under load

Mechanical Properties

Tensile properties. See Table 105.
Elastic modulus. Tension, 112 GPa (16.3 × 10^6 psi)
Fatigue strength. Reverse bending, O60 temper, 165 MPa (24 ksi) at 10^8 cycles; H04 temper, 185 MPa (27 ksi) at 10^8 cycles

Mass Characteristics

Density. 8.74 g/cm^3 (0.317 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1055 °C (1930 °F)
Solidus temperature. 1035 °C (1895 °F)
Thermal conductivity. 116 W/m · K (67 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, O61 temper: 30% IACS at 20 °C (68 °F)
Electrical resistivity. O61 temper: 57.5 nΩ · m at 20 °C (68 °F)

C68800
73.5Cu-22.7Zn-3.4Al-0.4Co

Commercial Names

Trade name. Alcoloy

Specifications

ASTM. Flat products: B 592

Chemical Composition

Composition limits. 72.3 to 74.7 Cu, 3.0 to 3.8 Al, 0.25 to 0.55 Co, 0.05 Pb max, 0.05 Fe max, 0.010 max other (total), bal Zn (25.1 to 27.1 Al + Zn)

Applications

Typical uses. Springs, switches, contacts, relays, terminals, plug receptacles, connectors

Mechanical Properties

Tensile properties. See Tables 106 and 107.
Hardness. See Table 106.
Elastic modulus. Tension, 116 GPa (16.8 ×10^6 psi)

Mass Characteristics

Density. 8.20 g/cm^3 (0.296 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 965 °C (1765 °F)

Table 105 Typical mechanical properties of C66400

Temper	Tensile strength MPa	Tensile strength ksi	Yield strength at 0.2% offset MPa	Yield strength at 0.2% offset ksi	Elongation in 50 mm (2 in.), %
O60	435	63	310	45	25
H01	495	72	455	66	13
H02	545	79	525	76	7
H03	570	83	560	81	6
H04	605	88	585	85	5
H06	650	94	615	89	4
H08	670	97	635	92	3
H10	690	100	640	93	3

Solidus temperature. 950 °C (1740 °F)
Coefficient of linear thermal expansion. 18 µm/m · K (10 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 375 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 69 W/m · K (40 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric: O61 temper: 18% IACS at 20 °C (68 °F); H08 temper, 16.6% IACS at 20 °C (68 °F)
Electrical resistivity. O61 temper, 96 nΩ · m at 20 °C (68 °F); H08 temper, 104 nΩ · m

Magnetic Properties

Magnetic permeability. 1.003

Chemical Properties

General corrosion behavior. C68800 is more resistant than C26000 to both corrosion and stress-corrosion cracking.

Fabrication Characteristics

Formability. Suitable for blanking, drawing, bending, shearing, and stamping. Bending characteristics are nearly nondirectional for all annealed and rolled tempers. Excellent for cold working and hot forming
Weldability. Can be joined by soft soldering when mildly activated commercial fluxes are used and exhibits substantially better tarnish resistance than most other copper alloys. Can also be joined by brazing and resistance welding
Annealing temperature. 400 to 600 °C (750 to 1100 °F)
Order strengthening. When heated to 220 °C (425 °F), temper-rolled C68800 undergoes an ordering reaction that increases strength (see Table 107) and decrease ductility. Because this decrease in ductility would adversely affect formability, parts should be order strengthened after forming. Specific times and temperatures for thermal treatment may vary, depending on cold-worked temper. Susceptibility to stress-corrosion cracking increases dramatically with an increase in the degree of ordering.
Stabilization treatment. Stabilization treatment is performed when enhanced stress relaxation is desired. This treatment causes little change in the 0.2% offset yield strength. Temperature and time of the treatment vary, depending on cold-worked temper; the ranges are 280 to 320 °C (535 to 610 °F) and 10 min to 2 h, respectively. To gain the maximum benefit from a stabilization treatment, parts should be stabilized after forming. There is no increase in stress-corrosion susceptibility as a result of this treatment.

C69000
73.3Cu-22.7Zn-3.4Al-0.6Ni

Chemical Composition

Composition limits. 72 to 74.5 Cu, 3.3 to 3.5 Al, 0.50 to 0.70 Ni, 0.05 Fe max, 0.025 Pb max, bal Zn

Applications

Typical uses. Electrical component parts, contacts, connectors, switches, relays, springs, high-strength shells

Mechanical Properties

Tensile properties. See Table 108.
Hardness. See Table 108.
Elastic modulus. Tension, 115 GPa (16.7 × 10^6 psi)

Mass Characteristics

Density. 8.19 g/cm^3 (0.296 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 960 °C (1760 °F)
Solidus temperature. 950 °C (1745 °F)
Coefficient of linear thermal expansion. 18 µm/m · K (10 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 40 W/m · K (23 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, O61 temper: 18% IACS at 20 °C (68 °F)
Electrical resistivity. O61 temper: 96 nΩ · m

Chemical Properties

General corrosion behavior. Significantly better corrosion performance than C26000, both in uniform corrosion rate and stress-corrosion resistance

Fabrication Characteristics

Formability. Behavior in blanking, drawing, forming, bending, stamping, and other cold forming operations is similar to that of C26000, but with lower directionality in bending of cold-worked tempers. Excellent for cold working and hot forming
Weldability. Resistance welding: good. Soldering and brazing: fair, provided that active flux is used. Oxyfuel gas and arc welding are not recommended.
Annealing temperature. 400 to 600 °C (750 to 1100 °F); stress relief anneal, 225 °C (435 °F) for 1 h
Hot-working temperature. 790 to 840 °C (1450 to 1550 °F)

Table 106 Typical mechanical properties of 1 mm (0.04 in.) thick C68800 strip

	Tensile strength		Yield strength at 0.2% offset		Elongation in 50 mm (2 in.), %	Hardness	
Temper	MPa	ksi	MPa	ksi		HRB	HR30T
O60(a)	565	82	365	53	35	78	69
O50	615	89	475	69	30	…	…
H01	650	94	525	76	20	90.5	78
H02	725	105	635	92	9	95	81
H04	780	113	705	102	5	97	82.5
H06	825	120	750	109	3	98	83
H08	885	128	785	114	2	99	83.5
H10	895 min	130 min	805 min	117 min	2 max	99 max	84 min

(a) Annealed C68800 usually has a very fine grain size (0.010 mm or less).

Table 107 Typical mechanical properties of C68800 after low-temperature thermal treatment

	As-rolled				Stabilization treated(a)			
	Tensile strength		Yield strength at 0.2% offset		Tensile strength		Yield strength at 0.2% offset	
Temper	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi
H02(b)	695	101	640	93	725	105	690	100
H04	750	109	670	97	780	113	740	107
H06	840	122	760	110	910	132	895	130
H08	890	129	785	114	960	139	925	134
H10	895 min	130 min	805 min	117 min	965	140	945	137

(a) Heated 1 h at 205 to 230 °C (400 to 445 °F). (b) Stabilization treatment is not effective on H00 or H01 temper material.

Table 108 Typical mechanical properties of C69000

	Tensile strength		Yield strength at 0.2% offset		Elongation in 50 mm (2 in.), %	Hardness	
Temper	MPa	ksi	MPa	ksi		HRB	HR30T
OS025	565	82	360	52	35	…	69
H01	650	94	525	76	19.5	90.5	…
H02	715	105	635	92	9	95	…
H04	780	113	700	102	4.5	97	…
H06	825	120	750	109	2.5	98	…
H08	870	126	785	114	1.5	96	…
H10	895 min	130 min	805	117	2 max	99 min	…
EHT(a)	930	135	875	127	1	…	84.5

(a) Cold rolled 50% and stress relief annealed 1 h at 220 °C (425 °F)

Table 109 Typical mechanical properties of copper alloy C69400 rod

	Section size		Tensile strength		Yield strength (0.5% extension under load)			
Temper	mm	in.	MPa	ksi	MPa	ksi	Elongation in 50 mm (2 in.), %	Hardness, HRB
O60	13	0.5	621	90	310	45	20	85
	25	1.0	586	85	296	43	25	85
	51	2.0	550	80	276	40	25	85
H00	19	0.75	689	100	393	57	21	95

Table 110 Nominal tensile properties of C70250 strip

	Tensile strength		Yield strength		
Temper	MPa	ksi	MPa	ksi	Elongation in 50 mm (2 in.), %
TM00	585	85	655	95	6
TM04	690	100	730	106	2

C69400
81.5Cu-14.5Zn-4Si

Commercial Names

Previous trade name. Silicon red brass, CA694

Specifications

ASTM. Rod B 371 (CA694)

Chemical Composition

Composition limits. 80.0 to 83.0 Cu, 0.30 Pb max, 0.20 Fe max, 3.5 to 4.5 Si, bal Zn

Applications

Typical uses. Valve stems requiring a combination of corrosion resistance and high strength; forged or screw-machined parts

Mechanical Properties

Tensile properties. See Table 109.
Hardness. See Table 109.
Elastic modulus. Tension, 110 GPa (16 × 10^6 psi)

Mass Characteristics

Density. 8.19 g/cm^3 (0.296 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 920 °C (1685 °F)
Solidus temperature. 820 °C (1510 °F)
Coefficient of linear thermal expansion. 20.2 μm/m · K (11.2 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 26 W/m · K (15 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 6.2% IACS at 20 °C (68 °F)
Electrical resistivity. 280 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 30% of C36000 (free-cutting brass)
Forgeability. 80% of C37700 (forging brass)
Formability. Excellent capacity for being hot formed; poor for being cold formed
Weldability. Soft soldering and silver alloy brazing: excellent. Oxyfuel gas welding and resistance welding: good. Arc welding is not recommended.
Annealing temperature. 425 to 650 °C (800 to 1200 °F)
Hot-working temperature. 650 to 875 °C (1200 to 1600 °F)

C70250
95.4Cu-3.0Ni-0.6Si-0.1Mg

Chemical Composition

Composition limits. 2.2 to 4.2 Ni, 0.25 to 1.2 Si, 0.05 to 0.3 Mg, 1.0 Zn max, 0.05 Pb max, 0.1 Mn max, 0.2 Fe max, 99.5 Cu + named elements min

Applications

Typical uses. Applications where high strength and good formability combined with good stress relaxation resistance and moderate conductivity are required. Specific uses include contact springs, connectors, and lead frames.

Mechanical Properties

Tensile properties. See Table 110.
Elastic modulus. 131 GPa (19.0 × 10^6 psi)

Mass Characteristics

Density. 8.80 g/cm^3 (0.318 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1095 °C (2003 °F)
Solidus temperature. 1075 °C (1967 °F)
Coefficient of linear thermal expansion. 17.6 μm/m · K (9.8 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Thermal conductivity. 147 to 190 W/m · K (85 to 110 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 35 to 40% IACS at 20 °C (68 °F)
Electrical resistivity. 43.1 to 49.3 nΩ · m at 20 °C (68 °F)

C70400
92.4Cu-5.5Ni-1.5Fe-0.6Mn

Specifications

ASTM. Pipe: B 466. Tubing: B 111, B 359, B 395, B 466, B 543

Chemical Composition

Composition limits. 91.2 Cu min, 4.8 to 6.2 Ni, 1.3 to 1.7 Fe, 0.3 to 0.8 Mn, 1.0 Zn max, 0.05 Pb max

Applications

Typical uses. Rolled strip, sheet, and tubing for industrial uses; condensers, condenser plates, evaporator and heat exchanger tubes, ferrules, saltwater piping, lithium bromide absorption system tubing, shipboard condenser intake systems

Mechanical Properties

Tensile properties. See Table 111.
Hardness. See Table 111.
Elastic modulus. Tension, 115 GPa (17 × 10^6 psi); shear, 44 GPa (6.4 × 10^6 psi)

Mass Characteristics

Density. 8.94 g/cm^3 (0.323 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1125 °C (2050 °F)
Coefficient of linear thermal expansion. 17.5 μm/m · K (9.7 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 64 W/m · K (37 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 14% IACS at 20 °C (68 °F)
Electrical resistivity. 120 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Formability. Excellent for cold working; good for hot forming
Weldability. Soldering, brazing, and gas-shielded arc welding: excellent. Coated metal arc and resistance spot, seam, and butt welding: good. Oxyacetylene welding: fair
Annealing temperature. 565 to 815 °C (1050 to 1500 °F)

Table 111 Typical mechanical properties of C70400

			Yield strength						
	Tensile strength		At 0.5% extension under load		At 0.2% offset			Hardness	
Temper	MPa	ksi	MPa	ksi	MPa	ksi	Elongation in 50 mm (2 in.), %	HRB	HR30T
Strip									
O61	260	38	83	12	…	…	41	8	…
H01	350	51	…	…	275	40	21	54	57
H02	395	57	…	…	380	55	11	67	65
H04	440	64	…	…	435	63	5	72	68
H06	485	70	…	…	475	69	3	75	69
H08	530	77	…	…	525	76	2 min	76 min	70 min
Tubing, 25 mm (1.0 in.) outside diameter × 1.65 mm (0.065 in.) wall thickness									
OS015	285	41	97	14	…	…	46	58 HRF	…
H55	330	48	250	36	…	…	18	67 HRF	…

Hot-working temperature. 815 to 950 °C (1500 to 1750 °F)

C70600
90Cu-10Ni

Commercial Names

Previous trade names. Copper-nickel, 10%; CA706
Common name. 90-10 cupronickel

Specifications

ASME. Flat products: SB171, SB402. Pipe: SB466, SB467. Tubing: SB111, SB359, SB395, SB466, SB467, SB543
ASTM. Flat products: B 122, B 171, B 402, B 432. Pipe: B 466, B 467. Rod: B 151. Tubing: B 111, B 359, B 395, B 466, B 467, B 543, B 552
SAE. Plate and tubing: J463
Government. Bar, flat products, forgings, rod: MIL-C-15726 E(2). Tubing: MIL-T-16420 J(3), MIL-T-1368 C(2), MIL-T-23520 A(4). Condenser tubing: MIL-T-15005 F

Chemical Composition

Composition limits. 0.05 Pb max, 1 to 1.8 Fe, 1.0 Zn max, 9 to 11 Ni, 1.0 Mn max, 0.5 max other (total), bal Cu

Applications

Typical uses. Condensers, condenser plates, distiller tubes, evaporator and heat exchanger tubes, ferrules, saltwater piping, boat hulls

Mechanical Properties

Tensile properties. See Table 112 and Fig. 49.
Elastic modulus. Tension, 140 GPa (20 × 10^6 psi); shear, 52 GPa (7.5 × 10^6 psi)
Fatigue strength. Tubing, H55 temper: 138 MPa (20 ksi) at 10^8 cycles

Mass Characteristics

Density. 8.94 g/cm^3 (0.323 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1150 °C (2100 °F)
Solidus temperature. 1100 °C (2010 °F)
Coefficient of linear thermal expansion. 17.1 μm/m · K (9.5 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 40 W/m · K (23 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 9.1% IACS
Electrical resistivity. 190 nΩ · m at 20 °C (68 °F)

Optical Properties

Color. Pink-silver

Chemical Properties

Resistance to specific agents. Excellent resistance to seawater

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Formability. Good capacity for being both cold worked and hot formed
Weldability. Soldering, brazing, gas-shielded arc, and resistance butt welding: excellent. Shielded metal arc and resistance spot and seam welding: good. Oxyfuel gas welding: fair
Annealing temperature. 600 to 825 °C (1100 to 1500 °F)
Hot-working temperature. 850 to 950 °C (1550 to 1750 °F)

C71000
80Cu-20Ni

Commercial Names

Previous trade names. Copper-nickel, 20%; CA710
Common name. 80-20 cupronickel

Specifications

ASME. Pipe: SB466, SB467. Tubing: SB111, SB359, SB395, SB466, SB467
ASTM. Bar and flat products: B 122. Pipe: B 466, B 467. Tubing: B 111, B 359, B 395, B 466, B 467. Wire: B 206
SAE. Bar, flat products, and tubing: J463

Chemical Composition

Composition limits. 0.05 Pb max, 1.00 Fe max, 1.00 Zn max, 19 to 23 Ni, 1.00 Mn max, 0.5 max other (total), bal Cu

Applications

Typical uses. Communication relays, condensers, condenser plates, electrical springs, evaporator and heat exchanger tubes, ferrules, resistors

Mechanical Properties

Tensile properties. See Table 112.
Fatigue strength. Tubing, H55 temper: 138 MPa (20 ksi) at 10^8 cycles
Elastic modulus. Tension, 140 GPa (20 × 10^6 psi); shear, 52 GPa (7.5 × 10^6 psi)

Mass Characteristics

Density. 8.94 g/cm^3 (0.323 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1200 °C (2190 °F)
Solidus temperature. 1150 °C (2100 °F)
Coefficient of linear thermal expansion. 16.4 μm/m · K (9.1 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 36 W/m · K (21 Btu/ft · h · °F) at 20 °C (68 °F)

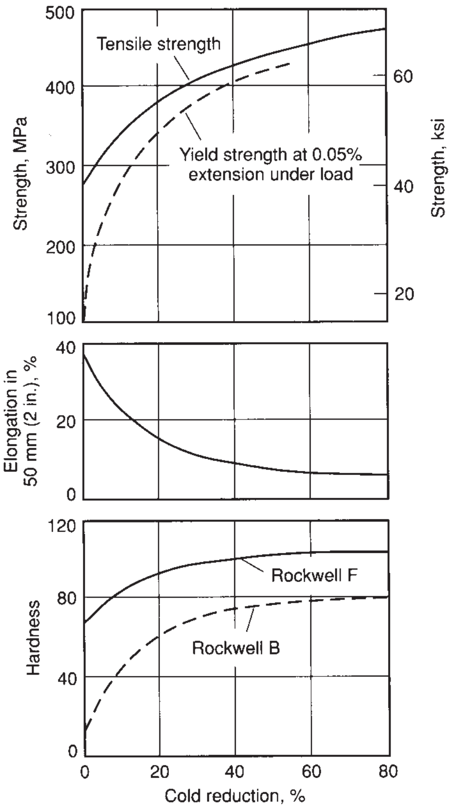

Fig. 49 Mechanical properties of cold drawn C70600 tubing. Data for variation in mechanical properties with amount of cold reduction for tubing with a diameter of 60 mm (2$\frac{3}{8}$ in.) and a wall thickness of 4.8 mm ($\frac{3}{16}$ in.) wall

LIVE GRAPH
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Table 112 Typical mechanical properties of C70600 and C71000

	Tensile strength		Yield strength					Hardness	
			0.5% extension under load		0.2% offset		Elongation in 50 mm (2 in.), %		
Temper	MPa	ksi	MPa	ksi	MPa	ksi		HRF	HRB
Flat products, 1 mm (0.04 in.) thick									
OS050	350	51	90	13	90	13	35	72	25
OS035	358	52	98	14	98	14	35	73	27
OS025	365	53	110	16	110	16	35	75	30
H01	415	60	330	48	338	49	20	92	58
H02	468	68	425	62	435	63	8	100	75
H04	518	75	490	71	500	72	5	…	80
H06	540	78	518	75	525	76	4	…	82
H08	565	82	540	78	545	79	3	…	84
H10	585	85	540	78	545	79	3	…	86
Tubing, 25 mm (1 in.) outside diameter × 1.65 mm (0.065 in.) wall thickness									
OS025	338	49	125	18	…	…	40	72	25
H55	468	68	430	62	…	…	14	…	76
Wire, 2 mm (0.080 in.) diameter									
H10	655	95	585	85	…	…	5	…	…

Electrical Properties

Electrical conductivity. Volumetric, O61 temper: 6.5% IACS at 20 °C (68 °F)
Electrical resistivity. O61 temper: 265 nΩ · m at 20 °C (68 °F)

Optical Properties

Color. Pale silver

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Formability. Good capacity for being cold worked by blanking, forming, and bending; good capacity for being hot formed
Weldability. Soldering, brazing, gas-shielded arc welding and resistance welding (all forms): excellent. Shielded metal arc welding: good. Oxyfuel gas welding: fair
Annealing temperature. 650 to 825 °C (1200 to 1500 °F)
Hot-working temperature. 875 to 1050 °C (1600 to 1900 °F)

C71500
70Cu-30Ni

Commercial Names

Previous trade names. Copper-nickel, 30%; CA715
Common name. 70-30 cupronickel

Specifications

ASME. Flat products: SB171, SB402. Pipe: SB466, SB467. Tubing: SB111, SB359, SB395, SB466, SB467, SB543
ASTM. Flat products: B 122, B 151, B 171, B 402. Pipe: B 466, B 467. Rod: B 151. Tube: B 111, B 359, B 395, B 466, B 467, B 552
SAE. Bar, flat products, tubing: J463
Government. Bar, flat products, forgings, rod, wire: MIL-C-15726. Tubing: MIL-T-15005, MIL-T-16420, MIL-T-22214

Chemical Composition

Composition limits. 0.05 Pb max, 0.4 to 0.7 Fe, 1.0 Zn max, 29 to 33 Ni, 1.0 Mn max, 0.5 max other (total), bal Cu

Applications

Typical uses. Condensers, condenser plates, distiller tubes, evaporator and heat exchanger tubes, ferrules, saltwater piping
Precautions in use. Stress relieving or full annealing should precede exposure to solders of all kinds.

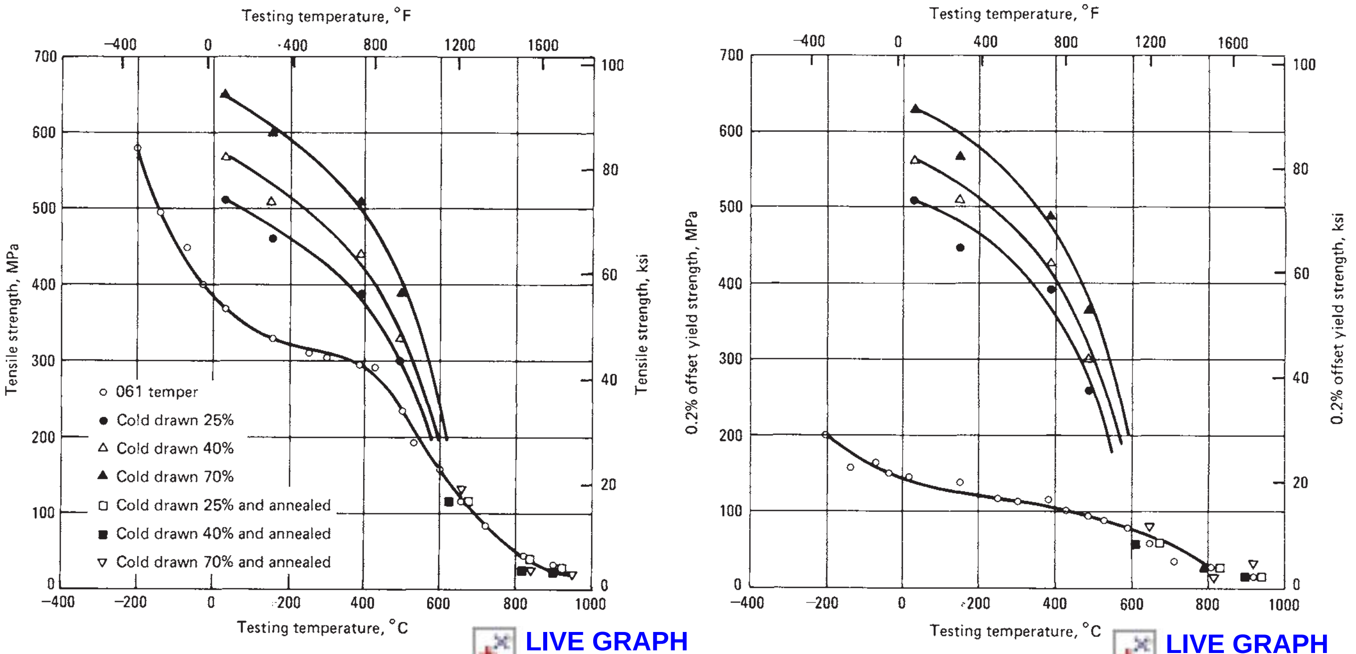
Mechanical Properties

Tensile properties. See Table 113 and Fig. 50.
Elastic modulus. Tension, 150 GPa (22×10^6 psi) at 20 °C (68 °F); shear, 57 GPa (8.3×10^6 psi) at 20 °C (68 °F)
Hardness. See Table 113.
Impact strength. Charpy keyhole data: 107 J (79 ft · lbf) at 21 °C (70 °F); 88 to 93 J (65 to 69 ft · lbf) at –73 °C (–100 °F) after holding 30 to 140 days at –87 °C (–125 °F). Data are for 10 mm (0.4 in.) square specimens machined from 25 mm (1 in.) thick plate having a room temperature hardness of 88 HRF. See Table 114 for additional impact data.
Fatigue strength. Rod, H80 temper, drawn 50% to 25 mm (1 in.) in diameter: 220 MPa (32 ksi) at 10^8 cycles. Rod, O61 temper, drawn 50% to 25 mm (1 in.) in diameter, then annealed at 760 °C (1400 °F): 150 MPa (22 ksi) at 10^8 cycles
Creep-rupture characteristics. Creep strength for 3.2 mm (0.125 in.) diam wire, OS020 temper: for a creep rate of 0.001% in 1000 h, 165 MPa (24 ksi) at 150 °C (300 °F) or 110 MPa (16 ksi) at 260 °C (500 °F); for a creep rate of 0.01% in 1000 h, 240 MPa (35 ksi) at 150 °C

Table 113 Typical mechanical properties of C71500

		Tensile strength		Yield strength(a)		Elongation in 50 mm (2 in.), %	Hardness, HRB
Size	Temper	MPa	ksi	MPa	ksi		
Flat products							
25 mm (1 in.) plate	M20 temper	380	55	140	20	45	36
1 mm (0.04 in.) strip	O61 temper(b)	380	55	125	18	36	40
	H80 temper	580	84	545	79	3	86
Rod							
< 25 mm (1 in.) diameter	O61 temper(c)	380	55	140	20	45	37
	H80 temper(d)	585	85	540	78	15	81
25 mm (1 in.) diameter	H02 temper(e)	515	75	485	70	15	80
Tubing							
19 mm (0.75 in.) outside diameter × 1.25 mm (0.049 in.) wall thickness	O61 temper(b)	340	49	…	…	50	…
	H80 temper	580	84	…	…	4	…
25 mm (1 in.) outside diameter × 1.65 mm (0.065 in.) wall thickness	OS025 temper	415	60	170	25	45	45
114 mm (4.5 in.) outside diameter × 2.75 mm (0.109 in.) wall thickness	OS035 temper	370	54	…	…	45	36

(a) 0.5% extension under load. (b) Annealed at 705 °C (1300 °F). (c) Annealed at 760 °C (1400 °F). (d) Cold drawn 50%. (e) Cold drawn 20%



LIVE GRAPH
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Fig. 50 Typical tensile and yield strengths of C71500 rod

LIVE GRAPH
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or 205 MPa (30 ksi) at 260 °C. Creep strength for 19 mm (¾ in.) diam rod, O61 temper, drawn to size and annealed at 550 °C (1020 °F): 63 MPa (9.1 ksi) for a creep rate of 0.01% in 1000 h at 400 °C (750 °F); 130 MPa (18.8 ksi) for a creep rate of 0.1% in 1000 h at 400 °C (750 °F)

Mass Characteristics

Density. 8.94 g/cm^3 (0.323 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1240 °C (2260 °F)
Solidus temperature. 1170 °C (2140 °F)
Coefficient of linear thermal expansion. 16.2 μm/m · K (9 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 29 W/m · K (17 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, O61 temper: 4.6% IACS at 20 °C (68 °F)
Electrical resistivity. O61 temper: 375 nΩ · m at 20 °C (68 °F); temperature coefficient, 4.8 × 10^{-5}/K (2.6 × 10^{-5}/ °F) at 20 to 200 °C (68 to 392 °F)

Optical Properties

Color. White

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Formability. Good capacity for being both cold worked and hot formed by bending and forming and welding processes
Weldability. Soldering, brazing, all forms of arc welding, and all forms of resistance welding: excellent. Oxyfuel gas welding: good
Annealing temperature. 650 to 825 °C (1200 to 1500 °F)
Hot-working temperature. 925 to 1050 °C (1700 to 1900 °F)

C71900
67.2Cu-30Ni-2.8Cr

Commercial Names

Previous trade names. Copper-nickel, chromium-bearing; CA719
Common name. Cupronickel with Cr

Chemical Composition

Composition limits. 28 to 32 Ni, 2.4 to 3.2 Cr, 0.5 Fe max, 0.2 to 1.0 Mn, 0.01 to 0.20 Ti, 0.02 to 0.25 Zr, 0.04 C max, 0.25 Si max, 0.5 max other (total), bal Cu

Applications

Typical uses. Heat exchanger tubes, tube sheets, water boxes, ferrules, saltwater pipe

Mechanical Properties (Spinodally Decomposed Condition)

Tensile properties. Tensile strength, 540 MPa (78 ksi); yield strength, 330 MPa (47 ksi) at 0.2% offset, elongation, 25%. See Table 115.
Elastic modulus. Tension, 150 GPa (22 × 10^6 psi); shear, 59 GPa (8.5 × 10^6 psi)
Fatigue strength. Smooth bar, rotating beam: 275 MPa (40 ksi) at 10^8 cycles for both spinodally decomposed condition and half-hard temper (spinodally decomposed plus 44% cold work)

Mass Characteristics

Density. 8.85 g/cm^3 (0.319 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1220 °C (2225 °F)
Solidus temperature. 1170 °C (2140 °F)
Coefficient of linear thermal expansion. 16.8 μm/m · K (9.3 μin./in. · °F) at 20 to 200 °C (68 to 392 °F); 17.1 μm/m · K (9.5 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Thermal conductivity. 29 W/m · K (16.5 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties (Spinodally Decomposed Condition)

Electrical conductivity. Volumetric, 4.4% IACS at 20 °C (68 °F)
Electrical resistivity. 395 nΩ · m at 20 °C (68 °F)

Magnetic Properties

Magnetic permeability. 1.0003 at magnetic field strength of 16 kA/m

Chemical Properties

Resistance to specific corroding agents. Seawater: C71900 resists both general and localized attack. The corrosion rate is very low (generally less than 0.1 mm/yr, or less than 4 mils/yr) in seawater flowing at velocities above about 1.8 m/s (6 ft/s). This level of corrosion resistance is comparable to or slightly less than the resistance of C71500 exposed to the same conditions. At low velocities or in stagnant seawater, C71900 exhibits slightly higher general weight loss than C71500, and corrosion is a broad, uniform type of attack. C71900 is not quite as resistant to crevice corrosion as C71500 at all velocities; for example, in a 3-month test in seawater flowing at intermediate velocity, C71900 incurred 0.2 to 0.33 mm (8 to 13 mils) penetration compared to nil penetration for C71500. Welding does not have an adverse effect on corrosion resistance; corrosion in seawater is about the same for the weld zone, heat-affected zone, and unaffected base metal. C71900 appears to be immune to stress-corrosion cracking in seawater, even when the seawater is contaminated with 5 ppm H_2S. C71900 is cathodic to carbon steel and Ni-Resist type cast iron, slightly cathodic to C71500, and anodic to austenitic stainless steels.

Fabrication Characteristics

Formability. C71900 can be cold worked in a manner similar to C71500, although C71900 has higher tensile and yield strengths at any given reduction. Hot working is readily accomplished from a starting temperature of 1040 to 1065 °C (1900 to 1950 °F), but working should not be continued below 840 °C (1550 °F) because of reduced ductility. About 25% more extrusion pressure is required for C71900 than for C71500. Because of microsegregation, cast billets should be homogenized 3 to 4 h at 1040 to 1065 °C (1900 to 1950 °F) before being extruded.
Weldability. Soldering, brazing, and all forms of arc welding: excellent. Resistance welding is not normally used for this alloy. Oxyfuel gas welding is not recommended. Material thick enough to require multipass welds develops a minimum yield strength of 345 MPa (50 ksi) as-welded. Single-pass welds develop a minimum yield strength of 275 MPa (40 ksi) as-welded. The yield strength can be raised to 345 MPa (50 ksi) by a postweld heat treatment consisting of 1 h at 480 °C (900 °F).
Heat treatment. Full properties of the spinodally decomposed condition can be achieved by slow cooling (furnace cooling or still air cooling) through the temperature range 760 to 425 °C (1400 to 800 °F) from a soaking temperature of 900 to 1000 °C (1650 to 1850 °F)
Hot-working temperature. 900 to 1065 °C (1650 to 1950 °F)

C72200
83Cu-16.5Ni-0.5Cr

Commercial Names

Previous trade names. Copper-nickel, chromium-bearing; CA722
Common name. Cupronickel with Cr

Table 114 Typical Charpy impact strengths for C71500

Testing temperature		Charpy impact strength(a)	
°C	°F	J	ft · lbf
–115	–175	81	60
–18	0	81	60
3	38	87	64
20	68	89	66
65	150	72	53
120	250	72	53
205	400	68	50

(a) For 10 mm (0.39 in.) square keyhole specimens machined from annealed rod

Table 115 Typical mechanical properties of C71900 strip

	Tensile strength		Yield strength at 0.2% offset			
Condition	MPa	ksi	MPa	ksi	Elongation in 50 mm (2 in.), %	Hardness, HRB
Heat treated(a)	600	87	365	53	32	87
Half-hard temper(b)	730	106	685	99	14	100
Hard temper(c)	780	113	740	107	8	100
Spring temper(d)	835	121	800	116	6	101

(a) Spinodally decomposed by air cooling from 900 °C (1650 °F). (b) Spinodally decomposed, then cold rolled 20%. (c) Spinodally decomposed, then cold rolled 37%. (d) Spinodally decomposed, then cold rolled 60%

Chemical Composition

Composition limits. 15 to 18 Ni, 0.3 to 0.7 Cr, 0.5 to 1.0 Fe, 0.4 to 0.9 Mn, 0.03 Si max, 0.03 Ti max, 0.03 C max, 0.5 max other (total), bal Cu

Applications

Typical uses. Condenser and heat exchanger tubing, saltwater pipe

Mechanical Properties

Tensile properties. O61 temper: tensile strength, 315 MPa (46 ksi); yield strength, 125 MPa (18 ksi) at 0.2% offset; elongation, 46%. H04 temper: tensile strength, 480 MPa (70 ksi); yield strength, 455 MPa (66 ksi) at 0.2% offset; elongation, 6%
Elastic modulus. Tension, 135 GPa (20 × 10^6 psi); shear, 55 GPa (8.2 × 10^6 psi)

Mass Characteristics

Density. 8.94 g/cm^3 (0.323 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1176 °C (2148 °F)
Solidus temperature. 1122 °C (2052 °F)
Coefficient of linear thermal expansion. 15.8 μm/m · K (8.8 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 396 J/kg · K (0.094 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 34.5 W/m · K (19.9 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 6.53% IACS
Electrical resistivity. 264 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Formability. Good capacity for being cold worked or hot formed
Weldability. Gas-shielded arc welding: excellent. Soldering, brazing, shielded metal arc welding, and resistance welding (all forms): good. Oxyfuel gas welding: fair
Annealing temperature. 730 to 815 °C (1350 to 1500 °F)
Hot-working temperature. 900 to 1040 °C (1650 to 1900 °F)

C72500
88.2Cu-9.5Ni-2.3Sn

Commercial Names

Previous trade names. Copper-nickel, tin-bearing; CA725
Common name. Cupronickel with Sn

Chemical Composition

Composition limits. 0.05 Pb max, 0.6 Fe max, 0.5 Zn max, 0.2 Mn max, 8.5 to 10.5 Ni, 1.8 to 2.8 Sn, 0.2 max other (total), bal Cu

Applications

Typical uses. Relay and switch springs, connectors, lead frames, control and sensing bellows, brazing alloy

Mechanical Properties

Tensile properties. See Table 116.
Elastic modulus. Tension, 137 GPa (20 × 10^6 psi); shear, 52 GPa (7.5 × 10^6 psi)

Mass Characteristics

Density. 8.89 g/cm^3 (0.321 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1130 °C (2065 °F)
Solidus temperature. 1060 °C (1940 °F)
Coefficient of linear thermal expansion. 16.5 μm/m · K (9.2 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Thermal conductivity. 55 W/m · K (31 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 11% IACS at 20 °C (68 °F)
Electrical resistivity. O61 temper, 157 nΩ · m at 20 °C (68 °F)

Optical Properties

Color. Silver

Chemical Properties

Resistance to specific agents. Excellent resistance to seawater

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Formability. Excellent capacity for being both cold worked and hot formed by blanking, coining, drawing, forming, bending, heading, upsetting, roll threading, knurling, shearing, spinning, squeezing, stamping, and swaging
Weldability. Soldering, brazing, and resistance spot and resistance butt welding: excellent. Gas-shielded arc, shielded metal arc, and resistance seam welding: good. Oxyfuel gas welding: fair
Annealing temperature. 650 to 800 °C (1200 to 1475 °F)
Hot-working temperature. 850 to 950 °C (1550 to 1750 °F)

Table 116 Tensile properties of C72500

			Yield strength					
	Tensile strength		0.5% extension under load		0.2% offset			
Temper	MPa	ksi	MPa	ksi	MPa	ksi	Elongation in 50 mm (2 in.), %	Hardness, HRB
Flat products, 1 mm (0.04 in.) thick								
Annealed(a)	380	55	150	22	150	22	35	42
Quarter hard	450	65	365	53	400	58	18	71
Half hard	490	71	450	65	475	69	6	78
Hard	570	83	515	75	555	81	3	85
Extra hard	600	87	555	81	590	86	2	88
Spring	625	91	570	83	620	90	1	90
Super spring	770	112	570	83	740	108	1	99
Wire, 2 mm (0.08 in.) diameter								
Annealed(a)	415	60	170	25	…	…	…	…

(a) Grain size, 0.015 mm

C74500
65Cu-25Zn-10Ni

Commercial Names

Common name: Nickel silver, 65-10

Specifications

ASTM. Flat products: B 122. Bar: B 122, B 151. Rod: B 151. Wire: B 206
Government. Flat products: QQ-C-585. Bar: QQ-C-585, QQ-C-586. Rod, shapes, flat wire: QQ-C-586. Wire: QQ-W-321

Chemical Composition

Composition limits. 63.5 to 68.5 Cu, 9.0 to 11.0 Ni, 0.10 Pb max, 0.25 Fe max, 0.5 Mn max, 0.5 max other, bal Zn

Applications

Typical uses. Hardware: rivets, screws, slide fasteners. Optical goods: optical parts. Miscellaneous: etching stock, hollowware, nameplates, platers' bars

Mechanical Properties

Tensile properties. See Table 117.
Hardness. See Table 117.
Elastic modulus. Tension, 120 GPa (17.5 × 10^6 psi); shear, 46 GPa (6.6 × 10^6 psi)

Mass Characteristics

Density. 8.69 g/cm^3 (0.314 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1020 °C (1870 °F)
Coefficient of linear thermal expansion. 16.4 μm/m · K (9.1 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/ft · °F) at 20 °C (68 °F)
Thermal conductivity. 45 W/m · K (26 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 9.0% IACS at 20 °C (68 °F)
Electrical resistivity. 192 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Formability. Excellent for cold working; poor for hot forming

Weldability. Soldering and brazing: excellent. Oxyfuel gas, resistance spot, and resistance butt welding: good. Gas metal arc and resistance seam welding: fair. Shielded metal arc welding: not recommended
Annealing temperature. 600 to 750 °C (1100 to 1400 °F)

C75200
65Cu-18Ni-17Zn

Commercial Names

Common name. Nickel silver, 65-18

Specifications

ASTM. Flat products: B 122. Bar: B 122, B 151. Rod: B 151. Wire: B 206
SAE. J463
Government. Flat products: QQ-C-585. Bar: QQ-C-585, QQ-C-586. Rod, shapes, flat wire: QQ-C-586. Wire: QQ-W-321

Chemical Composition

Composition limits. 63.0 to 66.5 Cu, 16.5 to 19.5 Ni, 0.1 Pb max, 0.25 Fe max, 0.5 Mn max, 0.5 max other (total), bal Zn

Applications

Typical uses. Hardware: rivets, screws, table flatware, truss wire, zippers. Optical goods: bows, camera parts, core bars, templates. Miscellaneous: base for silver plate, costume jewelry, etching stock, hollowware, nameplates, radio dials

Mechanical Properties

Tensile properties. See Table 118.
Hardness. See Table 118.
Elastic modulus. Tension, 125 GPa (18 × 10^6 psi); shear, 47 GPa (6.8 × 10^6 psi)

Mass Characteristics

Density. 8.73 g/cm^3 (0.316 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1110 °C (2030 °F)
Solidus temperature. 1070 °C (1960 °F)
Coefficient of linear thermal expansion. 16.2 μm/m · K (9.0 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 33 W/m · K (19 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 6% IACS at 20 °C (68 °F)
Electrical resistivity. 287 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Formability. Excellent for cold working; poor for hot forming
Weldability. Soldering and brazing: excellent. Oxyfuel gas, resistance spot, and resistance butt welding: good. Gas metal arc and resistance seam welding: fair. Shielded metal arc welding is not recommended.

C75400
65Cu-20Zn-15Ni

Commercial Names

Common name. Nickel silver, 65-15

Chemical Composition

Composition limits. 63.5 to 66.5 Cu, 14.0 to 16.0 Ni, 0.1 Pb max, 0.25 Fe max, 0.5 Mn max, 0.5 max other (total), bal Zn

Applications

Typical uses. Camera parts, optical equipment, etching stock, jewelry

Mechanical Properties

Tensile properties. See Table 119.
Hardness. See Table 119.
Elastic modulus. Tension, 125 GPa (18 × 10^6 psi); shear, 47 GPa (6.8 × 10^6 psi)

Mass Characteristics

Density. 8.70 g/cm^3 (0.314 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1075 °C (1970 °F)
Solidus temperature. 1040 °C (1900 °F)
Coefficient of linear thermal expansion. 16.2 μm/m · K (9.0 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 36 W/m · K (21 Btu/ft · h · °F) at 20 °C (68 °F)

Table 117 Typical mechanical properties of C74500

	Tensile strength		Yield strength(a)		Elongation in 50 mm	Hardness			Shear strength	
Temper	MPa	ksi	MPa	ksi	(2 in.), %	HRF	HRB	HR30T	MPa	ksi
Flat products, 1 mm (0.04 in.) thick										
OS070	340	49	125	18	49	67	22	30	…	…
OS050	350	51	130	19	46	71	28	34	…	…
OS035	365	53	140	20	43	76	35	38	285	41
OS025	385	56	160	23	40	80	42	44	…	…
OS015	415	60	195	28	36	85	52	51	…	…
H00	415	60	240	35	34	…	60	55	295	43
H01	450	65	310	45	25	…	70	63	310	45
H02	505	73	415	60	12	…	80	70	345	50
H04	590	86	515	75	4	…	89	76	380	55
H06	655	95	525	76	3	…	92	78	405	59
Wire, 2 mm (0.08 in.) diameter										
OS070	345	50	…	…	50	…	…	…	…	…
OS050	360	52	…	…	48	…	…	…	…	…
OS035	385	56	…	…	45	…	…	…	…	…
OS025	400	58	…	…	40	…	…	…	…	…
OS015	435	63	…	…	35	…	…	…	…	…
H00 (10%)	450	65	…	…	25	…	…	…	…	…
H01 (20%)	495	72	…	…	10	…	…	…	…	…
H02 (37%)	585	85	…	…	7	…	…	…	…	…
H04 (60%)	725	105	…	…	5	…	…	…	…	…
H06 (75%)	825	120	…	…	3	…	…	…	…	…
H08 (84%)	895	130	…	…	1	…	…	…	…	…

(a) At 0.5% extension under load

Table 118 Typical mechanical properties of C75200

	Tensile strength		Yield strength(a)		Elongation in 50 mm	Hardness		
Temper	MPa	ksi	MPa	ksi	(2 in.), %	HRF	HRB	HR30T
Flat products, 1 mm (0.04 in.) thick								
OS035	400	58	170	25	40	85	40	…
OS015	415	60	205	30	32	90	55	…
H01	450	65	345	50	20	…	73	65
H02	510	74	427	62	8	…	83	72
H04	585	85	510	74	3	…	87	75
Rod, 13 mm (0.5 in.) diameter								
OS035	385	56	170	25	42	…	…	…
H02 (20%)	485	70	415	60	20	…	78	…
Wires, 2 mm (0.08 in.) diameter								
OS035	400	58	170	25	45	…	…	…
OS015	415	60	205	30	35	…	…	…
H01	505	73	450	65	16	…	…	…
H02	590	86	550	80	7	…	…	…
H04	710	103	620	90	3	…	…	…

(a) At 0.5% extension under load

Electrical Properties

Electrical conductivity. Volumetric, 7% IACS at 20 °C (68 °F)
Electrical resistivity. 246 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Formability. Excellent for cold working by blanking, drawing, forming, bending, heading, upsetting, roll threading, knurling, shearing, spinning, squeezing, or swaging; poor for hot forming
Weldability. Soldering and brazing: excellent. Oxyfuel gas, resistance spot, and resistance butt welding: good. Gas metal arc and resistance seam welding: fair. Shielded metal arc welding is not recommended.
Annealing temperature. 600 to 815 °C (1100 to 1500 °F)

C75700

65Cu-23Zn-12Ni

Commercial Names

Common name. Nickel silver, 65-12

Specifications

ASTM. Bar, rod: B 151. Wire: B 206
Government. Wire: QQ-W-321

Chemical Composition

Composition limits. 63.5 to 66.5 Cu, 11.0 to 13.0 Ni, 0.05 Pb max, 0.25 Fe max, 0.5 Mn max, 0.5 max other (total), bal Zn

Applications

Typical uses. Slide fasteners, camera parts, optical parts, etching stock, nameplates

Mechanical Properties

Tensile properties. See Table 120.
Hardness. See Table 120.
Elastic modulus. Tension, 125 GPa (18×10^6 psi); shear, 47 GPa (6.8×10^6 psi)

Mass Characteristics

Density. 8.69 g/cm^3 (0.314 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1040 °C (1900 °F)
Coefficient of linear thermal expansion. 16.2 µm/m · K (9.0 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 40 W/m · K (23 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 8% IACS at 20 °C (68 °F)
Electrical resistivity. 216 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Formability. Excellent for cold working by blanking, drawing, etching, forming, bending, heading, upsetting, roll threading, knurling, shearing, spinning, squeezing, or swaging; poor for hot forming

Table 119 Typical mechanical properties of C75400 sheet or strip, 1 mm (0.04 in.) thick

	Tensile strength		Yield strength(a)		Elongation in 50 mm	Hardness		Shear strength	
Temper	MPa	ksi	MPa	ksi	(2 in.), %	HRF	HR30T	MPa	ksi
OS070	365	53	125	18	43	69	27	…	…
OS050	380	55	130	19	42	73	33	…	…
OS035	395	57	145	21	40	79	41	285	41
OS025	405	59	165	24	37	82	46	…	…
OS015	420	61	195	28	34	89	53	…	…
H00	425	62	240	35	30	60 HRB	55	295	43
H01	450	65	340	49	21	70 HRB	63	305	44
H02	510	74	425	62	10	80 HRB	70	325	47
H04	585	85	515	75	3	87 HRB	75	360	52
H06	635	92	545	79	2	90 HRB	77	370	54

(a) At 0.5% extension under load

Table 120 Typical mechanical properties of C75700 sheet or strip, 1 mm (0.04 in.) thick

	Tensile strength		Yield strength(a)		Elongation in 50 mm	Hardness			Shear strength	
Temper	MPa	ksi	MPa	ksi	(2 in.), %	HRF	HRB	HR30T	MPa	ksi
OS070	360	52	125	18	48	69	22	27	…	…
OS050	370	54	130	19	45	73	30	33	…	…
OS035	385	56	145	21	42	78	37	38	285	41
OS025	405	59	165	24	38	82	45	44	…	…
OS015	420	61	195	28	35	88	55	51	…	…
H00	415	60	240	35	32	…	60	55	295	43
H01	450	65	310	45	23	…	70	63	305	44
H02	505	73	415	60	11	…	80	70	325	47
H04	585	85	515	75	4	…	89	75	360	52
H06	640	93	545	79	2	…	92	77	385	56

(a) At 0.5% extension under load

Weldability. Soldering and brazing: excellent. Oxyfuel gas, resistance spot, and resistance butt welding: good. Gas metal arc and resistance seam welding: fair. Shielded metal arc welding is not recommended.
Annealing temperature. 600 to 825 °C (1100 to 1500 °F)

C77000

55Cu-27Zn-18Ni

Commercial Names

Common name. Nickel silver, 55-18

Specifications

ASTM. Flat products: B 122, Bar: B 122, B 151. Rod: B 151. Wire: B 206
SAE. J463
Government. Flat products: QQ-C-585. Bar: QQ-C-585, QQ-C-586. Rod, shapes, flat wire: QQ-C-586. Wire: QQ-W-321

Chemical Composition

Composition limits. 53.5 to 56.5 Cu, 16.5 to 19.5 Ni, 0.1 Pb max, 0.25 Fe max, 0.5 Mn max, 0.5 max other (total), bal Zn

Applications

Typical uses. Optical goods, springs, resistance wire

Mechanical Properties

Tensile properties. See Table 121.
Hardness. See Table 121.
Elastic modulus. Tension, 125 GPa (18×10^6 psi); shear, 47 GPa (6.8×10^6 psi)

Mass Characteristics

Density. 8.70 g/cm^3 (0.314 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1055 °C (1930 °F)
Coefficient of linear thermal expansion. 16.7 µm/m · K (9.3 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 29 W/m · K (17 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 5.5% IACS at 20 °C (68 °F)
Electrical resistivity. 314 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 30% of C36000 (free-cutting brass)
Formability. Good for cold working by blanking, forming, bending, and shearing; poor for hot forming
Weldability. Soldering and brazing: excellent. Oxyfuel gas, resistance spot, and resistance butt welding: good. Gas metal arc and resistance seam welding: fair. Shielded metal arc welding is not recommended.
Annealing temperature. 600 to 825 °C (1100 to 1500 °F)

Table 121 Typical mechanical properties of C77000

Temper	Tensile strength		Yield strength(a)		Elongation in 50 mm	Hardness		
	MPa	ksi	MPa	ksi	(2 in.), %	HRF	HRB	HR30T
Flat products, 1 mm (0.04 in.) thick								
OS035	415	60	185	27	40	90	55	…
H04	690	100	585	85	3	…	91	77
H06	745	108	620	90	2.5	…	96	80
H08	795	115	…	…	2.5	…	99	81
Wire, 2 mm (0.08 in.) diameter								
OS035	415	60	…	…	40	…	…	…
H08 (68%)	1000	145	…	…	2	…	…	…

(a) At 0.5% extension under load

Table 122 Typical mechanical properties of 1 mm (0.04 in.) thick C78200 sheet

Temper	Tensile strength		Yield strength(a)		Elongation in 50 mm	Hardness,	Shear strength	
	MPa	ksi	MPa	ksi	(2 in.), %	HRB	MPa	ksi
OS035	365	53	160	23	40	78 HRF	275	40
OS015	405	59	185	27	32	85 HRF	295	43
H01	425	62	290	42	24	65	305	44
H02	475	69	400	58	12	78	325	47
H03	540	78	435	63	5	84	350	51
H04	585	85	505	73	4	87	370	54
H06	625	91	525	76	3	90	400	58

(a) At 0.5% extension under load

C78200

65Cu-25Zn-8Ni-2Pb

Chemical Composition

Composition limits. 63.0 to 67.0 Cu, 1.5 to 2.5 Pb, 7.0 to 9.0 Ni, 0.35 Fe max, 0.50 Mn max, 0.10 max other (total), bal Zn

Applications

Typical uses. Key blanks, watch plates, watch parts

Mechanical Properties

Tensile properties. See Table 122.
Shear strength. See Table 122.
Hardness. See Table 122.
Elastic modulus. Tension, 117 GPa (17 × 10^6 psi); shear, 44 GPa (6.4 × 10^6 psi)

Mass Characteristics

Density. 8.69 g/cm^3 (0.314 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 1000 °C (1830 °F)
Solidus temperature. 970 °C (1780 °F)
Coefficient of linear thermal expansion. 18.5 μm/m · K (10.3 μin./in. · °F) at 20 to 100 °C (68 to 212 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 48 W/m · K (28 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 10.9% IACS at 20 °C (68 °F)
Electrical resistivity. 160 nΩ · m at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 60% of C36000 (free-cutting brass)
Formability. Cold working, good; hot forming, poor. Commonly fabricated by blanking, milling, and drilling
Weldability. Soldering: excellent. Brazing: good. Oxyfuel gas, arc, and resistance welding generally are not recommended.
Annealing temperature. 500 to 620 °C (930 to 1150 °F)

Properties of Cast Copper Alloys*

C81100

Commercial Names

Previous trade name. CA811

Chemical Composition

Composition limits. 99.70 Cu + Ag min, 0.30 max other (total), 0.01 P + Si max to achieve a conductivity of 92% IACS

Applications

Typical uses. Electrical and thermal conductors, applications requiring resistance to corrosion and oxidation

Mechanical Properties

Tensile properties. Typical data for sand-cast test bars: tensile strength, 170 MPa (25 ksi); yield strength, 62 MPa (9 ksi) at 0.5% extension under load; elongation, 40% in 50 mm (2 in.)
Hardness. 44 HB
Elastic modulus. Tension, 115 GPa (17×10^6 psi)
Fatigue strength. 62 MPa (9 ksi) at 10^8 cycles

Mass Characteristics

Density. 8.94 g/cm^3 (0.323 lb/in.^{3}) at 20 °C (68 °F)
Volume change on freezing. 4.92% contraction
Patternmaker's shrinkage. 21 mm/m ($\frac{1}{4}$ in./ft)

Thermal Properties

Liquidus temperature. 1083 °C (1981 °F)
Solidus temperature. 1065 °C (1948 °F)
Coefficient of linear thermal expansion. 16.9 μm/m · K (9.4 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 346 W/m · K (200 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 92% IACS at 20 °C (68 °F)

Magnetic Properties

Magnetic permeability. 1.0

Fabrication Characteristics

Machinability. 10% of C36000 (free-cutting brass)

C81300

Commercial Names

Previous trade name. CA813
Common name. Beryllium-copper

Chemical Composition

Composition limits. 98.5 Cu min, 0.20 to 0.10 Be, 0.6 to 1.0 Co. (Cu + sum of named elements shall be 99.5% minimum.)

