Low-Alloyed Copper Alloys

Properties · Processing · Applications
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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, and 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.

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 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.

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).

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

<table>
<thead>
<tr>
<th>Material designation</th>
<th>Kürzel</th>
<th>EN Number</th>
<th>UNS Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation-hardenable alloys</td>
<td>CuBr2</td>
<td>CW101C</td>
<td>C17200</td>
</tr>
<tr>
<td></td>
<td>CuCo1Ni1Be</td>
<td>CW103C</td>
<td>C17300</td>
</tr>
<tr>
<td></td>
<td>CuCo2Be</td>
<td>CW104C</td>
<td>C17400</td>
</tr>
<tr>
<td></td>
<td>CuCr1 / CuCr1-C</td>
<td>CW105C / CC140C</td>
<td>C18200 / C61500</td>
</tr>
<tr>
<td></td>
<td>CuCo1Zr</td>
<td>CW106C</td>
<td>C17500</td>
</tr>
<tr>
<td></td>
<td>CuFe2P</td>
<td>CW107C</td>
<td>C17600</td>
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<td>CuNi1P</td>
<td>CW108C</td>
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</tr>
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<td>CW110C</td>
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</tr>
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</tr>
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<td>C18700</td>
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<td>CuAg0.1</td>
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<td></td>
<td>CuMg0.4</td>
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<td>C18900</td>
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<td></td>
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<td>C19200</td>
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<tr>
<td>Non-precipitation-hardenable alloys</td>
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<td>CW124C</td>
<td>C19300</td>
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<tr>
<td></td>
<td>CuMg0.4</td>
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<td>CW128C</td>
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Table 3: Classification of low-alloyed coppers into different conductivity and strength classes

<table>
<thead>
<tr>
<th>Property</th>
<th>Rating</th>
<th>Value</th>
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<tr>
<td>Electrical conductivity (MS/m)</td>
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<tr>
<td></td>
<td>high</td>
<td>36–48</td>
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<tr>
<td></td>
<td>very high</td>
<td>&gt; 48</td>
</tr>
<tr>
<td>Tensile strength (Rm) MPa</td>
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<td></td>
<td>high</td>
<td>590–880</td>
</tr>
<tr>
<td></td>
<td>very high</td>
<td>&gt; 980</td>
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</table>

Figure 3a: Electrical and electronic components (DKI 6231)
2. Copper alloys with high electrical conductivity and good machinability

An important group of low-alloyed copper alloys is the copper-tellurium alloys, which are characterized by high electrical conductivity and good machinability. These alloys are particularly suitable for applications in electrical engineering, such as the production of electrical contacts, connectors, and brazing materials.

### Material Designation

<table>
<thead>
<tr>
<th>Material designation</th>
<th>Flat-rolled products</th>
<th>Pipes and tubes</th>
<th>Rods, shaped cross-sections and wires</th>
<th>Forging stocks and forged products</th>
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</thead>
<tbody>
<tr>
<td>CuZn13Pb3</td>
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<tr>
<td>CuZn20S</td>
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<td>x</td>
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</tbody>
</table>

### Processing

CuTeP can be cold worked and rolled to produce semi-finished products. However, its ductility is not as good as that of pure copper. To completely restore ductility, the alloy must be annealed in the temperature range 425–650 °C. CuTeP has excellent working properties at temperatures between 750 °C and 875 °C. This makes it an excellent material for forged parts that undergo subsequent machining. 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 key characteristics of CuTeP. When machined, it tends to form short chips and is therefore an excellent material for free-machining. The machinability rating of CuTeP is 80% of that of the free-cutting brass CuZn39Pb3. 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.

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 1018: Recommended machining parameters for copper and copper alloys).

2.1.2 Processing

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2. Copper alloys with high electrical conductivity and good machinability

An important group of low-alloyed copper alloys are those with a high to intermediate electrical conductivity that are used primarily in electrical engineering applications [3, 21]. Examples include copper-silver, copper-chromium-zinc and copper-magnesium. However, there are other low-alloyed copper alloys which offer mechanical properties and electrical conductivity.

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. Standard includes composition, mechanical properties, electrical conductivity, and tempering. Examples include copper-silver, copper-chromium-zinc and copper-magnesium.

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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 notch-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 operations and techniques that are taken into account (see DKI Monograph 1018: Recommended machining parameters for copper and copper alloys).

