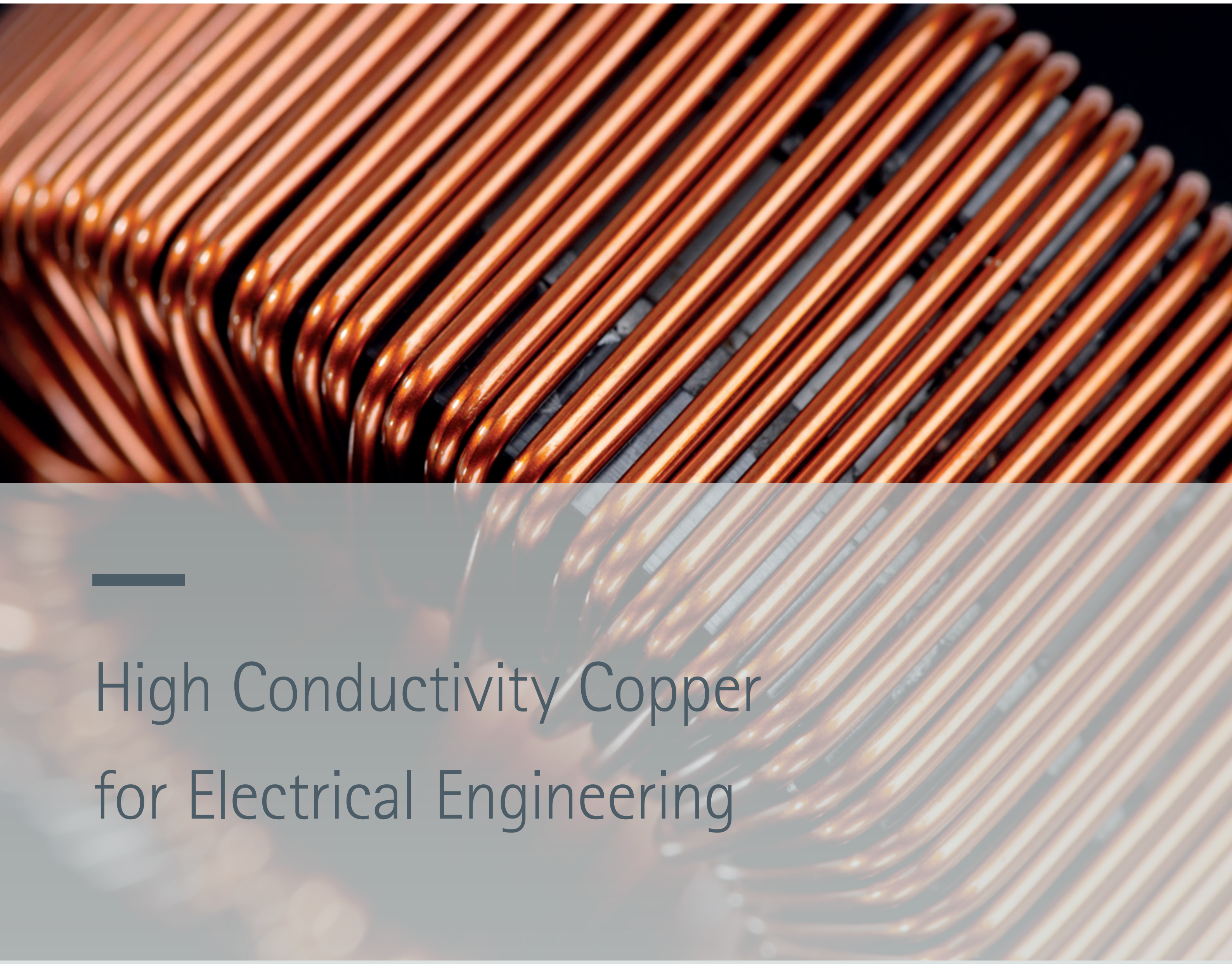
Copper Development Association
Copper Alliance



High Conductivity Copper for Electrical Engineering

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David Chapman was the Electrical Programme Manager for Copper Development Association in the UK, where his main interests included power quality and energy efficiency. He was an author and Chief Editor of the LPQI Power Quality Application Guide.

Cu Copper Development Association Copper Alliance

Copper Development Association is a non-trading organisation that promotes and supports the use of copper based on its superior technical performance and its contribution to a higher quality of life. Its services, which include the provision of technical advice and information, are available to those interested in the utilisation of copper and copper alloys in all their aspects. The Association also provides a link between research and the user industries and is part of an international network of trade associations, the Copper Alliance™.

Cu European Copper Institute Copper Alliance

Founded in 1996, ECI is a joint venture between the International Copper Association, Ltd (ICA), headquartered in New York, representing the majority of the world's leading mining companies, custom smelters and semi-fabricators, and the European copper industry. ECI is also part of the Copper Alliance, an international network of industry associations. Its shared mission is to work, with its members, to defend and grow markets for copper based on its superior technical performance and contributions to a higher quality of life.

Cover page image:
Macrodetail of a copper inductor in a transformer (Copyright demarcomedia/shutterstock)

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Summary

This publication describes the electrical and mechanical properties of high conductivity copper and copper alloys that are intended for use in electrical applications. It is primarily aimed at electrical engineers rather than metallurgists but gives the basic metallurgical detail needed to understand the processing requirements of alloys.

High conductivity copper is the best choice for bulk electrical conductors, such as cables, motor windings and busbars, but there are many electrical accessories, such as terminations, connectors, contactors and circuit breakers, where other material properties are equally or more important. For these applications there is a very wide range of copper alloys available with, for example, enhanced strength, resistance to stress relaxation or creep, while retaining excellent conductivity.

1.0 Introduction

Copper has the highest conductivity of any non-precious metal. This, combined with its high ductility, medium strength, ease of joining and good resistance to corrosion, makes copper the first choice as a conductor for electrical applications.

High conductivity copper is the most common form of the metal and it is widely available with consistent high quality. It is the first choice for the manufacture of bulk conductors such as cables, busbars, transformer windings and motor stators and rotors. However, for other electrical applications, such as connector parts, commutators and catenary wires, the mechanical properties may need to be enhanced by the addition of appropriate alloying elements. The ease with which copper can form alloys with other elements results in the availability of a very wide range of materials suitable for all electrical applications.