Applications

Typical uses. Higher-hardness electrical and thermal conductors

Mechanical Properties

Tensile properties. Properties for separately cast heat-treated (TF00 temper) test bars; tensile strength, 365 MPa (53 ksi) min; yield strength, 250 MPa (36 ksi) min at 0.2% offset; elongation, 11% in 50 mm (2 in.)
Hardness. 89 HB (500 kg), typical
Elastic modulus. Tension, 110 GPa (16×10^6 psi) at 20 °C (68 °F)

Mass Characteristics

Density. 8.81 g/cm^3 (0.318 lb/in.^{3}) at 20 °C (68 °F)
Volume change on freezing. Patternmaker's shrinkage, 21 mm/m ($\frac{1}{4}$ in./ft)

Thermal Properties

Liquidus temperature. 1093 °C (2000 °F)
Solidus temperature. 1066 °C (1950 °F)
Coefficient of linear thermal expansion. 18 μm/m · K (10.0 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 390 J/kg · K (0.093 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 260 W/m · K (150 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 60% IACS at 20 °C (68 °F)

Fabrication Characteristics

Machinability. TF00 temper: 20% of C36000 (free-cutting brass)
Solution heat-treating temperature. 980 to 1010 °C (1800 to 1850 °F)
Aging temperature. 480 °C (900 °F)
Stress-relieving temperature. 260 °C (500 °F)

C81400
99Cu-0.8Cr-0.06Be

Commercial Names

Previous trade name. Beryllium-copper 70C, CA814
Common name. Be-modified chrome copper

Specifications

RWMA. Class II

Chemical Composition

Composition limits. 98.5 Cu min, 0.6 to 1.0 Cr, 0.02 to 0.10 Be

Applications

Typical uses. Electrical parts that meet RWMA Class II standards. The beryllium content of this alloy ensures that the chromium content will be kept under control during melting and casting, thus allowing the production of chrome copper castings of consistently high quality.
Precautions from health hazard. See C82500.

Mechanical Properties

Tensile properties. Typical as-cast: tensile strength, 205 MPa (30 ksi); yield strength, 83 MPa (12 ksi) at 0.2% offset; elongation, 35% in 50 mm (2 in.). TF00 temper: tensile strength, 365 MPa (53 ksi); yield strength, 250 MPa (36 ksi) at 0.2% offset; elongation, 11% in 50 mm (2 in.)
Hardness. As-cast: 62 HRB. TF00 temper: 69 HRB
Elastic modulus. Tension, 110 GPa (16×10^6 psi); shear, 41 GPa (5.9×10^6 psi)

Mass Characteristics

Density. 8.81 g/cm^3 (0.318 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 1.96%

Thermal Properties

Liquidus temperature. 1095 °C (2000 °F)
Solidus temperature. 1065 °C (1950 °F)
Coefficient of linear thermal expansion. 18 μm/m · K (10 μin./in. · F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 389 J/kg · K (0.093 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 259 W/m · K (150 Btu/ft · h · °F) at 20 °C (68 °F)

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*Reprinted from *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials*, Volume 2, *ASM Handbook*, 1990, p 356–391. The article was prepared for that Volume by Arthur Cohen, Copper Development Association, Inc.

Fabrication Characteristics

Machinability. As-cast or TB00 temper: 30% of C36000 (free-cutting brass); TF00 temper: 40% of C36000
Melting temperature. 1065 to 1095 °C (1950 to 2000 °F)
Casting temperature. Light castings, 1200 to 1260 °C (2200 to 2300 °F); heavy castings, 1175 to 1230 °C (2150 to 2250 °F)
Solution temperature. 1000 to 1010 °C (1830 to 1850 °F)
Aging temperature. 480 °C (900 °F)

C81500
99Cu-1Cr

Commercial Names

Previous trade names. Chromium-copper; CA815
Common name. Chrome copper

Chemical Composition

Composition limits. 98.0 to 99.6 Cu, 0.40 to 1.50 Cr, 0.015 Pb max, 0.04 P max, 0.15 max other (total)
Consequence of exceeding impurity limits. Elements that contribute to hot shortness must be avoided. Because of the high solution temperatures necessary to develop the desired mechanical properties, elements that enter into solid solution must be held to close limits.

Applications

Typical uses. Electrical and/or thermal conductors used as structural members in applications requiring greater strength and hardness than that of cast coppers C80100 to C81100

Mechanical Properties

Tensile properties. Typical data for sand-cast test bars, heat treated: tensile strength, 350 MPa (51 ksi); yield strength, 275 MPa (40 ksi) at 0.5% extension under load; elongation, 17% in 50 mm (2 in.)
Hardness. Heat treated, 105 HB
Poisson's ratio. 0.32
Elastic modulus. Tension, 115 GPa (17×10^6 psi)
Impact strength. Izod, 41 J (30 ft · lbf); Charpy V-notch, 27 J (20 ft · lbf)
Fatigue strength. 105 MPa (15 ksi) at 10^8 cycles

Mass Characteristics

Density. 8.82 g/cm^3 (0.319 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 21 mm/m ($\frac{1}{4}$ in./ft)

Thermal Properties

Liquidus temperature. 1085 °C (1985 °F)
Solidus temperature. 1075 °C (1967 °F)
Coefficient of linear thermal expansion. 17.1 μm/m · K (9.5 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 376 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 315 W/m · K (182 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric: solution heat treated, 40 to 50% IACS at 20 °C (68 °F); precipitation hardened, 80 to 90% IACS at 20 °C (68 °F)
Electrical resistivity. Solution heat treated, 38.3 nΩ · m at 20 °C (68 °F); precipitation hardened, 21 nΩ · m at 20 °C (68 °F). Temperature coefficient: solution heat treated, 0.08 nΩ · m per K at 20 °C (68 °F); precipitation hardened, 0.06 nΩ · m per K at 20 °C (68 °F)

Magnetic Properties

Magnetic permeability. 1.0

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Weldability. Chromium copper can be silver soldered, soft soldered, or brazed; it can be carbon arc welded with copper-chromium filler rod and fused-borax flux.
Solution temperature. 1000 to 1010 °C (1830 to 1850 °F)
Aging temperature. 480 °C (900 °F)

C81800
97Cu-1.5Co-1Ag-0.4Be

Commercial Names

Previous trade name. Beryllium-copper alloy 50C, CA818

Specifications

RWMA. Class III

Chemical Composition

Composition limits. 0.30 to 0.55 Be, 1.4 to 1.7 Co, 0.8 to 0.12 Ag, 0.15 Si max, 0.20 Ni max, 0.10 Fe max, 0.10 Al max, 0.10 Sn max, 0.002 Pb max, 0.10 Zn max, 0.10 Cr max, bal Cu
Consequence of exceeding impurity limits. See C82500.

Applications

Typical uses. The silver content of C81800 provides an improved surface conductivity over other RWMA Class III alloys. Typical uses are resistance welding electrode tips and holders and arms.
Precautions as health hazard. See C82500.

Mechanical Properties

Tensile properties. See Table 1.
Hardness. See Table 1 and Fig. 1.
Poisson's ratio. 0.33
Elastic modulus. Tension, 110 GPa (16×10^6 psi); shear, 41 GPa (6×10^6 psi)

Mass Characteristics

Density. 8.62 g/cm^3 (0.311 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 1.56%

Thermal Properties

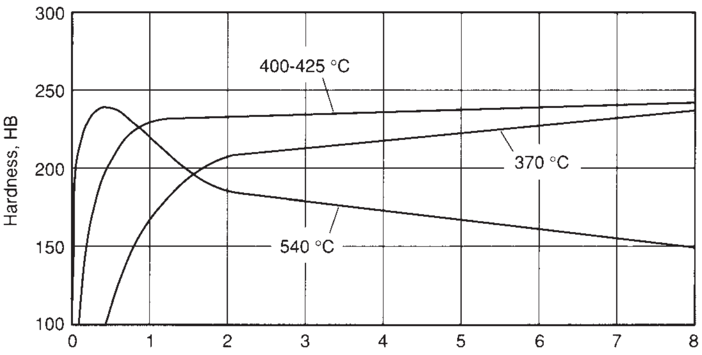
Liquidus temperature. 1070 °C (1955 °F)
Solidus temperature. 1010 °C (1855 °F)
Coefficient of linear thermal expansion. 18 μm/m · K (10 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 420 J/kg · K (0.10 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 218 W/m · K (126 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 48% IACS at 20 °C (68 °F)
Electrical resistivity. 359 μΩ· m at 20 °C (68 °F)

Magnetic Properties

Magnetic susceptibility. See C82000.



LIVE GRAPH
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Fig. 1 Aging curves for cast and solution-treated C81800

Table 1 Typical mechanical properties of C81800

	Tensile strength		Yield strength(a)			
Temper	MPa	ksi	MPa	ksi	Elongation(b), %	Hardness, HRB
As-cast	345	50	140	20	20	50
Cast and aged(c)	450	65	275	40	15	70
TB00(c)	310	45	83	12	25	40
TF00(d)(c)	705	102	515	75	8	96

(a) At 0.2% offset. (b) In 50 mm (2 in.). (c) Aged 3 h at 480 °C (900 °F). (d) Solution treated at 900 to 950 °C (1650 to 1750 °F

Nuclear Properties

Effect of neutron irradiation. See C82500.

Chemical Properties

See C82000.

Fabrication Characteristics

Machinability. As-cast or TB00 temper: 30% of C36000 (free-cutting brass). TF00 temper: 40% of C36000
Melting temperature. 1010 to 1070 °C (1855 to 1955 °F)
Casting temperature. Light castings, 1175 to 1230 °C (2150 to 2250 °F); heavy castings, 1120 to 1175 °C (2050 to 2150 °F)
Solution temperature. 900 to 925 °C (1650 to 1700 °F)
Aging temperature. 480 °C (900 °F) See also Fig. 1.

C82000
97Cu-2.5Co-0.5Be

Commercial Names

Previous trade name. Beryllium-copper alloy 10C, CA820
Common name. Beryllium-copper casting alloy 10C

Specifications

Government. QQ-C-390 (CA820), MIL-C-19464 (Class I)

Chemical Composition

Composition limits. 0.45 to 0.8 Be, 2.4 to 2.7 Co, 0.15 Si max, 0.20 Ni max, 0.10 Fe max, 0.10 Al max, 0.10 Sn max, 0.02 Pb max, 0.10 Zn max, 0.10 Cr max, bal Cu
Consequence of exceeding impurity limits. See C82500.

Table 2 Typical mechanical properties of C82000

Temper	Tensile strength		Yield strength(a)		Elongation(b), %	Hardness, HRB
	MPa	ksi	MPa	ksi		
As-cast	345	50	140	20	20	52
Cast and aged(c)	450	65	255	37	12	70
TB00(d)	325	47	105	15	25	40
TF00(d)(e)	660	96	515	75	6	96

(a) At 0.2% offset. (b) In 50 mm (2 in.). (c) Aged 2 h at 480 °C (900 °F). (d) Solution treated at 900 to 950 °C (1650 to 1750 °F). (e) Aged 3 h at 480 °C (900 °F)

Applications

Typical uses. C82000 castings are used when a combination of high conductivity and high strength is required. Applications include resistance welding tips, holders and arms, circuit-breaker parts, switch gear parts, plunger tips for die casting, concasting molds, for continuous casting installations, soldering-iron tips, brake drums, and whenever RWMA Class III properties are required.
Precautions as health hazard. See C82500.

Mechanical Properties

Tensile properties. See Table 2.
Hardness. See Table 2 and Fig. 2 and 3.
Poisson's ratio. 0.33
Elastic modulus. Tension, 115 GPa (17 × 10^6 psi); shear, 44 GPa (6.4 × 10^6 psi)
Fatigue strength. Rotating beam, 125 MPa (18 ksi) at 5 × 10^7 cycles

Mass Characteristics

Density. 8.62 g/cm^3 (0.311 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 1.56%

Thermal Properties

Liquidus temperature. 1090 °C (1990 °F)
Solidus temperature. 970 °C (1780 °F)
Coefficient of linear thermal expansion. 17.8 μm/m · K (9.9 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 420 J/kg · K (0.10 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 218 W/m · K (126 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 48% IACS at 20 °C (68 °F)
Electrical resistivity. 359 μΩ · m at 20 °C (68 °F)

Magnetic Properties

Magnetic susceptibility. Commercial beryllium-copper casting alloys containing 0.02 to 0.8% Be exhibit magnetic susceptibility of $^{+}$0.001 cgs units or less. Magnetic susceptibility varies principally with iron content—on the high side of the commercial range of iron content (0.10%), magnetic susceptibility is approximately 0.001 cgs units; on the low side of the range (0.05%), the value will be much lower (0.0001 cgs units or less). A high-temperature solution treatment of 950 °C (1750 °F) and a low aging temperature of 425 to 450 °C (800 to 850 °F) will tend to keep iron in solution and keep the alloy nonmagnetic—that is, with a magnetic susceptibility less than 0.0001 cgs units.

Nuclear Properties

Effect of neutron irradiation. See C82500.

Chemical Properties

General corrosion behavior. At elevated temperatures, beryllium is an active oxide former.

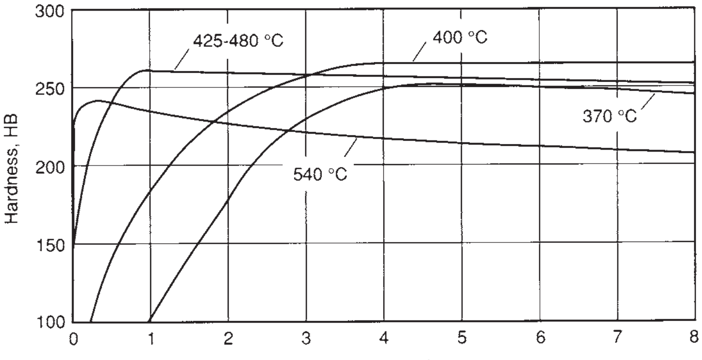

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Fig. 2 Aging curves for cast and solution-treated C82000

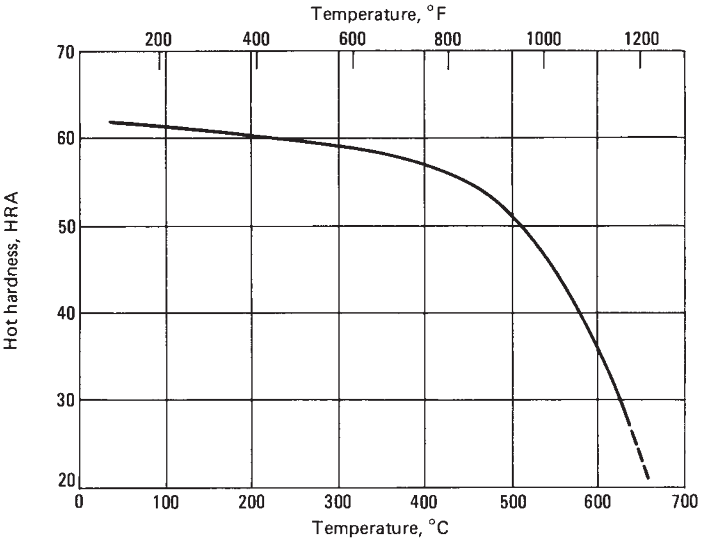

Fig. 3 Hot hardness of C82000, TF00 temper. Cast specimens were solution treated, then aged at 480 °C (900 °F). Useful design range is up to about 400 °C (750 °F).

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Beryllium in beryllium-copper alloys will preferentially form BeO when low partial pressures of oxygen are present. This causes intergranular oxidation during solution treating in air, often resulting in surface deterioration up to 0.05 mm (0.002 in.) deep. For resistance to water, chemical solutions, organic chemicals and chemical gases, and for resistance to stress-corrosion cracking, see C82500.

Fabrication Characteristics

Machinability. As-cast or TB00 temper: 30% of C36000 (free-cutting brass). TF00 temper: 40% of C36000
Melting temperature. 970 to 1090 °C (1780 to 1990 °F)
Casting temperature. Light castings, 1175 to 1230 °C (2150 to 2250 °F); heavy castings, 1120 to 1175 °C (2050 to 2150 °F)
Solution temperature. 900 to 925 °C (1650 to 1700 °F)
Aging temperature. 480 °C (900 °F). See also Fig. 2.

C82200
98Cu-1.5Ni-0.5Be

Commercial Names

Previous trade name. Beryllium-copper alloy 30C, CA822
Common name. Beryllium-copper casting alloy 30C, 35C, or 53B

Specifications

RWMA. Class III

Chemical Composition

Composition limits. 0.35 to 0.8 Be, 1.0 to 2.0 Ni, 0.15 Si max, 0.20 Co max, 0.10 Fe max, 0.10 Al max, 0.10 Sn max, 0.02 Pb max, 0.10 Zn max, 0.10 Cr max, bal Cu
Consequence of exceeding impurity limits. See C82500.

Applications

Typical uses. Seam welder electrodes, projection welder dies, spot welding tips, beam welder shapes, water-cooled holders, arms bushings for resistance welding, clutch rings, brake drums
Precautions as health hazard. See C82500.

Mechanical Properties

Tensile properties. See Table 3.
Hardness. See Table 3 and Fig. 4.
Poisson's ratio. 0.33
Elastic modulus. Tension, 114 GPa (16.5 × 10^6 psi); shear, 43 GPa (6.2 × 10^6 psi)

Mass Characteristics

Density. 8.75 g/cm^3 (0.316 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 1.56%

Thermal Properties

Liquidus temperature. 1115 °C (2040 °F)
Solidus temperature. 1040 °C (1900 °F)
Coefficient of linear thermal expansion. 16.2 μm/m · K (9 μin./in. · °F) at 20 to 200 °C (68 to 392 °F)
Specific heat. 420 J/kg · K (0.10 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 183 W/m · K (106 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 48% IACS at 20 °C (68 °F)
Electrical resistivity. 359 μΩ · m at 20 °C (68 °F)

Magnetic Properties

Magnetic susceptibility. See C82000.

Nuclear Properties

Effect of neutron irradiation. See C82500.

Chemical Properties

See C82000.

Fabrication Characteristics

Machinability. As-cast or TB00 temper: 30% of C36000 (free-cutting brass). TF00 temper: 40% of C36000
Melting temperature. 1035 to 1115 °C (1900 to 2040 °F)
Casting temperature. Light castings, 1200 to 1260 °C (2200 to 2300 °F); heavy castings, 1150 to 1200 °C (2100 to 2200 °F)
Solution temperature. 900 to 955 °C (1650 to 1750 °F)
Aging temperature. 445 to 455 °C (835 to 850 °F)

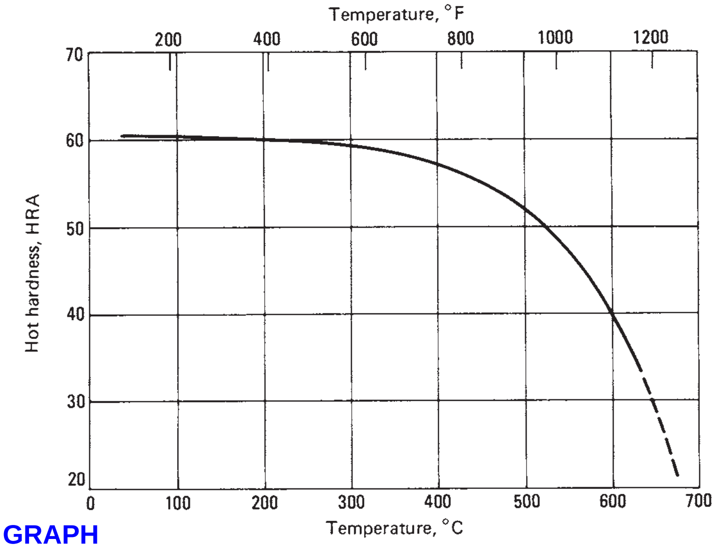

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Fig. 4 Hot hardness of C82200, TF00 temper. Aged at 480 °C (900 °F). Useful design range is up to 370 °C (700 °F).

Table 3 Typical mechanical properties of C82200

	Tensile strength		Yield strength(a)			
Temper	MPa	ksi	MPa	ksi	Elongation(b), %	Hardness, HRB
As-cast	345	50	170	25	20	55
Cast and aged(c)	450	65	275	40	15	75
TB00(d)	310	45	85	12	30	30
TF00(d)(c)	655	95	515	75	7	96

(a) At 0.2% offset. (b) In 50 mm (2 in.). (c) Aged 3 h at 480 °C (900 °F). (d) Solution treated at 900 to 955 °C (1650 to 1750 °F)

C82400
98Cu-1.7Be-0.3Co

Commercial Names

Previous trade name. Beryllium-copper alloy 165C; CA824
Common name. Beryllium-copper casting alloy 165C

Specifications

Government. QQ-C-390 (CA824)

Chemical Composition

Composition limits. 1.65 to 1.75 Be, 0.20 to 0.40 Co, 0.10 Ni max, 0.20 Fe max, 0.15 Al max, 0.10 Sn max, 0.02 Pb max, 0.10 Zn max, 0.10 Cr max, bal Cu
Consequence of exceeding impurity limits. See C82500.

Applications

Typical uses. C82400 was developed for use in marine service as a corrosion-resistant, pressure-tight casting material. Its lower beryllium content compared to C82500 makes this alloy the least expensive of the commercial high-strength beryllium-copper alloys. When its hardness is relatively low, C82400 exhibits greater-than-normal toughness. Typical uses include various

parts for the submarine telephone cable repeater system and hydrophone, molds for forming plastics, safety tools, plunger tips for die castings, cams, bushings, bearings, valves, pump parts, and gears.
Precautions as health hazard. See C82500.

Mechanical Properties

Tensile properties. See Table 4.
Hardness. See Table 4.
Poisson's ratio. 0.30
Elastic modulus. Tension, 128 GPa (18.5×10^6 psi); shear, 50 GPa (7.3×10^6 psi)
Fatigue strength. Rotating beam, 160 MPa (23 ksi) at 5×10^7 cycles

Structure

Crystal structure. See C82500.

Mass Characteristics

Density. 8.31 g/cm^3 (0.301 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 1.56%
Dilation during aging. Linear, 0.2%
Change in density during aging. 0.6% increase

Thermal Properties

Liquidus temperature. 995 °C (1825 °F)
Solidus temperature. 900 °C (1650 °F)
Incipient melting temperature. 865 °C (1585 °F)
Coefficient of linear thermal expansion. 17.0 µm/m · K (9.4 µin./in. · °F) at 20 to 200 °C (68 to 392 °F)
Specific heat. 420 J/kg · K (0.10 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 109 W/m · K (63 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 25% IACS at 20 °C (68 °F)
Electrical resistivity. 690 µΩ · m at 20 °C (68 °F)

Magnetic Properties

Magnetic susceptibility. See C82500.

Nuclear Properties

Effect of neutron irradiation. See C82500.

Chemical Properties

See C82500.

Fabrication Characteristics

Machinability. As-cast or TB00 temper: 30% of C36000 (free-cutting brass). Cast and aged or TF00 temper: 10 to 20%
Melting temperature. 900 to 1000 °C (1650 to 1825 °F)
Casting temperature. Light castings, 1080 to 1135 °C (1975 to 2075 °F); heavy castings, 1025 to 1080 °C (1875 to 1975 °F)
Solution temperature. 790 to 815 °C (1450 to 1500 °F)
Aging temperature. 345 °C (650 °F)

C82500
97.2Cu-2Be-0.5Co-0.25Si

Commercial Names

Previous trade name. Beryllium-copper 20C, CA825
Common name. Standard beryllium-copper casting alloy

Specifications

AMS. Investment castings: 4890
Government. Sand castings: QQ-C-390, MIL-C-19464 (class 2); centrifugal castings: QQ-C-390; precision castings: MIL-C-11866 (composition 17), MIL-C-17324; investment castings: MIL-C-22087
Other. ICI-Cu-2-10780

Chemical Composition

Composition limits. 95.5 Cu min, 1.90 to 2.15 Be, 0.35 to 0.7 Co, 0.20 to 0.35 Si, 0.20 Ni max, 0.25 Fe max, 0.15 Al max, 0.10 Sn max, 0.02 Pb max, 0.10 Zn max, 0.10 Cr max. Available with or without 0.02 to 0.10% Ti added as a grain refiner.
Consequence of exceeding impurity limits. Generally, electrical conductivity is lowered. High Fe raises magnetic susceptibility. High Sn, Zn, or Pb causes hot shortness. High Cr diminishes response to precipitation hardening.

Applications

Typical uses. Molds for forming plastics, die casting plunger tips, safety tools, cams, bushings, bearings, gears, sleeves, valves, wear parts, structural parts, resistance welding electrodes and inserts, holders, and structural members. Exhibits low casting temperature, good castability, excellent ability to reproduce fine detail in the pattern, high strength, high electrical and thermal conductivity, and excellent resistance to corrosion and wear. Can be sand, shell, ceramic, investment, permanent, pressure, and die cast. Especially suited for investment castings and often replaces ferrous castings having similar mechanical properties. Investment castings are used for communication, textile, aerospace, business machine, firearm, instrument, and ordnance parts.
Precautions in use as health hazard. Melting, casting, abrasive-wheel operations, abrasive blasting, welding, arc cutting, flame cutting, grinding, polishing, and buffing under improper conditions may raise the concentration of beryllium in the air to levels above the limits prescribed by OSHA, thus creating a potential for personnel to contract berylliosis, a chronic lung disease. Exhaust ventilation, the principal means of achieving compliances with these limits, is a specific OSHA requirement for processes involving beryllium alloys. Careful attention to the exhaust-ventilation requirements of these and any other effluent-producing operations is essential. Actual exposure of workers should be continually monitored using prescribed air-sampling and calculation methods to determine compliance or noncompliance with OSHA limits.

Mechanical Properties

Tensile properties. See Table 5 and Fig. 5.
Compressive properties. Compressive yield strength, 1030 to 1200 MPa (150 to 175 ksi) at a permanent set of 0.1%
Hardness. See Table 5 and Fig. 6 and 7.
Poisson's ratio. 0.30
Elastic modulus. Tension, 128 GPa (18.5×10^6 psi); shear, 50 GPa (7.3×10^6 psi)
Fatigue strength. Rotating beam, 165 MPa (24 ksi) at 5×10^7 cycles
Tensile properties and hardness versus temperature. See Fig. 5 and 7.

Structure

Crystal structure. Alpha phase, face-centered cubic. Lattice parameter; a: solution treated (2.1% Be in solid solution), 0.357 nm; precipitation hardened, 0.361 nm

Mass Characteristics

Density. 8.26 g/cm^3 (0.298 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 1.56%
Dilation during aging. Linear, 0.2%
Change in density during aging. 0.6% increase

Table 4 Typical mechanical properties of C82400

	Tensile strength		Yield strength(a)			
Temper	MPa	ksi	MPa	ksi	Elongation(b), %	Hardness
As-cast	485	70	275	40	15	78 HRB
Cast and aged(c)	690	100	550	80	3	21 HRC
TB00(d)	415	60	140	20	40	59 HRB
TF00(d)(c)	1070	155	1000	145	1	38 HRC

(a) At 0.2% offset. (b) In 50 mm (2 in.). (c) Aged 3 h at 345 °C (650 °F). (d) Solution treated at 800 to 815 °C (1475 to 1500 °F)

Table 5 Typical mechanical properties of C82500

	Tensile strength		Yield strength(a)			
Temper	MPa	ksi	MPa	ksi	Elongation(b), %	Hardness
As-cast	515	75	275	40	15	81 HRB
Cast and aged(c)	825	120	725	105	2	30 HRC
TB00(d)	415	60	170	25	35	63 HRB
TF00(d)(c)	1105	160	1035	150	1	43 HRC

(a) At 0.2% offset. (b) In 50 mm (2 in.). (c) Aged 3 h at 345 °C (650 °F). (d) Solution treated at 790 to 800 °C (1450 to 1475 °F)

Thermal Properties

Liquidus temperature. 980 °C (1800 °F)
Solidus temperature. 855 °C (1575 °F)
Incipient melting temperature. 835 °C (1535 °F)
Coefficient of linear thermal expansion. 17 μm/m · K (9.4 μin./in. · °F) at 20 to 200 °C (68 to 392 °F)

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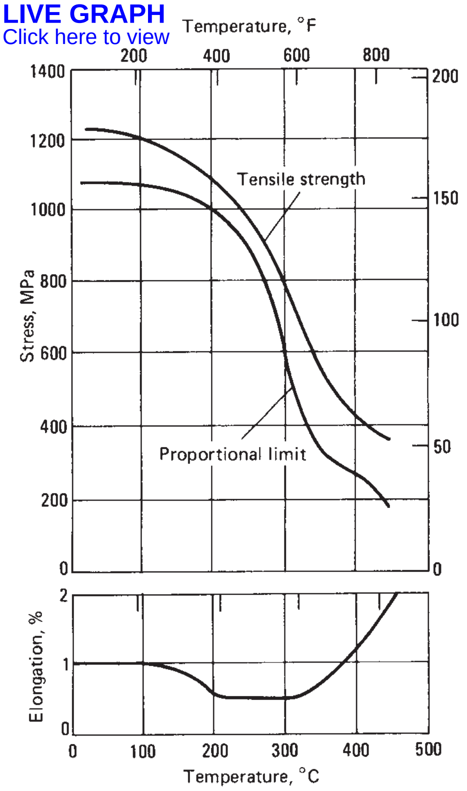

Fig. 5 Elevated-temperature tensile properties of C82500, TF00 temper. Sand cast test bars were solution treated, then aged at 345 °C (650 °F). Useful design range is limited to about 220 °C (425 °F).

Specific heat. 420 J/kg · K (0.10 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 105 W/m · K (61 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 20% IACS at 20 °C (68 °F)
Electrical resistivity. 862 μΩ · m at 20 °C (68 °F)

Magnetic Properties

Magnetic susceptibility. Commercial beryllium-copper casting alloys with 1.6 to 2.7% Be content exhibit magnetic susceptibility of approximately $^{+}$0.002 cgs units. Magnetic susceptibility varies principally with iron content. On the high side of the range for iron content (0.25%), magnetic susceptibility is greater than 0.002 cgs units. On the low side of the commercial range (0.05%), the value is much less than 0.001 cgs units. A high-temperature solution treatment of 815 °C (1500 °F) and a low aging temperature of 315 to 345 °C (600 to 650 °F) will tend to keep iron in solution and keep magnetic susceptibility below 0.002 cgs units.

Nuclear Properties

Effect of neutron irradiation. Neutron irradiation causes precipitation hardening because of thermal spikes and induced vacancies. This will affect as-cast or solution-treated tempers but have little effect on material already peak aged or overaged.

Chemical Properties

General corrosion behavior. At elevated temperatures, beryllium is an active oxide former. Beryllium in beryllium-copper alloys will preferentially form BeO when low partial pressures of oxygen are present, especially when the environment is reducing with respect to copper. This leads to preferential formation of BeO films during hot processing of alloys containing 1.6% Be or more. BeO films may be abrasive to fabricating tools, and may be removed mechanically or by pickling. The general corrosion resistance of beryllium-copper alloys is similar to that of deoxidized copper, except as indicated above.

Resistance to specific agents. Beryllium-copper alloys possess excellent resistance to atmospheric corrosion in marine, industrial, and rural environments. They have excellent resistance to organic chemicals such as alcohols, aldehydes, esters, and ketones. They are slightly more resistant to seawater than tough pitch or deoxidized copper. Resistance is good with respect to: fresh water; most organic acids, hot or cold dilute sulfuric acid, cold concentrated sulfuric acid, and cold dilute hydrochloric acid; hot or cold dilute alkalis and cold concentrated alkalis; salts, including most sulfates and chlorides. Resistance is only fair towards sulfides, especially at elevated temperatures. Resistance is poor towards: mercury and mercury compounds; nitric acid; ferric chloride, ferric sulfate, and other heavy-metal salts with oxidizing cations and strong acid anions; acid chromates; and halogens (fluorine, chlorine, bromine, and iodine), particularly at elevated temperatures.

Stress-corrosion cracking. Beryllium-copper alloys resist stress-corrosion cracking in marine and most chemical environments, even when stressed up to 90% of their 0.2% offset yield strengths. They are susceptible to stress-corrosion cracking in ammonia and halogen gas environments, especially at elevated temperature.

Fabrication Characteristics

Machinability. As-cast or TB00 temper: 30% of C36000 (free-cutting brass). Cast and aged or TF00 temper: 10 to 20%

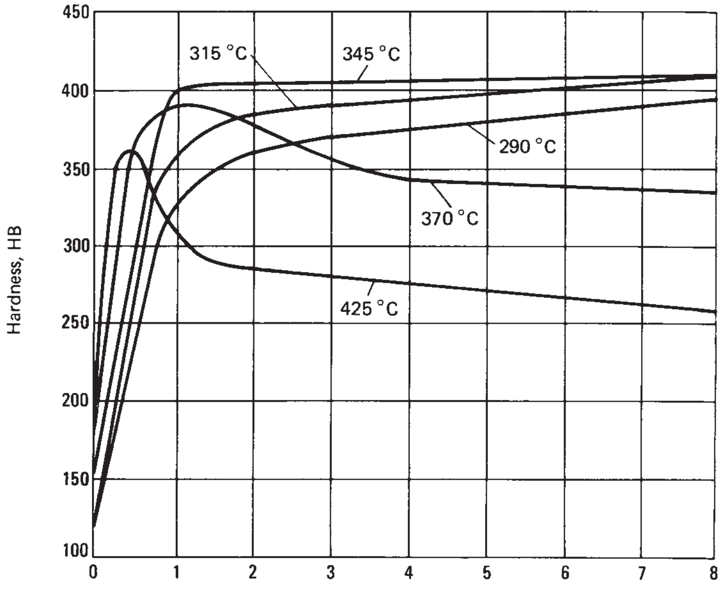

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Fig. 6 Aging curves for solution-treated C82500 or beryllium-copper alloy 21C

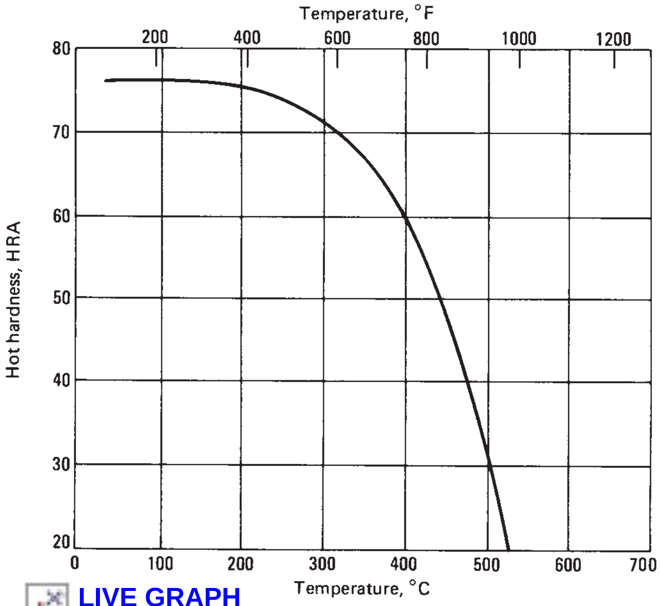

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Fig. 7 Hot hardness of C82500, TF00 temper. Specimens were solution treated, then aged at 345 °C (650 °F).

Melting temperature. 850 to 980 °C (1575 to 1800 °F)
Casting temperature. Light castings, 1065 to 1175 °C (1950 to 2150 °F); heavy castings, 1010 to 1065 °C (1850 to 1950 °F)
Solution temperature. 790 to 800 °C (1450 to 1475 °F)
Aging temperature. 345 °C (650 °F). See also Fig. 6.

C82600
97Cu-2.4Be-0.5Co

Commercial Names

Previous trade name. Beryllium-copper 245C
Common name. Beryllium-copper casting alloy 245C

Specifications

Government. QQ-C-390

Chemical Composition

Composition limits. 2.25 to 2.45 Be, 0.35 to 0.7 Co, 0.20 to 0.35 Si, 0.20 Ni max, 0.25 Fe max, 0.15 Al max, 0.10 Sn max, 0.02 Pb max, 0.10 Zn max, 0.10 Cr max, bal Cu
Consequence of exceeding impurity limits. See C82500.

Applications

Typical uses. C82600 is a beryllium-copper casting alloy intermediate in beryllium content between C82500 and C82800. It exhibits better fluidity, castability, and hardness than C82500 and better toughness and lower cost than C82800. C82600 is used primarily to produce molds for plastic parts. In pressure castings, the lower pouring temperature results in longer tool life than for similar castings of C82500.
Precautions as health hazard. See C82500.

Mechanical Properties

Tensile properties. See Table 6.
Hardness. See Table 6.
Poisson's ratio. 0.30
Elastic modulus. Tension, 130 GPa (19 × 10^6 psi); shear; 50 GPa (7.3 × 10^6 psi)

Structure

Crystal structure. Alpha phase, face-centered cubic

Mass Characteristics

Density. 8.16 g/cm^3 (0.295 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 1.56%
Dilation during aging. Linear, 0.2%
Change in density during aging. 0.6% increase

Thermal Properties

Liquidus temperature. 955 °C (1750 °F)
Solidus temperature. 855 °C (1575 °F)
Incipient melting temperature. 835 °C (1535 °F)
Coefficient of linear thermal expansion. 17 μm/m · K (9.4 μin./in. · °F) at 20 to 200 °C (68 to 392 °F)
Specific heat. 420 J/kg · K (0.10 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 100 W/m · K (58 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 19% IACS at 20 °C (68 °F)
Electrical resistivity. 907 μΩ · m at 20 °C (68 °F)

Magnetic Properties

Magnetic susceptibility. See C82500.

Nuclear Properties

Effect of neutron irradiation. See C82500.

Chemical Properties

See C82500.

Fabrication Characteristics

Machinability. As-cast or TB00 temper: 30% of C36000 (free-cutting brass). Cast and aged or TF00 temper: 10 to 20% of C36000
Melting temperature. 855 to 955 °C (1575 to 1750 °F)
Casting temperature. Light castings, 1040 to 1150 °C (1900 to 2100 °F); heavy castings, 980 to 1040 °C (1800 to 1900 °F)
Solution temperature. 790 to 800 °C (1450 to 1475 °F)
Aging temperature. 345 °C (650 °F)

C82800
96.6Cu-2.6Be-0.5Co-0.3Si

Commercial Names

Previous trade name. Beryllium-copper alloy 275C, CA828
Common name. Beryllium-copper casting alloy 275C

Specifications

Government. QQ-C-390, MIL-T-16243, MIL-C-19464 (Class IV)
Other. ICI-Cu-2-10785

Chemical Composition

Composition limits. 94.8 Cu min, 2.50 to 2.75 Be, 0.37 to 0.7 Co, 0.20 to 0.35 Si, 0.20 Ni max, 0.25 Fe max, 0.15 Al max, 0.10 Sn max, 0.02 Pb max, 0.10 Zn max, 0.10 Cr max
Consequence of exceeding impurity limits. See C82500.

Applications

Typical uses. C82800 is a special-purpose, high-fluidity casting alloy developed for molds for forming plastics and other applications where the casting process should replicate finest detail with maximum fidelity and the resultant part must exhibit maximum hardness and wear resistance for a cast beryllium-copper alloy. The relative slow pouring temperature results in increased tool life during pressure casting and permanent molding. Typical uses are molds for forming plastics, cams, bushings, bearings, valves, pump parts, sleeves, and precision cast parts for the communications, textile, aerospace, business machine, firearm, instrument, ordnance, and other industries.
Precautions in use. See C82500.

Mechanical Properties

Tensile properties. See Table 7 and Fig. 8.
Hardness. See Table 7 and Fig. 9 and 10.
Poisson's ratio. 0.30
Elastic modulus. Tension, 133 GPa (19.3 × 10^6 psi); shear, 51 GPa (7.4 × 10^6 psi)

Structure

Crystal structure. See C82500.

Mass Characteristics

Density. 8.09 g/cm^3 (0.292 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 1.56%
Linear dilation during aging. 0.2%
Change in density during aging. 0.6% increase

Thermal Properties

Liquidus temperature. 930 °C (1710 °F)
Solidus temperature. 835 °C (1535 °F)
Incipient melting temperature. 855 °C (1575 °F)
Coefficient of linear thermal expansion. 17 μm/m · K (9.4 μin./in. · °F) at 20 to 200 °C (68 to 392 °F)
Specific heat. 420 J/kg · K (0.10 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 95 W/m · K (55 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 18% IACS at 20 °C (68 °F)
Electrical resistivity. 958 μΩ · m at 20 °C (68 °F)

Magnetic Properties

Magnetic susceptibility. See C82500.

Nuclear Properties

Effect of neutron irradiation. See C82500.

Table 6 Typical mechanical properties of C82600

	Tensile strength		Yield strength(a)			
Temper	MPa	ksi	MPa	ksi	Elongation(b), %	Hardness
As-cast	550	80	345	50	10	86 HRB
Cast and aged(b)	825	120	725	105	2	31 HRC
TB00(c)	485	70	205	30	12	75 HRB
TF00(d)(c)	1140	165	1070	155	1	45 HRC

(a) At 0.2% offset. (b) In 50 mm (2 in.). (c) Aged 3 h at 345 °C (650 °F). (d) Solution treated at 790 to 800 °C (1450 to 1475 °F)

Chemical Properties

See C82500.

Fabrication Characteristics

Machinability. As-cast or TB00 temper: 30% of C36000 (free-cutting brass). Cast and aged or TF00 temper: 10 to 20% of C36000
Melting temperature. 860 to 930 °C (1575 to 1710 °F)
Casting temperature. Light castings, 1040 to 1150 °C (1900 to 2100 °F); heavy castings, 965 to 1040 °C (1770 to 1900 °F)
Solution temperature. 790 to 800 °C (1450 to 1475 °F)
Aging temperature. 345 °C (650 °F). See also Fig. 9.

C83300

Commercial Names

Previous trade name. CA833
Common name. Contact metal

Specification

Ingot code number. 131

Chemical Composition

Composition limits. 92.0 to 94.0 Cu, 1.0 to 2.0 Pb, 1.0 to 2.0 Sn, 2.0 to 6.0 Zn
Copper Specification. In reporting chemical analyses by the use of instruments such as spectrograph, x-ray, and atomic absorption, copper may be indicated as balance. In reporting chemical analyses obtained by wet methods, zinc may be indicated as balance on those alloys with over 2% Zn.

Table 7 Typical mechanical properties of C82800 sand cast test bars

	Tensile strength		Yield strength(a)			
Temper	MPa	ksi	MPa	ksi	Elongation(b), %	Hardness
As-cast	550	80	345	50	10	88 HRB
Cast and aged(c)	860	125	760	110	2	31 HRC
TB00(d)	550	80	240	35	10	85 HRB
TF00(d)(c)	1140	165	1070	155	1	46 HRC

(a) At 0.2% offset. (b) In 50 mm (2 in.). (c) Aged 3 h at 345 °C (650 °F). (d) Solution treated at 790 to 800 °C (1450 to 1475 °F)

Applications

Typical use. Terminal ends for electrical cables

Mechanical Properties

Tensile properties. Typical data for as-sand-cast separately cast test bars (M01 temper): tensile strength, 220 MPa (32 ksi); yield strength, 70 MPa (10 ksi) at 0.5% extension under load; elongation, 35% in 50 mm (2 in.)
Hardness. 35 HB (500 kg), typical
Elastic modulus. Tension: 105 GPa (15×10^6 psi) at 20 °C (68 °F)

Mass Characteristics

Density. 8.8 g/cm^3 (0.318 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 16 to 21 mm/m ($^3/_{16}$ to $^1/_4$ in./ft)

Thermal Properties

Liquidus temperature. 1060 °C (1940 °F)
Solidus temperature. 1030 °C (1886 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 32% IACS at 20 °C (68 °F)

Fabrication Characteristics

Machinability. M01 temper, 35% of C36000 (free-cutting brass)
Stress-relieving temperature. 260 °C (500 °F)

C83600
85Cu-5Sn-5Pb-5Zn

Commercial Names

Previous trade names. Leaded red brass; CA836
Common names. Ounce metal; 85-5-5-5; composition metal

Specifications

AMS. 4855
ASTM. B 30, B 62, B 271, B 505, B 584
SAE. J462 (CA836)
Ingot identification number. 115
Government. QQ-C-390 (CA836), MIL-C-15345 (Alloy 1)

Chemical Composition

Composition limits. 84.0 to 86.0 Cu, 4.0 to 6.0 Sn, 4.0 to 6.0 Pb, 4.0 to 6.0 Zn, 0.30 Fe max, 0.25 Sb max, 1.0 Ni max, 0.05 P max (1.5 max for continuous castings), 0.08 S max, 0.005 Al

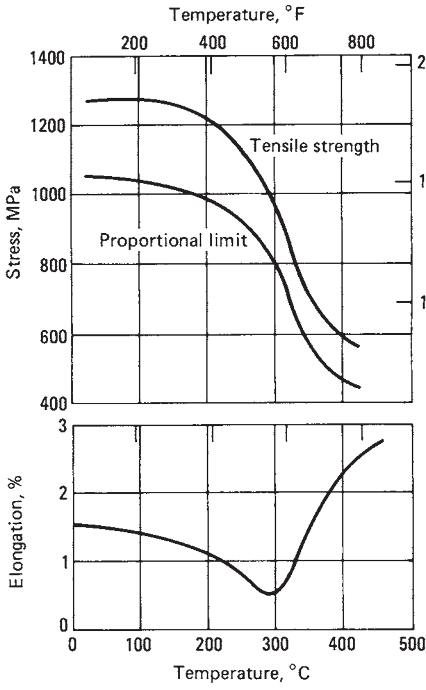

Fig. 8 Typical tensile properties of C82800, TF00 temper. Sand cast test bars were solution treated, then aged at 345 °C (650 °F).