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### 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 must be annealed in the temperature range 425–650 °C. CuTeP has excellent working properties at temperatures between 750 °C and 875 °C. This makes it an excellent material for forged parts that undergo subsequent machining. 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 key characteristics of CuTeP. When machined, it tends to form short chips and is therefore an excellent material for free-machining. The machinability rating of CuTeP is 80% of that of the free-cutting brass CuZn39Pb3. 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.

Table 4: Product forms for standardized low-alloyed coppers (based on Table 10 in DIN CEN/TS 13388)

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<td>CuZn20S</td>
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</tr>
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</table>
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 FH10 flux as defined in DIN EN 1045. Soldering is best done using a low-melting silver brazing filler of the type described in DIN EN ISO 17672 with 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 used successfully on tellurium copper CuPb1P is the only alloy of this class with phosphorus, with the lead imparting good machinability properties to the alloy. 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.

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

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Metal joining process</th>
<th>Surface treatment process</th>
<th>Mechanical properties</th>
<th>Electro-chemical properties</th>
<th>Sulfur solubility</th>
<th>Suitability for hot-rolling</th>
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<td>CuCo2Be</td>
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<tr>
<td>CuSi3Mn1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CuMn2</td>
<td>CuMg0.7</td>
<td>CuMg0.4</td>
<td>CuAg0.10</td>
<td>CuAg0.03</td>
<td>CuNi3Si</td>
<td>CuNi1.5Si</td>
</tr>
<tr>
<td>CuCo2Be</td>
<td>CuBE1.7</td>
<td>(CuFe2P)</td>
<td>(CuZn0.7)</td>
<td>CuSi3Mn1</td>
<td>CuMn2</td>
<td>CuMg0.7</td>
</tr>
<tr>
<td>CuPb1P</td>
<td>CuPb0.5</td>
<td>CuPb0.1</td>
<td>CuPb0.3</td>
<td>CuPb0.8</td>
<td>CuPb1P</td>
<td>CuPb0.5</td>
</tr>
<tr>
<td>CuSP</td>
<td>CuSi3Mn1</td>
<td>CuMn2</td>
<td>CuMg0.7</td>
<td>CuMg0.4</td>
<td>CuAg0.10</td>
<td>CuAg0.03</td>
</tr>
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<td>CuCo2Be</td>
<td>CuBE1.7</td>
<td>(CuFe2P)</td>
<td>(CuZn0.7)</td>
<td>CuSi3Mn1</td>
<td>CuMn2</td>
<td>CuMg0.7</td>
</tr>
</tbody>
</table>

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

2.3.2 Processing

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 machinering 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).

2.2.2 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 between 750 °C and 875 °C, but it is not recommended because of the lead content.

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Brazing is best done using low-melting silver brazing fillers of the type described in DIN EN ISO 9453 and DIN EN 1707-100 standards and a copper flux such as type FH10 specified in DIN EN 29454-1.

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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. 3) 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 phosphorus deoxidized 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).

### 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 380 °C).

Preferred solders are the tin-lead solders defined in the DIN EN ISO 468 and DIN EN 1007-100 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 CuAg(P) welding rods (see DIN EN ISO 24573), 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 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.

### 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. These alloys are readily amenable to both cold and hot working and are also 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.

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

<table>
<thead>
<tr>
<th>Test temperature(°C)</th>
<th>Material designation</th>
<th>Test load [MPa]</th>
<th>Creep elongation (%) after 5 h</th>
<th>Time to rupture (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>130</td>
<td>Cu-ETP</td>
<td>55</td>
<td>0.13</td>
<td>1750</td>
</tr>
<tr>
<td>130</td>
<td>CuAg0.1</td>
<td>95</td>
<td>0.03</td>
<td>1750</td>
</tr>
<tr>
<td>170</td>
<td>Cu-ETP</td>
<td>95</td>
<td>0.36</td>
<td>1750</td>
</tr>
<tr>
<td>170</td>
<td>CuAg0.1</td>
<td>95</td>
<td>0.06</td>
<td>1750</td>
</tr>
<tr>
<td>200</td>
<td>Cu-ETP</td>
<td>138</td>
<td>0.15</td>
<td>1750</td>
</tr>
<tr>
<td>200</td>
<td>CuAg0.04</td>
<td>138</td>
<td>0.15</td>
<td>1750</td>
</tr>
<tr>
<td>200</td>
<td>CuAg0.03</td>
<td>138</td>
<td>0.15</td>
<td>1750</td>
</tr>
</tbody>
</table>

CuAg0.1 with 0.086% Ag, cold worked, CuAg0.04 with 0.029% Ag, soft annealed.