2.0 High Conductivity Copper

The electrical properties of high conductivity copper were standardised in 1913 by the International Electrotechnical Commission which defined the International Annealed Copper Standard (IACS) in terms of the following properties at 20°C:

Table 1 – Properties of 100% IACS Copper at 20°C

Volume conductivity, σ_v	58 MS/m
Density, d	8890 kg/m^3
Temperature coefficient of resistance, α	0.00393/K

It follows from the first two values that:

Table 2 – Implied Properties of 100% IACS Copper at 20°C

Volume resistivity, ρ_v (= $1/\sigma_v$)	1.7241 mΩcm
Mass conductivity, σ_m (= σ_v/d)	6524 Sm^2/kg
Mass resistivity, ρ_m (= $1/\sigma_m$)	153.28 μΩkg/m^2

These values correspond to 100% IACS. Since 1913, processing technology has improved to the point where high conductivity copper in routine day-to-day production can reach or exceed a conductivity of 102% IACS. It has become normal practice to express the conductivity of all electrical alloys, often including aluminium alloys, in terms of IACS.

2.1 Effect of Impurities and Minor Alloying Additions on Conductivity

The degree to which the electrical conductivity is affected by the presence of an impurity depends largely on the element present and its concentration, as illustrated in Figure 1. The values given in this figure are approximate since the precise effect depends on the thermal and mechanical history of the copper, the oxygen content and on other inter-element effects.

Most of the elements shown have some solubility in copper and their proportionate effect is a function of difference in atomic size, as well as other factors. Elements that are largely insoluble in copper have little effect on the conductivity because they are present as discrete particles and do not affect the bulk of the material. Often they are intentionally added to improve, for example, the machinability of high conductivity copper. Further information is given in Section 3.0 Copper Alloys.

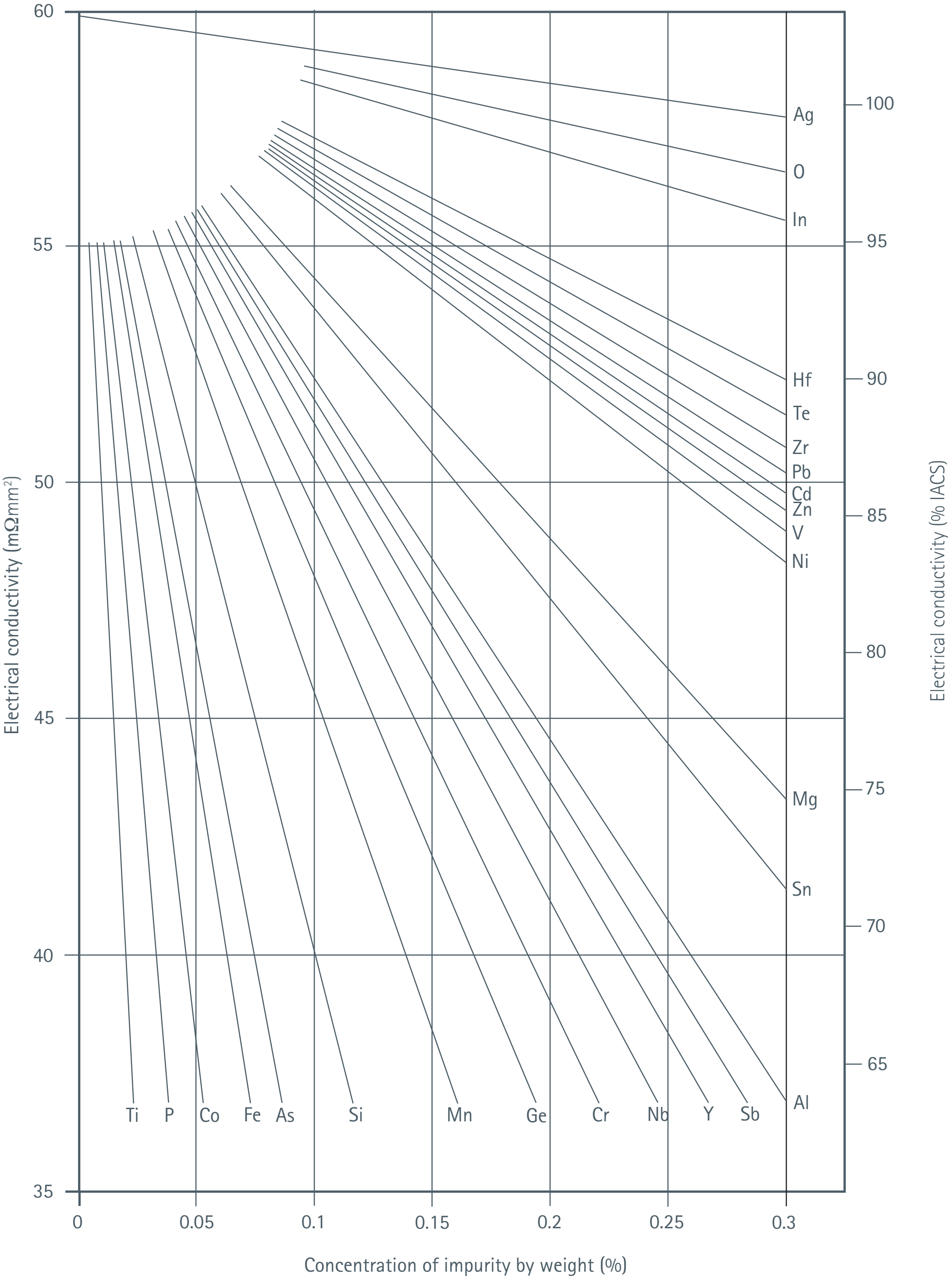

Figure 1 – Effect of various elements (impurities or intentional additions) on the conductivity of copper

Figures 2 and 3 show the effect of much lower concentrations of various individual impurities on the conductivity of oxygen-free (Cu-OF) and electrolytic tough pitch (Cu-ETP) copper respectively.

