THE COPPER ADVANTAGE

A Guide to Working With Copper and Copper Alloys

Antimicrobial Copper Cu+ ™

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PREFACE

The information in this guide includes an overview of the well-known physical, mechanical and chemical properties of copper, as well as more recent scientific findings that show copper has an intrinsic antimicrobial property. Working and finishing techniques, alloy families, coloration and other attributes are addressed, illustrating that copper and its alloys are so adaptable that they can be used in a multitude of applications in almost every industry, from door handles to electrical circuitry to heat exchangers.

Copper's malleability, machinability and conductivity have made it a longtime favorite metal of manufacturers and engineers, but it is its antimicrobial property that will extend that popularity into the future. This guide describes that property and illustrates how it can benefit everything from common touch surfaces to HVAC coils.

History is rich with evidence of copper's biocidal ability. For example, the ancient Egyptians, Greeks, Romans and Aztecs used copper compounds for the treatment of disease and good hygiene and, much later, the hulls of British naval ships were encased in copper to protect against biofouling. In support of the historical anecdotal evidence, recent laboratory testing has shown that copper and copper alloys are effective antimicrobial materials.

Copper, brass and bronze work effectively against the most troublesome antibiotic-resistant bacteria* including Methicillin-resistant *Staphylococcus aureus* (MRSA) and Vancomycin-resistant *enterococcus* (VRE), as well as other common harmful bacteria*.

Copper is the only solid surface material registered by the U.S. Environmental Protection Agency to continuously kill bacteria* that pose a threat to human health. No other touch surface material has this kind of registration.

This booklet will serve to answer immediate questions about using copper and copper alloys in familiar ways and in new applications, as well as guide the reader to sources of more in-depth information.

* Laboratory testing shows that, when cleaned regularly, Antimicrobial Copper™ kills greater than 99.9% of the following bacteria within 2 hours of exposure: Methicillin-resistant *Staphylococcus aureus* (MRSA), Vancomycin-resistant *enterococcus faecalis* (VRE), *Staphylococcus aureus*, *Enterobacter aerogenes*, *Pseudomonas aeruginosa*, and *E. coli* O157:H7. Antimicrobial Copper surfaces are a supplement to and not a substitute for standard infection control practices. Like other antimicrobial products, they have been shown to reduce microbial contamination, but do not necessarily prevent cross contamination; users must continue to follow all current infection control practices.

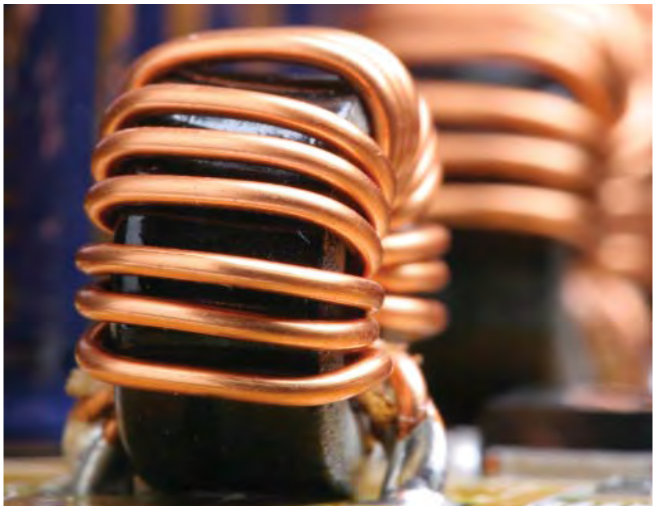
I. INTRODUCTION

Copper and copper alloys are widely used in a variety of products that enable and enhance our everyday lives. They have excellent electrical and thermal conductivities, exhibit good strength and formability, have outstanding resistance to corrosion and fatigue, and are generally nonmagnetic. They can be readily soldered and brazed, and many can be welded by various gas, arc and resistance methods. They can be polished and buffed to almost any desired texture and luster. Pure copper is used extensively for electrical wire and cable, electrical contacts and various other parts that are required to pass electrical current. Coppers and certain brasses, bronzes and copper nickels are used extensively for automotive radiators, heat exchangers, home heating systems, solar collectors, and various other applications requiring rapid conduction of heat across or along a metal section. Because of their outstanding ability to withstand corrosion, coppers, brasses, bronzes and copper nickels are also used for pipes, valves and fittings in systems carrying potable water, process water or other aqueous fluids, and industrial gases.

Copper alloys are also ideally suited where it is important to minimize bacterial* levels on touch surfaces. Because of their inherent ability to kill 99.9% of bacteria* within two hours, more than 280 copper alloys have been granted public health registration by the U.S. Environmental Protection Agency (EPA). This unprecedented registration recognizes copper's inherent ability to continually kill bacteria* between regular cleanings, and aids in reducing infection-causing bacteria* on touch surfaces in hospitals, schools, offices and other public establishments.

Conductivity

Of all common metals, copper possesses the highest rating for both electrical and thermal conductivity. High conductivity coupled with intrinsic strength, formability and corrosion resistance make copper alloys unique as conductors of electricity – making them ideal for connectors and other electrical/electronic products.



Strength

Copper is a relatively soft and malleable metal with excellent formability, making it ideal for architectural applications such as roofs, wall cladding, gutters and downspouts. Additions of other elements to copper strengthen it and form copper alloys, including brasses, phosphor bronzes and copper nickels. Copper alloys possess tensile properties that exceed some aluminum alloys and approach those of stainless steels, and can be used in a multitude of applications. Miniaturization of electronic devices and components has benefited from the high strength and moderate to high conductivities offered by specialty copper alloys.

Formability

Copper's exceptional formability is most readily illustrated by its ability to produce micron-sized wire with minimum softening anneals. In general, copper alloys exhibit increased strength proportional to the amount and the nature of the alloying element. In brasses, bronzes, nickel silvers, copper nickels and other alloy families, strength is increased in proportion to the amount of cold work. Deep drawing, coining, stretching, and bending are common methods used to form components such as bathroom fixtures and other household products. Cartridge brass reflects the deep drawing characteristic of that alloy. Copper nickel tubes are generally formed from strip and then custom installed as condenser bundles.

Joining

Copper and copper alloys can be easily joined by the common methods – soldering, brazing, welding, bolting, riveting, crimping and adhesive bonding. The installation of plumbing fixtures and components provide examples of typical soldering and brazing applications. Welding techniques are routinely used for copper and copper nickel welded tube used in water delivery systems, heat exchangers and air-conditioning units. Additional information is found in Section VII of this publication.

Corrosion

Copper and its alloys are widely used in many environments and applications because of their excellent corrosion resistance. Architectural fittings and fixtures made from copper, brass and bronze continue to provide service in both indoor and outdoor environments. Copper alloys corrode at negligible rates in unpolluted air, water and deaerated nonoxidizing acids. Many copper alloy artifacts have been found in nearly pristine condition after having been buried in the earth for millennia. Copper roofing has been found to corrode at rates of less than 0.015 in (0.4mm) in 200 years. Copper alloys resist many saline solutions, alkaline solutions and organic chemicals.

Typical applications where copper and copper alloys provide superior service include indoor and outdoor architectural components, freshwater supply lines and plumbing fixtures, heat exchangers and condensers, freshwater and seawater marine hardware, industrial and chemical plant process equipment, electrical wire and cable, printed circuit boards and industrial products.

Copper is Antimicrobial

The antimicrobial attributes of copper and its alloys are intrinsic and have been exploited for centuries. Egyptians used copper drinking vessels to clean water. The Hippocrates Collection, 460 to 380 B.C., recommends the use of copper for leg ulcers related to varicose veins. Pliny the Elder, A.D. 23 to 79, used copper oxide with honey to treat intestinal worms. The Aztecs gargled with a mixture containing copper to treat sore throats.

Recent independent laboratory testing led the EPA to register copper alloys for their inherent ability to kill 99.9% of the following listed organisms within two hours: Vancomycin-resistant *enterococci* (VRE), *Staphylococcus aureus*, *Enterobacter aerogenes*, *Escherichia coli* O157:H7, *Pseudomonas aeruginosa* and Methicillin-resistant *Staphylococcus aureus* (MRSA). No other solid metal surfaces have EPA registration to make public health claims.

Widely publicized statistics from the Centers for Disease Control and Prevention (CDC) estimate infections acquired in U.S. hospitals affect two million individuals every year and result in nearly 100,000 deaths annually. Results from a clinical trial in Birmingham, England, demonstrate that the use of copper alloys on certain surfaces in a busy hospital ward has the pot ential to reduce microbial contamination compared to non-copper surfaces.

Color

Variations in the color of copper alloys stem primarily from differences in chemical composition. Unalloyed coppers have a red tone. The addition of other elements causes a change toward yellow, bronze, silver or gray. These colors can then develop patinas when exposed to air. The degree of change depends upon the alloy chemistry and the composition of the atmosphere.

Copper Alloy Families

Copper alloys are identified by the Unified Numbering System (UNS) which categorizes families of alloys based upon their elemental make-up. Wrought products range from UNS C10000 through UNS C79999; cast products are assigned numbers between UNS C80000 and UNS C99999.

TABLE 1: UNS Copper Alloy Designations

ALLOY	WROUGHT	CAST
Copper	C10100 to C13000	C80100 to C81200
Brass	C20500 to C28580	C83300 to C85800
Tin Brass	C40400 to C48600	C83300 to C84800
Phosphor Bronze	C50100 to C52400	C90200 to C91700
Aluminum Bronze	C60800 to C64210	C95200 to C95900
Silicon Bronze	C64700 to C66100	C87000 to C87999
Silicon Red Brass	C69400 to C69710	C87300 to C87900
Copper Nickel	C70100 to C72950	C96200 to C96900
Nickel Silver	C73500 to C79900	C97300 to C97800

Copper in its pure, unalloyed state is soft, provides high electrical and thermal conductivity and has excellent corrosion resistance. There are various grades of unalloyed copper, which differ in the amount of impurities they contain. Oxygen-free coppers are used specifically in applications requiring high conductivity and exceptional ductility.

Brasses are alloys made from copper and zinc, they exhibit good strength and ductility and are easily cold worked, properties which improve with increased zinc content up to 35%. Brass coloration ranges from red to golden yellow, depending on the amount of zinc the alloy contains.

Gilding Metal, Commercial Bronze, Jewelry Bronze, Red Brass and Cartridge Brass are common names given to brass alloys with specific zinc contents.

Brasses containing between 32% and 39% zinc exhibit excellent hot working characteristics but limited cold workability. Brasses containing more than 39% zinc, such as Muntz Metal, have high strength and lower ductility at room temperature than alloys with less zinc.