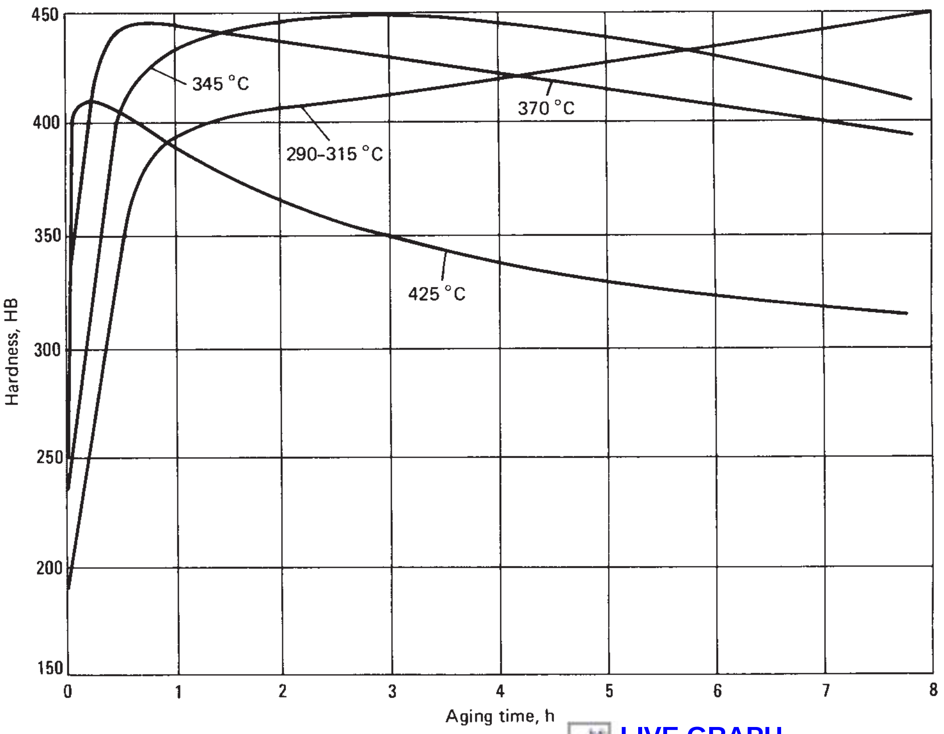

Fig. 9 Aging curves for solution-treated C82800

max, 0.005 Si max. In determining Cu min, Cu may be calculated as Cu + Ni.

Consequence of exceeding impurity limits. Aluminum and/or silicon in excess of 0.005% will adversely affect mechanical properties and pressure tightness.

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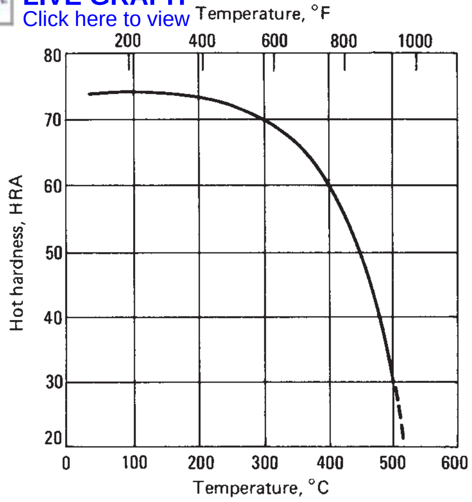

Fig. 10 Hot hardness of C82800, TF00 temper. Specimens were solution treated, then aged at 345 °C (650 °F).

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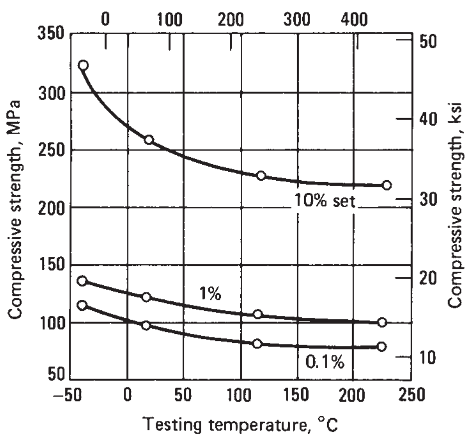

Fig. 11 Typical compressive strength for C83600

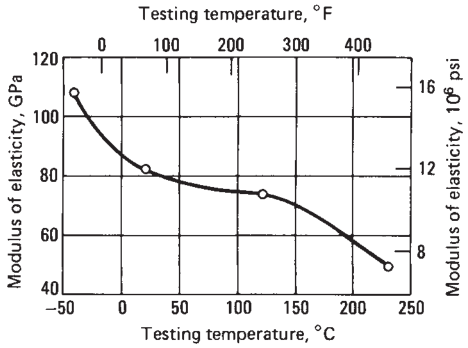

Fig. 12 Typical modulus of elasticity in tension for C83600

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Applications

Typical uses. Good general-purpose casting alloy. For castings requiring moderate strength, soundness, and good machinability, such as low-pressure valves, pipe fittings, gasoline- and oil-line fittings, fire-equipment fittings, small gears, small pump parts, general plumbing hardware

Mechanical Properties

Tensile properties. Typical data for separately cast test bars; tensile strength, 255 MPa (37 ksi); yield strength, 117 MPa (17 ksi) at 0.5% extension under load; elongation, 30% in 50 mm (2 in.)

Compressive properties. Compressive strength at room temperature: 97 MPa (14 ksi) at permanent set of 0.1%; 120 MPa (17.4 ksi) at permanent set of 1%; 258 MPa (37.5 ksi) at permanent set of 10%. See also Fig. 11.

Hardness. 60 HB, typical

Elastic modulus. Tension, 83 GPa (12 × 10^6 psi) at 20 °C (68 °F). See also Fig. 12.

Impact strength. Izod, 14 J (10 ft · lbf); Charpy V-notch, 15 J (11 ft · lbf)

Fatigue strength. 76 MPa (11 ksi) at 10^8 cycles. See also Fig. 13.

Creep strength. For 0.1% creep in 10,000 h: 86 MPa (12.5 ksi) at 180 °C (350 °F); 77 MPa (11.1 ksi) at 230 °C (450 °F); 48 MPa (7 ksi) at 290 °C (550 °F)

Mass Characteristics

Density. 8.83 g/cm^3 (0.318 lb/in.^{3}) at 20 °C (68 °F)

Volume change on freezing. 10.6% contraction

Patternmaker's shrinkage. 13 to 16 mm/m ($\frac{5}{32}$ to $\frac{3}{16}$ in./ft)

Thermal Properties

Liquidus temperature. 1010 °C (1850 °F)

Solidus temperature. 855 °C (1570 °F)

Coefficient of linear thermal expansion. 18.0 µm/m · K (10.0 µin./in. · °F) at 20 to 205 °C (68 to 400 °F). See also Fig. 14.

Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)

Thermal conductivity. 72.0 W/m · K (41.6 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 15% IACS

Magnetic Properties

Magnetic permeability. 1.0

Fabrication Characteristics

Machinability. 84% of C36000 (free-cutting brass)

C83800
83Cu-4Sn-6Pb-7Zn

Commercial Names

Previous trade name. CA838

Common names. Hydraulic bronze; 83-4-6-7

Specifications

ASTM. B 30 (CA838), B 271 (CA838), B 505 (CA838), B 584 (CA838)

SAE. J462

Ingot identification number. 120

Government. QQ-C-390

Chemical Composition

Composition limits. 82.0 to 83.8 Cu, 3.3 to 4.2 Sn, 5.0 to 7.0 Pb, 5.0 to 8.0 Zn, 0.30 Fe max, 0.25 Sb max, 1.0 Ni max, 0.03 P max (1.5 max for continuous castings), 0.08 S max, 0.005 Al max, 0.005 Si max. In determining Cu min, Cu may be calculated as Cu + Ni.

Consequence of exceeding impurity limits. Aluminum and/or silicon in excess of 0.005%

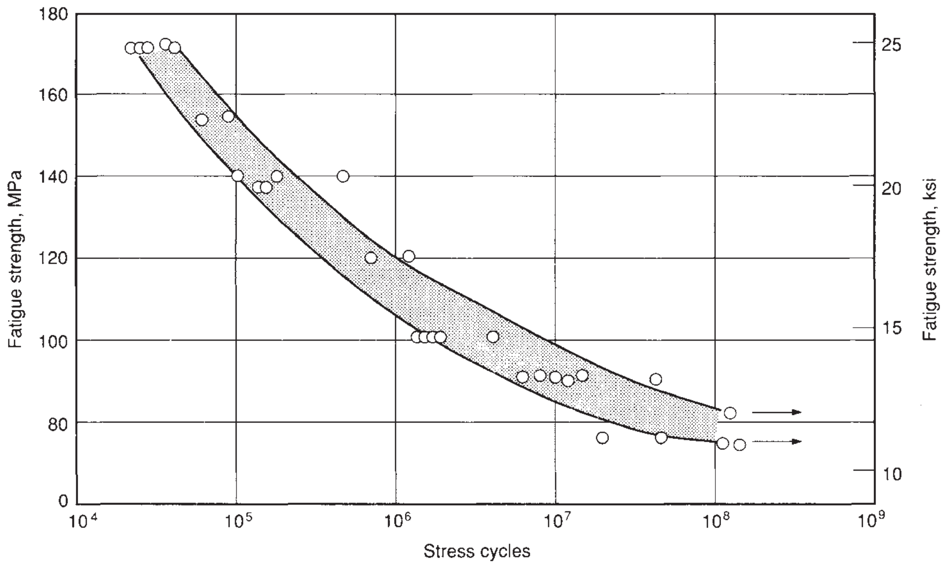

Fig. 13 Fatigue strength of C83600

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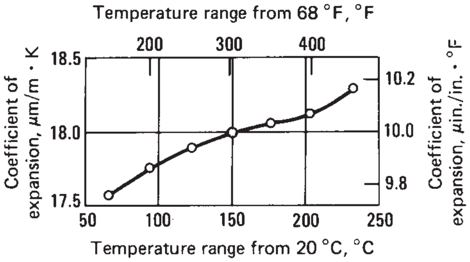

Fig. 14 Mean thermal expansion of C83600

will adversely affect mechanical properties and pressure tightness.

Applications

Typical uses. General-purpose free-machining alloy. For air, gas, and water fittings; plumbing supplies and fittings; pumps and pump fittings; hardware; carburetors; injectors; railroad catenary; and overhead fittings

Mechanical Properties

Tensile properties. Typical data for separately cast test bars: tensile strength, 240 MPa (35 ksi); yield strength, 110 MPa (16 ksi) at 0.5% extension under load; elongation, 25% in 50 mm (2 in.)
Compressive properties. Compressive strength: 79 MPa (11.5 ksi) at permanent set of 0.1%; 200 MPa (29 ksi) at permanent set of 10%
Hardness. 60 HB
Elastic modulus. Tension, 92 GPa (13.3 × 10^6 psi)
Impact strength. Izod, 11 J (8 ft · lbf)

Mass Characteristics

Density. 8.6 g/cm^3 (0.312 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 15.6 mm/m ($^{3}/_{16}$ in./ft)

Thermal Properties

Liquidus temperature. 1005 °C (1840 °F)
Solidus temperature. 845 °C (1550 °F)
Coefficient of linear thermal expansion. 18 µm/m · K (10 µin./in. · °F) at 20 to 232 °C (68 to 450 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 72.5 W/m · K (41.9 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 15% IACS

Magnetic Properties

Magnetic permeability. 1.0

Fabrication Characteristics

Machinability. 90% of C36000 (free-cutting brass)

C84400
81Cu-3Sn-7Pb-9Zn

Commercial Names

Previous trade names. Leaded semi-red brass; CA844
Common names. Valve metal; 81-3-7-9

Specifications

ASTM. B 30 (CA844), B 271 (CA844), B 505 (CA844), B 584 (CA844)
Ingot identification number. 123
Government. QQ-C-390

Chemical Composition

Composition limits. 78.0 to 82.0 Cu, 2.3 to 3.5 Sn, 6.0 to 8.0 Pb, 7.0 to 10.0 Zn, 0.40 Fe max, 0.25 Sb max, 1.0 Ni max, 0.02 P max (1.5 max for continuous castings), 0.08 S max, 0.005 Al max, 0.005 Si max. In determining Cu min, Cu may be calculated as Cu + Ni.
Consequence of exceeding impurity limits. Aluminum and/or silicon in excess of 0.005% will adversely affect mechanical properties and pressure tightness.

Applications

Typical uses. Low-pressure valves and fittings, general hardware fittings, plumbing supplies and fixtures, ornamental fixtures

Mechanical Properties

Tensile properties. Typical data for separately cast test bars: tensile strength, 235 MPa (34 ksi); yield strength, 105 MPa (15 ksi) at 0.5% extension under load; elongation, 26% in 50 mm (2 in.)
Hardness. 55 HB
Elastic modulus. Tension, 90 GPa (13.0 × 10^6 psi)
Impact strength. Izod, 11 J (8 ft · lbf)

Mass Characteristics

Density. 8.70 g/cm^3 (0.314 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 15.6 mm/m ($^{3}/_{16}$ in./ft)

Thermal Properties

Liquidus temperature. 1005 °C (1840 °F)
Solidus temperature. 840 °C (1540 °F)
Coefficient of linear thermal expansion. 18 µm/m · K (10 µin./in. · °F) at 20 to 260 °C (68 to 500 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 72.5 W/m · K (41.9 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 16.4% IACS

Magnetic Properties

Magnetic permeability. 1.0

Fabrication Characteristics

Machinability. 90% of C36000 (free-cutting brass)

C84800
76Cu-2½Sn-6½Pb-15Zn

Commercial Names

Common name. Leaded semi-red brass, plumbing goods brass, 76-2½-6½-15

Specifications

ASTM. B 30, B 271, B 505, B 584
Government. QQ-C-390, CA848
Other. Ingot code number 130

Chemical Composition

Composition limits. 75.0 to 77.0 Cu, 2.0 to 3.0 Sn, 5.5 to 7.0 Pb, 13.0 to 17.0 Zn, 0.40 Fe max, 0.25 Sb max, 1.0 Ni max, 0.02 P max (1.5 P max for continuous castings), 0.08 S max, 0.005 Al max, 0.005 Si max
Copper specification. In determining Cu, minimum may be calculated as Cu + Ni.
Consequence of exceeding impurity limits. Aluminum and/or silicon in excess of 0.005% will adversely affect mechanical properties and pressure tightness.

Applications

Typical uses. Plumbing fixtures, cocks, faucets, stops, wastes, air- and gas-line fittings, general hardware fittings, low-pressure valves and fittings

Mechanical Properties

Tensile properties. Typical data for separately cast test bars: tensile strength, 255 MPa (37 ksi); yield strength, 97 MPa (14 ksi) at 0.5% extension under load; elongation, 35% in 50 mm (2 in.)
Compressive properties. Typical compressive strength: 88.3 MPa (12.8 ksi) at a permanent set of 0.1%; 109 MPa (15.8 ksi) at a permanent set of 1%; 236 MPa (34.3 ksi) at a permanent set of 10%
Hardness. 55 HB
Elastic modulus. Tension, 105 GPa (15 × 10^6 psi)
Impact strength. Charpy V-notch, 16 J (12 ft · lbf)
Fatigue strength. 76 MPa (11 ksi) at 10^8 cycles
Creep-rupture characteristics. Limiting creep stress for 10^{-5}%/h: 82.0 MPa (11.9 ksi) at 177 °C (350 °F); 55 MPa (8 ksi) at 204 °C (400 °F); 20 MPa (3 ksi) at 288 °C (550 °F)

Mass Characteristics

Density. 8.58 g/cm^3 (0.310 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 16 mm/m ($^{3}/_{16}$ in./ft)

Thermal Properties

Liquidus temperature. 954 °C (1750 °F)
Solidus temperature. 832 °C (1530 °F)
Coefficient of linear thermal expansion. 18.7 µm/m · K (10.4 µin./in. · °F) at 20 to 260 °C (68 to 500 °F)
Specific heat. 376 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 72.0 W/m · K (41.6 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 16.4% IACS at 20 °C (68 °F)

Magnetic Properties

Magnetic permeability. 1.0

Fabrication Characteristics

Machinability. 90% of C36000 (free-cutting brass)

C85200
72Cu-1Sn-3Pb-24Zn

Commercial Names

Previous trade names. Leaded yellow brass; CA852
Common names. High-copper yellow brass; 72-1-3-24

Specifications

ASTM. B 30 (CA852), B 271 (CA852), B 584 (CA852)
SAE. J462
Ingot identification number. 400
Government. QQ-C-390 (CA852), MIL-C-15345 (Alloy 28)

Chemical Composition

Composition limits. 70.0 to 74.0 Cu, 0.7 to 2.0 Sn, 1.5 to 3.8 Pb, 20.0 to 27.0 Zn, 0.6 Fe max, 0.20 Sb max, 1.0 Ni max, 0.02 P max, 0.05 S max, 0.005 Al max, 0.05 Si max

Applications

Typical uses. Plumbing fittings and fixtures, ferrules, low-pressure valves, hardware fittings, ornamental brass, chandeliers, and irons

Mechanical Properties

Tensile properties. Typical data for separately cast test bars: tensile strength, 260 MPa (38 ksi); yield strength, 90 MPa (13 ksi) at 0.5% extension under load; elongation, 35% in 50 mm (2 in.)
Hardness. 45 HB
Elastic modulus. Tension, 76 GPa (11×10^6 psi)

Mass Characteristics

Density. 8.50 g/cm^3 (0.307 lb/in.^{3}) at 20 °C (68 °F)
Volume change on freezing. 12.4% contraction
Patternmaker's shrinkage. 16 mm/m ($\frac{3}{16}$ in./ft)

Thermal Properties

Liquidus temperature. 940 °C (1725 °F)
Solidus temperature. 925 °C (1700 °F)
Coefficient of linear thermal expansion. 21 μm/m · K (11.5 μin./in. · °F) at 20 to 100 °C (68 to 212 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 83.9 W/m · K (48.5 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 18.6% IACS

Magnetic Properties

Magnetic permeability. 1.0

Fabrication Characteristics

Machinability. 80% of C36000 (free-cutting brass)

C85400
67Cu-1Sn-3Pb-29Zn

Commercial Names

Previous trade names. Leaded yellow brass; CA854
Common names. No. 1 yellow brass; 67-1-3-29

Specifications

ASTM. B 30 (CA854), B 271 (CA854), B 584 (CA854)
SAE. J462 (CA854)
Ingot identification number. 403
Government. QQ-C-390 (CA854), MIL-C-15345 (Alloy 23)

Chemical Composition

Composition limits. 65.0 to 70.0 Cu, 0.50 to 1.5 Sn, 1.5 to 3.5 Pb, 24.0 to 32.0 Zn, 0.7 Fe max, 1.0 Ni max, 0.35 Al max, 0.05 Si max
Aluminum. Addition of 0.20 to 0.30% Al improves castability.

Applications

Typical uses. General-purpose casting alloy. For lightweight castings not subject to high internal pressure, such as furniture hardware, ornamental castings, radiator fittings, ship trimmings, gas cocks, light fixtures, battery clamps

Mechanical Properties

Tensile properties. Typical data for separately cast test bars: tensile strength, 235 MPa (34 ksi); yield strength, 83 MPa (12 ksi) at 0.5% extension under load; elongation, 35% in 50 mm (2 in.)
Hardness. 50 HB

Mass Characteristics

Density. 8.45 g/cm^3 (0.305 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 16 mm/m ($\frac{3}{16}$ in./ft)

Thermal Properties

Liquidus temperature. 940 °C (1725 °F)
Solidus temperature. 925 °C (1700 °F)
Coefficient of linear thermal expansion. 20.2 μm/m · K (11.2 μin./in. · °F) at 20 to 100 °C (68 to 212 °F)
Specific heat. 380 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 88 W/m · K (51 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 19.6% IACS

Magnetic Properties

Magnetic permeability. 1.0

Fabrication Characteristics

Machinability. 80% of C36000 (free-cutting brass)

C85700, C85800
63Cu-1Sn-1Pb-35Zn

Commercial Names

Previous trade names. CA857, CA858
Common names. Leaded yellow brass; 63-1-1-35

Specifications

ASTM. B 30 (CA857, CA858), B 176 (CA858), B 271 (CA857), B 584 (CA857)
SAE. J462
Ingot identification number. 406
Government. QQ-C-390 (CA857), MIL-C-15345 (Alloy 3)

Chemical Composition

Composition limits. See Table 8. Addition of 0.20 to 0.30% Al improves castability.

Applications

Typical uses. Bushings, hardware fittings, ornamental castings, lock hardware

Mechanical Properties

Tensile properties. Typical data for separately cast test bars. Sand castings or centrifugal castings (C85700): tensile strength, 345 MPa (50 ksi); yield strength, 125 MPa (18 ksi) at 0.5% extension under load; elongation, 40% in 50 mm (2 in.). Die castings (C85800): tensile strength, 380 MPa (55 ksi); yield strength, 205 MPa (30 ksi) at 0.5% extension under load; elongation, 15% in 50 mm (2 in.)
Hardness. Sand castings or centrifugal castings (C85700), 75 HB; die castings (C85800), 102 HB
Elastic modulus. Tension: sand castings or centrifugal castings (C85700), 97 GPa (14×10^6 psi); die castings (C85800), 105 GPa (15×10^6 psi)

Mass Characteristics

Density. 8.41 g/cm^3 (0.304 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 16 mm/m ($\frac{3}{16}$ in./ft)

Thermal Properties

Liquidus temperature. 920 °C (1688 °F)
Solidus temperature. 903 °C (1657 °F)
Coefficient of linear thermal expansion. 22 μm/m · K (12 μin./in. · °F) at 20 to 260 °C (68 to 500 °F)
Specific heat. 376 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 83.9 W/m · K (48.5 Btu/ft · h · °F) at 20 °C (68 °F)

Table 8 Composition limits of C85700 and C85800

Sand castings or centrifugal castings (C85700)	
Cu	58.0–64.0
Sn	0.50–1.50
Pb	0.80–1.50
Zn	32.0–40.0
Fe	0.7 max
Ni	1.0 max
Al	0.55 max
Si	0.05 max
Die castings (C85800)	
Cu	58.0 min
Sn	1.5 max
Pb	1.5 max
Zn	(a)
Fe	0.50 max
Al	(b)
Mn	0.25 max
Other	0.50 max(c)

(a) ASTM B 176, 31 to 41; SAE J462, 31.0 to 34.0. (b) ASTM B 176, 0.25 max; SAE J462, 0.50 max. (c) SAE J462 allows 0.05 Sb max, 0.50 Ni max, 0.05 As max, 0.05 S max, 0.01 P max, and 0.25 Si max before determination of total unnamed elements.

Electrical Properties

Electrical conductivity. Volumetric, 22% IACS

Magnetic Properties

Magnetic permeability. 1.0

Fabrication Characteristics

Machinability. 80% of C36000 (free-cutting brass)

C86100, C86200
64Cu-24Zn-3Fe-5Al-4Mn

Commercial Names

Common names. Manganese bronze (90,000 psi); High-strength yellow brass; CA861; CA862

Specifications

ASTM. C86100: none. C86200: Ingot, B 30; centrifugal castings, B 271; sand castings, B 584; continuous castings, B 505
SAE. J462. (Former alloy number: 430A)
Government. QQ-C-390, QQ-C-523. C86100: centrifugal castings, MIL-C-15345 (Alloy 5); investment castings, MIL-C-22087 (composition 7); sand castings, MIL-C-22229 (composition 10). C86200: investment castings, MIL-C-22087 (composition 9); precision castings, MIL-C-11866 (composition 20); sand castings, MIL-C-22229 (composition 9)
Ingot identification number. 423

Chemical Composition

Composition limits. C86100: 66.0 to 68 Cu, 4.5 to 5.5 Al, 2.0 to 4.0 Fe, 2.5 to 5.0 Mn, 1.0 Ni max, 0.2 Sn max, 0.2 Pb max, bal Zn. C86200: 60.0 to 68.0 Cu, 3.0 to 7.5 Al, 2.0 to 4.0 Fe, 2.5 to 5.0 Mn, 1.0 Ni max, 0.2 Sn max, 0.2 Pb max, bal Zn

Applications

Typical uses. Marine castings, gears, gun mounts, bushings, and bearings

Mechanical Properties

Tensile properties. Nominal. Tensile strength, 655 MPa (95 ksi); yield strength, 330 MPa (48 ksi); elongation, 20% in 50 mm (2 in.)
Compressive properties. Compressive strength, 345 MPa (50 ksi) at a permanent set of 0.1%
Hardness. 180 HB
Elastic modulus. Tension, 105 GPa (15 × 10^6 psi)
Impact strength. Izod, 16 J (12 ft · lbf)

Mass Characteristics

Density. 7.9 g/cm^3 (0.285 lb/in.^{3}) at 20 °C (68 °F)
Volume change on freezing. 2%

Thermal Properties

Liquidus temperature. 940 °C (1725 °F)
Solidus temperature. 900 °C (1650 °F)
Coefficient of linear thermal expansion. 22 μm/m · K (12 μin./in. · °F) at 20 to 260 °C (68 to 500 °F)
Specific heat. 376 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 35 W/m · K (20 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 7.5% IACS at 20 °C (68 °F)

Magnetic Properties

Magnetic permeability. 1.24 at field strength of 16 kA/m

Fabrication Characteristics

Machinability. 30% of C36000 (free-cutting brass)
Annealing temperature. 260 °C (500 °F)

C86300
64Cu-26Zn-3Fe-3Al-4Mn

Commercial Names

Common names. Manganese bronze (110,000 psi); High-strength yellow brass; CA863

Specifications

AMS. 4862
ASTM. Sand castings: B 22, B 584; centrifugal castings: B 271; continuous castings: B 505, ingot: B 30
SAE. J462
Government. QQ-C-390, QQ-C-523. Centrifugal castings, MIL-C-15345 (Alloy 6); investment castings, MIL-C-22087 (composition 9); precision castings, MIL-C-11866 (composition 21); sand castings, MIL-C-22229 (composition 8)
Ingot identification number. 424

Chemical Composition

Composition limits. 60.0 to 68.0 Cu, 2.5 to 5.0 Mn, 3.0 to 7.5 Al, 2.0 to 4.0 Fe, 0.2 Pb max, 0.2 Sn max, bal Zn
Consequence of exceeding impurity limits. Excessive Sn causes brittleness; excessive Pb or Ni decreases elongation.

Applications

Typical uses. Extra-heavy duty, high-strength alloy for gears, cams, bearings, screw-down nuts, bridge parts, hydraulic cylinder parts
Precautions in use. Not to be used in marine atmospheres, ammonia, or high-corrosive atmospheres

Mechanical Properties

Tensile properties. Nominal. Tensile strength, 820 MPa (119 ksi); yield strength, 460 MPa (67 ksi); elongation, 18% in 50 mm (2 in.)
Compressive properties. Compressive strength: 415 MPa (60 ksi) at permanent set of 0.1%; 670 MPa (97 ksi) at permanent set of 1%
Hardness. 225 HB
Elastic modulus. Tension, 105 GPa (15.5 × 10^6 psi)
Fatigue strength. Rotating beam, 170 MPa (25 ksi) at 100 million cycles
Impact strength. Izod, 20 J (15 ft · lbf). Charpy V-notch, 16 J (12 ft · lbf)
Creep-rupture characteristics. Stress for 0.17% creep in 10,000 h: 390 MPa (56.5 ksi) at 120 °C (250 °F); 225 MPa (32.5 ksi) at 150 °C (300 °F); 130 MPa (19 ksi) at 175 °C (350 °F); 3 MPa (0.5 ksi) at 230 °C (450 °F). See also Fig. 15 and 16.

Mass Characteristics

Density. 7.7 g/cm^3 (0.278 lb/in.^{3}) at 20 °C (68 °F)
Volume change on freezing. 2%

Thermal Properties

Liquidus temperature. 923 °C (1693 °F)
Solidus temperature. 885 °C (1625 °F)
Coefficient of linear thermal expansion. 22 μm/m · K (12 μin./in. · °F) at 20 to 260 °C (68 to 500 °F)
Specific heat. 376 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 36 W/m · K (21 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 9% IACS at 20 °C (68 °F)

Magnetic Properties

Magnetic permeability. 1.09 at field strength of 16 kA/m

Fabrication Characteristics

Machinability. 8% of C36000 (free-cutting brass)
Annealing temperature. 260 °C (500 °F)

C86400
59Cu-0.75Sn-0.75Pb-37Zn-1.25Fe-0.75Al-0.5Mn

Commercial Names

Previous trade name. Leaded high-strength yellow brass; stem manganese bronze
Common name. Manganese bronze (60,000 psi)

Specifications

ASTM. Sand castings: B 584; centrifugal castings: B 271; ingot: B 30
Government. QQ-C-390, QQ-C-523
Ingot identification number. 420

Chemical Composition

Composition limits. 56.0 to 62.0 Cu, 1.5 Sn max, 0.5 to 1.5 Pb, 2.0 Fe max, 1.5 Al max, 1.5 Mn max, 1.0 Ni max, bal Zn

Applications

Typical uses. Free-machining manganese bronze for valve stems, marine castings and fittings, pump bodies

Mechanical Properties

Tensile properties. Typical tensile strength, 450 MPa (65 ksi); yield strength, 170 MPa (25 ksi); elongation, 20% in 50 mm (2 in.)

Compressive properties. Compressive strength: 150 MPa (22 ksi) at 0.1% permanent set; 600 MPa (87 ksi) at 10% permanent set
Hardness. 105 HB
Elastic modulus. Tension, 96 GPa (14×10^6 psi)
Impact strength. Izod, 40 J (30 ft · lbf). Charpy V-notch, 34 J (25 ft · lbf)

Mass Characteristics

Density. 8.32 g/cm^3 (0.301 lb/in.^{3}) at 20 °C (68 °F)
Volume change on freezing. 2%

Thermal Properties

Liquidus temperature. 880 °C (1615 °F)
Solidus temperature. 860 °C (1585 °F)
Coefficient of linear thermal expansion. 20 µm/m · K (11.4 µin./in. · °F) at 21 to 204 °C (70 to 400 °F)
Specific heat. 376 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 88 W/m · K (51 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 22% IACS at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 60% of C36000 (free-cutting brass)
Casting temperature range. Light castings, 1040 to 1120 °C (1900 to 2050 °F); heavy castings, 955 to 1040 °C (1750 to 1900 °F)
Annealing temperature. 260 °C (500 °F)

C86500

58Cu-39Zn-1.3Fe-1Al-0.5Mn

Commercial Names

Previous trade name. High-strength yellow brass
Common name. Manganese bronze (65,000 psi)

Specifications

AMS. 4860A
ASTM. Sand castings: B 584; centrifugal castings: B 271, ingot: B 30
SAE. J 462
Government. QQ-C-390. Sand castings, MIL-C-22229 (composition 7); centrifugal castings, MIL-C-15345 (Alloy 4); investment castings, MIL-C-22087 (composition 5)
Ingot identification number. 421

Chemical Composition

Composition limits. 55.0 to 60.0 Cu, 0.4 to 2.0 Fe, 0.5 to 1.5 Al, 1.5 Mn max, 0.4 Pb max, 1.0 Sn max, 1.0 Ni max, bal Zn

Applications

Typical uses. Propeller hubs, blades, and other parts in contact with salt and fresh water, gears, liners

Mechanical Properties

Tensile properties. Typical. Tensile strength, 490 MPa (71 ksi); yield strength, 195 MPa (28 ksi);

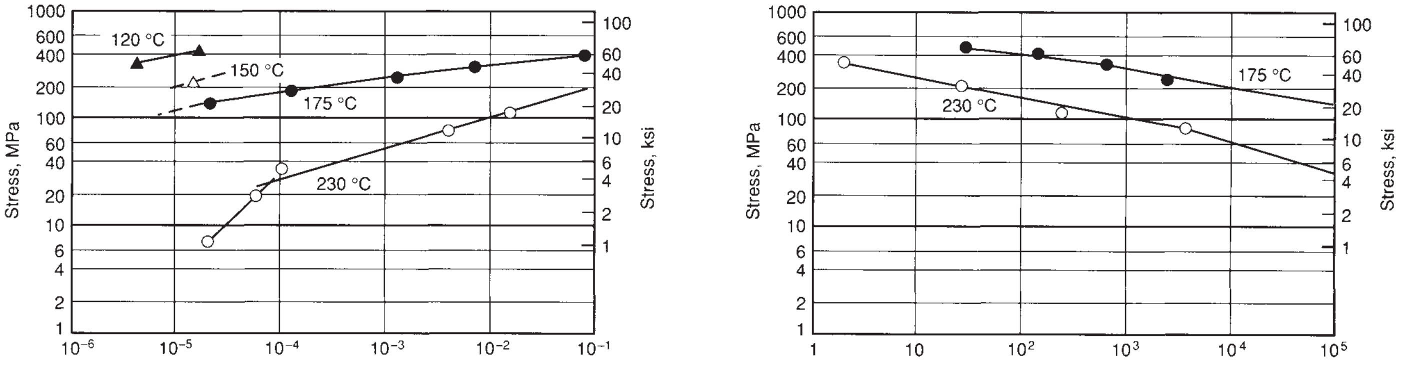

Fig. 15 Creep-rupture properties of C86300

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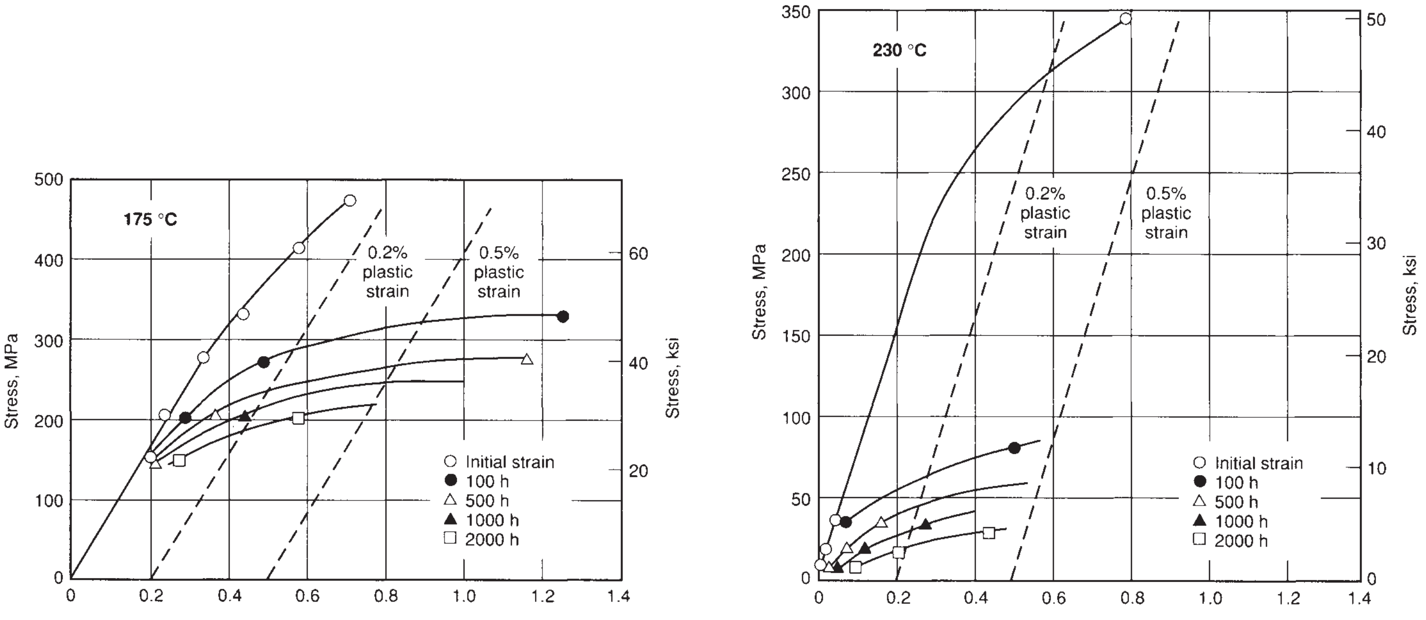

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Fig. 16 Isochronous stress-strain curves for C86300 elongation, 30% in 50 mm (2 in.). See also Fig. 17.

Compressive properties. Compressive strength: 165 MPa (24 ksi) at permanent set of 0.1%; 240 MPa (35 ksi) at permanent set of 1%; 545 MPa (79 ksi) at permanent set of 10%. See also Fig. 18.

Hardness. 130 HB. See also Fig. 19.

Elastic modulus. Tension, 105 GPa (15 × 10^6 psi). See also Fig. 20.

Fatigue strength. Reverse bending, 145 MPa (21 ksi) at 10^8 cycles. See also Fig. 21.

Impact strength. Charpy, 42 J (31 ft · lbf). See also Fig. 22.

Creep-rupture characteristics. Stress for 0.1% creep in 10,000 h: 190 MPa (28 ksi) at 120 °C (250 °F); 43 MPa (6.2 ksi) at 175 °C (350 °F); 12 MPa (1.7 ksi) at 230 °C (450 °F). See also Fig. 23 and 24.

Mass Characteristics

Density. 8.3 g/cm^3 (0.299 lb/in.3) at 20 °C (68 °F)

Patternmaker's shrinkage. 1.65 to 2.15% for pouring temperature of 905 °C (1665 °F)

Thermal Properties

Liquidus temperature. 880 °C (1616 °F)

Solidus temperature. 862 °C (1583 °F)

Coefficient of linear thermal expansion. 20.3 μm/m · K (11.3 μin./in. · °F) at 21 to 93 °C (70 to 200 °F). See also Fig. 25.

Specific heat. 373 J/kg · K (0.089 Btu/lb · °F) at 20 °C (68 °F)

Thermal conductivity. 87 W/m · K (50.2 Btu/ft · h · °F) at 20 °C (68 °F). See also Fig. 25.

Electrical Properties

Electrical conductivity. Volumetric, 20.5% IACS at 20 °C (68 °F). See also Fig. 26.

Electrical resistivity. See Fig. 26.

Magnetic Properties

Magnetic permeability. 1.09 at field strength of 16 kA/m

Fabrication Characteristics

Machinability. 26% of C36000 (free-cutting brass)

Annealing temperature. 260 °C (500 °F)

C86700

Commercial Names

Previous trade name. CA867

Common names. Leaded high-strength yellow brass; 80,000 psi tensile manganese bronze

Specifications

ASTM. Centrifugal, B 271; ingot, B 30; sand, B 584, B 763

Chemical Composition

Composition limits. 55.0 to 60.0 Cu, 1.0 to 3.0 Al, 1.0 to 3.0 Fe, 0.5 to 1.5 Pb, 1.0 to 3.5 Mn, 1.0 Ni max, 1.5 Sn max, 30.0 to 38.0 Zn. Ingot for remelting specifications may vary from the ranges shown.

Copper and zinc specifications. In reporting chemical analyses by the use of instruments such as spectrograph, x-ray, and atomic absorption, copper may be indicated as balance. In reporting chemical analyses obtained by wet methods, zinc may be indicated as balance on those alloys with over 2% Zn.

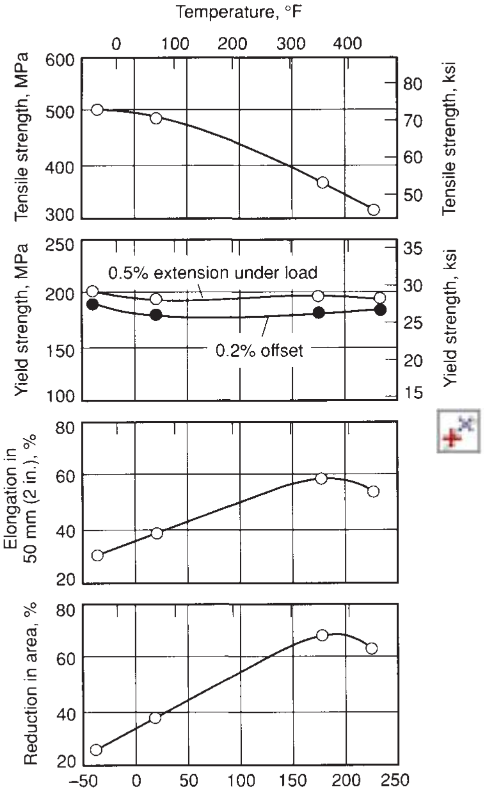

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Fig. 17 Typical tensile properties of C86500

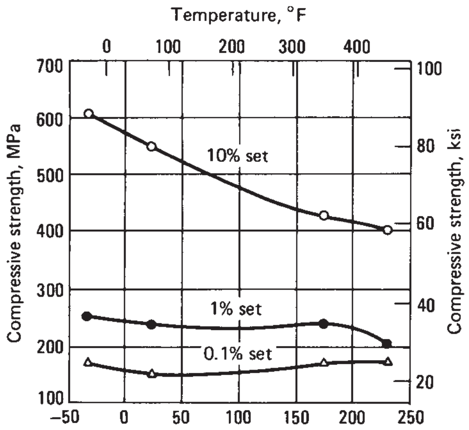

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Fig. 18 Typical compressive strength of C86500

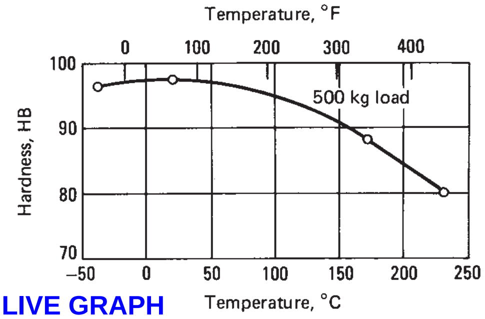

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Fig. 19 Typical Brinell hardness of C86500

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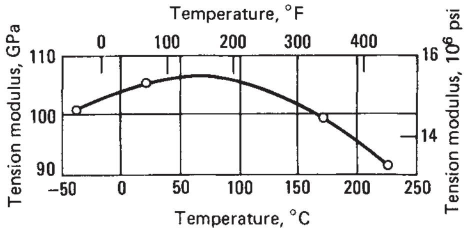

Fig. 20 Elastic modulus in tension for C86500

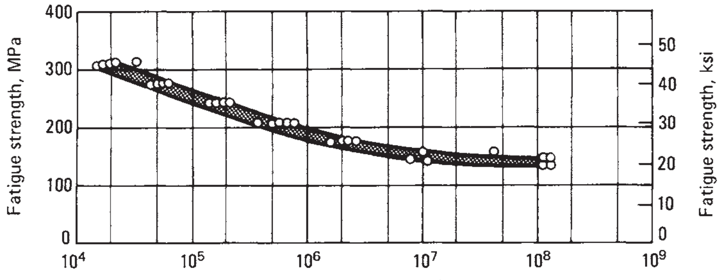

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Fig. 21 Typical reverse bending fatigue curve at room temperature for C86500

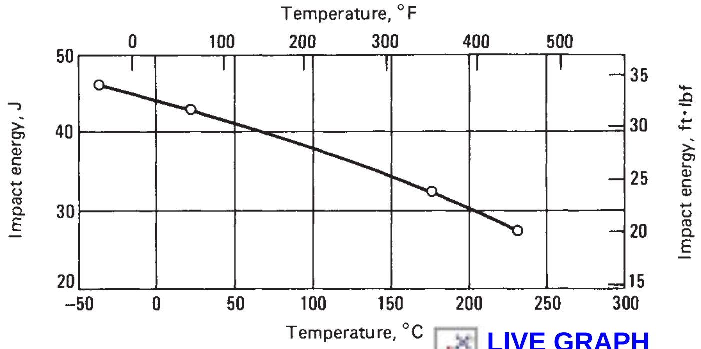

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Fig. 22 Typical Charpy V-notch impact strength for C86500

Applications

Typical uses. High-strength free-machining manganese bronze valve stems

Mechanical Properties

Tensile properties. Typical data for as-sand-cast separately cast test bar (M01 temper): tensile strength, 585 MPa (85 ksi); yield strength, 290 MPa (42 ksi) at 0.5% extension under load; elongation, 20% in 50 mm (2 in.)
Hardness. Typically 80 HRB or 155 HB (3000 kg)
Elastic modulus. Tension: 105 GPa (15 × 10^6 psi) at 20 °C (68 °F)

Mass Characteristics

Density. 8.32 g/cm^3 (0.301 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 21 mm/m ($^1/_4$ in./ft)

Thermal Properties

Liquidus temperature. 880 °C (1616 °F)
Solidus temperature. 862 °C (1583 °F)
Coefficient of linear thermal expansion. 19 μm/m · K (11 μin./in. · °F) at 20 to 200 °C (68 to 392 °F)
Specific heat. 376 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 32% IACS at 20 °C (68 °F)

Fabrication Characteristics

Machinability. M01 temper; 55% of C36000 (free-cutting brass)

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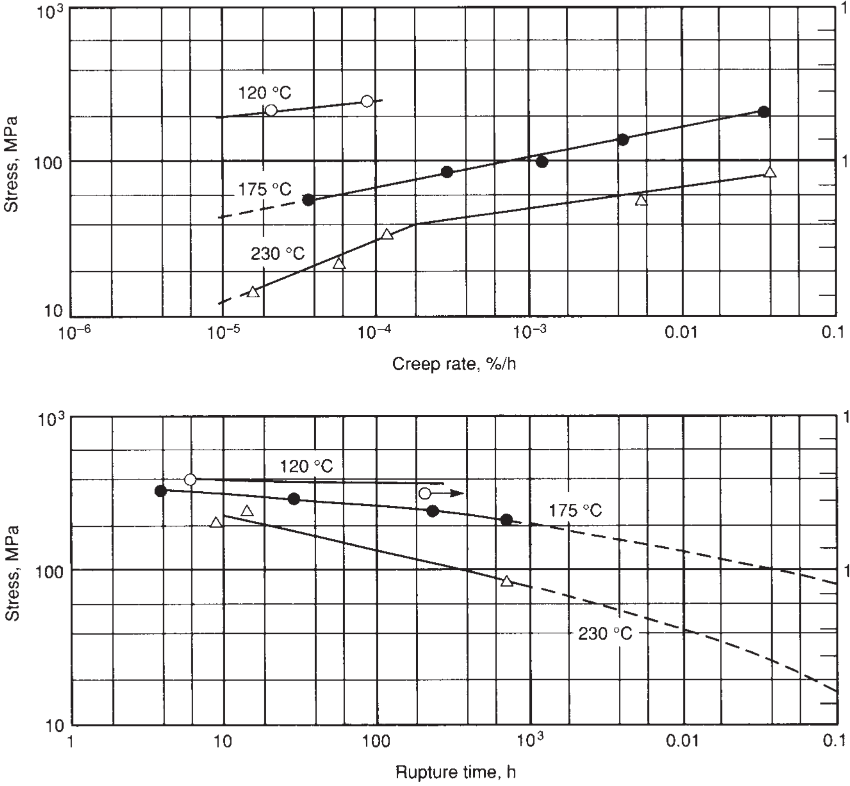

Fig. 23 Typical creep-rupture properties of C86500

Stress-relieving temperature. 260 °C (500 °F)

C86800

Commercial Names

Previous trade name. CA868
Common name. Nickel-manganese bronze

Specifications

ASTM. Die, B 176
Government. Sand, QQ-C-390; valves, WW-V-1967

Chemical Composition

Composition limits. 53.5 to 57.0 Cu, 2.0 Al max, 1.0 to 2.5 Fe, 0.20 Pb max, 2.5 to 4.0 Mn, 2.5 to 4.0 Ni, 1.0 Sn max, bal Zn. Ingot for remelting specifications may vary from the ranges shown.
Copper and zinc specifications. In reporting chemical analyses by the use of instruments such as spectrograph, x-ray, and atomic absorption, copper may be indicated as balance. In reporting chemical analyses obtained by wet methods, zinc may be indicated as balance on those alloys with over 2% Zn.