![Figure 6: Rotor for a turbo-generator with CuAg rotor bars](Image)

![Figure 7: The influence of zirconium content on selected properties of CuZr alloys (6), DIN EN 13388)](Image)
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.

3.3.3 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 cathenary 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.

3.3.4 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 87% IACS and thus higher than that of Cu-DHP.

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.

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.

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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.

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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 brazability 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).

<table>
<thead>
<tr>
<th>Material condition</th>
<th>0.2% yield strength [MPa]</th>
<th>Tensile strength [MPa]</th>
<th>Elongation after fracture [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>soft annealed</td>
<td>80</td>
<td>270</td>
<td>50</td>
</tr>
<tr>
<td>hard drawn (50 %)</td>
<td>410</td>
<td>450</td>
<td>5</td>
</tr>
<tr>
<td>hard drawn (80 %)</td>
<td>510</td>
<td>550</td>
<td>4</td>
</tr>
<tr>
<td>hard drawn (98 %)</td>
<td>640</td>
<td>695</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 7: Strength parameters for wires made from CuMg0.2 [8]

4.2 Copper-iron alloys

The solubility of iron in copper at 1085 °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. CuFe0.1P 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 400–600 °C depending on the initial condition of the alloy.

Figures 11a and 11b show the softening behaviour of the alloys CuFe0.1P and CuFe2P.
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 CO2, as refrigerant.

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 [8]. 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.

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

<table>
<thead>
<tr>
<th>Alloy</th>
<th>CuCr1 (annealed)</th>
<th>CuCr1 (60% cold worked)</th>
<th>CuCr1 (70% cold worked)</th>
<th>CuCr1 (80% cold worked)</th>
</tr>
</thead>
<tbody>
<tr>
<td>After 500 h no notch MPa</td>
<td>250</td>
<td>260</td>
<td>270</td>
<td>280</td>
</tr>
<tr>
<td>After 100 h no notch MPa</td>
<td>200</td>
<td>210</td>
<td>220</td>
<td>230</td>
</tr>
<tr>
<td>After 500 h no notch MPa</td>
<td>150</td>
<td>160</td>
<td>170</td>
<td>180</td>
</tr>
<tr>
<td>After 100 h no notch MPa</td>
<td>100</td>
<td>110</td>
<td>120</td>
<td>130</td>
</tr>
</tbody>
</table>

Figure 12a: Lead frame
Figure 12b: Precision stamped sheet for electrical applications
Figure 13: Contact strip made from CuFeP (CuFe0.1P)
Figure 14: Hardness and electrical conductivity of CuCr as a function of the degree of cold working after precipitation hardening [1]. DKI 1315
Figure 15: Resistance to tempering of CuCr with 0.6% Cr (solution annealed, 25% cold worked and aged) compared with CuCr with 0.13% Zr (solution annealed, 85% cold worked and aged) and Cu-ETP (cold worked). Aging time at each temperature: 5 h [10], DKI 4613
4.3.3 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 scavenging. 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 aging. The heat treatment of CuCr1 first involves solution annealing the semi-finished stock for about 600 °C, which is considerably higher than 450 °C, and cast about 110 °C. Then, a more heterogeneous microstructure, created through a combination of cold work and artificial aging, is used in the welding process may cause chromium precipitates to dissolve back into the solid-solution.

4.3.3.1 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.

As the precipitation of chromium produces a more heterogeneous microstructure, precipitation-hardened CuCr1-C (machinability rating: about 30%) are significantly easier to machine than pure copper. CuCr1-C can only be welded if certain precautions are taken. One technique that can be used is TIG welding using a CuCr1 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.

4.3.4 Properties

The advantages of CuCr are its high softening temperature and creep rupture strength [4] and its notch strength insensitivity at elevated temperatures. A disadvantage of copper-chromium 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 alloy CuCr1Zr. The ternary alloy CuCr1Zr is superior to both of the binary alloys CuCr and CuZr, as explained in 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 CuCr.