Brasses are known for their ease of fabrication by drawing, high cold-worked strength and corrosion resistance. Brasses are routinely blanked, coined, drawn and pierced to produce springs, fire extinguishers, jewelry, radiator cores, lamp fixtures, ammunition, flexible hose and the base for gold plate. Brasses have excellent castability. Cast brasses are used as plumbing fixtures, decorative hardware, architectural trim, low pressure valves, gears and bearings.

Tin Brasses are alloys made from copper, zinc (2% to 40%) and tin (0.2% to 3%). This family of alloys includes admiralty brasses, naval brasses and free-machining tin brasses. These alloys are used to make high-strength fasteners, electrical connectors, springs, corrosion-resistant mechanical products, marine hardware, pump shafts, and corrosion-resistant screw machine parts. They provide increased corrosion resistance, lower sensitivity to dezincification and higher strength compared with straight brasses. They possess good hot forgeability and good cold formability. These materials have moderate strength, high atmospheric and aqueous corrosion resistance and excellent electrical conductivity.

Silicon Bronzes are part of the subgroup of high-strength brasses. They contain less than 20% zinc and up to 6% silicon and are solid solution strengthened. Silicon red brasses are used for valve stems where corrosion resistance and high strength are critical. Included in this category are the silicon red bronzes, which are similar to silicon red brasses except for their very low concentrations of zinc. They are used to make bearings, gears and intricately shaped pump and valve components.

Nickel Silvers, also called nickel brasses, are alloys containing copper, nickel, and zinc. Though they do not contain silver, they have an attractive silver luster, moderately high strength and good corrosion resistance. They are used to make food and beverage handling equipment, decorative hardware, electroplated tableware, optical and photographic equipment and musical instruments.

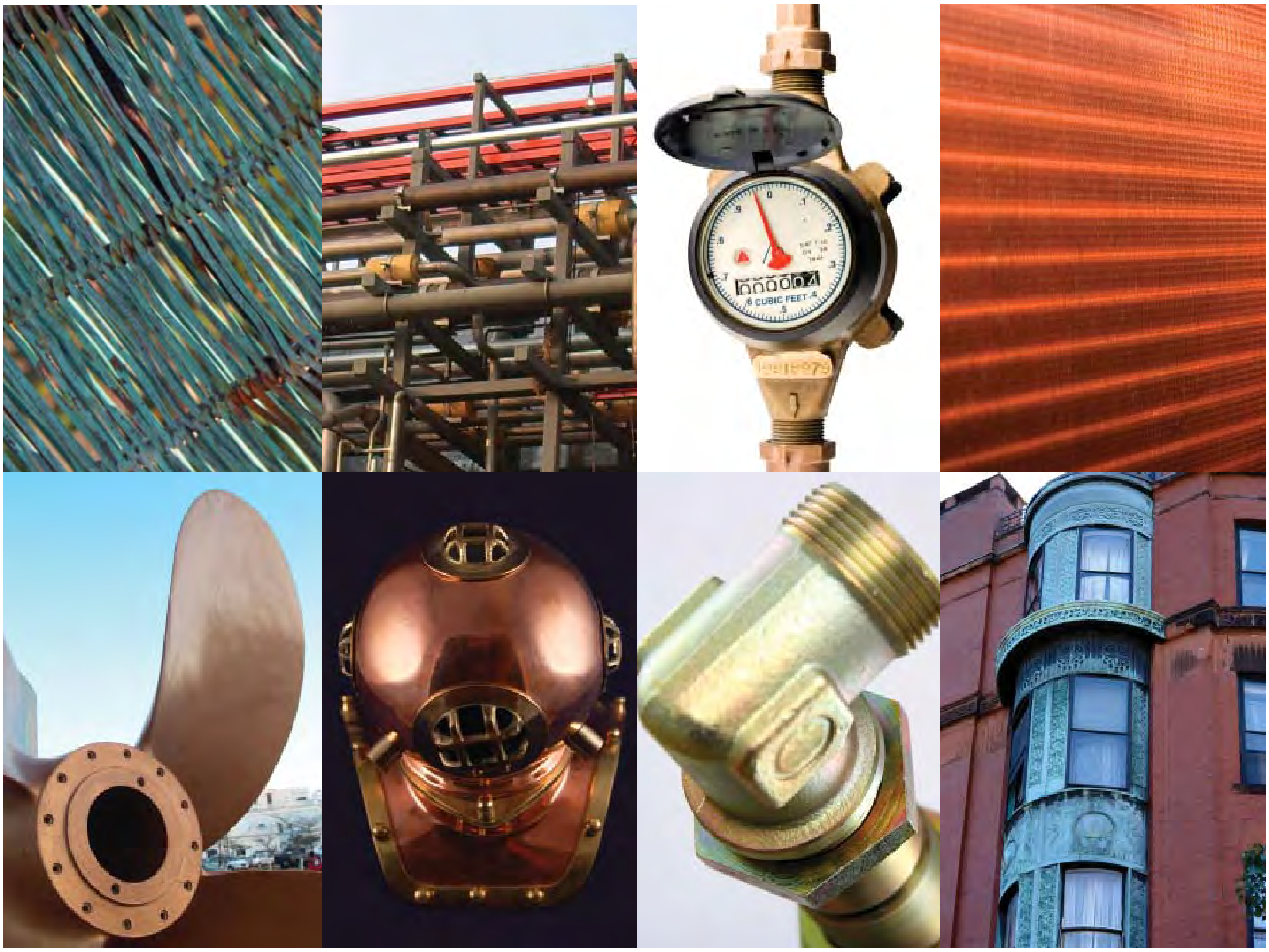
Copper Nickel alloys contain anywhere from 2% to 30% nickel, are highly corrosion-resistant and thermally stable. The addition of iron, chromium, niobium and/or manganese can improve their strength and corrosion resistance. They are virtually immune to stress corrosion cracking and exhibit high oxidation resistance in steam and moist air. The higher nickel alloys are well known for their corrosion resistance in sea water as well as resistance to marine biofouling. They are used to make electrical and electronic products, tubes for condensers in ships, on offshore platforms and in power plants, and various other marine products including valves, pumps, fittings and sheathing for ship hulls.

Phosphor Bronzes, or tin bronzes as they are sometimes called, contain between 0.5% and 11% tin and 0.01% to 0.35% phosphorous. Tin increases their corrosion resistance and tensile strength; phosphorous increases wear resistance and stiffness. Phosphor bronzes have superb spring qualities, high fatigue resistance, excellent formability and solderability, and high corrosion resistance. They are used primarily for electrical products; other uses include corrosion resistant bellows, diaphragms and spring washers.

TABLE 2: Compositions & Properties of the More Common Copper Alloys

ALLOY UNS No.	COMMON NAME	NOMINAL COMPOSITION Wt%	ELECTRICAL CONDUCTIVITY %IACS	TENSILE STRENGTH * Ksi (MPa)
C11000	Copper	99 min Cu	101	42 (290)
C12200	Phosphorus Deoxidized Copper	0.025 P	85	42 (290)
C17200	Beryllium Copper	1.90 Be	22	128 (882)**
C23000	Red Brass	15 Zn	37	56 (386)
C26000	Cartridge Brass	30 Zn	28	62 (427)
C28000	Muntz Metal	40 Zn	28	70 (483)
C42500	Tin Brass	10 Zn – 2 Sn	28	63 (434)
C51000	Phosphor Bronze A	5 Sn – 0.2 P	15	68 (469)
C52400	Phosphor Bronze D	10 Sn – 0.2 P	11	83 (572)
C65500	High Silicon Bronze A	3.3 Si – 1.0 Mn	7	78 (537)
C70600	Copper Nickel, 10%	10 Ni – 1.4 Fe	9	65 (448)
C71500	Copper Nickel, 30%	30 Ni – 0.7 Fe	4.6	73 (503)
C74500	Nickel Silver, 65-10	25 Zn – 10 Ni	9	73 (503)
C75200	Nickel Silver, 65-18	17 Zn – 18 Ni	6	74 (510)

* H02, 1/2 Hd Temper
** Mill Hardened, TMO2



Aluminum Bronzes contain 6% to 12% aluminum, up to 6% iron and nickel and provide high strength and excellent corrosion and wear resistance. Solid solution strengthening, cold work and precipitation of an iron rich phase contribute to these characteristics. High aluminum containing alloys can be quenched and tempered. Aluminum bronzes are used in marine hardware, shafts and pump and valve components for handling seawater, sour mine waters, nonoxidizing acids, and industrial process fluids. They are also used as heavy duty sleeve bearings and machine tool ways. Aluminum bronze castings have exceptional corrosion resistance, high strength, toughness and wear resistance. They also exhibit good casting and welding characteristics.

Specialty Copper Alloys, based, for example, on the copper-nickel-silicon and copper-nickel-tin systems, provide unique combinations of properties due to their intrinsic precipitation hardening capability. Their high strength coupled with good formability, thermal stability and electrical conductivity make them appropriate for use in electrical and electronic connectors and hardware. These alloys have designations throughout the UNS system based upon their composition.

As we have seen, copper and its alloys constitute a broad range of chemical compositions and are employed widely in applications that enable and enhance our everyday lives. Each application makes effective use of copper's attributes: strength, conductivity, color, formability, joinability and thermal stability.

II. PHYSICAL PROPERTIES

Properties

Copper, atomic number 29 with an atomic weight of 63.54, exhibits a face-centered cubic crystal structure. Copper is a transitional element and, being a noble metal, it has inherent properties similar to those of silver and gold. Its excellent conductivity, malleability, corrosion resistance and biofunctionality stem from copper's elemental origins. Copper has a high solubility for other elements such as nickel, zinc, tin and aluminum. This solid solution alpha (α) phase is responsible for the high ductility exhibited by copper alloys. Alloying additions beyond the solubility limit result in the beta (β) phase, which exhibits a body-centered cubic (bcc) structure. This β phase has high temperature stability, and alloys that exhibit an α+β structure have excellent hot forming capability.

The density of copper is 0.321 lb/in^2 (8.89 g/cc), and its melting point is 1981°F (1083°C). All of these properties and characteristics are significantly modified when copper is alloyed. **Table 3** lists the common physical properties of copper. The physical properties of five common wrought copper alloys are compared in **Table 4**.

The periodic table shown in **Figure 1** highlights copper and its common alloying elements.

Electrical & Thermal Conductivity

Conductivity is the primary characteristic that distinguishes copper from other metals. The electrical conductivity of materials is measured against that of a standard bar of "pure" copper that in 1913 was assigned a value of 100% IACS (International Annealed Copper Standard). Since that time, improved processing techniques and higher purity ingots have resulted in commercial copper with electrical conductivity values slightly above 100% IACS.

The thermal and mechanical processing variations used to produce commercial alloys can cause profound changes in their conductivity, and frequently the alloys with the highest strengths have the lowest conductivity. The IACS values are usually published as minimum values for annealed tempers. Tempered (cold-worked) products may have a value 1 to 5 percentage points below the annealed value. The drop in electrical conductivity with cold work is illustrated by **Figure 2**, where the electrical conductivity of the fully annealed and heavily cold drawn conditions of copper and copper-zinc wire samples are shown.