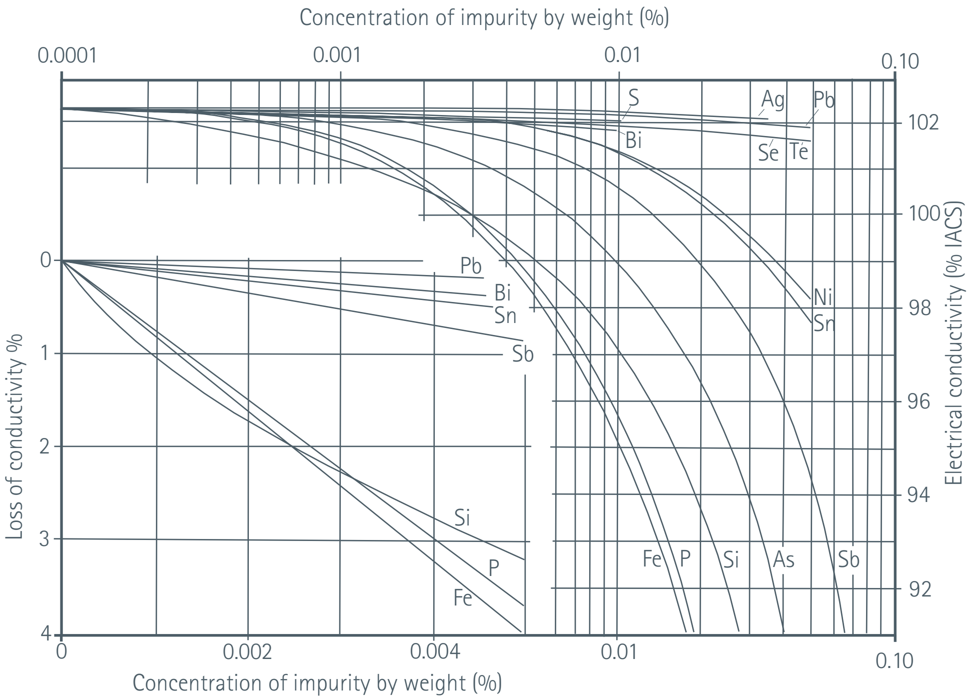

Figure 2 – Effect of various elements (impurities or intentional additions) on the conductivity of oxygen-free copper (Cu-OF)

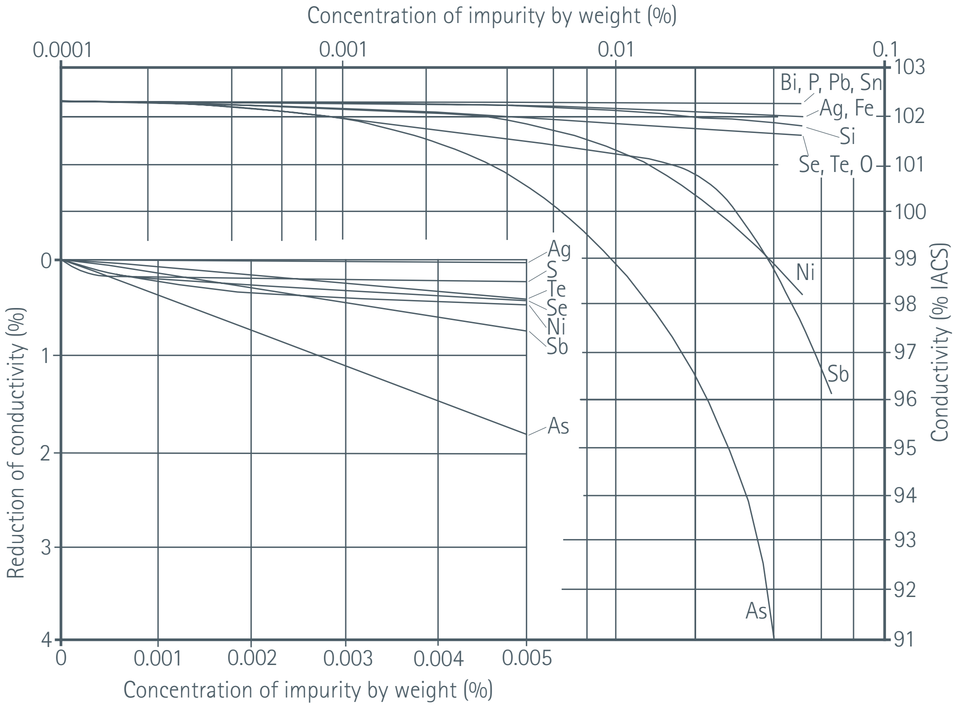

Figure 3 – Effect of various elements (impurities or intentional additions) on the conductivity of ETP copper (Cu-ETP)

2.1.1 Oxygen Content

The oxygen content is very important and is carefully controlled during manufacture. As shown in Figure 1 and Figure 2, the presence of impurities in solution reduces conductivity but, if oxygen is also present (Figure 3), many impurities form oxides which then exist as inclusions within the material. Because the impurities are no longer in solution, the effect on conductivity is reduced. However, the amount of oxygen that can be tolerated is limited for two reasons. Firstly, oxygen itself reduces conductivity by forming particles of copper oxide and, secondly, a high oxygen content gives rise to hydrogen embrittlement if the material is heated in a reducing atmosphere, such as during welding. Hydrogen embrittlement may also be referred to as steam embrittlement.

Traditionally, copper castings and refinery shapes for subsequent fabrication contain sufficient oxygen to give a level 'set' to the casting on solidification. This has two main advantages:

- The presence of oxygen ensures that most impurities are present as oxides, reducing their effect on conductivity and ductility.
- The oxygen reacts with hydrogen, which is picked up from the furnace atmosphere, forming steam. The micropores resulting from the steam counteract the shrinkage which would otherwise occur during solidification and this leads to the level set (correct pitch) of the casting. Further hot processing reduces the porosity. With the correct pitch and oxygen content, the properties are good and said to be 'tough', hence the term tough pitch copper for the most widely used high conductivity copper.

More recently improvements in refinery techniques have resulted in a reduction in impurity levels, making the presence of oxygen less necessary. Meanwhile, improvements in casting techniques, such as improved control of the melting atmosphere to reduce hydrogen pickup, has enabled the oxygen content to be reduced from about 0.06% to 0.02% or less. Today, all copper is continuously or semi-continuously cast so there are no longer static refinery shapes. The copper is fed continuously and a rolled product is produced at the end of the process. These improvements have resulted in high conductivity oxygen-free copper becoming commonly available.

2.1.1.1 Embrittlement of Tough Pitch Copper

Under adverse conditions, it is possible for high conductivity copper to become embrittled (or gassed) by hydrogen. This can occur when it is annealed, welded or brazed in an unsuitable reducing atmosphere.

If the material is heated for a significant time in a reducing atmosphere containing hydrogen, the oxide is reduced as hydrogen diffuses into the metal. The liberated oxygen reacts with the hydrogen to form steam that can rupture the copper. Normal hot working procedures avoid this potential problem by maintaining an oxidising atmosphere.

2.2 Mechanical Properties

The mechanical strength of the material is important to ensure that deformation does not occur during processing and use. Wrought high conductivity coppers can only be strengthened and hardened by cold working such as cold drawing or bending. They cannot be strengthened by heat treatment so, if a stronger grade of high conductivity copper is required, small amounts (less than 1%) of alloying elements such as silver, magnesium or tin are used. These additions give solid solution hardening and contribute to work hardening when the alloys are cold drawn into wires or tubes or rolled into sheet. High conductivity copper does not become harder with time; it does not have a 'shelf life'.