Applications

Marine fittings and propellers

Mechanical Properties

Tensile properties. Typical data for as-sand-cast separately cast test bars (M01 temper); tensile strength, 565 MPa (82 ksi); yield strength, 260 MPa (38 ksi) at 0.5% extension under load; elongation, 22% in 50 mm (2 in.)
Hardness. Typically 80 HB (3000 kg)
Elastic modulus. Tension, 105 GPa (15 × 10^6 psi) at 20 °C (68 °F)

Mass Characteristics

Density. 8.0 g/cm^3 (0.29 lb/in.^{3}) at 20 °C (68 °F)
Volume change on freezing. Patternmaker's shrinkage, 21 mm/m ($^1/_4$ in./ft)

Thermal Properties

Liquidus temperature. 900 °C (1652 °F)
Solidus temperature. 880 °C (1616 °F)
Specific heat. 376 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 9.0% IACS at 20 °C (68 °F)

Fabrication Characteristics

Machinability. M01 temper, 30% of C36000 (free-cutting brass)
Stress-relieving temperature. 260 °C (500 °F)

C87300 (formerly C87200)

Commercial Names

Trade name. Everdur, Herculor, Navy Tombasil
Common name. Silicon bronze, 95-1-4, 92-4-4, 89-6-5

Specifications

ASTM. Centrifugal, B 271; ingot, B 30; sand, B 585, B 763
SAE. J461, J462
Government. QQ-C-390, WW-V-1967
Military. MIL-C-11866 (composition 19); MIL-C-22229
Other. Ingot code number 500A

Chemical Composition

Composition limits. 94.0 Cu min, 0.20 Pb max, 0.25 Zn max, 0.20 Fe max, 3.5 to 4.5 Si, 0.8 to 1.5 Mn
Cu + sum of named elements. 99.5 min

Applications

Typical uses. As a substitute for tin bronze where good physical and corrosion resistance are required. Bearings, bells, impellers, pump and valve components, marine fittings, statuary and art castings

Mechanical Properties

Tensile properties. Typical data for separately cast test bars: tensile strength, 380 MPa (55 ksi); yield strength, 170 MPa (25 ksi) at 0.5% extension under load; elongation, 30% in 50 mm (2 in.)
Compressive properties. Typical compressive strength, 125 MPa (18 ksi) at permanent set of 0.1%, 415 MPa (60 ksi) at permanent set of 10%
Hardness. 85 HB
Elastic modulus. Tension, 105 GPa (15 × 10^6 psi)
Impact strength. Izod, 45 J (33 ft · lbf)

Mass Characteristics

Density. 8.36 g/cm^3 (0.302 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 21 mm/m ($^1/_4$ in./ft)

Thermal Properties

Liquidus temperature. 916 °C (1680 °F)
Solidus temperature. 821 °C (1510 °F)
Coefficient of linear thermal expansion. Linear, 19.6 μm/m · K (10.9 μin./in. · °F) at 20 to 260 °C (68 to 500 °F)
Thermal conductivity. 28 W/m · K (16 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 6.7% IACS at 20 °C (68 °F)

Magnetic Properties

Magnetic permeability. 1.0

Fabrication Characteristics

Machinability. 50% of C36000 (free-cutting brass)
Stress-relieving temperature. 260 °C (500 °F)

C87600

Commercial Names

Common names. Low-zinc silicon brass, CA876

Specifications

ASTM. Ingot, B 30; sand, B 584, B 763
Ingot code number. 500D

Chemical Composition

Composition limits. 88.0 Cu min, 0.50 Pb max, 4.0 to 7.0 Zn, 0.20 Fe max, 3.5 to 5.5 Si, 0.25 Mn max
Cu + sum of named elements. 99.5 min

Applications

Typical uses. Valve stems

Mechanical Properties

Tensile properties. Typical data for as-sand-cast separately cast test bars (M01 temper): tensile strength, 455 MPa (66 ksi); yield strength, 220 MPa (32 ksi) at 0.5% extension under load; elongation, 20% in 50 mm (2 in.)
Compressive strength. Typically, 415 MPa (60 ksi) at 0.1 mm/mm (0.1 in./in.) set
Elastic modulus. Tension, 115 GPa (17 × 10^6 psi) at 20 °C (68 °F)

Mass Characteristics

Density. 8.3 g/cm^3 (0.300 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 16 mm/m ($^3/_{16}$ in./ft)

Thermal Properties

Liquidus temperature. 971 °C (1780 °F)
Solidus temperature. 860 °C (1580 °F)
Specific heat. 376 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 6.0% IACS at 20 °C (68 °F)

Fabrication Characteristics

Machinability. M01 temper; 40% of C36000 (free-cutting brass)
Stress-relieving temperature. 260 °C (500 °F)

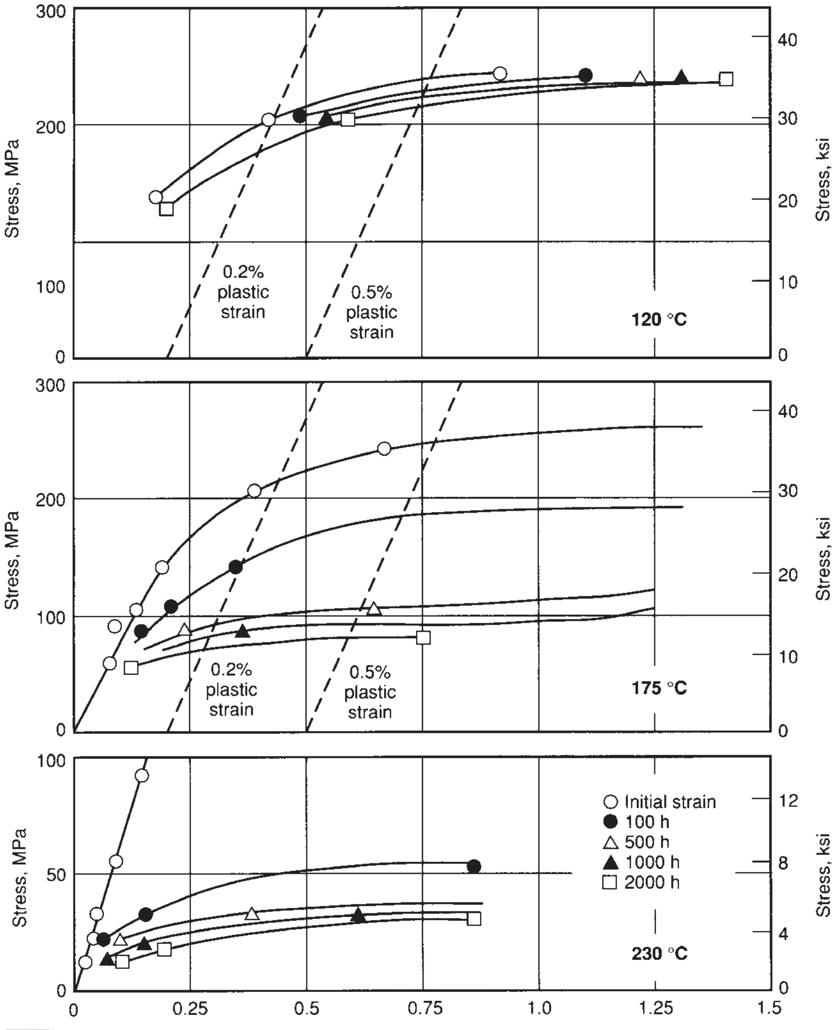

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Fig. 24 Isochronous stress-strain curves for C86500

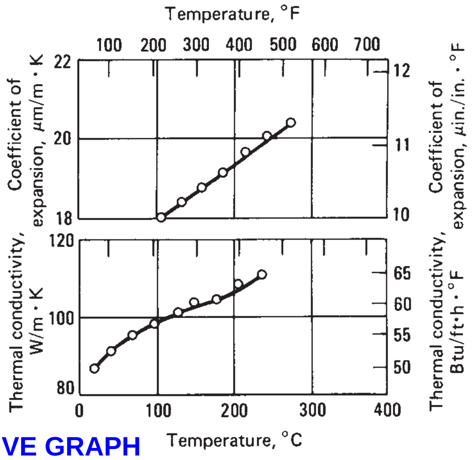

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Fig. 25 Typical thermal properties of C86500

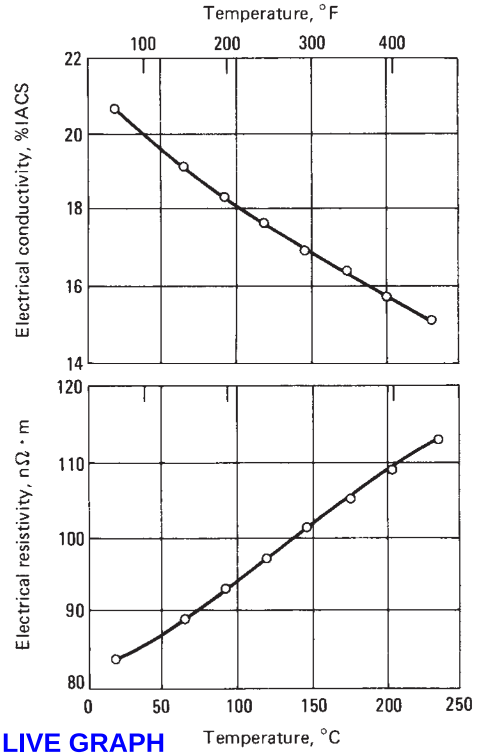

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Fig. 26 Variation of electrical properties with temperature for C86500

C87610, Silicon Bronze

Specifications

ASTM. Ingot: B 30
Ingot code number. 500E

Chemical Composition

Composition limits. 90.0 Cu min, 0.20 Pb max, 3.0 to 5.0 Zn, 0.20 Fe max, 3.0 to 5.0 Si, 0.25 Mn max
Cu + sum of named elements. 99.5 min

Applications

Typical uses. Bearings, bells, impellers, pump and valve components, marine fittings, corrosion-resistant castings

Mechanical Properties

Tensile properties. Typical data for as-sand-cast separately cast test bars (M01 temper): tensile strength, 380 MPa (55 ksi); yield strength, 170 MPa (25 ksi) at 0.5% extension under load; elongation, 30% in 50 mm (2 in.)
Compressive strength. Typically 125 MPa (18 ksi) at 0.001 mm/mm (0.001 in./in.) set and 415 MPa (60 ksi) at 0.01 mm/mm (0.01 in./in.) set
Shear strength. Typically 193 MPa (28 ksi)
Hardness. Typically 85 HB (500 kg)
Impact strength. Izod: 45 J (33 ft · lbf)
Elastic modulus. Tension, 105 GPa (15×10^6 psi) at 20 °C (68 °F)

Mass Characteristics

Density. 8.4 g/cm^3 (0.302 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 21 mm/m (¼ in./ft)

Thermal Properties

Specific heat. 376 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 6.0% IACS at 20 °C (68 °F)

Fabrication Characteristics

Machinability. M01 temper; 40% of C36000 (free-cutting brass)
Stress-relieving temperature. 260 °C (500 °F)

C87500, C87800
82Cu-4Si-14Zn

Commercial Names

Trade name. Tombasil
Common name. Silicon brass, 82-4-14

Specifications

ASTM. C87500: ingots, B 30; centrifugal castings, B 271; sand castings, B 584. C87800: die castings, B 176
SAE. J462
Government. C 87500: sand castings, QQ-C-390; investment castings, MIL-C-22087 (composition 4). C87800: die castings, MIL-B-15894 (class 3)
Other. Ingot code 500T

Chemical Composition

Composition limits. C87500: 79.0 min Cu, 0.50 Pb max, 12.0 to 16.0 Zn, 0.50 Al max, 3.0 to 5.0 Si. C87800: 80.0 to 83.0 Cu, 0.25 Sn max, 0.15 Pb max, 0.15 Fe max, 0.15 Mn max, 0.15 Al max, 3.75 to 4.25 Si, 0.01 Mg max, 0.25 max others (total), bal Zn, but As, Sb, and S not to exceed 0.05 each, and P not to exceed 0.01

Applications

Typical uses. Bearings, gears, impellers, rocker arms, valve stems, brush holders, bearing races, small boat propellers

Mechanical Properties

Tensile properties. Typical data for separately cast test bars. Sand castings: tensile strength, 460 MPa (67 ksi); yield strength, 205 MPa (30 ksi) at 0.5% extension under load; elongation, 21% in 50 mm (2 in.). Die castings: tensile strength, 585 MPa (85 ksi); yield strength, 310 MPa (45 ksi) at 0.5% extension under load; elongation, 25% in 50 mm (2 in.)
Compressive properties. Compressive strength, 183 MPa (26.5 ksi) at a permanent set of 0.1%; 515 MPa (75 ksi) at a permanent set of 10%
Hardness. Sand cast, 134 HB; die cast, 163 HB
Elastic modulus. Tension: sand cast, 106 GPa (15.4×10^6 psi); die cast, 138 GPa (20.0×10^6 psi)
Impact strength. Charpy V-notch, 43 J (32 ft · lbf)
Fatigue strength. Rotating beam, 150 MPa (22 ksi) at 10^8 cycles. See also Fig. 27.
Creep-rupture characteristics. Limiting creep stress for 10^{-5}%/h: 195 MPa (28 ksi) at 175 °C (350 °F); 75 MPa (11 ksi) at 230 °C (450 °F); 9.5 MPa (1.4 ksi) at 290 °C (550 °F). Stress for rupture in 100,000 h: 125 MPa (18 ksi) at 230 °C (450 °F); 20 MPa (3 ksi) at 290 °C (550 °F)

Mass Characteristics

Density. 8.28 g/cm^3 (0.299 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 1.5 to 1.9%

Thermal Properties

Liquidus temperature. 917 °C (1683 °F)
Solidus temperature. 821 °C (1510 °F)
Coefficient of linear thermal expansion. 19.6 μm/m · K (10.9 μin./in. · °F) at 20 to 260 °C (68 to 500 °F). See also Fig. 28.
Specific heat. 375 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 28 W/m · K (16 Btu/ft · h · °F) at 20 °C (68 °F). See also Fig. 28.

Electrical Properties

Electrical conductivity. Volumetric, 6.7% IACS at 20 °C (68 °F). See also Fig. 29.
Electrical resistivity. 284 nΩ · m at 20 °C (68 °F). See also Fig. 29.

Magnetic Properties

Magnetic permeability. 1.0

Fabrication Characteristics

Machinability. C87500: 50% of C36000 (free-cutting brass). C87800: 40% of C36000
Casting temperature. 980 to 955 °C (1800 to 1750 °F)
Stress-relieving temperature. 260 °C (500 °F)

C87900

Commercial Names

Common names. Silicon yellow brass, CA879

Specifications

ASTM. Ingot: B 30; die: B 176
Government. MIL-B-15894
SAE. J461, J462
Ingot identification number. 500G

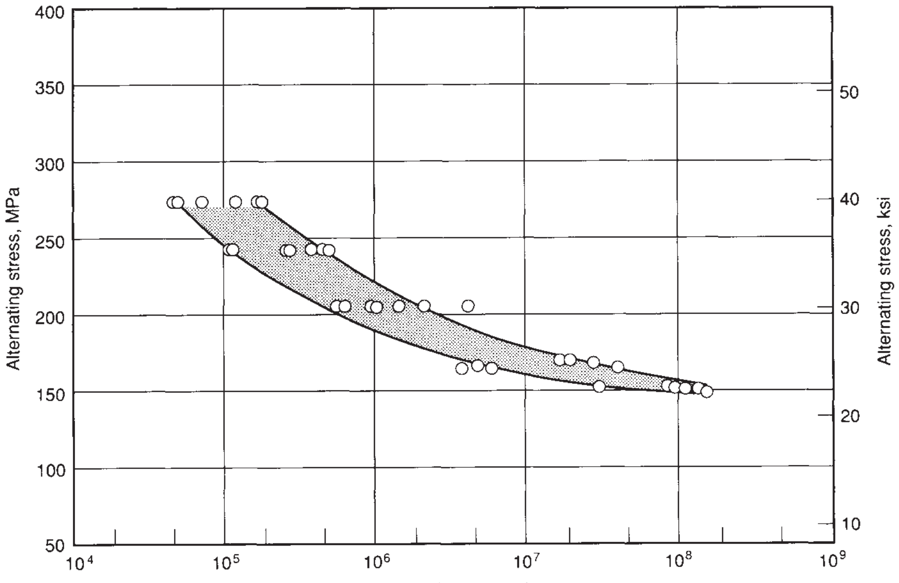

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Fig. 27 Fatigue curve for C87500 and C87800

Chemical Composition

Composition limits. 63.0 Cu min, 0.25 Sn max, 0.25 Pb max, 30.0 to 36.0 Zn, 0.40 Fe max, 0.15 Al max, 0.8 to 1.2 Si, 0.15 Mn max, 0.50 Ni (including Co) max, 0.05 S max, 0.01 P max, 0.05 As max, 0.05 Sb max. Total named elements shall be 99.5% minimum.
Copper and zinc specifications. In reporting chemical analyses by the use of instruments such as spectrograph, x-ray, and atomic absorption, copper may be indicated as balance. In reporting chemical analyses obtained by wet methods, zinc may be indicated as balance on those alloys with over 2% zinc. In determining Cu min, copper may be calculated as Cu + Ni.

Applications

Typical uses. General-purpose die-casting alloy having moderate strength

Mechanical Properties

Tensile properties. Typical data for as-die-cast test bars (M04 temper): tensile strength, 485 MPa (70 ksi); yield strength, 240 MPa (35 ksi) at 0.2% offset; elongation, 25% in 50 mm (2 in.)
Hardness. Typically 70 HRB
Impact strength. Charpy unnotched: 68 J (50 ft · lbf)
Elastic modulus. Tension, 105 GPa (15 × 10^6 psi) at 20 °C (68 °F)

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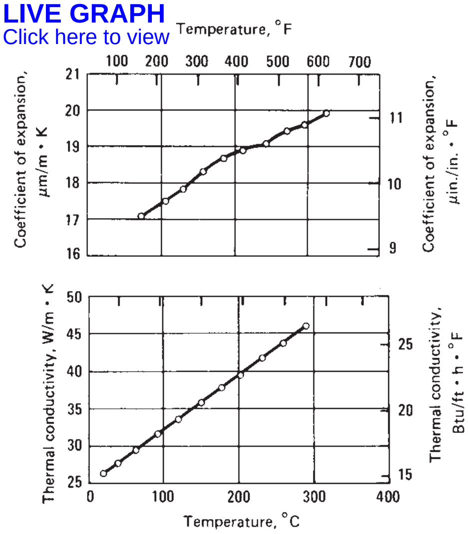

Fig. 28 Selected thermal properties of C87500 and C87800

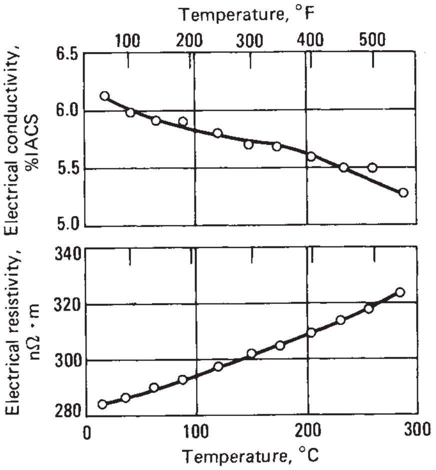

Fig. 29 Electrical conductivity and resistivity of C87500 and C87800

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Mass Characteristics

Density. 8.5 g/cm^3 (0.308 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 15.6 mm/m ($^3/_{16}$ in./ft)

Thermal Properties

Liquidus temperature. 926 °C (1700 °F)
Solidus temperature. 900 °C (1650 °F)
Specific heat. 376 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 15% IACS at 20 °C (68 °F)

Fabrication Characteristics

Machinability. M04 temper; 80% of C36000 (free-cutting brass)
Stress-relieving temperature. 260 °C (500 °F)

C90300
88Cu-8Sn-4Zn

Commercial Names

Common name. Tin bronze; 88-8-0-4; "G"-bronze

Specifications

ASTM. Sand castings: B 584; centrifugal castings: B 271; continuous castings: B 505; ingot: B 30
SAE. J462
Government. QQ-C-390, QQ-C-525. Sand castings: MIL-C-22229, composition 1; centrifugal castings: MIL-C-15345, alloy 8; investment castings: MIL-C-22087, composition 3; precision castings: MIL-C-11866, composition 26
Ingot identification number. 225

Chemical Composition

Composition limits. 86.0 to 89.0 Cu, 7.5 to 9.0 Sn, 3.0 to 5.0 Zn, 1.0 Ni max, 0.30 Pb max, 0.15 Fe max, 0.05 P max. (For continuous castings, 1.5 P max), 0.2 Sb max, 0.05 S max, 0.005 Si max, 0.005 Al max

Applications

Typical uses. Bearings, bushings, pump impellers, piston rings, valve components, seal rings, steam fittings, gears

Mechanical Properties

Tensile properties. Typical tensile strength, 310 MPa (45 ksi); yield strength, 145 MPa (21 ksi); elongation, 30% in 50 mm (2 in.)
Compressive properties. Compressive strength, 90 MPa (13 ksi)
Hardness. 70 HB
Elastic modulus. Tension, 97 GPa (14 × 10^6 psi)
Impact strength. Charpy V-notch, 19 J (14 ft · lbf)

Mass Characteristics

Density. 8.80 g/cm^3 (0.318 lb/in.^{3}) at 20 °C (68 °F)
Volume change on freezing. 1.6%

Thermal Properties

Liquidus temperature. 1000 °C (1830 °F)
Solidus temperature. 854 °C (1570 °F)
Coefficient of linear thermal expansion. 18 μm/m · K (10 μin./in. · °F) at 20 to 177 °C (68 to 340 °F)
Specific heat. 376 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 74 W/m · K (43 Btu/ft · h · °F)

Electrical Properties

Electrical conductivity. Volumetric, 12% IACS at 20 °C (68 °F)

Magnetic Properties

Magnetic permeability. 1.0

Fabrication Characteristics

Machinability. 30% of C36000 (free-cutting brass)

C90500
88Cu-10Sn-2Zn

Commercial Names

Common name. Tin bronze; Gun metal; 88-10 0–2

Specifications

AMS. 4845
ASTM. Sand castings: B 22, B 584; centrifugal castings: B 271; continuous castings: B 505; ingot: B 30
SAE. J462
Government. QQ-C-390
Ingot identification number. 210

Chemical Composition

Composition limits. 86.0 to 89.0 Cu, 9.0 to 11.0 Sn, 1.0 to 3.0 Zn, 1.0 Ni max, 0.3 Pb max, 0.15 Fe max, 0.05 P max. (For continuous castings, 1.5 max P), 0.2 Sb max, 0.05 S max, 0.005 Si max, 0.005 Al max

Applications

Typical uses. Bearings, bushings, pump impellers, piston rings, pump bodies, valve components, steam fittings, gears

Mechanical Properties

Tensile properties. Typical tensile strength, 310 MPa (45 ksi); yield strength, 150 MPa (22 ksi); elongation, 25% in 50 mm (2 in.); reduction in area, 40%
Compressive properties. Compressive strength, 275 MPa (40 ksi)
Elastic modulus. Tension, 105 GPa (15 × 10^6 psi)
Fatigue strength. Rotating beam, 90 MPa (13 ksi) at 10^8 cycles
Impact strength. Izod, 14 J (10 ft · lbf)

Mass Characteristics

Density. 8.72 g/cm^3 (0.315 lb/in.^{3}) at 20 °C (68 °F)
Volume change on freezing. 1.6%

Thermal Properties

Liquidus temperature. 1000 °C (1830 °F)
Solidus temperature. 854 °C (1570 °F)
Coefficient of linear thermal expansion. 20 µm/m · K (11 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 376 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 74 W/m · K (43 Btu/ft · h · °F)

Electrical Properties

Electrical conductivity. Volumetric, 11% IACS at 20 °C (68 °F)

Magnetic Properties

Magnetic permeability. 1.0

Fabrication Characteristics

Machinability. 30% of C36000 (free-cutting brass)

C90700
89Cu-11Sn

Commercial Names

Common name. Tin bronze, 65; Phosphor gear bronze

Specifications

ASTM Continuous castings: B 505; ingot: B 30
Ingot identification number. 205

Chemical Composition

Composition limits. 88.0 to 90.0 Cu, 10.0 to 12.0 Sn, 0.15 Fe max, 0.1 to 0.3 P, 0.005 Al max, 0.30 Pb max, 0.50 Zn max, Pb + Zn + Ni, 1.0 max
Consequence of exceeding impurity limits. Ductility decreases rapidly with tin contents over 12%, with 13% a practical limit for gear applications.

Applications

Typical uses. Worm wheels and gears; bearings expected to carry heavy loads at relatively low speeds

Mechanical Properties

Tensile Properties. Typical. Sand castings: tensile strength, 305 MPa (44 ksi); yield strength, 150 MPa (22 ksi); elongation, 20% in 50 mm (2 in.). Permanent mold castings: tensile strength, 380 MPa (55 ksi); yield strength, 205 MPa (30 ksi); elongation, 16% in 50 mm (2 in.)
Hardness. Sand castings, 80 HB; permanent mold castings, 102 HB
Elastic modulus. Tension, 105 GPa (15 × 10^6 psi)
Fatigue strength. Rotating beam, 170 MPa (25 ksi) at 10^8 cycles

Mass Characteristics

Density. 8.77 g/cm^3 (0.317 lb/in.^{3}) at 20 °C (68 °F)
Volume change on freezing. 1.6%

Thermal Properties

Liquidus temperature. 1000 °C (1830 °F)
Solidus temperature. 832 °C (1530 °F)
Coefficient of linear thermal expansion. 18 µm/m · K (10 µin./in. · °F) at 20 to 200 °C (68 to 392 °F)
Specific heat. 376 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 71 W/m · K (41 Btu/ft · h · °F)

Electrical Properties

Electrical conductivity. Volumetric, 9.6% IACS at 20 °C (68 °F)
Electrical resistivity. 15 nΩ · m at 20 °C (68 °F)

Magnetic Properties

Magnetic permeability. 1.0

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)

C91700
86½Cu-12Sn-1½Ni

Commercial Names

Common name. Nickel gear bronze, 86½-12-0-0-1½

Specifications

ASTM. Ingot: B 30; sand castings: B 427
Other. Ingot code number 205

Chemical Composition

Composition limits. 85.0 to 87.5 Cu, 11.3 to 12.5 Sn, 0.25 Pb max, 1.3 to 2.0 Ni, 0.30 P max

Applications

Typical uses. Worm wheels and gears, bearings with heavy loads and relatively low speeds

Mechanical Properties

Tensile properties. Typical data for sand-cast test bars: tensile strength, 305 MPa (44 ksi); yield strength, 150 MPa (22 ksi) at 0.5% extension under load; elongation, 16% in 50 mm (2 in.). Typical data for centrifugal or permanent mold test bars: tensile strength, 415 MPa (60 ksi); yield strength, 220 MPa (32 ksi) at 0.5% extension under load; elongation, 16% in 50 mm (2 in.)
Hardness. Sand cast, 85 HB; centrifugal or permanent mold cast, 106 HB
Elastic modulus. Tension, 105 GPa (15 × 10^6 psi)

Mass Characteristics

Density. 8.75 g/cm^3 (0.316 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 16 mm/m ($\frac{3}{16}$ in./ft)

Thermal Properties

Liquidus temperature. 1015 °C (1860 °F)
Solidus temperature. 850 °C (1565 °F)
Coefficient of linear thermal expansion. 16.2 µm/m · K (9.0 µin./in. · °F) at 20 to 200 °C (68 to 392 °F)
Specific heat. 376 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 71 W/m · K (41 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 10% IACS at 20 °C (68 °F)

Magnetic Properties

Magnetic permeability. 1.0

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)

C92200
88Cu-6Sn-1½Pb-4½Zn

Commercial Names

Common name. Navy "M" bronze, steam bronze, 88-6-1-4

Specifications

ASTM. B 584, B 61, B 271, B 505, B 30
SAE. J462 (C92200)
Government. CA922, QQ-B-225 (Alloy number 1), MIL-B-16541, MIL-B-15345
Other. Ingot code number 245

Chemical Composition

Composition limits. 86.0 to 90.0 Cu, 5.5 to 6.5 Sn, 1.0 to 2.0 Pb, 3.0 to 5.0 Zn, 1.0 Ni max, 0.25 Fe max, 0.05 P max, (1.5 P max for continuous castings), 0.05 S max, 0.005 Si max, 0.25 Sb max

Applications

Typical uses. Component castings of valves, flanges and fittings, oil pumps, gear, bushings, bearings, backing for babbitt-lined bearings, pressure-containing parts at temperatures up to 290 °C (550 °F), and stresses up to 20 MPa (3 ksi)

Mechanical Properties

Tensile properties. Typical data for sand-cast test bars: tensile strength, 275 MPa (40 ksi); yield strength, 140 MPa (20 ksi) at 0.5% extension under load; elongation, 30% in 50 mm (2 in.). See also Fig. 30.
Compressive properties. Compressive strength, 105 MPa (15 ksi) at permanent set of 10%; 260 MPa (38 ksi) at permanent set of 0.1%. See also Fig. 31.
Hardness. 65 HB (500 kg load). See also Fig. 32.
Elastic modulus. Tension, 97 GPa (14 × 10^6 psi). See also Fig. 33.
Fatigue strength. Rotating beam, 76 MPa (11 ksi) at 10^8 cycles. See also Fig. 34.
Creep-rupture characteristics. Limiting creep stress for 10^{-5}%/h: 110 MPa (16.0 ksi) at 177 °C

(350 °F); 77.2 MPa (11.2 ksi) at 232 °C (450 °F); 43 MPa (6.2 ksi) at 288 °C (550 °F). See also Fig. 35.

Mass Characteristics

Density. 8.64 g/cm^3 (0.312 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 16 mm/m ($^3\!/_{16}$ in./ft)

Thermal Properties

Liquidus temperature. 990 °C (1810 °F)
Solidus temperature. 825 °C (1520 °F)
Incipient melting temperature. Pb, 315 °C (600 °F)
Coefficient of linear thermal expansion. See Fig. 36.
Specific heat. 376 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 70 W/m · K (40 Btu/ft · h · °F) at 20 °C (68 °F). See also Fig. 36.

Electrical Properties

Electrical conductivity. Volumetric, 14.3% IACS at 20 °C (68 °F)
Electrical resistivity. 120 nΩ · m at 20 °C (68 °F)

Magnetic Properties

Magnetic permeability. 1.0

Fabrication Characteristics

Machinability. 42% of C36000 (free-cutting brass)
Weldability. Soldering: excellent. Brazing: excellent, but strain must be avoided during brazing and subsequent cooling because brazing is performed at temperatures within the hot short range. Oxyfuel gas welding and all forms of arc welding are not recommended.
Stress-relieving temperature. 260 °C (500 °F)

C92300
87Cu-8Sn-1Pb-4Zn

Commercial Names

Common names. Leaded tin bronze, leaded Navy "G"-bronze, 87-8-1-4

Specifications

ASTM. Sand castings: B 584; centrifugal castings: B 271; continuous castings: B 505; ingot: B 30
SAE: J462
Government. QQ-C-390. Centrifugal castings: MIL-C-15345 (Alloy 10)
Other. Ingot code number 230

Chemical Composition

Composition limits. 85.0 to 89.0 Cu, 7.0 to 9.0 Sn, 1.0 Pb max, 2.5 to 5.0 Zn, 1.0 Ni max, 0.25 Fe max, 0.05 P max (1.5 P max for continuous castings), 0.25 Sb max, 0.05 S max, 0.005 Si max, 0.005 Al max

Applications

Typical uses. Strong general-utility structural bronze for use under severe conditions; valves, expansion joints, special high-pressure pipe fittings, steam pressure castings

Mechanical Properties

Tensile properties. Typical data for sand-cast test bars: tensile strength, 275 MPa (40 ksi); yield strength, 140 MPa (20 ksi) at 0.5% extension under load; elongation, 25% in 50 mm (2 in.)
Compressive properties. Compressive strength, 69 MPa (10 ksi) at permanent set of 0.1%; 240 MPa (35 ksi) at permanent set of 10%
Hardness. 70 HB
Elastic modulus. Tension, 97 GPa (14 × 10^6 psi)
Impact strength. Izod, 18.3 J (13.5 ft · lbf)

Mass Characteristics

Density. 8.8 g/cm^3 (0.317 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 16 mm/m ($^3\!/_{16}$ in./ft)

Thermal Properties

Liquidus temperature. 1000 °C (1830 °F)
Solidus temperature. 855 °C (1570 °F)
Incipient melting temperature. Pb, 315 °C (600 °F)
Coefficient of linear thermal expansion. 18 µm/m · K (10 µin./in. · °F) at 20 to 177 °C (68 to 350 °F)
Specific heat. 376 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 75 W/m · K (43 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 12% IACS at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 42% of C36000 (free-cutting brass)
Weldability. Soldering: excellent. Brazing: good, but strain must be avoided during brazing and subsequent cooling because brazing is performed at temperatures within the hot short range. Oxyfuel gas welding and all forms of arc welding are not recommended.
Stress-relieving temperature. 260 °C (500 °F)

C92500
87Cu-11Sn-1Pb-1Ni

Commercial Names

Common name. Leaded tin bronze, 640; 87-11-1-0-1

Specifications

ASTM. Continuous castings: B 505; ingot: B 30
SAE. J462
Other. Ingot code number 250

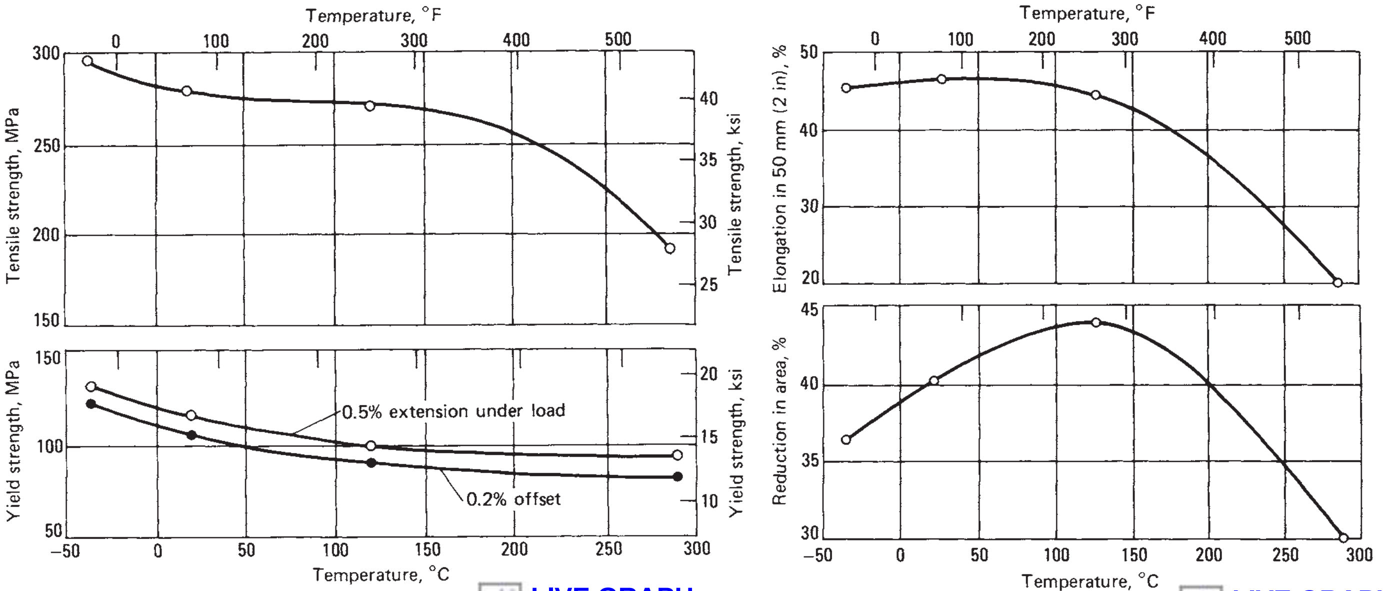

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Fig. 30 Tensile properties of C92200

Chemical Composition

Composition limits. 85.0 to 88.0 Cu, 10.0 to 12.0 Sn, 1.0 to 1.5 Pb, 0.5 Zn max, 0.8 to 1.5 Ni, 0.15 Fe max, 0.20 to 0.30 P, 0.005 Al max

Applications

Typical uses. Gears, automotive synchronizer rings

Mechanical Properties

Tensile properties. Typical data for sand-cast test bars: tensile strength, 305 MPa (44 ksi); yield strength, 140 MPa (20 ksi) at 0.5% extension under load; elongation, 20% in 50 mm (2 in.)
Hardness. 80 HB
Elastic modulus. Tension, 110 GPa (16 × 10^6 psi)

Mass Characteristics

Patternmaker's shrinkage. 16 mm/m ($^3/_{16}$ in./ft)

Thermal Properties

Incipient melting temperature. Pb, 315 °C (600 °F)
Specific heat. 376 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)

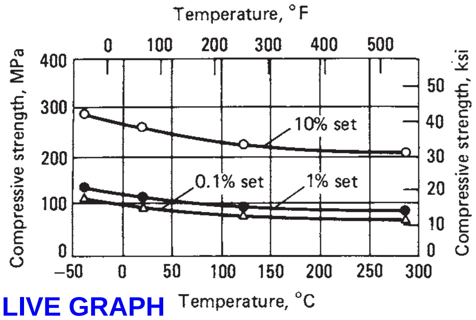

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Fig. 31 Compressive strength of C92200

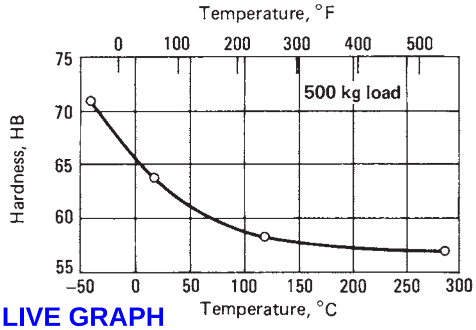

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Fig. 32 Brinell hardness of C92200

Fabrication Characteristics

Machinability. 30% of C36000 (free-cutting brass)
Weldability. Soldering: excellent. Brazing: good, but strain must be avoided during brazing and subsequent cooling because brazing is performed at temperatures within the hot short range. Oxyfuel gas welding and all forms of arc welding are not recommended.
Stress-relieving temperature. 260 °C (500 °F)

C92600
87Cu-10Sn-1Pb-2Zn

Commercial Names

Common name. Leaded tin bronze

Specifications

Ingot code number. 215

Chemical Composition

Composition limits. 86.0 to 88.5 Cu, 9.3 to 10.5 Sn, 0.8 to 1.2 Pb, 1.3 to 2.5 Zn, 0.75 Ni max, 0.15 Fe max, 0.25 Sb max, 0.05 S max, 0.005 Si max, 0.03 P max, 0.005 Al max

Applications

Typical uses. Commercial bronze for high-duty bearings where wear resistance is essential; strong general-utility structural bronze for use under severe conditions; bolts, nuts, gears; heavy-pressure bearings and bushings to use against hardened steel; valves, expansion joints, special high-pressure pipe fittings; pump pistons; elevator components; steam pressure castings

Mechanical Properties

Tensile properties. Typical data for sand-cast test bars: tensile strength, 304 MPa (44 ksi); yield strength, 140 MPa (20 ksi) at 0.5% extension under load; elongation, 30% in 50 mm (2 in.)
Compressive properties. Compressive strength, 85 MPa (12 ksi) at permanent set of 0.1%; 275 MPa (40 ksi) at permanent set of 10%
Hardness. 78 HRF, 72 HB
Elastic modulus. Tension, 105 GPa (15 × 10^6 psi)
Impact strength. Izod, 9 J (7 ft · lbf)

Mass Characteristics

Density. 8.70 g/cm^3 (0.315 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 16 mm/m ($^3/_{16}$ in./ft)

Thermal Properties

Liquidus temperature. 980 °C (1800 °F)
Solidus temperature. 845 °C (1550 °F)
Incipient melting temperature. Pb, 315 °C (600 °F)
Specific heat. 376 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 9% IACS at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 40% of C36000 (free-cutting brass)
Weldability. Soldering: excellent. Brazing: good, but strain must be avoided during brazing and subsequent cooling because brazing is done at temperatures within the hot short range. Oxyfuel gas welding and all forms of arc welding are not recommended.
Stress-relieving temperature. 260 °C (500 °F)

C92700
88Cu-10Sn-2Pb

Commercial Names

Common name. Leaded tin bronze, 88-10-2-0

Specifications

ASTM. Continuous castings: B 505; ingot: B 30
SAE. J462
Other. Ingot code number 206

Chemical Composition

Composition limits. 86.0 to 89.0 Cu, 9.0 to 11.0 Sn, 1.0 to 2.5 Pb, 0.7 Zn max, 1.0 Ni max, 0.15 Fe max, 0.25 P max, 0.005 Al max

Applications

Typical uses. Bearings, bushings, pump impellers, piston rings, valve components, steam fittings, gears

Mechanical Properties

Tensile properties. Typical data for sand-cast test bars: tensile strength, 290 MPa (42 ksi); yield strength, 145 MPa (21 ksi) at 0.5% extension under load; elongation, 20% in 50 mm (2 in.)
Hardness. 77 HB
Elastic modulus. Tension, 110 GPa (16 × 10^6 psi)

Mass Characteristics

Density. 8.8 g/cm^3 (0.317 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 16 mm/m ($^3/_{16}$ in./ft)

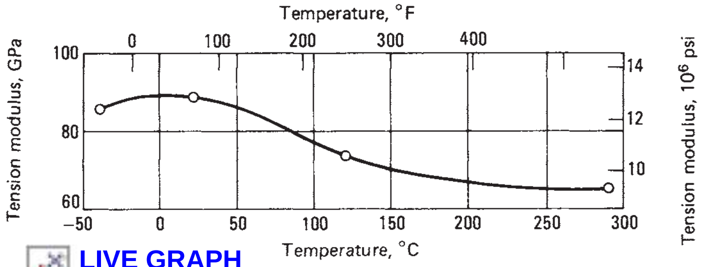

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Fig. 33 Elastic modulus in tension for C92200

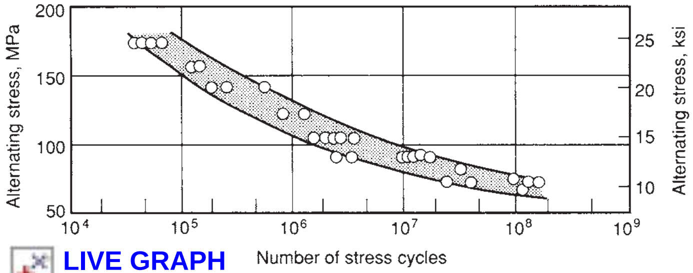

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Fig. 34 Fatigue strength of C92200

Thermal Properties

Liquidus temperature. 980 °C (1800 °F)
Solidus temperature. 845 °C (1550 °F)
Incipient melting temperature. Pb, 315 °C (600 °F)
Coefficient of linear thermal expansion. 18 µm/m · K (10 µin./in. · °F) at 20 to 177 °C (68 to 350 °F)
Specific heat. 376 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 11% IACS at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 45% of C36000 (free-cutting brass)
Weldability. Soldering: excellent. Brazing: good, but parts must not be strained during brazing or subsequent cooling because brazing is done at temperatures within the hot short range. Oxyfuel gas welding and all forms of arc welding are not recommended.
Stress-relieving temperature. 260 °C (500 °F)

C92900
84Cu-10Sn-2½Pb-3½Ni

Commercial Names

Common name. Leaded nickel-tin bronze, 84-10-2½-0-3½

Specifications

ASTM. Sand and centrifugal castings: B 427; continuous castings: B 505; ingot: B 30
SAE. J462

Chemical Composition

Composition limits. 81.0 to 85.5 Cu, 9.0 to 11.0 Sn, 2.0 to 3.2 Pb, 2.8 to 4.0 Ni, 0.50 P max, 0.50 max other (total)

Applications

Typical uses. Gears, wear plates and guides, cams

Mechanical Properties

Tensile properties. Typical data for sand-cast test bars: tensile strength, 325 MPa (47 ksi); yield strength, 180 MPa (26 ksi) at 0.5% extension under load; elongation, 20% in 50 mm (2 in.)
Hardness. 80 HB
Elastic modulus. Tension, 97 GPa (14 × 10^6 psi)
Impact strength. Izod, 16 J (12 ft · lbf)

Mass Characteristics

Density. 8.79 g/cm^3 (0.318 lb/in.^3) at 20 °C (68 °F)
Patternmaker's shrinkage. 16 mm/m (3/16 in./ft)

Thermal Properties

Liquidus temperature. 1030 °C (1887 °F)
Solidus temperature. 860 °C (1575 °F)
Incipient melting temperature. Pb, 315 °C (600 °F)
Coefficient of linear thermal expansion. 17 µm/m · K (9.5 µin./in. · °F) at 20 to 200 °C (68 to 392 °F)
Specific heat. 376 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 58.2 W/m · K (33.6 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 9.2% IACS at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 40% of C36000 (free-cutting brass)
Weldability. Soldering: excellent. Brazing: good, but parts must not be strained during brazing or subsequent cooling because brazing is done at temperatures within the hot short range. Oxyfuel gas welding and all forms of arc welding are not recommended.
Stress-relieving temperature. 260 °C (500 °F)

C93200
83Cu-7Sn-7Pb-3Zn

Commercial Names

Common name. High-leaded tin bronze; bearing bronze 660; 83-7-7-3

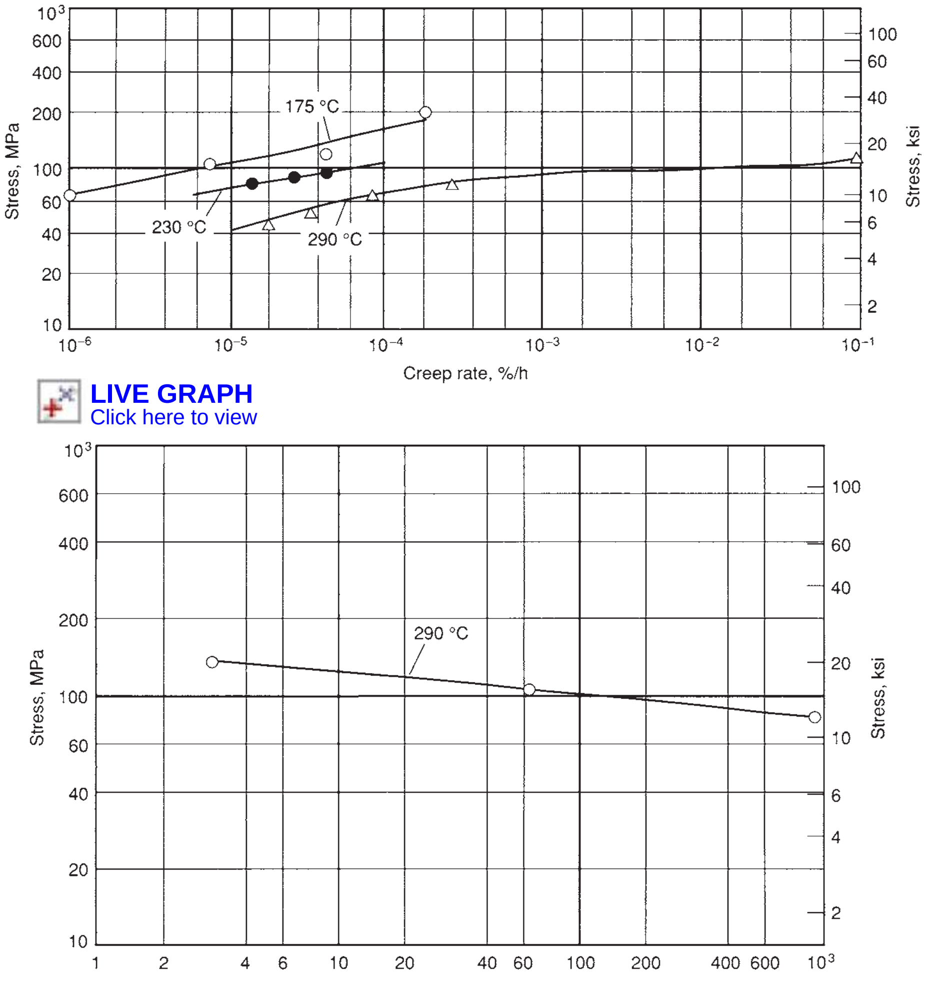

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Fig. 35 Creep-rupture properties of C92200

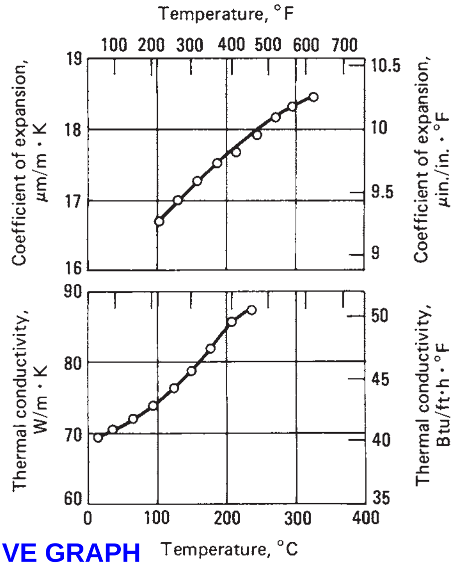

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Fig. 36 Thermal properties of C92200

Specifications

ASTM. Sand castings: B 584; centrifugal castings, B 271; continuous castings: B 505; ingot: B 30
SAE. J462
Government. QQ-C-390; QQ-C-525; QQ-L-225 (Alloy 12); MIL-C-15345 (Alloy 17); MIL-C-11553 (Alloy 12); MIL-B-16261 (Alloy VI)
Other. Ingot code number 315

Chemical Composition

Composition limits. 81.0 to 85.0 Cu, 6.3 to 7.5 Sn, 6.0 to 8.0 Pb, 2.0 to 4.0 Zn, 0.50 N max, 0.20 Fe max, 0.15 P max, 0.35 Sb max, 0.08 S max, 0.003 Si max. In determining Cu, minimum may be calculated as Cu + Ni.
Other phosphorus specifications. 1.5 P max for continuous castings; 0.50 P max for permanent mold castings

Applications

Typical uses. General-utility bearings and bushings, automobile fittings

Mechanical Properties

Tensile properties. Typical data for sand-cast test bars: tensile strength, 240 MPa (35 ksi); yield strength, 125 MPa (18 ksi) at 0.5% extension under load; elongation, 20% in 50 mm (2 in.)
Compressive properties. Compressive strength, 315 MPa (46 ksi) at permanent set of 10%
Hardness. 65 HB
Elastic modulus. Tension, 100 GPa (14.5 × 10^6 psi)
Impact strength. Izod, 8 J (6 ft · lbf)
Fatigue strength. Reverse bending, 110 MPa (16 ksi) at 10^8 cycles

Mass Characteristics

Density. 8.93 g/cm^3 (0.322 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 18 mm/m ($^7/_{32}$ in./ft)

Thermal Properties

Liquidus temperature. 975 °C (1790 °F)
Solidus temperature. 855 °C (1570 °F)
Incipient melting temperature. Pb, 315 °C (600 °F)
Coefficient of linear thermal expansion. 18 μm/m · K (10 μin./in. · °F) at 0 to 100 °C (32 to 212 °F)
Specific heat. 376 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 59 W/m · K (34 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 12% IACS at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 70% of C36000 (free-cutting brass)
Weldability. Soldering: excellent. Brazing: good, but parts must not be strained during brazing or subsequent cooling because brazing is done at temperatures within the hot short range. Oxyfuel gas welding and all forms of arc welding are not recommended.
Stress-relieving temperature. 260 °C (500 °F)

C93400

Commercial Names

Common name. High-leaded tin bronze, CA934, 84-8-8-0

Specifications

ASTM. Continuous, B 505; ingot, B 30
Government. QQ-C-390; MIL-C-22087; MIL-C-22229
Ingot identification number. 310

Chemical Composition

Composition limits. 82.0 to 85.0 Cu, 7.0 to 9.0 Sn, 7.0 to 9.0 Pb, 0.8 Zn max, 0.20 Fe max, 0.50 Sb max, Ni (including Co) 1.0 max, 0.08 S max, 0.50 P max (for continuous castings, phosphorus shall be 1.5% maximum), 0.005 Al max, 0.005 Si max. Ingot for remelting specifications vary from the ranges given.
Copper and zinc specifications. In reporting chemical analyses by the use of instruments such as spectrograph, x-ray, and atomic absorption, copper may be indicated as balance. In reporting chemical analyses obtained by wet methods, zinc may be indicated as balance on those alloys with over 2% zinc.

Applications

Typical uses. Bearings and bushings

Mechanical Properties

Tensile properties. Typical data for as-sand-cast separately cast test bars (M01 temper): tensile strength, 220 MPa (32 ksi); yield strength, 110 MPa (16 ksi) at 0.5% extension under load; elongation, 20% in 50 mm (2 in.)
Hardness. Typically 60 HB (500 kg)
Compressive strength. 330 MPa (48 ksi) at 0.1 mm/mm (0.1 in./in.) set
Impact strength. Izod, 6.8 J (5 ft · lbf)
Proportional limit. 55 MPa (8 ksi)
Fatigue strength. 100 MPa (15 ksi) at 10^8 cycles
Elastic modulus. Tension, 76 GPa (11 × 10^6 psi) at 20 °C (68 °F)

Mass Characteristics

Density. 8.87 g/cm^3 (0.320 lb/in.^{3}) at 20 °C (68 °F)
Volume change on freezing. Patternmaker's shrinkage, 16 mm/m ($^3/_{16}$ in./ft)

Thermal Properties

Specific heat. 376 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 12% IACS at 20 °C (68 °F)

Fabrication Characteristics

Machinability. M01 temper; 70% of C36000 (free-cutting brass)
Stress-relieving temperature. 260 °C (500 °F)

C93500
85Cu-5Sn-9Pb-1Zn

Commercial Names

Common name. High-leaded tin bronze, 85-5-9-1

Specifications

ASTM. Sand castings: B 584; centrifugal castings, B 271; continuous castings, B 505; ingot, B 30
SAE. J462
Government. QQ-C-390; QQ-L-225 (Alloy 14); MIL-B-11553B (Alloy 14)
Other. Ingot code number 326

Chemical Composition

Composition limits. 83.0 to 86.0 Cu, 4.5 to 6.0 Sn, 8.0 to 10.0 Pb, 2.0 Zn max, 0.50 Ni max, 0.20 Fe max, 0.02 P max (1.5 P max for continuous castings), 0.30 Sb max, 0.08 S max, 0.003 Si max. In determining Cu, minimum may be calculated as Cu + Ni.