The ternary alloy 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.

![Figure 16: Medium-voltage contact finger made from CuCr1-C](image)

![Figure 17: Creep behaviour of CuCr1Zr compared with CuCr (test temperature: 230 °C for the 1500 h curve) (7), DIN EN ISO 9543)](image)

![Table 8a: Comparison of strength parameters of Cu-C and CuCr1-C](image)

<table>
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<td>S</td>
<td>510</td>
<td>22</td>
<td>465</td>
</tr>
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<td></td>
<td>N</td>
<td>600</td>
<td>20</td>
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</table>

<table>
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</tr>
</thead>
<tbody>
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<td>S</td>
<td>510</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>445</td>
</tr>
</tbody>
</table>

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

Figure 19: Crucible made from CuCr1Zr
Figure 20: Tubes manufactured from CuCr1Zr
Figure 21: Plate made from CuCr1Zr

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 CuNi-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 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 CuNi-P (C19000) (temperature: 250°C, 75% Rp0.2)
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, CuNiP 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 plugs, electrode holders, earth (ground) clamps and seam-welding rollers. These products are used in the IT, aviation, telecommunication 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 1756), while CuSn0.3 is chosen for the fine-gauge stranded wire in cable harnesses and for catenary wires.

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, CuBe2Zn, CuCu10Be, 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 760–810 °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.

5.2 Processing
Solution-annealed CuNiP shows excellent cold workability. The CuNiP 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, CuNiP can be alloyed with up to 1% lead (Fig. 24).

5.3 Use
CuNiP 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 CuNiP alloys are used in the production of springs, clips, contact supports and connectors. Rods and hollow tubing are processed to make welding plugs, electrode holders, earth (ground) clamps and seam-welding rollers. These products are used in the IT, aviation, telecommunication and automotive industries.

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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.

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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.

5.4.3 Use
A typical use of CuSn0.15 is in the manufacture of lead frames (DIN EN 1756), while CuSn0.3 is chosen for the fine-gauge stranded wire in cable harnesses and for catenary wires.

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.

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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.

5.5 Copper alloys with moderate electrical conductivity and high strength
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.

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 760–810 °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.
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.

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 350 °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 semiconductor heat sinks. Due to its combination of superior hardness and good thermal conductivity, CuCo2Be is the most suitable material for the nozzles used in the oxy-fuel 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 Ni3Si, Ni5Si3 or Ni13Si11 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 CuNi13Si3, CuNi25Si and CuNi35Si 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.

Figure 28: Hardness and electrical conductivity of CuCo2Be as a function of precipitation hardening time at a temperature of 460 °C [6], DIN 13433
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 650 °C. The exact annealing temperature depends on the nickel content of the alloy: Ni$_2$Si requires a higher temperature than Ni$_5$Si$_2$ (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.

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.

Copper-nickel-aluminium 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 side-walls. 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 phosphate 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. CuNi1Sn1B, 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.

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Figure 29: Solution annealing temperature of Cu-Ni-Si as a function of the chemical composition of the alloy [18], D014501

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
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 ductility (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 13381 (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.

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 cold 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.

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.

Figure 31: Strength parameters of copper-manganese alloy in its soft annealed state at elevated temperatures [7], DKI 3809

Figure 32: Strength parameters of copper-silicon alloys as a function of silicon content [8], DKI 3803

Figure 33: The influence of cold working on the strength of CuSi3Mn1 [6], DKI 3981

Figure 34: Low-temperature behaviour of CuSi3Mn1 [6], DKI 4022

The good weldability and corrosion resistance of copper-silicon-manganese alloys make them excellent materials for the manufacture of chemical and process plant equipment.
Dispersion-strengthened coppers contain 0.15–0.6% vol. of finely dispersed particles, such as \( \text{Al}_2\text{O}_3 \), 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.

7. Dispersion-strengthened materials
8. Literature / Technical Standards


Standards*

Basic standards:

DIN CEN/TS 13388 Compendium of compositions and products
DIN EN 1712 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 12148 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 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 1070-100 Soft solder alloys
DIN EN 29454-1 (ISO 9454-1) Soft soldering fluxes
DIN EN 1045 Fluxes for brazing
DIN EN ISO 17672 Brazing – Filter metals
DIN EN ISO 24373 Welding consumables

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