Typical mechanical properties of wrought coppers are shown in Table 8. These figures can only be taken as an approximate guide since they vary with the product form and the previous mechanical and thermal history of the material. For actual minimum values the appropriate EN Standards or manufacturer's data sheets should be consulted regarding the product form and temper designation required. Shear strength may be taken as approximately two thirds of the tensile strength for many of these materials.

While there is a large amount of data available on low and elevated temperature tensile and creep properties, the wide variety of testing conditions employed prevents the data being presented in a common table. Similar problems are present when comparing impact and fatigue data.

2.2.1 Cold Working

The effect on the mechanical properties of cold work by rolling (to reduce the thickness) on high conductivity copper strip is shown in Figure 4. Cold working of the material has the effect of raising the tensile strength, proof strength and hardness but reducing its elongation. Note that the relationship between tensile strength and hardness is not linear.

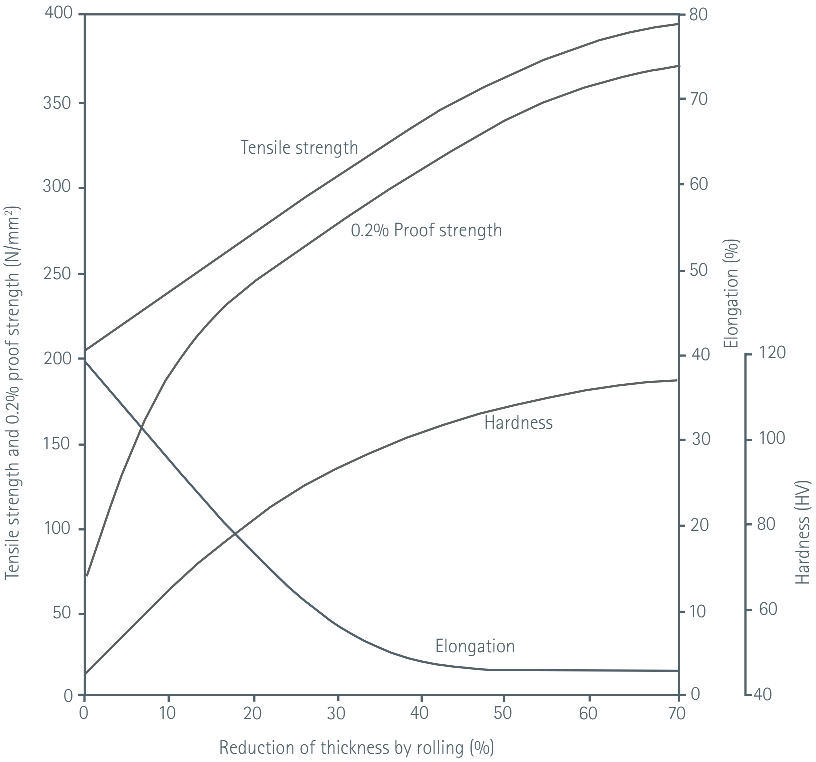

Figure 4 – Effect of cold rolling on mechanical properties and hardness of high conductivity copper strips

If the extent of cold work required is severe, inter-stage annealing may be required to give full softening and allow further cold working. Generally this should be carried out for the shortest time at the minimum temperature needed to achieve the required softening in order to avoid excessive grain growth which can lead to surface roughness effects (orange peel) or even embrittlement.

2.2.2 Annealing

Although high conductivity coppers are extremely ductile and can be cold worked considerably, an annealing step will sometimes be required to re-soften the metal. The temperature to be used (350-600°C) depends on the composition of the copper, the extent to which it has been cold worked and the time spent within the annealing temperature range. The metal section size and the type of furnace used also affect time and temperature relationships. In Figure 5 the effect that various amounts of prior cold work have on the annealability of electrolytic tough pitch copper is shown. The annealing time in each case is 1 hour. It will be noted that the more cold work present, the more readily is the copper annealed.

2.2.2.1 Effect of Impurities on Annealability

High-speed wiredrawing plant requires highly consistent and reproducible materials so manufacturers now use several quality control tests to check wire rod before release. One of these is the Spiral Elongation Test, described in EN 12893 for copper wire rod suitable for wiredrawing. This involves drawing the copper sample to 2 mm diameter, annealing it under closely controlled standard conditions, winding it to a specified helical coil and then measuring the extension of this limp 'spring' under load. The effects of very low levels of impurities and combinations of impurities on the results of this test have been described in recent papers showing, for example, that selenium, sulphur, arsenic, lead and antimony have marked influences on annealability at levels of around 1.5 to 3 g/t. Bismuth immediately affects annealing behaviour, even at 0.1 g/t. It is on the basis of this work that the impurity group totals specified for Cu-CATH-1 and Cu-ETP1 have been established.

2.2.3 Stress Relieving

In finished components it may be necessary to stress relieve high conductivity copper to reduce the possibility of distortion or cracking after machining or cold work. This may be done at 150-200°C. This does not soften the copper. If this is required, then a full anneal at 350-600°C is needed.

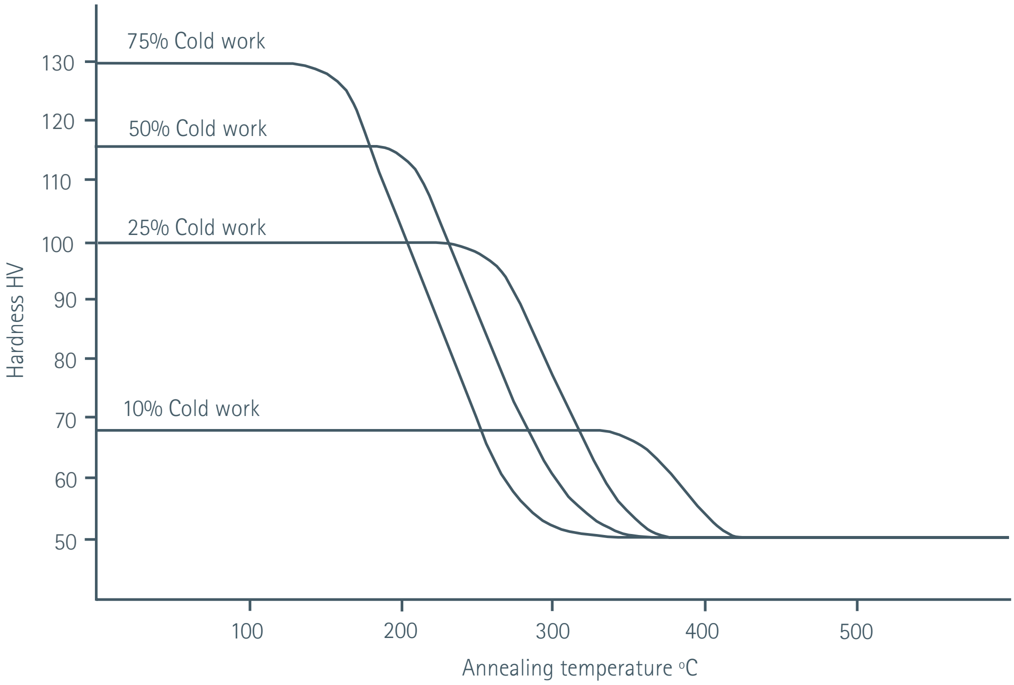

Figure 5 – Typical effect of the extent of previous cold work on the annealing behaviour of Cu-ETP

As shown in Figure 6, the lower the temperature, the longer it will take for the material to soften.