Applications

Typical uses. Small bearings and bushings, bronze backings for babbitt-lined automotive bearings

Mechanical Properties

Tensile properties. Typical data for sand-cast test bars: tensile strength, 220 MPa (32 ksi); yield strength, 110 MPa (16 ksi) at 0.5% extension under load; elongation, 20% in 50 mm (2 in.)
Compressive properties. Compressive strength, 90 MPa (13 ksi) at permanent set of 0.1%
Hardness. 60 HB
Elastic modulus. Tension, 100 GPa (14.5 × 10^6 psi)
Impact strength. Charpy V-notch or Izod, 11 J (8 ft · lbf)

Mass Characteristics

Density. 8.87 g/cm^3 (0.320 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 16 mm/m ($^3/_{16}$ in./ft)

Thermal Properties

Liquidus temperature. 1000 °C (1830 °F)
Solidus temperature. 855 °C (1570 °F)
Incipient melting temperature. Pb, 315 °C (600 °F)
Coefficient of linear thermal expansion. 18 μm/m · K (10 μin./in. · °F) at 20 to 200 °C (68 to 392 °F)
Specific heat. 376 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 71 W/m · K (41 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 15% IACS at 20 °C (68 °F)

Magnetic Properties

Magnetic permeability. 1.0

Fabrication Characteristics

Machinability. 70% of C36000 (free-cutting brass)

Weldability. Soldering: good. Brazing: good, but parts must not be strained during brazing or subsequent cooling because brazing is done at temperatures within the hot short range. Oxyfuel gas welding and all forms of arc welding are not recommended.

Stress-relieving temperature. 260 °C (500 °F)

C93700
80Cu-10Sn-10Pb

Commercial Names

CDA and UNS number. C93700

Common names. High-leaded tin bronze; bushing and bearing bronze; 80-10-10

Specifications

AMS. Sand and centrifugal castings: 4842

ASTM. Sand castings: B 22, B 584; centrifugal castings: B 271; continuous castings: B 505; ingot: B 30

SAE. J462

Government. QQ-C-390; MIL-B-13506 (Alloy A2)

Other. Ingot code number 305

Chemical Composition

Composition limits. 78.0 to 82.0 Cu, 9.0 to 11.0 Sn, 8.0 to 11.0 Pb, 0.70 Zn max, 0.70 Ni max, 0.15 Fe max, 0.05 P max, 0.50 Sb max, 0.08 S max, 0.003 Si max

Applications

Typical uses. Bearings for high speed and heavy pressure, pump, impellers, applications requiring corrosion resistance, pressure-tight castings

Mechanical Properties

Tensile properties. Typical data for sand-cast test bars: tensile strength, 240 MPa (35 ksi); yield strength, 125 MPa (18 ksi) at 0.5% extension under load; elongation, 20% in 50 mm (2 in.). See also Fig. 37.

Compressive properties. Compressive strength, 90 MPa (13 ksi) at permanent set of 0.1%; 325 MPa (47 ksi) at permanent set of 10%. See also Fig. 38.

Hardness. 60 HB

Elastic modulus. See Fig. 39.

Impact strength. Izod, 7 J (5 ft · lbf); Charpy V-notch, 15 J (11 ft · lbf)

Fatigue strength. Reverse bending, 90 MPa (13 ksi) at 10^8 cycles. See also Fig. 40.

Creep-rupture characteristics. Limiting creep stress for 10^{-5}%/h: 71.7 MPa (10.4 ksi) at 177 °C (350 °F); 51 MPa (7.4 ksi) at 232 °C (450 °F); 12 MPa (1.8 ksi) at 288 °C (550 °F). See also Fig. 41.

Mass Characteristics

Density. 8.95 g/cm^3 (0.323 lb/in.^{3}) at 20 °C (68 °F)

Volume change on freezing. 7.3%

Patternmaker's shrinkage. 11 mm/m ($^1/_8$ in./ft)

Thermal Properties

Liquidus temperature. 930 °C (1705 °F)

Solidus temperature. 762 °C (1403 °F)

Incipient melting temperature. Pb, 315 °C (600 °F)

Coefficient of linear thermal expansion. 18.5 μm/m · K (10.3 μin./in. · °F) at 20 to 200 °C (68 to 392 °F). See also Fig. 42.

Specific heat. 376 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 ° F)

Thermal conductivity. 46.9 W/m · K (27.1 Btu/ft · h · °F) at 20 °C (68 °F). See also Fig. 42.

Electrical Properties

Electrical conductivity. See Fig. 43.

Electrical resistivity. 170 nΩ · m at 20 °C (68 °F)

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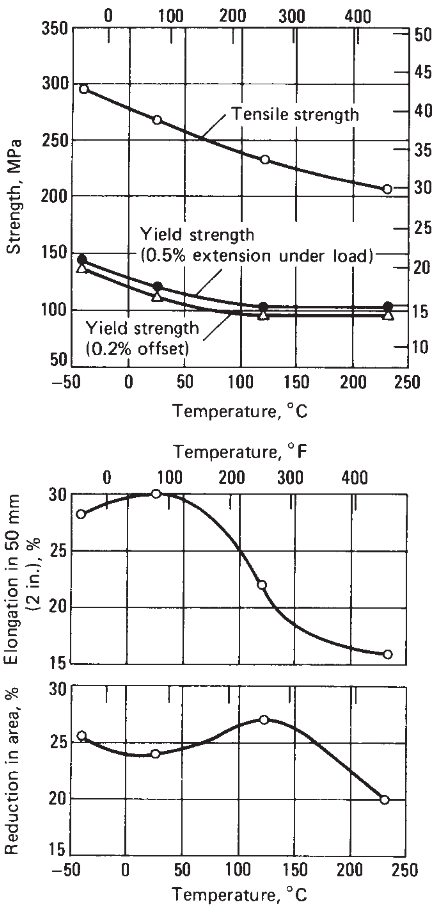

Fig. 37 Typical tensile properties of C93700 at various temperatures

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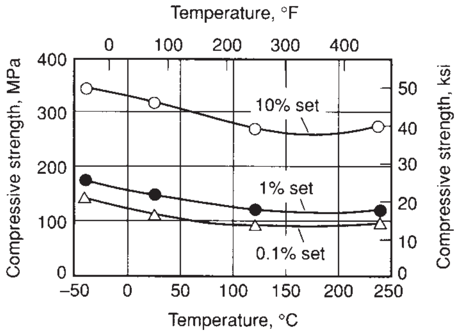

Fig. 38 Variation of compressive strength with temperature for C93700

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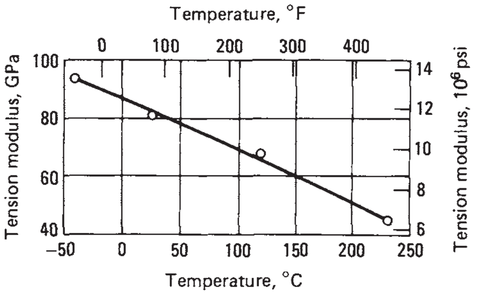

Fig. 39 Variation of elastic modulus with temperature for C93700

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Magnetic Properties

Magnetic permeability. 1.0

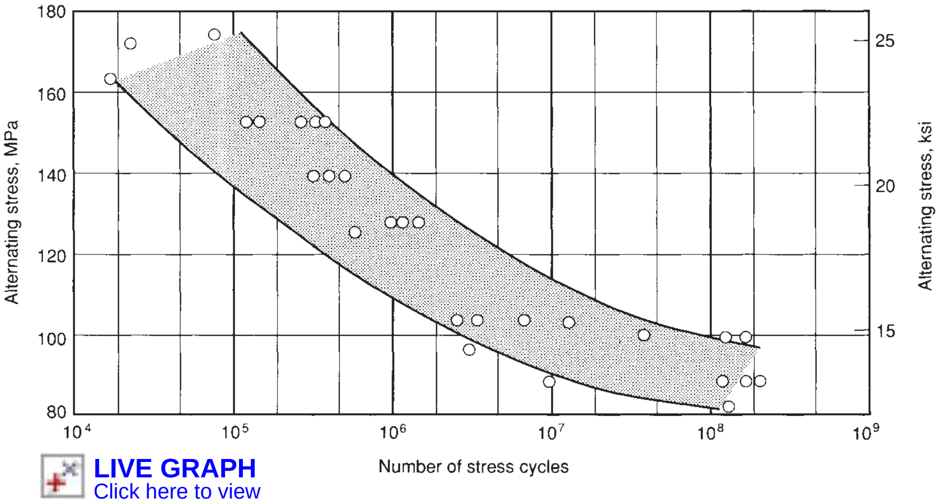

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Fig. 40 Typical reverse bending fatigue curve for C93700

Fabrication Characteristics

Machinability. 80% of C36000 (free-cutting brass)
Weldability. Soldering: good. Brazing: good, but parts must not be strained during brazing or subsequent cooling because brazing is done at temperatures in the hot short range. Oxyfuel gas welding and all forms of arc welding are not recommended.
Stress-relieving temperature. 260 °C (500 °F)

C93800
78Cu-7Sn-15Pb

Commercial Names

Common names. High-leaded tin bronze, anti-acid metal, 78-7-15

Specifications

ASTM. Sand castings: B 66, B 584; centrifugal castings: B 271; continuous castings: B 505; ingot: B 30
SAE. J462
Government. QQ-C-390; QQ-C-525 (Alloy 7); QQ-L-225 (Alloys 19 and 7); MIL-B-16261 (Alloy IV)
Other. Ingot code number 319

Chemical Composition

Composition limits. 75.0 to 79.0 Cu, 6.3 to 7.5 Sn, 13.0 to 16.0 Pb, 0.70 Zn max, 0.70 Ni max, 0.15 Fe max, 0.05 P max, 0.70 Sb max, 0.08 S max, 0.003 Si max, 0.005 Al max. In determining Cu, minimum may be calculated as Cu + Ni.
Consequence of exceeding impurity limits. Aluminum or silicon causes lead sweating during solidification and may cause a substantial portion of castings to be unsound.

Applications

Typical uses. Locomotive engine castings and general-service bearings for moderate pressure; general-purpose wearing metal for rod bushings, shoes, and wedges; freight car bearings; backs for lined journal bearings for locomotive tenders and passenger cars; pump impellers, and bodies for use in acid mine water.

Mechanical Properties

Tensile properties. Typical data for sand-cast test bars: tensile strength, 205 MPa (30 ksi); yield strength, 110 MPa (16 ksi) at 0.5% extension under load; elongation, 18% in 50 mm (2 in.). Typical data for chilled centrifugally cast test bars: tensile strength, 230 MPa (33 ksi); yield strength, 140 MPa (20 ksi) at 0.5% extension under load; elongation, 12% in 50 mm (2 in.)
Shear strength. 105 MPa (15 ksi)
Compressive properties. Compressive strength: sand cast: 83 MPa (12 ksi) at permanent set of 0.1%; 260 MPa (38 ksi) at permanent set of 10%. Centrifugally cast: 130 MPa (19 ksi) at permanent set of 0.1%
Hardness. Sand-cast: 55 HB
Elastic modulus. Sand-cast test bars: tension, 72.4 GPa (10.5×10^6 psi)
Impact strength. Sand cast: Charpy V-notch or Izod, 7 J (5 ft · lbf)
Fatigue strength. Reverse bending, sand-cast test bars: 69 MPa (10 ksi) at 10^8 cycles

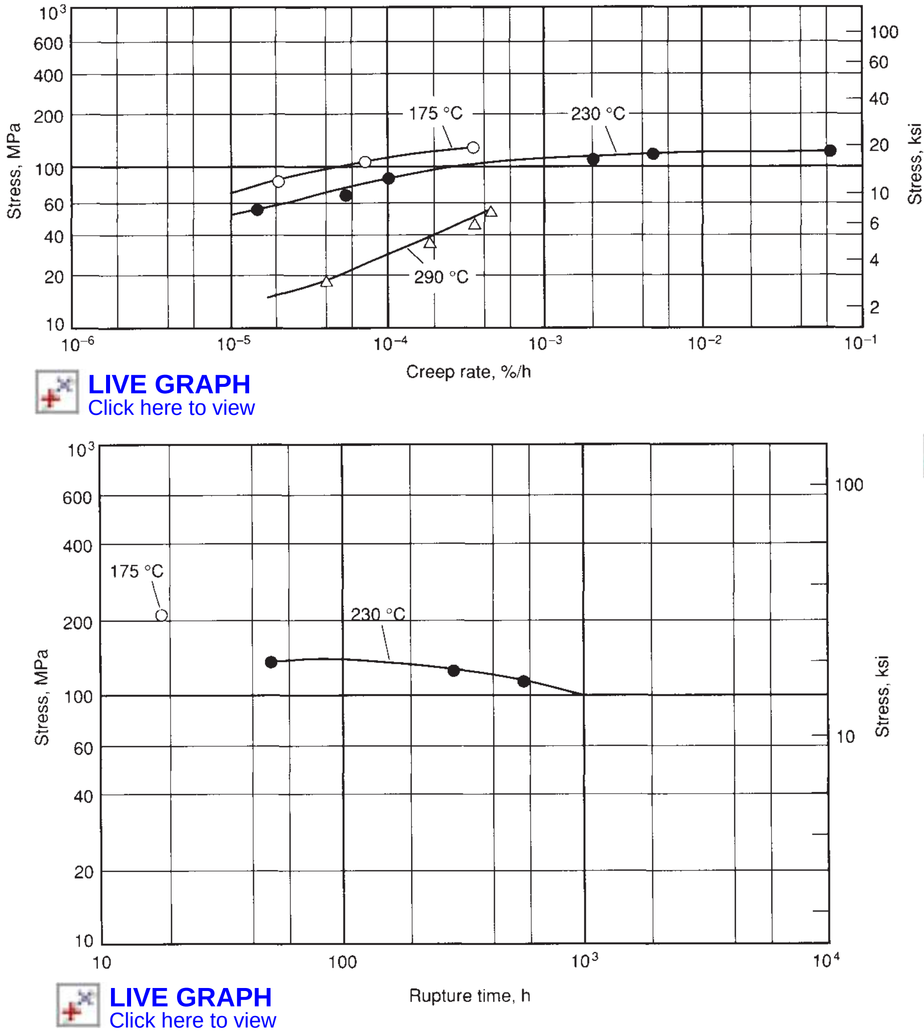

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Fig. 41 Typical creep-rupture properties of C93700

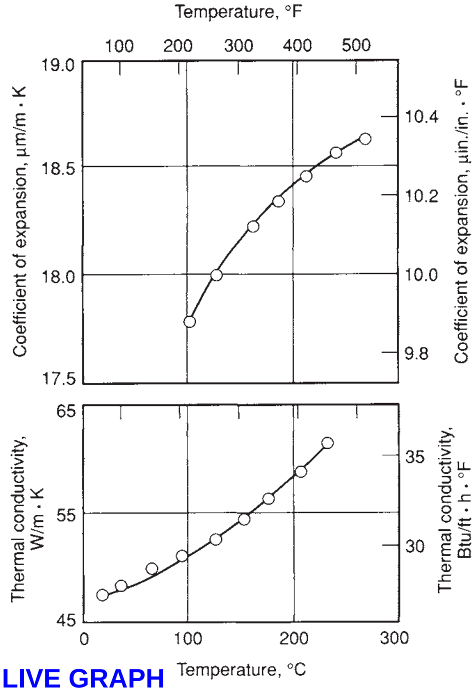

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Fig. 42 Selected thermal properties of C93700

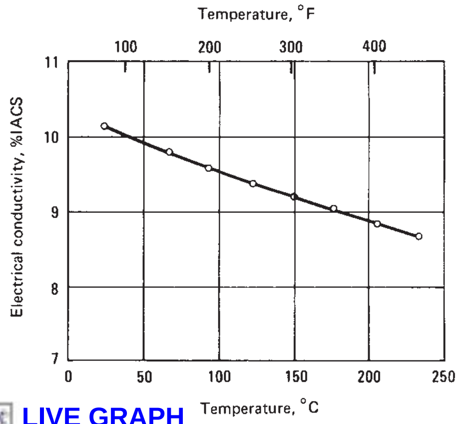

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Fig. 43 Variation of electrical conductivity with temperature for C93700

Mass Characteristics

Density. 9.25 g/cm^3 (0.334 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 11 mm/m ($\frac{1}{8}$ in./ft)

Thermal Properties

Liquidus temperature. 945 °C (1730 °F)
Solidus temperature. 855 °C (1570 °F)
Incipient melting temperature. Pb, 315 °C (600 °F)
Coefficient of linear thermal expansion. 18.5 µm/m · K (10.3 µin./in. · °F) at 20 to 205 °C (68 to 400 °F)
Specific heat. 376 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 52 W/m · K (30 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 11.5% IACS at 20 °C (68 °F)

Magnetic Properties

Magnetic permeability. 1.0

Fabrication Characteristics

Machinability. 80% of C36000 (free-cutting brass)
Weldability. Soldering: good. Brazing: poor. Oxyfuel gas welding and all forms of arc welding are not recommended.
Stress-relieving temperature. 260 °C (500 °F)

C93900
79Cu-6Sn-15Pb

Commercial Names

Common name. High-leaded tin bronze, 79-6-15

Specifications

ASTM. B 505, B 30

Chemical Composition

Composition limits. 76.5 to 79.5 Cu, 5.0 to 7.0 Sn, 14.0 to 18.0 Pb, 1.5 Zn max, 0.80 Ni max, 0.40 Fe max, 0.05 P max (1.5 P max for continuous castings)

Applications

Typical uses. Continuous castings only; common products include bearings for general service, pump bodies and impellers for mine use

Mechanical Properties

Tensile properties. Typical tensile strength, 220 MPa (32 ksi); yield strength, 150 MPa (22 ksi) at 0.5% extension under load; elongation, 7% in 50 mm (2 in.)
Hardness. 63 HB, typical
Elastic modulus. Tension, 76 GPa (11 × 10^6 psi)

Mass Characteristics

Density. 9.25 g/cm^3 (0.334 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 11 mm/m ($\frac{1}{8}$ in./ft)

Thermal Properties

Liquidus temperature. 943 °C (1730 °F)
Solidus temperature. 854 °C (1570 °F)
Incipient melting temperature. Pb, 315 °C (600 °F)
Coefficient of linear thermal expansion. 18.5 µm/m · K (10.3 µin./in. · °F) at 20 to 204 °C (68 to 400 °F)
Specific heat. 376 J/kg · K (0.09 Btu/lb · °F)
Thermal conductivity. 52 W/m · K (30 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 11.5% IACS at 20 °C (68 °F)

Magnetic Properties

Magnetic permeability. 1.0

Fabrication Characteristics

Machinability. 80% of C36000 (free-cutting brass)

C94300
70Cu-5Sn-25Pb

Commercial Names

Common name. High-leaded tin bronze, soft bronze, 70-5-25

Specifications

ASTM. B 584, B 66, B 271, B 505, B 30
SAE. J462 (CA943)
Government. QQ-L-225, Alloy 18; MIL-B-16261, Alloy V
Other. Ingot code number 322

Chemical Composition

Composition limits. 68.5 to 73.5 Cu, 4.5 to 6.0 Sn, 22.0 to 25.0 Pb, 0.50 Zn max, 0.70 Ni max, 0.15 Fe max, 0.70 Sb max, 0.05 P max, 0.08 S max
Supplementary composition limits. In determining Cu, minimum may be calculated as Cu + Ni. 0.35 Fe max when used for steel-backed bearings. 1.5 P max for continuous castings

Applications

Typical uses. Bearings under light loads and high speed, driving boxes, railroad bearings

Mechanical Properties

Tensile properties. Typical data for sand-cast test bars: tensile strength, 185 MPa (27 ksi); yield strength, 90 MPa (13 ksi) at 0.5% extension under load; elongation, 10% in 50 mm (2 in.); reduction in area, 8%
Compressive properties. Typical compressive strength: 76 MPa (11 ksi) at permanent set of 0.1%; 160 MPa (23 ksi) at permanent set of 10%
Hardness. 48 HB
Elastic modulus. Tension, 72.4 GPa (10.5 × 10^6 psi)
Impact strength. Izod, 7 J (5 ft · lbf)

Mass Characteristics

Density. 9.29 g/cm^3 (0.336 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 11 mm/m ($\frac{1}{8}$ in./ft)

Thermal Properties

Solidus temperature. 900 °C (1650 °F)
Incipient melting temperature. Pb, 315 °C (600 °F)
Specific heat. 376 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 62.7 W/m · K (36.2 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 9% IACS at 20 °C (68 °F)

Magnetic Properties

Magnetic permeability. 1.0

Fabrication Characteristics

Machinability. 80% of C36000 (free-cutting brass)

C94500
73Cu-7Sn-20Pb

Commercial Names

Common name. Medium bronze

Specifications

ASTM. Sand castings: B 66; ingot: B 30
Government. QQ-L-225, Alloy 15; MIL-B-16261, Alloy I

Chemical Composition

Composition limits. 6.0 to 8.0 Sn, 16 to 22 Pb, 1.2 Zn max, 1.0 Ni max, 0.8 Sb max, 0.005 Al max, 0.15 Fe max, 0.5 P max (1.5 P max for continuous castings), 0.08 S max, 0.005 Si max, bal Cu

Applications

Typical uses. Locomotive wearing parts, high-load low-speed bearings

Mechanical Properties

Tensile properties. Typical. Tensile strength, 170 MPa (25 ksi); yield strength, 83 MPa (12 ksi); elongation, 12% in 50 mm (2 in.)
Compressive properties. Compressive strength, 250 MPa (36 ksi)
Hardness. 50 HB
Elastic modulus. Tension, 72 GPa (10.5 × 10^6 psi); shear, 90 GPa (13 × 10^6 psi)
Fatigue strength. Rotating beam, 69 MPa (10 ksi) at 10^8 cycles
Impact strength. Izod, 5.4 J (4.0 ft · lbf)

Mass Characteristics

Density. 9.4 g/cm^3 (0.34 lb/in.^{3}) at 20 °C (68 °F)
Volume change on freezing. 1.1%

Thermal Properties

Liquidus temperature. 940 °C (1725 °F)
Solidus temperature. 800 °C (1475 °F)
Incipient melting temperature. 315 °C (600 °F)
Coefficient of linear thermal expansion. 18.5 µm/m · K (10.3 µin./in. · °F) at 20 to 200 °C (68 to 392 °F)
Specific heat. 376 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)

Thermal conductivity. 52 W/m · K (30 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 10% IACS at 20 °C (68 °F)

Magnetic Properties

Magnetic permeability. 1.0

Fabrication Characteristics

Machinability. 80% of C36000 (free-cutting brass)

C95200

88Cu-3Fe-9Al

Commercial Names

Previous trade name. Ampco Al
Common name. Aluminum bronze 9A; 88-3-9

Specifications

ASME. Sand castings: SB148; centrifugal castings: SB271
ASTM. Sand castings: B 148; centrifugal castings: B 271; continuous castings: B 505; ingot: B 30
SAE. J462
Government. Centrifugal, sand, and continuous castings: QQ-C-390; sand castings: MIL-C-22229
Other. Ingot code number 415

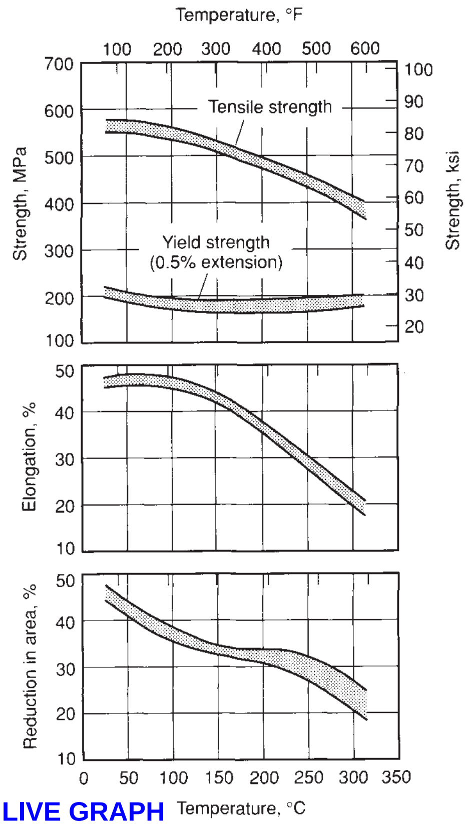

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Fig. 44 Typical short-time tensile properties of C95200, as-cast

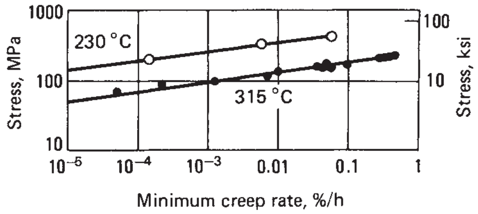

Fig. 45 Typical creep properties of C95200, as-cast

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Chemical Composition

Composition limits. 86 Cu min, 8.5 to 9.5 Al, 2.5 to 4.0 Fe, 1.0 max other (total)
Consequence of exceeding impurity limits. Possible hot shortness and/or hot cracking, embrittlement, and reduced soundness of castings

Applications

Typical uses. Acid-resisting pumps, bearings, bushings, gears, valve seats, guides, plungers, pump rods, pickling hooks, non-sparking hardware
Precautions in use. Not suitable for use in oxidizing acids

Mechanical Properties

Tensile properties. Typical data for sand-cast test bars: tensile strength, 550 MPa (80 ksi); yield strength, 185 MPa (27 ksi); elongation, 35% in 50 mm (2 in.). See also Fig. 44.
Hardness. 64 HRB; 125 HB (3000 kg load)
Poisson's ratio. 0.31
Elastic modulus. Tension, 105 GPa (15 × 10^6 psi); shear, 39 GPa (5.7 × 10^6 psi)
Impact strength. Charpy keyhole, 27 J (20 ft · lbf) at –18 to 38 °C (0 to 100 °F); Izod, 40 J (30 ft · lbf) at –18 to 38 °C (0 to 100 °F)
Fatigue strength. Rotating beam, 150 MPa (22 ksi) at 10^8 cycles
Creep-rupture characteristics. Limiting creep stress for 10^{-5}%/h: 145 MPa (21 ksi) at 230 °C (450 °F); 54 MPa (7.9 ksi) at 315 °C (600 °F). See also Fig. 45.

Structure

Microstructure. As cast, the microstructure is primarily fcc alpha, with precipitates of iron-rich alpha in the form of rosettes and spheres. Depending on the cooling rate, small amounts of metastable cph beta or alpha-gamma eutectoid decomposition products may be present. Annealing followed by rapid cooling reduces the amount of residual beta to about 5% of the apparent volume.
Metallographic etchant. Acid ferric chloride (10% HCl, 5% FeCl3)

Mass Characteristics

Density. 7.64 g/cm^3 (0.276 lb/in.^{3}) at 20 °C (68 °F)
Volume change on freezing. Approximately 1.7% contraction
Patternmaker's shrinkage. 2%

Thermal Properties

Liquidus temperature. 1045 °C (1915 °F)
Solidus temperature. 1040 °C (1905 °F)
Coefficient of linear thermal expansion. 16.2 μm/m · K (9.0 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 380 J/kg · K (0.091 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 50 W/m · K (29.1 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 12% IACS at 20 °C (68 °F)
Electrical resistivity. 144 nΩ · m at 20 °C (68 °F)

Magnetic Properties

Magnetic permeability. 1.20 at 16,000 A/m (200 oersteds)

Chemical Properties

General corrosion behavior. C95200 has generally fair resistance to attack in nonoxidizing mineral acids such as sulfuric, hydrochloric, and phosphoric, and in alkalies such as sodium and potassium hydroxide. Cast components are used successfully in systems for seawater, brackish water, and potable water. The alloy resists many organic acids, including acetic and lactic, plus all esters and ethers. Moist ammonia atmospheres can cause stress-corrosion cracking.

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass). Carbide or tool steel cutters may be used. Good surface finish and precision attainable with all conventional methods. Typical conditions using tool steel cutters: roughing speed, 105 m/min (350 ft/min) with a feed of 0.3 mm/rev (0.011 in./rev); finishing speed, 350 m/min (1150 ft/min) with a feed of 0.15 mm/rev (0.006 in./rev)
Annealing temperature. 650 to 745 °C (1200 to 1375 °F)

C95300

89Cu-1Fe-10A1

Commercial Names

Trade name. Ampco B2
Common names. Aluminum bronze 9B; 89-1-10

Specifications

ASTM. Sand castings: B 148; centrifugal castings: B 271; continuous castings: B 505; ingots: B 30
SAE. J462
Government. Centrifugal and sand castings: QQ-C-390; precision castings: MIL-C-11866, composition 22
Ingot identification number. 415

Chemical Composition

Composition limits. 86 Cu min, 9.0 to 11.0 Al, 0.8 to 1.5 Fe, 1.0 max other (total)
Consequence of exceeding impurity limits. Possible hot shortness, loss of casting soundness, embrittlement, reduced response to heat treatment

Applications

Typical uses. Pickling baskets, nuts, gears, steel mill slippers, marine equipment, welding jaws, nonsparking hardware

Precautions in use. Not suitable for exposure to oxidizing acids. Prolonged heating in the 320 to 565 °C (610 to 1050 °F) range can result in a loss of ductility and notch toughness.

Mechanical Properties

Tensile properties. Minimum values. As cast: tensile strength, 450 MPa (65 ksi); yield strength, 170 MPa (25 ksi); elongation, 20% in 50 mm (2 in.); reduction in area, 25%. TQ50 temper: tensile strength, 550 MPa (80 ksi); yield strength, 275 MPa (40 ksi); elongation, 12% in 50 mm (2 in.); reduction in area, 14%
Compressive properties. Compressive ultimate strength: as-cast, 760 MPa (110 ksi); TQ50 temper, 825 MPa (120 ksi). Elastic limit: as-cast, 125 MPa (18 ksi); TQ50 temper, 205 MPa (30 ksi)
Hardness. As-cast, 67 HRB; TQ50 temper, 81 HRB
Poisson's ratio. 0.314
Elastic modulus. Tension, 110 GPa (16 × 10^6 psi); shear, 42 GPa (6.1 × 10^6 psi)
Impact strength. Cast and annealed: Charpy keyhole, 31 J (23 ft · lbf); Izod, 38 J (28 ft · lbf) at –20 to 100 °C (–5 to 212 °F). TQ50 temper: Charpy keyhole, 37 J (27 ft · lbf) at –20 to 100 °C (–5 to 212 °F)

Structure

Crystal structure. Alpha phase, face-centered cubic; beta phase, close-packed hexagonal
Microstructure. As-cast and properly cooled or annealed, the structure is approximately 70% alpha and 30% metastable beta. Quenched and tempered (TQ50 temper), the structure is largely tempered metastable beta martensite, but also contains both primary alpha and reprecipitated acicular alpha.

Mass Characteristics

Density. 7.53 g/cm^3 (0.272 lb/$in.^3$) at 20 °C (68 °F)
Patternmaker's shrinkage. 1.6%

Thermal Properties

Liquidus temperature. 1045 °C (1915 °F)
Solidus temperature. 1040 °C (1905 °F)
Coefficient of linear thermal expansion. 16.2 µm/m · K (9.0 µin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 375 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 63 W/m · K (36 Btu/ft · h · °F) at 20 °C (68 °F); temperature coefficient, 0.12 W/m · K per K at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 13% IACS at 20 °C (68 °F)
Electrical resistivity. 133 nΩ · m at 20 °C (68 °F)

Magnetic Properties

Magnetic permeability. 1.07 at field strength of 8 kA/m

Chemical Properties

General corrosion behavior. Corrosion characteristics of C95300 are slightly inferior to those of C95200, primarily because C95300 has more and larger beta areas. Heat treatment enhances corrosion resistance, particularly in mediums that promote dealloying. The alloy shows characteristic resistance to nonoxidizing mineral acids, neutral salt solutions, seawater, brackish water, and some organic acids.

Fabrication Characteristics

Machinability. 55% of C36000 (free-cutting brass). Tool steel or carbide cutters may be used. Good surface and precision finish may be obtained in the as-cast, cast and annealed, and TQ50 tempers. Typical conditions using tool steel cutters: roughing speed, 90 m/min (300 ft/min) at a feed of 0.2 mm/rev (0.009 in./rev); finishing speed, 290 m/min (950 ft/min) at a feed of 0.1 mm/rev (0.004 in./rev)
Annealing temperature. 595 to 650 °C (1100 to 1200 °F)

C95400
(85Cu-4Fe-11Al) and C95410

Commercial Names

Trade name. Ampco C3
Common names. Aluminum bronze 9C; G5; 85-4-11

Specifications

ASME. Sand castings: SB148
ASTM. Sand castings: B 148; centrifugal castings: B 271; continuous castings: B 505; ingots: B 30
Government. QQ-C-390. Sand castings, MIL-C-22229 (composition 6); investment castings, MIL-C-15345 (Alloy 13); centrifugal castings, MIL-C-22087 (composition 8)
Ingot identification number. 415

Chemical Composition

Composition limits of C95400. 83 min Cu, 10.0 to 11.5 Al, 3.0 to 5.0 Fe, 0.50 Mn max, 2.5 Ni max (+ Co), 0.5 max other (total)
Composition limits of C95410. 83.0 Cu min, 3.0 to 5.0 Fe, 1.5 to 2.5 Ni (including Co), 10.0 to 11.5 Al, 0.50 Mn max
Cu + sum of named elements. 99.5 min
Consequence of exceeding impurity limits. Possible hot shortness, reduced casting soundness, embrittlement and loss of heat treating response

Applications

Typical uses. Pump impellers, bearings, gears, worms, bushings, valve seats and guides, rolling mill slippers, slides, nonsparking hardware
Precautions in use. Not suitable for use in oxidizing acids. Prolonged heating in the 320 to 565 °C (610 to 1050 °F) range can result in loss of ductility and notch toughness.

Mechanical Properties

Tensile properties. Minimum values. As cast: tensile strength, 515 MPa (75 ksi); yield strength, 205 MPa (30 ksi); elongation, 12% in 50 mm (2 in.); reduction in area, 12%. TQ50 temper: tensile strength, 620 MPa (90 ksi); yield strength, 310 MPa (45 ksi); elongation, 6% in 50 mm (2 in.), reduction in area, 6%. See also Fig. 46.
Compressive properties. Compressive strength, ultimate: as-cast, 940 MPa (136 ksi); TQ50 temper, 1070 MPa (155 ksi)
Hardness. As-cast, 83 HRB; TQ50 temper: 94 HRB
Poisson's ratio. 0.316
Elastic modulus. Tension, 110 GPa (16 × 10^6 psi); shear, 41 GPa (6.1 × 10^6 psi)
Impact strength. As-cast: Charpy keyhole, 15 J (11 ft · lbf); Izod, 22 J (16 ft · lbf) at 20 °C (68 °F). TQ50 temper: Charpy keyhole, 9 J (7 ft · lbf); Izod, 15 J (11 ft · lbf) at 20 °C (68 °F)
Fatigue strength. Reverse bending, 240 MPa (35 ksi) at 10^8 cycles (TQ50 temper)
Creep-rupture characteristics. Limiting creep stress at a strain rate of 10^{-5}%/h: 115 MPa (17 ksi) at 230 °C (450 °F); 51 MPa (7.4 ksi) at 315 °C (600 °F); 30 MPa (4.4 ksi) at 370 °C (700 °F); 20 MPa (2.9 ksi) at 425 °C (800 °F). See also Fig. 47.

Structure

Crystal structure. Alpha, face-centered cubic; beta, close-packed hexagonal
Microstructure. As-cast and annealed material normally consists of approximately 50% alpha and 50% metastable beta. Under some conditions, eutectoid decomposition may produce an alpha-gamma-2 structure instead of the beta phase. Quenched-and-tempered structures consist of fine acicular alpha crystals in a tempered beta matrix.

Mass Characteristics

Density. 7.45 g/cm^3 (0.269 lb/$in.^3$) at 20 °C (68 °F)
Patternmaker's shrinkage. 1.6%

Thermal Properties

Liquidus temperature. 1040 °C (1900 °F)
Solidus temperature. 1025 °C (1880 °F)

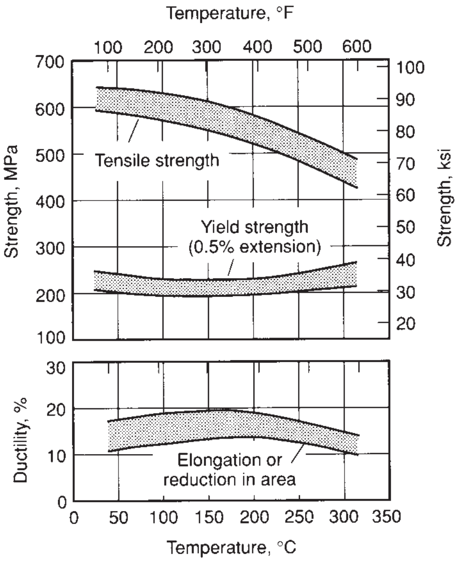

Fig. 46 Typical short-time tensile properties of C95400, as-cast

LIVE GRAPH
Click here to view

Coefficient of linear thermal expansion. 16.2 μm/m · K (9.0 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 420 J/kg · K (0.10 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 59 W/m · K (34 Btu/ft · h · °F) at 20 °C (68 °F); temperature coefficient, 0.117 W/m · K per K at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 13% IACS at 20 °C (68 °F)
Electrical resistivity. 133 nΩ · m at 20 °C (68 °F)

Magnetic Properties

Magnetic permeability. As-cast, 1.27 at field strength of 16 kA/m; TQ50 temper, 1.20 at field strength of 16 kA/m

Chemical Properties

General corrosion behavior. C95400 has fair resistance to attack by nonoxidizing solutions of mineral acids such as sulfuric and phosphoric, as well as to neutral salts such as sodium chloride. The alloy also resists acetic, lactic, and oxalic acids; organic solvents such as esters and ethers; and seawater, brackish water, and potable waters. In some environments, C95400 can undergo dealloying caused by corrosive attack on the beta phase. Heat treatment improves resistance to dealloying. Moist ammonia environments may cause stress-corrosion cracking under high levels of applied stress.

Fabrication Characteristics

Machinability. 60% of C36000 (free-cutting brass). C95400, in either as-cast or TQ50 temper, is easily machined by all standard operations using high-strength tool steel or carbide cutters. Typical conditions using tool steel cutters: roughening speed, 90 m/min (300 ft/min) at a feed of 0.3 mm/rev (0.011 in./rev); finishing speed, 290 m/min (950 ft/min) at a feed of 0.1 mm/rev (0.004 in./rev)
Annealing temperature. 620 °C (1150 °F)

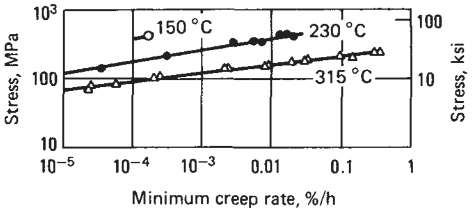

Fig. 47 Typical creep properties of C95400, as-cast

LIVE GRAPH
Click here to view

C95500
81Cu-4Fe-4Ni-11Al

Commercial Names

Previous trade name. Ampco D4
Common names. Aluminum bronze 9D; 415; 81-4-4-11

Specifications

AMS. 4880
ASTM. Sand castings: B 148; centrifugal castings: B 271; continuous castings: B 505; ingots; B 30
SAE. J462
Government. QQ-C-390; centrifugal castings, MIL-C-15345 (Alloy 14); sand castings, MIL-C-22229 (composition 6); investment castings, MIL-C-22087 (composition 8)
Ingot identification number. 415

Chemical Composition

Composition limits. 78 Cu min, 10.0 to 11.5 Al, 3.0 to 5.0 Fe, 3.5 Mn max, 3.0 to 5.5 Ni (+ Co), 0.5 max other (total)
Consequence of exceeding impurity limits. Possible hot shortness in welding, embrittlement, increased quench-cracking susceptibility, possible loss of heat-treating response. Excessive Si can cause machining difficulties.

Applications

Typical uses. Valve guides and seats in aircraft engines, corrosion-resistant parts, bushings, gears, worms, pickling hooks and baskets, agitators
Precautions in use. Not suitable for use in strong oxidizing acids

Mechanical Properties

Tensile properties. Typical. As-cast: tensile strength, 620 MPa (90 ksi); yield strength, 275 MPa (40 ksi); elongation, 6% in 50 mm (2 in.); reduction in area, 7%. TQ50 temper: tensile strength, 760 MPa (110 ksi); yield strength, 415 MPa (60 ksi); elongation, 5% in 50 mm (2 in.); reduction in area, 5%
Compressive properties. As-cast: compressive strength, 895 MPa (130 ksi); compressive yield strength, 825 MPa (120 ksi) at a permanent set of 10%; elastic limit, 310 MPa (45 ksi). TQ50 temper: compressive strength, 1140 MPa (165 ksi); compressive yield strength, 1030 MPa (150 ksi) at a permanent set of 10%; elastic limit, 415 MPa (60 ksi)
Hardness. As-cast, 87 HRB; TQ50 temper, 96 HRB
Poisson's ratio. 0.32
Elastic modulus. Tension: as-cast, 110 GPa (16×10^6 psi); TQ50 temper, 115 GPa (17×10^6 psi). Shear: as-cast, 42 GPa (6.1×10^6 psi); TQ50 temper, 44 GPa (6.4×10^6 psi)
Impact strength. Charpy keyhole, 14 J (10 ft · lbf); Izod, 18 J (13 ft · lbf) at 20 °C (68 °F)
Fatigue strength. Rotating beam, as-cast, 215 MPa (31 ksi) at 10^8 cycles; TQ50 temper, 260 MPa (38 ksi) at 10^8 cycles
Creep-rupture characteristics. Limiting creep stress at a strain rate of 10^{-5}%/h: 72 MPa (10.5 ksi) at 315 °C (600 °F); 38 MPa (5.5 ksi) at 370 °C (700 °F); 17 MPa (2.5 ksi) at 425 °C (800 °F)

Structure

Crystal structure. Alpha, face-centered cubic; beta, close-packed hexagonal; kappa, ordered face-centered cubic
Microstructure. As-cast or annealed structures consist of alpha crystals plus kappa precipitates, forming a pearlitic appearance. Small areas of metastable beta may exist. Heat-treated structures consist of tempered beta martensite with very fine reprecipitated alpha needles. Some undissolved equiaxed alpha crystals may be evident, depending on the actual composition and quenching temperature.

Mass Characteristics

Density. 7.53 g/cm^3 (0.272 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 1.6%

Thermal Properties

Liquidus temperature. 1055 °C (1930 °F)
Solidus temperature. 1040 °C (1900 °F)
Coefficient of linear thermal expansion. 16.2 μm/m · K (9.0 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 418 J/kg · K (0.10 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 42 W/m · K (24 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 8.5% IACS at 20 °C (68 °F)
Electrical resistivity. 203 nΩ · m at 20 °C (68 °F)

Magnetic Properties

Magnetic permeability. As-cast, 1.30 at field strength of 16 kA/m; TQ50 temper, 1.20 at field strength of 16 kA/m

Chemical Properties

General corrosion behavior. Good cavitation resistance in salt water and fresh tap water. Avoid nitric acid and strong aeration when using other acids.

Fabrication Characteristics

Machinability. 50% of C36000 (free-cutting brass). Heat treating reduces machinability in drilling and tapping operations. Tool steel or carbide cutters may be used. Typical conditions using tool steel cutters follow. Roughing speed: as-cast, 76 m/min (250 ft/min) at a feed of 0.3 mm/rev (0.011 in./rev); TQ50 temper, 90 m/min (300 ft/min) at a feed of 0.2 mm/rev (0.009 in./rev). Finishing speed: as-cast and TQ50 temper, 290 m/min (950 ft/min) at a feed of 0.1 mm/rev (0.004 in./rev)
Annealing temperature. 620 to 705 °C (1150 to 1300 °F)

C95600
91Cu-2Si-7Al

Commercial Names

Common name. Aluminum-silicon bronze

Specifications

ASTM. Ingot: B 30; sand castings: B 148, B 763
Government. QQ-B-675, MIL-V-11 87
Ingot identification number. 415E

Chemical Composition

Composition limits. 88.0 Cu min, 0.25 Ni (including Co) max, 6.0 to 8.0 Al, 1.8 to 3.3 Si.

Cu + sum of named elements. 99.0% min

Applications

Typical uses. Cable connectors, terminals, valve stems, marine hardware, gears, worms, pole-line hardware

Mechanical Properties

Tensile properties. Typical data for as-sand-cast separately cast test bars (M01 temper): tensile strength, 515 MPa (75 ksi); yield strength, 235 MPa (34 ksi) at 0.5% extension under load; elongation, 18% in 50 mm (2 in.)
Hardness. Typically, 140 HB (3000 kg)
Elastic modulus. Tension, 105 GPa (15 × 10^6 psi) at 20 °C (68 °F)

Mass Characteristics

Density. 7.69 g/cm^3 (0.278 lb/in.^{3}) at 20 °C (68 °F)
Volume change on freezing. Patternmaker's shrinkage, 16 mm/m ($\frac{3}{16}$ in./ft)

Thermal Properties

Liquidus temperature. 1005 °C (1840 °F)
Solidus temperature. 982 °C (1800 °F)
Specific heat. 376 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 8.5% IACS at 20 °C (68 °F)

Fabrication Characteristics

Machinability. M01 temper; 60% at C36000 (free-machining brass)
Stress-relieving temperature. 260 °C (500 °F)

C95700
75Cu-3Fe-8Al-2Ni-12Mn

Commercial Names

Previous trade name. Superstone 40, Novoston, Ampcoloy 495
Common name. Manganese-aluminum bronze; 75-3-8-2-12

Specifications

ASTM. Sand castings: B 148; ingot: B 30
Government. Sand castings: MIL-B-24480

Chemical Composition

Composition limits. 71.0 Cu min, 11.0 to 14.0 Mn, 7.0 to 8.5 Al, 2.0 to 4.0 Fe, 1.5 to 3.0 Ni, 0.10 Si max, 0.03 Pb max, 0.5 max others (total)
Consequence of exceeding impurity limits. Possible hot shortness and reduced cast strength

Applications

Typical uses. Propellers, impellers, stator clamp segments, safety tools, welding rods, valves, pump casings, marine fittings
Precautions in use. Slow cooling or prolonged heating in the 350 to 565 °C (660 to 1050 °F) range may cause embrittlement. Not suitable for use in oxidizing acids

Mechanical Properties

Tensile properties. Typical data for sand-cast test bars: tensile strength, 620 MPa (90 ksi); yield strength, 275 MPa (40 ksi); elongation, 20% in 50 mm (2 in.); reduction in area, 24%
Compressive properties. Compressive strength, as-cast: 1035 MPa (150 ksi) at a permanent set of 0.1%
Hardness. As-cast, or cast and annealed: 85 to 90 HRB
Poisson's ratio. 0.326
Elastic modulus. Tension, 125 GPa (18 × 10^6 psi); shear, 44 GPa (6.4 × 10^6 psi)
Impact strength. Izod, 27 J (20 ft · lbf) at 20 °C (68 °F)
Fatigue strength. Reverse bending, 231 MPa (33.5 ksi) at 10^8 cycles
Creep-rupture characteristics. Limiting creep stress for 10^{-5}%/h: 66 MPa (9.6 ksi) at 205 °C (400 °F); 31 MPa (4.5 ksi) at 290 °C (550 °F). Rupture stress for 105 h life: 470 MPa (68 ksi) at 205 °C (400 °F); 232 MPa (33.6 ksi) at 260 °C (500 °F); 39 MPa (5.7 ksi) at 370 °C (700 °F)

Structure

Microstructure. As-cast and annealed tempers: fcc alpha crystals with cph beta phase in various amounts, typically, 25% by volume

Mass Characteristics

Density. 7.53 g/cm^3 (0.272 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 1.6%

Thermal Properties

Liquidus temperature. 990 °C (1815 °F)
Solidus temperature. 950 °C (1740 °F)
Coefficient of linear thermal expansion. 17.6 μm/m · K (9.8 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 400 J/kg · K (0.105 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 12.1 W/m · K (7.0 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 3.1% IACS at 20 °C (68 °F)
Electrical resistivity. 556 nΩ · m at 20 °C (68 °F)

Magnetic Properties

Magnetic permeability. Magnetic condition (as-cast, slow cooled): 2.2 to 15.0. Demagnetized (annealed, fast cooled): 1.03

Chemical Properties

General corrosion behavior. Generally comparable to that of the aluminum bronzes and nickel-aluminum bronzes. See C95200.