Alloys of higher electrical resistivity (R) will waste more energy, since heat generated due to an electric current (I) is proportional to I^2 times the resistance. The heat generated will increase the temperature of the component, with potentially adverse consequences. Higher thermal conductivity alloys allow the designer to dissipate some of that heat, minimizing any temperature rise.

Within alloy families, thermal conductivity tends to be related to electrical conductivity; *i.e.*, alloys of higher electrical conductivity will tend to have higher thermal conductivity. This rule of thumb is convenient since thermal conductivity is rather difficult to measure, while electrical conductivity, or its inverse, electrical resistivity, is easy to measure. The nearly linear relationship between thermal and electrical conductivity at 68°F (20°C) is shown by **Figure 3** for selected copper alloys.

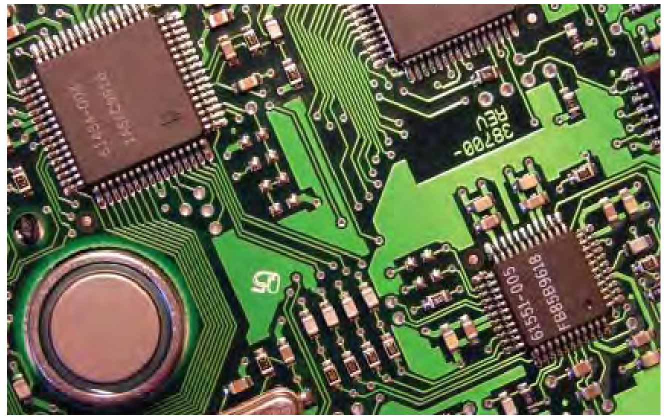


TABLE 3: Physical Properties of Copper

PROPERTY	ENGLISH		METRIC	
	VALUE	UNITS	VALUE	UNITS
Atomic Number			29	
Atomic Weight			63.54	
Density	0.322	lb/in³	8.92	g/cm³
Melting Point	1981	°F	1083	°C
Boiling Point	4703	°F	2595	°C
Latent Heat of Fusion	88	Btu/lb	205	J/g
Linear Coefficient of Thermal Expansion at: 77°F - 212°F (25°C - 100°C)	9.33×10^{-6}	in/in°F	16.8×10^{-6}	cm/cm°C
Specific Heat (Thermal Capacity) at: 68°F (20°C) 212°F (100°C)	0.0921 0.0939	Btu/lb °F Btu/lb °F	0.386 0.393	J/g°C J/g°C
Thermal Conductivity at: 68°F (20°C) 212°F (100°C)	227 223	Btu ft/ft²hr °F Btu ft/ft²hr °F	3.94 3.85	Wcm/cm² °C Wcm/cm² °C
Electrical Conductivity (Volume) at: 68°F (20°C) Annealed 68°F (20°C) Fully Cold Worked	100 - 101.5 97.0	%IACS %IACS	58.0 - 58.9 56.3	MS/m(mΩmm2) MS/m(mΩmm2)
Electrical Resistivity (Volume) at: 68°F (20°C) Annealed 68°F (20°C) Fully Cold Worked	0.6788 - 0.669 0.700	μΩ·in μΩ·in	1.7241 - 1.70 1.78	μΩ·cm μΩ·cm
Modulus of Elasticity (Tension) at: 68°F (20°C) Annealed	17×10^3	Ksi	118,000	MPa
Modulus of Rigidity (Torsion) at: 20°C: 68°F (20°C) Annealed	6.4×10^3	Ksi	44,000	MPa

Most coppers used for electrical transmission and interconnection have electrical conductivity of 85% IACS or greater. Commercially pure copper has 101% IACS as do several of the oxygen free (pure) coppers like C10100 and C10200. Note the conductivity of Phosphorous Deoxidized Copper; it has a copper content of 99.9%, yet its conductivity is “only” 85% IACS. Phosphorous is one of the elements that severely depresses conductivity.

The range of conductivity of copper alloys differs, depending on the alloying elements. High copper alloys made with tellurium, zirconium, magnesium, chromium, and iron provide increased strength with conductivity in the 75% to 90% range. Another alloy group, with combinations of elements including boron, iron, tin, zinc, cobalt, magnesium and phosphorous, provides good strength with conductivity in the range of 50% to 75% IACS.

Certain beryllium coppers, brasses, tin brasses, phosphor bronzes and copper-silicon alloys range from 25% to 50% IACS conductivity.

High-strength beryllium coppers, copper-nickel-silicon and copper-nickel-tin alloys, which can be strengthened by precipitation hardening, provide very high strength with low to medium electrical conductivity in the range from 10% to 25% IACS. Recent development of alloys in these categories have optimized high strength with conductivities of >50% IACS.

FIGURE 1: Periodic Table of Elements Showing Copper & Its Common Alloying Elements

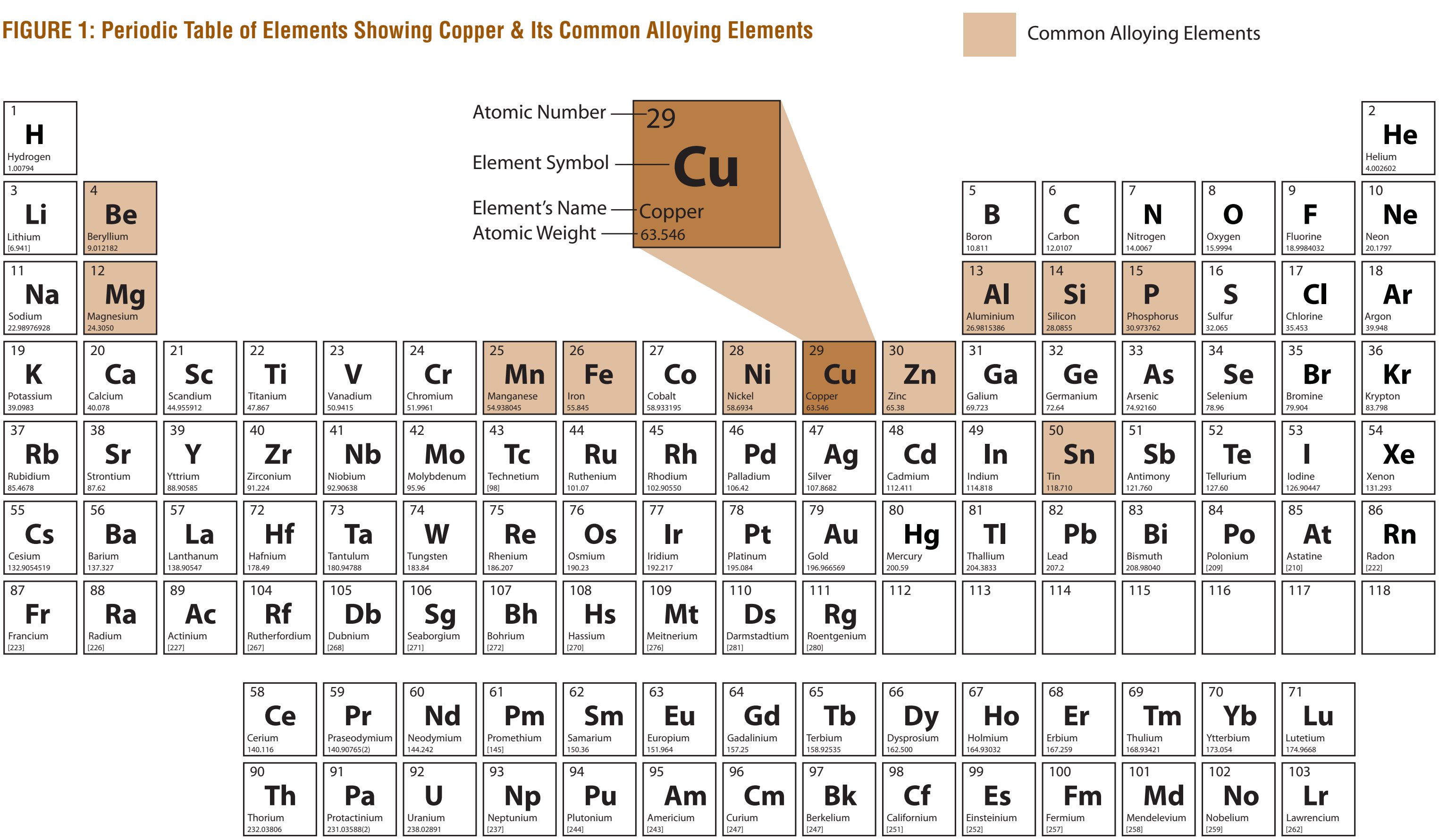


FIGURE 2: Electrical Conductivity of the Annealed & the Heavily Drawn Condition of Copper and Copper-Zinc Wire Samples

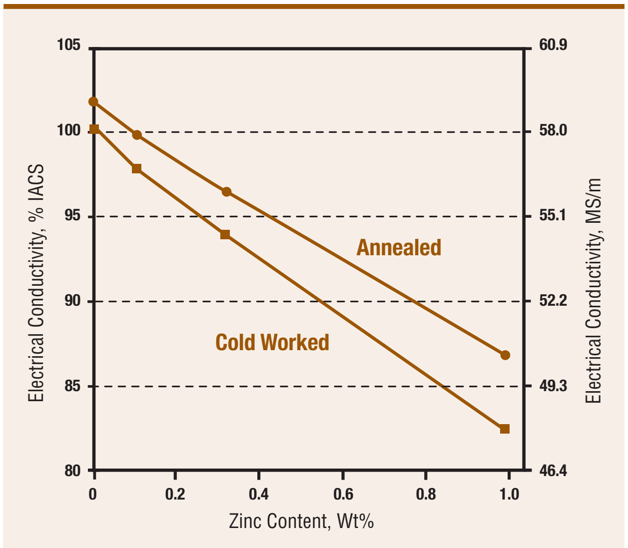


FIGURE 3: Relationship Between Thermal & Electrical Conductivity for Selected Copper Alloys