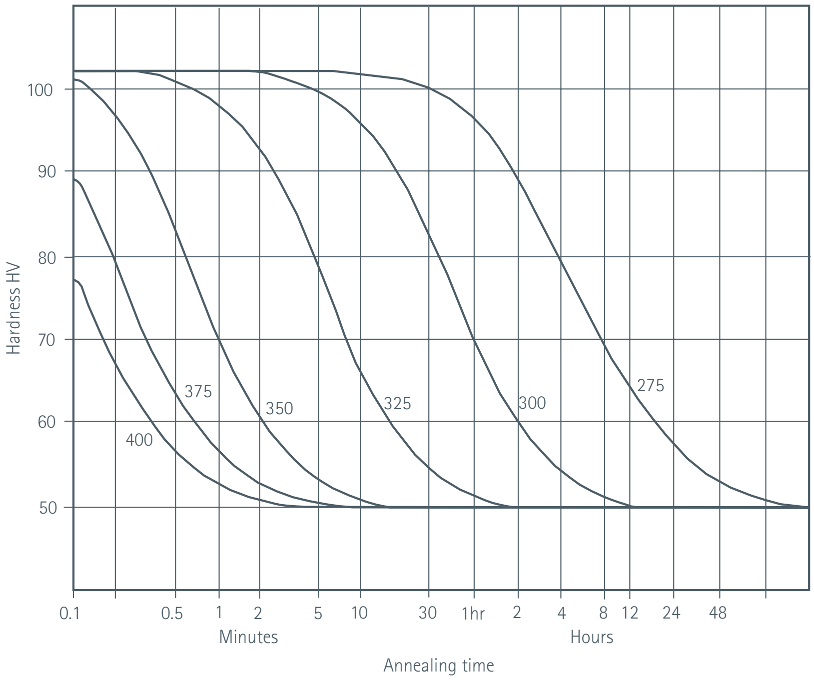

Figure 6 – Typical effect of annealing temperature on annealing behaviour of Cu-ETP

The results of annealability tests on four different materials are shown in Figure 7, which emphasises the effect of alloying on elevated temperature behaviour.

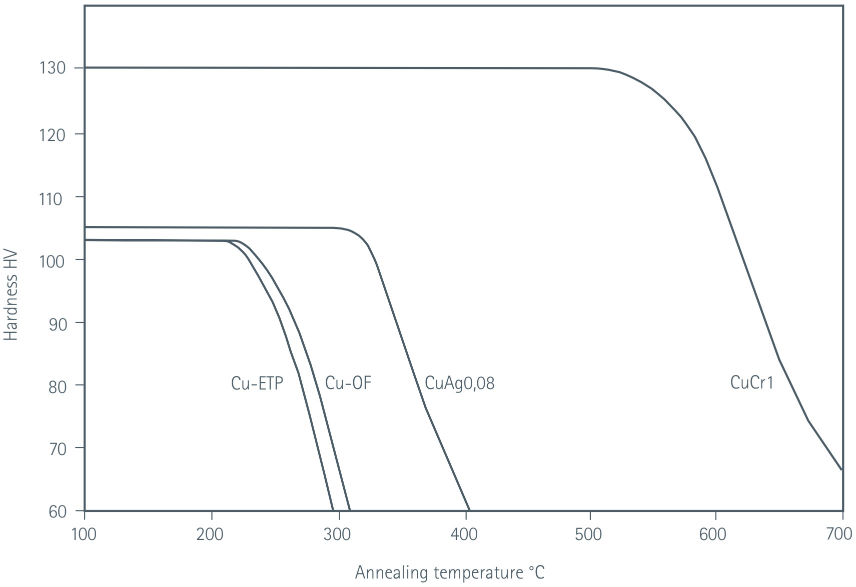

Figure 7 – Annealing behaviour of four high conductivity coppers

The interrelationship of temperature with time is shown in Figure 8 for both electrolytic tough pitch copper and for a similar copper with about 0.08% silver added. The very beneficial effect of silver on creep strength is evident.

