COPPER ALLOYS, WROUGHT

1. Introduction

Among the metals of commercial importance, copper [7440-50-8] (qv) and its alloys are surpassed only by iron (qv) and aluminum (see ALUMINUM AND ALUMINUM ALLOYS) in worldwide consumption. Typically, copper is alloyed with other elements to provide a broad range of mechanical, physical, and chemical properties that account for widespread use. The principal characteristics of copper alloys are moderate-to-high electrical and thermal conductivities combined with good corrosion resistance, good strength, good formability, unique decorative appearance, and moderate cost (see also CORROSION AND CORROSION CONTROL). Most copper alloys are readily hot and cold formed, joined (soldered, brazed, and welded), and plated (see also SOLDERS AND BRAZING FILLER METALS; WELDING).

Chief consumers of copper and copper alloys are the building construction industry for electrical wire, tubing, builder's hardware, plumbing, and sheathing (see BUILDING MATERIALS, SURVEY); electrical and electronic products for motors, connectors, printed circuit copper foil, and leadframes (see ELECTRICAL CONNECTORS; ELECTRONIC MATERIALS; INTEGRATED CIRCUITS); and the transportation (qv) sector for radiators and wiring harnesses. Other industries include ordnance, power utilities, coinage, decorative hardware, musical instruments and flatware. (see EXPLOSIVES AND PROPELLANTS; POWER GENERATION).

2. Alloy Designations

Copper is primarily alloyed to increase strength. Such alloying can, however, strongly affect other properties; eg electrical and thermal conductivities, corrosion resistance, formability, and color. Elements typically added to copper, both singly and in combination are zinc, tin, nickel, iron, aluminum, silicon, silver, chromium, titanium, and beryllium.

Copper and its alloys are classified in the United States by composition according to the Unified Numbering System (UNS) for metals and alloys. Wrought materials are assigned five-digit numerical designations which range from C10100 through C79999, but only the first three or sometimes four numerals are used for brevity. The designations of wrought copper alloys are given in Table 1. Designations that start with numeral 8 or 9 are reserved for cast alloys (see COPPER ALLOYS, CAST COPPER ALLOYS) (1).

Under the UNS designation system, coppers that contain no or very small amounts of intentional alloy additives (including Ag, P, Zr, Mg, Sn), ie, 99.3 wt% minimum copper, are distinguished from the dilute copper alloys. These latter are called the high coppers and contain a minimum of 96 wt% copper. Alloys of copper are grouped according to the principal elemental addition, such as zinc, tin, nickel, aluminum, silicon, or combinations of these. Important alloys within these groupings and the associated nominal compositions are listed in Table 2.

Table 1. **UNS Designation for Copper and Copper Alloy Families**

Alloy group	UNS designation	Principal alloy elements
coppers[a]	C10100–C15999	Ag, As, Mg, P, Zr
high coppers[b]	C16000–C19999	Cd, Be, Cr, Fe, Ni, P, Mg, Co
brasses	C20500–C28580	Zn
leaded brasses	C31200–C38590	Zn—Pb
tin brasses	C40400–C486	Sn, Zn
phosphor bronzes	C50100–C52400	Sn—P
leaded bronzes	C53200–C54800	Sn—P—Pb
phosphorus–silver	C55180–C55284	P, Ag—P
aluminum bronze	C60600–C64400	Al, Fe, Ni, Co, Si
silicon bronze	C64700–C66100	Si, Sn
modified brass	C662–C69950	Zn, Al, Si, Mn
cupronickels	C70100–C72950	Ni, Fe, Sn
nickel silvers	C73150–C77600	Ni—Zn
leaded nickel silvers	C78200–C79900	Ni—Zn—Pb

[a] Contains a minimum of 99.3 wt% copper.

[b] Contains a minimum of 96 wt% copper.

Table 2. **Nominal Compositions of Industrially Important Copper Alloys**

Alloy group	UNS designation	Elemental composition, wt%[a]
coppers (99.3 min Cu)	C101[b]	
	C107	0.085% min Ag
	C110[c]	
	C122	0.02 P
	C150,C151	0.05–0.2 Zr
	C155	0.11 Mg,0.06 Ag,0.06 P
	C1572	0.4 Al_2O_3
high coppers (96 min Cu)	C172	1.9 Be, 0.2 Co
	C17410	0.33Be,0.5 Co
	C17460	0.33 Be, 1.2 Ni
	C1751	0.3 Be, 1.7 Ni
	C182	0.9 Cr
	C190	1.1 Ni, 0.20 P
	C194	2.4 Fe, 0.03 P, 0.12 Zn
	C197	0.6 Fe, 0.2 P, 0.05 Mg
zinc brass	C260	30 Zn
leaded brass	C360	35 Zn, 3 Pb
tin brass	C425	9.5 Zn, 2.0 Sn
phosphor bronze	C510	5.0 Sn, 0.1 P
aluminum bronze	C638	2.8 Al, 1.8 Si
	C651	1.5 Si
silicon bronze	C654	3.0 Si, 1.5 Sn, 0.1 Cr
	C655	3.3 Si, 0.9 Mn
modified Cu—Zn	C688	22.7 Zn, 3.4 Al, 0.4 Co
cupronickel	C7025	3 Ni, 0.65 Si, 0.1 Mg
	C7026	2 Ni–0.5 Si
	C706	10 Ni, 1.4 Fe
	C725	9.5 Ni, 2.3 Sn
	C729	15 Ni, 8 Sn
nickel silver	C752	17 Zn, 18 Ni

[a] Remaining percentage is copper.
[b] Contains a maximum of 0.01 wt% impurities.
[c] Contains a maximum of 0.10 wt% impurities, excluding silver.

Most wrought alloys are provided in conditions that have been strengthened by various amounts of cold work or heat treatment. Cold worked tempers are the result of cold rolling or drawing by prescribed amounts of plastic deformation from the annealed condition. Alloys that respond to strengthening by heat treatment are referred to as precipitation or age hardenable. Cold worked conditions can also be thermally treated at relatively low temperatures (stress relief annealed) to produce a slight decrease in strength to benefit other properties, such as corrosion resistance, formability, and stress relaxation.

2.1. Temper. The system for designating material condition, whether the product form is strip, rod, or wire, is defined in ASTM Recommended Practice B601 (1). The ASTM system uses an alpha-numeric code for each of the standard temper designations. This system replaces the historical terminology of one-half hard, hard, spring, etc. Table 3 summarizes temper designations. Commercially, wrought tempers are specified by a narrow range of tensile properties for any given alloy.

Table 3. **Copper and Copper Alloy Temper Designations**

Condition	Historical	ASTM B601(1)
annealed	soft annealed	060
cold worked	1/4 hard	H01
	1/2 hard	H02
	3/4 hard	H03
	hard	H04
	extra hard	H06
	spring	H08
	extra spring	H10
	super spring	H14
cold worked and relief annealed	1/2 hard/RA	HR02
	hard/RA	HR04
	spring/RA	HR08
precipitation hardened alloys		
solution treated	A	TB00
solution treated + rolled	1/2 H	TD02
	H	TD04
	T002 + aged	TH04
mill hardened	AM,AT	TM00
	1/2 HM,1/2 HT	TM02
	HM, HT	TM04
	XHM	TM06
	XHMS	TM08

3. Product Forms and Processing

The output from brass mills in the United States is split nearly equally between copper and the alloys of copper. Copper and dilute copper alloy wrought products are made using electrically refined copper so as to maintain low impurity content. Copper alloys are commonly made from either refined copper plus elemental additions or from recycled alloy scrap. Copper alloys can be readily manufactured from remelted scrap while maintaining low levels of impurities. A greater proportion of the copper alloys used as engineering materials are made from recycled materials than most other commercial materials.

Generally, processing of wrought copper alloys will include melting, alloying, casting, homogenization, hot working, cold working, and annealing, with the latter two steps being repeated to achieve the desired product dimensions and property combinations. Wrought alloy product forms are varied and include plate, sheet, strip and foil, round and special cross-section bars, rod, and wire. Plate includes flat products that are >5 mm (0.2 in.) in thickness. The generally accepted difference between rod and wire is that the former is provided in straight lengths, as intended for screw machining of parts. Wire is usually a coiled product for redrawing to a smaller diameter or for cold heading. Diameter is not a distinguishing feature between rod and wire except for C110 electrical wire that is provided as 7.9 mm (0.312 in.) diameter rod intended for subsequent processing to wire.

3.1. Sheet and Strip.

The manufacture of wrought copper materials starts with either semicontinuously cast slabs that are hot rolled, or cast plate that is thin enough, near 13 mm (0.5 in.), to be cold rolled directly. The surfaces of both hot rolled slabs and as-cast plate are milled to remove defects before proceeding to cold rolling and annealing operations. Spray casting and powder consolidation are alternative methods of producing feedstock for cold rolling and annealing.

Cold rolling is used to process to thinner gauges and to increase the strength of the finished product of copper and its alloys. A variety of mills, including four-high, tandem or reversing mills and cluster or Sendzimir, mills are used. On four-high mills, and especially on cluster mills, rolling forces on the work rolls are controlled to limit roll bending and thus ensure uniform thickness and flatness of the rolled product. Four-high mills are used for both in-process and finish rolling; cluster mills are most effectively used in the final rolling operation because of superior capability for maintaining tight control of thickness and shape. Cluster mills are also used for final rolling of foil as thin as 0.013 mm (0.0005 in.).

Strengthening by cold rolling is accompanied by decreased ductility. A softening heat treatment is needed when ductility is lowered to levels below that required for subsequent processing. Annealing, which is done at temperatures and for times sufficient to soften and recrystallize the cold worked material, can be either a batch or a continuous operations.

Batch (or bell) annealing is done within a sealed inner retort that contains a protective atmosphere. Continuous (strand or strip) annealing uses a furnace sealed at both ends to contain a protective atmosphere while permitting passage of the strip. Strand annealing can generally be carried out at strip thicknesses from 0.1 mm (0.004 in.) to 3.18 mm (0.125 in.).

Neutral or reducing atmospheres are used to protect copper alloys when being annealed. These atmospheres range from nitrogen to mixtures of nitrogen and hydrogen derived from cracked ammonia (qv) to which nitrogen is often added. Products of combustion from natural gas that has been partially burned so as to contain the reducing gases, carbon monoxide and hydrogen, may be used as well (see GAS, NATURAL). Strip is usually acid cleaned following annealing.

The final processing operation for strip may be tension leveling for the purpose of improving flatness across the width and removing curvature (coil set). Strip is passed through a set of several intermeshed rolls, in serpentine fashion, to mildly deform the material in bending while under tension. The amount of bending strain is varied locally across the width of sheet to balance more highly strained wavy edges or center-of-width buckles and thereby remove these undesirable features.

Most sheet is slit to various narrow widths before shipping for use in stamping presses and other applications. Slitting is done by opposing rotary disk knives that intersect the pass line of strip while it is moving at high line speed. The finished, slit product is shipped as flat pancake coils or is transversely wound on wide spools.

3.2. Rod and Tubular Products.

Rod products having round and special cross-sections are hot extruded from cast billets. Seamless tubing is either hot extruded over a mandrel held in position within the die orifice, or is formed by rotary piercing of heated billets. Tubes of both round and other cross-sections can also be made at high line speed by high frequency induction welding of strip that is formed in-line before entering the welding head. Weld beads are scarfed from the internal and external surfaces, in-line with the welding operation. The tube is finally sized by cold drawing or tube reducing operations. These operations also develop a cold worked temper in the final product. Cold drawing can be done using either a fixed or floating mandrel. Alternatively, tube reducing uses semicircular grooved dies that oscillate along the tube over an internal mandrel. The latter method is capable of providing better tolerance control of diameter, wall thickness, and concentricity relative to cold drawing.

3.3. Wire. Most copper wire is cold drawn directly from continuously cast electrolytic cathode feedstock. Earlier, cast bars were hot worked to wire rods. By eliminating the hot working step, the continuous casting process offers higher quality, lower operating cost and longer product lengths. Alloy wires, on the other hand, are hot rolled from cast bars. Semifinished copper and copper alloy wire rod is subsequently processed through drawing, annealing, and acid cleaning operations to the finished condition. A common practice, especially for very fine wire products, is die shaving of rod at an intermediate processing step to facilitate processing and provide a high quality product. In addition to round wire, square, flat or shaped wire is also produced.

3.4. General Processing Behavior. Copper is readily strengthened by the cold working processes used to shape or form the material into the desired shape or thickness. Repeated cycles of working and annealing from the hot rolled or cast strip condition are typical for most copper alloys. Solid solution and dispersion strengthened alloys are usually annealed to their softest condition before the final working step. This fully annealed condition product can be used, without further cold work, to fabricate items which require the maximum ductility. More commonly, this product is cold worked to develop the desired balance of strength and ductility.

The effect of cold working the fully annealed condition by cold rolling of sheet on the yield strength, at 0.2% offset strain, and tensile strength of copper sheet is shown in Figure 1. As is typical for many alloys, the rolling curve exhibits an initial stage of rapid hardening followed by a lower hardening rate for continued reduction in thickness. The initial work hardening results from the generation and entanglement of dislocations in the initial, relatively defect-free, annealed grains. Dislocation generation and motion permit the initially equiaxed grains to elongate in the direction of the working operation.

Precipitation hardening is another means of increasing the strength of certain copper alloys, which involves heat treating the material to produce a fine array of very small particles in the alloy. These particles restrict dislocation motion and thus strengthen the material. Strengthening can also be accomplished via a combination of second phase precipitation, grain size, and cold work.

Figure 1 also shows the decrease in tensile elongation (a common measure of ductility) that accompanies the strength increase with cold working. Whereas these particular rolling curves include up to 70% reduction in thickness, pure copper is capable of being rolled much further without fracturing.

