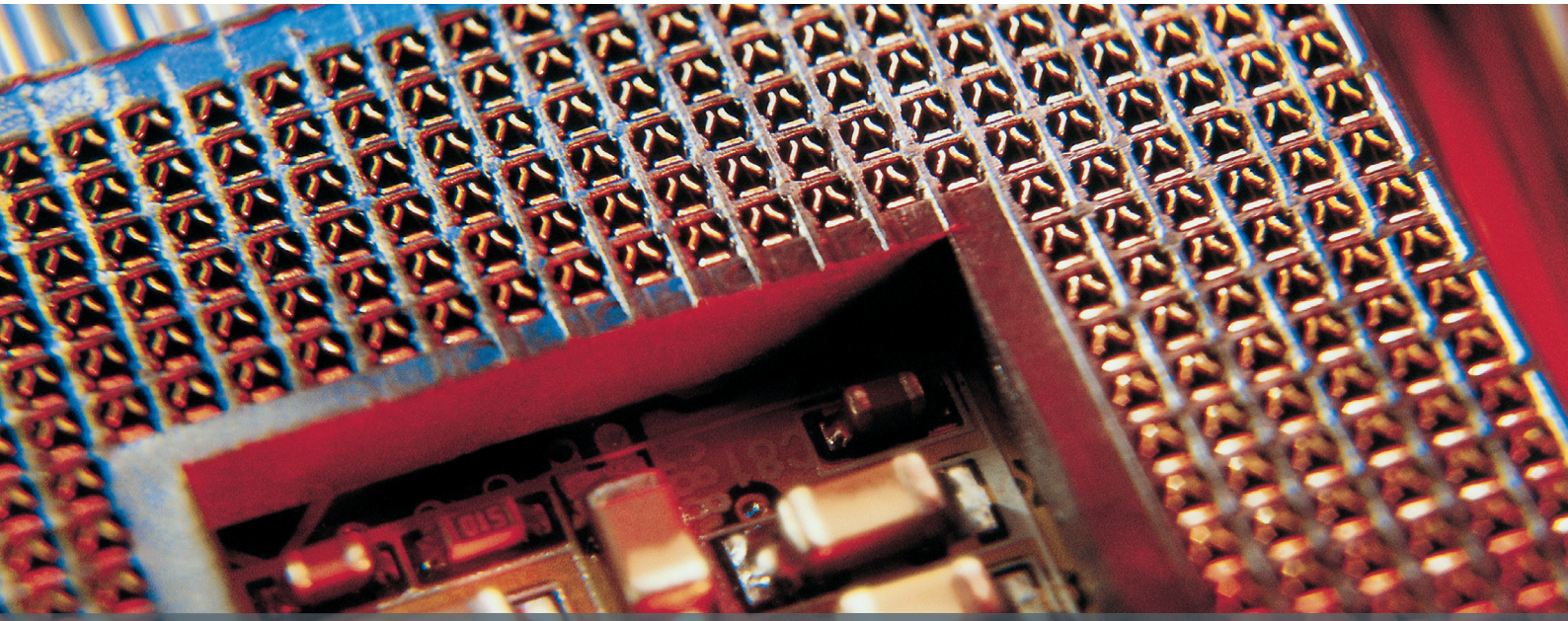
Deutsches Kupferinstitut
Copper Alliance



Low-Alloyed Copper Alloys

Properties · Processing · Applications

DKI-i8-2018

Contents

1. Introduction

Copper is a material with very high thermal and electrical conductivity, excellent corrosion resistance, medium strength and good formability. In some cases, however, the individual properties of pure copper **(Table 1)** may not be adequate for a particular application. This has led to the development of a series of copper-based materials containing small concentrations of alloying elements [1, 20].

Relatively small amounts of other elements can significantly improve one or more properties of pure copper, such as its strength **(Fig. 1)**, softening temperature **(Fig. 2)** and machinability, while other properties, such as electrical conductivity, thermal conductivity and corrosion resistance, remain essentially unchanged.

Alloying elements include beryllium, chromium, cobalt, iron, magnesium, manganese, nickel, phosphorus, silicon, silver, sulfur, tellurium, tin, titanium, zinc, zirconium, and can be used either individually or in combination.

A number of these alloying elements, such as manganese and silicon, cause a relatively strong decrease in conductivity **(Fig. 3)**, but they also improve the material's high-temperature stability, its suitability for welding and its resistance to corrosion.

The extent to which the material's properties are modified also depends strongly on the quantity of alloying element added.

Symbol	Cu
Atomic number	29
Standard atomic weight	63,546
Density	8.96 g/cm ²
Melting point	1083.4 °Ca
Boiling point	2567 °C
Electrical conductivity at 20 °C	max. 60 MS/m (corresponding to 103.4% IACS[1])
Thermal conductivity at 20 °C	approx. 395 W/(m K)
Temperature coefficient (of electrical conductivity)	0.0039 / K
Coefficient of linear thermal expansion	17×10^{6} / K (25 °C to 300 °C)
Specific heat capacity	0.38 J/gK (20 ° C bis 400 ° C)
Enthalpy of fusion	214 J/g
Crystal structure	face-centred cubic (fcc)

Table 1: Physical properties of pure copper

[1]Electrical conductivity is expressed in MS/m or in % IACS (International Annealed Copper Standard): 100% IACS is defined as 58 MS/m, which is the conductivity of conventional grade Cu-ETP at 20 °C.

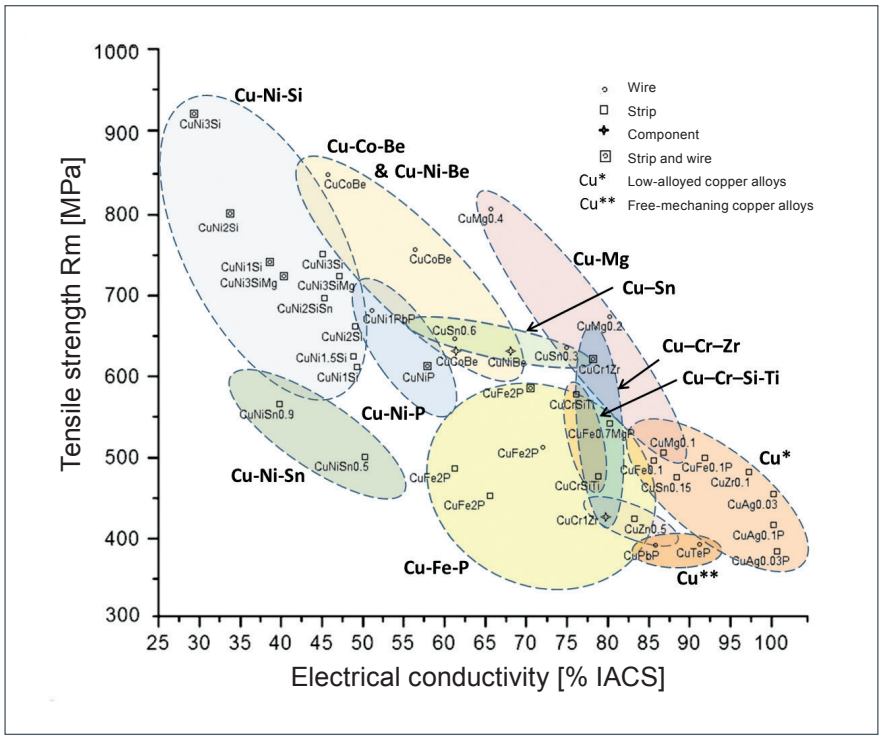


Figure 1: Property map for various types of low-alloyed coppers, DKI 4501

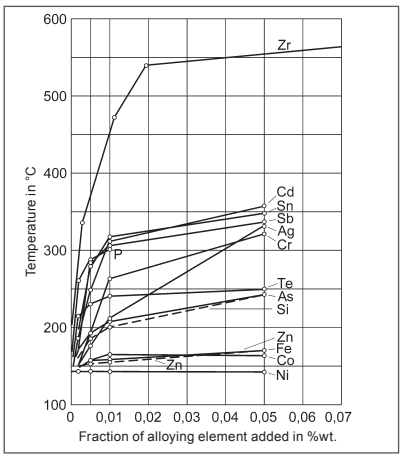


Figure 2: Raising the softening temperature of copper by adding alloying elements

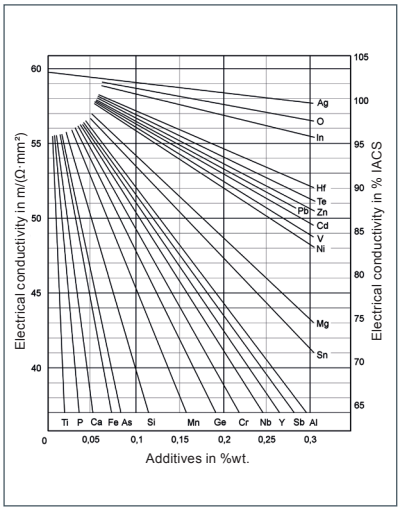


Figure 3: The effect of alloying elements on the electrical conductivity of copper [2], DKI 3373

The response of these materials to changes in temperature is striking. No embrittlement is observed even down to temperatures as low as -200 °C.

Copper alloys with low concentrations of alloying elements are referred to as the group of **'low-alloyed coppers'** or **'low-alloyed copper alloys'**. In most of these alloys the concentrations of the individual alloying elements remain below 1–2% and the cumulative concentration is under 5% **(see fold-out table)**.

Copper alloys not included in this group are CuZn5, CuSn2, CuSn4, CuSn5, CuAl5As and CuNi2, as these are normally classified in accordance with DIN CEN/TS 13388 as belonging to the copper-zinc, copper-tin, copper-aluminium and copper-nickel alloys.

1.1 Classification

A distinction is made between non-precipitation-hardenable (also known as non-age-hardenable) and precipitation-hardenable (i.e. age-hardenable) alloys **(Table 2)**.

Non-precipitation-hardenable alloys are those whose strength can only be improved by cold working.

The strength of **precipitation-hardenable** alloys on the other hand can be improved by cold working and, in particular, by suitable precipitation heat treatment.

For precipitation-hardening to occur, the following conditions must be met:

1. Significant reduction in the solid solubility of the alloying elements with decreasing temperature
2. Quenching to produce a homogeneous supersaturated solid solution
3. Precipitation of a second phase at a controlled, intermediate temperature
4. The precipitated phase must strengthen the alloy.

In this technical monograph we do not distinguish between non-precipitation-hardenable and precipitation-hardenable alloys.

For the purposes of clarity, Sections 1 to 5 classify the low-alloyed coppers in terms of their specific properties and/or areas of application. There is therefore some inevitable overlap with respect to the types of finished and semi-finished products made from them, their dimensions, material conditions and numerous other parameters.

A number of low-alloyed coppers will also be discussed that, although not currently standardized, have proved their value in practical applications.

These materials are designated as 'special materials' in the fold-out table.

Material designation

Kurzzeichen		EN Number	UNS Number
CuBe2	**Precipitation-hardenable alloys**	CW101C	C17200
CuCo1Ni1Be		CW103C	-
CuCo2Be		CW104C	C17500
CuCr1 / CuCr1-C		CW105C / CC140C	C18200/C81500
CuCr1Zr		CW106C	C18150
CuFe2P		CW107C	C19400
CuNi1P		CW108C	C19000
CuNi1Si		CW109C	C19010
CuNi2Be		CW110C	C17510
CuNi2Si		CW111C	C70260
CuNi3Si1		CW112C	C70250
CuZr		CW120C	C15000
CuAg0.1	**Non-precipitation-hardenable alloys**	CW013A	C11600
CuMg0.4		CW128C	C18665
CuPb1P		CW113C	C18700
CuSP		CW114C	C14700
CuSi1		CW115C	C65100
CuSi3Mn1		CW116C	C65500
CuSn0.15		CW117C	C14410
CuTeP		CW118C	C14500
CuZn0.5		CW119C	-

Table 2: Classification of low-alloyed coppers into precipitation-hardenable and non-precipitation-hardenable groups

1.2 Standardized low-alloyed coppers and their applications

The compositions of low-alloyed coppers are specified in DIN CEN/TS 13388. The electrical conductivity and tensile strength of these copper alloys can be described in terms of the following classification scheme **(see Table 3)**.

The different forms in which semi-finished low-alloyed wrought copper alloys are manufactured and the standards that apply to the semi-finished and finished products are contained in Table 10 of the DIN CEN/TS 13388 compendium **(Table 4)**.

Standards that also refer to low-alloyed wrought copper alloys include those in the aviation and aeronautics industry (e.g. LN 9421 'Spring wire, copper alloys, drawn; dimensions') and the standards issued by CENELEC Technical Committee concerning electrical and electronic applications for railways **(Fig. 3a)**.