Fabrication Characteristics

Machinability. 50% of C36000 (free-cutting brass). Tool steel or carbide cutters may be used. Good surface finishes and tolerance are possible in all conventional machining operations. Typical conditions using tool steel cutters: roughing speed, 75 m/min (250 ft/min) with a feed of 0.3 mm/rev (0.011 in./rev); finishing speed, 290 m/min (950 ft/min) with a feed of 0.1 mm/rev (0.004 in./rev)
Annealing temperature. 620 °C (1150 °F)

C95800
82Cu-4Fe-9Al-4Ni-1Mn

Commercial Names

Common names. Alpha nickel-aluminum bronze; propeller bronze

Specifications

ASTM. Sand castings: B 148; centrifugal castings: B 271; continuous castings: B 505; ingots: B 30
SAE. J462
Government. Sand and centrifugal castings: QQ-C-390; MIL-B-24480; centrifugal castings only: MIL-C-15345, Alloy 28
Ingot identification number. 415

Chemical Composition

Composition limits. 79.0 Cu min, 0.03 Pb max, 3.5 to 4.5 Fe, 4.0 to 5.0 Ni (+ Co), 0.8 to 1.5 Mn, 8.5 to 9.5 Al, 0.10 Si max
Consequence of exceeding impurity limits. Hard spots, embrittlement, possible hot shortness, possible weld cracking

Applications

Typical uses. Propeller blades and hubs for fresh-and salt-water service, fittings, gears, worm wheels, valve guides and seals, structural applications
Precautions in use. Not suitable for use in oxidizing acids or strong alkalies

Mechanical Properties

Tensile properties. Typical. Cast and annealed: tensile strength, 585 MPa (85 ksi); yield strength, 240 MPa (35 ksi); elongations, 15% in 50 mm (2 in.); reduction in area, 16%
Compressive properties. Compressive strength, cast and annealed: 240 MPa (35 ksi) at a permanent set of 0.1%; 330 MPa (48 ksi) at a permanent set of 1%; 690 MPa (100 ksi) at a permanent set of 10%
Hardness. Cast and annealed, 84 to 89 HRB
Poisson's ratio. 0.32
Elastic modulus. Tension, 110 GPa (16 × 10^6 psi); shear, 42 GPa (6.1 × 10^6 psi)
Impact strength. Charpy keyhole, 13 J (10 ft · lbf) at –23 to 66 °C (–10 to 150 °F); Charpy V-notch, 22 J (16 ft · lbf) at –23 to 66 °C (–10 to 150 °F)
Fatigue strength. Rotating beam, 230 MPa (33 ksi) at 10^8 cycles

Structure

Crystal structure. Alpha, face-centered cubic; beta, close-packed hexagonal; kappa, ordered face-centered cubic
Microstructure. As-cast or annealed structures are generally continuous equiaxed alpha crystals with small areas of metastable beta phase. Kappa phase precipitates are found in the alpha phase, in grain boundaries, and in beta areas. Quench-and-temper treatments results in refine-

ment and redistribution of the kappa phase throughout a matrix of tempered beta martensite and alpha-kappa eutectoid decomposition product. Some undissolved primary alpha crystals may also be present.

Mass Characteristics

Density. 7.64 g/cm^3 (0.276 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 1.6%

Thermal Properties

Liquidus temperature. 1060 °C (1940 °F)
Solidus temperature. 1045 °C (1910 °F)
Coefficient of linear thermal expansion. 16.2 μm/m · K (9.0 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 440 J/kg · K (0.105 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 36 W/m · K (21 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 7.1% IACS at 20 °C (68 °F)
Electrical resistivity. 243 nΩ · m at 20 °C (68 °F)

Magnetic Properties

Magnetic permeability. 1.05 at field strength of 16 kA/m

Chemical Properties

General corrosion behavior. Corrosion properties of C95800 are similar to those of other nickel-aluminum bronzes, except that C95800 has better resistance to cavitation and seawater fouling attack. Resists dealloying in most mediums

Fabrication Characteristics

Machinability. 50% of C36000 (free-cutting brass). Excellent surface finish and tolerances possible in all standard machining operations. Carbide or tool steel cutters may be used. Typical conditions using tool steel cutters: roughing speed, 76 m/min (250 ft/min) at a feed of 0.3 mm/rev (0.011 in./rev); finishing speed, 290 m/min (950 ft/min) at a feed of 0.1 mm/rev (0.004 in./rev)
Annealing temperature. 650 to 705 °C (1200 to 1300 °F)

C96200
90Cu-10Ni

Commercial Names

Common name. 90 Cu-10 Ni

Specifications

ASTM. Centrifugal, B 369; sand, B 369; ingot, B 30
Government. Centrifugal: QQ-C-390; MIL-C-15345, Alloy 25; MIL-C-20159, type II. Sand: QQ-C-390; MIL-C-20159, type II; MIL-V-18436
SAE. Centrifugal and sand: J461, J462

Chemical Composition

Composition limits. 84.5 to 87.0 Cu, 1.0 to 1.8 Fe, 9 to 11.0 Ni, 0.15 C max, 0.03 Pb max (0.01 Pb max for welding grades), 1.5 Mn max, 1.0 Nb max, 0.30 Si max

Applications

Typical uses. Component parts of items being used for seawater corrosion resistance

Mechanical Properties

Tensile properties. Properties for as-sand-cast separately cast (M01 temper) test bars: Tensile strength, 310 MPa min (45 ksi min); yield strength, 172 MPa min (25 ksi min); elongation, 20% min in 50 mm (2 in.)
Compressive strength. Typically, 255 MPa (37 ksi) at 0.1 mm/mm (0.1 in./in.) set
Impact strength. Charpy V-notch, 135 J (100 ft · lbf)
Elastic modulus. Tension, 124 GPa (18 × 10^6 ksi) at 20 °C (68 °F)

Mass Characteristics

Density. 8.94 g/cm^3 (0.323 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 16 mm/m ($^3/_{16}$ in./ft)

Thermal Properties

Liquidus temperature. 1150 °C (2100 °F)
Solidus temperature. 1100 °C (2010 °F)
Specific heat. 376 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 45 W/m · K (26 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 11% IACS at 20 °C (68 °F)

Fabrication Characteristics

Machinability. M01 temper; 10% of C36000 (free-cutting brass)
Weldability. Soldering and brazing: excellent. Gas shielded arc welding: poor. Metal arc welding: good, using R, Cu, Ni, or E, Cu, Ni filler metal. Oxyacetylene and carbon arc welding are not recommended.

C96400
70Cu-30Ni

Commercial Names

Previous trade name. 70-30 copper-nickel

Specifications

ASTM. Centrifugal castings: B 369; continuous castings: B 505; sand castings, ingot: B 30
Government. Centrifugal castings: MIL-C-15345 (Alloy 24); sand castings: QQ-C-390, MIL-C-20159 (type 1)

Chemical Composition

Composition limits. 65.0 to 69.0 Cu, 28.0 to 32.0 Ni, 0.50 to 1.5 Nb, 0.25 to 1.5 Fe, 1.5 Mn max, 0.50 Si max, 0.15 C max, 0.03 Pb max (0.01 Pb max for welding applications)

Applications

Typical uses. Centrifugal, continuous, and sand castings for valves, pump bodies, flanges, and elbows for applications requiring resistance to seawater corrosion

Mechanical Properties

Tensile properties. Typical data for sand-cast test bars: tensile strength, 470 MPa (68 ksi); yield strength, 255 MPa (37 ksi) at 0.5% extension under load; elongation, 28% in 50 mm (2 in.)
Hardness. Typical, 140 HB using 3000 kg load
Elastic modulus. Tension, 145 GPa (21 × 10^6 psi)
Impact strength. Charpy V-notch, 106 J (78 ft · lbf)
Fatigue strength. Reverse bending, 125 MPa (18 ksi) at 10^8 cycles

Mass Characteristics

Density. 8.94 g/cm^3 (0.323 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 19 mm/m ($^7/_{32}$ in./ft)

Thermal Properties

Liquidus temperature. 1240 °C (2260 °F)
Solidus temperature. 1170 °C (2140 °F)
Coefficient of linear thermal expansion. 16 μm/m · K (9.0 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 375 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 29 W/m · K (17 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, as-cast tempers: 5% IACS at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 20% of C36000 (free-cutting brass)
Weldability. Soldering, brazing: excellent. Gas-shielded arc and shielded metal-arc welding: good, using RCuNi or ECuNi filler metal. Oxyfuel gas and carbon arc welding are not recommended.

C96600
69.5Cu-30Ni-0.5Be

Commercial Names

Previous trade name. Beryllium cupro-nickel alloy 71C; CA966
Common name. Beryllium cupro-nickel

Specifications

Government. Sand castings: MIL-C-81519

Chemical Composition

Composition limits. 0.40 to 0.7 Be, 29.0 to 33.0 Ni, 0.8 to 1.1 Fe, 1.0 Mn max, 0.15 Si max, 0.01 Pb max, bal Cu
Consequence of exceeding impurity limits. An excessive amount of Si will increase as-cast hardness and lower ductility. High Pb will cause hot shortness.

Applications

Typical uses. C96600 is a high-strength version of the well-known cupro-nickel alloy C96400,

possessing twice the strength. Like C96400, C96600 exhibits excellent corrosion resistance to seawater. Typical uses are high-strength constructional parts for marine service; pressure housings for long, unattended submergence; pump bodies; valve bodies; seawater line fittings; marine low-tide hardware; gimbal assemblies; and release mechanisms.
Precautions in use. See C82500.

Mechanical Properties

Tensile properties. Typical data for separately cast test bars. TB00 temper: tensile strength, 515 MPa (75 ksi); yield strength, 260 MPa (38 ksi); elongation in 50 mm (2 in.), 12%. TF00 temper: tensile strength, 825 MPa (120 ksi); yield strength, 515 MPa (75 ksi); elongation, 12%
Hardness. TB00 temper: 74 HRB. TF00 temper: 24 HRC
Poisson's ratio. 0.33
Elastic modulus. Tension, 150 GPa (22 × 10^6 psi); shear, 57 GPa (8.3 × 10^6 psi)

Mass Characteristics

Density. 8.80 g/cm^3 (0.320 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 1.8%

Thermal Properties

Liquidus temperature. 1180 °C (2160 °F)
Solidus temperature. 1100 °C (2010 °F)
Coefficient of linear thermal expansion. 16 μm/m · K (9 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 377 J/kg · K (0.091 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 30 W/m · K (17.3 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 4.3% IACS at 20 °C (68 °F)
Electrical resistivity. 4 nΩ · m at 20 °C (68 °F)

Chemical Properties

General corrosion behavior. Essentially identical to that of C96400

Fabrication Characteristics

Machinability. TF00 temper, 40% of C36000 (free-cutting brass)
Melting temperature. 1100 to 1180 °C (2010 to 2160 °F)
Casting temperature. 1260 to 1370 °C (2300 to 2500 °F)
Solution temperature. 995 °C (1825 °F)
Aging temperature. 510 °C (950 °F). Typical aging time, 3 h

C97300
56Cu-2Sn-10Pb-20Zn-12Ni

Commercial Names

Previous trade name. 12% nickel silver
Common name. Leaded nickel brass; 56-2-10-20-12

Specifications

ASTM. Centrifugal castings: B 271; sand castings: B 584; ingot: B 30

Chemical Composition

Composition limits. 53.0 to 58.0 Cu, 1.5 to 3.0 Sn, 8.0 to 11.0 Pb, 17.0 to 25.0 Zn, 11.0 to 14.0 Ni, 1.5 Fe max, 0.50 Mn max, 0.35 Sb max, 0.15 Si max, 0.08 S max, 0.05 P max, 0.005 Al max

Applications

Typical uses. Investment, centrifugal, permanent mold, and sand castings for hardware fittings; valves and valve trim; statuary, and ornamental castings

Mechanical Properties

Tensile properties. Typical data for sand-cast test bars: tensile strength, 240 MPa (35 ksi); yield strength, 115 MPa (17 ksi) at 0.5% extension under load; elongation, 20% in 50 mm (2 in.)
Hardness. Typical, 55 HB using 500 kg load
Elastic modulus. Tension, 110 GPa (16 × 10^6 psi)

Mass Characteristics

Density. 8.95 g/cm^3 (0.321 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 16 mm/m ($^3/_{16}$ in./ft)

Thermal Properties

Liquidus temperature. 1040 °C (1904 °F)
Solidus temperature. 1010 °C (1850 °F)
Coefficient of linear thermal expansion. 16.2 μm/m · K (9.0 μin./in. · °F) at 20 to 260 °C (68 to 500 °F)
Specific heat. 375 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 28.5 W/m · K (16.5 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, as-cast tempers: 5.7% IACS at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 70% of C36000 (free-cutting brass)
Weldability. Soldering, brazing: excellent. Welding: not recommended
Stress-relieving temperature. 260 °C (500 °F), 1 h for each 25 mm (1 in.) of section thickness
Casting temperature. Light castings, 1200 to 1315 °C (2200 to 2400 °F); heavy castings, 1090 to 1200 °C (2000 to 2200 °F). Melt rapidly at no more than 55 to 85 °C (100 to 150 °F) above maximum casting temperature.

C97600
64Cu-4Sn-4Pb-8Zn-20Ni

Commercial Names

Previous trade name. 20% nickel silver
Common name. Dairy metal, leaded nickel bronze, 64-4-4-8-20

Specifications

ASME. Sand castings: SB584
ASTM. Centrifugal castings: B 271; sand castings: B 584; ingot: B 30
Government. Sand castings: MIL-C-17112
Other. Ingot code number 412

Chemical Composition

Composition limits. 63.0 to 67.0 Cu, 3.5 to 4.5 Sn, 3.0 to 5.0 Pb, 3.0 to 9.0 Zn, 19.0 to 21.5 Ni, 1.5 Fe max, 1.0 Mn max, 0.25 Sb max, 0.15 Si max, 0.08 S max, 0.05 P max, 0.005 Al max

Applications

Typical uses. Centrifugal, investment, and sand castings for marine castings; sanitary fittings; ornamental hardware; valves, and pumps

Mechanical Properties

Tensile properties. Typical data for sand-cast test bars: tensile strength, 310 MPa (45 ksi); yield strength, 165 MPa (24 ksi) at 0.5% extension under load; elongation, 20% in 50 mm (2 in.)
Compressive properties. Compressive strength, 205 MPa (30 ksi) at a permanent set of 1%; 395 MPa (57 ksi) at a permanent set of 10%
Hardness. Typical, 80 HB using 500 kg load
Elastic modulus. Tension, 130 GPa (19 × 10^6 psi)
Impact strength. Charpy V-notch, 15 J (11 ft · lbf)
Fatigue strength. Reverse bending, 107 MPa (15.5 ksi) at 10^8 cycles
Creep-rupture characteristics. Limiting stress for creep of 10^{-5}%/h: 224 MPa (32.5 ksi) at 230 °C (450 °F); 153 MPa (22.2 ksi) at 290 °C (550 °F)

Mass Characteristics

Density. 8.90 g/cm^3 (0.321 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 11 mm/m ($^1/_8$in./ft)

Thermal Properties

Liquidus temperature. 1143 °C (2089 °F)
Solidus temperature. 1108 °C (2027 °F)
Coefficient of linear thermal expansion. 17 μm/m · K (9.3 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 375 J/kg · K (0.90 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 22 W/m · K (13 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, as-cast tempers: 5% IACS at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 70% of C36000 (free-cutting brass)
Weldability. Soldering, brazing: excellent. Welding: not recommended
Stress-relieving temperature. 260 °C (500 °F), 1 h for each 25 mm (1 in.) of section thickness
Casting temperature. Light castings, 1260 to 1430 °C (2300 to 2600 °F); heavy castings, 1230 to 1320 °C (2250 to 2400 °F). Melt rapidly at no more than 55 to 85 °C (100 to 150 °F) above casting temperature range.

C97800
66.5Cu-5Sn-1.5Pb-2Zn-25Ni

Commercial Names

Previous trade name. 25% nickel silver

Common name. Leaded nickel bronze; 66-5-2-2-25

Specifications

ASTM. Centrifugal castings: B 271; sand castings: B 584; ingot, B 30

Chemical Composition

Composition limits. 64.0 to 67.0 Cu, 4.0 to 5.5 Sn, 1.0 to 2.5 Pb, 1.0 to 4.0 Zn, 24.0 to 27.0 Ni, 1.5 Fe max, 1.0 Mn max, 0.20 Sb max, 0.15 Si max, 0.08 S max, 0.05 P max, 0.005 Al max

Applications

Typical uses. Investment, permanent mold, and sand castings for ornamental castings; sanitary fittings; valve bodies; valve seats; and musical instrument components

Mechanical Properties

Tensile properties. Typical data for sand-cast test bars: tensile strength, 380 MPa (55 ksi); yield strength, 205 MPa (30 ksi) at 0.5% extension under load; elongation, 15% in 50 mm (2 in.)
Hardness. Typical, 130 HB using 3000 kg load
Elastic modulus. Tension, 130 GPa (19 × 10^6 psi)

Mass Characteristics

Density. 8.86 g/cm^3 (0.320 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 16 mm/m ($^3/_{16}$ in./ft)

Thermal Properties

Liquidus temperature. 1180 °C (2156 °F)
Solidus temperature. 1140 °C (2084 °F)
Coefficient of linear thermal expansion. 17.5 μm/m · K (9.7 μin./in. · °F) at 20 to 260 °C (68 to 500 °F)
Specific heat. 375 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 25.4 W/m · K (14.7 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, as-cast tempers: 4.5% IACS at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 60% of C36000 (free-cutting brass)
Weldability. Soldering, brazing: excellent. Welding: not recommended
Stress-relieving temperature. 260 °C (500 °F)

C99400
90.4Cu-2.2Ni-2.0Fe-1.2Al-1.2Si-3.0Zn

Commercial Names

Common name. Nondezincification alloy, NDZ

Chemical Composition

Composition limits. 0.25 Pb max, 1.0 to 3.5 Ni, 1.0 to 3.0 Fe, 0.50 to 2.0 Al, 0.50 to 2.0 Si, 0.50 to 5.0 Zn, 0.50 Mn max, bal Cu

Applications

Typical uses. Centrifugal, continuous, investment, and sand castings for valve stems; propeller wheels; electrical parts; gears for mining equipment; outboard motor parts; marine hardware; and other environmental uses where resistance to dezincification and dealuminification is required

Mechanical Properties

Tensile properties. Typical. M01 temper: tensile strength, 455 MPa (66 ksi); yield strength, 235 MPa (34 ksi) at 0.5% extension under load; elongation, 25% in 50 mm (2 in.). TF00 temper: tensile strength, 545 MPa (79 ksi); yield strength, 370 MPa (54 ksi) at 0.5% extension under load
Shear strength. M01 temper, 330 MPa (48 ksi)
Hardness. M01 temper, 125 HB; TF00 temper, 170 HB. Determined using 3000 kg load
Elastic modulus. Tension, 133 GPa (19.3 × 10^6 psi)

Mass Characteristics

Density. 8.30 g/cm^3 (0.30 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 16 mm/m ($^3/_{16}$ in./ft)

Electrical Properties

Electrical conductivity. Volumetric, TF00 temper: 16.8% IACS at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 50% of C36000 (free-cutting brass)
Weldability. Shielded metal-arc welding: poor
Solution temperature. 885 °C (1625 °F), 1 h for each 25 mm (1 in.) of section thickness
Aging temperature. 480 °C (900 °F), 1 h at temperature
Stress-relieving temperature. 315 °C (600 °F), 1 h for each 25 mm (1 in.) of section thickness

C99500

Commercial Name

Trade name. NDZ-S

Specifications

ASTM. Sand castings: B 763

Chemical Composition

Composition limits. 0.25 Pb max, 3.5 to 5.5 Ni, 3.0 to 5.0 Fe, 0.50 to 2.0 Al, 0.50 to 2.0 Si, 0.50 Mn max, 0.50 to 2.0 Zn, bal Cu

Applications

Typical uses. Valve stems, marine, and other environmental uses where resistance to dezincification and dealuminification is required, propeller wheels, electrical parts, gears for mining equipment and outboard marine industry; same as C99400 but used where higher yield strength is required

Mechanical Properties

Tensile properties. Properties for as-sand-cast separately cast (M01 temper) test bars: tensile strength, 483 MPa min (70 ksi min); yield strength, 275 MPa min (40 ksi min); elongation, 12% min in 50 mm (2 in.)
Hardness. Typically, 145 HB (500 kg); 50 HB (3000 kg)
Proportional limit. Typically, 145 MPa (21 ksi)

Mass Characteristics

Density. 8.3 g/cm^3 (0.30 lb/in.^{3}) at 20 °C (68 °F)
Volume change on freezing. Patternmaker's shrinkage, 16 mm/m ($^3/_{16}$ in./ft)

Electrical Properties

Electrical conductivity. Volumetric, 13.7% IACS at 20 °C (68 °F)

Fabrication Characteristics

Machinability. M01 temper; 50% of C36000 (free-cutting brass)
Stress-relieving temperature. 315 °C (600 °F)

C99700
56.5Cu-5Ni-1Al-1.5Pb-12Mn-24Zn

Commercial Names

Common name. White manganese brass
Trade name. White Tombasil

Chemical Composition

Composition limits. 54.0 Cu min, 19.0 to 25.0 Zn, 11.0 to 15.0 Mn, 4.0 to 6.0 Ni, 2.0 Pb max, 1.0 Sn max, 1.0 Fe max 0.50 to 3.0 Al

Applications

Typical uses. Building hardware (interior and exterior), architectural and ornamental fittings, marine hardware, floor drain covers, food handling equipment, swimming pool hardware, valves

Mechanical Properties

Tensile properties. Typical data for separately cast test bars. Sand cast: tensile strength, 380 MPa (55 ksi); yield strength, 170 MPa (25 ksi) at 0.5% extension under load; elongation, 25% in 50 mm (2 in.). Die cast: tensile strength, 450 MPa (65 ksi); yield strength, 185 MPa (27 ksi) at 0.5% extension under load; elongation, 15% in 50 mm (2 in.)
Hardness. Sand cast: 110 HB (300 kg load); die cast: 125 HB
Elastic modulus. Tension, 114 GPa (16.5 × 10^6 psi)

Mass Characteristics

Density. 8.19 g/cm^3 (0.296 lb/in.^{3}) at 20 °C (68 °F)
Patternmaker's shrinkage. 21 mm/m (0.25 in./ft)

Thermal Properties

Liquidus temperature. 900 °C (1655 °F)
Solidus temperature. 880 °C (1615 °F)

Electrical Properties

Electrical conductivity. Volumetric, 3% IACS at 20 °C (68 °F)

Fabrication Characteristics

Machinability. 80% of C36000 (free-cutting brass)

C99750

Specifications

ASTM. Die castings: B 176

Chemical Composition

Composition limits. 0.25 to 3.0 Al, 55.0 to 61.0 Cu, 0.50 to 2.5 Pb, 17.0 to 23.0 Mn, 5.0 Ni max, 17.0 to 23.0 Zn, 1.0 Fe max (iron content shall not exceed nickel content)

Mechanical Properties

Tensile properties. Typical properties for as-sand-cast separately cast (M01 temper) test bars: tensile strength, 448 MPa (65 ksi); yield strength, 220 MPa (32 ksi) at 0.2% offset; elongation, 30% in 50 mm (2 in.)
Hardness. Typically, 77 HRB, 110 HB (500 kg)
Compressive strength. Typically, 193 MPa (28 ksi) at 0.001 mm/mm (0.001 in./in.) set, 262 MPa (38 ksi) at 0.01 mm/mm (0.01 in./in.) set, and 495 MPa (72 ksi) at 0.1 mm/mm (0.1 in./in.) set
Impact strength. Charpy V-notch, 100 J (75 ft · lbf)
Fatigue strength. 128 MPa (18.5 ksi) at 10^8 cycles
Elastic modulus. Tension, 117 GPa (17×10^6 psi) at 20 °C (68 °F)

Mass Characteristics

Density. 8.0 g/cm^3 (0.29 lb/in.^{3}) at 20 °C (68 °F)

Thermal Properties

Liquidus temperature. 843 °C (1550 °F)
Solidus temperature. 819 °C (1505 °F)
Specific heat. 376 J/kg · K (0.09 Btu/lb · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 2% IACS at 20 °C (68 °F)

Fabrication Properties

Stress-relieving temperature. 260 °C (500 °F)

Beryllium copper 21C
97Cu-2Be-1Co

Commercial Names

Common name. Grain-refined beryllium-copper casting alloy 21C

Chemical Composition

Composition limits. 2.00 to 2.25 Be, 1.0 to 1.2 Co, 0.20 to 0.40 Si, 0.20 Ni max, 0.25 Fe max, 0.15 Al max, 0.10 Sn max, 0.02 Pb max, 0.10 Zn max, 0.10 Cr max
Consequence of exceeding impurity limits. See C82500.

Applications

Typical uses. The 1% Co content is a strong grain refiner, and as a result, this alloy is used instead of beryllium-copper alloys C82500 and C82400 when thin sections must be cast at high temperatures or when thick and thin sections are present within the same casting in order to achieve a uniform fine-grained structure. The higher cobalt content imparts better wear resistance but less desirable polishability and machinability. Typical uses are comparable to those of beryllium-copper alloys C82400 and C82500.
Precautions in use. See C82500.

Mechanical Properties

Tensile properties. See Table 9.
Hardness. See Table 9
Poisson's ratio. 0.30
Elastic modulus. Tension, 128 GPa (18.5×10^6 psi); shear, 50 GPa (7.3×10^6 psi)

Mass Characteristics

Density. 8.26 g/cm^3 (0.298 lb/in.^{3}) at 20 °C (68 °F)
Dilation during aging. Linear, 0.2%
Change in density during aging. 0.6% increase
Patternmaker's shrinkage. 1.56%

Thermal Properties

Liquidus temperature. 980 °C (1800 °F)
Solidus temperature. 860 °C (1575 °F)
Incipient melting temperature. 835 °C (1535 °F)
Coefficient of linear thermal expansion. 10 µm/m · K (5.5 µin./in. · °F) at 20 to 200 °C (68 to 392 °F)
Specific heat. 419 J/kg · K (0.10 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 105 W/m · K (61 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 20% IACS at 20 °C (68 °F)
Electrical resistivity. 862 µΩ· m at 20 °C (68 °F)

Magnetic Properties

Magnetic susceptibility. See C82500.

Nuclear Properties

Effect of irradiation. See C82500.

Chemical Properties

Same as C82500

Fabrication Characteristics

Machinability. As-cast or solution treated, 30% of C36000 (free-cutting brass). Cast and aged, or solution treated and aged, 10 to 20% of C36000
Solution temperature. 790 to 800 °C (1450 to 1475 °F)
Aging temperature. 340 °C (650 °F)
Melting temperature. 860 to 980 °C (1575 to 1800 °F)
Casting temperature. Light castings, 1065 to 1175 °C (1950 to 2150 °F); heavy castings, 1000 to 1065 °C (1850 to 1950 °F)

Beryllium copper nickel 72C
68.8Cu-30Ni-1.2Be

Commercial Names

Common name. Modified beryllium cupro-nickel alloy 72C

Chemical Composition

Composition limits. 1.1 to 1.2 Be, 29.0 to 33.0 Ni, 0.7 to 1.0 Fe, 0.10 to 0.20 Zr, 0.10 to 0.20 Ti, 0.7 Mn max, 0.15 Si max, 0.1 Pb max, bal Cu
Consequence of exceeding impurity limits. High silicon will raise as-cast hardness and lower ductility. High lead will cause hot shortness. High carbon will result in undesirable carbides.

Applications

Typical uses. Alloy 72C is a modified version of beryllium cupro-nickel alloy 71C, its increased beryllium content providing improved castability. Its field of application is the plastic tooling industry. Alloy 72C generally is ceramic mold cast into tooling used for molding flame-retardant plastics containing bromine, bromine-boron, chlorinated paraffins and phosphates, and other halogens. Additionally, alloy 72C tooling is resistant to corrosion by the foaming agents used in structural plastics that generate ammonia at elevated temperatures, as well as to decompositional products of PVC that contain HCl. The good castability of 72C allows it to be cast into tooling of fine detail.
Precautions in use. See C82500.

Mechanical Properties

Tensile properties. See Table 10.
Hardness. See Table 10.

Table 9 Typical mechanical properties of beryllium-copper alloy 21C

	Tensile strength		Yield strength(a)			
Temper	MPa	ksi	MPa	ksi	Elongation in 50 mm (2 in.), %	Hardness
As-cast	515	75	275	40	25	75 HRB
Cast and aged(a)	825	120	725	105	5	30 HRC
Solution treated(b)	415	60	170	25	40	63 HRB
Solution treated(b) and aged(a)	1105	160	1035	150	1	42 HRC

(a) Aged 3 h at 345 °C (650 °F). (b) At 790 to 800 °C (1450 to 475 °F)

Table 10 Typical mechanical properties of cast beryllium cupro-nickel alloy 72C

	Tensile strength		Yield strength(a)			
Temper	MPa	ksi	MPa	ksi	Elongation in 50 mm (2 in.), %	Hardness
As-cast and aged(a)	555	81	310	45	15	90 HRB
Solution treated(b) and aged(a)	860	125	550	80	70	26 HRC

(a) Aged 3 h at 510 °C (950 °F). (b) Water quenched from 995 °C (1825 °F)

Poisson's ratio. 0.33
Elastic modulus. Tension, 150 GPa (22 × 10^6 psi); shear, 57 GPa (8.3 × 10^6 psi)

Mass Characteristics

Density. 8.60 g/cm^3 (0.311 lb/$in.^3$) at 20 °C (68 °F)
Patternmaker's shrinkage. 1.8%

Thermal Properties

Liquidus temperature. 1155 °C (2110 °F)
Solidus temperature. 1065 °C (1950 °F)
Coefficient of linear thermal expansion. 16 μm/m · K (9 μin./in. · °F) at 20 to 300 °C (68 to 572 °F)
Specific heat. 337 J/kg · K (0.08 Btu/lb · °F) at 20 °C (68 °F)
Thermal conductivity. 30 W/m · K (17 Btu/ft · h · °F) at 20 °C (68 °F)

Electrical Properties

Electrical conductivity. Volumetric, 43% IACS at 20 °C (68 °F)
Electrical resistivity. 4 μΩ · m at 20 °C (68 °F)

Chemical Properties

General corrosion behavior. Essentially the same as C96400

Fabrication Characteristics

Machinability. Solution treated and aged, 40% of C36000 (free-cutting brass)
Solution temperature. 995 °C (1825 °F)
Aging temperature. 510 °C (950 °F)
Melting temperature. 1065 to 1155 °C (1950 to 2110 °F)
Casting temperature. 1200 to 1300 °C (2200 to 2400 °F)

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Appendix

Specification Cross-Reference for Wrought and Cast Products

Table 1 Specification cross-reference for wrought and cast products

Alloy	Product	Specification							
		ASTM	AMS	Military	Federal	ASME	SAE	AWS	Ingot No.
Wrought products									
C10100	Bar	B 133, B 152, F 68	…	…	…	…	…	…	…
	Bar, bus	B 187	…	…	…	…	…	…	…
	Foil, printed circuits	B 451, F 68	…	…	…	…	…	…	…
	Pipe, bus	B 188	…	…	…	…	…	…	…
	Plate	B 152, F 68	…	…	…	…	…	…	…
	Plate, clad	B 432	…	…	…	…	…	…	…
	Rod	B 133, F 68	…	…	…	…	…	…	…
	Rod, bus	B 187	…	…	…	…	…	…	…
	Shapes	B 133, F 68	…	…	…	…	…	…	…
	Shapes, bus	B 187	…	…	…	…	…	…	…
	Sheet	B 152, F 68	…	…	…	…	…	…	…
	Sheet, printed circuits	B 451, F 68	…	…	…	…	…	…	…
	Strip	B 152, B 272, F 68	…	…	…	…	…	…	…
	Strip, printed circuits	B 451, F 68	…	…	…	…	…	…	…
	Tube, bus	B 188	…	…	…	…	…	…	…
	Tube, finned	B 359	…	…	…	…	…	…	…
	Tube, rectangular wave guide	B 372, F 68	…	MIL-W-85	…	…	…	…	…
	Tube, seamless	B 75, B 641, F 68	…	…	…	…	…	…	…
	Tube, seamless for air conditioning and refrigeration field service	B 280	…	…	…	…	…	…	…
	Tube, welded	B 447, B 641	…	…	…	…	…	…	…
	Tube, welded for air conditioning and refrigeration service	B 640	…	…	…	…	…	…	…
	Wire, coated with lead alloy	B 189	…	…	…	…	…	…	…
	Wire, coated with nickel	B 355	…	…	…	…	…	…	…
	Wire, coated with silver	B 298	…	…	…	…	…	…	…
	Wire, coated with tin	B 33, B 246	…	…	…	…	…	…	…
	Wire, hard drawn	B 1, B 272, F 68	…	…	QQ-W-343	…	…	…	…
	Wire, medium-hard drawn	B 2, F 68	…	…	…	…	…	…	…
	Wire, soft	B 3, B 48, F 68	4700	…	…	…	…	…	…
	Wire, stranded	B 8, B 172, B 173, B 174, B 226, B 286, B 470, B 496	…	…	QQ-B-575	…	…	…	…
C10200	Bands, projectile rotating	…	…	MIL-B-18907, MIL-B-20292	…	…	…	…	…
	Bar	B 133, B 152	4602	…	…	SB133, SB152	J461, J463	…	…
	Bar, bus	B 187	…	…	…	…	J461, J463	…	…
	Brazing filler metal	…	…	…	QQ-B-650	…	…	…	…
	Fittings	…	…	…	…	B16.22	…	…	…
	Foil, printed circuits	B 451	…	…	…	…	…	…	…
	Nipples	B 687	…	…	…	…	…	…	…
	Pipe	B 42	…	…	…	SB42	…	…	…
	Pipe, bus	B 188	…	…	…	…	…	…	…
	Plate	B 152	4501	…	…	SB152	J461, J463	…	…
	Plate, clad	B 432	…	…	…	…	…	…	…
	Rod	B 133	4602	…	…	SB133	J461, J463	…	…
	Rod, bus	B 187	…	…	…	…	…	…	…
	Shapes	B 133	4602	…	…	…	J461, J463	…	…
	Shapes, bus	B 187	…	…	…	…	…	…	…
	Sheet	B 152	4501	…	…	SB152	J461, J463	…	…
	Sheet, clad	B 506	…	…	…	…	…	…	…
	Sheet, printed circuits	B 451	…	…	…	…	…	…	…
	Strip	B 152	4501	…	…	SB152	J461, J463	…	…
	Strip, clad	B 506	…	…	…	…	…	…	…

(continued)

Table 1 Specification cross-reference for wrought and cast products (continued)

		Specification							
Alloy	**Product**	**ASTM**	**AMS**	**Military**	**Federal**	**ASME**	**SAE**	**AWS**	**Ingot No.**
Wrought products (continued)									
C10200	Strip, printed circuits	B 451	…	…	…	…	…	…	…
	Tube, air conditioning and refrigeration field service	…	…	…	…	…	J461, J463	…	…
	Tube, bus	B 188	…	…	…	…	…	…	…
	Tube, coils	B 743	…	…	…	…	…	…	…
	Tube, condenser	B 111	…	…	…	SB111	…	…	…
	Tube, finned	B 359	…	…	…	SB359	…	…	…
	Tube, rectangular waveguide	B 372	…	MIL-W-85	…	…	…	…	…
	Tube, seamless	B 75, B 641	…	MIL-T-24107	…	SB75	…	…	…
	Tube, seamless bright annealed	B 68	…	…	…	…	…	…	…
	Tube, seamless for air conditioning and refrigeration field service	B 280	…	…	…	…	J461, J463	…	…
	Tube, seamless for torpedo use	…	…	MIL-T-3235	…	…	…	…	…
	Tube, U-bend	B 395	…	…	…	SB395	…	…	…
	Tube, welded	B 447, B 641, B 716	…	MIL-T-24107	…	…	J461, J463	…	…
	Tube, welded for air conditioning and refrigeration service	B 640	…	…	…	…	…	…	…
	Wire, coated with lead alloy	B 189	…	…	…	…	…	…	…
	Wire, coated with nickel	B 355	…	…	…	…	…	…	…
	Wire, coated with silver	B 298	…	…	…	…	…	…	…
	Wire, coated with tin	B 33, B 246	…	…	…	…	…	…	…
	Wire, flat	B 272	…	…	…	…	…	…	…
	Wire, hard drawn	B 1	…	…	QQ-W-343	…	…	…	…
	Wire, medium-hard drawn	B 2	…	…	QQ-W-343	…	…	…	…
	Wire, metallizing	…	…	MIL-W-6712	…	…	…	…	…
	Wire, soft	B 3, B 48, B 738, F 9	4701	…	QQ-W-343	…	…	…	…
	Wire, stranded	B 8, B 172, B 173, B 174, B 226, B 286, B 470, B 496	…	…	QQ-B-575	…	…	…	…
C10300	Bands, projectile rotating	…	…	MIL-B-20292	…	…	…	…	…
	Bar	B 133, B 152	…	…	…	…	…	…	…
	Bar, bus	B 187	…	…	…	…	…	…	…
	Brazing filler metal	…	…	…	QQ-B-650	…	…	…	…
	Nipples	B 687	…	…	…	…	…	…	…
	Pipe	B 42	…	…	…	…	…	…	…
	Pipe, bus	B 188	…	…	…	…	…	…	…
	Pipe, threadless (seamless)	B 302	…	…	…	…	…	…	…
	Plate	B 152	…	…	…	…	…	…	…
	Plate, clad	B 432	…	…	…	…	…	…	…
	Rod	B 133	…	…	…	…	…	…	…
	Rod, bus	B 187	…	…	…	…	…	…	…
	Shapes	B 133	…	…	…	…	…	…	…
	Shapes, bus	B 187	…	…	…	…	…	…	…
	Sheet	B 152	…	…	…	…	…	…	…
	Strip	B 152	…	…	…	…	…	…	…
	Tube, bus	B 188	…	…	…	…	…	…	…
	Tube, coils	B 743	…	…	…	…	…	…	…
	Tube, condenser	B 111	…	…	…	…	…	…	…
	Tube, drainage (DWV)	B 306	…	…	…	…	…	…	…
	Tube, finned	B 359	…	…	…	…	…	…	…
	Tube, rectangular waveguide	B 372	…	…	…	…	…	…	…
	Tube, seamless	B 75, B 641	…	…	…	…	…	…	…
	Tube, seamless bright annealed	B 68	…	…	…	…	…	…	…
	Tube, seamless for air conditioning and refrigeration service	B 280	…	…	…	…	…	…	…
	Tube, seamless for torpedo use	…	…	MIL-T-3235	…	…	…	…	…
	Tube, U-bend	B 395	…	…	…	…	…	…	…
	Tube, welded	B 447, B 641, B 716	…	…	…	…	…	…	…
	Tube, welded for air conditioning and refrigeration service	B 640	…	…	…	…	…	…	…
C10400	Bands, projectile rotating	…	…	MIL-B-20292	…	…	…	…	…
	Bar	B 133, B 152	…	…	…	SB152	…	…	…
	Bar, bus	B 187	…	…	…	…	…	…	…
	Brazing filler metal	…	…	…	QQ-B-650	…	…	…	…
	Pipe, bus	B 188	…	…	…	…	…	…	…

(continued)

Table 1 (continued)

Alloy	Product	Specification							
		ASTM	AMS	Military	Federal	ASME	SAE	AWS	Ingot No.
Wrought products (continued)									
C10400	Plate	B 152	…	…	…	SB152	…	…	…
	Rod	B 133	…	…	…	…	…	…	…
	Rod, bus	B 187	…	…	…	…	…	…	…
	Shapes	B 133	…	…	…	…	…	…	…
	Shapes, bus	B 187	…	…	…	…	…	…	…
	Sheet	B 152	…	…	…	SB152	…	…	…
	Sheet, clad	B 506	…	…	…	…	…	…	…
	Strip	B 152, B 272	…	…	…	SB152	…	…	…
	Strip, clad	B 506	…	…	…	…	…	…	…
	Tube, bus	B 188	…	…	…	…	…	…	…
	Wire, coated with lead alloy	B 189	…	…	…	…	…	…	…
	Wire, coated with nickel	B 355	…	…	…	…	…	…	…
	Wire, coated with silver	B 298	…	…	…	…	…	…	…
	Wire, coated with tin	B 246	…	…	…	…	…	…	…
	Wire, flat	B 272	…	…	…	…	…	…	…
	Wire, hard drawn	B 1	…	…	QQ-W-343	…	…	…	…
	Wire, medium-hard drawn	B 2	…	…	QQ-W-343	…	…	…	…
	Wire, soft	B 3	…	…	QQ-W-343	…	…	…	…
C10500	Bar	B 133, B 152	…	…	…	SB152	…	…	…
	Bar, bus	B 187	…	…	…	…	…	…	…
	Pipe, bus	B 188	…	…	…	…	…	…	…
	Plate	B 152	…	…	…	SB152	…	…	…
	Rod	B 133	…	…	…	…	…	…	…
	Rod, bus	B 187	…	…	…	…	…	…	…
	Shapes	B 133	…	…	…	…	…	…	…
	Shapes, bus	B 187	…	…	…	…	…	…	…
	Sheet	B 152	…	…	…	SB152	…	…	…
	Sheet, clad	B 506	…	…	…	…	…	…	…
	Strip	B 152	…	…	…	SB152	…	…	…
	Strip, clad	B 506	…	…	…	…	…	…	…
	Tube, bus	B 188	…	…	…	…	…	…	…
	Wire, coated with lead alloy	B 189	…	…	…	…	…	…	…
	Wire, coated with nickel	B 355	…	…	…	…	…	…	…
	Wire, coated with silver	B 298	…	…	…	…	…	…	…
	Wire, coated with tin	B 246	…	…	…	…	…	…	…
	Wire, flat	B 272	…	…	…	…	…	…	…
	Wire, hard drawn	B 1	…	…	QQ-W-343	…	…	…	…
	Wire, medium-hard drawn	B 2	…	…	QQ-W-343	…	…	…	…
C10700	Bands, projectile rotating	…	…	MIL-B-20292	…	…	…	…	…
	Bar	B 133, B 152	…	…	…	SB152	…	…	…
	Bar, bus	B 187	…	…	…	…	…	…	…
	Brazing filler metal	…	…	…	QQ-B-650	…	…	…	…
	Pipe, bus	B 188	…	…	…	…	…	…	…
	Plate	B 152	…	…	…	SB152	…	…	…
	Rod	B 133	…	…	…	…	…	…	…
	Rod, bus	B 187	…	…	…	…	…	…	…
	Shapes	B 133	…	…	…	…	…	…	…
	Shapes, bus	B 187	…	MIL-B-19231	…	…	…	…	…
	Sheet	B 152	…	…	…	SB152	…	…	…
	Sheet, clad	B 506	…	…	…	…	…	…	…
	Strip	B 152	…	…	…	SB152	…	…	…
	Strip, clad	B 506	…	…	…	…	…	…	…
	Tube, bus	B 188	…	…	…	…	…	…	…
	Wire, coated with lead alloy	B 189	…	…	…	…	…	…	…
	Wire, coated with nickel	B 355	…	…	…	…	…	…	…
	Wire, coated with silver	B 298	…	…	…	…	…	…	…
	Wire, coated with tin	B 246	…	…	…	…	…	…	…
	Wire, flat	B 272	…	…	…	…	…	…	…
	Wire, hard drawn	B 1	…	…	QQ-W-343	…	…	…	…
	Wire, medium-hard drawn	B 2	…	…	QQ-W-343	…	…	…	…
C10800	Bands, projectile rotating	…	…	MIL-B-20292	…	…	…	…	…
	Bar	B 133, B 152	…	…	…	…	…	…	…
	Brazing filler metal	…	…	…	QQ-B-650	…	…	…	…
	Nipples	B 687	…	…	…	…	…	…	…
	Pipe	B 42	…	…	…	…	…	…	…
	Pipe, threadless	B 302	…	…	…	…	…	…	…
	Plate	B 152	…	…	…	…	…	…	…
	Plate, clad	B 432	…	…	…	…	…	…	…
	Rod	B 133	…	…	…	…	…	…	…
	Shapes	B 133	…	…	…	…	…	…	…
	Sheet	B 152	…	…	…	…	…	…	…
	Strip	B 152	…	…	…	…	…	…	…
	Tube, capillary	B 360	…	…	…	…	…	…	…
	Tube, coils	B 743	…	…	…	…	…	…	…
	Tube, condenser	B 111	…	…	…	…	…	…	…
	Tube, drainage (DWV)	B 306	…	…	…	…	…	…	…
	Tube, finned	B 359	…	…	…	…	…	…	…

(continued)

Table 1 Specification cross-reference for wrought and cast products (continued)

		Specification							
Alloy	**Product**	**ASTM**	**AMS**	**Military**	**Federal**	**ASME**	**SAE**	**AWS**	**Ingot No.**
Wrought products (continued)									
C10800	Tube, seamless	B 75, B 641	…	MIL-T-24107	…	…	…	…	…
	Tube, seamless bright annealed	B 68	…	…	…	…	…	…	…
	Tube, seamless for air conditioning and refrigeration service	B 280	…	…	…	…	…	…	…
	Tube, U-bend	B 395	…	…	…	…	…	…	…
	Tube, welded	B 447, B 543, B 641, B 716	…	…	…	…	…	…	…
	Tube, welded for air conditioning and refrigeration service	B 640	…	…	…	…	…	…	…
C10920	Brazing filler metal	…	…	…	QQ-B-650	…	…	…	…
C10930	Brazing filler metal	…	…	…	QQ-B-650	…	…	…	…
C10940	Brazing filler metal	…	…	…	QQ-B-650	…	…	…	…
C11000	Bands, projectile rotating	…	…	MIL-B-20292	…	…	…	…	…
	Bar	B 133, B 152	…	…	…	SB133	J461, J463	…	…
	Bar, bus	B 187	…	…	…	…	…	…	…
	Bar, forging	B 124	…	…	…	…	…	…	…
	Brazing filler metal	…	…	…	QQ-B-650	…	…	…	…
	Bolts	F 468	…	…	…	…	…	…	…
	Foil, printed circuits	B 451	…	…	…	…	…	…	…
	Forgings, die	B 283	…	…	…	…	…	…	…
	Nuts	F 467	…	…	…	…	…	…	…
	Pipe, bus	B 188	…	…	…	…	…	…	…
	Plate	B 152	4500	…	…	…	J461, J463	…	…
	Rod	B 133	…	MIL-C-12166	…	SB133	J461, J463	…	…
	Rod, bus	B 187	…	…	…	…	…	…	…
	Rod, forging	B 124	…	…	…	…	…	…	…
	Screws	F 468	…	…	…	…	…	…	…
	Shapes	B 133	…	…	…	…	J461, J463	…	…
	Shapes, bus	B 187	…	…	…	…	…	…	…
	Shapes, forging	B 124	…	…	…	…	…	…	…
	Sheet	B 152, B 694	4500	…	…	…	J461, J463	…	…
	Sheet, building construction	B 370	…	…	…	…	…	…	…
	Sheet, clad	B 506	…	…	…	…	…	…	…
	Sheet, lead coated	B 101	…	…	…	…	…	…	…
	Sheet, printed circuits	B 451	…	…	…	…	…	…	…
	Strip	B 152, B 694	4500	…	…	…	J461, J463	…	…
	Strip, building construction	B 370	…	…	…	…	…	…	…
	Strip, clad	B 506	…	…	…	…	…	…	…
	Strip, printed circuits	B 451	…	…	…	…	…	…	…
	Studs	F 468	…	…	…	…	…	…	…
	Tube, bus	B 188	…	…	…	…	…	…	…
	Tube, welded	B 447	…	…	…	…	…	…	…
	Wire, coated with lead alloy	B 189	…	…	…	…	…	…	…
	Wire, coated with nickel	B 355	…	…	…	…	…	…	…
	Wire, coated with silver	B 298	…	…	…	…	…	…	…
	Wire, coated with tin	B 33, B 246	…	…	…	…	…	…	…
	Wire, flat	B 272	4500	…	…	…	…	…	…
	Wire, hard drawn	B 1	…	…	QQ-W-343	…	…	…	…
	Wire, medium-hard drawn	B 2	…	…	QQ-W-343	…	…	…	…
	Wire, metallizing	…	…	MIL-W-6712	…	…	…	…	…
	Wire, soft	B 3, B 48, B 738	…	…	QQ-W-343	…	J461, J463	…	…
	Wire, stranded	B 8, B 172, B 173, B 174, B 226, B 229, B 286, B 470, B 496	…	…	QQ-B-575	…	…	…	…
	Wire, trolley	B 47, B 116	…	…	…	…	…	…	…
C11010	Brazing filler metal	…	…	…	QQ-B-650	…	…	…	…
C11020	Brazing filler metal	…	…	…	QQ-B-650	…	…	…	…
C11030	Brazing filler metal	…	…	…	QQ-B-650	…	…	…	…
C11040	Rod, wire	B 49	…	…	…	…	…	…	…
C11100	Brazing filler metal	…	…	…	QQ-B-650	…	…	…	…
	Shapes	…	…	…	QQ-C-502	…	…	…	…
C11300	Bands, projectile rotating	…	…	MIL-B-20292	…	…	…	…	…
	Bar	B 152	…	…	…	…	J461, J463	…	…
	Bar, bus	B 187	…	…	…	…	…	…	…
	Brazing filler metal	…	…	…	QQ-B-650	…	…	…	…
	Pipe, bus	B 188	…	…	…	…	…	…	…
	Plate	B 152	…	…	…	…	J461, J463	…	…
	Rod, bus	B 187	…	…	…	…	…	…	…
	Shapes, bus	B 187	…	…	…	…	…	…	…
	Sheet	B 152	…	…	…	…	J461, J463	…	…
	Sheet, clad	B 506	…	…	…	…	…	…	…
	Strip	B 152, B 272	…	…	…	…	J461, J463	…	…
	Strip, clad	B 506	…	…	…	…	…	…	…

(continued)

Table 1 (continued)