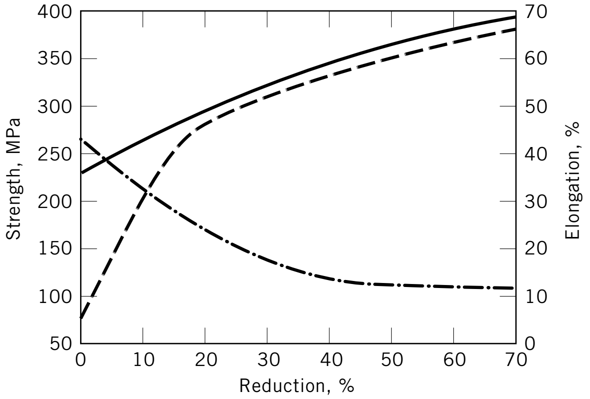

Fig. 1. The effect of cold rolling upon the tensile properties of unalloyed copper (C110): (—) represents tensile strength; (– – –), the 0.2% yield strength; and (–•–) the tensile elongation. To convert MPa to psi, multiply by 145.

Elements that can dissolve in copper, such as zinc, tin, and nickel, eg, increase annealed strength by varying amounts depending on the element and the quantity in solution. The effect of selected solution hardening elements on tensile properties of annealed copper alloys is illustrated by the data in Table 4, where the yield strength is the stress at 0.2% offset strain in a tensile test.

Solid solution hardened alloys also show different cold work hardening response relative to pure copper and each other as illustrated in Figure 2. These differences originate from the effects that the dissolved atom has on microplastic processes that occur during cold working. Finer grain sizes generally translate into stronger materials. Note that for alloy C260, finer grain size has higher strength at corresponding cold reduction. A higher quality, smooth surface that requires no buffing after forming operations is a further benefit from a fine grained microstructure.

The annealing response of cold worked copper is illustrated by Figure 3 in terms of changes in tensile properties determined at room temperature after an

Table 4. **Annealed Tensile Properties of Solution Strengthened Copper Alloys**

Alloy	Principal alloying element, %	0.2% Yield strength, MPa[a]	Tensile strength, MPa[a]	Elongation in 50 mm, %
C110		76	235	45
C220	10 Zn	83	260	45
C260	30 Zn	150	365	54
C425	10 Zn + 2 Sn	125	340	46
C510	5 Sn + 0.1 P	145	345	52
C521	8 Sn + 0.1 P	165	415	63
C706	10 Ni + 1.4 Fe	110	365	35
C752	18 Ni + 17 Zn	205	415	32

[a] To convert MPa to psi, multiply by 145.

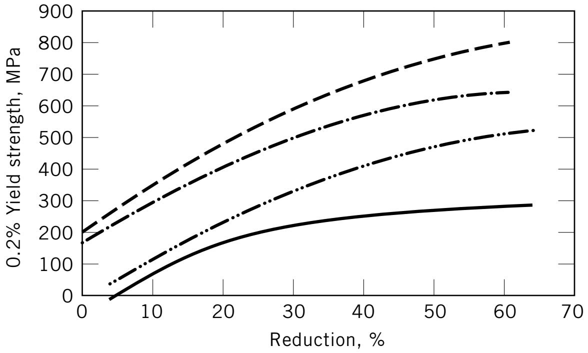

Fig. 2. Comparison of alloy cold rolling behaviors: (—) represents unalloyed copper (C110) having a grain size of 25 µm; (–••–) and (–•–), copper–30% zinc (C260) of 50- and 15-µm grain size, respectively; and (– – –), copper–8% tin (C521) having a 15-µm grain size. To convert MPa to psi, multiply by 145.

elevated temperature anneal for 1 h. Also important is the grain size obtained from each annealing temperature because this microstructural characteristic influences properties. In general, more uniform and finer grain size is promoted by annealing at a lower temperature, which is made possible by increasing the amount of cold work before annealing. Many products are offered in the fully soft or annealed condition to maximize available formability.

The annealing curves for several copper alloys are compared to copper in Figure 4. As for cold working, solute additions affect the annealing response by interaction with microplastic processes that cause softening via dislocation and subgrain elimination during the anneal.

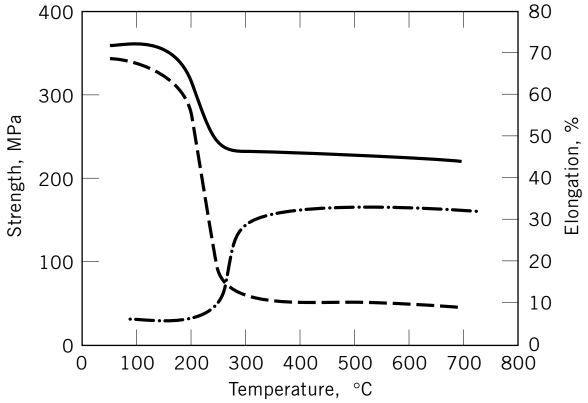

Fig. 3. Changes in tensile properties of cold rolled copper (C110), after 50% reduction in thickness, that attend annealing for one hour at each of the temperatures shown: (—) represents tensile strength; (– – –), the 0.2% yield strength; and (–•–), the tensile elongation. To convert MPa to psi, multiply by 145.

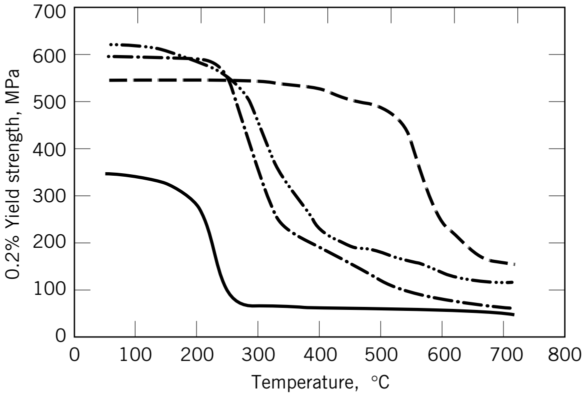

Fig. 4. Comparison of the annealing response in terms of yield strength of cold rolled (—) copper (C110) and cold rolled alloys; (–•–) copper–30% zinc (C260), (–••–) copper–5% tin (C510), and (– – –) copper–10% nickel (C706). The condition prior to annealing was after 50% cold reduction in thickness from the soft condition. The time of annealing at each of the temperatures is 1 h. To convert MPa to psi, multiply by 145.

4. Alloying for Strengthening

Elements added to pure copper can remain in solid solution in the copper or can form second phases separate from the copper, which forms the bulk of the alloy. Copper alloys where the principal elemental additions remain in solution comprise a group we will refer to as “solid solution alloys”. Those copper alloys whose principal elemental additions cause discrete second phases to form during processing comprise groups referred to as “dispersed phase alloys” or “precipitation hardening alloys”. Phase diagrams that show limits of solid solubility and equilibrium phases that form in binary and ternary combinations with copper are found in the literature (2,3).

4.1. Solid Solution Alloys. Copper dissolves other elements to varying degrees to produce a single-phase alloy that is strengthened relative to unalloyed copper. The contribution to strengthening from an element depends on the amount in solution and by its particular physical characteristics such as atom size and valency. Tin, silicon, and aluminum show the highest strengthening efficiency of the common solute additives, whereas nickel and zinc are the least efficient (4,5). Many alloys are ternary combinations of these elements. The limiting factor in their alloy range is the extent to which these elements, either singly or in combination, remain dissolved in the copper parent during processing.

Alloys containing zinc, tin, aluminum, and nickel represent most of the commercial alloys, namely, the brasses, phosphor bronzes, cupronickels and nickel silvers (see Tables 1 and 2). The tensile properties of selected solid solution strengthened alloys, in the annealed condition, are listed in Table 4 (6). These alloys generally provide good formability, together with varying degrees of corrosion and oxidation resistance. Alloying for solution strengthening is accompanied by lowered electrical conductivity. Because of high alloy content, these solution strengthened alloys tend to have conductivities that are typically less than one-half that of unalloyed copper.

4.2. Dispersed Phase Alloys. The presence of finely dispersed second-phase particles in copper alloys contributes to strength, by refining the grain size and increasing the amount of hardening due to cold working. These phases are developed in many commercially important copper alloys in several ways. A dispersion of fine particles can be incorporated into the alloy through thermomechanical processing where the alloy content exceeds the solid-state solubility limit, causing precipitation and coarsening of the excess solute as dispersed second-phase particles. These dispersed phases enhance the work hardening response relative to unalloyed copper to produce high strength while maintaining reasonably good conductivity.

One example of this kind of alloy is C194, where an anneal is used to form dispersions of iron particles. Solid solution alloys based on Cu–Zn and Cu–Al have also been modified by additions that react to form dispersions of intermetallic phases. Addition of aluminum and cobalt to a zinc-containing alloy (C688) and cobalt and silicon to an aluminum-containing alloy (C638) are two examples. Fine-grain sizes below ten μm and smaller amounts of cold work to develop strength combine to produce highly formable alloys that offer the highest strengths available from nonage-hardenable alloys.

Dispersed phases can also be produced by separation from the melt during casting. Examples include iron phosphides, as in C194, and cobalt or nickel beryllides, as in C172 and C17410, respectively.

Powder metallurgy is used to incorporate second phases into copper (see METALLURGY, POWDER). An example is the manufacture of oxide dispersed alloys like C15720. Aluminum oxide powder, that otherwise does not dissolve in copper, is incorporated in C15720 by mixing powders of copper, copper oxide particles, and a dilute copper–aluminum alloy. Hot extrusion is used to consolidate the mixture. Subsequent heat treatment reduces the copper oxide and the resultant oxygen diffuses into the alloy powder where it reacts with the dissolved aluminum to form uniformly dispersed sub micrometer-sized aluminum oxide particles. It is this ultrafine oxide that is principally responsible for the alloy's notable resistance to softening during subsequent high temperature exposure.

4.3. Precipitation (Age) Hardening Alloys. Only a few copper alloy systems are capable of responding to precipitation or age hardening (7). Those that do have the constitutional characteristics of being single-phase (solid solution) at elevated temperatures and are able to develop into two or more phases at lower temperatures that are capable of resisting plastic deformation. The copper alloy systems of commercial importance are based on individual additions of Be, Cr, Ti, Zr, or Ni + X, where X = Al, Sn, Si, or P.

Processing involves heat treating the alloys at a sufficiently high temperature to put alloying elements into solution, followed by rapid cooling to near room temperature to retain this solid solution. A second lower temperature aging treatment to form the hardening phase particles is the final step. Cold work may be introduced between the two heat treatments to promote aging response and also add to final strength.

The preferred precipitation structure is one with uniformly dispersed particles within the grains of the alloy. Alloy composition and thermal treatments are chosen to achieve this structure through control of intermediate, metastable precipitate phases. The equilibrium, thermodynamically stable precipitate phases are generally coarse and provide little strengthening. When the latter are formed at grain boundaries, ductility of the material is significantly decreased. This grain boundary precipitation is avoided for strip that is intended to be formed into parts after having been previously hardened by the mill.

4.4. Special Addition Alloys. The most notable of the special additives to copper alloys are those added to enhance machinability. Lead, tellurium, selenium, and sulfur are within this group of additives. Because of increasing concern over lead toxicity, interest has centered on use of bismuth, which is nearly as effective as lead for improving machinability. The alloys that contain such additives are limited because of the difficulty they cause to hot and cold working. High zinc brasses such as C360, which undergo a change in crystal structure at elevated temperature, are favored because of the ability to accommodate lead and bismuth additions in processing. Whereas lead and bismuth are added to both copper and copper alloys, tellurium and selenium are added separately to copper (C145 and C147) to form copper-telluride and -selenide particles to enhance machinability.

Other special additions are used to deoxidize copper and prevent the formation of copper oxide. Such alloys may be preferred in applications where embrittlement by hydrogen through reaction with internally dispersed copper oxide particles is a concern, such as in C110. The most common deoxidized copper is C122, in which phosphorus reacts with copper oxide to form phosphorus pentoxide, which is removed as a slag while the copper is molten.

Many elemental additions to copper for strengthening and other properties also deoxidize the alloy. A side benefit of such additions is elimination of susceptibility to hydrogen embrittlement. Such deoxidizing additions include beryllium, aluminum, silicon, chromium, zirconium, and magnesium.

5. Properties

5.1. Strength. Table 5 illustrates the range of property combinations available in copper alloys by listing properties of selected commercially important alloys. The principal source of strengthening and the individual product forms in which each alloy is usually available are also identified.

Table 6 illustrates the increase in strength and the accompanying decrease in electrical conductivity that derives from alloying of copper. This trend is clearly apparent among solid solution strengthened alloys, namely those that contain zinc, tin, nickel, and zinc plus nickel as their principal alloying constituents. Notable exceptions to this trend are precipitation hardening alloys where the precipitating phases remove elements from solid solution leaving a leaner, higher conductivity matrix; eg, C1751, C182, and C7025. For the latter group, strength–conductivity combinations not possible with solid solution alloys are achieved.

Other properties are just as important as strength and conductivity for alloy selection. For example, the cupronickels have about the same strength as do copper–zinc brasses, and also have much lower conductivity. However, the

Table 5. **Properties of Copper Alloys**

UNS designation	Alloy type[a]	Product forms[b]	Electrical conductivity, %IACS[c]	Modulus of elasticity, GPa[d]	Temper	Tensile strength, MPa[e]	Yield strength (0.2% offset), MPa[e]	Elongation, %
C110	pure	S, R, W, T	100	117	060	221	59	35
C151	D	S, R, W	95	117	H04	330	317	4
C1572	D	R, W	89	105	CW 97%	605	580	5
C172	P	S, R, W, T	20	128	TM04	980	860	12
C1751	P	S, R	45	130	AT	845	740	12
C182	P	S, R, W	80	130	TH04	460	405	14
C194	D	S	65	117	H08	503	482	2
C260	S	S, R, W, T	28	110	H08	662	600	2
C360	SA	S, R	26	97	H02	470	360	18
C425	S	S	28	110	H04	524	503	8
C510	S	S, R, W	15	110	H08	696	682	2
C638	D	S	10	117	H04	834	750	5
C688	D	S	18	117	H08	880	800	2
C655	S	S, R, W	7	105	H04	650	400	8
C706	S	S, R, T	9	124	H04	530	517	1
C7025	P	S	40	130	TM03	690	655	5
C725	S	S, R, W	11	138	H08	641	620	1
C729	P	S, W	7	127	TM04	860	790	15
C752	S	S, R, W	6	124	H08	655	641	1

[a] S is solution strengthened; D, dispersed phase; P, precipitation strengthened; SA, special addition.