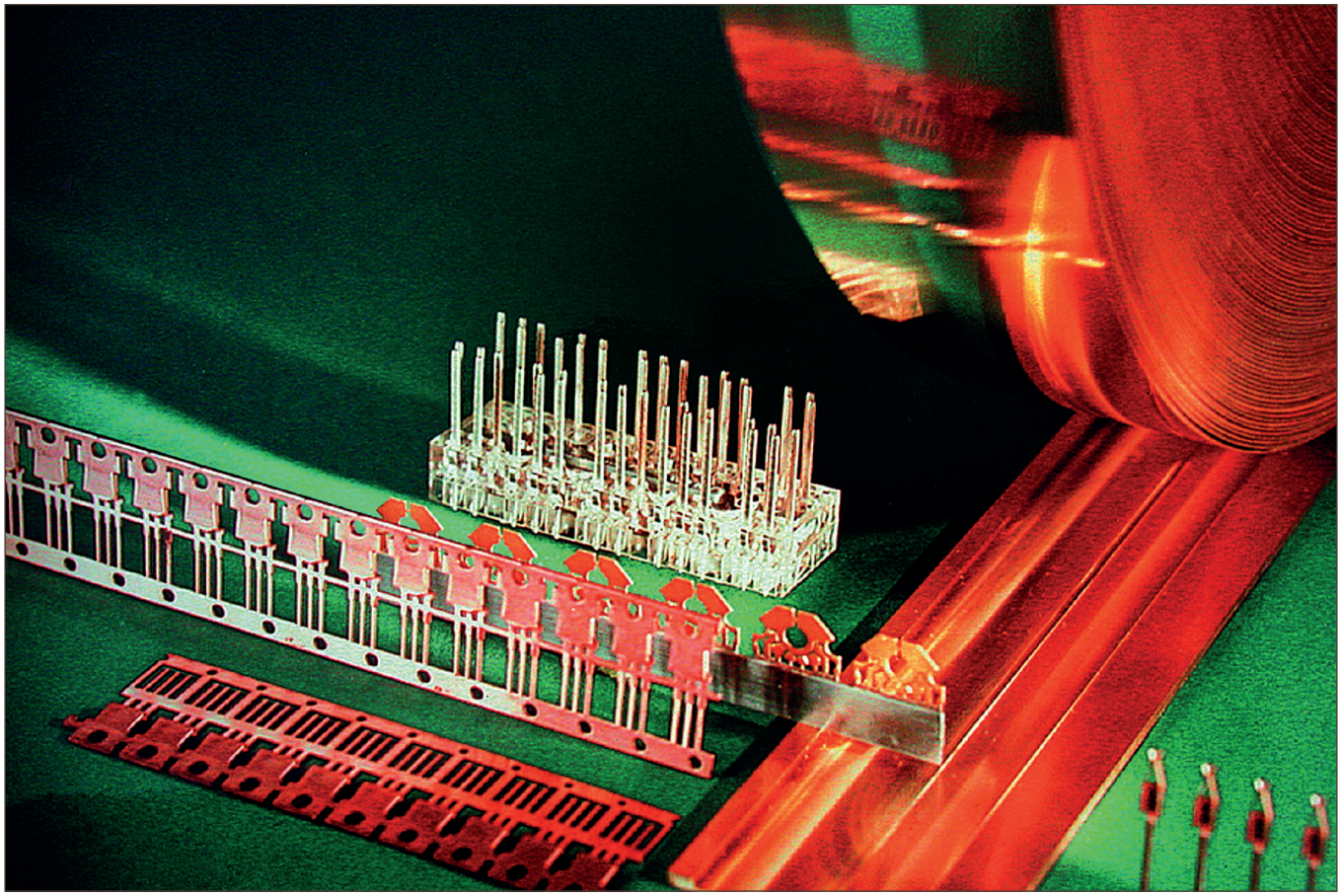


Figure 3a: Electrical and electronic components (DKI 6231)

Electrical conductivity MS/m	Rating
12–36	medium
36–48	high
> 48	very high

Tensile strength (R_m) MPa	Rating
390–590	medium
590–980	high
> 980	very high

Table 3: Classification of low-alloyed coppers into different conductivity and strength classes

Cast products are defined in the DIN EN 1982 standard. The only low-alloyed copper casting alloy included in DIN EN 1982 is the copper chromium casting alloy CuCr1-C.

Material properties specified in the standard include composition, mechanical properties and electrical conductivity.

An important group of low-alloyed coppers alloys are those with a high to intermediate conductivity that are used primarily in electrical engineering applications [3, 21]. Examples include copper-silver, copper-chromium-zirconium and copper-magnesium.

However, there are other low-alloyed coppers for which electrical conductivity is not the key consideration and these materials, such as copper-silicon-manganese, tend to be used in **mechanical construction** applications.

Material designation		Types of products and available materials																													
		Flat-rolled products								Pipes and tubes										Rods, shaped cross-sections and wires									Forging stock and forged products		C*
Symbol	Number	EN 1172	EN 1652	EN 1653	EN 1654	EN 1758	EN 13148	EN 13599	EN 14436	EN 1057	EN 12449	EN 12450	EN 12451	EN 12452	EN 12735-1	EN 12735-2	EN 13348	EN 13349	EN 13600	EN 1977	EN 12163	EN 12164	EN 12166	EN 12167	EN 12168	EN 13601	EN 13602	EN 13605	EN 12165	EN 12420	EN 13604
CuAg0.10P	CW016A							x											x	x						x		x			
CuBe1.7	CW100C				x		x		x																						
CuBe2	CW101C		x		x		x		x												x		x	x					x	x	
CuCo1Ni1Be	CW103C		x																		x		x	x					x	x	
CuCo2Be	CW104C		x		x		x		x												x		x	x					x	x	
CuCr1	CW105C																				x			x					x	x	
CuCr1Zr	CW106C																				x		x	x					x	x	
CuFe2P	CW107C				x	x	x		x		x																				
CuNi1P	CW108C																				x										
CuNi1Si	CW109C																				x								x	x	
CuNi2Be	CW110C		x		x		x		x												x								x	x	
CuNi2Si	CW111C		x		x		x		x		x										x								x	x	
CuNi3Si1	CW112C																				x								x	x	
CuPb1P	CW113C																					x									
CuSP	CW114C																					x			x						
CuSi1	CW115C																						x								
CuSi3Mn1	CW116C																				x		x								
CuSn0.15	CW117C					x	x		x																						
CuTeP	CW118C																					x	x		x						
CuZn0,5	CW119C	x	x				x		x																						
CuZr	CW120C																				x		x	x					x	x	

Table 4: Product forms for standardized low-alloyed coppers (based on Table 10 in DIN CEN/TS 13388)
*C: Copper plates, sheets, strips, seamless tubing, rods, wires and shaped cross-sections for electronic tubes and valves, semiconductor components and for applications in vacuum technology

2. Copper alloys with high electrical conductivity and good machinability

Although pure copper has the highest electrical conductivity of all the engineering metals, it is particularly difficult to be free machined **(Fig. 4)**. Machinability can be improved by the addition of alloying elements such as tellurium **(Fig. 5)**, sulfur or lead.

A general classification of these alloys in terms of their machinability is only possible if the various machining operations and techniques are taken into account (see DKI Monograph i018: Recommended machining parameters for copper and copper alloys).

2.1 Copper-tellurium alloys

Tellurium exhibits extremely low solubility in copper and is present as finely dispersed Cu2Te precipitates. The only standardized copper-tellurium alloy listed in DIN CEN/TS 13388 is the phosphorous deoxidized oxygen-free alloy CuTeP **(see fold-out table)**.

The oxygen-containing CuTe alloy is not included in the standard due to its tendency to exhibit hydrogen embrittlement and because of the higher levels of tool wear when it is machined.

2.1.1 Properties of CuTeP

CuTeP has good machining properties and high electrical conductivity (90–96% IACS). As a result of the tellurium-containing inclusions, CuTeP has a notched-bar impact strength of between 39 and 78 J/cm², which is less than that of pure copper This fact must be taken into account for screws that are machined rather than cold formed, as it limits the maximum torque that can be applied to the head of the screw.

An important property of CuTeP compared to pure copper is its higher s**oftening temperature (approx. 350 °C)** due to the small amounts of tellurium dissolved in the copper. The concentration of the tellurium is so low, however, that it has no significant effect on electrical conductivity. Similarly, the small quantity of tellurium in the alloy does not impair corrosion resistance, which is like that of copper. Other mechanical and physical properties of CuTeP are listed in the fold-out table.

2.1.2 Processing

CuTeP can be **cold worked** and rolled and drawn to produce semi-finished products. However, its ductility is not as good as that of copper. To completely restore ductility, the alloy has to be **annealed** in the temperature range 425–650 °C. CuTeP has excellent **hot working properties at temperatures between 750 °C and 875 °C**. This makes it an excellent material for forged parts that undergo subsequent machining. Hot rolling is the only forming technique in which even very small amounts of tellurium can have an adverse effect.

Good machining properties and high electrical conductivity are the key characteristics of CuTeP. When machined, it tends to form short chips and is therefore an excellent material for free-mechaning. The **machinability rating** of CuTeP is 80% of that of the free-cutting brass **CuZn39Pb3**[2]. To minimize wear, hard-coated tools should be used when machining CuTeP. Particularly good surface finishes can be achieved if low-viscosity blends of fatty mineral oils are used as the lubricant.

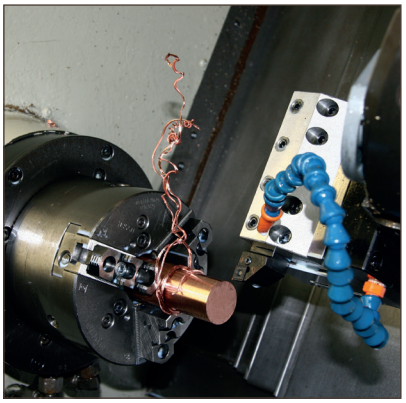


Figure 4: Chip formation when turning the difficult-to-machine alloy CuCr1Zr

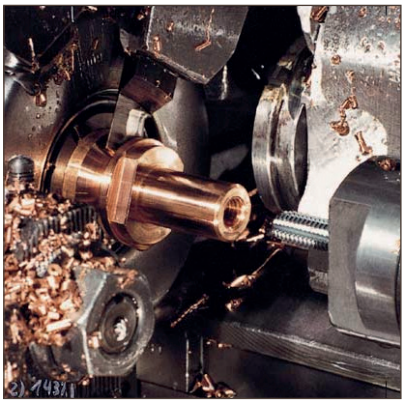


Figure 5: Chip formation when turning the highly machinable alloy CuTeP

[2] In Europe, CuZn39Pb3 is used as the reference for machining and has a machinability rating of 100% (note: in the USA, the reference alloy is CuZn36Pb3).

				Metal joining process					Surface treatment process			
Symbol	Hot working	Cold working	Manchin-ability	Soldering	Brazing	Gas welding	Gas metal arc welding	Resistance welding	Mecha-nical polishing	Electro-chemical polishing	Galvani-zability	Suitability for hot-dip tinning
CuAg0.03	very good	very good	poor	good	fair	poor	poor	good	very good	very good	very good	very good
CuAg0.10	good	very good	poor	good	fair	poor	poor	good	very good	very good	very good	very good
CuAg0.10P	good	very good	poor	very good	very good	very good	very good	very good	very good	very good	very good	very good
CuMg0.4	good	very good	fair	good	good	good	good	good	very good	good	good	good
CuMg0.7	good	very good	fair	good	good	good	good	good	very good	good	good	good
CuMn2	good	very good	fair	good	good	good	very good	very good	very good	good	good	good
CuMn5	good	very good	fair	good	good	good	very good	very good	very good	good	good	good
CuSi2Mn	good	very good	poor	good	good	very good	very good	very good	good	fair	fair	good
CuSi3Mn1	good	very good	poor	fair	good	very good	very good	very good	good	fair	fair	good
CuSP	fair	good	very good	good	fair	poor	poor	good	good	good	good	good
CuTeP	very good	good	very good	good	good	good	good	very good	good	good	good	good
(CuZn0.7)	good	very good	fair	very good	very good	good	very good	good	good	good	good	good
(CuFe2P)	good	good	fair	good	fair	very good	very good	good	good	good	good	good
CuBE1.7	good	good	fair	good	good	fair	good	good	good	good	good	good
CuBe2	good	good	fair	good	good	fair	good	good	good	good	good	good
CuCo2Be	good	good	fair	good	good	fair	good	good	good	good	good	good
CuCr1	good	very good	fair	fair	fair	fair	fair	good	good	fair	good	good
CuCr1Zr	good	good	fair	fair	fair	poor	fair	good	good	fair	good	good
CuNi1.5Si	good	good	fair	good	fair	poor	fair	good	good	good	good	good
CuNi2Si	good	good	fair	good	fair	poor	fair	good	good	good	good	good
CuNi3Si	good	good	fair	good	fair	poor	fair	good	good	good	good	good
CuZr	good	good	fair	fair	fair	poor	fair	good	good	fair	good	good
Casting alloy in acc. DIN EN 1982												
CuCr1-C	-	-	fair	fair	fair	fair	fair	good	good	fair	good	good

Table 5: Suitability of low-alloyed coppers for various processing operations.

CuTeP can be **soldered** with ease using lead-tin and tin-lead solders that meet the DIN EN ISO 9453 and DIN EN 1707-100 standards and a type 2.1.2 flux as defined in DIN EN 29454-1. **Brazing** is best done using a low-melting silver brazing filler of the type described in DIN EN ISO 17672 and a type FH10 brazing flux as defined in DIN EN 1045.

CuTeP is only moderately **weldable**. Typical **surface treatment methods** can all be used successfully on tellurium copper **(Table 5)**. If CuTeP is to be silver coated, it is recommended that the alloy is first copper coated.

2.1.3. Use

CuTeP has a high electrical conductivity and therefore finds extensive use in electrical and electronic engineering applications, e.g. for connectors, for welding nozzles, screws and bolts, nuts, fastenings, valve components, etc. It is also the material of choice for applications requiring a copper alloy with good machining properties, a high electrical conductivity and a higher softening temperature.