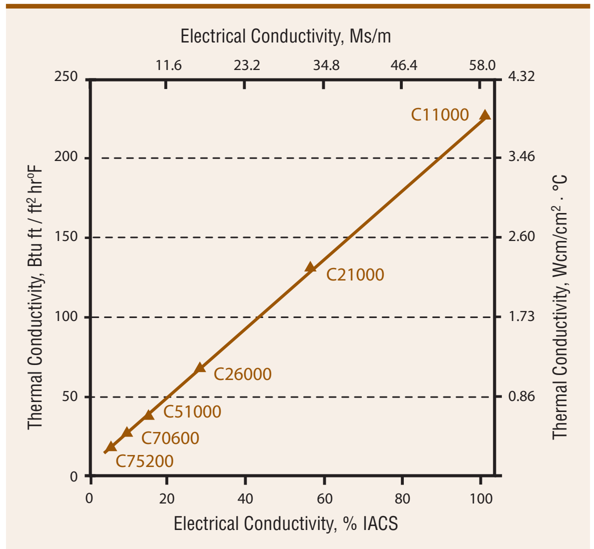


TABLE 4: Physical Properties of Five Common Wrought Copper Alloys

ALLOY UNS No	DENSITY lb/in^3 (g/cm^3)	MELTING POINT (or SOLIDUS) °F (°C)	ELECTRICAL CONDUCTIVITY %IACS (MS/m)	THERMAL CONDUCTIVITY Btu ft/ft^2 hr °F (Wcm/cm^2 °C)	THERMAL EXPANSION COEFFICIENT (Linear) X10^{-6}in/in °F (X10^{-6}cm/cm °C)
C11000	0.322 (8.92)	1949 (1065)	101 (58)	226 (3.94)	9.33 (16.8)
C26000	0.308 (8.53)	1680 (915)	28 (16)	70 (1.21)	11.1 (19.9)
C51000	0.320 (8.86)	1750 (950)	15 (8.7)	40 (0.71)	9.9 (17.8)
C70600	0.323 (8.94)	2010 (1100)	9 (5.2)	26 (0.46)	9.5 (17.1)
C75200	0.316 (8.73)	1960 (1070)	6 (3.5)	19 (0.33)	9.0 (16.2)

III. MECHANICAL PROPERTIES

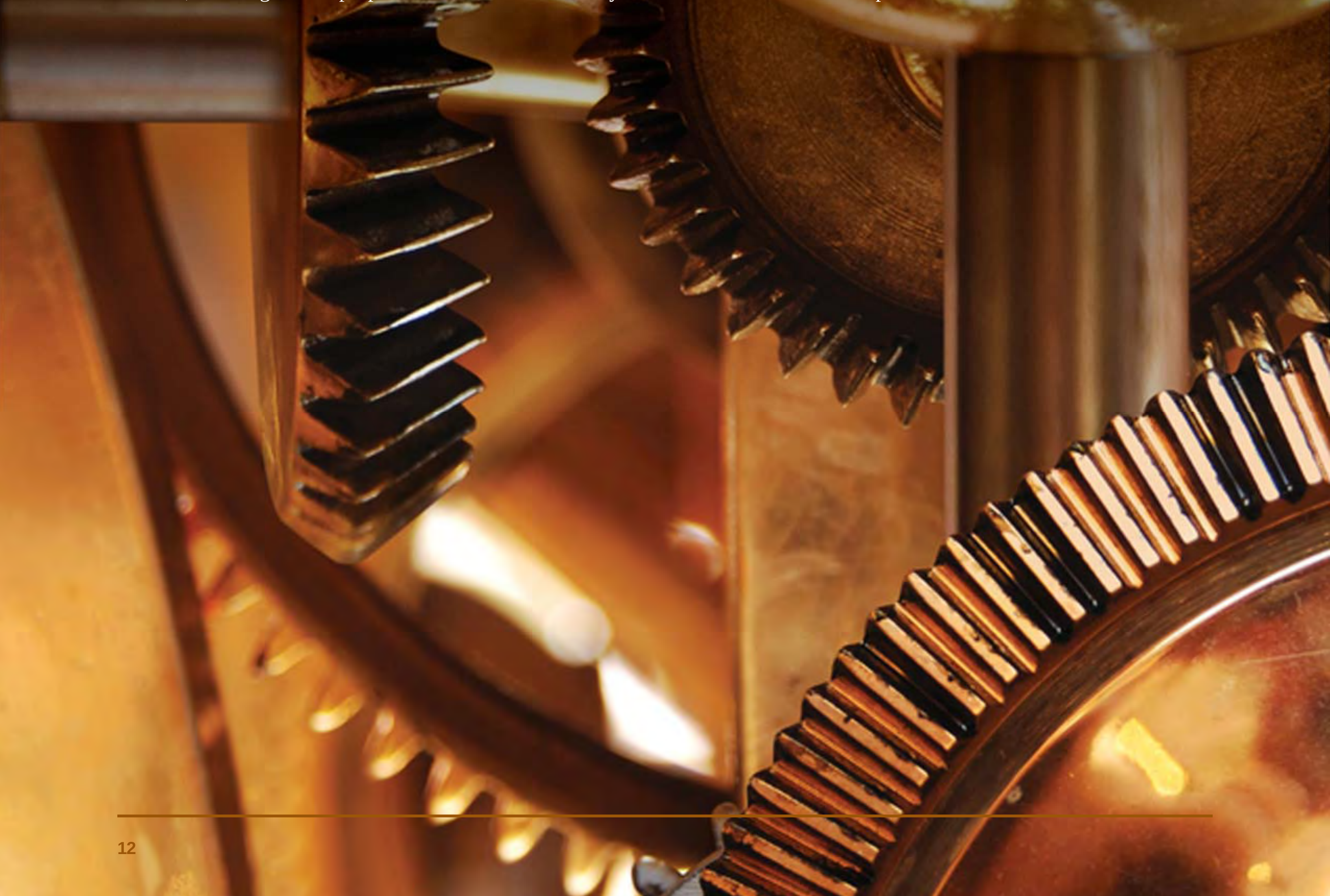
Copper is well-known to be a soft, malleable metal. Copper alloys, however, offer a wide variety and combination of mechanical properties that reflect a degree of adaptability not available in other alloy systems. Copper and high copper alloys are used extensively for cables, wires, electrical contacts and a multitude of other components that carry electrical current. These applications demand low to moderate tensile strength with moderate thermal stability or stress relaxation resistance. Alloys with a finely dispersed second phase, which provides grain refinement, are selected to maximize strength, ductility and conductivity.

Many brasses, bronzes and copper nickels are used extensively for automotive radiators, heat exchangers, home heating systems and other applications requiring rapid conduction of heat. They are chosen to provide higher strengths coupled with ease of fabrication. The highest strength and stress relaxation resistance characteristics, which are demanded by electronic connectors, are offered by the precipitation strengthened alloys. Examples of temper designations used to specify the condition of commercial copper alloys are listed in **Table 5.**

Tensile Properties

Copper alloys are primarily strengthened by cold work or by solid solution additions that enhance strain hardening. In the annealed condition, the yield and tensile strength vary inversely with grain size. The addition of alloying elements to copper increases tensile strength, yield strength and the rate of work hardening. For example, in brasses, the tensile strength and yield strength both increase as the zinc content increases.

Different alloying elements vary in their effectiveness at increasing strength and work hardening, thus providing a spectrum of property combinations. The tensile property data in **Table 6** illustrate the rolled temper effect (increasing cold work) in brass alloy C26000. The role of zinc content on rolled temper tensile properties is illustrated by data in **Table 7**, showing tensile properties of various brass alloys in the H02 or half-hard temper.



The cold rolling curves in **Figure 4** illustrate the effect of work hardening on the tensile properties of annealed, or soft, brass alloy C26000. The ultimate tensile and yield strengths increase, while the ductility and tensile elongation drops with cold rolling reduction. The cold rolling curves in **Figure 5** show the increasing tensile strength with cold rolling reduction of wrought copper alloys initially in the soft or annealed temper.

The elastic modulus ranges from 16 to 20 million pounds per square inch (about 110–138 Gpa). Poisson's Ratio, a material property that relates strain in the transverse direction in a tension test to strain in the longitudinal direction, is also nearly constant for copper alloys; a value of 0.3 is usually assigned. The brasses and bronzes exhibit higher work hardening characteristics.

These variations in elastic properties, although less than the ranges of strength and conductivity available within the alloy families, are influenced by temper, grain orientation, and stress mode. It is important to remember that stiffness is an important factor in spring design because it affects contact force.

Precipitation strengthened alloys, e.g., C17200, offer the opportunity to form parts in the maximum ductility condition (solution annealed), and then increase the tensile strength with a precipitation heat treatment. Should component fabrication preclude this approach, a mill hardened temper allows the component to be formed from the stronger but less ductile mill supplied material in favor of avoiding customized component aging.

Table 8 compares the tensile properties of the annealed (soft) and extra-hard (cold rolled 50% reduction) tempers for several important commercial copper alloys. Also included for comparison is a sampling of similar properties for low carbon steel, stainless steel and aluminum alloys.

FIGURE 4: Effect of Work Hardening on Tensile Strength, Yield Strength & Elongation (Ductility) of Annealed (Soft) Brass Alloy C26000

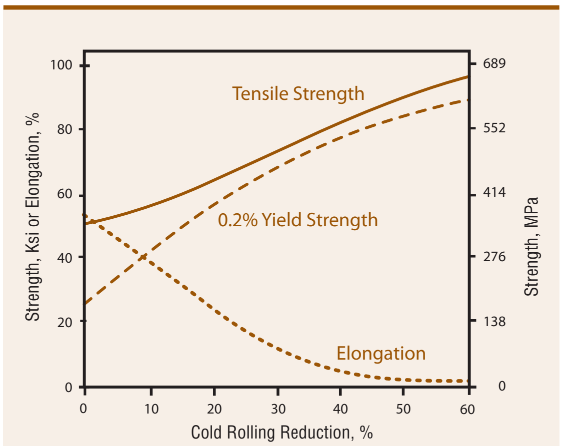


TABLE 5: Examples of Temper Designations for Copper Alloys, ASTM B 601

TEMPER DESIGNATION	TEMPER NAME OR CONDITION
Annealed Conditions	
O10	Cast & Annealed
O20	Hot Forged & Annealed
O60	Soft Annealed
O61	Annealed
O81	Annealed to Temper: 1/4 Hard
OS015	Average Grain Size: 0.015mm
Cold Worked Tempers	
H01	1/4 Hard
H02	1/2 Hard
H04	Hard
H08	Spring
Cold Worked & Stress Relieved Tempers	
HR01	H01 & Stress Relieved
HR04	H04 & Stress Relieved
Precipitation Hardened Tempers	
TB00	Solution Heat Treated
TF00	TB00 & Age Hardened
TH02	TB00 & Cold Worked & Aged
TM00 / TM02 / TM08	Mill Hardened Tempers
Manufactured Tempers	
M01	As Sand Cast
M04	As Pressure Die Cast
M06	As Investment Cast

FIGURE 5: Tensile Strength as a Function of Increasing Cold Rolling Reduction of Commercial Wrought Copper Alloys Initially in the Annealed or Soft Temper (0% Reduction)