[b] S is sheet and strip; R, rod and shapes; T, tube; and W, wire.

[c] IACS = International Annealed Copper Standard. Pure copper has a value of 100.

[d] To convert GPa to psi, multiply by 145,000.

[e] To convert MPa to psi, multiply by 145.

Table 6. **Electrical Conductivity versus Strength Among Copper Alloys**

UNS designation	Principal alloy element, %	Conductivity, annealed, %IACS	0.2% Yield strength hard temper, MPa[a]
C110		100	310
C210	5 Zn	56	365
C230	15 Zn	37	420
C260	30 Zn	28	495
C505	1.25 Sn	48	425
C510	5 Sn	15	560
C521	8 Sn	13	590
C706	10 Ni	9	520
C715	30 Ni	4	540
C1751	0.4 Be, 1.8 Ni	45	740
C182	1 Cr	80	400
C7025	3 Ni, 0.65 Si, 0.15 Mg	40	690

[a] To convert MPa to psi, multiply by 145.

corrosion resistance of the cupronickels far exceeds that of brass and is worth the higher cost if needed in the application. Similar trade-offs exist between these properties and formability, softening resistance, and other properties.

5.2. Electrical-Thermal Conductivities. Electrical conductivities of alloys (Tables 5 and 6) are often expressed as a percentage relative to an International Annealed Copper Standard (IACS), ie, units of % IACS, where the value of 100% IACS is assigned to pure copper having a measured resistivity value at room temperature of $17.24\text{n}\,\Omega\cdot\text{m}$. The measurement of resistivity and its conversion to % IACS is covered under ASTM B193 (8).

Copper has a high electrical conductivity that is second only to that of silver. The conductivity of silver in % IACS units is 108; gold, 73; aluminum, 64; and iron, 18. Wrought copper having a conductivity near 102% IACS is not uncommon because of improvements in refining practices since the standard was first established.

Electrical conductivity of copper is affected by temperature, alloy additions and impurities, and cold work (9–12). The electrical conductivity of annealed copper falls from 100% IACS at room temperature to 65% IACS at 150°C. Alloying invariably decreases conductivity. Cold work also decreases electrical conductivity as more and more dislocation and microstructural defects are incorporated into the annealed grains. These defects interfere with the passage of conduction electrons. Conductivity decreases by about 3–5% IACS for pure copper when cold worked 75% reduction in area. The conductivity of alloys is also affected to about the same degree by cold work.

Copper and its alloys also have relatively good thermal conductivity, which accounts for their application where heat removal is important, such as for heat sinks, heat exchanger tubes and electronic packaging (see HEAT EXCHANGE TECHNOLOGY, MICROELECTRONIC PACKAGING). Thermal conductivity and electrical conductivity depend similarly on composition primarily because the conduction electrons carry most of the thermal energy.

To a good approximation, thermal conductivity at room temperature is linearly related to electrical conductivity through the Wiedemann-Franz rule. This

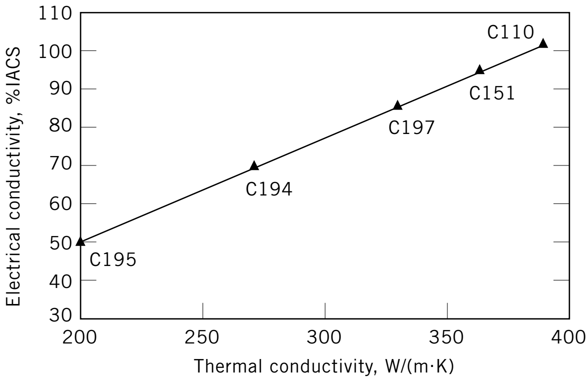

Fig. 5. The Wiedemann-Franz relationship at 20°C between electrical and thermal conductivities of copper alloys having moderate to high conductivities.

relationship is dependent on temperature, however, because the temperature variations of the thermal and the electrical conductivities are not the same. At temperatures above room temperature, thermal conductivity of pure copper decreases more slowly than does electrical conductivity. For many copper alloys the thermal conductivity increases, whereas electrical conductivity decreases with temperature above ambient. The relationship at room temperature between thermal and electrical conductivity for moderate to high conductivity alloys is illustrated in Figure 5.

6. Formability

Copper and most of the wrought alloys are readily formed by bending, drawing, upset forging, stamping, and coining (13–15). The maximum formability condition is the fully soft or annealed condition. When additional strength or hardness is desired in the final part, the forming step is done starting with a cold worked temper or the part is not annealed between forming steps. Cold forming operations always work-harden alloys and in many cases sufficient strength for the application is produced in the formed part.

A variety of tests have been established to indicate whether a specific forming operation can be safely accomplished without failure. Three of the most commonly used tests are bend testing around a mandrel, limiting draw ratio testing, and bulge height formability testing. Temper, strip thickness, grain size, crystallographic texture, and alloy composition are important variables in these tests. An alloy in the annealed temper that can be formed into a particular shape may not be able to be similarly formed starting from a work hardened temper.

6.1. Bending. The smallest radius over which strip of a particular alloy can be formed without failing is important in the selection of materials for a given application. The industry tests formability using samples cut from strip material to rank materials and thereby indicate whether a particular alloy/temper is suited for an application (15). Performance of the material during fabrication is, however, the best final judge of suitability.

In a bend test, a rectangular strip sample is formed around a die with a precisely machined edge of a known radius. The sample is formed by 90 or 180° about an axis in the plane of the sheet. The outer surface of the bend is inspected for cracking or unacceptably deep surface rumpling. The minimum bending radius (MBR) about which strip can be successfully formed depends on the strip thickness, *t*, and is reported with the test thickness specified or normalized with regard to thickness as MBR/*t*. Thus smaller MBR/*t* values indicate better formability, since tighter radii can be achieved for a given strip thickness.

Formability is not the same for all orientations of rolled temper alloy strip because of crystallographic texturing or mechanical fibering. The amount of directionality relative to the rolling direction depends on the amount of final cold reduction to temper, the intermediate processing history, and the specific alloy. For most alloys, bend formability is better around an axis that is perpendicular to the rolling direction relative to one that parallels the rolling direction. The industry has termed these goodway and badway bends, respectively. The terms longitudinal and transverse for goodway and badway bending, respectively, are also used. Longitudinal and transverse refers to the direction of material movement, relative to the rolling direction, during bending.

Examples of bend formability in alloys C510 and C725 are provided in Figure 6. These curves of bend formability illustrate several characteristics of most copper alloys. The minimum bending radius increases (formability decreases) with increasing strength (or temper). Also, the badway (transverse) bend formability degrades more rapidly with increasing strength than goodway formability, as shown for C510. The comparison alloy, C725, is more isotropic in formability for equivalent strength. This comparison illustrates that directional uniformity in properties is both alloy and process dependent. The minimum bend radii shown can be affected by special processing to produce better formability in some alloys, such as in phosphor bronze.

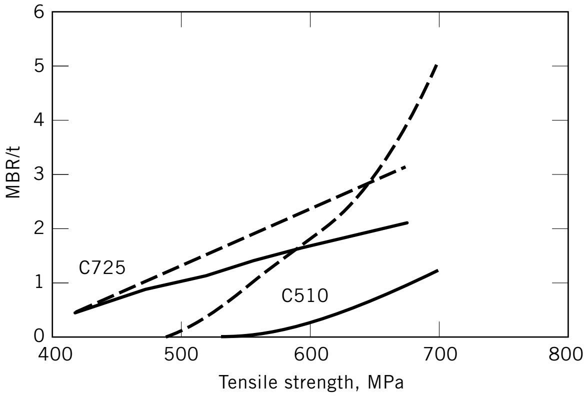

Fig. 6. The minimum radius over which alloy strip can be formed in bending without failure, normalized by thickness (MBR/t) for alloys C510 and C725 as affected by increasing strength (temper) where (—) represents orientation of bending relative to the rolling direction of strip, ie, goodway (longitudinal), and (– – –) badway (transverse). To convert MPa to psi, multiply by 145.

Precipitation strengthened alloys show the same general trend of degrading formability with increasing strength, albeit at high strength levels. The directionality of formability is often different for precipitation hardening alloys in the mill hardened temper with the badway bends being better than the good way bends. Bend formability of these alloys is often superior in the rolled temper condition; ie, before the aging treatment. Therefore, parts having the most demanding forming requirements can be first formed from rolled temper strip and then aged to obtain required strength. Disadvantages of this approach are possible distortion of formed parts during aging and the need for cleaning the parts after the aging anneal.

6.2. Drawing. Copper alloys are often deep drawn or cupped. A second drawing step is commonly applied to the more severe or “deeper drawn” shapes required for some applications, such as ballpoint pen cartridge cases.

The deep drawability of alloy sheet is often determined from its capability of being drawn into a cylindrical cup (13–18). In this test, a circular disk or blank is held in place with a hold down ring over the female die of a punch and die set. Lubricant used between the hold down ring and the workpiece allows the disk to slide under the high loads generated as the blank is forced by the punch through the die. The test is run using blanks of various radii until the largest radius is found that does not fracture during drawing; fracture usually occurs at the base of the cup. The results of this test are expressed in terms of a formability parameter called the limiting drawability ratio (LDR), which is defined as the ratio of the largest circular blank diameter to the punch diameter. This parameter is used to compare the relative drawability of various alloys or various conditions of the same alloy, with higher values indicating better performance.

This cupping test also provides a direct measure of anisotropy in the sheet resulting from crystallographic texture. Lobes, also called ears, that occur at the rim of formed cups are an indication of non-uniform thinning of the sheet. This effect is called planar anisotropy, the degree of which is measured from the average height of the ears. The location of earing with respect to the original rolling direction identifies the type of planar anisotropy. Earing is undesirable because it requires trimming and scrapping of metal from the rim area of the cup. Earing is directly related to the crystallographic texture and is reduced by control of texture through appropriate processing.

6.3. Plastic Strain Ratio. The plastic strain ratio(R) is the ratio of strains measured in the width and the thickness directions in tensile tests. This ratio characterizes the ability of materials to resist thinning during forming operations (13). In particular, high R-values indicate the ability of a sheet material to resist the thinning and failure at the base of a deep drawn cup. The plastic strain ratio is measured at 0, 45, and 90° relative to the rolling direction. These three plastic strain ratios R_0, R_{45}, and R_{90}, are combined to obtain the average strain ratio, called the R or the R value, and its variation in strain ratio, called ΔR:

$$\bar{R} = \frac{1}{4}(R_0 + 2\,R_{45} + R_{90})$$

$$\Delta R = \frac{1}{2}(R_0 - 2\,R_{45} + R_{90})$$

Much can be predicted from these parameters. Linear correlations have been established between the R value and the drawability parameter, LDR. Thus higher R values are associated with better deep drawability. ΔR, on the other hand, predicts the height and location of ears. For example, larger absolute values of ΔR predict higher ears during deep drawing cup shapes.

The sign of ΔR indicates the location of the individual ears with respect to the sheet rolling direction. For example, if ΔR is positive, the ears are located at 0 and 90° to the original rolling direction. This occurs when annealed copper has a pronounced cube crystallographic texture. When ΔR is negative, ears are at 45° to the rolling direction. This occurs when annealed fully recrystallized copper has a crystallographic texture that includes a significant component of the prior cold rolled texture. When annealed copper has no preferred crystallographic texture, called a random texture, ΔR is zero and there is no earing. But the random texture condition does not necessarily show the optimum R value, or drawability, that the material is capable of providing. The most desirable situation is for the ΔR parameter to be zero, predicting no plastic anisotropy, and the R value to be a maximum, predicting optimum drawability. In practice, it is difficult to achieve both situations with the same crystallographic texture. Over the years much work has been done with copper alloys and with brass in particular to develop mill processing schedules designed to provide sheet products having balanced textures that offer the best combination of high drawability and minimum earing.

6.4. Forming Limit Analysis.

The ductility of sheet and strip can be predicted from an analysis that produces a forming limit diagram (FLD), which defines critical plastic strains at fracture over a range of forming conditions. The FLD encompasses the simpler, but limited measures of ductility represented by the percentage elongation from tensile tests and the minimum bend radius from bend tests.

The forming limit analysis involves deforming a clamped sheet specimen over a hemispherical punch into a dome shape until failure. At fracture, the dome height and the dimensional changes in a pregridded circle mesh pattern on the surface of a specimen are recorded, and the local strain pattern is calculated. From this strain pattern, the FLD is drawn, as shown in Figure 7 for C260 (14). Various deformation paths, ie, pure drawing (circles narrowed), pure bending (circles elongated), pure stretching (circles expanded), and in-between combinations modes, are produced by varying the test specimen width and the applied lubricant (13,14,17). The strains at the fracture, which are obtained from the distortion in the gridded circles closest to the fracture, are used to construct the forming limit diagram.

The region above the forming limit curve represents combinations of strain that lead to failure. Conversely, the region below the curve represents plastic deformation strains that the sheet material can withstand without failure. Pure drawing corresponds to a combination of positive and negative strain to the left side of the diagram. Pure biaxial stretching (both strains are positive), such as forming a bulge in a flat strip, is to the right side of the diagram. The case of bending is in between with strain equal to zero in one direction.

A second diagram, the limiting dome height (LDH) diagram, is also available from this analysis. The LDH diagram defines the limiting dome height

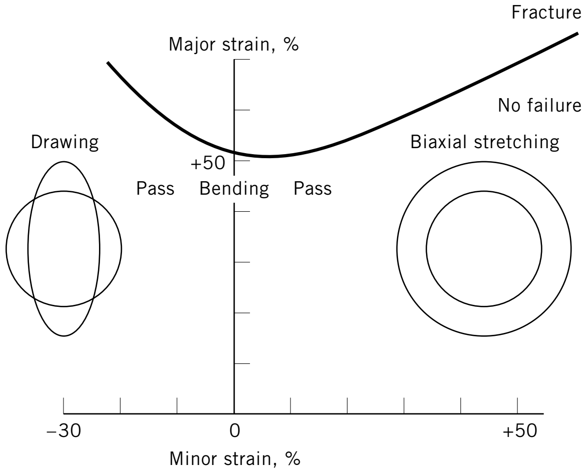

Fig. 7. The forming limit diagram (FLD) for C260−061 (annealed) showing limits to forming by various degrees of drawing (left of the origin), biaxial stretching (right of the origin), and pure bending (at the origin). Failure occurs at combinations of strains above the curve (14).

obtainable for these various forming modes and as such is a measure of the overall ductility (14).