2.2. Copper-lead-phosphorus alloys

The alloy CuPb1P is typically deoxidized with phosphorus, with the lead imparting good machining properties to the copper. CuPb1P is the only alloy of this class standardized in DIN CEN/TS 13388.

2.2.1 Properties

Leaded free-cutting copper has a very high electrical conductivity of about 96% IACS, which is only marginally less than that of ETP copper, and is therefore suitable for most current-carrying applications.

The melting range (excluding pure lead) extends from 953 °C to 1080 °C.
The mechanical properties of the standardized alloy CuPb1P in rod form (see DIN EN 12164) are similar to those of CuTeP **(fold-out table)**.

2.2.2 Processing
Leaded copper is well suited to cold working. Hard rods are typically used for machining applications, whereas a softer state is preferred for cold forming work.

To completely restore ductility, the alloy has to be **annealed** in the temperature range 425–650 °C. Leaded copper can be hot worked at temperatures of between 750 °C and 875 °C, but it is not recommended because of the lead content.

CuPb1P can be **soldered** very readily and can also be **brazed** with relative ease. However, it is generally not welded because of the lead content.

The presence of the lead means that the alloy can be machined easily; its machinability rating is about 80%.

2.2.3 Use
Due to its favourable machining properties, CuPb1P rods are commonly machined to produce load-bearing elements such as locating pins, screws and nails that are used at room temperature. Nails with hollow shafts are also manufactured from CuPb1P rods. The alloy is also chosen for precision machining operations and is widely used in the production of electrical connectors and motor parts.

2.3. Copper-sulfur alloys
Sulfur exhibits low solubility in copper. The only standardized copper-sulfur alloy listed in DIN CEN/TS 13388 is the deoxidized oxygen-free alloy CuSP **(see fold-out table)**.

2.3.1 Properties
Even small amounts of sulfur raise the **softening temperature of the copper to about 300 °C**. As sulfur is only sparingly soluble in copper, the **electrical conductivity** and **thermal conductivity** of the metal are hardly affected. The corrosion resistance of CuSP corresponds approximately to that of unalloyed copper.

2.3.2 Processing
CuSP can be **cold** and **hot worked**. Hot working can be done at temperatures between 700 °C and 900 °C. CuSP has a machinability rating of about 80%. CuSP can be **soldered** using lead-tin and tin-lead solders as defined in the DIN EN ISO 9453 and DIN EN 1707-100 standards and a copper flux such as type 2.1.2 specified in DIN EN 29454-1.

Brazing is best done with low-melting silver brazing fillers of the type described in DIN EN ISO 17672 with a type FH10 brazing flux as defined in DIN EN 1045. CuSP shows only moderate **suitability for welding**.

2.3.3 Use
CuSP is primarily used for screw-machine products and for terminals in electronic applications. Other areas in which CuSP is used include nozzles for welding and cutting torches, engine components, valves and fittings

3. Copper alloys with very high electrical conductivity and a high softening temperature

The addition of suitable alloying elements, such as silver or zirconium, allows the softening temperature of copper to be raised **(see Fig. 2)** without significantly impairing its electrical conductivity **(see Fig. 3). This combination of properties makes these alloys particularly suitable for the production of certain electrical engineering components, such as connectors that are subjected to high-temperature mechanical stresses or components that can be soldered without softening (commutator segments, armature windings, etc.).**

3.1. Copper-silver alloys

The copper-silver alloy has a eutectic system with a maximum solubility of 8% silver at the eutectic temperature of 779 °C.

Commercially available copper-silver alloys contain between 0.03% and 0.12% Ag and exhibit a single-phase microstructure. At these silver concentrations the softening temperatures are higher.

The DIN EN 1976 and DIN EN 1977 standards list oxygen-containing, oxygen-free and phosphorous deoxidised copper-silver alloys containing varying concentrations of silver.

3.1.1 Properties

One of the benefits of copper-silver alloys compared to pure copper is that the hardness achieved through cold working the material can be maintained even at relatively high temperatures. The softening temperature of CuAg0.10 is around 300 °C.

A further outstanding property of these materials is their relatively high **creep rupture** strength [4], which is of major significance in applications subjected to mechanical stress at elevated temperatures. These beneficial properties are readily apparent in Table 6, which presents data for the alloys CuAg0.04 and CuAg0.10. The high **electrical** and **thermal conductivity** of copper is only marginally influenced by the presence of silver **(see Fig. 3)**.

Test temperature(°C)	Material designation	Test load [MPa]	Creep elongation (%) after 5 h	Time to rupture (h)
130	Cu-ETP	55	0.10	1750
	CuAg0.1	55	0.03	1750
	Cu-ETP	96	0.36	1750
	CuAg0.1	96	0.06	1750
	Cu-ETP	138	0.15	1750
	CuAg0.1	138	0.15	1750
175	Cu-ETP	55	0.62	1100
	CuAg0.1	55	0.06	1100
	Cu-ETP	96	0.12	1100
	CuAg0.1	96	0.12	1100
	CuAg0.1	138	0.38	1100
200	Cu-ETP	124	-	40
	CuAg0.03	124	-	>1000
	Cu-ETP	138	-	10
	CuAg0.03	138	-	>1000
	Cu-ETP	154	-	2.5
	CuAg0.03	154	-	80
	Cu-ETP	165	-	0.5
	CuAg0.03	165	-	15

CuAg0.1 with 0.086% Ag, cold worked CuAg0.03 with 0.029% Ag, soft annealed

Table 6: Creep rupture behaviour of copper-silver compared with copper [5]

3.1.2 Processing

Like pure copper, the copper-silver alloys (CuAg) are readily amenable to both **cold** and **hot working**. Hot working is generally performed at temperatures in the range 750–900 °C. The machinability of these alloys corresponds approximately to that of unalloyed copper. If the material is to be **heat treated** in a **reducing atmosphere**, the oxygen-free alloys CuAg(P) and CuAg(OF) should be used.

A further beneficial feature for many applications is that cold-worked copper-silver alloys can be **soldered** without suffering a deterioration in their mechanical properties, provided that the soldering is carried out carefully (maximum 10 s at 360 °C).

Preferred solders are the tin-lead solders defined in the DIN EN ISO 9453 and DIN EN 1707-100 standards, which contain between 40% and 60% tin. **Brazing** is usually carried out using a low-melting silver filler as defined in DIN EN ISO 17672. To avoid hydrogen embrittlement, gas metal arc welding should only be performed on the oxygen-free alloys CuAg(P) and CuAg(OF). In the case of CuAg(P), for example, good welding results can be achieved using CuAg1 welding rods (see DIN EN ISO 24373), which produces welds with good electrical conductivity.

3.1.3 Use

The main applications of copper-silver alloys are: high-strength catenary wires (for high-speed trains); commutator segments and rotor windings in electric motors; transformers and generators that are subjected to high-temperature stresses **(Fig. 6)**; induction heating coils; and electrodes for the resistance welding of aluminium.

3.2 Copper–zirconium alloys

The solubility of zirconium in copper at 972 °C is about 0.17% [20]. These alloys can be precipitation hardened as the solubility of the zirconium in the copper diminishes with decreasing temperature. DIN CEN/TS 13388 lists only one standardized copper-zirconium alloy, which contains 0.1% zirconium. CuZr is oxygen-free and therefore not susceptible to hydrogen embrittlement.

3.2.1 Properties

CuZr alloys combine high electrical conductivity values of approx. 54 MS/m (95% IACS) with strengths of up to 480 MPa, which is unusual in copper materials that contain a comparatively low amount of alloying element. This alloy also has a very high softening temperature, which is particularly advantageous in soldering processes **(Fig. 7)**.

The actual **precipitation hardening effect** is relatively minor and only really of technological significance if combined with cold working. For practical applications, the material is generally solution annealed, cold worked and then precipitation hardened, or it is first hardened and then subsequently cold worked. The precipitation hardening effect begins to decline at temperatures above 525 °C.

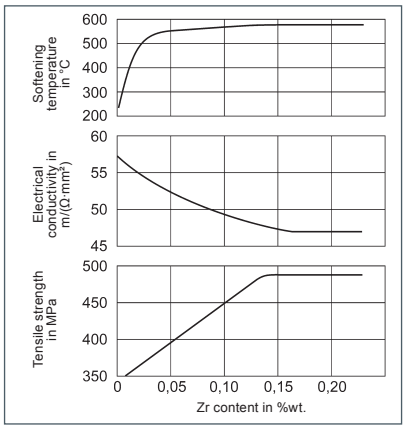


Figure 7: The influence of zirconium content on selected properties of CuZr alloys [6], DKI 3967

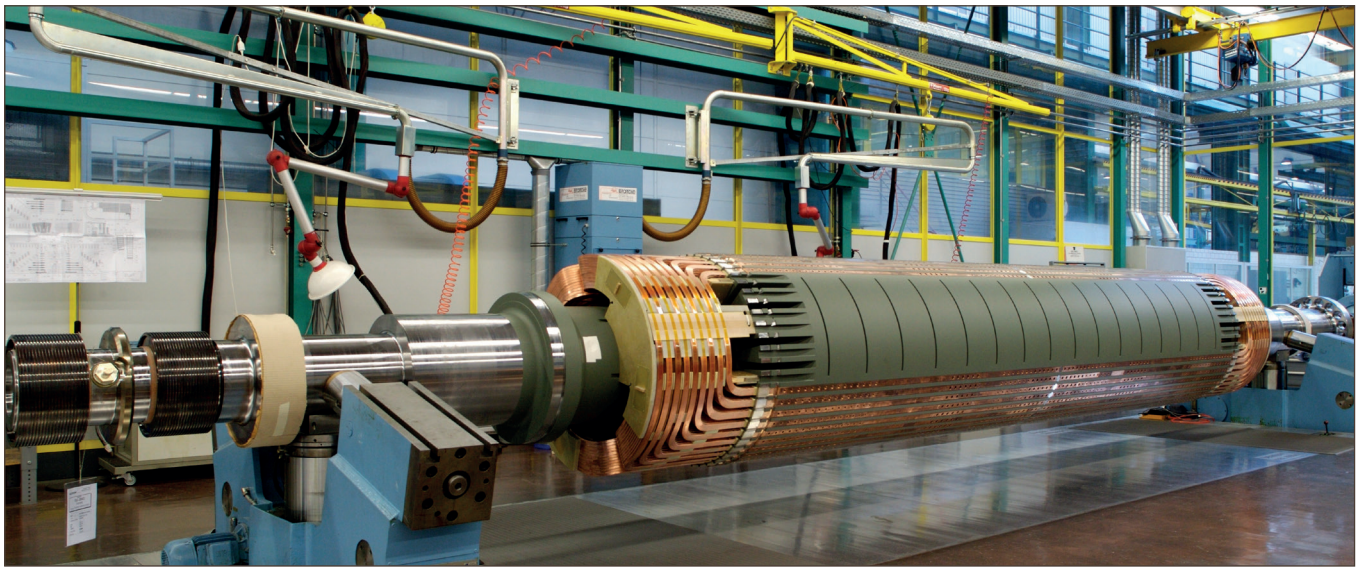


Figure 6: Rotor for a turbo-generator with CuAg rotor bars

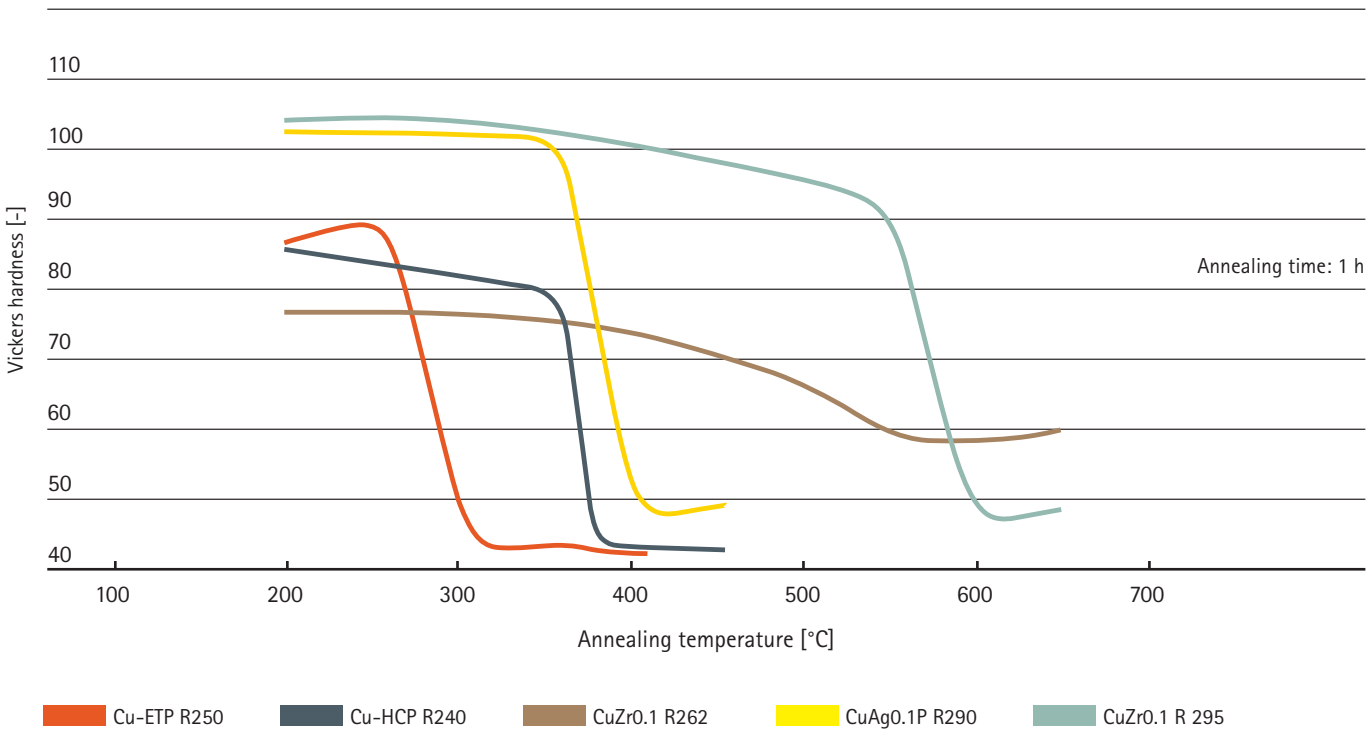


Figure 8: Improving the softening behaviour of a number of highly conductive copper alloys through the addition of phosphorus, silver and zirconium, DKI 4502

However, no such reduction in hardness is observed after annealing for about one hour at 425 °C **(Fig. 8)**. It is also noteworthy that the presence of zirconium results in a significant increase in **creep rupture strength** even at elevated temperatures.