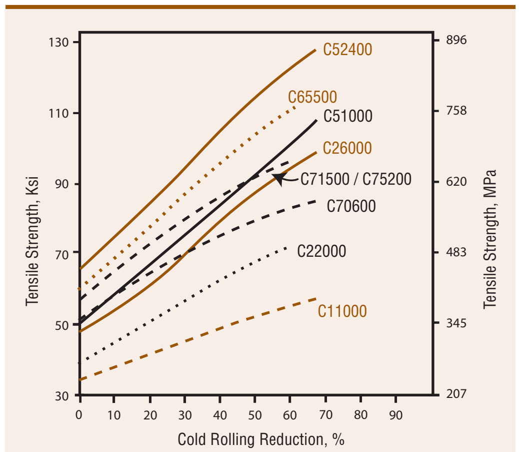


TABLE 6: Tensile Properties of Various Rolled Tempers of Alloy C26000 Flat Products at 0.040" in Thickness

ROLLED TEMPER	NOMINAL COLD REDUCTION (%)	TENSILE STRENGTH Ksi (MPa)	0.2% YIELD STRENGTH Ksi (MPa)	ELONGATION IN 2.0 in (%)
OS040 (Annealed)	0	48 (331)	16 (110)	59
H01 (1/4 Hard)	11	55 (379)	33 (228)	46
H02 (1/2 Hard)	21	62 (427)	51 (352)	30
H04 (Hard)	37	76 (524)	72 (496)	10
H06 (Extra Hard)	50	88 (607)	83 (572)	3
H08 (Spring)	60	94 (648)	89 (614)	2
H10 (Extra Spring)	68	99 (682)	92 (634)	1

TABLE 7: Tensile Properties of Various Brass Alloys in the Half-Hard (H02) Temper

ALLOY UNS No.	NOMINAL ZINC CONTENT (WT%)	TENSILE STRENGTH Ksi (MPa)	0.2% YIELD STRENGTH Ksi / MPa	ELONGATION IN 2.0 in (%)
C11000	0	41 (283)	37 (255)	20
C21000	5	47 (324)	44 (303)	17
C22000	10	52 (358)	47 (324)	12
C23000	15	56 (386)	48 (331)	14
C24000	20	60 (414)	43 (296)	18
C26000	30	62 (427)	51 (352)	23
C28000	40	70 (483)	50 (345)	10

TABLE 8: Tensile Properties of Commerical Copper Alloys in the Annealed & Extra Hard (Nominally CR 50%) Tempers Compared to Steels & Aluminum

ALLOY UNS No.	TENSILE STRENGTH Ksi (MPa)	0.2% YIELD STRENGTH Ksi (MPa)	ELONGATION IN 2.0 in (%)
C11000 Copper			
Annealed	34 (235)	11 (76)	45
H06 (Extra Hard)	52 (358)	47 (324)	5
C26000 Brass			
Annealed	53 (365)	22 (150)	54
H06 (Extra Hard)	88 (607)	83 (572)	3
C51000 Phosphor Bronze			
Annealed	50 (345)	22 (150)	50
H06 (Extra Hard)	92 (635)	80 (550)	6
C70600 Copper Nickel			
Annealed	51 (350)	13 (90)	35
H06 (Extra Hard)	79 (545)	76 (525)	4
C75200 Nickel Silver			
Annealed	58 (400)	25 (170)	41
H06 (Extra Hard)	89 (614)	83 (572)	1
1008 Low-Carbon Steel			
Annealed	44 (303)	25 (170)	41
Hard	70 (483)	60 (413)	18
304 Stainless Steel			
Annealed	87 (600)	36 (245)	52
Cold Worked 50%	158 (1089)	135 (931)	8
3004 Aluminum			
(Soft)	26 (180)	10 (69)	22
H38	41 (285)	36 (250)	5

IV. CHEMICAL PROPERTIES

Biological Importance

Copper is a micronutrient and is required for the normal functioning of plants, animals and most microorganisms. It is incorporated into a variety of proteins which perform specific metabolic functions. Because it is an essential metal, daily dietary requirements have been recommended by a number of agencies. The U.S. Department of Agriculture and the National Academy of Sciences have recommended 0.9 mg/day as the adult dietary requirement for copper. Some of the uses of copper are related to its ability to control the growth of organisms. This occurs when copper is biologically available and at certain concentrations. As a result, copper is used in a range of biocidal agents. For example, copper has been demonstrated to be an effective antibacterial*, antiplaque agent in mouthwashes and toothpastes. Copper also continues to be widely used for the control of unwanted organisms in marine applications, such as fish farming. Evidence in both fresh water and salt water indicates no hazardous effect to consumers or the fish. Copper antifouling agents used on fish net pens have been considered a source of metal to the sediments but there is little evidence that they provide a significant source of dissolved copper when there is adequate water exchange for fish farming.

Color & Tarnishing

The distinctive colors of copper and copper alloys make them prized for architectural and consumer items and objects of art. Their natural metallic tones range from red to yellow to silvery gray (**Figure 6**). A number of other colors can be obtained by chemical or electrochemical processing of their surfaces. Copper and its alloys are extremely resistant to atmospheric corrosion, but over time a superficial discoloring or tarnish layer eventually forms. All metals tarnish or form an oxide layer when exposed to the atmosphere. The thickness and chemical content of the layer varies as a function of exposure time, atmospheric conditions and base alloy chemistry.

Most metals develop a darkened surface which, as with stainless steel, may make it difficult to see the underlying base metal color. The appearance of the underlying base metal color can be preserved by applying thin, clear protective coatings. These coatings are organic chemicals which harden at room temperature or with baking and are usually applied in a solvent vehicle. Coatings do, however, interfere with and negate the fundamental antimicrobial nature of the copper alloy surface.

The tarnish film that forms on copper alloys is generally a copper oxide which, when thin, creates a darkened base color but, with time, can develop into a gray film. Although such oxides change the physical appearance of the surface, they can be removed with standard cleaning solutions.

Testing indicates that oxidation and tarnishing do not interfere with copper alloy antimicrobial performance but, in fact, enhance surface efficacy. These oxides play the crucial role of interacting with membranes of bacteria* to establish the antimicrobial efficacy of copper alloy surfaces. Base alloy chemistry and atmospheric conditions dictate the kinetics and nature of surface oxidation. Tarnishing of the alloy surface is considerably less in an indoor environment as compared with outdoor exposures. Some copper alloys, copper nickels, silicon-containing alloys and nickel silvers, in particular, show a resistance to tarnishing and retention of the base color.

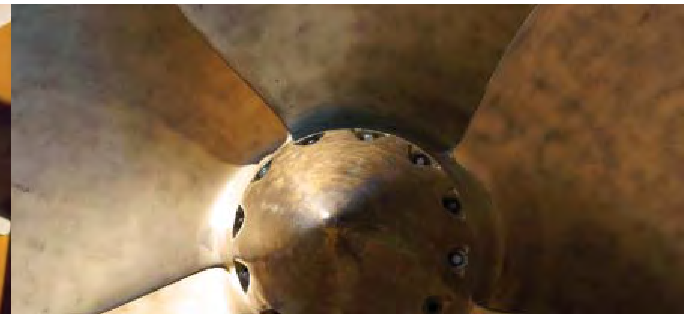
Architectural applications such as roofing and hardware (lock sets, doorknobs, kick plates, hand rails, and etc.) capitalize on the atmospheric corrosion resistance of copper and copper alloys.

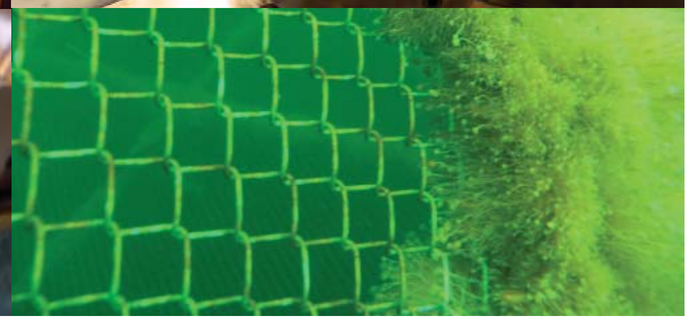
Corrosion Resistance

The inherent chemical stability of copper and copper alloys makes them superior for many applications. Fresh water supply lines and plumbing fixtures, which require resistance to corrosion by various types of water and soil, use a variety of copper alloy products. Marine components, such as fresh water and seawater supply lines, heat exchangers, condensers, shafting, valve stems and other hardware, utilize copper alloys' resistance to salt water corrosion. Heat exchangers and condensers in steam power plants and

FIGURE 6: Various Copper Alloy Colorations

Copper C11000	Admiralty Metal C44300	Aluminum Bronze C63000	Copper Nickel C70600
Commercial Bronze C22000	Phosphor Bronze C51000	Silicon Aluminum Bronze C64200	Copper Nickel C71500
Red Brass C23000	Phosphor Bronze C52100	Silicon Bronze C65100	Nickel Silver C75200
Brass C24000	Aluminum Bronze C61400	Silicon Bronze C65500	Nickel Silver (Coin) C76500
Cartridge Brass C26000	Aluminum Bronze C62400	Silicon Manganese Aluminum Brass C67400	Tin Bronze C90700
Yellow Brass C27000	Aluminum Bronze C62500	Manganese Bronze C67500	Aluminum Bronze C95400



chemical process applications use copper alloys, especially where resistance to process stream chemicals is required. Copper is also a preferred choice in industrial and chemical plant process equipment where exposure to organic and inorganic chemicals is a concern. Selection of a suitably resistant alloy requires consideration of many factors. The Copper Development Association has compiled much field experience in the form of ratings that list the behavior of different copper alloys in given environments.

Copper alloys most used in atmospheric exposure are C11000, C22000, C23000, C38500 and C75200. For roofing and flashing, C11000 is favored. Copper, zinc, lead and iron are the metals most used in underground construction. Data on the corrosion of these metals in various types of soil show copper to have the highest resistance in all cases. The largest single application of copper tube is for hot and cold water distribution in homes and other buildings. Copper is used where long-term reliability is paramount.

Copper and copper alloys are resistant to pure steam, except in the presence of ammonia (see Stress Corrosion below). When the condensate is corrosive, copper nickel alloys are preferred. Copper alloys are most suitable for handling seawater in ships and tidewater power stations. Copper, although fairly useful, is usually less resistant than C44300 (inhibited admiralty brass), C61300 (aluminum bronze), C70600 (copper nickel 10%) or C71500 (copper nickel 30%). These alloys are inherently insoluble in seawater and form corrosion product films that resist erosion corrosion.

Although copper alloys generally may be coupled to each other without serious acceleration of galvanic corrosion, close attention to galvanic effects will considerably enhance performance. The use of stainless steel or titanium tubes in copper alloy systems will generally require cathodic protection to prevent the accelerated corrosion of copper alloys that would otherwise occur.

Copper alloys are stable in a wide variety of potentially corrosive environments. Their inherent resistance to biofouling adds to their usefulness as components of seawater cooling systems.