6.5. Springback. During most kinds of cold-forming operations, regardless of material, elastic springback is encountered that can affect part dimensions (13). After metal is plastically deformed, elastic recovery occurs in the direction opposite to that of the plastic forming. The amount of springback can be predicted for simple bending, but prediction is more difficult for complicated shapes because plastic deformation is seldom homogeneous or uniform throughout formed parts.

A bending springback test is performed by bending a flat strip to a predetermined angle, A_0, which is the angle of the die around which the strip is bent. The strip is then released and the included angle, A_1, of the strip is measured. The springback function, A_0/A_1 shown in Figure 8, is a guideline measure of springback. The angle to which the strip was initially formed by the tooling is, A_0, may be 90° and thus the angle of bend that remains after forming, as A_1 in this index would be 90° or greater. The value of 1.0 represents no springback and increasing springback is indicated by decreasing values of this parameter. It is important to note that tests should be done at radii large enough to avoid cracking which would affect the amount of springback.

Manufacturers of copper alloy sheet and strip have developed springback data using this test as a guide for selecting alloys and tempers. The test is best used to compare springback among various tempers of an alloy or among different alloys. By allowing for springback, forming tools and dies can be designed to ensure that dimensional specifications are met in formed parts.

The degree of springback is higher for higher temper strip, for thinner strip, for larger radii of bending, and varies with the direction of bending (longitudinal or transverse). As illustrated by Figure 8 for C260, the amount of springback

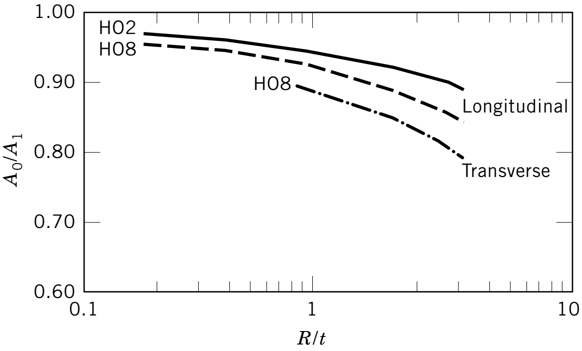

Fig. 8. Springback behavior for alloy C260, as defined by the ratio of the original forming angle, 90° or A_0, divided by the final relaxed angle, A_1. The effects of temper and orientation are shown as a function of bending radius R, normalized by the thickness of the strip t.

increases with temper and increases with applied bending radius. The stronger tempers exhibit more directional behavior.

6.6. Softening Resistance. The ability of being readily annealed or softened in a controlled manner to restore ductility is beneficial in mill processing, but resistance to softening of the wrought product is often preferred during fabrication and subsequent service (19). Joining operations such as welding, brazing, and soldering are prime examples where softening resistance is essential. Most alloying elements and impurities increase softening resistance. The amount by which softening resistance is increased is specific to the element being added and also depends on whether the element remains in solid solution or forms a second-phase particle.

Metallurgical mechanisms that impede the kinetics of thermally induced changes, such as recrystallization, may also enhance softening resistance. The lowering of diffusion rates so as to delay the onset of recrystallization results from nickel and manganese additions. Segregation of solute to dislocations, subboundaries, and grain boundaries to impede motion and thereby prevent recrystallization results from phosphorus and zirconium additions. The presence of fine precipitates to pin dislocations and internal boundaries effectively interferes with recrystallization; eg, age and dispersion hardened alloys. In general, finer and more homogeneous dispersions result in the most softening resistance.

In addition to compositional effects, softening resistance depends strongly on the amount of prior cold work; softening resistance is lowered with increasing amounts of cold work (Fig. 9). Thus the thermomechanical condition of the material must be known when applying softening data. Softening resistance data are best obtained using the pertinent service or process condition. Measurement of hardness or strength at room temperature after exposure for various times at a fixed temperature (isothermal data), or after exposure to various temperatures for a fixed time (isochronal data) provide the most useful softening information. For general comparisons between various alloys and conditions, the half-softening temperature is reported. This temperature is defined as that where hardness or strength (measured at room temperature) is lowered to the average

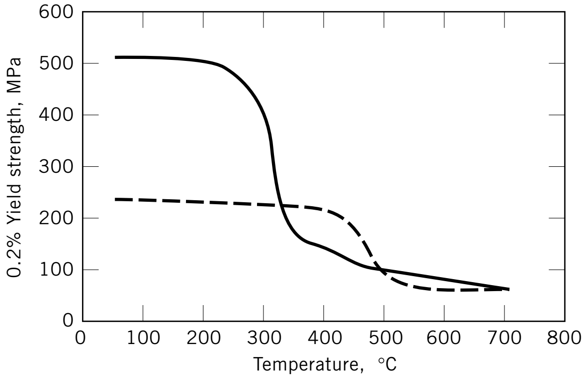

Fig. 9. The effect of prior cold work on softening resistance, as illustrated for C230 (copper−15% zinc) where (—) is CR 55%; (– – –) CR 10% in thickness. To convert MPa to psi, multiply by 145.

of the as-rolled and fully soft values after isochronal anneals (typically one hour). Half-softening temperatures of alloys shown in Figure 4, all having near 50% prior cold work are 220°C for alloy C110, 295°C for alloy C260, 340°C for alloy C510, and 525°C for alloy C706.

6.7. Stress Relaxation Resistance. Stress relaxation and creep both result from unwanted plastic deformation of metals under load at elevated temperature. Copper alloys are used extensively in applications where they are subjected to moderately elevated temperatures while under load. An important example is the spring member for contacts in electrical and electronic connectors. Critical to reliable performance is the maintenance of adequate contact force, or stability, while in service. Excessive decrease in this force to below a minimum threshold value because of losses in spring property can lead to premature open-circuit failure (see ELECTRICAL CONNECTORS). Such a loss is termed stress relaxation.

Stress relaxation (20–23) is the time-dependent decrease in load (stress) at the contact displacement resulting from connector mating. Creep, on the other hand, relates to time-dependent geometry change (strain or displacement) under fixed load, which is a condition that does not apply to connectors.

The amount of stress relaxation depends on the alloy, its temper, the temperature of exposure, and the duration of the exposure. Resistance to stress relaxation of copper is improved by alloying with solid solution elements, as well as by dispersion and precipitation strengthening. Changing temper to higher strength for a given alloy results in some loss in relaxation resistance, thus offsetting some of the initial strength gain of the higher temper by more loss due to stress relaxation. Relief annealing where yield strength is decreased slightly while causing little or no change in tensile strength is used to improve relaxation resistance.

Stress relaxation performance is usually determined in bending, by setting the initially imposed stress at the surface of the bent sample to be 50–100% of the tensile yield strength. Test details are presented in Ref. 23. Data is presented either as the percentage of the initial stress lost or the percentage that remains

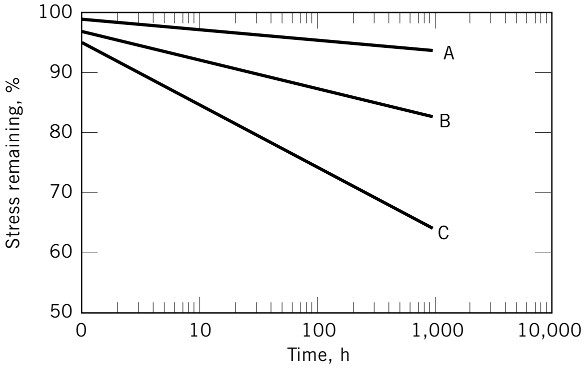

Fig. 10. Stress relaxation behavior at 105°C of the phosphor bronze alloy C521, in the A, relief annealed HR04 and rolled B, H04, tempers compared to C, rolled temper brass, C260–H04.

as a function of time at the exposure temperature. Often the data is plotted as percent stress remaining versus log time as shown in Figure 10, resulting in a plot where the data can be represented by one or two straight lines.

Individual effects of alloying and processing on stress relaxation behavior are illustrated by Figure 10. Alloying with zinc or tin improves stress relaxation relative to copper; C260 (copper–30% zinc) and C521 (copper–8% tin) are solid solution hardened alloys. The phosphor bronzes offer higher resistance to stress relaxation than brass. Relief annealing also improves resistance to stress relaxation as illustrated by comparison of C521 in a rolled temper (H04) with the same material after relief annealing (HR04). Acceptable stability is often limited to 70% stress remaining or higher, depending on the application. Thus brass in the H04 temper would not be acceptable for applications at this temperature where expected duration of exposure can exceed 1000 h.

The highest stress relaxation resistance, at both high strength and moderate conductivity, is available from precipitation hardened alloys. This effect is an important consideration for applications that have high exposure temperatures, as found in present-day automobile engine compartments where 125–150°C exposure temperatures are possible. Precipitation hardened alloys C172 and C7025 are compared to a relief annealed solid solution hardened alloy, C521, in Figure 11. It is important to note that the temperature of the alloy is comprised of the ambient temperature plus the temperature rise due to ohmic heating caused by the current flowing through the connector. This latter component is dependent on the electrical resistance of the alloy and a higher conductivity may assist in reducing relaxation by lowering the temperature of the alloy.

6.8. Fatigue Resistance. Imposed cyclic stressing of metals may result in localized cracking that leads to fracture. The pattern of stressing can be in reversed bending, reversed torsion, and tension–compression, or half cycles of these such as bending in only one direction. The number of cycles of stressing that can be endured without fracture depends on the magnitude of the peak applied stress, the pattern of stressing, and the alloy's mechanical properties (20,24–29).

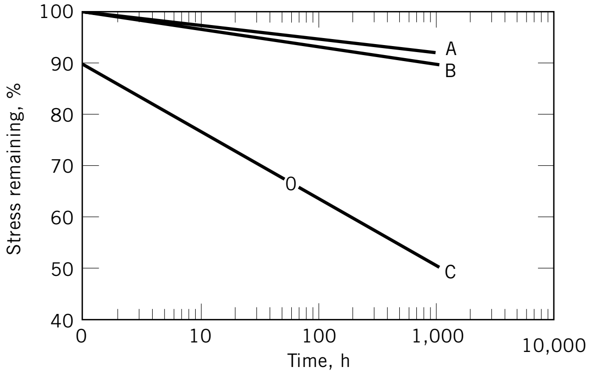

Fig. 11. Comparison between the stress relaxation resistance at 150°C, precipitation hardened alloys A, C172–TH02, and B, C7025–TM02, and C, a solution hardened alloy C521–HR02.

Fatigue properties are usually presented as graphs of applied stress, S, versus the logarithm of the number, N, of cycles to failure. The S–N curve for C510–H08 (spring) temper strip, tested in reversed bending, is shown in Figure 12 (25). Unlike steel, the S–N curve does not eventually become horizontal at high cycles so that an endurance limit does not exist. Thus fatigue resistance of copper and other face-centered cubic metals are reported as fatigue strength, which is defined as the applied stress at which failure occurs at 10^8 cycles.

Fatigue strengths for several copper alloys are listed in Table 7. Generally, fatigue strength increases with tensile strength of the material. This generality refers to the regime of high cycle fatigue where applied stress is a small fraction of its alloy's tensile strength (24). The rule-of-thumb is that the fatigue strength of a copper alloy is about one-third of its tensile strength.

Fatigue properties in bending are most appropriate for copper alloys as these are often used as spring contact components in bellows and electrical

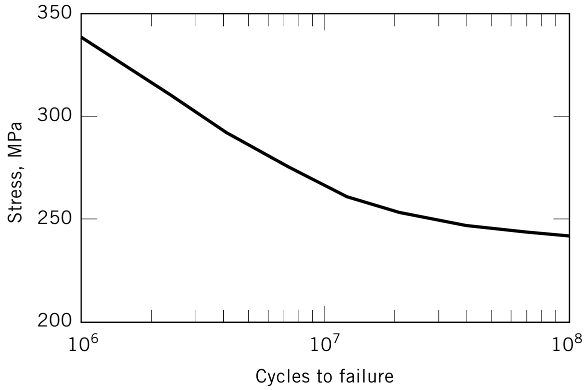

Fig. 12. Fatigue curve for C510–H08. To convert MPa to psi, multiply by 145.

Table 7. **Fatigue Strengths of Copper Alloys**[a]

Alloy	Average 0.2% yield strength, MPa[b]	Fatigue strength 10^8 cycles, MPa[b]
C172[c]	760	275
C194	480	150
C260	615	185
C510	690	235
C762	725	205

[a] All are H08, spring temper unless indicated.
[b] To convert MPa to psi, multiply by 145.
[c] TM02 (1/2 HM).

switches and connectors. These articles are usually designed for acceptable service lives at a moderate to high number of stress cycles.

Lead frames used in electronic packages have a different requirement for resistance to fracture such that the exposed leads must be capable of sustaining a few bending cycles without fracture but at high applied stress levels. Such conditions can be caused by handling damage prior to the packages being assembled onto a circuit board. The resistance to low cycle fatigue by a material is controlled by ductility rather than strength (26). The ability to straighten a damaged lead without its breaking is simulated in a lead bend fatigue test that is covered under Military Standard 883C (30,31). The test is done either on assembled packages or on appropriate samples prepared from alloy strip. Generally, lead materials are required to sustain at least three reversed 0–90° bends without fracture to ensure against scrapping packages.