3.2.2 Processing

As zirconium has a high affinity for oxygen and nitrogen, zirconium copper has to be cast in the absence of air and is often done under a blanket of argon.

The processing characteristics of CuZr are slightly different to those of pure copper due to the precipitation microstructure of the alloy. This is particularly apparent in non-cutting forming operations. In its solution-annealed state, zirconium copper can be cold worked to more than 90% without requiring additional process annealing.

If the alloy is to undergo subsequent precipitation hardening, process annealing should be carried out at the solution annealing temperature.

Once hardened, the **machinability** of CuZr is somewhat better than that of pure copper.

Material softening and zirconium's high affinity for oxygen must be taken into account when attempting to join zirconium-copper alloys using thermal methods. Only soldering does not require additional measures to be taken; the high softening temperature allows higher-melting solders to be used.

If **brazing** is performed with a filler metal whose melting temperature is above the softening temperature of copper-zirconium, brazing times must be kept short to avoid reducing the strength of the hardened parent metal.

Welding is best done using the TIG process and CuAg1 (see DIN EN ISO 24373) as the filler material.

3.2.3 Use

Copper-zirconium alloy is chosen primarily for applications that require the highest levels of electrical conductivity and a high softening temperature. Examples of such applications include catenary wires, busbars and highly conducting connectors. Because of its high softening temperature and its high resistance to wear, copper-zirconium alloy is also well suited for commutator segments in large electric motors.

CuZr also finds use as an electrode material for seam welding machines and for rotor windings in highly stressed electric motors.

3.3 Copper–zinc alloys

Copper and zinc form homogeneous alloys up to a zinc content of around 37%.

The commercially available low-alloyed materials contain between around 0.5% and 0.9% Zn. Phosphorous is also present, but only in trace amounts.

Due to the deoxidizing effect of the zinc, these alloys are oxygen-free and consequently immune to hydrogen embrittlement. The alloy CuZn0.5 is standardised in the DIN CEN/TS 13388 compendium.

3.3.1 Properties

The tensile strength of copper-zinc alloys lies between 220 MPa and 360 MPa depending on the extent to which the alloy has been cold worked. While their **softening temperatures** are not as high as those of CuAg0.1 or CuZr, temperatures above 250 °C are still required to soften copper-zinc alloys. Their corrosion **resistance** is similar to that of unalloyed copper. The electrical conductivity of CuZn0.5 is about 83% IACS and thus higher than that of Cu-DHP.

3.3.2 Processing

Copper-zinc alloys can be readily **cold worked** using techniques such as bending, stamping, beading, drawing and deep drawing. Of particular importance is the much greater ease with which copper-zinc alloys can be deep drawn compared to Cu-DHP, Cu-FRHC and Cu-ETP. **Hot working** can also be carried out without difficulty at temperatures between 750 °C and 950 °C.

Annealing should not be carried out at too high a temperature, as it can cause formation of a coarse grain structure that impairs cold workability. Copper-zinc alloys can be **soldered** and **brazed** using the same fluxes that are used for copper.

It can also be **welded** using the usual welding techniques. The weldability of copper-zinc alloys is similar to that of unalloyed oxygen-free copper.

3.3.3 Use

Due to the better deep drawing capabilities of copper-zinc alloys, copper strip is now predominantly manufactured using CuZn0.5 rather than Cu-ETP. Copper-zinc alloys are used to manufacture a wide variety of structural components and hollow parts, printed conductors, semiconductor socket, connectors and heat-transfer elements.

4. Copper alloys with high or moderate electrical conductivity and medium strength

Depending on the temper condition of the metal, the tensile strength of pure copper ranges from around 200 MPa to more than 400 MPa, which may be insufficient for some applications. The tensile strength of copper can be increased by the addition of alloying elements such as magnesium, chromium and iron. These higher tensile strength copper alloys are required, for example, in the manufacture of the highly stressed electrodes used in resistance welding.

4.1 Copper–magnesium alloys

As is apparent in the Mg-Cu phase diagram, a maximum of 3.2% of magnesium can be dissolved in copper at a temperature of 722 °C, though the solubility of the magnesium in the copper decreases with decreasing temperature. Generally, copper-magnesium alloys are manufactured with a maximum of 1% Mg, as the microstructure is still homogeneous at this concentration and no hardening occurs during artificial ageing.

4.1.1 Properties

Compared to copper, copper-magnesium alloys are better able to withstand static and dynamic loads even at elevated temperatures. The excellent abrasion resistance of copper-magnesium alloys is particularly noteworthy. With increasing magnesium content, the hardening of the alloy during cold working also increases substantially **(Table 7)**.

The presence of magnesium increases the softening temperature to about 350 °C, while the reduction in electrical conductivity is slightly greater than that caused by silver **(see Fig. 3)**.

4.1.2 Processing

The large freezing range exhibited by copper-magnesium alloys and their propensity to form magnesium oxide at the surface creates a number of difficulties for **smelting** and **casting** operations, though these problems can be overcome by metallurgical adjustments and adapting the casting procedures used.

Like unalloyed copper, copper-magnesium alloys can be readily **hot** and **cold worked**. Their higher recrystallisation temperatures compared to pure copper means that soft annealing is done at around 650 °C. The **machinability**, **solderability** and **brazeability** of copper-magnesium alloys are roughly similar to those of unalloyed copper.

4.1.3 Use

CuMg0.2 is used to manufacture the stranded wires in cable harnesses **(Fig. 9)** and telephone wires. The alloy grades containing higher levels of magnesium, such as CuMg0.4, CuMg0.5 and CuMg0.7, are mainly used for overhead contact wires in railways and for overhead power transmission cables **(Fig. 10)**.

Figure 9: Cable harness comprising numerous thin stranded wires

Figure 10: Overhead contact wire for high-speed trains

Material condition	0.2% yield strength [MPa]	Tensile strength [MPa]	Elongation after fracture [A %]
soft annealed	80	270	50
hard drawn (50 %)	410	450	5
hard drawn (80 %)	510	550	4
hard drawn (98 %)	640	695	2

Table 7: Strength parameters for wires made from CuMg0.7 [8]

4.2 Copper–iron alloys

The solubility of iron in copper at 1095 °C is about 4.1% [20]. As the solubility of the iron decreases with falling temperature, this alloy system can, in principle, undergo precipitation hardening. However, the increase in strength associated with the precipitation is negligible and is of little technical value. The properties of copper-iron alloys that offer technical benefits are the increased electrical conductivity and the higher recrystallisation temperature.

The alloys CuFe2P and CuFe0.1P are readily available commercially. CuFe2P is included in the DIN EN 1654 and DIN EN 1758 standards. In the UNS classification scheme (Unified Numbering System), CuFe0.1P is designated as C19210.

4.2.1 Properties

Iron-copper alloy is characterized by its high **thermal** and **electrical conductivity**. Depending on the composition and the heat treatment regime applied, thermal conductivities of up to 350 W/(mK) and electrical conductivities up to 90% IACS are attainable.

Cold-worked CuFe2P can achieve a tensile strength in excess of 500 MPa and an electrical conductivity of 74% IACS. The **softening temperature** lies in the range 400–500 °C depending on the initial condition of the alloy.

Figures 11a and **11b** show the softening behaviour of the alloys CuFe0.1P and CuFe2P.

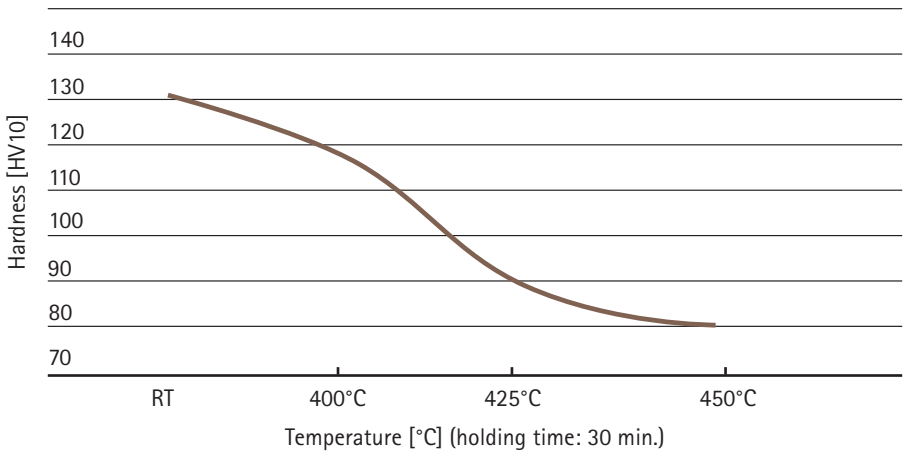


Figure 11a: The influence of iron on the softening behaviour of copper (CuFe0.1P R360-430)

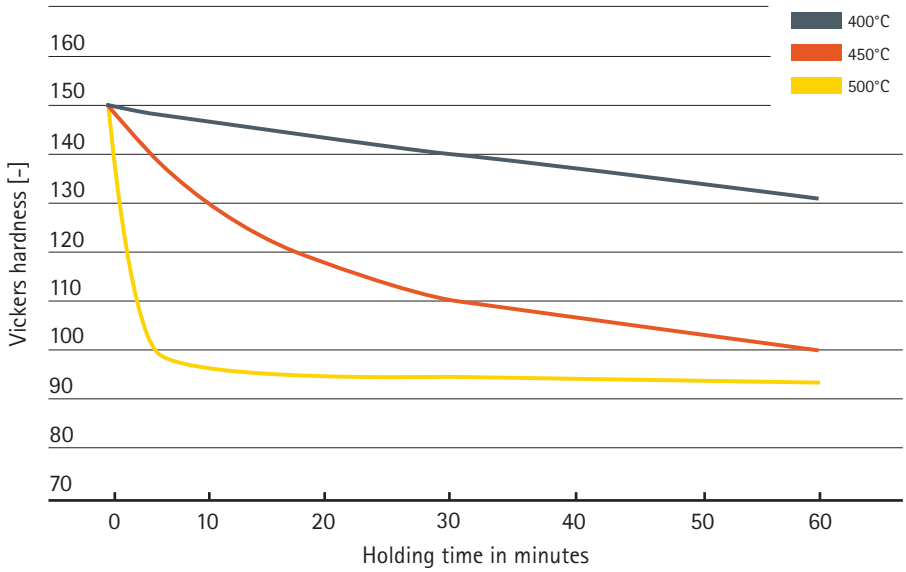


Figure 11b: The influence of iron on the softening behaviour of copper (CuFe2P R470)

The **corrosion resistance** of the copper-iron alloys is better than that of pure copper. When placed in aqueous saline or alkaline solutions, copper-iron alloys form a protective layer of iron hydroxide, which, if damaged, regenerates rapidly [23]. Copper-iron alloys also exhibit good resistance to erosion corrosion. Higher water flow velocities are therefore permitted in water pipes made from copper-iron alloys than in pipes made from unalloyed copper. Copper-iron alloys are also resistant to stress corrosion cracking.

4.2.2 Processing

Copper-iron alloys have excellent cold and hot working and bending properties.

They are also readily **welded**, **soldered and brazed**. Both laser welding and resistance welding techniques can be applied. The machinability rating quoted for copper-iron alloys is 20%.

4.2.3 Use

As the mechanical properties of copper-iron alloys are superior to those of unalloyed copper, they are in widespread use in the electronics and electrical engineering sectors. They are used for the manufacture of lead frames and LEDs in the semiconductor industry **(Fig. 12a)**, for stamped contacts and precision stampings **(Fig. 12b)** in the automotive sector, and for contact strip **(Fig. 13)**. CuFe2P is also used in strip form to protect buried telephone cables and as piping for car brake lines.

Tubes and fittings made from CuFe2P are also used for refrigeration and cooling applications. When compared with pure copper, the superior mechanical properties of this low-alloyed copper material enable very high operating pressures to be achieved in refrigeration equipment, such as units that contain CO_2 as refrigerant.