Stress Corrosion

Stress corrosion cracking (sometimes called season cracking) occurs when a susceptible alloy component is subjected to the combined effects of sustained stress and chemical exposure. Experience with copper alloys has served to document mitigating conditions, so that today such failures are rare. Ammonia and ammonium compounds are the substances most associated with the stress corrosion susceptibility of copper alloys. These compounds can be in the atmosphere, in cleaning compounds or water treatment chemicals. All copper alloys are not susceptible to these compounds and the appropriate selection of an alloy composition and a forming process can mitigate the issue. For instance, brasses containing less than 15% zinc, copper nickels, phosphor bronzes and coppers are generally not susceptible to stress corrosion cracking.

V. ANTIMICROBIAL BEHAVIOR

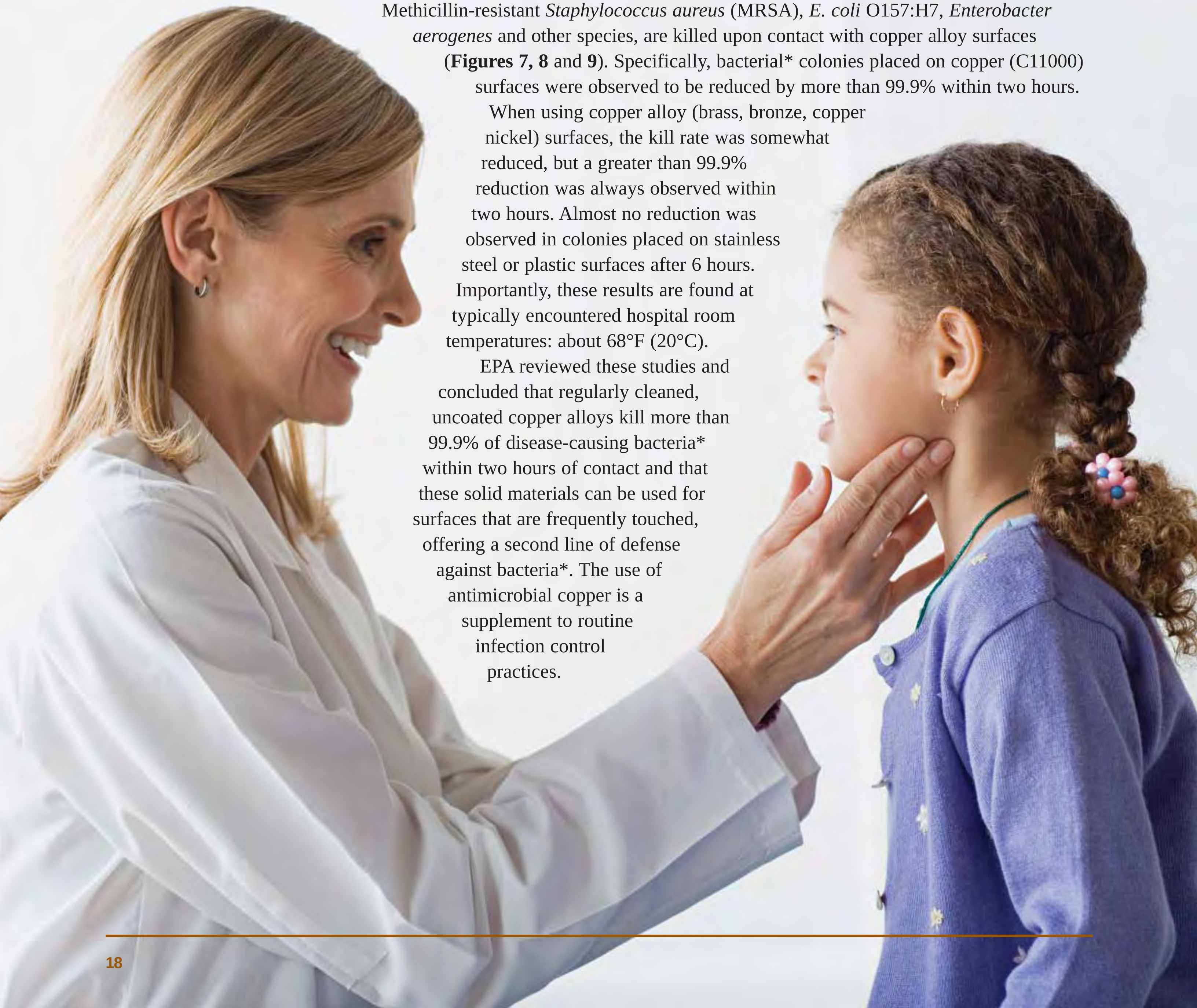
Louis Pasteur developed the germ theory of disease in the nineteenth century. It states that infections are caused by microbes invading the human body. However, long before that, the beneficial antimicrobial attributes of copper, brass and bronze were recognized. The Hippocrates Collection, 460 to 380 B.C., to which the father of medicine contributed, recommends the use of copper for leg ulcers related to varicose veins. Pliny the Elder, A.D. 23 to 79, used copper oxide with honey to treat intestinal worms. The Aztecs gargled with a mixture containing copper to treat sore throats.

More recently, a 1983 study (P. Kuhn) measured bacteria levels on brass and stainless steel doorknobs in a hospital. Results confirmed that the brass doorknob exhibited almost no microbial growth while the stainless steel doorknob was heavily contaminated. Two decades later, these observations spurred in-depth and scientifically controlled studies using test protocols specified by the U.S. Environmental Protection Agency (EPA) to quantify the antimicrobial property of copper and copper alloys.

EPA Testing

Independent laboratory tests demonstrate that disease-causing bacteria*, including Methicillin-resistant *Staphylococcus aureus* (MRSA), *E. coli* O157:H7, *Enterobacter aerogenes* and other species, are killed upon contact with copper alloy surfaces (**Figures 7, 8** and **9**). Specifically, bacterial* colonies placed on copper (C11000) surfaces were observed to be reduced by more than 99.9% within two hours. When using copper alloy (brass, bronze, copper nickel) surfaces, the kill rate was somewhat reduced, but a greater than 99.9% reduction was always observed within two hours. Almost no reduction was observed in colonies placed on stainless steel or plastic surfaces after 6 hours. Importantly, these results are found at typically encountered hospital room temperatures: about 68°F (20°C).

EPA reviewed these studies and concluded that regularly cleaned, uncoated copper alloys kill more than 99.9% of disease-causing bacteria* within two hours of contact and that these solid materials can be used for surfaces that are frequently touched, offering a second line of defense against bacteria*. The use of antimicrobial copper is a supplement to routine infection control practices.



EPA registered over 280 copper alloys with a minimum copper content of 60% as antimicrobial. As these studies continue, EPA registration of additional copper alloys, affecting more organisms and approved for additional applications, are anticipated. They are currently not registered for use in food-contact or drinking water applications.

Clinical Trials

There are or have been clinical trials at major hospitals in the United States, Chile, Germany, the United Kingdom and Japan. The critical touch surfaces in typical patient care settings have been catalogued and prototypes of hospital equipment made from antimicrobial copper alloys have been manufactured and installed. These surfaces include I.V. poles, bedrails, overbed tables, door hardware, room furniture, medical equipment, bathroom furniture and other items in close proximity to the patient. "Copperized" equipment installed in the hospital rooms are swabbed for microbial contamination and are compared with non-copper equivalents in control rooms. The impact of copper surfaces on surface contamination and, eventually, infection rates is being investigated in these trials. Data suggest that the copper surfaces installed exhibit a high reduction in microbial contamination.

Stipulations

To maintain the inherent antimicrobial property of copper, products must not be painted, lacquered, varnished, waxed or coated in any way. As with liquid and gaseous disinfectants, antimicrobial copper alloys have been shown to reduce microbial* contamination but do not necessarily prevent cross-contamination.

Manufacturers, fabricators and suppliers who have EPA registration may use Antimicrobial Copper™ and the Cu+ mark to indicate that their products are made from EPA registered antimicrobial alloys.

* Laboratory testing shows that, when cleaned regularly, Antimicrobial Copper™ kills greater than 99.9% of the following bacteria within 2 hours of exposure: Methicillin-resistant *Staphylococcus aureus* (MRSA), Vancomycin-resistant *enterococcus faecalis* (VRE), *Staphylococcus aureus*, *Enterobacter aerogenes, Pseudomonas aeruginosa*, and *E. coli* O157:H7. Antimicrobial Copper surfaces are a supplement to and not a substitute for standard infection control practices. Like other antimicrobial products, they have been shown to reduce microbial contamination, but do not necessarily prevent cross contamination; users must continue to follow all current infection control practices.

FIGURE 7: MRSA Viability on Copper Alloys and Stainless Steel at 68°F (20°C)**

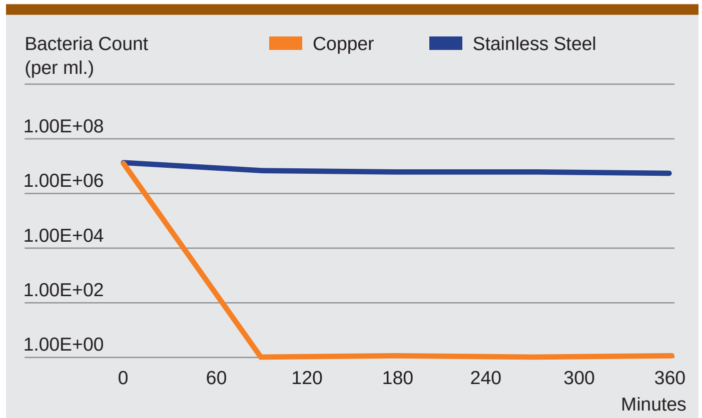


FIGURE 8: Viability of *E. Coli* O157:H7 on Copper and Stainless Steel Surfaces**

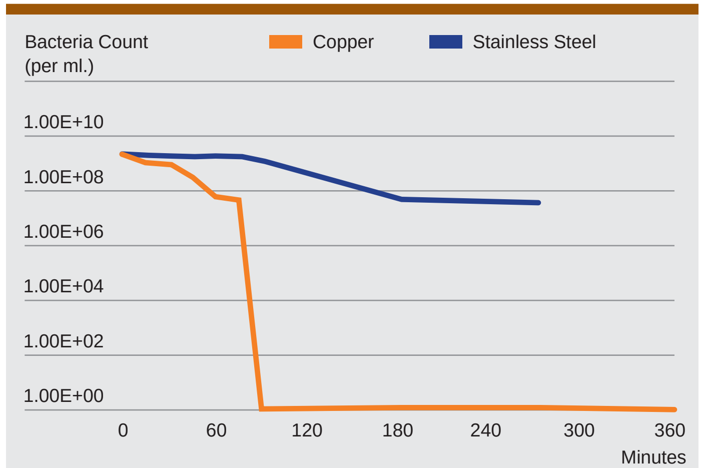
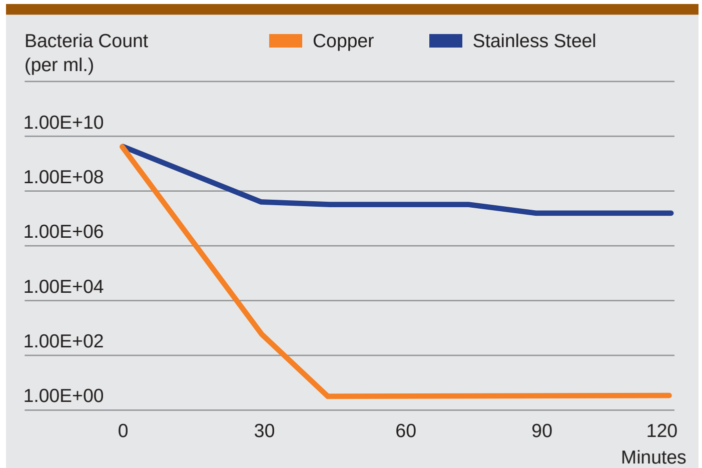


FIGURE 9: Viability of *Enterobacter Aerogenes* on Copper and Stainless Steel Surfaces**



** Stainless steel was used as a control material (as required by the U.S. EPA) in all registration efficacy testing of copper and copper alloys.