6.9. Corrosion Resistance.

Copper and selected copper alloys perform admirably in many hostile environments. Copper alloys with the appropriate corrosion resistance characteristics are recommended for atmospheric exposure (architectural and builder's hardware, cartridge cases), for use in fresh water supply (plumbing lines and fittings), in marine applications (desalination equipment and biofouling avoidance), for industrial and chemical plant equipment (heat exchangers such as condensers and radiators), and for electrical/electronic applications (connectors and semiconductor package lead-frames) (32) (see PACKAGING).

Atmospheric exposure, fresh and salt waters, and many types of soil can cause uniform corrosion of copper alloys. The relative ranking of alloys for resistance to general corrosion depends strongly on environment and is relatively independent of temper. Atmospheric corrosion, the least damaging of the various forms of corrosion, is generally predictable from weight loss data obtained from exposure to various environments (33) (see CORROSION AND CORROSION CONTROL).

Pitting corrosion may occur generally over an entire alloy surface or be localized in a specific area. The latter is the more serious circumstance. Such attack occurs usually at surfaces on which incomplete protective films exist or at external surface contaminants such as dirt. Potentially serious types of corrosion that have clearly defined causes include stress–corrosion cracking, dealloying, and corrosion fatigue (32–36).

Table 8. **Relative Susceptibility to Stress Corrosion and Dealloying of Commercial Copper Alloys**

UNS designation	Susceptibility Scale Stress corrosion[a] (0–1000)	Dealloying[b] (0–10)
C260	1000	10
C230	200	4
C770	175	9
C422		4
C425	100	
C688	75	3
C510	20	
C521	10	
C706	0	
C194	0	0
C110	0	0

[a] 1000 is most susceptible and 0 is essentially immune under normal service conditions.

[b] 10 is most susceptible, 0 is least.

Stress corrosion is cracking that develops in sensitive alloys under tensile stress (either internally imposed or a residual stress after forming) in environments such as those containing amines and moist ammonia. The crack path can be either inter- or trans-granular, depending on alloy and environment. Not all alloys are susceptible to stress corrosion (33).

The relative susceptibility of several commercial alloys is presented in Table 8. The index used is a relative rating based on integrating performance in various environments. These environments include the harsh condition of exposure to moist ammonia, light-to-moderate industrial atmospheres, marine atmosphere, and an accelerated test in Mattsson's solution. The latter testing is described in ASTM G30 and G37 (37,38) and is intended to simulate industrial atmospheres. The index is linear. A rating of 1000 relates to the most susceptible and zero designates immunity to stress corrosion.

Dealloying refers to the selective removal of the more chemically active constituent of an alloy to leave a porous, weak deposit of the more noble constituent. Copper–zinc alloys containing >20% zinc are susceptible to dealloying, where it is called dezincification. High zinc brasses having zinc contents near 39% are particularly prone to this form of attack. In brass, dezincification is easily apparent to the unassisted eye as a reddish copper "blush" on the surface of the metal (32,36).

The relative susceptibility to dealloying of alloys that contain varying amounts of zinc is also summarized in Table 8. The index of susceptibility was derived from testing in a 3.4% sodium chloride solution at 40°C. A ranking of 10 relates to high susceptibility, zero relates to immunity. The relative rankings among the alloys may differ for different exposure time and environment.

Corrosion fatigue refers to the combination of chemical attack and cyclic stressing, where cracking propagates more rapidly than under static stressing.

Often, corrosion fatigue can be recognized by the presence of several cracks that initiate from stress raisers such as corrosion pits. The mode of fatigue failure is often transgranular.

Impingement or erosion attack can occur when liquids or gases impact metal surfaces at high velocity. The corrosion rate is high under such circumstances because any corrosion product films that can be protective if adherent are swept away as quickly as they are formed to leave exposed fresh surface.

6.10. Hydrogen Embrittlement. Copper alloys that contain cuprous oxide in their microstructures, as in C110, are potentially susceptible to embrittlement when heated in hydrogen-containing gases (39–41). Hydrogen that readily diffuses into the alloy and reduces the cuprous oxide to produce water vapor that subsequently collects under substantial internal pressure, to cause internal pores. This porosity is typically found along grain boundaries, leading to fractures along these boundaries (41). Accordingly, susceptible alloys are annealed during processing in nitrogen or very low hydrogen-containing gas, at low temperatures, and short times, to avoid embrittlement.

Oxygen-free or deoxidized copper and its alloys are not susceptible to hydrogen embrittlement. Phosphorus is a commonly used deoxidizer (as in C122–phosphorus deoxidized copper). Aluminum, beryllium, magnesium, phosphorus, silicon, and zirconium can react with oxygen and cuprous oxide to form more stable oxides that are not readily reduced by hydrogen. These elements are often added to alloys to improve mechanical properties with resistance to hydrogen embrittlement being an added benefit. Examples of the latter are C151, C172, C194, C197, C260, C510, C688, and C7025.

6.11. Solderability. Most copper alloys have good solderability (tinnability), meaning that they are wet by molten tin, tin–lead, and modifications of these to produce a continuous coating that has few to no pinhole sized nonwet areas. This characteristic of copper and its alloys accounts for the significant use of tin and solders (both lead containing and lead free) to provide corrosion resistance and in joining (see SOLDERS AND BRAZING FILLER METALS) (42).

The inherent solderability of copper alloys for coating and joining purposes is determined by a variety of methods. The most commonly used is the vertical dip test where a sample is first fluxed, then immersed for a specific time (~5 s) in tin or solder, removed, cooled and visually inspected. This test procedure is provided in Military-Standard (43,44) and ASTM Specifications. A solderability rating system is summarized in Table 9. The flux that is used must also be specified. Fluxes used by the electronics industry are very mild and include resin (Type R)

Table 9. **Solderability Rating System and Alloy Ratings**

Rating system class	Description	UNS designation[a]
I	uniform smooth coating, 100% wetting	C110, C194, C220, C510
II	>95% wetting	C195, C762
III	50–95% wetting	C260, C688
IV	<50% wetting	
V	no wetting	

[a] Ratings are for a mildly activated resin (Type RMA) flux.

and mildly activated resin (Type RMA). Joining operations, as in radiator manufacture and plumbing, generally use much more aggressive chloride or acid-type fluxes because these applications are more tolerant to residual flux than electronic equipment.

The inherent solderabilities of selected alloys are listed in Table 9. Class IV and V ratings with this particular flux indicate the presence of oxides or other surface contaminants that may be removable with more aggressive flux or acid pickling.

Tin and solder coatings are applied to copper and its alloys to provide the ability to be soldered after prolonged storage and to provide corrosion resistance (45–47). Such coatings are applied in several ways, each providing different coating characteristics. Coatings can be applied from a molten bath, wherein the strip surface is mechanically wiped as it exits the bath in order to produce a uniform coating thickness. Depending on the base alloy and process variables, the coating thickness is ~20–80 μm. Thicker coatings than those produced by mechanical wiping are made by directing strong air jets or "knives" at the surface. Reaction between the coating and the substrate copper alloy results in a 20–40 μm thick Cu–Sn intermetallic compound for both application methods. Finally, tin coatings can be applied by electrodeposition over a range of thicknesses of up to 300 μm. No intermetallic is formed during the plating process. However, rapid intermetallic growth subsequently occurs at room temperature, such that 20–30- μm thick intermetallic is present after 30 days. Further, electrotin coatings are often reflowed at just above the melting point by hot oil immersion or infrared radiation. This reflow operation results in a smooth, high quality surface. Additional intermetallic compound forms during the reflow operation and in storage or service.

Coating characteristics affect performance. For example, the intermetallic layer is easily oxidized during assembly and storage. If it is required that the material be soldered at some future time, it is necessary (but not always sufficient) for a residual layer of tin to be present. But this residual tin requirement is not necessary in many cases where the coating is intended to provide only tarnish resistance rather than extend shelf life solderability. Solder coatings are also degraded by diffusion of alloy constituents to the surface where they can react with the atmosphere to form sulfides, oxides, etc, that impede subsequent soldering. The quality of tin coatings is evident by several accelerated tests, including a 150°C bake test and a steam aging test (44).

6.12. Brazeability. Brazing is, by definition, elevated temperature soldering, that is, soldering above the arbitrarily defined temperature of 425°C. Copper and its alloys are readily brazed and often are brazed in order to take advantage of the stronger and more stable brazed joint compared to the soldered joint. In addition, it is easy to match the properties of the filler metal to the copper alloy to be brazed because many of the brazing alloys are themselves copper-base alloys (42). As with soldering, brazing is done at a temperature above the melting point of the brazing (filler) alloy and below that of the alloy being joined. The filler or brazing metal is placed in or near the joining surfaces in the form of a strip, wire, or powder. With application of heat, the filler melts and by capillary action completely fills the gap and forms a metallurgical bond between the joining surfaces. For successful brazing it is necessary to set the proper clearance between the joining surfaces and to preclean the surfaces to be joined. In addition, oxidation protection must be provided via proper fluxing and atmosphere to ensure a sound braze and adequate flow characteristics of the filler metal.

Filler alloys for brazing of copper alloys are usually copper base. These include copper–zinc alloys (RBCuZn), copper–phosphorus alloys (BCuP-1), and copper–silver (Zn, Cd, or Li) alloys (BAg). The copper–zinc brazing alloys are low in cost, but they require a flux and are not recommended for pure copper because of the potential for corrosion. The phosphorus-containing filler alloys are self-fluxing and are reasonably low cost, but are to be avoided with high nickel cupronickels because of an embrittling reaction between nickel and phosphorus. The copper–silver base alloys (BAg) produce good sound joints for most copper alloys, but carry the increased cost burden of the silver component.

The heating required for the brazing operation is readily done using commonly available industrial equipment: muffle furnace, oxy-gas torch, and induction heating. To protect against oxidation and to ensure good filler metal fluidity, fluxing agents and appropriate atmospheres are specified for each heating method. The fluxing agents comprise various mixtures of borates, fluorides, boric acid, and wetting agents. These agents are usually applied in paste form. The atmospheres used in brazing furnaces are usually products of natural gas combustion, nitrogen, or dissociated ammonia, all having maintenance of low dew points. Whereas hydrogen can be used for many alloys, it must not be used for brazing electrolytic tough pitch copper, C11000, because of the embrittling steam reaction between hydrogen and the cuprous oxide particles. Moreover, the presence of hydrogen should be avoided during any brazing operation where cuprous oxide has the potential of forming.

Fluxes must be used when brazing the copper–zinc brasses. For copper alloys above $\sim$20% zinc content, lower melting point brazes must be used to control zinc fuming and dezincification. Aluminum bronzes can be successfully brazed only when the proper flux (Type 4) is used to reduce the formation of alumina films. Various copper alloys can be successfully brazed only after they have received a stress relieving heat treatment and if they are heated slowly to the brazing temperature in order to avoid liquid metal embrittlement or fire cracking. Susceptibility to these latter problems is shown by the leaded alloys, the phosphor bronzes, the silicon bronzes, and the nickel silvers. When brazing precipitation hardening alloys, the brazing alloy and conditions can be chosen so that the alloy is solutionized during the brazing treatment. After a suitably rapid quench, the brazed alloy can be given an age hardening heat treatment.

6.13. Weldability. Welding has long been an important method of fabricating copper alloy parts as these alloys are generally readily weldable (42). But, as is the case with all materials, successful welding requires the proper match of welding technique to the specific application and copper alloy. There are four primary concerns for successful welding of copper. The first and foremost is the high thermal conductivity of copper and its resulting ability to conduct heat away from the weld zone. The second concern is the chemical and in some cases toxic properties of the typical elements alloyed with copper. Adequate ventilation must be provided for the lead vapor, the zinc fumes, or the toxic compounds of Be, As, or Sb that can be emitted from the copper alloys containing these elements. The third concern is the ready solubility of oxygen in copper at elevated temperatures and the subsequent precipitation of cuprous oxide particles at grain boundaries during solidification and cooling, which if uncontrolled cause reduced strength and ductility in the weld zone. The fourth concern is that alloys containing Pb, Te, and S (eg, the free-machining alloys) are prone to hot shortness (hot cracking) during cooling.

Arc Welding. has long been used to join copper alloys. The gas tungsten-arc welding (GTAW) and the inert gas metal arc welding (GMAW) methods are the preferred arc welding methods for copper alloys. The GTAW technique is appropriate for workpiece thicknesses up to $\sim$3 mm (0.125 in.) because of its capability of delivering intense heat into a narrow area. The GMAW technique is used for workpiece thicknesses $>$12 mm (0.5 in.) because of its ability to provide rapid delivery of high heat. The rapid delivery of high heat is important for either technique to counter the high thermal conductivity of the high conductivity copper alloys. Besides heating efficiency, the importance of rapid delivery of the heat is to shorten the welding time to minimize oxygen pickup. The inert gases used are argon or mixtures of argon–helium . Although argon is cheaper, the helium content is often specified because of its higher thermal conductivity properties enabling higher heat input to the workpiece, especially for alloys with higher thermal conductivities.

In general, it is difficult to avoid porous welds of low ductility when arc welding oxygen-bearing electrolytic tough pitch copper, C11000. The situation is improved for arc welding of oxygen-free copper, but pickup of oxygen during welding must be avoided. Higher quality welds are more easily obtained when the workpiece and/or the filler metal is a deoxidized alloy or otherwise contains deoxidizing elements. For this reason the phosphorus deoxidized alloys, the silicon and aluminum bronzes, and the cupronickels are arc weldable.

In order to enable GTAW equipment to provide the required highly penetrating input of heat, a dc straight polarity current is applied. Using such equipment, copper alloy tubes are welded to copper alloy tube sheets. The ends of processed strip or wire are easily joined in this technique to create longer coils of strip, wire, or rod product. When age hardening alloys are welded, such as the beryllium or chromium coppers, they must be given a postwelding age hardening heat treatment. Such a treatment usually does not return the weld region to the same strength as the rest of the workpiece, but it is adequate for most applications. Arc welding is not recommended for the newer oxygen dispersion hardened alloys (C15720), because the desirable uniform array of fine oxide particles (alumina) is destroyed by melting of the alloy. Arc welding can be used for welding of copper to other metals, for which care must be taken to design for the differences in thermal expansion characteristics and during which the arc should be directed toward the higher conductivity alloy in the combination.