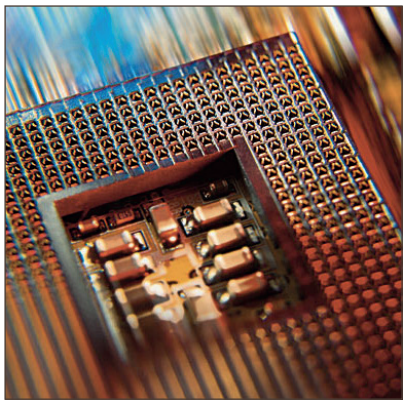


Figure 12a: Lead frame

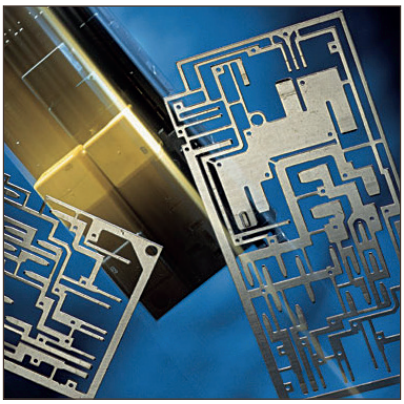


Figure 12b: Precision stamped sheet for electrical applications

Figure 13: Contact strip made from CuFeP (CuFe0.1P)

4.3 Copper-chromium alloys

The maximum solubility of chromium in copper is only 0.65% at the eutectic temperature of 1075 °C and this very low value decreases significantly with decreasing temperature. At 400 °C, the solubility of chromium in copper has fallen to below 0.03%. As a result of this temperature dependence, the chromium can be precipitated out of solution and these alloys can therefore be precipitation hardened. The only copper-chromium casting alloy listed in EN 1982 is CuCr1-C **(see fold-out table)**. The CEN/TS 13388 standard also lists only one wrought copper-chromium alloy (CuCr1).

4.3.1 Properties

The hardening process results in a significant increase in both mechanical strength and electrical conductivity. In their fully hardened states, CuCr alloys exhibit a useful relationship between strength and electrical conductivity. **Figure 14** shows how cold working of precipitation-hardened CuCr1 influences the material's hardness and electrical conductivity.

One disadvantage of CuCr1 in certain situations is its relatively high notch sensitivity at elevated temperatures, a property not exhibited by other copper alloys, such as CuZr [9]. This can be seen in **Table 8** , which compares copper-chromium with a number of other low-alloyed copper materials.

The **strength parameters** are low particularly perpendicular to the direction of deformation or rolling. CuCr1 exhibits a very high resistance to softening **(Fig. 15)**. However, at temperatures above 475 °C, the precipitation hardening effect decreases as the precipitated chromium particles redissolve.

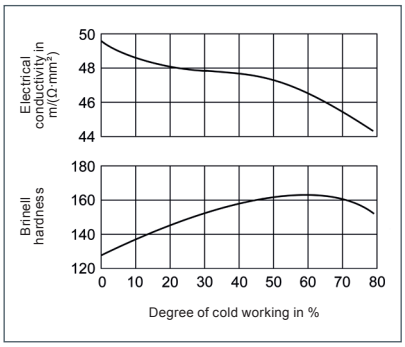


Figure 14: Hardness and electrical conductivity of CuCr as a function of the degree of cold working after precipitation hardening [1], DKI 3913

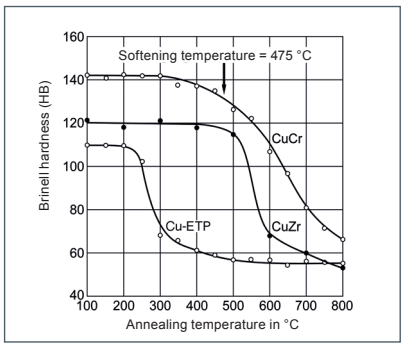


Figure 15: Resistance to tempering of CuCr with 0.6% Cr (solution annealed, 25% cold worked and aged) compared with CuZr with 0.33% Zr (solution annealed, 60% cold worked and aged) and Cu-ETP (cold worked). Ageing time at each temperature: 5 h [10], DKI 4613

Alloy	After 100 h no notch MPa	After 100 h notched MPa	After 500 h no notch MPa	After 500 h notched MPa
Sample aligned parallel to rolling direction				
Copper-zirconium	235	260	220	245
Copper-chromium	250	195	225	160
Copper-silver	120	110	70	
Sample aligned perpendicular to rolling direction				
Copper-zirconium	260	285	250	265
Copper-chromium	130	115	90	83
Copper-silver	140	105	95	-

Table 8: Strengths of several low-alloyed, high-conductivity copper alloys after extended ageing at 290 °C [3]

4.3.2 Processing

As chromium has a high chemical affinity for oxygen, **smelting** and **casting** of copper-chromium alloy should be carried out in the absence of air. If air is present, there is a risk of chromium scorification. **Hot working** is typically carried out at temperatures between 725 °C and 900 °C.

CuCr1 has the advantage that it can be cold worked in its solution-annealed state. A broad range of properties can be created through a combination of cold working and artificial ageing. **The heat treatment** of CuCr1 first involves solution annealing the semi-finished stock for about 15 minutes at around 1000 °C and then quenching in water. This is typically followed by cold working the material to about a 40–50% reduction in thickness.

The final thermal hardening stage is performed at a temperature between 400 °C and 500 °C with annealing times ranging from 10 minutes to 20 hours, depending on the temperature (typically: 470 °C for 4 hours). It is also possible to cold work the wrought alloy CuCr1 after the thermal hardening (ageing) stage.

The temperature ranges and processing times specified for the heat treatment of CuCr1 are also applicable to the casting alloy CuCr1-C **(see Table 8a)**.

As the precipitation of chromium produces a more heterogeneous microstructure, precipitation-hardened CuCr and CuCr1-C **(machinability rating: about 30%)** are significantly easier to machine than pure copper.

The presence of chromium also raises the recrystallisation temperature of CuCr1 to about 600 °C, which is considerably higher than that of pure copper.

CuCr1 and CuCr1-C can be soldered using lead-tin solders (or the higher-melting special solders listed in DIN EN ISO 9543 and DIN EN 1707-100) and a suitable flux without any loss in mechanical strength. This is of significance in applications at elevated operating temperatures, such as electrical contacts.

Brazing is best carried out using low-melting silver brazing fillers. If brazing is done rapidly with, for example, the filler Ag 156 (see DIN EN ISO 17672), the reduction in strength is only relatively minor. CuCr1 and CuCr1-C can only be welded if certain precautions are taken.

One technique that can be used is TIG welding using a CuSn1 welding rod (as defined in DIN EN ISO 24373).

Welding of CuCr1-C is restricted almost exclusively to casting repair work. It should be noted that the mechanical properties of the alloy may change as the temperatures used in the welding process may cause chromium precipitates to dissolve back into the solid-solution.

4.3.3 Use

Copper-chromium alloys exhibit high strength, high electrical and thermal conductivity and a very high resistance to softening [7].

Conducting springs and electrical contacts that are subjected to high mechanical loads are frequently made from CuCr1. CuCr1 is also suitable for the manufacture of commutator segments and busbars.

Cast components made from CuCr1-C **(Fig. 16)** are used in a variety of electrical engineering applications, such as die-cast electrode holders in spot welding machines, injection valves and electrically conducting parts.

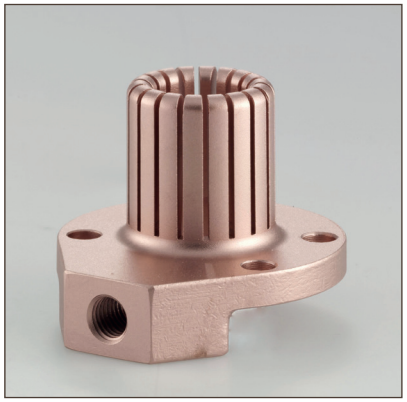


Figure 16: Medium-voltage contact finger made from CuCr1-C

4.4 Copper-chromium-zirconium alloys

The precipitation hardening achievable in copper-chromium-zirconium alloys is slightly greater than that attainable in binary copper-chromium alloys. The commercially available alloys contain between 0.4% and 1.1% Cr and between 0.03% and 0.3% Zr **(see fold-out table)**, cf. DIN CEN/TS 13388.

4.4.1 Properties

The advantages of CuZr are its high softening temperature and creep rupture strength [4] and its notch strength insensitivity at elevated temperatures. A disadvantage of copper-zirconium alloys is that they only undergo minimal precipitation hardening. CuCr, in contrast, exhibits good strength parameters in its precipitation-hardened state. However, the relatively high notch sensitivity of CuCr at higher temperatures can be a disadvantage in certain situations. The beneficial properties of each of CuCr and CuZr can be usefully combined in the ternary copper-chromium-zirconium (CuCrZr) alloy system. The characteristics of CuCrZr are:

- **high strength at room temperature**
- **high softening temperature**
- **improved creep rupture strength** even at elevated temperatures.

The ternary alloy CuCr1Zr is superior to both of the binary alloys CuCr and CuZr in all three of these properties. This behaviour is explained by the increased solubility of chromium in copper at high temperatures due to the presence of zirconium [7]. When subjected to creep stress, CuCr1Zr also exhibits a certain propensity to brittleness at temperatures above about 100 °C as a result of the formation of pores at the grain boundaries [4]. The precipitation hardening behaviour of CuCr1Zr is roughly equivalent to that of CuCr1.

Although Brinell hardness values above 160 HB are almost impossible to achieve in CuCr1, no matter how skilfully cold working and precipitation hardening are combined, they can be attained in CuCr1Zr **(see Fig. 15)**. The other **strength parameters** of CuCr1Zr are also more favourable than those of the binary alloy CuCr1, particularly at higher temperatures **(see Table 9)**.However, at temperatures above 500 °C, the precipitation hardening effect begins to diminish **(Fig. 17)**. **Figure 18** shows the creep behaviour of CuCr1Zr compared with two copper-zirconium alloys. Of the alloys examined, CuCr1Zr shows the most favourable properties.

The **physical properties** of CuCr1Zr correspond approximately to those of CuCr1 **(see fold-out table)**. The **electrical conductivity** of the alloy in its fully hardened state is in the range 78–86% IACS.

Symbol and material number	0.2% yield strength $Rp_{0.2}$ (MPa)	Tensile strength R_m (MPa)	Elongation after fracture A_5%	Brinell hardness HB
Cu-C (CC040A) 'Type A'	40	150	25	40
CuCr1-C (CC140C) 'Artificially aged'	250	350	10	110

Table 8a: Comparison of strength parameters of Cu-C and CuCr1-C

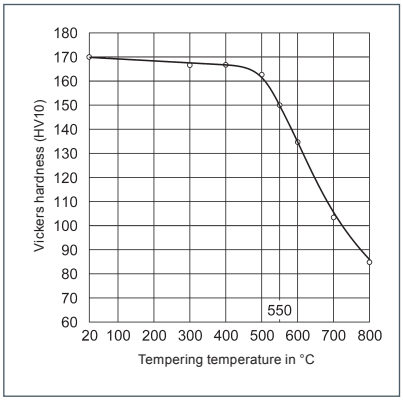


Figure 17: Tempering curve for CuCrZr rods with an initial hardness of 170 HV10 (condition: solution annealed, cold worked, hardened); annealing time: 30 min

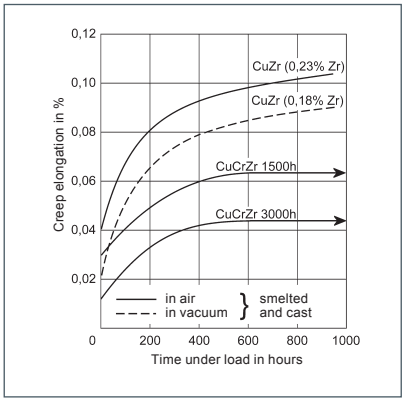


Figure 18: Creep behaviour of CuCr1Zr compared with CuZr, test temperature: 230 °C (250 °C for the 1500 h curve) [1], DKI 3970

Alloy	Type of specimen	20°C		200°C		300°C	
		R_m [MPa]	A [%]	R_m [MPa]	A [%]	R_m [MPa]	A [%]
CuCr1Zr rod Diameter: 9.5 mm	S	550	22	465	21	415	19
	N	600	20	490	17	450	13
CuCr1 strip 6 x 76 mm	S	510	17	420	10	280	7
	N	445	13	415	10	355	7

Table 9: Comparison of the strength parameters of CuCrZr and CuCr at different temperatures, S = smooth specimen, N = notched specimen [3]

4.4.2 Processing

The **cold workability** of CuCr1Zr is particularly good when the alloy is in its soft annealed state. **Hot working** is best carried out between 850 °C and 950 °C. The **machinability** of the solution-annealed alloy is similar to that of unalloyed copper (machinability rating: 20%), but is significantly improved when the alloy is in its hardened state (machinability rating: 30%).

Like pure copper, CuCr1Zr can be readily **soldered** without any real loss in the strength of the base material. However, the material can only be **brazed** or **welded** under special conditions. Electron beam welding and laser welding can be used.

4.4.3 Use

CuCr1Zr is used in the manufacture of springs and electrical contacts, resistance-welding electrodes, crucibles **(Fig. 19)**, tubes **(Fig. 20)**, plates **(Fig. 21)**, etc.

4.5 Copper-nickel-phosphorus alloys

Copper-nickel-phosphorus alloys can be hardened by carefully adjusting the quantities of small finely dispersed particles of nickel phosphides within the alloy's microstructure. The presence of these nickel phosphides can improve the alloy's mechanical and physical properties, such as strength, hardness and its electrical and thermal conductivities. Commercially available CuNiP alloys contain between 0.8% and 1.2% Ni and between 0.15% and 0.25% P **(see fold-out table)**. The optimum Ni/P mass ratio is in the range 4.3 to 4.8 **(Fig. 22)**.