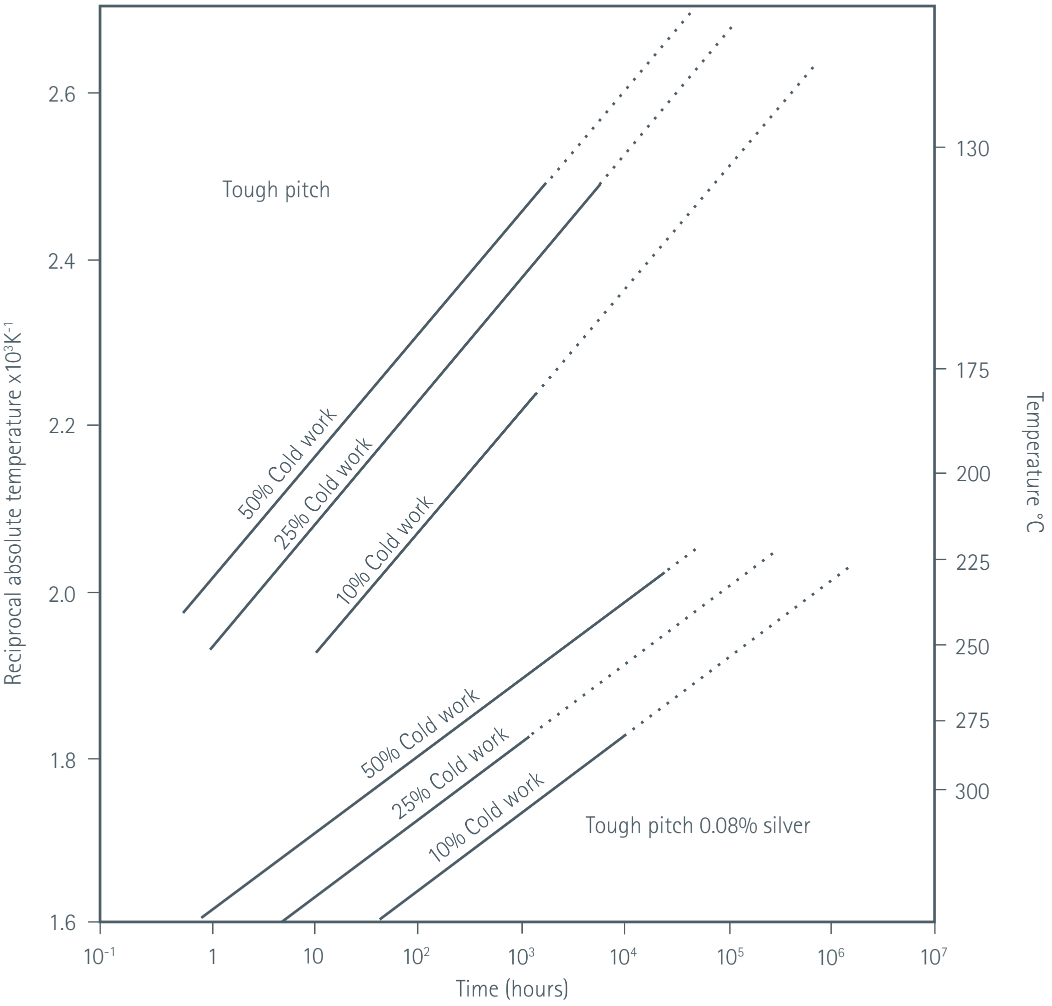

Figure 8 – Relationship between time and reciprocal absolute annealing temperature to produce 50% softening of cold-worked Cu-ETP and CuAg0,08

2.2.4 Tensile Strength

In the 'as-cast' condition, high conductivity copper has a tensile strength of 150-170 N/mm². The changes in structure brought about by hot working raise the tensile strength to the order of 200-220 N/mm².

Cold working increases the tensile strength further (Figure 4) but the maximum obtainable in practice depends on the shape and cross-sectional area of the conductor. The larger the cross-sectional area of a conductor, the lower its tensile strength since the amount of cold work that can be applied is limited by the reduction in area which can be achieved.

2.2.5 Proof Strength

The 'proof strength' is the stress required to produce a defined amount of permanent deformation in the metal and is a valuable guide to its physical properties. Proof strength is defined as the stress at which a non-proportional elongation equal to a specified percentage (usually 0.2%) of the original gauge length occurs.

As with the tensile strength, the proof strength varies with the amount of cold work put into the material (see Figure 4).

2.2.6 Hardness

Standards applicable to conductors do not specify hardness measurement as part of the testing requirements but, because hardness measurement is easier than a tensile test, it is convenient as a guide to the strength of a conductor. The results have to be used with discretion for two reasons:

- Unlike ferrous materials, the relationship between hardness and tensile strength is not constant (see Figure 4).
- A hardness test is a measurement of the outer skin of the material tested. If the conductor is of large cross-sectional area and has received a minimum amount of cold work, the skin will be harder than the underlying metal. Consequently, variations in hardness measurement may be obtained dependent on where the measurement is made in relation to its cross-section.

As a guide, typical hardness figures of the temper range of conductors supplied are as indicated in Table 3 below:

Table 3 – Typical Hardness Values for a Range of Tempers

Condition	Symbol	Hardness (HV)
Annealed	(O)	60 max.
Half-hard	(½H)	70-95
Hard	(H)	90 min.

The terms 'hard' and 'half-hard' were used in UK Standards and are still recognised by stockists. UK Standards have been replaced by European Standards where H represents a hardness range and R represents a tensile strength range. Copper alloys can be specified either by hardness or tensile properties, though not by both.

2.2.7 Resistance to Softening

Exposure of cold worked copper to elevated temperatures results in softening and the mechanical properties become more typical of those of annealed material. Softening is cold work and temperature dependent so it is difficult to estimate precisely the time at which it starts and finishes. It is usual therefore to consider the time to 'half-softening', i.e. the time taken for the hardness to fall by 50% of the original increase in hardness caused by cold reduction.

In the case of high conductivity copper this softening occurs at temperatures above 150°C. It has been established experimentally that hard-drawn copper conductors will operate successfully at a temperature of 105°C for periods of 20-25 years, and that they can withstand temperatures as high as 250°C for a few seconds, typical of short circuit conditions, without any adverse effect. Where conductors are required to operate at higher than normal temperatures without loss of strength, a silver-bearing high conductivity copper should be used. The addition of 0.06% silver raises the softening temperature by approximately 100°C without any significant effect on its conductivity while, at the same time, appreciably increasing its creep resistance.

2.2.8 Creep Resistance

Creep, another time and temperature dependent property, is the non-recoverable plastic deformation of a metal under prolonged stress. The ability of a metal to resist creep is of prime importance to design engineers.

From published creep data, it can be seen that high conductivity aluminium exhibits evidence of significant creep at ambient temperature if heavily stressed. Some typical data are shown in Figure 9. At the same stress, a similar rate of creep is only shown by high conductivity copper at a temperature of 150°C, which is well above the usual operating temperature.

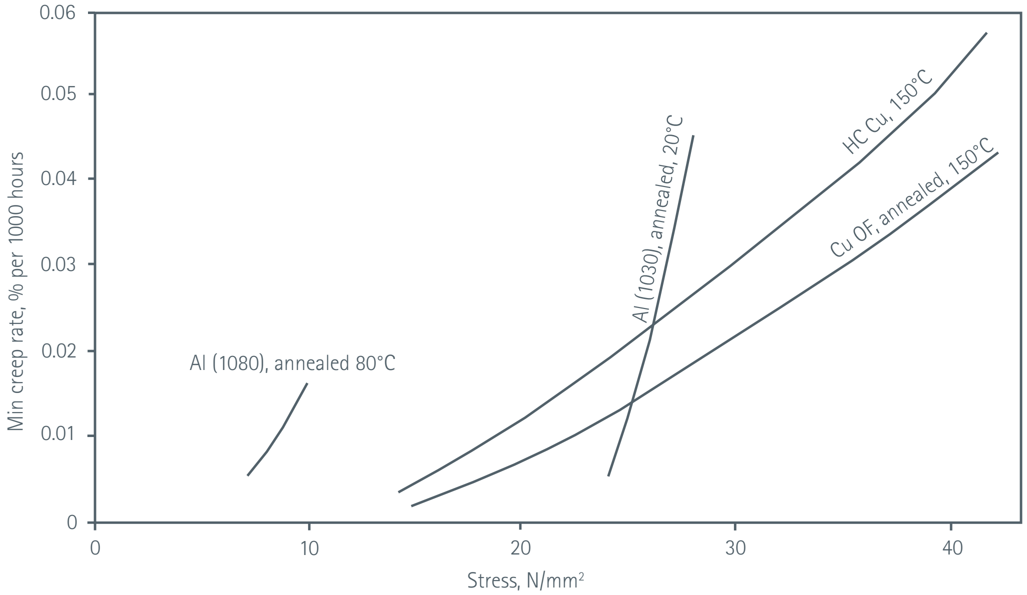

Figure 9 – Typical creep properties of commercially pure copper and aluminium

Table 4 – Comparison of Creep Properties of High Conductivity Copper and Aluminium

Material	Testing Temp °C	Min Creep Rate % per 1000 h	Stress N/mm^2
Aluminium (1030) annealed	20	0.022	26 *
High conductivity copper annealed	150	0.022	26 *
CuAg0,10 (0.086% Ag) 50% cold worked	130	0.004	138
	225	0.029	96.5

* Interpolated from Figure 9.