Resistance Welding. has been successfully applied to copper alloys in all of its various spot, seam, or butt joining modes. Because the process depends on ohmic (I^2R) heating at the interface to be joined, the ability to resistance weld is inversely related to electrical conductivity of the alloys being welded. The current is applied via opposing electrodes on either side of the joint. The electrodes themselves are usually made of high conductivity, softening resistant copper alloys, such as chromium– or zirconium–copper. The electrodes may be coated with a refractory metal, such as molybdenum, to prevent electrode pickup or sticking to the work piece. Most copper alloys having strip thicknesses on the order of 0.025–3.2 mm can be welded by this method. The leaded copper alloys are susceptible to liquid metal embrittlement as well as lead bleed out. As is the case for arc welding, steps must be taken to control the oxide fuming from alloys containing high levels of zinc, beryllium, and lead. Projection welding can be used to prevent electrode sticking and to control the shape of the weld nugget in high conductivity strip thicker than 0.5 mm. In this method, point, linear, or annular projections (ridges) are formed or machined in the workpiece to concentrate the welding current where the heat is needed. Flatter electrodes can then be used, leading to less electrode pickup.

Induction Welding. also depends on I^2R heating. In this case, the electrical current is induced in the workpiece via an imposed high frequency magnetic field. The high frequency equipment is designed to concentrate the induced eddy currents near the surface at the edges of the workpiece to be joined. This method has been successfully applied to most copper alloys and, in particular, has been effectively used to make the longitudinal seam in the high speed manufacture of welded tube from copper alloy strip.

6.14. Machinability. Copper and its alloys can be machined with differing degrees of ease. Special additives such as lead, bismuth, tellurium, selenium, and sulfur, are added, to enhance machinability (48) , although other properties, such as formability and tensile ductility, normally suffer. These particular alloying elements form second-phase particles that promote chip fracture and the development of lubricating films at the tool-to-chip interface. Smaller, easier to handle chips and lower cutting forces leading to longer tool life result from use of these additives. Notable uses for special alloys having high machinability are rod, for high production rate screw machine items such as fasteners, connectors and plumbing components, and strip for keys.

Copper and its alloys are ranked according to a machinability rating index that is a percentage of the machinability of the most machinable copper alloy, C360, also known as free-cutting brass. The rating is based on relative tool

Table 10. **Machinability Ratings for Wrought Copper Alloys**

UNS designation	Rating[a]	Comment
C110	20	
C145	85	phosphorus deox, Te bearing (0.5%)
C147	85	sulfur bearing (0.45%)
C172	20	
C187	85	leaded copper
C260	30	
C353	90	high leaded brass
C360	100	free-cutting brass
C425	30	
C443	30	
C510	20	
C544	80	
C706	20	
C752	20	
C782	60	leaded nickel silver

[a] Rating is a relative scale based on C360 having a value of 100.

life, where C360 is assigned a rating of 100. The actual performance of an alloy is dependent on the operation (turning, drilling, threading, etc), tool design, the lubricant, and the precise criterion used to define machinability (tool life, cutting rate, surface finish). Machinability ratings for several wrought alloys are given in Table 10.

The characteristics of chips also follow the machinability rating. The most highly machinable alloys, (ie, those having ratings near 60 and greater) develop short, brittle chips that are easily cleared from tools to make them suited to high production rate machining. Somewhat longer but brittle helical chips are often characteristic of alloys having ratings near 30, such as C260. The least machinable alloys, such as copper, phosphor bronzes, and the copper-nickel alloys having ratings of 20, form long, continuous chips that are easily entangled and difficult to handle.

7. Alloy Specific Properties

The physical properties of pure copper are given in Table 11. The mechanical properties of pure copper are essentially the same as those for C101 and C110, discussed later, which are often described as copper.

Trace elements in copper exert a significant influence on electrical conductivity. Effects on conductivity vary because of inherent differences in effective atomic size, valency, and solubility. The decrease in conductivity produced by those elements appearing commonly in copper, at a fixed weight percent, rank as follows: Cd (least detrimental), Au, Zn, Ag, Ni, Sn, Mg, Al, Si, Fe, P, O, Ti(most detrimental). Table 12 summarizes these effects. In the absence of chemical or physical interactions, the increase in electrical resistivity is linear with amounts of each element, and the effect of multiatom additions is additive.

7.1. Coppers.

The coppers represent a series of alloys ranging from the commercially pure copper, C101, to the dispersion hardened alloy C157. The difference within this series is the specification of small additions of phosphorus,

Table 11. **Physical Properties of Copper**[a]

Parameter	Value
mp, °C	1083
density, g/mL	8.94
electrical conductivity, % IACS min	101
electrical resistivity, n Ω · m	17.1
thermal conductivity, W/(m · K)	391
coefficient of thermal expansion from 20–300°C, μm/(m · K)	17.7
specific heat, J/(kg · K)[b]	385
elastic modulus, GPa[c]	
tension	115
shear	44

[a] All properties at 20°C unless otherwise noted.

[b] To convert J to cal, divide by 4.184.

[c] To convert GPa to psi, multiply by 145,000.

Table 12. **Solubility Limits and Electrical Conductivity Effects of Elemental Additions to Copper**[a]

Element	Solubility at room temperature, wt%	Resistivity increase, $(\mu\Omega\cdot\mathrm{cm})/\mathrm{wt}\%$	Electrical conductivity[b] at 0.5 wt %, % IACS
Ag	0.1	0.355	93
Al	9.4	2.22	62
As	6.5	5.67	38
Au	100.0	0.185	97
Be	0.2	4.57	44
Cd	0.5	0.172	98
Co	0.2	7.3	32
Cr	0.03	4.9	42
Fe	0.14	10.6	25
Mg	1.0	2.1	63
Mn	24.0	3.37	51
Ni	100.0	1.2	76
O	0.0002	21.0	14
P	0.5	14.3	20
Pb	0.02	1.02	79
Sb	2.0	2.9	55
Si	2.0	7.0	33
Sn	1.2	1.65	69
Ti	0.4	21.6	14
Zn	30	0.31	94
Zr	0.01	8.0	30

[a] Refs. (9–12).

[b] Assuming solubility at 0.5 wt%.

arsenic, cadmium, tellurium, sulfur, magnesium, zirconium, as well as oxygen. To be classified as one of the coppers, the alloy must contain at least 99.3% copper.

The mechanical properties of coppers having UNS designations between C10100 and C13000 are listed in Table 13. The coppers include high purity copper (C101, C102), electrolytic tough pitch (C110), phosphorus deoxidized (C120, C122), and silver-bearing copper (C115, C129, etc). The mechanical properties of

Table 13. **Tensile Properties of Copper (C10100–C13000)**

Temper	Tensile strength, MPa[b]	Yield strength,[a] MPa[b]	Elongation, %	Hardness, HRF[c]
OS 025[d]	235	76	45	45
H01	260	205	25	70
H02	290	250	14	84
H04	345	310	6	90
H08	380	345	4	94
H10	395	365	4	95

[a] 0.5% offset.

[b] To convert MPa to psi, multiply by 145.

[c] Hardness is on the Rockwell-F scale.

[d] Annealed to average grain size of 0.025 mm.

Table 14. **Tensile Properties of Dilute Alloy Coppers (C14300–C15720)**

Alloy	Temper	Tensile strength, MPa[a]	0.2% Yield strength, MPa[a]	Elongation, % 50 mm
C14300	H04	310	275	14
C14500[b]				
C14700[b]	H04	330	304[c]	20
C15000	TH04[d]	445	411[c]	18
C15100	H04	400	386	4
C15500	H04	425	394	5
C15720[b]	061	485	380	13

[a] To convert MPa to psi, multiply by 145.

[b] Rod of 25 mm diameter.

[c] 0.5% offset for rod products.

[d] Solution treated at 950°C, cold worked 90%, aged 1 h at 450°C.

these alloys are essentially the same. Other coppers, C142 through C157, offer higher strength at usually lower conductivity. The mechanical properties of alloys within the latter range are listed in Table 14.

Excellent resistance to saltwater corrosion and biofouling are notable attributes of copper and its dilute alloys. High resistance to atmospheric corrosion and stress corrosion cracking, combined with high conductivity, favor use in electrical–electronic applications.

7.2. C101 and C102. The oxygen-free coppers, C10100 and C10200, are manufactured by melting prime quality, electrolytically produced cathode copper under reducing conditions designed to restrict oxygen content to below 0.0005% (C101) and 0.001% (C102). C101 has a minimum copper content, which may also include a trace of silver, of 99.99%. Oxygen-free copper is immune to hydrogen embrittlement, and provides low outgassing tendency, along with very high (101% IACS min) conductivity at 20°C for annealed material.

7.3. C110. The most common commercial purity copper is C110. The principal difference between C110 and C102 is oxygen content, which is deliberately controlled at 0.04% in C110 to eliminate many impurities that are deleterious to conductivity. Oxygen is present as cuprous oxide particles, which do not significantly affect strength and ductility, but C110 is susceptible to hydrogen embrittlement. The properties of C110 are adequate for most applications and this alloy is less costly than higher purity copper.

7.4. Deoxidized Copper. Cuprous oxide can be readily removed from copper by small additions of phosphorus, calcium, and magnesium. Phosphorus is the most common deoxidizing element. Most phosphorus-deoxidized coppers contain residual phosphorus in concentrations of 0.01–0.04%. The most common alloy in this family is C122, containing 0.015–0.040% phosphorus. Because of residual dissolved phosphorus, the minimum electrical conductivity of C122 is 85% IACS, versus 100% IACS for C110. Applications involving brazing and welding in hydrogen-rich atmospheres are important uses for deoxidized copper where embrittlement by hydrogen has to be avoided.

7.5. Specialty Coppers. Additions are made to copper to satisfy specific needs. Tellurium at a nominal 0.5 wt% addition, sulfur at 0.35 wt%, and lead at 1 wt% enhance machinability. These alloys are identified as C145, C147, and

C187, respectively. The solubility limit for each element is <0.001%, so that the excess is present as second-phase particles that assist in fracture of chips and lubrication during machining.

Additions of 0.1 wt% cadmium to phosphorus deoxidized copper (C143), 0.05–0.2 wt% zirconium to copper (C150, C151), or Mg, Ag and P to copper (C155) significantly enhance softening resistance while maintaining high (85–95% IACS) conductivity. Because of environmental concerns, however, cadmium-containing alloys are being replaced by others that meet product and manufacturing requirements.

Extremely high softening resistance is available in alloy C15720 through dispersion strengthening by aluminum oxide. This alloy has been used successfully as a welding rod material and in other specific applications that can bear its cost.

7.6. High Copper Alloys. The high copper alloys contain a minimum of 96 wt% copper; most contain about 98.5 wt%. These alloys are found within the UNS classification of C162 to C199. As a group, they offer higher strength and better softening resistance than the specialty coppers. Like the coppers, the high copper alloys have excellent resistance to general and stress corrosion cracking. However, the high copper alloys have lower electrical conductivities than the coppers, they are more expensive, and special processing may be required to incorporate dispersoids or precipitates for optimal effectiveness. Nominal electrical conductivities and tensile properties of selected high coppers in hard rolled temper are summarized in Table 15.

7.7. Cadmium Copper (C162). Containing 1 wt% Cd, C162 has been used for many years in electrical connectors because of its excellent (90%

Table 15. **Conductivity and H04 (Hard) Temper Tensile Properties**

UNS	Electrical conductivity, % IACS	Tensile strength, MPa[a]	0.2% Yield strength, MPa[a]	Elongation in 50 mm, %
		High copper alloys		
C16200	90	414	310	5
C182[b]	80	460	405	14
C19000	60	579	531	3
C19200	65	448	414	7
C19400	65	462	434	4
C19500	50	593	572	2
C19700	80	448	414	7
		Cu—Zn brass alloys		
C210	56 (5% Zn)	379	365	5
C220	44 (10% Zn)	428	400	4
C230	37 (15% Zn)	469	421	7
C240	32 (20% Zn)	496	421	4
C260	28 (30% Zn)	524	496	10
C353	26 (34% Zn, 2% Pb)	503	462	12
C360[c]	26 (35% Zn, 3% Pb)	386	310	20

[a] To convert MPa to psi, multiply by 145.

[b] TH04 Temper material.

[c] H02 Temper material.

IACS) electrical conductivity and formability. Much of the cadmium is in solution; the remainder is dispersed as Cu_2Cd particles. Unique arc quenching ability, which reduces the surface degradation from electric-arc erosion during switching, is characteristic of this alloy. However, environmental concern because of cadmium 's toxicity has all but eliminated its use, thus restricting its availability.

7.8. C190 to C197. The C190 to C197 alloys constitute a series of commercially useful copper alloys containing low levels of phosphorus; some contain Ni (C190−C191) and some contain Fe (C192−C197). They are relatively inexpensive and offer excellent combinations of strength, ductility, conductivity, and moderate softening resistance. As a group, these alloys are readily processed to provide a uniform array of iron and iron or nickel phosphide dispersoids for hardening and grain size control. Offering electrical conductivities of 50−80% IACS, they find extensive use in electronic products as leadframes and in electrical connectors. C194 (nominally, Cu−2.4 Fe−0.04 P−0.1 Zn) has the distinction of being the copper alloy that during the early 1970s replaced ASTM F30 (42 Ni—Fe alloy) as the dominant leadframe material in the electronics industry. Of increasing importance is the higher capacity for these alloys to dissipate heat from semiconductor packages and thus prolong integrated circuit (IC) life. Also of importance are their nonmagnetic properties permitting high clock speeds for IC devices (see INTEGRATED CIRCUITS; SEMICONDUCTOR TECHNOLOGY).

7.9. Copper−Zinc Brasses. copper−zinc alloys have been the most widely used copper alloys during the 1990s. It is no accident that the word brass is included in the name of many copper alloy manufacturers. The manufacture of brass buttons and other brass artifacts was the principal reason for the establishment of the U.S. copper alloy industry in Connecticut during the 1800s.

Brass alloys fall within the designations C205 to C280 and cover the entire solid solution range of up to 35 wt% zinc in the Cu−Zn alloy system. Zinc, traditionally less expensive than copper, does not too greatly impair conductivity and ductility as it solution hardens copper.