Copper and nickel are completely soluble in both the molten and solid states. As the amount of phosphorus in the alloy increases, the solubility of the resulting nickel phosphides decreases significantly in the solid solution. The solubility of the nickel phosphides in the solid solution is much smaller than the solubility observed in other low-alloy, precipitation-hardenable copper alloy systems, such as Cu-Ni-Si or Cu-Be, and the electrical and thermal conductivity observed in hardened Cu-Ni-P alloys is correspondingly greater.

4.5.1 Properties

The copper-nickel-phosphorus alloy system combines high electrical conductivity and high strength. The formation of fine nickel phosphide precipitates and the purity of the copper are critical parameters in controlling the microstructure, and thus the strength and conductivity of the alloy. Because of the high strengths (550–700 MPa) that can be achieved in the precipitation-hardened state **(see fold-out table)** and the relatively good electrical conductivity of between 50% and 65% IACS, these alloys are frequently used for the production of electrical contacts. The optimum parameters for the precipitation hardening process depend on the preceding cold working stage as this influences the precipitation kinetics.

As a result of the stress relief that accompanies artificial ageing, the elongation after fracture in these alloys can be increased from 3% to 20%. Hardening is carried out most efficiently at temperatures in the range 380–420 °C. Cu-Ni-P also exhibits good stress-relaxation behaviour at high operating temperatures **(Fig. 23)**.

Figure 19: Crucible made from CuCr1Zr

Figure 20: Tubes manufactured from CuCr1Zr

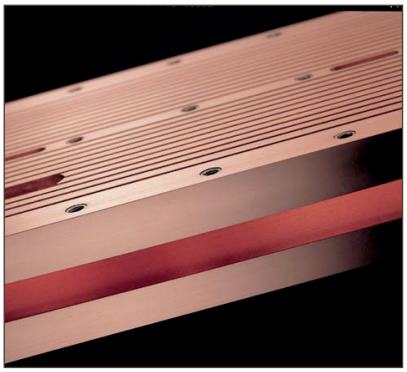


Figure 21: Plate made from CuCr1Zr

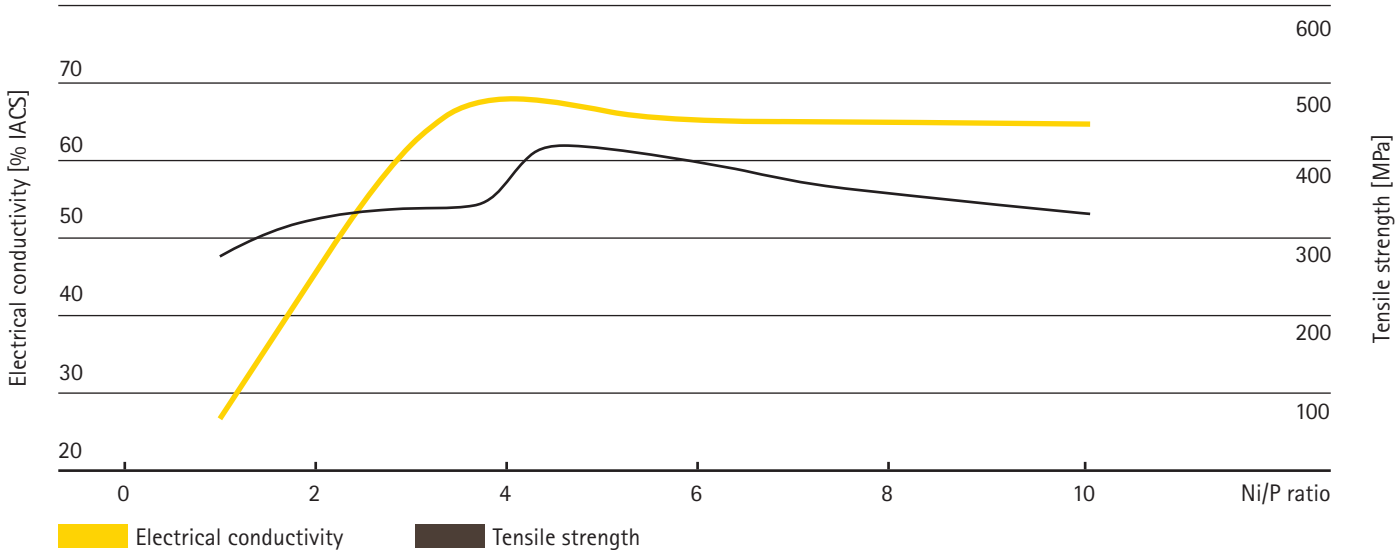


Figure 22: Influence of the Ni/P ratio on the mechanical properties and electrical conductivity of CuNiP0.2 (at 450 °C after age hardening for 24 h) [22], DKI 4503

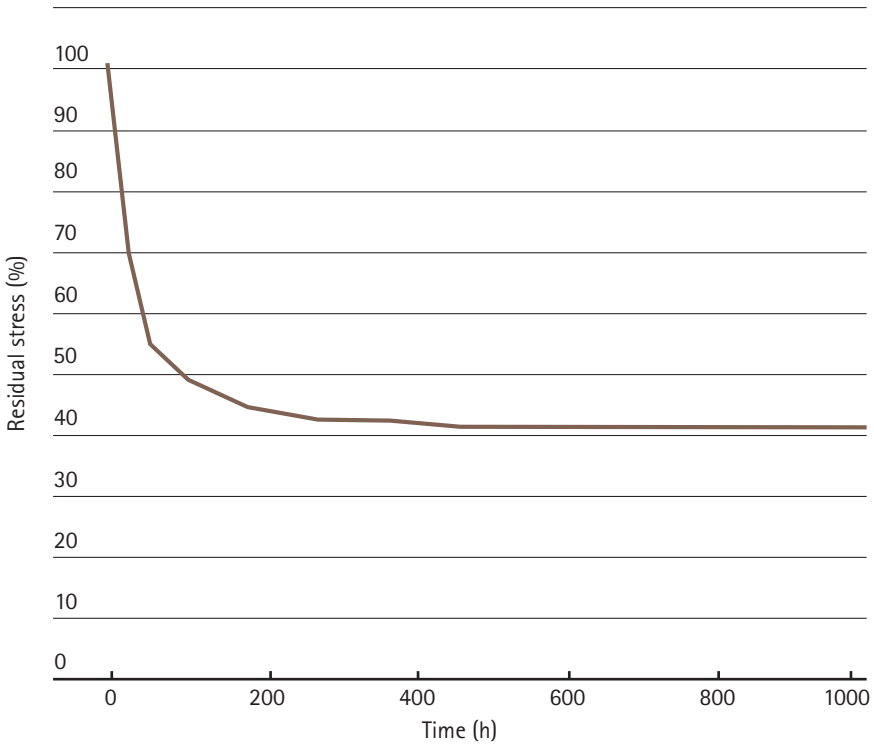


Figure 23: Thermal relaxation of residual stress in Cu-Ni-P (C19000) (temperature: 250°C, 75% Rp0.2)

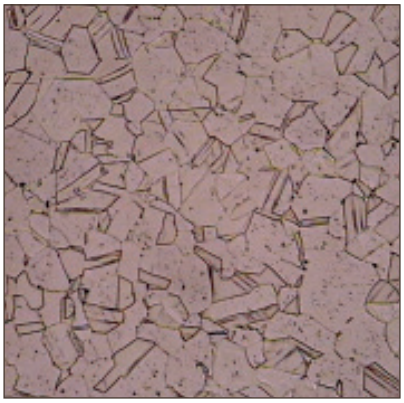


Figure 24: Microstructure of the alloy CuNi1P0.2Pb1 (C19160) in its solution-annealed state

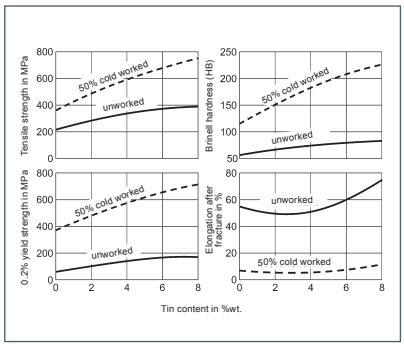


Figure 25: Hardening behaviour of copper-tin wrought alloys as a function of tin content [24], DKI 1557

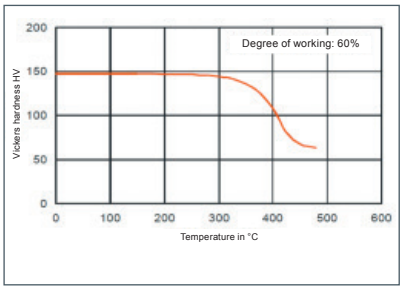


Figure 26: softening benaviour of CuSn0.15 [25], DKI 4506

4.5.2 Processing

Solution-annealed Cu-Ni-P shows excellent cold workability. The Cu-Ni-P alloy system has the following features:

- Phosphorus has a deoxidizing effect in the melt and leads to the formation of nickel phosphide precipitates during age hardening.
- Hot working and solution annealing are carried out at temperatures in the range 700–800 °C.
- The machinability of these alloys in their solution-annealed state is similar to that of unalloyed copper. To improve machinability, CuNi1P can be alloyed with up to 1% lead **(Fig. 24)**.

4.5.3 Use

Cu-Ni-P alloys are used to manufacture connector components, such as the contact pins, push-on terminal strips and conducting springs used in electronic and electrical applications. Strips of Cu-Ni-P alloys are used in the production of springs, clips, contact supports and connectors. Rods and hollow tubing are processed to make welding pliers, electrode holders, earth (ground) clamps and seam-welding rollers. These products are used in the IT, aviation, telecommunications and automotive industries.

4.6 Copper-tin alloys

Copper-tin alloys belong to the oldest known copper-based materials used for technical applications. Even small quantities of the alloying element tin will improve softening behaviour compared to that of pure copper. Provided that the amount of tin does not exceed 1%, the segregation behaviour observed in high-alloyed bronzes is not particularly pronounced. To ensure deoxidation of the copper-tin melt, a small quantity of phosphorus can be added to the melt.

To avoid too great a reduction in electrical conductivity, low-alloyed CuSn alloys generally contain up to 0.6% tin and no more than 0.01% of phosphorus. There are also oxygen-containing CuSn alloys in that form when the oxygen in the melt reacts to produce tin oxide.

4.6.1 Properties

Compared with pure copper, low-alloyed copper-tin materials exhibit slightly greater strength while retaining good electrical conductivity. With increasing tin content, the hardening of the alloy during cold working also increases **(Fig. 25)**. The **softening temperature** also increases to about **330 °C (Fig. 26)**. The reduction in the **electrical conductivity** of copper caused by the presence of tin is slightly greater than the reduction caused by magnesium **(see Fig. 3)**.

4.6.2 Processing

Copper-tin alloys are easy to cast and have excellent **hot** and **cold working** properties. These alloys can be drawn to make fine wire. Annealing is normally performed at 400 °C.

4.6.3 Use

A typical use of CuSn0.15 is in the manufacture of lead frames (DIN EN 1758), while CuSn0.3 is chosen for the fine-gauge stranded wire in cable harnesses and for catenary wires.

5. Copper alloys with moderate electrical conductivity and high strength

Although a number of alloying elements, such as beryllium (+ cobalt or nickel), nickel + silicon, nickel + tin or titanium, reduce the electrical conductivity, they also produce a significant increase in yield strength, tensile strength and hardness.

5.1 Copper-beryllium alloys

The precipitation hardening that can be achieved in copper-beryllium alloys is due to the solubility of beryllium in copper at elevated temperatures (max. solubility: 2.1% Be) and the fact that this solubility decreases as the temperature falls. The alloys CuBe1.7, CuBe2, CuBe2Pb, CuCo-1NiBe, CuCo2Be and CuNi2Be are standardized in DIN CEN/TS 13388 **(fold-out table)**.

5.1.1 Properties

Copper-beryllium alloys can be precipitation hardened (age hardened), leading to substantial increases in material strength and hardness. The electrical conductivity is around 43% IACS.

In its solution-annealed state, the material exhibits high ductility and is well suited to **deep-drawing** operations. **Figure 27** shows how the **strength** and **electrical conductivity** of CuBe2 vary as precipitation hardening proceeds. At temperatures above about 350 °C, the **precipitation hardening effect** begins to diminish. The **corrosion resistance** is similar to that of deoxidized copper. Copper-beryllium alloys are not sensitive to stress corrosion cracking.

5.1.2 Processing

Copper-beryllium alloys can be readily cast using most established casting techniques. However, it is important to note that beryllium fumes and dust are toxic.

Casting must be carried out in accordance with the applicable health and safety regulations. (E.g. in Germany, these would be the accident prevention regulations issued by the relevant employers' liability insurance association.) The casting temperature is in the range 1040–1120 °C for CuBe1.7 and between about 1010 °C and 1120 °C for CuBe2.

Hot working is carried out at temperatures between 600 °C and 800 °C. After solution annealing in the range 780–810 °C, the material is quenched in water and then possibly cold worked.

Soldering e.g. with S-Pb50Sn50E (as defined in DIN EN ISO 9453) is always carried out after precipitation hardening, as the flow temperature of the solder is below the temperature required for hardening. The surfaces to be soldered must be clean and free of any surface oxidation.