Above about 220°C tough pitch copper under low stress creeps relatively rapidly. The addition of silver to both oxygen-free and tough pitch coppers results in a significant increase in creep resistance.

The creep resistance of oxygen-free high conductivity copper is better than that of tough pitch high conductivity copper because the very small amounts of remaining impurities in oxygen-free copper remain in solid solution, while in tough pitch copper they are present as oxide particles.

2.2.9 Fatigue Resistance

Fatigue is the mechanism leading to fracture under repeated or fluctuating stresses such as might be caused by vibration or rotation. Fatigue fractures are progressive, beginning as minute cracks which grow under the action of the stress. As the crack propagates, the load bearing area is reduced and failure occurs by ductile fracture before the crack develops across the full area.

Table 5 – Comparison of Fatigue Properties of High Conductivity Copper and Aluminium

Material		Fatigue Strength N/mm^2	No of Cycles x 10^6
High conductivity aluminium	Annealed	20	50
	Half-hard (H8)	45	50
High conductivity copper	Annealed	62	300
	Half-hard	115	300

2.3 Physical Properties

The physical properties for the wrought material, Cu-ETP/CW004A, are shown in Table 6. These are also typical for similar coppers.

Table 6 – Properties of Cu-ETP (CW004A)

	Value	Units
Density:		
IEC standard value (1913)	8.89	g/cm^3
Typical value at 20°C	8.92	g/cm^3
at 1083°C (solid)	8.32	g/cm^3
at 1083°C (liquid)	7.99	g/cm^3
Melting Point	1083	°C
Boiling Point	2595	°C
Linear Coefficient of Thermal Expansion at:		
-253°C	0.3 x 10^{-6}	/K
-183°C	9.5 x 10^{-6}	/K
-191 to 16°C	14.1 x 10^{-6}	/K
25 to 100°C	16.8 x 10^{-6}	/K
20 to 200°C	17.3 x 10^{-6}	/K
20 to 300°C	17.7 x 10^{-6}	/K
Specific Heat (Thermal Capacity) at:		
-253°C	0.013	J/gK
-150°C	0.282	J/gK
50°C	0.361	J/gK
20°C	0.386	J/gK
100°C	0.393	J/gK
200°C	0.403	J/gK
Thermal Conductivity at:		
-253	12.98	Wcm/cm^{2}K
-200	5.74	Wcm/cm^{2}K
-183	4.73	Wcm/cm^{2}K
-100	4.35	Wcm/cm^{2}K
20	3.94	Wcm/cm^{2}K
100	3.85	Wcm/cm^{2}K
200	3.81	Wcm/cm^{2}K
300	3.77	Wcm/cm^{2}K
Electrical Conductivity (Volume) at:		
20°C (annealed)	58.0-58.9	MS/m (m/Ωmm^2)
20°C (annealed)	100.0-101.5	% IACS
20°C (fully cold worked)	56.3	MS/m (m/Ωmm^2)
20°C (fully cold worked)	97.0	% IACS
Electrical Resistivity (Volume) at:		
20°C (annealed)	0.017241-0.0170	
20°C (annealed)	1.724-1.70	
20°C (fully cold worked)	0.0178	
20°C (fully cold worked)	1.78	
Electrical Resistivity (Mass) at 20°C (Annealed)		
Mandatory maximum	0.15328	μΩg/m^2
Temperature Coefficient of Electrical Resistance		
Annealed copper of 100% IACS (applicable from –100°C to 200°C)	0.00393	/°C
Fully cold worked copper of 97% IACS (applicable from 0°C to 100°C)	0.00381	/°C
Modulus of Elasticity (Tension) at 20°C		
Annealed	118 000	N/mm^2
Cold worked	118 000-132 000	N/mm^2
Modulus of Rigidity (Torsion) at 20°C		
Annealed	44 000	N/mm^2
Cold worked	44 000-49 000	N/mm^2
Latent Heat of Fusion	205	J/g

2.4 Production of High Conductivity Copper

2.4.1 Cathode Copper

The end product of most copper refining processes is in the form of cathodes which commonly contain more than 99.9% copper. They are too brittle for fabrication but are used as the basic raw material for most subsequent melting and casting processes prior to fabrication. Sizes of cathodes vary depending on the refinery. Typically they may be plates of 1000 mm x 1000 mm in size, weighing 50-100 kg each. For primary refineries the trace impurity levels depend on the ore being worked and the precise control of the refining process.

2.4.2 Refinery Shapes

Billets, usually about 250–350 mm diameter, are cast for subsequent extrusion to rod and bar. Normally these are cut to no more than 750 mm in length to fit the extrusion chamber and this controls the maximum pieceweight which may be made. Extrusions are usually subsequently drawn to the required finished sizes by one or more passes through drawblocks.

Cakes (or slabs) are used when flat plate, sheet, strip and foil are required. They are now mostly cast continuously, which gives an improvement of pieceweight, yield and quality over the earlier static casting methods. Copper is commonly hot rolled from a thickness of 150 mm down to about 9 mm and cold rolled thereafter.

Wirebars were previously the usual starting point for hot rolling of rod. They were generally cast horizontally and therefore had a concentration of oxide at and near the upper surface. It is now possible to continuously cast them vertically, with a flying saw being used to cut them to length. Wirebars are almost obsolete now, there being only four registered brands.

Wire rod is the term used to describe coils of copper of 6 to 35 mm diameter (typically 8 mm) which provide the starting stock for wiredrawing. At one time these were limited in weight to about 100 kg, the weight of the wirebars from which they were rolled. Flash-butt welding end to end was then necessary before they could be fed in continuous wiredrawing machines.

It is now general practice to melt cathode continuously in a shaft furnace and feed the molten copper at a carefully controlled oxygen content into a continuously formed mould which produces a feedstock led directly into a multistand hot-rolling mill and in-line cleaning.