VI. WORKING WITH COPPER ALLOYS

Commercial Product Forms

Copper and copper alloys are commercially available as both wrought and cast products, including wire and cable, sheet, strip, plate, rod, bar, tubing, forgings, extrusions, castings and powder metallurgy shapes. Certain mill products, chiefly wire, cable and most tubular products, are used by customers without further metal working. On the other hand, most flat rolled products, rod, bar, mechanical wire, forgings and castings go through multiple metal working, machining, finishing and/or assembly operations before emerging as finished products.

In each copper alloy class, certain alloy compositions for wrought products have cast counterparts. As noted in the introduction, this enables designers to make alloy selections before choosing a manufacturing process. Most wrought alloys, whether sheet, strip, bar or wire, are available in various cold-worked conditions, and their strengths and formability depend upon the amount of cold work during processing, as well as their alloy content. Typical applications for cold-worked products include springs, fasteners, hardware, small gears, cams, electrical contacts and components. Certain parts, mostly plumbing fittings and valves, are produced by hot forging, because no other fabrication process can economically produce the required shapes and properties.

Because copper is one of the most sustainable and recyclable of metals, it is common for some commercial operations to use 100% scrap. Fully integrated commercial mills melt blended scrap with appropriate elements to create the required chemistry. Traditional metal casting, hot working, annealing and cold working steps are then employed to provide a wrought product.

Copper and alloyed products come in a variety of forms. Flat products such as plate, sheet and strip are typically hot rolled. The surfaces are milled to be defect free and then cold rolled with interanneals to the finished mill product. Tube and rod products are typically hot extruded and then cold drawn. Wire products are usually produced in a continuous manner where hot working and then cold working steps are employed to produce the finished mill product. The same versatility in mill processing of copper alloys is available to the fabricators of final products such as hardware, springs, coinage and other end products.

Hot Forming Processes

Hot working, a standard step in alloy manufacture, breaks down the dendritic solidification microstructure present in all castings. Some alloys, such as the high zinc brasses, bronzes and nickel silvers, generally exist in an $\alpha+\beta$ two-phase condition. Their ability to be cold worked is limited, and they are generally supplied in an extruded and/or lightly drawn temper close to their final form and shape. Fabrication of components then employs hot forging and/or machining.

Extrusion

Copper and copper alloy tube and pipe are used extensively for carrying potable water in buildings and homes. They are also used throughout the oil, chemical and process industries and can carry diverse types of fluids ranging from seawater to a broad range of chemicals. In the automotive and industrial sector, many copper alloy tubes and machinable fittings carry hydraulic fluids and refrigerants.

These tubular and machined fittings typically originate from an extrusion. This production step heats a cast billet above the alloy's recrystallization temperature and forces the material through a shaped die. In tube manufacture a mandrel is employed to establish and control the wall thickness. Copper and α phase alloys are then drawn to finish on draw blocks or draw benches; the tube diameter and the wall thickness are reduced with each step.

Some extruded copper alloy rod and bar products exhibit the dual $\alpha+\beta$ phase structure which shows some solubility of any deliberate lead addition which, in turn, enhances the hot workability but restricts the cold ductility. Recent legislation now mandates reduced lead levels or explored alternative additions, such as bismuth and selenium, or silicon. A balance is being sought between the machinability, alloy and processing costs, and the logistical acceptance of the machined fittings industry.

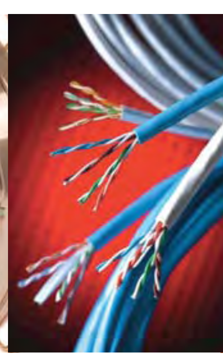
Forgings

Copper alloy forgings offer a number of advantages, including high strength, closer tolerances and modest overall cost. Brass forgings are commonly used in valves, fittings, refrigeration components and gas and liquid handling products. Industrial and decorative hardware products also employ forgings. Most copper alloy forgings are hot formed in closed dies. Common forging alloys are the high coppers, C10200, C10400 and C11000, which exhibit excellent ductility, or high strength alloys, all of which exhibit the high-temperature ductile $\alpha+\beta$ phase structure.

Cold Forming Processes

No single material property completely defines formability. Strength, work hardening and ductility all play a role. Copper alloys use alloying additions that enhance strain hardening and provide strength. Grain-size control by annealing or use of a finely dispersed second phase helps to maximize strength/ductility combinations and ensures good surface finish. Compared with other materials, the formability of copper alloys lies intermediate between that of aluminum and stainless steel, with a range of work hardening rates available.

Forming limit analysis provides a scientific means of assessing sheet metal formability over a wide range of conditions. The strain state developed during forming can be expressed relative to the major and minor strains. A forming limit curve and a limiting dome height curve can be used to show the biaxial deformation limits beyond which failure

may occur. These curves display relative formability between materials and identify operational issues that may arise from changes in tooling, lubrication or material lots.

Consideration of the limiting draw ratio with the plastic strain ratio (r) for various metals shows copper alloys to offer better strength/formability combinations than most other systems.

Blanking, piercing and related cutting operations are often used to provide parts which are formed to final shape by bending, drawing, coining and spinning. Cutting operations can be conducted in the same press tooling used to form and shape the final geometry. The quality of a blanked edge is determined by the die clearance and material characteristics. Burr-free and distortion-free parts can be cut from annealed copper alloy strip to about 5% of strip thickness.

In drawing and stretch forming, a coupon is formed into a die cavity. A clamping ring, draw beads and/or other restraints are applied to prevent wrinkling and tearing. Deep drawn parts have a depth greater than the minimum part width. A single draw or multiple steps can be employed. A shallow drawn part may be stretch formed by applying a restraint at the periphery of the coupon. Copper alloys such as brasses and bronzes (e.g., C26000 and C52100) with a high plastic strain r value (the ratio of the true strain of the width vs. that of the thickness) are most suitable for a single draw operation. Other alloys with low work hardening rates, such as C11000, are readily formed in multiple draw steps. Grain size is the basic parameter that influences the drawability of the single α phase alloys. In general, formability increases and strength decreases at larger grain sizes. However, very large grain sizes impair surface quality and should be avoided.

Many electrical connectors, terminals and spring components are fabricated by simple bending operations. Bending is where a blanked coupon is wrapped, wiped or formed over a die. Bend formability is usually expressed as a minimum bending radius in terms of strip thickness and is the smallest radius to which the strip can be bent without cracking. Ductility is defined by the ability of the material to absorb and distribute strain in a highly localized region; necking strain is the principal material property that determines bend formability. As alloy strength increases, the ability to distribute strain typically decreases, but this is alloy dependent. Conventional tensile elongation cannot be used to predict bend formability. Bend formability of strip is usually dependent on bend direction with respect to the rolling direction. It also varies by alloy. Bend performance of any alloy improves if the width to thickness ratio of the coupon is reduced.

Coining operations compress a metal coupon between two dies to fill any depressions in the die surfaces. The minting of currency is the most common coining operation. The contact surfaces on electronic connectors are also frequently coined.

Spinning is a method of forming copper alloy sheet or tube into hollow metal cylinders, cones, hemispheres and other shapes. Musical instruments, lighting fixture components, vases, tumblers, and decorative articles are formed by spinning.

When forming copper alloy parts with complex shapes, designers have learned to take springback and stepped strain distributions into consideration. Springback is the elastic recovery that occurs when a plastically formed part is released from tooling and causes the final part to have a different geometry from that of the press tooling. Overbending, restriking and use of special dies can counter springback.

VII. JOINING

Soldering & Brazing

For many years, the two most common methods of joining copper components have been soldering and brazing. The most common method of joining copper tube is with the use of a socket-type, copper or copper alloy fitting into which the tube sections are inserted. This capillary or lap joint created by the overlap of fitting and tube end is then sealed by the melting of filler metal into the capillary space. The filler metal, an alloy that has a melting temperature below that of either the tube or fitting, adheres to these surfaces.

Soldering and brazing are fast and efficient methods of joining. The difference between the two processes, according to the American Welding Society (AWS), is predicated on the melting point of the filler material, if the filler metal melts below 842ºF, the process being performed is soldering, if it melts above that temperature, the process is brazing.

The installation standard (ASTM B 828) details procedures for joint preparation, cleaning and the proper application of heat and filler metal, all of which are explained in detail in the *CDA Copper Tube Handbook*. A variety of standard torches and gases or electric resistance tools can be employed. Also refer to the *CDA Welding Copper and Copper Alloys Handbook.*

Solder filler metals are most usually tin alloys. Their low melting point and affinity for copper ensures adhesion to copper alloy components. Prior to 1986, the most common solder filler metal was 50% tin (Sn) and 50% lead (Pb). The Safe Drinking Water Act prohibited the use of lead-containing solders in potable drinking water systems. Many new and stronger lead-free alloys are commonly used for all soldering applications. These are tin alloys with various added combinations of nickel, bismuth, antimony, silver and even copper.

Brazed joints use copper- or silver-base filler metals to provide higher joint strength and fatigue resistance than tin-base solders. There are two groups of commonly used brazing filler metal. One is BCuP (2,3,4,5), primarily a copper-phosphorous brazing alloy group that may contain from 0%–15.5% silver with a melting range of 1400–1700°F (760–927°C). The other is BAg (1, 2, 5, 7), alloys with a silver content ranging from 34% to 57% and a melting range of 1145–1610°F (619–877°C).

The depth of overlap or socket depth in a lap type or capillary joint fitting is an important dimension. Ideally, the filler metal should be melted into the capillary space so that it flows and completely bridges the space. Although 100% penetration and fill of the capillary space fitting is desired, a solder joint fill of 70% (or no greater than 30% voids) is considered satisfactory to obtain joints that can withstand the maximum recommended pressures for soldered copper tube and fitting systems.