		Specification							
Alloy	Product	ASTM	AMS	Military	Federal	ASME	SAE	AWS	Ingot No.
Wrought products (continued)									
C11300	Tube, bus	B 188	…	…	…	…	…	…	…
	Wire, coated with lead alloy	B 189	…	…	…	…	…	…	…
	Wire, coated with nickel	B 355	…	…	…	…	…	…	…
	Wire, coated with silver	B 298	…	…	…	…	…	…	…
	Wire, coated with tin	B 33, B 246	…	…	…	…	…	…	…
	Wire, flat	B 272	…	…	…	…	…	…	…
	Wire, hard drawn	B 1	…	…	QQ-W-343	…	…	…	…
	Wire, medium-hard drawn	B 2	…	…	QQ-W-343	…	…	…	…
	Wire, soft	B 3, B 48	…	…	QQ-W-343	…	…	…	…
	Wire, stranded	B 8, B 172, B 173, B 174, B 226, B 229, B 286, B 470, B 496	…	…	QQ-B-575	…	…	…	…
	Wire, trolley	B 47, B 116	…	…	…	…	…	…	…
C11400	Bands, projectile rotating	…	…	MIL-B-20292	…	…	…	…	…
	Bar	B 152	…	…	…	…	J461, J463	…	…
	Bar, bus	B 187	…	…	…	…	…	…	…
	Brazing filler metal	…	…	…	QQ-B-650	…	…	…	…
	Pipe, bus	B 188	…	…	…	…	…	…	…
	Plate	B 152	…	…	…	…	J461, J463	…	…
	Rod, bus	B 187	…	…	…	…	…	…	…
	Shapes, bus	B 187	…	…	…	…	…	…	…
	Sheet	B 152	…	…	…	…	J461, J463	…	…
	Sheet, clad	B 506	…	…	…	…	…	…	…
	Strip	B 152, B 272	…	…	…	…	J461, J463	…	…
	Strip, clad	B 506	…	…	…	…	…	…	…
	Tube, bus	B 188	…	…	…	…	…	…	…
	Wire, coated with lead alloy	B 189	…	…	…	…	…	…	…
	Wire, coated with nickel	B 355	…	…	…	…	…	…	…
	Wire, coated with silver	B 298	…	…	…	…	…	…	…
	Wire, coated with tin	B 33, B 246	…	…	…	…	…	…	…
	Wire, flat	B 272	…	…	…	…	…	…	…
	Wire, hard drawn	B 1	…	…	QQ-W-343	…	…	…	…
	Wire, medium-hard drawn	B 2	…	…	QQ-W-343	…	…	…	…
	Wire, soft	B 3, B 48	…	…	QQ-W-343	…	…	…	…
	Wire, stranded	B 8, B 172, B 173, B 174, B 226, B 229, B 286, B 470, B 496	…	…	QQ-B-575	…	…	…	…
	Wire, trolley	B 47, B 116	…	…	…	…	…	…	…
C11500	Bar	…	…	…	…	…	J461, J463	…	…
	Brazing filler metal	…	…	…	QQ-B-650	…	…	…	…
	Plate	…	…	…	…	…	J461, J463	…	…
	Sheet	…	…	…	…	…	J461, J463	…	…
	Strip	B 272	…	…	…	…	J461, J463	…	…
	Wire, coated with lead alloy	B 189	…	…	…	…	…	…	…
	Wire, coated with nickel	B 355	…	…	…	…	…	…	…
	Wire, coated with silver	B 298	…	…	…	…	…	…	…
	Wire, coated with tin	B 33, B 246	…	…	…	…	…	…	…
	Wire, flat	B 272	…	…	…	…	…	…	…
	Wire, hard drawn	B 1	…	…	QQ-W-343	…	…	…	…
	Wire, medium-hard drawn	B 2	…	…	QQ-W-343	…	…	…	…
	Wire, stranded	B 8, B 172, B 173, B 174, B 226, B 229, B 286, B 470, B 496	…	…	QQ-B-575	…	…	…	…
	Wire, trolley	B 47, B 116	…	…	…	…	…	…	…
C11600	Bands, projectile rotating	…	…	MIL-B-20292	…	…	…	…	…
	Bar	B 152	…	…	…	…	J461, J463	…	…
	Bar, bus	B 187	…	…	…	…	…	…	…
	Bar, commutator	…	…	MIL-B-19231	…	…	…	…	…
	Brazing filler metal	…	…	…	QQ-B-650	…	…	…	…
	Pipe, bus	B 188	…	…	…	…	…	…	…
	Plate	B 152	…	…	…	…	J461, J463	…	…
	Rod, bus	B 187	…	…	…	…	…	…	…
	Shapes, bus	B 187	…	MIL-B-19231	…	…	…	…	…
	Sheet	B 152	…	…	…	…	J461, J463	…	…
	Sheet, clad	B 506	…	…	…	…	…	…	…
	Strip	B 152, B 272	…	…	…	…	J461, J463	…	…
	Strip, clad	B 506	…	…	…	…	…	…	…
	Tube, bus	B 188	…	…	…	…	…	…	…
	Wire, coated with lead alloy	B 189	…	…	…	…	…	…	…
	Wire, coated with nickel	B 355	…	…	…	…	…	…	…
	Wire, coated with silver	B 298	…	…	…	…	…	…	…
	Wire, coated with tin	B 33, B 246	…	…	…	…	…	…	…
	Wire, flat	…	…	…	QQ-C-502	…	…	…	…
	Wire, hard drawn	B 1	…	…	QQ-W-343	…	…	…	…

(continued)

Table 1 Specification cross-reference for wrought and cast products (continued)

		Specification							
Alloy	**Product**	**ASTM**	**AMS**	**Military**	**Federal**	**ASME**	**SAE**	**AWS**	**Ingot No.**
Wrought products (continued)									
C11600	Wire, medium-hard drawn	B 2	…	…	QQ-W-343	…	…	…	…
	Wire, soft	B 3, B 48	…	…	QQ-W-343	…	…	…	…
	Wire, stranded	B 8, B 172, B 173, B 174, B 226, B 229, B 286, B 470, B 496	…	…	QQ-B-575	…	…	…	…
	Wire, trolley	B 47, B 116	…	…	…	…	…	…	…
C11700	Brazing filler metal	…	…	…	QQ-B-650	…	…	…	…
C12000	Bands, projectile rotating	…	…	MIL-B-18907, MIL-B-20292	…	…	…	…	…
	Bar	B 133, B 152	…	…	…	SB133	J461, J463	…	…
	Bar, bus	B 187	…	…	…	…	…	…	…
	Brazing filler metal	…	…	…	QQ-B-650	…	…	…	…
	Fittings	…	…	…	…	B16.22	…	…	…
	Foil, printed circuits	B 451	…	…	…	…	…	…	…
	Nipples	B 687	…	…	…	…	…	…	…
	Pipe	B 42	…	…	…	SB42	…	…	…
	Pipe, bus	B 188	…	…	…	…	…	…	…
	Pipe, threadless	B 302	…	…	…	…	…	…	…
	Plate	B 152	…	…	…	…	J461, J463	…	…
	Rod	B 133	…	…	…	SB133	…	…	…
	Rod, bus	B 187	…	…	…	…	…	…	…
	Shapes	B 133	…	…	…	…	J461, J463	…	…
	Shapes, bus	B 187	…	…	…	…	…	…	…
	Sheet	B 152	…	…	…	…	J461, J463	…	…
	Sheet, clad	B 506	…	…	…	…	…	…	…
	Sheet, printed circuits	B 451	…	…	…	…	…	…	…
	Strip	B 152	…	…	…	…	J461, J463	…	…
	Strip, clad	B 506	…	…	…	…	…	…	…
	Strip, printed circuits	B 451	…	…	…	…	…	…	…
	Tube, bus	B 188	…	…	…	…	…	…	…
	Tube, coils	B 743	…	…	…	…	…	…	…
	Tube, condenser	B 111	…	…	…	SB111	…	…	…
	Tube, drainage (DWV)	B 306	…	…	…	…	…	…	…
	Tube, finned	B 359	…	…	…	SB359	…	…	…
	Tube, rectangular waveguide	B 372	…	MIL-W-85	…	…	…	…	…
	Tube, seamless	B 75, B 641	…	MIL-T-24107	…	SB75	J461, J463	…	…
	Tube, seamless bright annealed	B 68	…	…	…	…	…	…	…
	Tube, seamless for air conditioning and refrigeration service	B 280	…	…	…	…	J461, J463	…	…
	Tube, seamless for torpedo use	…	…	MIL-T-3235	…	…	…	…	…
	Tube, U-bend	B 395	…	…	…	SB395	…	…	…
	Tube, welded	B 447, B 641, B 716	…	…	…	…	…	…	…
	Tube, welded for air conditioning and refrigeration service	B 640	…	…	…	…	…	…	…
C12100	Bands, projectile rotating	…	…	MIL-B-20292	…	…	…	…	…
	Brazing filler metal	…	…	…	QQ-B-650	…	…	…	…
C12200	Bands, projectile rotating	…	…	MIL-B-18907, MIL-B-20292	…	…	…	…	…
	Bar	B 133, B152	…	…	…	SB133, SB152	J461, J463	…	…
	Brazing filler metal	…	…	…	QQ-B-650	…	…	…	…
	Fittings	…	…	…	WW-T-725	B16.22, B16.29	…	…	…
	Nipples	B 687	…	…	…	…	…	…	…
	Pipe	B 42	…	…	…	SB42	…	…	…
	Pipe, threadless	B 302	…	…	…	…	…	…	…
	Plate	B 152	…	…	…	SB152	…	…	…
	Plate, clad	B 432	…	…	…	…	…	…	…
	Rod	B 133	…	…	…	SB133	J461, J463	…	…
	Shapes	B 133	…	…	…	…	J461, J463	…	…
	Sheet	B 152	…	…	…	SB152	J461, J463	…	…
	Sheet, building construction	B 370	…	…	…	…	…	…	…
	Sheet, clad	B 506	…	…	…	…	…	…	…
	Sheet, lead coated	B 101	…	…	…	…	…	…	…
	Strip	B 152	…	…	…	SB152	J461, J463	…	…
	Strip, building construction	B 370	…	…	…	…	…	…	…
	Strip, clad	B 506	…	…	…	…	…	…	…
	Tube, capillary	B 360	…	…	…	…	…	…	…
	Tube, coils	B 743	…	…	…	…	…	…	…
	Tube, condenser	B 111	…	…	…	SB111	…	…	…
	Tube, drainage (DWV)	B 306	…	…	…	…	…	…	…
	Tube, finned	B 359	…	MIL-T-22214	…	SB359	…	…	…
	Tube, seamless	B 75, B 641	…	MIL-T-24107	…	SB75	J461, J463	…	…

(continued)

Table 1 (continued)

		Specification							
Alloy	Product	ASTM	AMS	Military	Federal	ASME	SAE	AWS	Ingot No.
Wrought products (continued)									
C12200	Tube, seamless (water)	B 88	…	…	…	…	…	…	…
	Tube, seamless bright annealed	B 68	…	…	…	…	…	…	…
	Tube, seamless for air conditioning and refrigeration field service	B 280	…	…	…	…	J461, J463	…	…
	Tube, seamless for torpedo use	…	…	MIL-T-3235	…	…	…	…	…
	Tube, U-bend	B 395	…	…	…	SB395	…	…	…
	Tube, welded	B 447, B 543, B 641, B 716	…	…	…	SB543	…	…	…
	Tube, welded for air conditioning and refrigeration service	B 640	…	…	…	…	…	…	…
C12300	Bar	B 152	…	…	…	SB152	…	…	…
	Brazing filler metal	…	…	…	QQ-B-650	…	…	…	…
	Plate	B 152	…	…	…	SB152	…	…	…
	Sheet	B 152	…	…	…	SB152	…	…	…
	Sheet, clad	B 506	…	…	…	…	…	…	…
	Strip	B 152	…	…	…	SB152	…	…	…
	Strip, clad	B 506	…	…	…	…	…	…	…
C12900	Bands, projectile rotating	…	…	MIL-B-20292	…	…	…	…	…
C14200	Bar	B 133, B 152	…	…	…	SB152	…	…	…
	Plate	B 152	…	…	…	…	…	…	…
	Rod	B 133	…	…	…	SB133	…	…	…
	Shapes	B 133	…	…	…	…	…	…	…
	Sheet	B 152	…	…	…	…	…	…	…
	Strip	B 152	…	…	…	…	…	…	…
	Tube, condenser	B 111	…	…	…	SB111	…	…	…
	Tube, finned	B 359	…	…	…	SB359	…	…	…
	Tube, seamless	B 75	…	MIL-T-24107	…	SB75	…	…	…
	Tube, U-bend	B 395	…	…	…	SB395	…	…	…
	Tube, welded	B 447	…	…	…	…	…	…	…
C14300	Brazing filler metal	…	…	…	QQ-B-650	…	…	…	…
C14400	Brazing filler metal	…	…	…	QQ-B-650	…	…	…	…
C14420	Bar	B 152	…	…	…	…	…	…	…
	Plate	B 152	…	…	…	…	…	…	…
	Sheet	B 152	…	…	…	…	…	…	…
	Strip	B 152	…	…	…	…	…	…	…
C14500	Bar	B 301	…	…	…	…	…	…	…
	Bar, forging	B 124	…	…	…	…	…	…	…
	Brazing filler metal	…	…	…	QQ-B-650	…	…	…	…
	Fittings	…	…	…	…	B16.22	…	…	…
	Forgings, die	B 283	…	…	…	…	…	…	…
	Rod	B 301	…	…	…	…	J461, J463	…	…
	Rod, forging	B 124	…	…	…	…	…	…	…
	Shapes, forging	B 124	…	…	…	…	…	…	…
C14520	Bar	B 301	…	…	…	…	…	…	…
	Rod	B 301	…	…	…	…	…	…	…
C14700	Bar	B 301	…	…	…	…	…	…	…
	Bar, forging	B 124	…	…	…	…	…	…	…
	Brazing filler metal	…	…	…	QQ-B-650	…	…	…	…
	Fittings	…	…	…	…	B16.22	…	…	…
	Forgings, die	B 283	…	…	…	…	…	…	…
	Rod	B 301	…	…	…	…	J461, J463	…	…
	Rod, forging	B 124	…	…	…	…	…	…	…
	Shapes, forging	B 124	…	…	…	…	…	…	…
C15000	Rod	…	…	…	…	…	J461, J463	…	…
C15100	Sheet	B 747	…	…	…	…	…	…	…
	Strip	B 747	…	…	…	…	…	…	…
C16200	Bar	…	…	…	…	…	J461, J463	…	…
	Forgings	…	…	…	…	…	J461, J463	…	…
	Rod	…	…	…	…	…	J461, J463	…	…
	Wire	B 105, B 624	…	MIL-W-82598	…	…	…	…	…
C16500	Wire	B 105	…	…	…	…	…	…	…
	Wire, trolley	B 9	…	…	…	…	…	…	
C17000	Bar	B 194, B 196	…	…	…	…	…	…	…
	Extrusions	B 570	…	…	…	…	…	…	…
	Forgings	B 570	…	…	…	…	…	…	…
	Plate	B 194	…	…	…	…	…	…	…
	Rod	B 196	…	…	…	…	J461, J463	…	…
	Sheet	B 194	…	…	…	…	…	…	…
	Strip	B 194	…	…	…	…	J461, J463	…	…
C17200	Bar	B 194, B 196	4533, 4650, 4651	MIL-C-21657	…	…	J461, J463	…	…
	Extrusions	B 570	…	…	…	…	…	…	…
	Forgings	B 570	4650	…	…	…	…	…	…

(continued)

Table 1 Specification cross-reference for wrought and cast products (continued)

		Specification							
Alloy	**Product**	**ASTM**	**AMS**	**Military**	**Federal**	**ASME**	**SAE**	**AWS**	**Ingot No.**
Wrought products (continued)									
C17200	Plate	B 194	…	…	…	…	…	…	…
	Rod	B 196	4533, 4534, 4650, 4651	MIL-C-21657	…	…	J461, J463	…	…
	Rod, forging	…	4650	…	…	…	…	…	…
	Sheet	B 194	…	…	…	…	…	…	…
	Strip	B 194	…	…	…	…	J461, J463	…	…
	Tube, seamless	B 643	4535	…	…	…	…	…	…
	Wire	B 197	4725	…	…	…	J461, J463	…	…
C17300	Bar	B 196	…	MIL-C-21657	…	…	…	…	…
	Rod	B 196	…	MIL-C-21657	…	…	…	…	…
	Wire	B 197	…	…	…	…	…	…	…
C17410	Sheet	B 768	…	…	…	…	…	…	…
	Strip	B 768	…	…	…	…	…	…	…
C17500	Bar	B 441	…	…	…	…	…	…	…
	Bar, rolled	B 534	…	…	…	…	…	…	…
	Plate	B 534	…	…	…	…	…	…	…
	Rod	B 441	…	…	…	…	J461, J463	…	…
	Shapes	…	…	…	…	…	J461, J463	…	…
	Sheet	B 534	…	…	…	…	…	…	…
	Strip	B 534	…	MIL-C-81021	…	…	J461, J463	…	…
	Tube	…	…	…	…	…	J461, J463	…	…
C17510	Bar	B 441	…	…	…	…	…	…	…
	Bar, rolled	B 534	…	…	…	…	…	…	…
	Plate	B 534	…	…	…	…	…	…	…
	Rod	B 441	…	…	…	…	J461, J463	…	…
	Shapes	…	…	…	…	…	J461, J463	…	…
	Sheet	B 534	…	…	…	…	…	…	…
	Strip	B 534	…	MIL-C-81021	…	…	J461, J463	…	…
	Tube	…	…	…	…	…	J461, J463	…	…
C18200	Bar	…	…	MIL-C-19311	…	…	…	…	…
	Forgings	…	…	MIL-C-19311	…	…	…	…	…
	Rod	…	…	MIL-C-19311	…	…	…	…	…
	Strip	…	…	MIL-C-19311	…	…	…	…	…
	Wire, soft	F 9	…	…	…	…	…	…	…
C18400	Bar	…	…	MIL-C-19311	…	…	J461, J463	…	…
	Forgings	…	…	MIL-C-19311	…	…	J461, J463	…	…
	Rod	…	…	MIL-C-19311	…	…	J461, J463	…	…
	Strip	…	…	MIL-C-19311	…	…	…	…	…
C18700	Bar	B 301	…	…	…	…	…	…	…
	Rod	B 301	…	…	…	…	J461, J463	…	…
C18900	Electrode, welding	…	…	MIL-E-45829	…	…	…	A5.6	…
	Rod, welding	…	…	…	…	…	…	A5.27	…
C18980	Rod, welding	…	…	…	…	…	…	A5.27	…
C19200	Bar, rolled	B 465	…	…	…	…	…	…	…
	Plate	B 465	…	…	…	…	…	…	…
	Sheet	B 465	…	…	…	…	…	…	
	Strip	B 465	…	…	…	…	…	…	
	Tube	…	…	…	…	…	J461, J463	…	…
	Tube, condenser	B 111	…	…	…	SB111	…	…	…
	Tube, finned	B 359	…	…	…	SB359	…	…	…
	Tube, seamless	B 469	…	…	…	…	…	…	…
	Tube, U-bend	B 395	…	…	…	SB395	…	…	…
	Tube, welded for air conditioning and refrigeration service	B 640	…	…	…	…	…	…	…
C19210	Bar, rolled	B 465	…	…	…	…	…	…	…
	Foil	B 465	…	…	…	…	…	…	…
	Plate	B 465	…	…	…	…	…	…	…
	Sheet	B 465	…	…	…	…	…	…	…
	Strip	B 465	…	…	…	…	…	…	…
C19400	Bar, rolled	B 465	…	…	…	…	…	…	…
	Plate	B 465	…	…	…	…	…	…	…
	Sheet	B 465, B 694	…	…	…	…	…	…	…
	Strip	B 465, B 694	…	…	…	…	…	…	…
	Tube, welded	B 543	…	…	…	SB543	…	…	…
	Tube, welded for air conditioning and refrigeration service	B 640	…	…	…	…	…	…	…
C19600	Bar, rolled	B 465	…	…	…	…	…	…	…
	Plate	B 465	…	…	…	…	…	…	…
	Sheet	B 465	…	…	…	…	…	…	…
	Strip	B 465	…	…	…	…	…	…	…
C19700	Bar, rolled	B 465	…	…	…	…	…	…	…
	Plate	B 465	…	…	…	…	…	…	…
	Sheet	B 465	…	…	…	…	…	…	…
	Strip	B 465	…	…	…	…	…	…	…
C21000	Bar	B 36	…	…	…	…	J461, J463	…	…

(continued)

Table 1 (continued)

Alloy	Product	Specification							
		ASTM	AMS	Military	Federal	ASME	SAE	AWS	Ingot No.
Wrought products (continued)									
C21000	Plate	B 36	…	…	…	…	…	…	…
	Sheet	B 36	…	…	…	…	J461, J463	…	…
	Strip	B 36	…	…	…	…	J461, J463	…	…
	Tube, welded	B 587	…	…	…	…	…	…	…
	Wire	B 134	…	…	…	…	…	…	…
C22000	Bands, projectile rotating	…	…	MIL-B-18907, MIL-B-20292	…	…	…	…	…
	Bar	B 36	…	…	…	…	J461, J463	…	…
	Cups, bullet jacket	B 131	…	MIL-C-3383	…	…	…	…	…
	Plate	B 36	…	…	…	…	…	…	…
	Sheet	B 36, B 694	…	…	…	…	J461, J463	…	…
	Strip	B 36, B 130, B 694	…	…	…	…	J461, J463	…	…
	Tube	B 135	…	…	…	…	J461, J463	…	…
	Tube, rectangular waveguide	B 372	…	MIL-W-85	…	…	…	…	…
	Tube, welded	B 587	…	…	…	…	…	…	…
	Wire	B 134	…	…	…	…	…	…	…
	Wire, metallizing	…	…	MIL-W-6712	…	…	…	…	…
C23000	Bar	B 36	…	…	…	…	…	…	…
	Fittings	…	…	…	…	B16.22, B16.29	…	…	…
	Nipples	B 687	…	…	…	…	…	…	…
	Pipe	B 43	…	…	…	SB43	…	…	…
	Plate	B 36	…	…	…	…	…	…	…
	Sheet	B 36	…	…	…	…	J461, J463	…	…
	Strip	B 36	…	…	…	…	J461, J463	…	…
	Tube, condenser	B 111	…	…	…	SB111	…	…	…
	Tube, finned	B 359	…	…	…	SB359	…	…	…
	Tube, seamless	B 135	4553	MIL-T-20168	WW-T-791	SB135	J461, J463	…	…
	Tube, U-bend	B 395	…	…	…	SB395	…	…	…
	Tube, welded	B 543, B 587	…	…	…	SB543	…	…	…
	Wire	B 134	…	…	…	…	…	…	…
C24000	Bar	B 36	…	…	…	…	…	…	…
	Brazing filler metal	…	…	…	QQ-B-650	…	…	…	…
	Plate	B 36	…	…	…	…	…	…	…
	Sheet	B 36	…	…	…	…	J461, J463	…	…
	Strip	B 36	…	…	…	…	J461, J463	…	…
	Wire	B 134	…	…	…	…	…	…	…
C26000	Bar	B 19, B 36	…	…	…	…	J461, J463	…	…
	Brazing filler metal	…	…	…	QQ-B-650	…	…	…	…
	Cups, cartridge case	B 129	…	MIL-C-10375	…	…	…	…	…
	Disk	B 19	…	…	…	…	…	…	…
	Plate	B 19, B 36	4505, 4507	…	…	…	…	…	…
	Rod	…	…	…	…	…	J461, J463	…	…
	Sheet	B 19, B 36	4505, 4507, 4508	…	…	…	J461, J463	…	…
	Shim stock, laminated	…	…	MIL-S-22499	…	…	…	…	…
	Strip	B 19, B 36, B 569	4505, 4507	…	…	…	J461, J463	…	…
	Tube, seamless	B 135	…	MIL-T-20219	WW-T-791	…	J461, J463	…	…
	Tube, welded	B 587	…	…	…	…	…	…	…
	Wire	B 134	…	…	…	…	J461, J463	…	…
C26100	Cups, cartridge case	…	…	MIL-C-10375	…	…	…	…	…
	Shim stock, laminated	…	…	MIL-S-22499	…	…	…	…	…
C26800	Bar	B 36	…	…	…	…	J461, J463	…	…
	Plate	B 36	…	…	…	…	…	…	…
	Rod	…	…	…	…	…	J461, J463	…	…
	Sheet	B 36	…	…	…	…	J461, J463	…	…
	Strip	B 36	…	…	…	…	J461, J463	…	…
	Tube, welded	B 587	…	…	…	…	…	…	…
	Wire	…	…	…	…	…	J461, J463	…	…
	Wire, metallizing	…	…	MIL-W-6712	…	…	…	…	…
C27000	Bolts	F 468	…	…	…	…	…	…	…
	Nuts	F 467	…	…	…	…	…	…	…
	Rod	…	…	…	…	…	J461, J463	…	…
	Screws	F 468	…	…	…	…	…	…	…
	Studs	F 468	…	…	…	…	…	…	…
	Tube	B 135	…	…	…	…	…	…	…
	Tube, welded	B 587	…	…	…	…	…	…	…
	Wire	B 134	4712, 4713	…	…	…	J461, J463	…	…
	Wire, tinned	…	4710	…	…	…	…	…	…
C27200	Bar	B 36	…	…	…	…	…	…	…
	Plate	B 36	…	…	…	…	…	…	…
	Sheet	B 36	…	…	…	…	…	…	…
	Strip	B 36	…	…	…	…	…	…	…
	Tube	B 135	…	…	…	…	…	…	…
	Tube, welded	B 587	…	…	…	…	…	…	…
C27400	Wire	B 134	…	…	…	…	…	…	…
C28000	Bar	B 36	…	…	…	…	…	…	…
	Plate	B 36	…	…	…	…	…	…	…

(continued)

Table 1 Specification cross-reference for wrought and cast products (continued)

Alloy	Product	Specification							
		ASTM	AMS	Military	Federal	ASME	SAE	AWS	Ingot No.
Wrought products (continued)									
C28000	Sheet	B 36	…	…	…	…	…	…	…
	Strip	B 36	…	…	…	…	…	…	…
	Tube, condenser	B 111	…	…	…	SB111	…	…	…
	Tube, seamless	B 135	…	…	WW-T-791	…	…	…	…
C31400	Bar	B 140	…	…	…	…	…	…	…
	Rod	B 140	…	…	…	…	…	…	…
	Shapes	B 140	…	…	…	…	…	…	…
	Valves	…	…	MIL-V-18436	…	…	…	…	…
C31600	Bar	B 140	…	…	…	…	…	…	…
	Rod	B 140	…	…	…	…	…	…	…
	Shapes	B 140	…	…	…	…	…	…	…
	Valves	…	…	MIL-V-18436	…	…	…	…	…
C32000	Bar	B 140	…	…	…	…	…	…	…
	Rod	B 140	…	…	…	…	…	…	…
	Shapes	B 140	…	…	…	…	…	…	…
C33000	Tube, seamless	B 135	4544, 4555	MIL-T-46072	WW-T-791	…	J461, J463	…	…
C33100	Tube	…	…	MIL-T-46072	…	…	J461, J463	…	…
C33200	Tube	B 135	4558	MIL-T-46072	…	…	…	…	…
C33500	Bar	B 121	…	…	…	…	…	…	…
	Plate	B 121	…	…	…	…	…	…	…
	Rod	B 453	…	…	…	…	…	…	…
	Sheet	B 121	…	…	…	…	…	…	…
	Strip	B 121	…	…	…	…	…	…	…
C34000	Bar	B 121	…	…	…	…	…	…	…
	Plate	B 121	…	…	…	…	…	…	…
	Rod	B 453	…	…	…	…	…	…	…
	Sheet	B 121	…	…	…	…	…	…	…
	Strip	B 121	…	…	…	…	…	…	…
C34200	Bar	B 121	…	…	…	…	…	…	…
	Plate	B 121	…	…	…	…	…	…	…
	Rod	…	…	…	…	…	J461, J463	…	…
	Sheet	B 121	…	…	…	…	J461, J463	…	…
	Strip	B 121	…	…	…	…	J461, J463	…	…
C34500	Rod	B 453	…	…	…	…	J461, J463	…	…
C35000	Bar	B 121	…	…	…	…	…	…	…
	Plate	B 121	…	…	…	…	…	…	…
	Rod	B 453	…	…	…	…	J461, J463	…	…
	Sheet	B 121	…	…	…	…	J461, J463	…	…
	Strip	B 121	…	…	…	…	J461, J463	…	…
C35300	Bar	B 121	…	…	…	…	…	…	…
	Plate	B 121	…	…	…	…	…	…	…
	Rod	B 453	…	…	…	…	…	…	…
	Sheet	B 121	…	…	…	…	…	…	…
	Strip	B 121	…	…	…	…	…	…	…
C35340	Rod	B 453	…	…	…	…	…	…	…
C35600	Bar	B 121	…	…	…	…	…	…	…
	Plate	B 121	…	…	…	…	…	…	…
	Rod	B 453	…	…	…	…	…	…	…
	Sheet	B 121	…	…	…	…	…	…	…
	Strip	B 121	…	…	…	…	…	…	…
C36000	Bar	B 16	4610	…	…	…	J461, J463	…	…
	Rod	B 16	4610	…	…	…	J461, J463	…	…
	Shapes	B 16	…	…	…	…	J461, J463	…	…
	Valves	…	…	MIL-V-18436	…	…	…	…	…
C36500	Bar, forging	B 124	…	…	…	…	…	…	…
	Forgings, die	B 283	…	…	…	…	…	…	…
	Plate, clad	B 432	…	…	…	…	…	…	…
	Plate, condenser tube	B 171	…	…	…	SB171	…	…	…
	Rod, forging	B 124	…	…	…	…	…	…	…
	Shapes, forging	B 124	…	…	…	…	…	…	…
C37000	Tube	B 135	…	MIL-T-46072	…	…	…	…	…
C37700	Bar, forging	B 124	…	…	…	…	…	…	…
	Forgings, die	B 283	4614	…	…	SB283	J461, J463	…	…
	Rod, forging	B 124	4614	…	…	…	…	…	…
	Shapes, forging	B 124	…	…	…	…	…	…	…
C38000	Shapes	B 455	…	…	…	…	…	…	…
C38500	Shapes	B 455	…	…	…	…	…	…	…
C40500	Bar, rolled	B 591	…	…	…	…	…	…	…
	Plate	B 591	…	…	…	…	…	…	…
	Sheet	B 591	…	…	…	…	…	…	…
	Strip	B 591	…	…	…	…	…	…	…
C41100	Bar, rolled	B 591	…	…	…	…	…	…	…
	Bearings and bushings	…	…	MIL-B-13501	…	…	…	…	…
	Bushing stock	…	…	MIL-B-13501	…	…	…	…	…
	Plate	B 591	…	…	…	…	…	…	…
	Sheet	B 591	…	…	…	…	…	…	…
	Strip	B 591	…	…	…	…	…	…	…

(continued)

Table 1 (continued)

		Specification							
Alloy	Product	ASTM	AMS	Military	Federal	ASME	SAE	AWS	Ingot No.
Wrought products (continued)									
C41100	Strip, flexible hose	B 508	…	…	…	…	…	…	…
	Wire	B 105	…	…	…	…	…	…	…
C41300	Bar, rolled	B 591	…	…	…	…	…	…	…
	Plate	B 591	…	…	…	…	…	…	…
	Sheet	B 591	…	…	…	…	…	…	…
	Strip	B 591	…	…	…	…	…	…	…
C41500	Bar, rolled	B 591	…	…	…	…	…	…	…
	Plate	B 591	…	…	…	…	…	…	…
	Sheet	B 591	…	…	…	…	…	…	…
	Strip	B 591	…	…	…	…	…	…	…
C42200	Bar, rolled	B 591	…	…	…	…	…	…	…
	Plate	B 591	…	…	…	…	…	…	…
	Sheet	B 591	…	…	…	…	…	…	…
	Strip	B 591	…	…	…	…	…	…	…
C42500	Bar, rolled	B 591	…	…	…	…	…	…	…
	Plate	B 591	…	…	…	…	…	…	…
	Sheet	B 591	…	…	…	…	…	…	…
	Strip	B 591	…	…	…	…	…	…	…
C43000	Bar, rolled	B 591	…	…	…	…	…	…	…
	Plate	B 591	…	…	…	…	…	…	…
	Sheet	B 591	…	…	…	…	…	…	…
	Strip	B 591	…	…	…	…	…	…	…
C43400	Bar, rolled	B 591	…	…	…	…	…	…	…
	Plate	B 591	…	…	…	…	…	…	…
	Sheet	B 591	…	…	…	…	…	…	…
	Strip	B 591	…	…	…	…	…	…	…
C44300	Plate, clad	B 432	…	…	…	…	…	…	…
	Plate, condenser tube	B 171	…	…	…	SB171	…	…	…
	Tube, condenser	B 111	…	…	…	SB111	…	…	…
	Tube, finned	B 359	…	…	…	SB359	…	…	…
	Tube, U-bend	B 395	…	…	…	SB395	…	…	…
	Tube, welded	B 543	…	…	…	SB543	…	…	…
C44400	Plate, clad	B 432	…	…	…	…	…	…	…
	Plate, condenser tube	B 171	…	…	…	SB171	…	…	…
	Tube, condenser	B 111	…	…	…	SB111	…	…	…
	Tube, finned	B 359	…	…	…	SB359	…	…	…
	Tube, U-bend	B 395	…	…	…	SB395	…	…	…
	Tube, welded	B 543	…	…	…	SB543	…	…	…
C44500	Plate, clad	B 432	…	…	…	…	…	…	…
	Plate, condenser tube	B 171	…	…	…	SB171	…	…	…
	Tube, condenser	B 111	…	…	…	SB111	…	…	…
	Tube, finned	B 359	…	…	…	SB359	…	…	…
	Tube, U-bend	B 395	…	…	…	SB395	…	…	…
	Tube, welded	B 543	…	…	…	SB543	…	…	…
C46200	Bar	B 21	…	…	QQ-B-639	…	…	…	…
	Bolts	F 468	…	…	…	…	…	…	…
	Nuts	F 467	…	…	…	…	…	…	…
	Plate	…	…	…	QQ-B-639	…	…	…	…
	Rod	B 21	…	…	…	…	…	…	…
	Screws	F 468	…	…	…	…	…	…	…
	Shapes	B 21	…	…	…	…	…	…	…
	Sheet	…	…	…	QQ-B-639	…	…	…	…
	Studs	F 468	…	…	…	…	…	…	…
C46400	Bar	B 21	4611, 4612	…	QQ-B-639	…	J461, J463	…	…
	Bar, forging	B 124	…	…	…	…	…	…	…
	Bolt	F 468	…	…	…	…	…	…	…
	Forgings, die	B 283	…	…	…	…	…	…	…
	Nuts	F 467	…	…	…	…	…	…	…
	Plate	…	…	…	QQ-B-639	…	…	…	…
	Plate, clad	B 432	…	…	…	…	…	…	…
	Plate, condenser tube	B 171	…	…	…	SB171	…	…	…
	Rod	B 21	4611, 4612	…	…	…	J461, J463	…	…
	Rod, forging	B 124	…	…	…	…	…	…	…
	Screws	F 468	…	…	…	…	…	…	…
	Shapes	B 21	…	…	…	…	…	…	…
	Shapes, forging	B 124	…	…	…	…	…	…	…
	Sheet	…	…	…	QQ-B-639	…	…	…	…
	Strip	…	…	…	QQ-B-639	…	J461, J463	…	…
	Studs	F 468	…	…	…	…	…	…	…
	Wire, metallizing	…	…	MIL-W-6712	…	…	…	…	…
C46500	Bar	…	…	…	…	…	J461, J463	…	…
	Plate, clad	B 432	…	…	…	…	…	…	…
	Plate, condenser tube	B 171	…	…	…	SB171	…	…	…
	Rod	…	…	…	…	…	J461, J463	…	…
C47000	Brazing filler metal	…	…	…	QQ-B-650	…	…	A5.8	…
	Rod, welding	…	…	…	QQ-R-571	…	…	A5.15, A5.27	…
C47940	Bar	B 21	…	…	…	…	…	…	…

(continued)

Table 1 Specification cross-reference for wrought and cast products (continued)

		Specification							
Alloy	**Product**	**ASTM**	**AMS**	**Military**	**Federal**	**ASME**	**SAE**	**AWS**	**Ingot No.**
Wrought products (continued)									
C47940	Rod	B 21	…	…	…	…	…	…	…
	Shape	B 21	…	…	…	…	…	…	…
C48200	Bar	B 21	…	…	QQ-B-639	…	…	…	…
	Bar, forging	B 124	…	…	…	…	…	…	…
	Forgings, die	B 283	…	…	…	…	…	…	…
	Plate	…	…	…	QQ-B-639	…	…	…	…
	Rod	B 21	…	…	…	…	…	…	…
	Rod, forging	B 124	…	…	…	…	…	…	…
	Shapes	B 21	…	…	…	…	…	…	…
	Shapes, forging	B 124	…	…	…	…	…	…	…
	Sheet	…	…	…	QQ-B-639	…	…	…	…
	Strip	…	…	…	QQ-B-639	…	…	…	…
C48500	Bar	B 21	…	…	QQ-B-639	…	…	…	…
	Bar, forging	B 124	…	…	…	…	…	…	…
	Forgings, die	B 283	…	…	…	…	…	…	…
	Plate	…	…	…	QQ-B-639	…	…	…	…
	Rod	B 21	…	…	…	…	…	…	…
	Rod, forging	B 124	…	…	…	…	…	…	…
	Shapes	B 21	…	…	…	…	…	…	…
	Shapes, forging	B 124	…	…	…	…	…	…	…
	Sheet	…	…	…	QQ-B-639	…	…	…	…
	Strip	…	…	…	QQ-B-639	…	…	…	…
C50100	Wire	B 105	…	…	…	…	…	…	…
C50200	Wire	B 105	…	…	…	…	…	…	…
C50500	Strip, flexible hose	B 508	…	…	…	…	…	…	…
	Wire	B 105	…	…	…	…	…	…	…
	Wire, trolley	B 9	…	…	…	…	…	…	…
C50700	Wire	B 105	…	…	…	…	…	…	…
C51000	Bar	B 103, B 139	4625	…	…	…	…	…	…
	Bearings and bushings	…	…	MIL-B-13501	…	…	…	…	…
	Bolts	B 468	…	…	…	…	…	…	…
	Bushing stock	…	…	MIL-B-13501	…	…	…	…	…
	Nuts	F 467	…	…	…	…	…	…	…
	Plate	B 103	4510	…	…	…	…	…	…
	Plate, bridge and bearing	B 100	…	…	…	…	…	…	…
	Rod	B 139	4625	…	…	…	J461, J463	…	…
	Screws	F 468	…	…	…	…	…	…	…
	Shapes	B 139	…	…	…	…	…	…	…
	Sheet	B 103	4510	…	…	…	J461, J463	…	…
	Sheet, bridge and bearing	B 100	…	…	…	…	…	…	…
	Strip	B 103	4510	…	…	…	J461, J463	…	…
	Studs	F 468	…	…	…	…	…	…	…
	Tube	…	4625	MIL-T-3595	…	…	…	…	…
	Wire	B 159	4720	…	…	…	J461, J463	…	…
	Wire, metallizing	…	…	MIL-W-6712	…	…	…	…	…
C51100	Bar	B 103	…	…	…	…	…	…	…
	Bearings and bushings	…	…	MIL-B-13501	…	…	…	…	…
	Plate	B 103	…	…	…	…	…	…	…
	Plate, bridge and bearing	B 100	…	…	…	…	…	…	…
	Sheet	B 103	…	…	…	…	…	…	…
	Sheet, bridge and bearing	B 100	…	…	…	…	…	…	…
	Strip	B 103	…	…	…	…	…	…	…
C51800	Electrode, welding	…	…	MIL-E-23765/3	…	…	…	…	…
	Rod, welding	…	…	…	QQ-R-571	…	…	A5.13, A5.15, A5.7	…
C51900	Bar, rolled	B 103	…	…	…	…	…	…	…
	Plate	B 103	…	…	…	…	…	…	…
	Sheet	B 103	…	…	…	…	…	…	…
	Strip	B 103	…	…	…	…	…	…	…
C52100	Bar	B 103, B 139	…	…	…	…	…	…	…
	Electrode, welding	…	…	MIL-E-23765/3	…	…	…	A5.6	…
	Plate	B 103	…	…	…	…	…	…	…
	Rod	B 139	…	…	…	…	…	…	…
	Rod, welding	…	…	…	…	…	…	A5.15	…
	Shapes	B 139	…	…	…	…	…	…	…
	Sheet	B 103	…	…	…	…	J461, J463	…	…
	Strip	B 103	…	…	…	…	J461, J463	…	…
	Wire	B 159	…	…	…	…	…	…	…
C52400	Bar	B 103, B139	…	…	…	…	…	…	…
	Plate	B 103	…	…	…	…	…	…	…
	Rod	B 139	…	…	…	…	J461, J463	…	…
	Rod, welding	…	…	…	…	…	…	A5.13	…
	Shapes	B 139	…	…	…	…	…	…	…
	Sheet	B 103	…	…	…	…	…	…	…
	Strip	B 103	…	…	…	…	J461, J 463	…	…
	Wire	B 159	…	…	…	…	…	…	…
C53400	Bar	B 103, B 139	…	…	…	…	…	…	…

(continued)

Table 1 (continued)

		Specification							
Alloy	Product	ASTM	AMS	Military	Federal	ASME	SAE	AWS	Ingot No.
Wrought products (continued)									
C53400	Bearing and bushings	…	…	MIL-B-13501	…	…	…	…	…
	Plate	B 103	…	…	…	…	…	…	…
	Rod	B 139	…	…	…	…	…	…	…
	Shapes	B 139	…	…	…	…	…	…	…
	Sheet	B 103	…	…	…	…	…	…	…
	Strip	B 103	…	…	…	…	…	…	…
C54400	Bar	B 103, B 139	…	…	…	…	J461, J463	…	…
	Bearings and bushings	…	…	MIL-B-13501	…	…	…	…	…
	Plate	B 103	…	…	…	…	…	…	…
	Rod	B 139	…	…	…	…	J461, J463	…	…
	Shapes	B 139	…	…	…	…	…	…	…
	Sheet	B 103	…	…	…	…	J461, J463	…	…
	Strip	B 103	4520	…	…	…	J461, J463	…	…
C55180	Brazing filler metal	…	…	…	…	…	…	A5.8	…
C55181	Brazing filler metal	…	…	…	…	…	…	A5.8	…
C55280	Brazing filler metal	…	…	…	…	…	…	A5.8	…
C55281	Brazing filler metal	…	…	…	…	…	…	A5.8	…
C55282	Brazing filler metal	…	…	…	…	…	…	A5.8	…
C55283	Brazing filler metal	…	…	…	…	…	…	A5.8	…
C55284	Brazing filler metal	…	…	…	…	…	…	A5.8	…
C60800	Tube, condenser	B 111	…	…	…	SB111	…	…	…
	Tube, finned	B 359	…	…	…	SB359	…	…	…
	Tube, U-bend	B 395	…	…	…	SB395	…	…	…
C61000	Bar	…	…	…	QQ-C-450	…	…	…	…
	Electrode, welding	…	…	MIL-E-23765/3	…	…	…	…	…
	Plate	…	…	…	QQ-C-450	…	…	…	…
	Sheet	…	…	…	QQ-C-450	…	…	…	…
	Strip	…	…	…	QQ-C-450	…	…	…	…
C61300	Bar	B 169	…	…	QQ-C-450	…	…	…	…
	Pipe	B 315	…	…	…	…	…	…	…
	Pipe, welded	B 608	…	…	…	…	…	…	…
	Plate	B 169, B 171	…	…	QQ-C-450	…	…	…	…
	Plate, clad	B 432	…	…	…	…	…	…	…
	Plate, condenser tube	B 171	…	…	…	…	…	…	…
	Sheet	B 169	…	…	QQ-C-450	…	…	…	…
	Strip	B 169	…	…	QQ-C-450	…	…	…	…
	Tube	B 315	…	…	…	…	…	…	…
C61400	Bar	B 169	…	…	QQ-C-450	SB169	J461, J463	…	…
	Bolts	B 468	…	…	…	…	…	…	…
	Nuts	F 467	…	…	…	…	…	…	…
	Pipe	B 315	…	…	…	…	…	…	…
	Pipe, welded	B 608	…	…	…	…	…	…	…
	Plate	B 169, B 171	…	…	QQ-C-450	SB169	…	…	…
	Plate, clad	B 432	…	…	…	…	…	…	…
	Plate, condenser tube	B 171	…	…	…	SB171	…	…	…
	Rod	B 150	…	…	…	SB150	J461, J463	…	…
	Screws	F 468	…	…	…	…	…	…	…
	Shapes	…	…	…	…	…	J461, J463	…	…
	Sheet	B 169	…	…	QQ-C-450	SB169	J461, J463	…	…
	Strip	B 169	…	…	QQ-C-450	SB169	J461, J463	…	…
	Studs	F 468	…	…	…	…	…	…	…
	Tube	B 315	…	…	…	…	…	…	…
C61800	Electrode, welding	…	…	…	…	…	…	A5.6	…
	Rod, welding	…	…	…	…	…	…	A5.13, A5.15, A5.7	…
	Wire, metallizing	…	…	MIL-W-6712	…	…	…	…	…
C61900	Bar	B 150	…	…	…	…	…	…	…
	Bar, forging	B 124	…	…	…	…	…	…	…
	Electrode, welding	…	…	MIL-E-23765/3	…	…	…	…	…
	Forgings, die	B 283	…	…	…	…	…	…	…
	Rod	B 150	…	…	…	…	…	…	…
	Rod, forging	B 124	…	…	…	…	…	…	…
	Shapes	B 150	…	…	…	…	…	…	…
	Shapes, forging	B 124	…	…	…	…	…	…	…
C62200	Rod, welding	…	…	…	…	…	…	A5.13	…
C62300	Bar	B 150	4635	…	…	SB150	J461, J463	…	…
	Bar, forging	B 124	…	…	…	…	…	…	…
	Forgings, die	B 283	4635	MIL-B-16166	…	…	J461, J463	…	…
	Rod	B 150	4635	…	…	SB150	J461, J463	…	…
	Rod, forging	B 124	…	…	…	…	…	…	…
	Shapes	B 150	…	…	…	…	…	…	…
	Shapes, forging	B 124	…	…	…	…	…	…	…
C62400	Forgings	…	…	…	…	…	J461, J463	…	…
	Rod	B 150	…	…	…	…	…	…	…
	Rod, welding	…	…	…	…	…	…	A5.7	…
C62500	Rod, welding	…	…	…	…	…	…	A5.13	…
C63000	Bar	B 150	4640	…	QQ-C-450	SB150	J461, J463	…	…

(continued)

Table 1 Specification cross-reference for wrought and cast products (continued)

		Specification							
Alloy	**Product**	**ASTM**	**AMS**	**Military**	**Federal**	**ASME**	**SAE**	**AWS**	**Ingot No.**
Wrought products (continued)									
C63000	Bar, forging	B 124	…	…	…	…	…	…	…
	Bolts	F 468	…	…	…	…	…	…	…
	Forgings, die	B 283	4640	MIL-B-16166	…	…	…	…	…
	Nuts	F 467	…	…	…	…	…	…	…
	Plate	B 171	…	…	QQ-C-450	…	…	…	…
	Plate, condenser tube	B 171	…	…	…	SB171	…	…	…
	Rod	B 150	4640	…	…	SB150	J461, J463	…	…
	Rod, forging	B 124	…	…	…	…	…	…	…
	Screws	F 468	…	…	…	…	…	…	…
	Shapes	B 150	4640	…	…	…	J461, J463	…	…
	Shapes, forging	B 124	…	…	…	…	…	…	…
	Sheet	…	…	…	QQ-C-450	…	…	…	…
	Strip	…	…	…	QQ-C-450	…	…	…	…
	Tube	…	4640	…	…	…	…	…	…
C63020	Pipe	B 315	…	…	…	…	…	…	…
	Shapes	…	4590	…	…	…	…	…	…
	Tube	B 315	…	…	…	…	…	…	…
C63200	Bar	B 150	…	…	…	…	…	…	…
	Bar, forging	B 124	…	…	…	…	…	…	…
	Electrode, welding	…	…	MIL-E-23765/3	…	…	…	A5.6	…
	Forgings, die	B 283	…	…	…	…	…	…	…
	Plate	B 171	…	…	…	…	…	…	…
	Rod	B 150	…	…	…	…	…	…	…
	Rod, forging	B 124	…	…	…	…	…	…	…
	Shapes	B 150	…	…	…	…	…	…	…
	Shapes, forging	B 124	…	…	…	…	…	…	…
C64200	Bar	B 150	4631	…	…	SB150	…	…	…
	Bar, forging	B 124	…	…	…	…	…	…	…
	Bolts	F 468	…	…	…	…	…	…	…
	Forgings, die	B 283	4631	…	…	SB283	…	…	…
	Nuts	F 467	…	…	…	…	…	…	…
	Rod	B 150	4631	…	…	SB150	J461, J463	…	…
	Rod, forging	B 124	…	…	…	…	…	…	…
	Screws	F 468	…	…	…	…	…	…	…
	Shapes	B 150	…	…	…	…	…	…	…
	Shapes, forging	B 124	…	…	…	…	…	…	…
	Studs	F 468	…	…	…	…	…	…	…
C64210	Bar, forging	B 124	…	…	…	…	…	…	…
	Forgings, die	B 283	…	…	…	…	…	…	…
	Rod, forging	B 124	…	…	…	…	…	…	…
	Shapes, forging	B 124	…	…	…	…	…	…	…
C64700	Bar	B 411	…	…	…	…	…	…	…
	Rod	B 411	…	…	…	…	…	…	…
	Wire	B 412	…	…	…	…	…	…	…
C65100	Bar	B 98	…	…	…	SB98	…	…	…
	Bolts	F 468	…	…	…	…	…	…	…
	Nuts	F 467	…	…	…	…	…	…	…
	Pipe	B 315	…	…	…	…	…	…	…
	Plate	B 96	…	…	…	…	…	…	…
	Plate, clad	B 432	…	…	…	…	…	…	…
	Rod	B 98	…	…	…	SB98	…	…	…
	Screws	F 468	…	…	…	…	…	…	…
	Shapes	B 98	…	…	…	SB98	…	…	…
	Sheet	B 96	…	…	…	…	…	…	…
	Strip	B 96	…	…	…	…	…	…	…
	Studs	F 468	…	…	…	…	…	…	…
	Tube	B 315	…	…	…	…	…	…	…
	Wire	B 99, B 105	…	…	…	…	…	…	…
C65400	Bar	B 98	…	…	…	…	…	…	…
C65500	Bar	…	…	…	…	…	J461, J463	…	…
	Bar, forging	B 124	…	…	…	…	…	…	…
	Bar, rolled	B 96, B 98	…	…	…	SB96, SB98	J461, J463	…	…
	Bar, rolled, pressure vessels	B 96	…	…	…	SB96	…	…	…
	Bolts	B 468	…	…	…	…	…	…	…
	Electrode, welding	…	…	MIL-E-23765	…	…	…	…	…
	Forgings, die	B 283	…	…	…	…	…	…	…
	Nuts	F 467	…	…	…	…	…	…	…
	Pipe	B 315	…	…	…	SB315	…	…	…
	Plate	B 96	…	…	…	SB96	…	…	…
	Plate, bridge and bearing	B 100	…	…	…	…	…	…	…
	Plate, clad	B 432	…	…	…	…	…	…	…
	Plate, pressure vessels	B 96	…	…	…	SB96	…	…	…
	Rod	B 98	…	…	…	SB98	J461, J463	…	…
	Rod, forging	B 124	…	…	…	…	…	…	…
	Screws	F 468	…	…	…	…	…	…	…
	Shapes	B 98	…	…	…	SB98	J461, J463	…	…
	Shapes, forging	B 124	…	…	…	…	…	…	…

(continued)

Table 1 (continued)