Brazing is almost always done prior to the hardening stage. It is best carried out using low-melting silver brazing fillers with operating temperatures between 610 °C and 650 °C. To ensure that the alloy can be subsequently precipitation hardened, the workpiece must be heated rapidly (it may also be necessary to cool the areas surrounding the joint) and then quenched in water once the filler metal has solidified. Precipitation hardening will be impaired if the brazing time exceeds 1 minute.

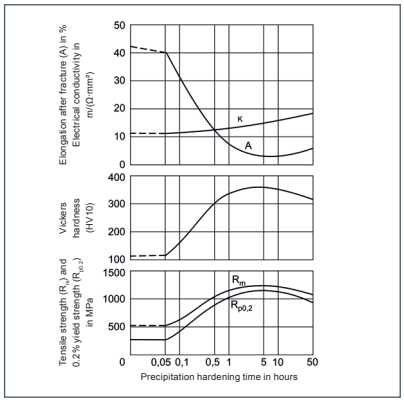


Figure 27: Hardening of CuBe2 at 325 °C [1] DKI 3962

CuBe alloys can be welded using gas metal arc and resistance welding methods. Given the toxicity of beryllium fumes, welding must be carried out in accordance with the applicable occupational health and safety regulations. Welding is typically done on the unhardened alloy using copper-beryllium filler metals. However, excellent results can also be achieved when springs made from hardened copper-beryllium alloys are spot welded. Weld times should be kept short.

5.1.3 Use

The greater strength and wear resistance of copper-beryllium alloys, their high modulus of elasticity and high fatigue strength limit make them particularly well suited for the manufacture of **springs**. The most common products made from these alloys are **connectors**, **contacts**, **springs** and **switches**.

Copper-beryllium alloys are also used to make non-sparking tools for use in oil drilling platforms, refineries and petrochemical plants.

Precision-cast components made from CuBe alloys are characterized by their hardness and high elastic resilience. Such components are used, for example, in the aviation construction sector.

Plastic processing molds are also made from copper-beryllium. CuBe alloys are also chosen for crucible molds and high-pressure die casting molds, such as those used for casting brass, as these molds have long service lives and are therefore cost-effective.

Copper-cobalt-beryllium and copper-nickel-beryllium alloys

The addition of the alloying elements cobalt and nickel improves resistance to softening to about 550 °C. The commercially available alloy CuCo2Be contains 2.0–2.8% cobalt and 0.4–0.7% beryllium. This composition of the alloy is standardized in DIN CEN/TS 13388 **(see fold-out table)**. Some of the cobalt in CuCo2Be can be replaced by nickel (CuCo1Ni1Be). The properties of copper-nickel-cobalt-beryllium are practically identical to those of copper-cobalt-beryllium.

It is in fact possible to completely replace the cobalt by nickel. CuNi2Be is defined in the DIN CEN/TS 13388 standard (see fold-out table).

The advantage of CuNiBe over CuCoBe is in its slightly higher conductivity.

5.2.1 Properties

Compared with the copper-beryllium alloys discussed in Section 5.1, copper-cobalt-beryllium alloys have **slightly lower hardness and strength values**, but **higher electrical and thermal conductivities**. By carefully combining cold working and precipitation hardening treatment, the properties of the material can be adjusted to meet specific application requirements.

Figure 28 demonstrates how material properties depend on precipitation hardening time at a particular precipitation hardening temperature.

It is apparent that the **precipitation hardening effect** begins to diminish above 500 °C.

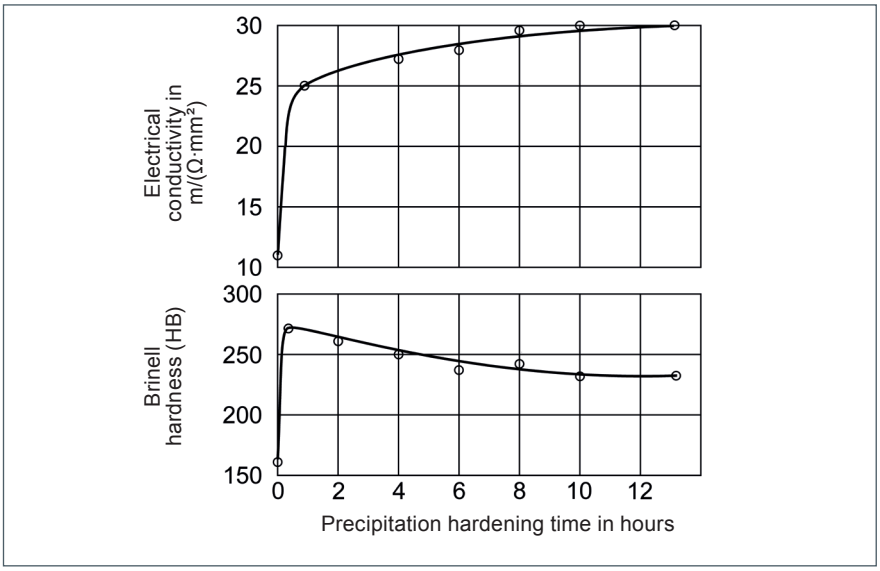


Figure 28: Hardness and electrical conductivity of CuCo2Be as a function of precipitation hardening time at a temperature of 480 °C [8], DKI 3963

5.2.2 Processing

CuCo2Be alloy can be cast using most established casting techniques. However, as beryllium fumes are toxic, there must be adequate ventilation when smelting, casting or welding this alloy and the work must be carried out in accordance with the applicable health and safety regulations. Casting is done at temperatures between 1100 °C and 1180 °C.

Hot working is carried out at temperatures between 750 °C and 950 °C. The material can be readily **cold worked** once it has been solution annealed. **Solution annealing** is performed in the temperature range 920–960 °C, after which the material is water-quenched and may then also be cold worked. Any intermediate process annealing steps should be carried out as a full solution annealing procedure. The alloy is usually machined in its cold worked or precipitation-hardened state.

CuCo2Be can be readily **soldered** and does not result in any deterioration in the properties of the hardened material. If the material needs to be **brazed** without suffering too great a loss in hardness, low-melting silver brazing fillers and short brazing times should be used. Like pure copper, CuCo2Be can be **welded** but it leads to a loss of strength.

5.2.3 Use

CuCo2Be is used to make the highly stressed, conducting springs in relays and switches and to manufacture semi-conductor heat sinks.

The alloy is also used for resistance-welding electrodes. Due to its combination of superior hardness and good thermal conductivity, CuCo2Be is the most suitable material for the nozzles used in the oxyfuel cutting of steel.

One particularly interesting application of CuCo2Be is its use in the manufacture of membrane components for aviation instruments. CuCo2Be is chosen for such applications because of its corrosion resistance, durability and good workability in its solution-annealed state, as well as its excellent strength in its precipitation-hardened state and its outstanding spring properties. CuNi2Be is used to make casting molds because of its high fatigue strength and wear resistance.

5.3 Copper-nickel-silicon alloys

The high solubility of silicon in copper can be significantly reduced by the addition of nickel and the solubility decreases further with falling temperature. The temperature-dependent solubility of the intermetallic compounds Ni_2Si, Ni_5Si_2 (or $Ni_{31}Si_{12}$) means that copper-nickel-silicon alloys can be precipitation hardened. The crystal structures of the silicides are semi-coherent or incoherent with the matrix. The three alloys CuNi1,5Si, CuNi2Si and CuNi3Si are standardized in DIN CEN/TS 13388 **(see fold-out table)**.

5.3.1 Properties

Copper-nickel-silicon alloys exhibit high tensile strengths (up to about 900 MPa for some thin Cu-Ni-Si sheets), electrical conductivities of up to 50% IACS, good corrosion resistance and good workability. The excellent thermal stability of the higher nickel alloys make them well suited for the manufacture of springs elements that will be used at temperatures above 150 °C. Adding small quantities of magnesium improves resistance to stress relaxation.

Partial substitution of nickel by cobalt can increase mechanical strength by up to 100 MPa.

Age-hardened Cu-Ni-Si alloys are highly resistant to stress corrosion cracking. These alloys are particularly wear resistant due to their high levels of hardness.

5.3.2 Processing

Hot working is carried out between 800 °C and 900 °C. If the material is quenched in water after being hot worked, there is no need for a separate solution annealing stage.

Solution annealing is performed at temperatures above 850 °C. The exact annealing temperature depends on the nickel content of the alloy: Ni_5Si_2 requires a higher temperature than Ni_2Si **(Fig. 29)**. The material is then quenched to freeze-in the high-temperature microstructure.

Cold working is carried out when the alloy is in its solution-annealed state. Depending on the application, cold working of up to 70% can be achieved. The alloys harden between 400 °C and 525 °C. Machining is generally done in the hardened state; the machinability index of 30% is better than that of pure copper.

Cu-Ni-Si alloys can be soldered without difficulty using lead-free solders. Brazing is best done using low-melting silver brazing fillers. When welding these alloys it is important to ensure that there is no thermal modification of the microstructure in the heat-affected zone.

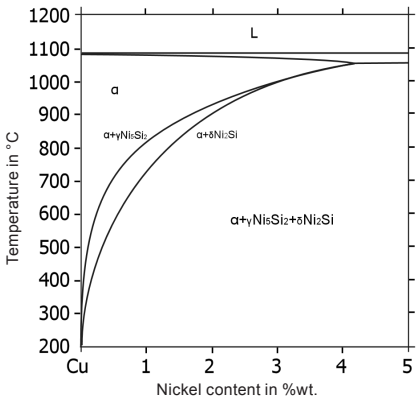


Figure 29: Solution annealing temperature of Cu-Ni-Si as a function of the chemical composition of the alloy [18], DKI 4507

If too much heat is applied, these alloys may soften or may become brittle.

They can be readily welded using laser, electron beam and gas metal arc welding, as the amount of heat input into the welding joint is relatively low with these techniques. Gas welding is not recommended.

5.3.3 Use

The good ductility of these alloys means that a number of different forming techniques can be applied. Switch rollers that facilitate the low-maintenance throwing of railway switches are forged from Cu-Ni-Si **(Fig. 30a)**, as are the clamps used in distribution boxes and for holding overhead contact wires **(Fig. 30b)**; screws, pins and circular plug connectors are manufactured by cold heading or cold extrusion. Cu-Ni-Si alloy strip is a popular semi-finished material used in the production of stamped and bent box-type electromechanical connectors **(Fig. 30c)** or spring elements.

Figure 30a: Switch rollers made from Cu-Ni-Si alloy for railway switch rails

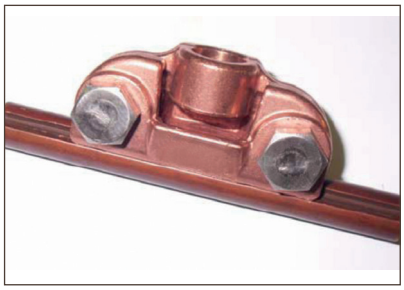


Figure 30b: Clamp made from CuNi2Si1 for holding overhead railway contact wire

Figure 30c: Plug-type connector

Copper-nickel-silicon alloys are chosen for some of these applications, because they can be bent to produce sharp-edged structures. They are also able to withstand high mechanical, electrical and thermal loads. In the electronics sector, these alloys are used to make lead frames, which act as electrical connectors and passive cooling elements for semiconductor devices. In some cases, the strips used in the manufacture of lead frames are silver plated.

Their good self-lubricating properties make them well suited as materials for highly stressed bushings, thrust washers and slideways. The excellent corrosion resistance of Cu-Ni-Si alloys has led to their frequent use for marine construction applications, including inboard marine motors and engines, and for chemical and process plant equipment.

This class of copper alloys is also chosen for high-strength, corrosion-resistant nuts and bolts, for wire cables in electric overhead line systems, for roller bearing cages and valve guides.

5.4 Copper–nickel–tin alloys

When alloying the copper-nickel-tin system, added phosphorus converts some of the nickel to nickel phosphide precipitates. The precipitated particles are then finely dispersed throughout the microstructure by a carefully controlled sequence of rolling and annealing operations.

As a result, these alloys offer an excellent combination of electrical conductivity and material strength. The alloys are not currently standardized in Europe, but some are standardized in the USA in ASTM B 422 and B 888 (e.g. CuNi1Sn0.9, which appears as C19025).

5.4.1 Properties

In addition to their good **conductivity** and **strength parameters** these alloys also exhibit significant resistance to **stress relaxation**.

These materials are therefore particularly well suited for high-temperature applications (above 150 °C). Depending on the specific Cu-Ni-Sn alloy used, cold working of small workpieces can increase mechanical strength to more than 540 MPa while retaining good material flexibility. Softening begins at 400 °C to 450 °C. These alloys are particularly suitable for manufacturing small electrical and electronic components. They are resistant to stress corrosion cracking.

5.4.2 Processing

Cu-Ni-Sn alloys are well suited to cold working. They can be readily welded and brazed The surface can be electroplated (with tin, nickel, silver or gold) or hot-dipped tin plated.

5.4.3 Use

Copper-nickel-tin alloys are used for electrical connectors and contacts (e.g. in the automotive sector), precision stampings, central electrical control units, relays, switches and lead frames.

6. Copper alloys for non-electrical applications in the process and plant equipment sectors

This final section presents a number of materials in the group of low-alloyed copper alloys whose electrical conductivity is of secondary relevance but that have established themselves as important materials in the plant and process equipment industry due to their high corrosion resistance and good processability (e.g. weldability). These alloys include elements such as arsenic, manganese, or silicon + manganese.

6.1 Copper-manganese alloys

Copper and manganese form homogeneous alloys up to a manganese content of about 20 %.

These alloys are oxygen-free due to the deoxidizing effect of the manganese and are therefore resistant to reducing gases even at high temperatures.

