

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 non-magnetic. 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 C1xxxx to C7xxxx, and cast alloys are designated C8xxxx to C9xxxx. 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 ($0.017241 \mu\Omega \cdot \text{m}$) 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.

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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 (lead 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

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

Element	Solubility at 293 K, wt%	Resistivity increase per 1 wt% addition, $\mu\Omega \cdot \text{cm}$
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

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.

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

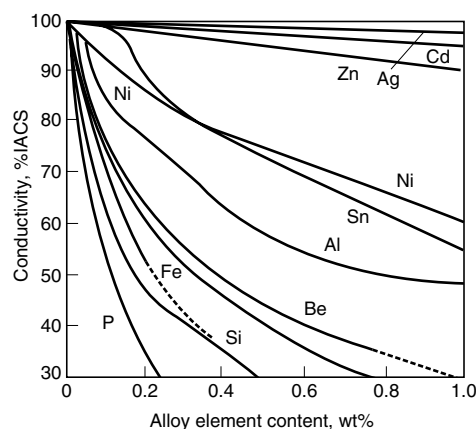


Fig. 1 Effect of alloying elements on the conductivity of oxygen-free high-conductivity copper

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 oper-

ations reintroduce stresses and resensitize the parts to SCC.

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.

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%

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

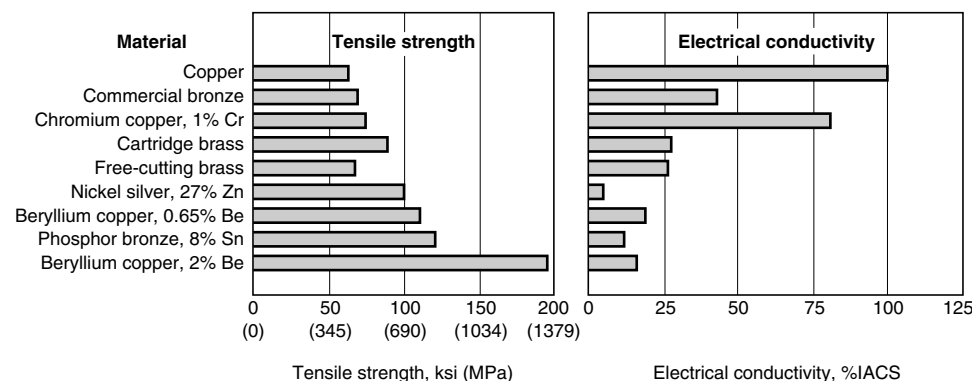


Fig. 2 Relationship between strength and electrical conductivity for copper and copper alloys

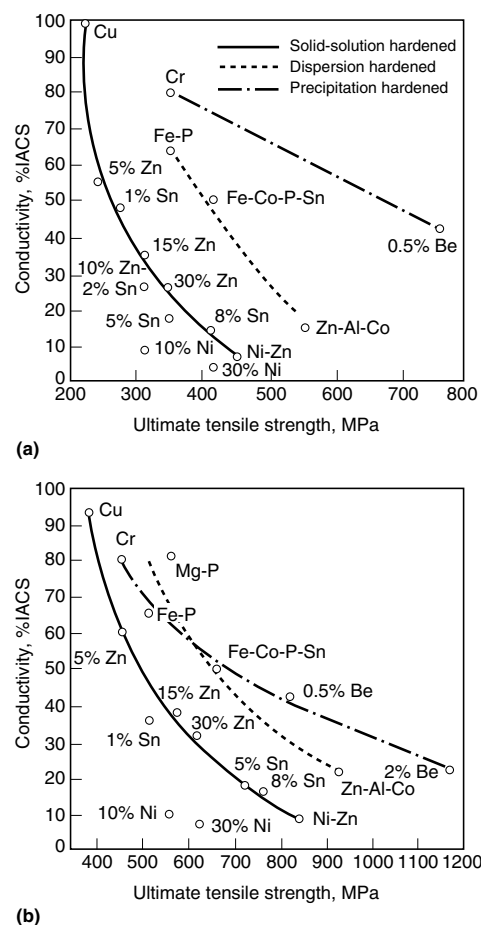


Fig. 3 Electrical conductivity as a function of tensile strength for (a) annealed and (b) 60% cold-reduced copper alloy strip

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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 of 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 (C36000) 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.

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.

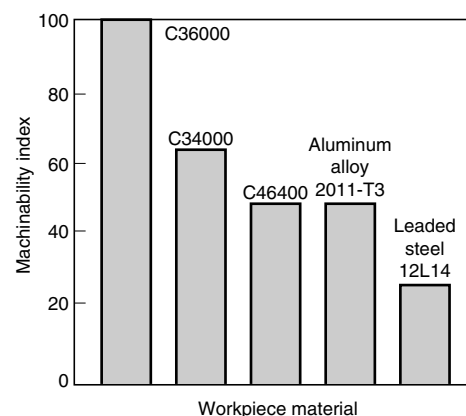


Fig. 4 Machinability ratings for copper alloys, aluminum alloy 2011, and a free-machining steel. The theoretical maximum machining rate for free-cutting brass (C36000) is five times higher than that of leaded low-carbon free-machining steel AISI 12L14 (UNS G12144). In this figure, production rates (determined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

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

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-lead bronzes 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-lead brass* and *high-lead brass*.

extra-high-lead 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

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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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