Brass alloys are highly formable, either hot or cold, and provide moderate strength and conductivity. Moreover, the alloys have a pleasing yellow "brass" color at zinc levels $>$20 wt%. The material is amenable to polishing, buffing, plating, and soldering. By far, the best known and most used composition is the 30 wt% zinc alloy, Cartridge Brass. Door knobs and bullet cartridges are the best known applications and illustrate the material's excellent formability and general utility. Properties of representative brass alloys in the hard temper are also summarized in Table 15.

The series of brasses, C312 to C385, contain from 0.25−5.0 wt% lead for the purpose of improving machinability. C360, having the composition Cu−35.4 Zn−3.1 Pb, has become the industry standard for machinability performance. It is given the descriptive name of free-machining brass and a machinability rating value defined as 100 (Table 10).

Brasses are susceptible to dezincification in aqueous solutions when they contain $>$15wt% zinc. Stress corrosion cracking susceptibility is also significant $>$15 wt% zinc. Over the years, other elements have been added to the Cu—Zn base alloys to improve corrosion resistance. For example, a small addition of arsenic, antimony, phosphorus, or tin helps prevent dezincification to make brasses more useful in tubing applications.

Table 16. **Conductivity and Wrought Tensile Strength of Tin–Brasses Showing the Hardening Effect of Tin Additions**

UNS	Zinc, wt%	Tin, wt%	Electrical conductivity, % IACS	Tensile strength, MPa[a] H04 Temper	Tensile strength, MPa[a] H08 Temper
C411	10	0.5	32	448	552
C425	10	2.0	28	524	634
C220	10		44	428	524
C443	30	1.0	25	607	
C260	30		28	524	690

[a] To convert MPa to psi, multiply by 145.

7.10. Tin Brasses. The tin brass series of alloys consists of various copper–(2.5–35 wt%) zinc alloys to which up to ~4 wt% tin has been added. These are solid solution alloys that have their own classification as the C40000 series of alloys. Tin provides better general corrosion resistance and strength without greatly reducing electrical conductivity. As with all the brasses, these alloys are strengthened by cold work and are available in a wide range of tempers. These alloys offer the combined strength, formability, and corrosion resistance required by their principal applications, namely, fuse clips, weather stripping, electrical connectors, heat exchanger tubing, and ferrules. Several tin brasses have lead additions to enhance machinability. For example, the high leaded Naval Brass C485, containing Cu–37 Zn–0.7, Sn–1.8 Pb, has a machinability rating of 78.

Table 16 illustrates the property enhancements and tradeoffs seen when tin is added to a copper–zinc brass base composition. The most commonly used alloys for electrical connectors are the Cu–10 Zn–Sn brasses, such as C411, C422, and C425. These tin brasses offer improved corrosion and stress relaxation resistance relative to the base Cu–Zn alloy.

Admiralty Brass and Naval Brass are 30 and 40% zinc alloys, respectively, to which a 1% tin addition has been added. Resistance to dezincification of Cu–Zn alloys is increased by tin additions. Therefore, these alloys are important for their corrosion resistance in condenser tube applications. In these, as well as the other higher zinc compositions, it is common to use other alloying additives to enhance corrosion resistance. In particular, a small amount (0.02–0.10 wt%) of arsenic (C443), antimony (C444), or phosphorus (C445) is added to control dezincification. When any of these elements are used, the alloy is referred to as being "inhibited." For good stress corrosion resistance, it is recommended that these alloys be used in the fully annealed condition or in the cold worked plus stress relief annealed condition.

7.11. Tin Bronzes. Tin bronzes may be the most familiar of copper alloys with roots going back into ancient times. Whereas bronze is still used for statuary, these alloys are found in many modern applications, such as electrical connectors, bearings, bellows, and diaphragms. The wrought tin bronzes are also called phosphor bronzes because 0.03–0.35 wt% phosphorus is commonly added for deoxidation and improved melt fluidity during casting.

Table 17. **Conductivity and Wrought Tensile Strength of Tin Bronze Alloys**

UNS	Tin, wt%	Electrical conductivity, % IACS	Tensile strength, MPa[a] H04 Temper	Tensile strength, MPa[a] H08 Temper
C505	1.0	48	441	552
C511	4.0	20	545	696
C510	5.0	15	572	738
C521	8.0	13	634	800
C524	10.0	11	690	882
C544	4.0[b]	19	545	703

[a] To convert MPa to psi, multiply by 145.

[b] Also contain 4 wt % each of zinc and lead.

The several wrought alloys of commercial importance span the range of 1.0–10 wt% tin and are mostly used in work hardened tempers. These alloys are single phase and offer excellent cold working and forming characteristics. Strength, corrosion resistance, and stress relaxation resistance increase with tin content. The tin–phosphorus alloys are highly resistant to stress corrosion cracking and have good resistance to impingement corrosion attack. Unfortunately, conductivity decreases, cost increases (tin has been historically more costly than copper), and the capability of being hot processed is impaired as tin level is increased. Only compositions up to ~4.5 wt% tin show good hot processing characteristics. The richer compositions are cast in thinner cross-sections that can be cold rolled directly. Several cycles of working and annealing are employed to homogenize the cast microstructure.

One of the most highly used specialty tin bronzes is C544, containing Cu–4 Sn–4 Zn–4 Pb. Zinc provides increased strength to this tin bronze, whereas the lead addition provides good machinability (machinability rating of 80)and enhances wear resistance. C544 is used in many applications where these two latter properties are of the utmost benefit, namely, bearings, bushings, gears, pinions, washers, and valve parts. Table 17 indicates the range of properties available for the commonly used phosphor bronzes.

7.12. Aluminum Bronzes. Aluminum bronze alloys comprise a series of alloys (C606 to C644) based on the copper–aluminum (2–15 wt%) binary system, to which iron, nickel, and/or manganese are added to increase strength. The mechanical properties of commercially important alloys in this group are listed in Table 18.

Aluminum bronze alloys are used for their combined good strength, wear, and corrosion-resistance properties where high electrical and thermal conductivity are not required. Corrosion resistance results from the formation of an adherent aluminum oxide that protects the surface from further oxidation. Mechanical damage to the surface is readily healed by the redevelopment of this oxide. The aluminum bronzes are resistant to nonoxidizing mineral acids such as sulfuric or hydrochloric acids, but are not resistant to oxidizing acids such as nitric acid. However, these alloys must be properly heat treated to be resistant to dealloying and general corrosion.

The aluminum oxide surface layer that provides wear and corrosion resistance is not without drawbacks. This adherent film is difficult to remove during

Table 18. **Conductivity and H04 (Hard) Temper Tensile Properties of Aluminum Bronze Alloys**

UNS	Constituents, wt% Al	Fe	Ni	Electrical conductivity, % IACS	Tensile strength, MPa[a]	0.2% Yield strength, MPa[a]	Elongation in 50 mm, %
C614	7	2.5		14	586	400	35
C615	8		2	13	862	620	5
C625	13	4.5		10	690	379	1
C630[b]	10	3.0	5	7	814	517	15

[a] To convert MPa to psi, multiply by 145.

[b] Also contains 1.5 wt% manganese.

industrial cleaning of the alloys. Cleaning techniques have been developed that fragment the tightly adherent aluminum oxide film before removing it by the nonoxidizing mineral acids commonly used in brass mill processing. Furthermore, excessive tool wear in stamping and shearing equipment is caused by the presence of this film. Soldering and brazing are also made difficult by this oxide film.

Two single-phase, binary alloys are used commercially: C606, containing 5 wt% Al, and C610, 8 wt% Al. Both alloys have a golden color and are used in rod or wire applications, such as for bolts, pump parts, and shafts. Most of the available aluminum bronzes contain additional alloy elements, however. For example, C608 is a commonly specified condenser or heat exchanger tube alloy that is essentially 5% aluminum to which 0.02–0.35 wt% arsenic has been added to improve corrosion resistance. Alloy C613, having 7 Al–2.5 Fe also has a 0.3 wt% tin addition for improved resistance to stress corrosion.

Most of the aluminum bronzes contain substantial iron, nickel, or manganese additions. These alloying elements increase strength by forming second phases during heat treatment. Iron, the most commonly added element in these bronzes, separates as an iron-rich particle that controls grain size while it enhances strength. Nickel also reacts with aluminum to form NiAl precipitates during heat treatment with the same result as the iron addition.

Several Cu—Al—Si alloys have commercial importance. For example, C636 containing 3.5 Al—1.0 Si, is a rod and wire alloy that is processed to around 590 MPa 85,000 (psi) tensile strength. C638, containing 2.8 Al–1.8 Si–0.4 Co, is a strip product that owes its good strength and formability to dispersion strengthening and a very fine grain size that results from precipitation of cobalt silicide particles. The latter alloy attains tensile strengths of 566 MPa (82,000 psi) and 883 MPa (128,000 psi) in the annealed and spring rolled (H08) tempers, respectively.

7.13. Silicon Bronzes. Silicon bronzes have long been available for use in electrical connectors, heat exchanger tubes, and marine and pole line hardware because of their high solution hardened strength and resistance to general and stress corrosion. As a group, these alloys also have excellent hot and cold formability. Unlike the aluminum bronzes, the silicon bronzes have moderately good soldering and brazing characteristics. Their compositions are limited to below 4.0 wt% silicon because above this level, an extremely brittle phase

Table 19. **Conductivity and H04 (Hard) Temper Tensile Properties of Silicon Bronze Alloys**

UNS	Si, wt%	Electrical conductivity, % IACS	Tensile strength, MPa[a]	0.2% Yield strength, MPa[a]	Elongation in 50 mm,%
C651 wire	1.5	12	690	485	11
C654 flat[b]	3.0	7	790	700	6
C655 flat	3.0	7	650	400	8

[a] To convert MPa to psi, multiply by 145.

[b] Also contains 1.5 wt% tin.

(kappa) is developed that prevents cold processing. Electrical conductivities of silicon bronzes are low, however, because of the strong effect that silicon has in degrading this property. The three most popular of the commercially available alloys are listed in Table 19 with their typical properties.

7.14. Modified Copper–Zinc Alloys. The series of copper–zinc base alloys identified as C664 to C698 have been modified by additions of manganese (manganese brasses and the manganese bronzes), aluminum, silicon, nickel, and cobalt. Each of the modifying additions provides some property improvement to the already workable, formable, and inexpensive Cu—Zn brass base alloy. Aluminum and silicon additions improve strength and corrosion resistance. Nickel and cobalt form aluminide precipitates for dispersion strengthening and grain size control. The high zinc-containing alloys are formulated to facilitate hot processing by transforming to a highly formable (beta) phase at elevated temperature.

Representative properties of alloys from this group are summarized in Table 20. C664, C688, and C690 are strip products that are used in electrical connectors, springs, and switches. These alloys are designed to provide beneficial combinations of strength and formability in cold rolled tempers. All three utilize dispersion hardening through iron plus cobalt particles (C664), cobalt aluminides (C688), and nickel aluminides (C690).

Table 20. **Conductivity and Wrought Tensile Properties of Modified Copper–Zinc Alloys H04 (Hard) Temper**

UNS	Form	Composition, wt %	Electrical conductivity, % IACS	Tensile strength, MPa[a]	0.2% Yield strength, MPa[a]	Elongation in 50 mm, %
C664	flat	11.5 Zn–1.5 Fe–0.5 Co	30	605	585	5
C674	rod	36.5 Zn–2.8 Mn–1.2 Al–1.0 Si	23	634	379	20
C687	tube	20.5 Zn–2.0 Al–0.04 As	23	414	186	55
C688	flat	22.7 Zn–3.4 Al–0.4 Co	18	750	670	4
C690	flat	22.7 Zn–3.4 Al–0.6 Ni	18	780	700	4
C694	rod	14.5 Zn–4.0 Si	6	690	393	21

[a] To convert MPa to psi, multiply by 145.

C674 and C694 are commonly used in rod and wire forms. These alloys are used in valve stems, shafts, bushings, and gears. Dispersoids of second phases that come about from beta-phase decomposition products account for their higher strength. C687, inhibited by the arsenic addition, is primarily a tube alloy that is used in condensers, evaporators, heat exchangers, and ferrules.

7.15. Copper–Nickels.

The copper–nickel alloy system is essentially single phase across its entire range. Alloys made from this system are easily fabricated by casting, forming, and welding. They are noted for excellent tarnishing and corrosion resistance. Commercial copper alloys extend from 5 to 40 wt% nickel.

Iron is added in small (usually 0.4–2.3 wt%) amounts to increase strength. More importantly, iron additions also enhance corrosion resistance, especially when precautions are taken to retain the iron in solution. Precipitation of the iron–nickel-rich phase does not result in strengthening and can cause degradation of corrosion resistance (49). A small (up to 1.0 wt%) amount of manganese is usually added to react with and remove both sulfur and oxygen from the melt. These copper alloys are most commonly applied where corrosion resistance is paramount, as in condenser tube or heat exchangers.

The common cupronickels are C704, which has 5 Ni–1.5 Fe; C706, 10 Ni–1.4 Fe; C710, 20 Ni; and C715, 30 Ni–0.7 Fe. Mechanical properties of these alloys are summarized in Table 21. The best resistance to aqueous corrosion is available from C715 containing 30 wt% nickel. Both C715 and the lower cost C706 are suited for condenser and heat exchanger tubes in power plants. This group of alloys is also highly resistant to stress corrosion and impingement corrosion.

C725, a 9 wt% nickel alloy that is further strengthened by 2 wt% tin, is used in electrical connectors and bellows. Properties are summarized in Table 21. The alloy has good resistance to stress relaxation at room and moderately elevated temperatures, which accounts for its use in electrical connectors and electrical circuit wire wrap pins.