6.1.1 Properties

The addition of manganese increases the tensile strength of the copper both at room temperature and at higher temperatures **(Fig. 31)**. The **softening temperatures** of CuMn2 and CuMn5 are in the range **400 °C** to **450 °C**. However, the presence of manganese causes a large reduction in **electrical conductivity (see Fig. 3)**. Compared to copper, these alloys exhibit greater **resistance to corrosion** in many different media.

6.1.2 Processing

As a result of their greater strength, copper-manganese alloys exhibit a higher **deformation resistance** than unalloyed copper. With a machinability index of 20%, the **machinability** is similar to that of pure copper.

Materials in this group can be readily **soldered** and **brazed** and exhibit excellent **welding** properties as they are essentially oxygen-free and have low thermal conductivities [11].

6.1.3 Use

The thermal stability and corrosion resistance of Cu-Mn alloys make them particularly suitable for **plant equipment** used in the chemical and general process industries, and for the manufacture of marine boilers.

Copper-silicon and copper-silicon-manganese alloys

The maximum solubility of silicon in copper is 5.3% at 842 °C and the solubility decreases with decreasing temperature [7]. The engineering alloys with a maximum silicon content of 3.6% exhibit a homogeneous microstructure. These alloys typically contain between 1.8% to 3.6% Si and 0.3% to 1.3% Mn. The presence of manganese has only a minor influence on the solubility of the silicon in copper. The alloys CuSi1 and CuSi3Mn are standardized in DIN CEN/TS 13388 **(see fold-out table)**.

6.2.1 Properties

Silicon significantly improves the mechanical properties of copper **(Fig. 32)**. The addition of 3% of silicon improves the strength of copper to the same extent as adding around 42% Zn, 8% Al or 6% Sn. The addition of silicon also improves workability.

The presence of the alloying elements silicon and manganese produces greater hardening of the material as a result of cold working than is achievable in pure copper.

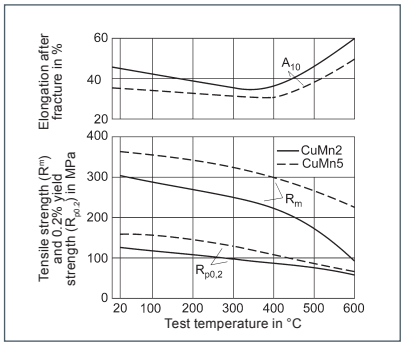


Figure 31: Strength parameters of copper-manganese alloy in its soft annealed sate at elevated temperatures [1], DKI 3959

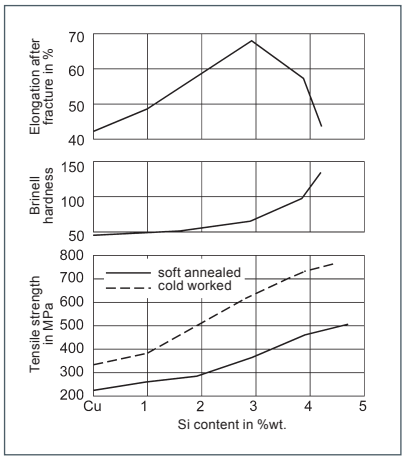


Figure 32: Strength parameters of copper-silicon alloys as a function of silicon content [8], DKI 3960

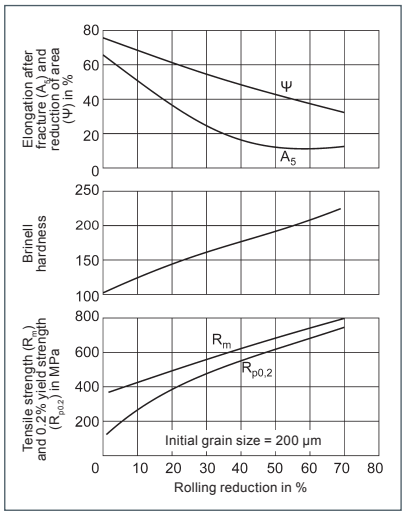


Figure 33: The influence of cold working on the strength of CuSi3Mn1 [8], DKI 3961

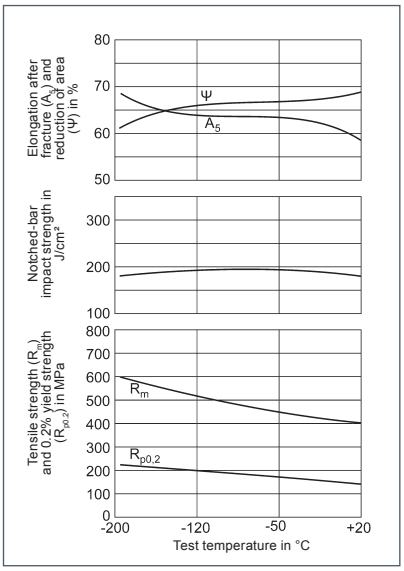


Figure 34: Low-temperature behaviour of CuSi3Mn1 [8], DKI 4622

The effect of cold working on the strength of the alloy CuSi3Mn1 is shown in **Figure 33**. The **softening temperature** of CuSi3Mn1 is around 300 °C. **Figure 34** shows the temperature-dependence of a number of mechanical strength parameters of CuSi3Mn1 and demonstrates that these alloys are suitable for low-temperature applications. The **electrical conductivity** is only about 5–10% of that of copper. The **corrosion resistance** is better than that of unalloyed copper.

6.2.2 Processing

Copper-silicon-manganese alloys can be readily c**old worked** and can be **hot worked** at temperatures between 700 °C and 750 °C. It should be noted that workability is reduced at temperatures around 400 °C and above 800 °C.

Their machinability is similar to that of copper. Machining with carbide tools is generally recommended as these alloys may contain hard inclusions (silicides).

Soldering is problematic due to the build up of SiO_2-containing scale. The recommended approach is to pre-tin the workpiece and then solder using one of the lead-tin solders defined in DIN EN ISO 9543 and DIN EN 1707-100.

Brazing can be carried out using brass or silver brazing alloys as per DIN EN ISO 17672 and a fluoride-containing flux.

These alloys exhibit excellent **weldability** as the presence of the silicon and manganese ensure continuous deoxidation of the weld pool resulting in dense, pore-free welds. The alloy CuSi3Mn1 defined in DIN EN ISO 24373 acts a suitable filler metal. The low thermal conductivity of these alloys also means that the welding heat propagates only slowly into the parent metal so that it is generally not necessary to preheat the parts to be joined.

6.2.3 Use

The good weldability and corrosion resistance of copper-silicon-manganese alloys make them excellent materials for the manufacture of chemical and process plant equipment.

7. Dispersion-strengthened materials

Dispersion-strengthened coppers contain 0.15–0.6%vol. of finely dispersed particles, such as Al_2O_3, ranging in size from 3 nm to 12 nm. They are produced using powder metallurgical methods and combine the high electrical conductivity of copper with the high strength of the composite material. Because of the way in which these dispersoid materials are produced, they are best classified as composites and are mentioned here for the sake of completeness.

Publishing information

Issued by:

Picture credits:
Aurubis AG
Buntmetall Amstetten GmbH
Gebr. Kemper GmbH & Co. KG
LEONI Draht GmbH
KME Germany GmbH & Co. KG
Piel & Adey GmbH & Co. KG
Swissmetall AG

Revised by:
Dr. Alexander Lerch
Helge Lehmann
Dr. Uwe Hofmann
Dr. Michael Köhler
Ahmad Parsi
Dr. Dirk Rode
Vincent Runser
Dr. Jürgen Schmidt
Volker Tietz
Dr. Ladji Tikana
Dietmar Zenker

8. Literature / Technical Standards

[1] Niedriglegierte Kupferlegierungen, Fachbuch; Deutsches Kupferinstitut, Berlin (1966)

[2] F. Pawlek, K. Reichel: Der Einfluss von Verunreinigungen auf die elektrische Leitfähigkeit von Kupfer. Z. f. Metallkde. 47 (1956), p. 347–351

[3] E. Tuschy: Kupferwerkstoffe für die Elektrotechnik. Metall 17 (1963), p. 1122–1133

[4] A. Baukloh, K. Drefahl, U Heubner, M. Rühle: Zeitstanduntersuchungen an niedrig- und unlegierten Kupferwerkstoffen Metall 30 (1976), p. 19–26

[5] Metals Handbook; Hrsg The American Society for Metals. Cleveland (1961)

[6] Werkstoff-Handbuch Nichteisenmetalle; Teil 111 Cu. VDI-Verlag. Düsseldorf (1960)

[7] K. Dies: Kupfer und Kupferlegierungen in der Technik. Springer Verlag. Berlin 1967

[8] H. J. Wallbaum in Landolt-Bornstein: Zahlenwerte und Funktionen IV Bd., 2. Teil, Bandteil b, p. 639-690 Springer-Verlag, Berlin (1964) (new edition – DKI)

[9] H. Hübner: Kupfer in Motoren und Generatoren. Metall 26 (1972), p. 1172–1173

[10] H.-G. Petri; H. Voßkühler: Kupfer-Chrom-Knetlegierungen als Werkstoffe für die Elektrotechnik ETZ-A 76 (1955), p. 360–385

[11] H. Haseke, R Köcher: CuMn2 – Herstellung Eigenschaften, schweißtechnische Verarbeitung und Anwendung, Metall 26 (1972), p. 333–241

[12] M. G. Corson: "Copper Hardened by a New Method", Z. Metallkde 19 (1927), p. 370–371

[13] S. A. Lockyer, F.M. Noble: "Precipitate Structure in a Cu-Ni-Si Alloy", J. Mater. Sci. 29 (1994), p. 218

[14] A. Bögel: "Spannungsrelaxation in Kupfer-Legierungen für Steckverbinder und Federelemente" METALL 48 (1994), p. 872

[15] J. Kinder, J. Fischer-Bühner: "Ausscheidungsuntersuchungen an höherfesten und höher leitfähigen CuNi2Si-Legierungen", METALL 59 (2005), p. 722

[16] H.-A. Kuhn, A. Käufler, D. Ringhand, S. Theobald: "A New High Performance Copper Based Alloy for Electromechanical Connectors", Mat.-Wiss. U. Werkstofftech. 38 (2007), p. 624

[17] M. Bohsmann, S. Gross: "Understanding Stress Relaxation", Matscience Techn. 2008, Pittsburgh /USA, Oct 5-9, 2008, Conf. Proceeding, p. 41

[18] J. Kinder, D. Hüter: "TEM-Untersuchungen an höherfesten und elektrisch hoch leitfähigen CuNi2Si-Legierungen" METALL 63 (2009), p. 298

[19] D. Ringhand: "Einflussgrößen bei der umformtechnischen Verarbeitung von Hochleistungs-Kupferwerkstoffen", METALL 63 (2009), p. 304

[20] J. R. Davis: Copper and Copper alloys, ASM International, (2001)

[21] J. Günter, J. A. K. Kundig: Copper – Its trade, manufacture, use and environmental status, ASM International & ICA, (1999)

[22] D.K. Crampton, H.L. Burghoff: The copper-rich alloys of the copper-nickel-phosphorus system, Trans AIME 137, (1940)

[23] M. Jasner, http://www.copper.org/applications/cuni/txt_KME.html

[24] Deutsches Kupferinstitut: Legierungen des Kupfers mit Zinn, Nickel, Blei und anderen Metallen, Berlin (1970)

Standards*

Basic standards
DIN CEN/TS 13388 Compendium of compositions and products
DIN EN 1172 Sheet and strip for building purposes
DIN EN 12163 Rod for general purposes
DIN EN 12164 Rod for free machining purposes
DIN EN 12165 Wrought and unwrought forging stock
DIN EN 12166 Wire for general purposes
DIN EN 12167 Profiles and bars for general purposes
DIN EN 12168 Hollow rod for free machining purposes
DIN EN 12288 Industrial valves – Copper alloy gate valves
DIN EN 12420 Forgings
DIN EN 12449 Seamless round tubes for general purposes
DIN EN 12450 Seamless round copper capillary tubes
DIN EN 12451 Seamless round tubes for heat exchangers
DIN EN 12452 Rolled, finned, seamless tubes for heat exchangers
DIN EN 13148 Hot-dip tinned strip
DIN EN 13599 Copper plate, sheet and strip for electrical purposes
DIN EN 13601 Copper rod, bar and wire for general electrical purposes
DIN EN 1412 European numbering system
DIN EN 14436 Electrolytically tinned strip;
DIN EN 1652 Plate, sheet, strip and circles for general purposes
DIN EN 1653 Plate, sheet and circles for boilers, pressure vessels and hot water storage units
DIN EN 1654 Strip for springs and connectors
DIN EN 1758 Strip for lead frames
DIN EN 1982 Ingots and castings

Standards relating to joining techniques
DIN EN 29453 (ISO 9453) Soft solder alloys
DIN EN 1707–100 Soft solder alloys
DIN EN 29454–1 (ISO 9454–1) Soft soldering fluxes
DIN EN 1045 Fluxes for brazing
DIN EN ISO 17672 Brazing – Filler metals
DIN EN ISO 24373 Welding consumables

*) This list does not claim to be complete.
The most recent edition of each standard shall apply.

Deutsches Kupferinstitut
Copper Alliance

Deutsches Kupferinstitut
Berufsverband e. V.
Heinrich Straße 24
40239 Düsseldorf

Phone: +49 211 239469-0
Fax: +49 211 239469-10

info@copperalliance.de
www.kupferinstitut.de