		Specification							
Alloy	Product	ASTM	AMS	Military	Federal	ASME	SAE	AWS	Ingot No.
Wrought products (continued)									
C65500	Sheet	B 96	…	…	…	SB96	J461, J463	…	…
	Sheet, bridge and bearing	B 100	…	…	…	…	…	…	…
	Sheet, pressure vessels	B 96	…	…	…	SB96	…	…	…
	Strip	B 96	…	…	…	SB96	J461, J463	…	…
	Studs	F 468	…	…	…	…	…	…	…
	Tube	B 315	…	MIL-T-8231	…	SB315	…	…	…
C65600	Electrode, welding	…	…	…	…	…	…	A5.6	…
	Rod, welding	…	…	…	…	…	…	A5.27, A5.7	…
C65620	Bar	…	4616	…	…	…	…	…	…
	Forgings	…	4616	…	…	…	…	…	…
	Rod	…	4616	…	…	…	…	…	…
	Tube	…	4616	…	…	…	…	…	…
C66100	Bar	B 98	…	…	…	SB98	…	…	…
	Bolts	F 468	…	…	…	…	…	…	…
	Nuts	F 467	…	…	…	…	…	…	…
	Rod	B 98	…	…	…	SB98	…	…	…
	Screws	F 468	…	…	…	…	…	…	…
	Shapes	B 98	…	…	…	SB98	…	…	…
	Studs	F 468	…	…	…	…	…	…	…
C66400	Sheet	B 694	…	…	…	…	…	…	…
	Strip	B 694	…	…	…	…	…	…	…
C66410	Sheet	B 694	…	…	…	…	…	…	…
	Strip	B 694	…	…	…	…	…	…	…
C67000	Bar	B 138	…	…	…	…	J461, J463	…	…
	Forgings	…	…	…	…	…	J461, J463	…	…
	Rod	B 138	…	…	…	…	J461, J463	…	…
	Shapes	B 138	…	…	…	…	…	…	…
C67300	Bar	…	…	…	…	…	J461, J463	…	…
	Forgings	…	…	…	…	…	J461, J463	…	…
	Rod	…	…	…	…	…	J461, J463	…	…
	Shapes	…	…	…	…	…	J461, J463	…	…
C67400	Bar	…	…	…	…	…	J461, J463	…	…
	Forgings	…	…	…	…	…	J461, J463	…	…
	Rod	…	…	…	…	…	J461, J463	…	…
	Shapes	…	…	…	…	…	J461, J463	…	…
C67500	Bar	B 138	…	…	…	…	J461, J463	…	…
	Bar, forging	B 124	…	…	…	…	…	…	…
	Bolts	F 468	…	…	…	…	…	…	…
	Forgings, die	B 283	…	…	…	…	J461, J463	…	…
	Nuts	F 467	…	…	…	…	…	…	…
	Rod	B 138	…	…	…	…	J461, J463	…	…
	Rod, forging	B 124	…	…	…	…	…	…	…
	Screws	F 468	…	…	…	…	…	…	…
	Shapes	B 138	…	…	…	…	J461, J463	…	…
	Shapes, forging	B 124	…	…	…	…	…	…	…
	Studs	F 468	…	…	…	…	…	…	…
C67600	Brazing filler metal	…	…	…	…	…	…	A5.8	…
C68000	Rod, welding	…	…	…	…	…	…	A5.15, A5.27	…
C68100	Rod, welding	…	…	…	…	…	…	A5.15, A5.27	…
C68700	Tube, condenser	B 111	…	…	…	SB111	…	…	…
	Tube, finned	B 359	…	…	…	SB359	…	…	…
	Tube, U-bend	B 395	…	…	…	SB395	…	…	…
	Tube, welded	B 543	…	…	…	SB543	…	…	…
C68800	Bar, rolled	B 592	…	…	…	…	…	…	…
	Plate	B 592	…	…	…	…	…	…	…
	Sheet	B 592	…	…	…	…	…	…	…
	Strip	B 592	…	…	…	…	…	…	…
C69100	Pipe	B 315, B 706	…	…	…	…	…	…	…
	Tube	B 315, B 706	…	…	…	…	…	…	…
C69400	Rod	B 371	…	…	…	…	…	…	…
C69430	Rod	B 371	…	…	…	…	…	…	…
C69700	Rod	B 371	…	…	…	…	…	…	…
C69710	Rod	B 371	…	…	…	…	…	…	…
C70200	Bands, projectile rotating	…	…	MIL-B-18907, MIL-B-20292	…	…	…	…	…
C70400	Pipe, seamless	B 466	…	…	…	…	…	…	…
	Tube, condenser	B 111	…	…	…	SB111	…	…	…
	Tube, finned	B 359	…	…	…	SB359	…	…	…
	Tube, seamless	B 466	…	…	…	SB466	…	…	…
	Tube, U-bend	B395	…	…	…	…	…	…	…
	Tube, welded	B 543	…	…	…	SB543	…	…	…
C70600	Bar	B 122, B 151	…	MIL-C-15726	…	…	…	…	…
	Forgings	…	…	MIL-C-24679	…	…	…	…	…
	Pipe, seamless	B 466	…	…	…	SB466	…	…	…
	Pipe, welded	B 467, B 608	…	…	…	SB467	…	…	…
	Plate	B 122	…	MIL-C-15726	…	…	…	…	…
	Plate, clad	B 432	…	…	…	…	…	…	…

(continued)

Table 1 Specification cross-reference for wrought and cast products (continued)

		Specification							
Alloy	**Product**	**ASTM**	**AMS**	**Military**	**Federal**	**ASME**	**SAE**	**AWS**	**Ingot No.**
Wrought products (continued)									
C70600	Plate, condenser tube	B 171	…	…	…	SB171	J461, J463	…	…
	Rod	B 151	…	MIL-C-15726	…	…	…	…	…
	Rod, welding	…	…	…	…	…	…	A5.15	…
	Sheet	B 122	…	MIL-C-15726	…	…	J461, J463	…	…
	Strip	B 122	…	MIL-C-15726	…	…	…		
	Tube, condenser	B 111, B 552	…	MIL-T-15005	…	SB111	J461, J563	…	…
	Tube, finned	B 359	…	MIL-T-22214	…	SB359	…	…	…
	Tube, seamless	B 466, B 469	…	MIL-T-16420	…	SB466	…	…	…
	Tube, U-bend	B 395	…	…	…	SB395	…	…	…
	Tube, welded	B 543	…	MIL-T-16420	…	SB543	…	…	…
	Wire	…	…	MIL-C-15726	…	…	…	…	…
C70690	Bar	F 96	…	…	…	…	…	…	…
	Plate	F 96	…	…	…	…	…	…	…
	Sheet	F 96	…	…	…	…	…	…	…
	Strip	F 96	…	…	…	…	…	…	…
C71000	Bar	B 122	…	…	…	…	J461, J463	…	…
	Bolts	F 468	…	…	…	…	…	…	…
	Nuts	F 467	…	…	…	…	…	…	…
	Pipe, seamless	B 466	…	…	…	SB466	…	…	…
	Plate	B 122	…	…	…	…	…	…	…
	Screws	F 468	…	…	…	…	…	…	…
	Sheet	B 122, B 694	…	…	…	…	J461, J463	…	…
	Strip	B 122, B 694	…	…	…	…	J461, J463	…	…
	Studs	F 468	…	…	…	…	…	…	…
	Tube, condenser	B 111	…	…	…	SB111	J461, J463	…	…
	Tube, finned	B 359	…	…	…	SB359	…	…	…
	Tube, seamless	B 466	…	…	…	SB466	…	…	…
	Tube, U-bend	B 395	…	…	…	SB395	…	…	…
	Wire	B 206	…	…	…	…	…	…	…
C71110	Wire	…	4732	…	…	…	…	…	…
C71500	Bar	B 122, B 151	…	MIL-C-15726	…	…	J461, J463	…	…
	Bolts	F 468	…	…	…	…	…	…	…
	Electrode, welding	…	…	MIL-E-22200/4	…	…	…	A5.6	…
	Forgings	…	…	MIL-C-24679	…	…	…	…	…
	Nuts	F 467	…	…	…	…	…	…	…
	Pipe, seamless	B 466	…	…	…	SB466	…	…	…
	Pipe, welded	B 467, B 608	…	…	…	…	…	…	…
	Plate	B 122	…	MIL-C-15726	…	…	J461, J463	…	…
	Plate, clad	B 432	…	…	…	…	…	…	…
	Plate, condenser tube	B 171	…	…	…	SB171	J461, J463	…	…
	Rod	B 151	…	MIL-C-15726	…	…	…	…	…
	Screws	F 468	…	…	…	…	…	…	…
	Sheet	B 122	…	MIL-C-15726	…	…	J461, J463	…	…
	Strip	B 122	…	MIL-C-15726	…	…	J461, J463	…	…
	Studs	F 468	…	…	…	…	…	…	…
	Tube, condenser	B 111, B 552	…	MIL-T-15005	…	SB111	J461, J463	…	…
	Tube, finned	B 359	…	MIL-T-22214	…	SB359	…	…	…
	Tube, seamless	B 466	…	MIL-T-16420	…	SB466	…	…	…
	Tube, U-bend	B 395	…	…	…	SB395	…	…	…
	Tube, welded	B 543	…	MIL-T-15762	…	SB543	…	…	…
	Wire	…	…	MIL-C-15726	…	…	…	…	…
C71580	Bar	F 96	…	…	…	…	…	…	…
	Plate	F 96	…	…	…	…	…	…	…
	Rod, welding	…	…	…	…	…	…	A5.27	…
	Sheet	F 96	…	…	…	…	…	…	…
	Strip	F 96	…	…	…	…	…	…	…
C71590	Bar	F 96	…	…	…	…	…	…	…
	Plate	F 96	…	…	…	…	…	…	…
	Sheet	F 96	…	…	…	…	…	…	…
	Strip	F 96	…	…	…	…	…	…	…
C71640	Tube, condenser	B 111	…	…	…	…	…	…	…
	Tube, welded	B 543	…	…	…	…	…	…	…
C72000	Bar	B 122	…	…	…	…	…	…	…
C72200	Pipe, seamless	B 466	…	…	…	…	…	…	…
	Plate	B 122	…	…	…	…	…	…	…
	Plate, condenser tube	B 171	…	…	…	…	…	…	…
	Sheet	B 122	…	…	…	…	…	…	…
	Strip	B 122	…	…	…	…	…	…	…
	Tube, condenser	B 111	…	…	…	…	…	…	…
	Tube, finned	B 359	…	…	…	…	…	…	…
	Tube, U-bend	B 395	…	…	…	…	…	…	…
	Tube, welded	B 543	…	…	…	…	…	…	…
C72500	Bar	B 122	…	…	…	…	…	…	…
	Plate	B 122	…	…	…	…	…	…	…
	Sheet	B 122	…	…	…	…	…	…	…
	Strip	B 122	…	…	…	…	…	…	…
C72650	Strip	B 740	…	…	…	…	…	…	…

(continued)

Table 1 (continued)

		Specification							
Alloy	**Product**	**ASTM**	**AMS**	**Military**	**Federal**	**ASME**	**SAE**	**AWS**	**Ingot No.**
Wrought products (continued)									
C72700	Strip	B 740	…	…	…	…	…	…	…
C72900	Strip	B 740	…	…	…	…	…	…	…
C73500	Bar	B 122	…	…	…	…	…	…	…
	Plate	B 122	…	…	…	…	…	…	…
	Sheet	B 122	…	…	…	…	…	…	…
	Strip	B 122	…	…	…	…	…	…	…
C74000	Bar	B 122	…	…	…	…	…	…	…
	Plate	B 122	…	…	…	…	…	…	…
	Sheet	B 122	…	…	…	…	…	…	…
	Strip	B 122	…	…	…	…	…	…	…
C74500	Bar	B 122, B 151	…	…	…	…	…	…	…
	Plate	B 122	…	…	…	…	…	…	…
	Rod	B 151	…	…	…	…	…	…	…
	Sheet	B 122	…	…	…	…	…	…	…
	Strip	B 122	…	…	…	…	…	…	…
	Wire	B 206	…	…	…	…	…	…	…
C75200	Bar	B 122, B 151	…	…	…	…	J461, J463	…	…
	Plate	B 122	…	…	…	…	…	…	…
	Rod	B 151	…	…	…	…	J461, J463	…	…
	Sheet	B 122	…	…	…	…	J461, J463	…	…
	Strip	B 122	…	…	…	…	J461, J463	…	…
	Wire	B 206	…	…	…	…	…	…	…
C75700	Bar	B 151	…	…	…	…	…	…	…
	Rod	B 151	…	…	…	…	…	…	…
	Wire	B 206	…	…	…	…	…	…	…
C76200	Bar	B 122	…	…	…	…	…	…	…
	Plate	B 122	…	…	…	…	…	…	…
	Sheet	B 122	…	…	…	…	…	…	…
	Strip	B 122	…	…	…	…	…	…	…
C76400	Bar	B 151	…	…	…	…	…	…	…
	Rod	B 151	…	…	…	…	…	…	…
	Wire	B 206	…	…	…	…	…	…	…
C77000	Bar	B 122, B 151	…	…	…	…	J461, J463	…	…
	Plate	B 122	…	…	…	…	…	…	…
	Rod	B 151	…	…	…	…	J461, J463	…	…
	Sheet	B 122	…	…	…	…	J461, J463	…	…
	Strip	B 122	…	…	…	…	J461, J463	…	…
	Wire	B 206	…	…	…	…	…	…	…
C77300	Brazing filler metal	…	…	…	QQ-B-650	…	…	A5.8	…
	Rod, welding	…	…	…	…	…	…	A5.27	…
C77400	Bar, forging	B 124	…	…	…	…	…	…	…
	Forgings, die	B 283	…	…	…	…	…	…	…
	Rod, forging	B 124	…	…	…	…	…	…	…
	Shapes, forging	B 124	…	…	…	…	…	…	…
C79200	Bar	B 151	…	…	…	…	…	…	…
	Rod	B 151	…	…	…	…	…	…	…
	Wire	B 206	…	…	…	…	…	…	…
Cast products									
C80100	Ingot	…	…	…	QQ-C-521	…	…	…	…
C81400	Sand	B 770	…	…	…	…	…	…	…
C82000	Sand	B 770	…	…	QQ-C-390	…	…	…	…
C82200	Sand	B 770	…	…	…	…	…	…	…
C82400	Centrifugal	…	…	…	QQ-C-390	…	…	…	…
	Sand	B 770	…	…	QQ-C-390	…	…	…	…
	Valves	…	…	…	WW-V-1967	…	…	…	…
C82500	Centrifugal	…	4511	…	QQ-C-390	…	…	…	…
	Investment	…	4511, 4890	…	…	…	…	…	…
	Precision	…	…	MIL-C-11866	…	…	…	…	…
	Sand	B 770	4511	…	QQ-C-390	…	…	…	…
C82510	Sand	B 770	…	…	…	…	…	…	…
C82600	Sand	B 770	…	…	QQ-C-390	…	…	…	…
	Valves	…	…	…	WW-V-1967	…	…	…	…
C82700	Sand	…	…	…	QQ-C-390	…	…	…	…
	Valves	…	…	…	WW-V-1967	…	…	…	…
C82800	Sand	B 770	…	…	QQ-C-390	…	…	…	…
	Valves	…	…	…	WW-V-1967	…	…	…	…
C83300	Ingot	…	…	…	…	…	…	…	131
C83400	Bands, projectile rotating	…	…	MIL-B-46066	…	…	…	…	…
C83450	Ingot	B 30	…	…	…	…	…	…	…
	Sand	B 584, B 763	…	…	…	…	…	…	…
C83500	Ingot	…	…	…	…	…	…	…	251
C83600	Centrifugal	B 271	4855	…	QQ-C-390	…	J461, J462	…	…
	Continuous	B 505	…	…	QQ-C-390	…	J461, J462	…	…
	Fittings	B 62	…	…	WW-P-460, WW-T-725	B16.15, B16.18, B16.23, B16.26, B16.32, SB62	…	…	…

(continued)

Table 1 Specification cross-reference for wrought and cast products (continued)

		Specification							
Alloy	Product	ASTM	AMS	Military	Federal	ASME	SAE	AWS	Ingot No.
Cast products (continued)									
C83600	Flanges	B 62	…	…	…	B16.24, SB62	…	…	…
	Ingot	B 30	…	…	…	…	…	…	115
	Precision	…	…	MIL-C-11866	…	…	…	…	…
	Sand	B 62, B 584	4855	…	QQ-C-390	SB62	J461, J462	…	…
	Unions	…	…	…	WW-U-516	…	…	…	…
	Valves	…	…	MIL-V-18436	…	…	…	…	…
C83800	Centrifugal	B 271	…	…	QQ-C-390	…	J461, J462	…	…
	Continuous	B 505	…	…	QQ-C-390	…	J461, J462	…	…
	Fittings	B 584	…	…	…	B16.15, B 16.18, B16.23, B16.32	…	…	…
	Ingot	B 30	…	…	…	…	…	…	120
	Sand	B 584, B 763	…	…	QQ-C-390	…	J461, J462	…	…
	Unions	…	…	…	WW-U-516	…	…	…	…
	Valves	…	…	…	WW-V-1967	…	…	…	…
C84200	Continuous	B 505	…	…	QQ-C-390	…	…	…	…
	Fittings	…	…	…	WW-P-460	…	…	…	…
C84400	Centrifugal	B 271	…	…	QQ-C-390	…	…	…	…
	Continuous	B 505	…	…	QQ-C-390	…	…	…	…
	Fittings	B 584	…	…	WW-T-725	B16.15, B16.18, B16.23, B16.24, B16.26, B16.32	…	…	…
	Ingot	B 30	…	…	…	…	…	…	123
	Sand	B 584, B 763	…	…	QQ-C-390	…	…	…	…
	Unions	…	…	…	WW-U-516	…	…	…	…
C84500	Ingot	…	…	…	…	…	…	…	125
C84800	Centrifugal	B 271	…	…	QQ-C-390	…	…	…	…
	Continuous	B 505	…	…	QQ-C-390	…	…	…	…
	Ingot	B 30	…	…	…	…	…	…	130
	Sand	B 584, B 763	…	…	QQ-C-390	…	…	…	…
C85200	Centrifugal	B 271	…	…	…	…	J461, J462	…	…
	Continuous	…	…	…	…	…	J461, J462	…	…
	Ingot	B 30	…	…	…	…	…	…	400
	Sand	B 584, B 763	…	…	QQ-C-390	…	…	…	…
	Valves	…	…	…	WW-V-1967	…	…	…	…
C85400	Centrifugal	B 271	…	…	…	…	J461, J462	…	…
	Continuous	…	…	…	…	…	J461, J462	…	…
	Ingot	B 30	…	…	…	…	…	…	403
	Sand	B 584, B 763	…	…	QQ-C-390	…	J461, J462	…	…
	Valves	…	…	…	WW-V-1967	…	…	…	…
C85500	Centrifugal	…	…	…	QQ-C-390	…	…	…	…
	Sand	…	…	…	QQ-C-390	…	…	…	…
	Valves	…	…	…	WW-V-1967	…	…	…	…
C85700	Centrifugal	B 271	…	…	QQ-C-390	…	…	…	…
	Die	B 176	…	…	…	…	…	…	…
	Ingot	B 30	…	…	…	…	…	…	405.2
	Sand	B 584, B 763	…	…	QQ-C-390	…	…	…	…
C85800	Die	B 176	…	…	…	…	J461, J462	…	…
	Ingot	B 30	…	…	…	…	…	…	405.1
C86100	Centrifugal	…	…	…	QQ-C-390	…	…	…	…
	Ingot	…	…	…	…	…	…	…	423
	Sand	…	…	…	QQ-C-390	…	…	…	…
	Valves	…	…	…	WW-V-1967	…	…	…	…
C86200	Centrifugal	B 271	4862	…	QQ-C-390	…	J461, J462	…	…
	Continuous	B 505	…	…	QQ-C-390	…	J461, J462	…	…
	Ingot	B 30	…	…	QQ-C-523	…	…	…	423
	Precision	…	…	MIL-C-11866	…	…	…	…	…
	Sand	B 584, B 763	4862	…	QQ-C-390	…	J461, J462	…	…
	Valves	…	…	…	WW-V-1967	…	…	…	…
C86300	Centrifugal	B 271	4862	…	QQ-C-390	…	J461, J462	…	…
	Continuous	B 505	…	…	QQ-C-390	…	…	…	…
	Ingot	B 30	…	…	QQ-C-523	…	…	…	424
	Precision	…	…	MIL-C-11866	…	…	…	…	…
	Sand	B 22, B 584, B 763	4862	…	QQ-C-390	…	J461, J462	…	…
	Valves	…	…	…	WW-V-1967	…	…	…	…
C86400	Centrifugal	B 271	…	…	…	…	…	…	…
	Continuous	B 505	…	…	QQ-C-390	…	…	…	…
	Ingot	B 30	…	…	QQ-C-523	…	…	…	420
	Sand	B 584, B 763	…	…	QQ-C-390	…	J461, J462	…	…
	Valves	…	…	…	WW-V-1967	…	…	…	…
C86500	Centrifugal	B 271	4860	…	QQ-C-390	…	J461, J462	…	…
	Continuous	B 505	…	…	…	…	…	…	…
	Die	B 176	…	…	…	…	…	…	…
	Ingot	B 30	…	…	QQ-C-523	…	…	…	421
	Sand	B 584, B 763	4860	…	QQ-C-390	…	J461, J462	…	…
	Valves	…	…	…	WW-V-1967	…	…	…	…
C86700	Centrifugal	B 271	…	…	…	…	…	…	…
	Ingot	B 30	…	…	…	…	…	…	…

(continued)

Table 1 (continued)

		Specification							
Alloy	Product	ASTM	AMS	Military	Federal	ASME	SAE	AWS	Ingot No.
Cast products (continued)									
C86700	Sand	B 584, B 763	…	…	…	…	…	…	…
C86800	Sand	…	…	…	QQ-C-390	…	…	…	…
	Valves	…	…	…	WW-V-1967	…	…	…	…
C87300	Centrifugal	B 271	…	…	…	…	J461, J462	…	…
	Ingot	B 30	…	…	…	…	…	…	500A
	Precision	…	…	MIL-C-11866	…	…	…	…	…
	Sand	B 584, B 763	…	…	QQ-C-390	…	J461, J462	…	…
	Valves	…	…	…	WW-V-1967	…	…	…	…
C87400	Centrifugal	B 271	…	…	…	…	…	…	…
	Ingot	B 30	…	…	…	…	…	…	500B
	Sand	B 584, B 763	…	…	QQ-C-390	…	…	…	…
	Valves	…	…	…	WW-V-1967	…	…	…	…
C87500	Centrifugal	B 271	…	…	…	…	J461, J462	…	…
	Ingot	B 30	…	…	…	…	…	…	500C
	Permanent	B 806	…	…	…	…	…	…	…
	Sand	B 584, B 763	…	…	QQ-C-390	…	…	…	…
C87600	Ingot	B 30	…	…	…	…	…	…	500D
	Sand	B 584, B 763	…	…	…	…	…	…	…
C87610	Ingot	…	…	…	…	…	…	…	500E
	Sand	B 584, B 763	…	…	…	…	…	…	…
C87800	Die	B 176	…	…	…	…	J461, J462	…	…
	Ingot	B 30	…	…	…	…	…	…	500F
	Permanent	B 806	…	…	…	…	…	…	…
C90200	Ingot	…	…	…	…	…	…	…	242
C90300	Centrifugal	B 271	…	…	QQ-C-390	…	J461, J462	…	…
	Continuous	B 505	…	…	QQ-C-390	…	J461, J462	…	…
	Ingot	B 30	…	…	…	…	…	…	225
	Precision	…	…	MIL-C-11866	…	…	…	…	…
	Sand	B 584, B 763	…	…	QQ-C-390	…	J461, J462	…	…
	Valves	…	…	…	WW-V-1967	…	…	…	…
C90500	Centrifugal	B 271	4845	…	QQ-C-390	…	J461, J462	…	…
	Continuous	B 505	…	…	QQ-C-390	…	J461, J462	…	…
	Ingot	B 30	…	…	…	…	…	…	210
	Sand	B 584, B 763	4845	…	QQ-C-390	…	J461, J462	…	…
C90700	Centrifugal	B 427	…	…	…	…	J461, J462	…	…
	Continuous	B 505	…	…	QQ-C-390	…	J461, J462	…	…
	Ingot	B 30	…	…	…	…	…	…	205
	Sand	B 427	…	…	…	…	J461, J462	…	…
C90800	Centrifugal	B 427	…	…	…	…	…	…	…
	Ingot	B 30	…	…	…	…	…	…	…
	Sand	B 427	…	…	…	…	…	…	…
C91000	Centrifugal	…	…	…	QQ-C-390	…	…	…	…
	Continuous	B 505	…	…	QQ-C-390	…	…	…	…
	Ingot	B 30	…	…	…	…	…	…	197
	Sand	…	…	…	QQ-C-390	…	…	…	…
C91100	Sand	B 22	…	…	…	…	…	…	…
C91300	Centrifugal	…	7322	…	QQ-C-390	…	…	…	…
	Continuous	B 505	7322	…	QQ-C-390	…	…	…	…
	Ingot	B 30	…	…	…	…	…	…	194
	Sand	B 22	7322	…	QQ-C-390	…	…	…	…
C91600	Centrifugal	B 427	…	…	QQ-C-390	…	…	…	…
	Continuous	…	…	…	QQ-C-390	…	…	…	…
	Ingot	B 30	…	…	…	…	…	…	205N
	Sand	B 427	…	…	…	…	…	…	…
C91700	Centrifugal	B 427	…	…	…	…	…	…	…
	Ingot	B 30	…	…	…	…	…	…	…
	Sand	B 427	…	…	…	…	…	…	…
C92200	Centrifugal	B 271	…	…	QQ-C-390	…	J461, J462	…	…
	Continuous	B 505	…	…	QQ-C-390	…	J461, J462	…	…
	Fittings	B 61	…	…	WW-P-460, WW-T-725	B16.24, SB61	…	…	…
	Flanges	B 61	…	…	WW-P-460	SB61	…	…	…
	Ingot	B 30	…	…	…	…	…	…	245
	Sand	B 61, B 584	…	…	QQ-C-390	SB61, SB584	J461, J462	…	…
	Valves	…	…	MIL-V-17547	WW-V-1967	…	…	…	…
C92300	Centrifugal	B 271	…	…	QQ-C-390	…	J461, J462	…	…
	Continuous	B 505	…	…	QQ-C-390	…	J461, J462	…	…
	Ingot	B 30	…	…	…	…	…	…	230
	Sand	B 584, B 763	…	…	QQ-C-390	…	J461	…	…
C92400	Ingot	…	…	…	…	…	…	…	220
C92500	Continuous	B 505	…	…	QQ-C-390	…	J461, J462	…	…
	Ingot	B 30	…	…	…	…	…	…	200N
	Sand	…	…	…	…	…	J461, J462	…	…
	Valves	…	…	…	WW-V-1967	…	…	…	…
C92600	Ingot	…	…	…	…	…	…	…	215
	Sand	B 584	…	…	…	…	…	…	…
C92700	Continuous	B 505	…	…	QQ-C-390	…	J461, J462	…	…

(continued)

Table 1 Specification cross-reference for wrought and cast products (continued)

		Specification							
Alloy	**Product**	**ASTM**	**AMS**	**Military**	**Federal**	**ASME**	**SAE**	**AWS**	**Ingot No.**
Cast products (continued)									
C92700	Ingot	B 30	…	…	…	…	…	…	206
	Sand	…	…	…	…	…	J461, J462	…	…
C92800	Continuous	B 505	…	…	…	…	…	…	…
	Ingot	B 30	…	…	…	…	…	…	…
C92900	Centrifugal	B 427	…	…	…	…	…	…	…
	Continuous	B 505	…	…	…	…	J461, J462	…	…
	Ingot	B 30	…	…	…	…	…	…	206N
	Sand	B 427	…	…	…	…	J461, J462	…	…
C93200	Centrifugal	B 271	…	…	QQ-C-390	…	J461, J462	…	…
	Continuous	B 505	…	…	QQ-C-390	…	J461, J462	…	…
	Ingot	B 30	…	…	…	…	…	…	315
	Permanent mold	…	…	…	…	…	J461, J462	…	…
	Sand	B 584, B 763	…	…	QQ-C-390	…	J461, J462	…	…
C93400	Centrifugal	…	…	…	QQ-C-390	…	…	…	…
	Continuous	B 505	…	…	QQ-C-390	…	…	…	…
	Ingot	B 30	…	…	…	…	…	…	310
	Sand	…	…	…	QQ-C-390	…	…	…	…
C93500	Centrifugal	B 271	…	…	QQ-C-390	…	J461, J462	…	…
	Continuous	B 505	…	…	QQ-C-390	…	J461, J462	…	…
	Ingot	B 30	…	…	…	…	…	…	326
	Sand	B 584, B 763	…	…	QQ-C-390	…	J461, J462	…	…
C93600	Sand	…	…	…	QQ-C-390	…	…	…	…
C93700	Bearings	…	4827	…	…	…	…	…	…
	Centrifugal	B 271	4842	…	QQ-C-390	…	J461, J462	…	…
	Continuous	B 505	…	…	QQ-C-390	…	J461, J462	…	…
	Ingot	B 30	…	…	…	…	…	…	305
	Sand	B 22, B 584, B 763	4842	…	QQ-C-390	SB584	J461, J462	…	…
C93800	Centrifugal	B 271	…	…	QQ-C-390	…	J461, J462	…	…
	Continuous	B 505	…	…	QQ-C-390	…	J461, J462	…	…
	Ingot	B 30	…	…	…	…	…	…	319
	Permanent mold	…	…	…	…	…	J461, J462	…	…
	Sand	B 66, B 584, B 763	…	…	QQ-C-390	…	J461, J462	…	…
C93900	Continuous	B 505	…	…	QQ-C-390	…	…	…	…
	Ingot	B 30	…	…	…	…	…	…	…
C94000	Centrifugal	…	…	…	QQ-C-390	…	…	…	…
	Continuous	B 505	…	…	QQ-C-390	…	…	…	…
	Ingot	B 30	…	…	…	…	…	…	…
	Sand	…	…	…	QQ-C-390	…	…	…	…
C94100	Centrifugal	…	…	…	QQ-C-390	…	…	…	…
	Continuous	B 505	…	…	QQ-C-390	…	…	…	…
	Ingot	B 30	…	…	…	…	…	…	325
	Sand	B 67	…	…	QQ-C-390	…	…	…	…
C94300	Centrifugal	B 271	…	…	QQ-C-390	…	J461, J462	…	…
	Continuous	B 505	…	…	QQ-C-390	…	J461, J462	…	…
	Ingot	B 30	…	…	…	…	…	…	322
	Sand	B 66, B 584, B 763	…	…	QQ-C-390	…	J461, J462	…	…
C94400	Ingot	B 30	…	…	…	…	…	…	…
	Sand	B 66	…	…	…	…	…	…	…
C94500	Ingot	B 30	…	…	…	…	…	…	321
	Sand	B 66	…	…	…	…	…	…	…
C94700	Continuous	B 505	…	…	QQ-C-390	…	J461, J462	…	…
	Ingot	B 30	…	…	…	…	…	…	…
	Sand	B 584, B 763	…	…	QQ-C-390	…	J461, J462	…	…
	Valves	…	…	…	WW-V-1967	…	…	…	…
C94800	Continuous	B 505	…	…	QQ-C-390	…	…	…	…
	Ingot	B 30	…	…	…	…	…	…	…
	Sand	B 584, B 763	…	…	QQ-C-390	…	J461, J462	…	…
	Valves	…	…	…	WW-V-1967	…	…	…	…
C94900	Ingot	B 30	…	…	…	…	…	…	…
	Sand	B 584, B 763	…	…	…	…	…	…	…
C95200	Centrifugal	B 271	…	…	QQ-C-390	SB271	J461, J462	…	…
	Continuous	B 505	…	…	QQ-C-390	SB505	J461, J462	…	…
	Flanges	B 148	…	…	…	B16.24, SB148	…	…	…
	Ingot	B 30	…	…	…	…	…	…	415A
	Sand	B 148, B 763	…	…	QQ-C-390	SB148	J461, J462	…	…
	Valves	…	…	…	WW-V-1967	…	…	…	…
C95300	Centrifugal	B 271	…	…	QQ-C-390	…	J461, J462	…	…
	Continuous	B 505	…	…	QQ-C-390	…	J461, J462	…	…
	Ingot	B 30	…	…	…	…	…	…	415B
	Permanent	B 806	…	…	…	…	…	…	…
	Precision	…	…	MIL-C-11866	…	…	…	…	…
	Sand	B 148, B 763	…	…	QQ-C-390	…	J461, J462	…	…
	Valves	…	…	…	WW-V-1967	…	…	…	…
C95400	Centrifugal	B 271	…	…	QQ-C-390	SB271	J461, J462	…	…
	Continuous	B 505	…	…	QQ-C-390	…	J461, J462	…	…
	Ingot	B 30	…	…	…	…	…	…	415C
	Permanent	B 806	…	…	…	…	…	…	…

(continued)

Table 1 (continued)

		Specification							
Alloy	**Product**	**ASTM**	**AMS**	**Military**	**Federal**	**ASME**	**SAE**	**AWS**	**Ingot No.**
Cast products (continued)									
C95400	Precision	…	…	MIL-C-11866	…	…	…	…	…
	Sand	B 148, B 763	…	…	QQ-C-390	SB148	J461, J462	…	…
	Valves	…	…	…	WW-V-1967	…	…	…	…
C95410	Ingot	…	…	…	…	…	…	…	415C + Ni
	Precision	B 806	…	…	…	…	…	…	…
	Sand	B 148, B 763	…	…	…	…	…	…	…
C95420	Centrifugal	B 271	4870, 4871, 4873	…	QQ-C-390	…	J461, J462	…	…
	Sand	…	4870, 4871, 4873	…	QQ-C-390	…	J461, J462	…	…
C95500	Centrifugal	B 271	…	…	QQ-C-390	…	J461, J462	…	…
	Continuous	B 505	…	…	QQ-C-390	…	J461, J462	…	…
	Ingot	B 30	…	…	…	…	…	…	415D
	Precision	B 806	…	…	…	…	…	…	…
	Sand	B 148, B 763	…	…	QQ-C-390	…	J461, J462	…	…
	Valves	…	…	…	WW-V-1967	…	…	…	…
C95510	Centrifugal	B 271	4880	…	QQ-C-390	…	J461, J462	…	…
C95520	Centrifugal	B 271	4881	…	QQ-C-390	…	J461, J462	…	…
	Continuous	B 505	…	…	…	…	…	…	…
	Sand	…	4881	…	QQ-C-390	…	J461, J462	…	…
C95600	Ingot	B 30	…	…	…	…	…	…	415E
	Sand	B 148, B 763	…	…	…	…	…	…	…
C95700	Centrifugal	…	…	…	QQ-C-390	…	…	…	…
	Ingot	B 30	…	…	…	…	…	…	415F
	Sand	B 148	…	…	QQ-C-390	…	…	…	…
C95800	Centrifugal	B 271	…	…	QQ-C-390	…	J461, J462	…	…
	Continuous	B 505	…	…	…	…	J461, J462	…	…
	Ingot	B 30	…	…	…	…	…	…	415G
	Precision	B 806	…	…	…	…	…	…	…
	Sand	B 148, B 763	…	MIL-B-24480	QQ-C-390	…	J461, J462	…	…
	Valves	…	…	…	WW-V-1967	…	…	…	…
C95900	Sand	B 148	…	…	…	…	…	…	…
C96200	Centrifugal	B 369	…	…	QQ-C-390	…	J461, J462	…	…
	Ingot	B 30	…	…	…	…	…	…	…
	Sand	B 369	…	…	QQ-C-390	…	J461, J462	…	…
	Valves	…	…	MIL-V-18436	…	…	…	…	…
C96400	Centrifugal	B 369	…	…	QQ-C-390	…	…	…	…
	Continuous	B 505	…	…	QQ-C-390	…	…	…	…
	Ingot	B 30	…	…	…	…	…	…	…
	Sand	B 369	…	…	QQ-C-390	…	…	…	…
	Valves	…	…	…	WW-V-1967	…	…	…	…
C96700	Sand	B 770	…	…	…	…	…	…	…
C96800	Ingot	B 30	…	…	…	…	…	…	…
C97300	Centrifugal	B 271	…	…	…	…	…	…	…
	Continuous	B 505	…	…	…	…	J461, J462	…	…
	Ingot	B 30	…	…	…	…	…	…	410
	Sand	B 584, B 763	…	…	…	…	…	…	…
C97400	Ingot	…	…	…	…	…	…	…	411
C97600	Centrifugal	B 271	…	…	…	…	…	…	…
	Continuous	B 505	…	…	…	…	J461, J462	…	…
	Ingot	B 30	…	…	…	…	…	…	412
	Sand	B 584, B 763	…	MIL-C-17112	…	SB584	…	…	…
	Valves	…	…	MIL-V-18436	…	…	…	…	…
C97800	Centrifugal	B 271	…	…	…	…	…	…	…
	Continuous	B 505	…	…	…	…	…	…	…
	Ingot	B 30	…	…	…	…	…	…	413B
	Sand	B 584, B 763	…	…	…	…	…	…	…
	Valves	…	…	MIL-V-18436	…	…	…	…	…
C98200	Bearings	…	4824	…	…	…	…	…	…
C98400	Bearings	…	4820	…	…	…	…	…	…
C99400	Sand	B 763	…	…	…	…	…	…	…
C99500	Sand	B 763	…	…	…	…	…	…	…
C99700	Die	B 176	…	…	…	…	…	…	…
C99750	Die	B 176	…	…	…	…	…	…	…

Source: Copper Development Association Inc.

Approximate Equivalent Hardness Numbers for Wrought Coppers

Table 1 Approximate equivalent hardness numbers for wrought coppers (>99% Cu, alloys C10200 through C14200)

Vickers hardness No.		Knoop hardness No.		Rockwell superficial hardness No.			Rockwell hardness No.		Rockwell superficial hardness No.			Brinell hardness No.	
1 kgf, HV	100 gf, HV	1 kgf, HK	500 gf HK	15T scale,15 kgf, 1⁄16 in. (1.588 mm) ball, HR15T(a)	15T scale,15 kgf, 1⁄16 in. (1.588 mm) ball, HR15T(b)	30T scale, 30 kgf, 1⁄16 in. (1.588 mm) ball, HR30T(b)	B scale, 100 kgf, 1⁄16 in. (1.588 mm) ball, HRB(c)	F scale, 60 kgf, 1⁄16 in. (1.588 mm) ball, HRF(c)	15T scale, 15 kgf, 1⁄16 in. (1.588 mm) ball, HR15T(c)	30T scale, 30 kgf, 1⁄16 in. (1.588 mm) ball, HR30T(c)	45T scale, 45 kgf, 1⁄16 in. (1.588 mm) ball, HR45T(c)	500 kgf, 10 mm diam ball, HBS(d)	20 kgf, 2 mm diam ball, HBS(e)
130	127.0	138.7	133.8	…	85.0	…	67.0	99.0	…	69.5	49.0	…	119.0
128	125.2	136.8	132.1	83.0	84.5	…	66.0	98.0	87.0	68.5	48.0	…	117.5
126	123.6	134.9	130.4	…	84.0	…	65.0	97.0	…	97.5	46.5	120.0	115.0
124	121.9	133.0	128.7	82.5	83.5	…	64.0	96.0	86.0	966.5	45.0	117.5	113.0
122	121.1	131.0	127.0	…	83.0	…	62.5	95.5	85.5	66.0	44.0	115.0	111.0
120	118.5	129.0	125.2	82.0	82.5	…	61.0	95.0	…	65.0	42.5	112.0	109.0
118	116.8	127.1	123.5	81.5	…	…	59.5	94.0	85.0	64.0	41.0	110.0	107.5
116	115.0	125.1	121.7	…	82.0	…	58.5	93.0	…	63.0	40.0	107.0	105.5
114	113.5	123.2	119.9	81.0	81.5	…	57.0	92.5	84.5	62.0	38.5	105.0	103.5
112	111.8	121.4	118.1	80.5	81.0	…	55.0	91.5	…	61.0	37.0	102.0	102.0
110	109.9	119.5	116.3	80.0	…	…	53.5	91.0	84.0	60.0	36.0	99.5	100.0
108	108.3	117.5	114.5	…	80.5	…	52.0	90.5	83.5	59.0	34.5	97.0	98.0
106	106.6	115.6	112.6	79.5	80.0	…	50.0	89.5	…	58.0	33.0	94.5	96.0
104	104.9	113.5	110.0	79.0	79.5	…	48.0	88.5	83.0	57.0	32.0	92.0	94.0
102	103.2	111.5	108.0	78.5	79.0	…	46.5	87.5	82.5	56.0	30.0	89.5	92.0
100	101.5	109.4	106.0	78.0	78.0	…	44.5	87.0	82.0	55.0	28.5	87.0	90.0
98	99.8	107.3	104.0	77.5	77.5	…	42.0	85.5	81.0	53.5	26.5	84.5	88.0
96	98.0	105.3	102.1	77.0	77.0	…	40.0	84.5	80.5	52.0	25.5	82.0	86.5
94	96.4	103.2	100.0	76.5	76.5	…	38.0	83.0	80.0	51.0	23.0	79.5	85.0
92	94.7	101.0	98.0	76.0	75.5	…	35.5	82.0	79.0	49.0	21.0	77.0	83.0
90	93.0	98.9	96.0	75.5	75.0	…	33.0	81.0	78.0	47.5	19.0	74.5	81.0
88	91.2	96.9	94.0	75.0	74.5	…	30.5	79.5	77.0	46.0	16.5	…	79.0
86	89.7	95.5	92.0	74.5	73.5	…	28.0	78.0	76.0	44.0	14.0	…	77.0
84	87.9	92.3	90.0	74.0	73.0	…	25.5	76.5	75.0	43.0	12.0	…	75.0
82	86.1	90.1	87.9	73.5	72.0	…	23.0	74.5	74.5	41.0	9.5	…	73.0
80	84.5	87.9	86.0	72.5	71.0	…	20.0	73.0	73.5	39.5	7.0	…	71.5
78	82.8	85.7	84.0	72.0	70.0	…	17.0	71.0	72.5	37.5	5.0	…	69.5
76	81.0	83.5	81.9	71.5	69.5	…	14.5	69.0	71.5	36.0	2.0	…	67.5
74	79.2	81.1	79.9	71.0	68.5	…	11.5	67.5	70.0	34.0	…	…	66.0
72	77.6	78.9	78.7	70.0	67.5	…	8.5	66.0	69.0	32.0	…	…	64.0
70	75.8	76.8	76.6	69.5	66.5	…	5.0	64.0	67.5	30.0	…	…	62.0
68	74.3	74.1	74.4	69.0	65.5	…	2.0	62.0	66.0	28.0	…	…	60.5
66	72.6	71.9	71.9	68.0	64.5	…	…	60.0	64.5	25.5	…	…	58.5
64	70.9	69.5	70.0	67.5	63.5	…	…	58.0	63.5	23.5	…	…	57.0
62	69.1	67.0	67.9	66.5	32.0	…	…	56.0	61.0	21.0	…	…	55.0
60	67.5	64.6	65.9	66.0	31.0	…	…	54.0	59.0	18.0	…	…	53.0
58	65.8	62.0	63.8	65.0	60.0	…	…	51.5	57.0	15.5	…	…	51.5
56	64.0	59.8	61.8	64.5	58.5	…	…	49.0	55.0	13.0	…	…	49.5
54	62.3	57.4	59.5	63.5	57.5	…	…	47.0	53.0	10.0	…	…	48.0
52	60.7	55.0	57.2	63.0	56.0	…	…	44.0	51.5	7.5	…	…	46.5
50	58.9	52.8	55.0	62.0	55.0	…	…	41.5	49.5	4.5	…	…	44.5
48	57.3	50.3	52.7	61.0	53.5	…	…	39.0	47.5	1.5	…	…	42.0
46	55.8	48.0	50.2	60.5	52.0	…	…	36.2	45.0	…	…	…	41.0
44	53.9	45.9	47.8	59.5	51.0	…	…	33.5	43.0	…	…	…	…
42	52.2	43.7	45.2	58.5	49.5	…	…	30.5	41.0	…	…	…	…
40	51.3	40.2	42.8	57.5	48.0	…	…	28.0	38.5	…	…	…	…

(a) For 0.010 in. (0.25 mm) strip. (b) For 0.020 in. (0.51 mm) strip. (c) For 0.040 in. (1.02 mm) strip and greater. (d) For 0.080 in. (2.03 mm) strip. (e) For 0.040 in. (1.02 mm) strip. Source: "Standard Hardness Conversion Tables for Metals (Relationship among Brinell Hardness, Vickers Hardness, Rockwell Hardness, Rockwell Superficial Hardness, Knoop Hardness, and Scleroscope Hardness)," E 140, *Annual Book of ASTM Standards,* ASTM

Approximate Equivalent Hardness Numbers for Cartridge Brass

Table 1 Approximate equivalent hardness numbers for cartridge brass (70% Cu, 30% Zn)

	Rockwell hardness No.		Rockwell superficial hardness No.			
Vickers hardness No., HV	B scale, 100 kgf, 1/16 in. (1.588 mm) ball, HRF	F scale, 60 kgf, 1/16 in. (1.588 mm) ball, HRF	15T scale, 15 kgf, 1/16 in. (1.588 mm) ball, HR15T	30T scale, 30 kgf, 1/16 in. (1.588 mm) ball, HR30T	45T scale, 45 kgf, 1/16 in. (1.588 mm) ball, HR45T	Brinell hardness No., 500 kgf, 10 mm ball, HBS
196	93.5	110.0	90.0	77.5	66.0	169
194	...	109.5	...	...	65.5	167
192	93.0	...	...	77.0	65.0	166
190	92.5	109.0	...	76.5	64.5	164
188	92.0	...	89.5	...	64.0	162
186	91.5	108.5	...	76.0	63.5	161
184	91.0	...	...	75.5	63.0	159
182	90.5	108.0	89.0	...	62.5	157
180	90.0	107.5	...	75.0	62.0	156
178	89.0	...	...	74.5	61.5	154
176	88.5	107.0	...	...	61.0	152
174	88.0	...	88.5	74.0	60.5	150
172	87.5	106.5	...	73.5	60.0	149
170	87.0	...	...	...	59.5	147
168	86.0	106.0	88.0	73.0	59.0	146
166	85.5	...	...	72.5	58.5	144
164	85.0	105.5	...	72.0	58.0	142
162	84.0	105.0	87.5	...	57.5	141
160	83.5	...	...	71.5	56.5	139
158	83.0	104.5	...	71.0	56.0	138
156	82.0	104.0	87.0	70.5	55.5	136
154	81.5	103.5	...	70.0	54.5	135
152	80.5	103.0	...	...	54.0	133
150	80.0	...	86.5	69.5	533.5	131
148	79.0	102.5	...	69.0	53.0	129
146	78.0	102.0	...	68.5	52.5	128
144	77.5	101.5	86.0	68.0	51.5	126
142	77.0	101.0	...	67.5	51.0	124
140	76.0	100.5	85.5	67.0	50.0	122
138	75.0	100.0	...	66.5	49.0	121
136	74.5	99.5	85.0	66.0	48.0	120
134	73.5	99.0	...	65.5	47.5	118
132	73.0	98.5	84.5	65.0	46.5	116
130	72.0	98.0	84.0	64.5	45.5	114
128	71.0	97.5	...	63.5	45.0	113
126	70.0	97.0	83.5	63.0	44.0	112
124	69.0	96.5	...	62.5	43.0	110
122	68.0	96.0	83.0	62.0	42.0	108
120	67.0	95.5	...	61.0	41.0	106
118	66.0	95.0	82.5	60.5	40.0	105
116	65.0	94.5	82.0	60.0	39.0	103
114	64.0	94.0	81.5	59.5	38.0	101
112	63.0	93.0	81.0	58.5	37.0	99
110	62.0	92.6	80.5	58.0	35.5	97
108	61.0	92.0	...	57.0	34.5	95
106	59.5	91.2	80.0	56.0	33.0	94
104	58.0	90.5	79.5	55.0	32.0	92
102	57.0	89.8	79.0	54.5	30.5	90
100	56.0	89.0	78.5	53.5	29.5	88
98	54.0	88.0	78.0	52.5	28.0	86
96	53.0	87.2	77.5	51.5	26.5	85
94	51.0	86.3	77.0	50.5	24.5	83
92	49.5	85.4	76.5	49.0	23.0	82
90	47.5	84.4	75.5	48.0	21.0	80
88	46.0	83.5	75.0	47.0	19.0	79
86	44.0	82.3	74.5	45.5	17.0	77
84	42.0	81.2	73.5	44.0	14.5	76

(continued)

Table 1 (continued)

	Rockwell hardness No.		Rockwell superficial hardness No.			
Vickers hardness No., HV	B scale, 100 kgf, 1/16 in. (1.588 mm) ball, HRF	F scale, 60 kgf, 1/16 in. (1.588 mm) ball, HRF	15T scale, 15 kgf, 1/16 in. (1.588 mm) ball, HR15T	30T scale, 30 kgf, 1/16 in. (1.588 mm) ball, HR30T	45T scale, 45 kgf, 1/16 in. (1.588 mm) ball, HR45T	Brinell hardness No., 500 kgf, 10 mm ball, HBS
82	40.0	80.0	73.0	43.0	12.5	74
80	37.5	78.6	72.0	41.0	10.0	72
78	35.0	77.4	71.5	39.5	7.5	70
76	32.5	76.0	70.5	38.0	4.5	68
74	30.0	74.8	70.0	36.0	1.0	66
72	27.5	73.2	69.0	34.0	...	64
70	24.5	71.8	68.0	32.0	...	63
68	21.5	70.0	67.0	30.0	...	62
66	18.5	68.5	66.0	28.0	...	61
64	15.5	66.8	65.0	25.5	...	59
62	12.5	65.0	63.5	23.0	...	57
60	10.0	62.5	62.5	...	...	55
58	...	61.0	61.0	18.0	...	53
56	...	58.8	60.0	15.0	...	52
54	...	56.5	58.5	12.0	...	50
52	...	53.5	57.0	...	...	48
50	...	50.5	55.5	...	...	47
49	...	49.0	54.5	...	...	46
48	...	47.0	53.5	...	...	45
47	...	45.0	...	...	...	44
46	...	43.0	...	...	...	43
45	...	40.0	...	...	...	42

Source: "Standard Hardness Conversion Tables for Metals (Relationship among Brinell Hardness, Vickers Hardness, Rockwell Hardness, Rockwell Superficial Hardness, Knoop Hardness, and Scleroscope Hardness)," E 140, *Annual Book of ASTM Standards,* ASTM