In a brazed joint, complete fill of this joint space throughout this entire length is not necessary to achieve full joint strength. According to the AWS, it is suggested that the brazing filler metal penetrate the capillary space at least three times the thickness of the thinnest component being joined, which is usually the tube. This is known in the industry as the AWS 3-T Rule. In addition, a brazed joint should be fabricated so that a well-developed fillet, or "cap," of filler metal is provided between the tube and fitting on the face of the fitting. This fillet, or cap, permits the stresses developed within the joint (by thermal expansion, pressure or other cyclic reactions such as vibration or thermal fatigue) to be distributed along the face of the fillet.

When choosing whether to use soldered or brazed joints, the overall strength of the joint or assembly (tube, fitting and joint) following the joining operation must be considered. It is important because the process of making a brazed joint causes the base metals to anneal or soften, resulting in a reduction in the overall strength of the assembly. The overall amount of annealing that occurs, and thus strength that is lost, is determined by the temperature and the time the material spends at the brazing temperature. While brazed joints are stronger and, in general, are more resistant to fatigue (vibration, thermal movement, etc.), the system working pressures must conform to the allowable limits of annealed tube.

Flameless Joining

Soldering and brazing have long been the industry standard for joining copper tube and fittings, but recent innovations in solderless or "flameless" connection methods promise to change the way copper plumbing systems are designed and built. Solderless systems do not require heat, solder or flux materials. Solderless push-connect and press-connect systems can be used for most plumbing applications, including cold and hot water distribution, heating and cooling, compressed air, inert gases and fuel gas systems. In addition, solderless systems are approved for use by most local, state and national building codes.

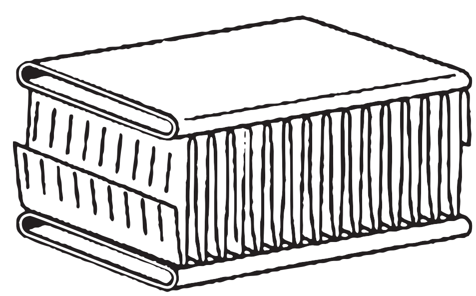
In press-connect solderless systems, fittings with integral O-rings are placed on copper tube, and a special tool is used to clamp them permanently in place. Push-connect systems do not require special tools to make the connections and, in some cases, can be easily removed and reinstalled without damaging the connection. The copper tube is simply inserted into the fitting until it engages a retaining ring that grips it tightly. Elastomeric gaskets at each end of the fittings further compress the fitting to the tube. Water (or air) pressure in the line helps to strengthen the seal. Fittings have internal stops or sleeves and washers to aid in positioning and aligning the tubing.

*Cu*proBraze®

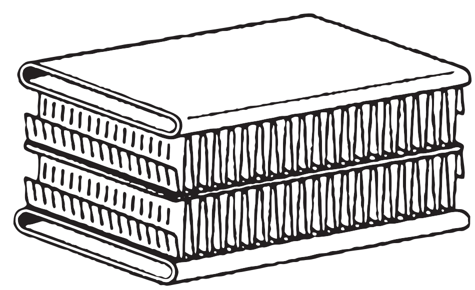
*Cu*proBraze technology was developed for use in automotive radiators and other heat exchangers. It illustrates the flexibility of copper alloys and the versatility available for meeting new challenges. Brazing gives copper-brass radiators a mechanical strength in fin, tube and header joints that

FIGURE 10: Conventional Radiator Fin Design Vs. Compact Core Design Using *Cu*proBraze® Technology

CONVENTIONAL FIN DESIGN



COMPACT CORE DESIGN



is far superior to aluminum, or even soldered copper-brass designs.

The technology allows thinner fin and tube material to be employed; copper fins are 0.002 in (0.051mm) thick or less; brazed brass tubes are 0.005 in (0.127mm) thick, compared with most aluminum fins and tubes, which are 0.005 in (0.127mm) and 0.016 in (0.406mm), respectively. Thinner copper-brass metal leads to 30% or more lower air-side pressure drop compared with aluminum radiators. This translates to more efficient radiators, lower cooling module costs, less parasitic engine losses and greater fuel economy. The brazing of copper-brass radiators uses a non-toxic, 75% copper, 5% nickel, 15% tin, and 5% phosphorus, low temperature melting alloy that works well in either a conventional vacuum brazing furnace that is back filled with nitrogen, or in a CAB furnace (an electrically heated furnace containing a nitrogen atmosphere). A typical temperature for the brazing is 1148–1175ºF (620–635°C).

The brazed copper-brass joints are significantly stronger than the solder metal and do not suffer from galvanic corrosion. Anneal-resistant header, fin and tube materials, developed for this process, assure the strength of the radiator cores. To make brazed copper-brass radiators, little or no change is needed in fin rolling, tube welding, or the drawing of header plates. The tube ends are reformed on line as part of the core assembly.

These technological advances and design innovations allow the production of radiators with 35% to 40% lower weight, compared with traditional, non-optimized copper-brass radiators, and they are correspondingly lower in material costs. They have lower weight because they are manufactured with far less material in their fins and tubes than previous models and because the heavy lead-base solder traditionally used in copper-brass radiators is replaced with a very small amount of light brazing alloy. This system is self-fluxing. No lead or other environmentally risky material is used in the brazing material, and rinsing after brazing isn't needed.

Welding

Welding can be successfully used with copper alloys. However, attention should be paid to joint area annealing and localized expansion during the welding process. Copper nickel welded tube is used extensively in condensers and brass welded tube in furniture and decorative fittings. Silicon bronzes are readily welded as well.

Welding uses high temperature or pressure to fuse the base metals together, often with an additional filler metal. Thin sections and sheet metal are seldom welded. Spot welding is an option that can be used to join thin copper

sheets to themselves and other metals. A complete review of this joining method should be done before usage, see the *CDA Welding Copper and Copper Alloys Handbook.*

Copper's biocidal property and non-corrosive nature make it a beneficial option for marine applications and welding is an appropriate process in this setting. In 1984, copper nickel sheathing was welded directly to steel legs on marine production and accommodation platforms, three drill platforms and a flare stack in the Morecambe Field, a major gas field in the Irish Sea. The sheathing vertically spanned +42.6 ft to -6.7 ft (+13 m to -2 m) Lowest Astronomical Tide. This sheathing has performed well, with the biofouling mass on the sheathing reduced to about 30% compared with the adjacent steel, despite the cathodic protection it received. What fouling has occurred on the sheathed legs is loosely adhered and can be easily removed with a light scraping action.

Supporting these findings of Morecambe Field, 10-year trials at the LaQue Corrosion Services, in Wrightsville Beach, North Carolina, have showed that, although biofouling will occur when cathodic protection is applied, some biofouling resistance is retained. The biofouling mass accumulated on a bare steel piling is more than twice as great as that on steel sheathed with direct welded 90-10 copper nickel, whether or not it was cathodically protected, and more than 20 times of that attached to insulated copper nickel sheathing.

Metallurgical Bonding

Since 1965, the higher-denominations of U.S. coins have been minted by metallurgically bonding (cladding) outer layers of copper nickel to a copper core. More recently, a new cladding alloy using a copper-zinc-manganese-nickel alloy was developed for the dollar coin (88.5% copper, overall). It matches earlier bonded products in all regards with the exception of color, which is golden and ranges between that for 14 karat and 22 karat gold. Such roll bonded composite coins are difficult to counterfeit. Cladding using such metallurgical bonding allows flexible designs, with the copper alloy being employed in selected areas.

Mechanical Fasteners

Mechanical fasteners, such as screws, bolts and rivets provide the simplest and most common joining technique. They typically do not require specialized tools for installation, and many can be removed for disassembly. **Table 9** lists the companion fasteners for each sheet or plate alloy by simplifying the color matching and reducing the risk of material incompatibility.

Adhesive Bonding

Adhesives can also be used in certain applications. The process of laminating a sheet onto a substrate is dependent on the adhesive available. Relatively thin sheets of copper alloy material can be bonded to other material substrates (i.e., steel, aluminum, wood, foam and plastics). The integrity of the bond is dependent on surface preparation, adhesive selection, bonding procedure and joint design. Edges and joints are the most vulnerable areas, as they are the most likely to admit moisture. Laminated panels should use a thermosetting or high-quality thermoplastic adhesive.

TABLE 9: Chart Showing How Color Matching is Achieved with Various Fixture Forms of Compatible Copper Alloys

COLOR	VARIOUS SHEET & PLATE ALLOYS	EXTRUSIONS	CASTINGS	FASTENERS	TUBE & PIPE	ROD & WIRE	FILLER METALS
Copper-Red	C11000 C12500 Copper	C11000 C12500 Simple Shapes	Copper (99.9% Min.)	C65100 Low Silicon Bronze	C12200	C11000 C12500	C18900 Copper
Copper-Red	C12200 Copper	C11000 C12500 Simple Shapes	Copper (99.9% Min.)	C65100 Low Silicon Bronze	C12200	C11000 C12500	C18900 Copper
Bronze-Gold	C22000 Commercial Bronze, 90%	C31400 Leaded Commercial Bronze	C83400	C65100 Low Silicon Bronze	C22000	C22000	C65500
Tan-Gold	C23000 Red Brass, 95%	C38500 Architectural Bronze	C83600	C28000 C65100 Low Silicon Bronze	C23000	C23000	C65500
Yellow-Gold	C26000 Cartridge Brass, 70%	C26000 Simple Shapes	C85200 C85300	C26000 C36000 C46400 C46500	C26000	C26000	C68100 Low Fuming Bronze
Light Brown Gold	C28000 Muntz Metal	C38500 Architectural Bronze	C85500 C85700	C28000 C65100 Low Silicon Bronze	C23000	C28000	C68100 Low Fuming Bronze
Lavender-Brown	C65500 High Silicon Bronze	C65500 Simple Shapes	C87500	C65100 C65500	C65100 C65500	C65100 C65500	C65500
Pink	C70600 Copper-Nickel	C70600	C96200	C70600	C70600	C70600	C70600
Gray-White	C74500 C75200 Nickel-Silver	C79600 Leaded Nickel-Silver	C97300	C74500	C74500 C75200	C74500 C75200	C77300

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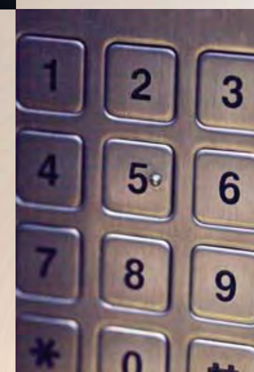

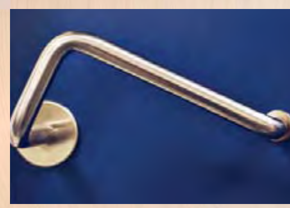

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