Environmental factors must be considered when specifying copper–nickel alloys. The higher nickel compositions are less resistant to sulfides in seawater applications, for example. C713, containing 25 wt% nickel, is extensively used in U.S. coinage because of its good tarnish resistance. C722, containing Cu–17 Ni–0.8 Fe–0.5 Cr, is intended as a tube alloy having improved resistance

Table 21. **Conductivity and H04 (Hard) Temper Tensile Properties of Cupro–Nickel Alloys**

UNS	Alloy, wt %	Electrical conductivity, % IACS	Tensile strength, MPa[a]	0.2% Yield strength, MPa[a]	Elongation in 50 mm, %
C704	5.5 Ni–1.5 Fe	14.0	440	435	5
C706	10 Ni–1.4 Fe	9.0	518	500	5
C710	20 Ni	6.5	518	500	5
C715	30 Ni–0.5 Fe	4.6	580	545	3
C725	9 Ni–2 Sn	11.0	570	555	3

[a] To convert MPa to psi, multiply by 145.

Table 22. **Conductivity and Hard Temper Tensile Properties of Cu—Ni—Zn Alloys**

UNS	Nickel, wt %	Zinc, wt %	Electrical conductivity, % IACS	Tensile strength, MPa[a]	0.2% Yield strength, MPa	Elongation in 50 mm, %
C745	10	25	9	590	515	4
C752	18	17	6	585	510	3
C754	15	20	7	585	515	3
C757	12	23	8	585	515	4
C770	18	27	6	585	505	4

[a] To convert MPa to psi, multiply by 145.

to impingement corrosion in flowing water in condenser or heat exchanger applications.

7.16. Nickel–Silvers. Nickel–silver alloys, once called German silver, are a series of solid solution Cu–Ni–Zn alloys, the compositions of which encompass the ranges of 3–30 wt% Zn and 4–25 wt% Ni. This family of alloys falls within the UNS designation numbers C731 to C770. Leaded nickel–silvers that contain from 1.0 to 3.5 wt% lead for improved machining characteristics are designated as C782 to C799.

Nickel–silver alloys are not readily hot worked but have excellent cold fabricating characteristics. Because of the high nickel and zinc contents, these alloys exhibit good resistance to corrosion, good strength, and usually adequate formability, but have low electrical conductivity. Wire and strip are the dominant forms used for hardware, rivets, nameplates, hollowware, and optical parts. Table 22 lists common nickel–silvers and compares electrical conductivities and tensile strengths. Because of high nickel contents, these alloys are highly resistant to dezincification in spite of the high zinc content. Good resistance to corrosion in both fresh and seawater is another attribute.

Of the several leaded nickel–silvers, C782 (Cu–23Zn–10Ni–2Pb) is one of the most commonly used. This alloy is not hot processable and has limited cold processing capacity. It is usually available as strip for application as keystock, watch parts, and plates because of its excellent machinability, hardness and corrosion resistance.

7.17. Precipitation Hardening Alloys. Copper alloys that can be precipitation hardened to high strength are limited in number. In addition to the metallurgical requirement that the solubility of the added element(s) decreases with decreasing temperature, the precipitated phase that forms during aging must be distributed finely and have characteristics that act to resist plastic deformation.

Commercial precipitation hardening copper alloys are based on beryllium, chromium, titanium, and nickel, the latter in combination with silicon or tin. The principal attributes of these alloys are high strength in association with adequate formability. Electrical conductivity varies according to alloy and ranges from ~20–80% IACS.

Usually, the aging treatment is done by the strip manufacturer, to produce “mill hardened” strip. The resulting strip properties are a practical compromise between good formability and less-than-peak strength. The advantage of these tempers is that the fabricator does not need to heat treat the strip, eliminating the need for post-form cleaning and the possibility of part distortion during the anneal. The highest strength can, however, be achieved by the fabricator performing the precipitation hardening thermal treatment following fabrication of parts from solution treated–cold rolled temper strip. This allows the fabricator to take advantage of the superior formability to make the most geometrically demanding parts and achieve high strength by aging after part fabrication.

7.18. C170 to C175 (Beryllium Copper). The addition of beryllium to copper results in a significant age hardening response, making these alloys one of the few nonferrous materials that can reach 1400-MPa (200,000 psi) tensile strength (7). These alloys are more precisely ternary alloys. Additions of cobalt or nickel control grain size through the formation of coarse beryllides that pin grain boundaries and promote the hardening precipitation reaction.

Table 23 illustrates yield strength–bend formability trade-offs associated with making parts from a mill hardened temper (TM02) versus forming rolled temper strip (H02) and then aging to produce a TH02 temper product. Parts that require the same formability can be made using both the rolled temper and mill hardened material, but it is possible to achieve higher strength by aging after forming. However, aging after forming can introduce dimensional changes that accompany the hardening reaction in beryllium coppers. Moreover, the parts must be chemically cleaned with aggressive reagents to remove beryllium oxide formed during the thermal treatment. For these reasons, mill hardened strip represents the majority of the beryllium copper that is used.

The trade-off between conductivity and formability, at comparable strength, is also shown in Table 23. More dilute compositions (C17410 and C1751) provide higher conductivity in the mill hardened condition, but at a sacrifice in formability relative to mill hardened C172.

Toxicity concerns regarding beryllium result principally from possible consequences from inhaling its oxide. Any operation that produces airborne particles or dust of the oxide must be carried out using proper precautions to personnel.

7.19. C180 to C182 (Chromium–Copper). Chromium–copper alloys have widespread use in those applications requiring good formability, conductivity,

Table 23. **Properties of Beryllium Copper Alloys**

UNS	Temper	Conductivity, % IACS[b]	Yield strength, MPa[c]	Formability, MBR/t[a] GW	Formability, MBR/t[a] BW
C172	H02	15	586	0.5	1
	TH02[d]	20	1207	>5	>5
	TM02	18	758	0.5	1
C17410	HT	45	758	1.2	5.0
C17460	HT	50	792	1.5	1.5
C1751	TH04	50	758	2	2

[a] For 90° bend forming angle.

[b] Minimum values given.

[c] To convert MPa to psi, multiply by 145.

[d] H02 temper + aged at 315°C for 2 h.

Table 24. **Conductivity and Age Hardened Tensile Properties of Chromium–Copper Alloys**

UNS	Composition, wt %	Electrical conductivity, % IACS	Tensile strength, MPa[a]	0.2% Yield strength, MPa[a]	Elongation in 50 mm, %
C18080	0.5 Cr–0.1 Ag–0.1 Fe–0.06Ti–0.03Si	80	515	480	9
C181	0.8 Cr–0.15 Zr–0.04 Mg	80	496	455	10
C18135	0.4 Cr–0.4 Cd	92	469	421	12
C182	0.9 Cr	80	460	405	14

[a] To convert MPa to psi, multiply by 145.

stress relaxation resistance and strength. For example, both welding electrode tips and electrical connectors require moderate strength and relatively high conductivity, but the former also requires good softening resistance, whereas the latter also requires good formability. As much as 0.65 wt% chromium can be dissolved in copper to produce a uniform array of pure chromium precipitates during the age hardening treatment. The low room temperature solubility of chromium ($<0.03\%$) ensures good (usually $\sim$85% IACS) conductivity after the subsequent age hardening heat treatment. Moreover, compositions above the maximum solubility level are commercially made in order to take advantage of the dispersion of coarser chromium particles that are useful for control of grain size. Typical properties of chromium–copper alloys in age hardened temper are summarized in Table 24.

7.20. Cu–Ni–Si Alloys. This commercially important alloy family is precipitation hardened through the formation of Ni_2Si for optimum combinations of strength, conductivity, and formability. The composition and processing of C7025 also results in high temperature resistance to both stress relaxation and softening, required for part manufacturing and service of elevated temperature connectors. These alloys are notable also for good general corrosion and stress corrosion resistance that is equivalent to the highly resistant phosphor bronzes. High strength combined with moderate conductivity available from the alloy is important for applications where ohmic (I^2R) heating from high electrical currents are possible.

Cu—Ni—Si alloys are also available in more dilute versions such as C19010. Higher conductivity but lower strength is available from the latter alloy. Table 25 compares mechanical properties of the mill hardened condition of these alloys.

7.21. C726 to C729. Very high strength, nearly equal to that available from beryllium–copper, is possible with precipitation hardened Cu—Ni—Sn alloys. These alloys, referred to in the literature as spinodal alloys are hardened by a precipitation reaction known as spinodal decomposition. They encompass a range of compositions that includes Cu–7.5 Ni–5 Sn (C7265), Cu–9 Ni–6 Sn (C727) and Cu–15 Ni–8 Sn (C729). More dilute compositions such as Cu–4 Ni–4 Sn (C726) do not precipitation harden appreciably, as do C727 and C729. The latter two alloys are not easily hot worked and are usually made by strip casting followed directly by cold working, or by consolidation of alloy powder.

Table 25. **Properties of Precipitation Hardened Cu—Ni—Base Alloys**

UNS	Composition, wt %	Temper	Cond., % IACS	Tensile strength, MPa[a]	0.2% Yield strength, MPa[a]	Elongation in 50 mm, %
C180	2.5 Ni–0.6 Si–0.4 Cr	H50	48	690	525	12
C19010	1.3 Ni–0.25 Si–0.03P	Extra Hard	60	551	517	6
C7025	3 Ni–0.65 Si–0.15 Mg	TM00	40	690	530	12
		TM03	35	785	735	7
C7026	2 Ni–0.5 Si	TM04	50	670	620	6
C7265	7.5 Ni–5 Sn	TH04		1015	945	4
		TM04	15	860	755	12
C729	15 Ni–8 Sn	TH04		1240	1100	3
		TM04	8	860	790	15

[a] To convert MPa to psi, multiply by 145.

Like beryllium copper, C729 is available in the rolled temper condition, for subsequent aging after forming, or in the mill hardened condition. Typical properties of these alloys are shown in Table 25. In addition, these alloys exhibit notably excellent resistance to stress relaxation at high application temperatures, eg, 200°C, and in this respect outperform beryllium–copper. However, the 8% IACS electrical conductivity of the strongest Cu–Ni–Sn composition (C729) is lower than that of C172.

8. Economic Aspects

One of the factors affecting the relative pricing of commercial copper alloys is metal value. The metal value of copper was around $1.65/kg ($0.75/lb) at the end of 2002. Other factors affecting costs include metal value of the constituent alloy elements, order quantities, the supplier, and specified dimensional tolerances. Oxygen-free copper, C102, is sold as a premium product relative to copper. Brass, eg, C260, is less costly than copper because zinc is historically lower priced than copper. Tin-containing phosphor bronzes, such as C510, and nickel containing alloys such as the 700-series are more costly than brass and copper because of higher tin and nickel metal cost, respectively.

9. Applications

Alloy selection for a particular application generally involves consideration of a combination of physical and mechanical properties as well as cost. Heat exchangers, including automobile radiators and domestic heating systems, are prime examples. Alloys used for such applications require not only good corrosion resistance and reasonable thermal conductivity, but also the capabilities of being formed into a variety of shapes and joined easily by soldering or brazing. C110 and C122 coppers are therefore widely used in such applications. C260 brass has also been used extensively in automobile radiators because of the good formability it possesses for manufacture of headers and because of its strength. Copper–nickel alloys such as C706 and C715 find application in condensers used in power utilities and desalination units because of their good corrosion resistance and reasonable conductivity relative to alternative materials.

Electrical interconnections that range from home wall receptacles to miniature connectors used in electronic products all require good formability and other properties specific to their application. Automotive connectors are frequently situated in the harsh environment of the engine compartment, where resistance to stress relaxation is needed to provide stable contact force for reliable performance. Alloys like the beryllium coppers and C7025 are supplanting C260 brass and the phosphor bronzes in such elevated temperature applications. Interconnection systems, which carry large currents, require high electrical conductivity to minimize ohmic (I^2R) heating. Unacceptable loss in contact force due to stress relaxation can result in open-circuit failure of the connector if the operating temperature is too high for the alloy being used. The high copper alloys are therefore to be favored in such applications, provided that they also have adequate stress relaxation resistance. Alloys C151, C18080, C182, and C194 can more easily meet these property requirements. Computers, consumer electronics and telecommunications systems require connectors which carry only small, signal level, currents. The miniaturization trend in these applications, however, results in a requirement for copper alloys with yield strength >100 ksi, conductivity $>45\%$ IACS and good formability; eg, C7025 and C17460.

Strength, thermal conductivity and formability account for selection of particular alloys for use as leadframes in plastic encapsulated devices. Leads having high strength are needed to ensure against damage to the electronic package during handling before and during assembly to circuit boards. This requirement is particularly critical for high lead count packages where the leadframe material is thin ($\sim$0.15 mm) and leads are extremely narrow (0.30 mm). The leadframe also provides a path for heat to be dissipated from the operating integrated circuit (chip) to prolong its service lifetime. Alloys that provide high strength near 690 MPa (100,000 psi) yield strength combined with high thermal conductivity (at least 175 W/(m·K), equivalent to around 40% IACS electrical conductivity) are preferred for such applications.

Other applications that take advantage of the high electrical and thermal conductivity of copper and its alloys include superconducting wires and RF/EMI shielding. Controlled electrical resistance is required for applications such as resistance heating as in heated car seats.

An additional virtue of many copper alloys is the capacity for deep drawing such as cartridge cases and flexible bellows. C260 and C510 are well known for their drawability. Be–Cu that is drawn and then aged is used for bellows that have excellent fatigue life.

Finally, coinage and architectural uses take advantage of the variety of distinctive colors inherent to copper and its alloys, from red, through gold-yellow and silver-white, as well as tarnish and corrosion resistance. Among the alloys used are C713, a white-appearing alloy used in U.S. coinage; gold-appearing aluminum–bronze (C6155) and brass (C260); and red-brown copper–tin bronze. Clad coinage having dissimilar copper alloys for the clad and core components have the further advantage of being difficult to counterfeit when used in vending machines. The worldwide trend has been to use coins to replace low denomination paper bills because the useful lifetime of coins is much longer.

Finally, it is important to note that the ability to be plated or coated with a wide range of materials including tin, solder, chromium, nickel, gold and palladium is an important attribute of copper alloys which contributes to their selection for many applications. For example automotive connectors may be tin or solder coated, whereas electronics connectors are nickel and gold plated with palladium used also. Decorative brass hardware may receive a chromium coating for cosmetic purposes.

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