Commercial processes include Southwire, Properzi and Contirod for ETP and Rautomead and Up-cast for OF quality. The competing Dip Forming process utilises cold copper rod feedstock pushed through molten copper to emerge with an increase in diameter of some 65%. The output from this may be in coils of several tons weight each. For subsequent wiredrawing these go to high speed rod breakdown machines which carry out interstage anneals by resistance heating the wire at speed in line. This has superseded previous batch annealing techniques and shows considerable economies but it does require a consistently high quality of copper.

2.5 Types of High Conductivity Copper

2.5.1 High Conductivity Copper Grades (Non-Alloyed)

European Standards set minimum limits for the purity of coppers and their minimum conductivity. The designations and typical applications are given in Table 7. The standard compositions and typical properties of some common grades of copper and copper alloys are given in Table 8. The requirements clearly define the maximum cumulative total of 19 listed impurities. This total has had to be defined with cautious regard for superseded standards and the accuracy of analytical methods. It is believed that, in fact, most commercial coppers are of significantly higher purity than that specified.

2.5.1.1 Cathode Copper (Cu-CATH-1 and Cu-CATH-2)

Cathode copper is the end product of the refining process and is the basic raw material for most subsequent melting and casting processes. Two grades are specified, Cu-CATH-1 and Cu-CATH-2, the former being the higher grade material with a lower impurity level and higher conductivity. Cu-CATH-2 meets the majority of requirements for most coppers but, as previously described, high speed wire drawing and modern enamelling plants need the reproducibility of the higher specification.

2.5.1.2 Fire-refined High Conductivity Copper (Cu-FRHC)

This material, numbered CW005A in wrought form, is very similar to Cu-ETP with slightly less stringent impurity requirements. There is little material made to this specification now because the vast majority of copper is electrolytically refined.

2.5.1.3 Fire-refined Tough Pitch Copper (Cu-FRTP)

In ingot form this copper provides the feedstock for castings and is also suitable as the basis for certain alloys. Although there is a specification (CW006A) for this material in wrought form, it is rarely made.

2.5.1.4 Electrolytic Tough Pitch Copper (Cu-ETP and Cu-ETP1)

This is the basic grade of high conductivity copper. It is an oxygen-bearing high conductivity copper which has been electrolytically refined from Cu-CATH-2 to reduce the impurity levels to total less than 0.03%. It has a minimum conductivity of 100% IACS. The cast material is designated CR004A and the wrought material is CW004A, formerly commonly known in the UK as C101. This copper is readily available in a variety of forms and can be worked both hot and cold.

A higher grade, Cu-ETP1, designated CR003A as cast and CW003A when wrought and formerly known in the UK as C100, is the most frequently used copper quality for electrical applications. It has a minimum conductivity of 101% IACS and is often used for high-speed wire production because it is resistant to breakage and is easily annealed in-line. The very low impurity levels in this product are achieved by using high grade cathode (Cu-CATH-1) and minimising contamination during processing.

2.5.1.5 Oxygen-free Copper (Cu-OF and Cu-OF1)

Cu-OF is ‘oxygen-free’ copper, designated CR008A (cast) and CW008A (wrought), has substantially no oxygen and is free of deoxidants. It is suitable for use in applications where high conductivity material must be processed at elevated temperatures in reducing atmospheres and for high speed drawing operations.

Oxygen-free copper must be produced under closely controlled inert atmosphere conditions. The level of other contaminants, many of which have a much greater effect on conductivity in the absence of oxygen, must be kept to a minimum.

Cu-OF1 is a higher grade than Cu-OF with lower impurity levels and higher conductivity. Because it is oxygen-free, it is free from hydrogen embrittlement.

2.5.1.6 Oxygen-free Copper - Electronic Grade (Cu-OFE)

This high purity 'certified' grade of oxygen-free high conductivity copper is intended for applications in high vacuum where no volatile materials can be tolerated. The oxide film on this copper is very strongly adherent to the metal which makes it a suitable base for glass-to-metal seals. In wrought form it is numbered CW009A.

2.5.2 Low-Alloyed High Conductivity Copper Alloys

2.5.2.1 Copper-silver (Cu-Ag)

The addition of silver to pure copper raises its softening temperature considerably with very little effect on electrical conductivity. Silver also improves the mechanical properties, especially the creep resistance. The material is therefore preferred when resistance to softening is required (as in commutators) or when the material is expected to sustain stresses for long times at elevated working temperatures (as in large alternators and motors). Because it is difficult to control the oxygen content of small batches of copper, this product is normally produced by the addition of silver or copper-silver master alloy just before the pouring of refinery output of tough pitch copper. It is, therefore, generally regarded as a refinery product rather than a copper alloy. Apart from a greater rate of work hardening and, of course, the need for higher annealing temperatures, copper-silvers may be worked and fabricated as for conventional tough pitch copper.

The same three ranges of silver concentration are available in tough pitch, phosphorus deoxidised and oxygen-free coppers.

CuAg0,04 (CW011A) contains a minimum of 0.03% of silver and is suitable for the production of transformer and other winding strips with a controlled proof strength. For applications requiring good softening resistance during hard soldering, such as commutators, CuAg0,07 (CW012A) with a minimum of 0.06-0.08% silver is required. CuAg0,10 (CW013A), containing 0.08-0.12% silver gives very good resistance to creep and is suitable for use in highly stressed rotor winding strips and trolley wire. The conductivity of these alloys is 100% IACS.

CuAg0,04P (CW014A), CuAg0,07P (CW015A) and CuAg0,10P (CW016A) are the equivalent deoxidised copper grades with 0.001-0.007% of phosphorus added. The minimum conductivity is 98.3% IACS.

CuAg0,04OF (CW017A), CuAg0,07OF (CW018A) and CuAg0,10OF (CW019A) are the equivalent grades in oxygen-free copper. The minimum conductivity is 100% IACS. Where embrittlement resistance is required without the loss of conductivity caused by deoxidants, the oxygen-free coppers should be selected.

2.5.2.2 Phosphorus Deoxidised Copper

Deoxidised copper is used to avoid hydrogen embrittlement when the material is likely to be heated in a reducing atmosphere containing hydrogen, as in many types of welding and brazing fabrication techniques. There are several grades of phosphorus deoxidised copper; only those with very low concentrations of phosphorus are suitable for electrical conductor applications.

Cu-PHC (CW020A) contains 0.001-0.006% (10–60 ppm) phosphorus and retains a conductivity of 100% IACS. Cu-PHCE (CW021A), Cu-HCP (CW022A) and Cu-DLP (CW023A) contain higher concentrations of phosphorus up to 0.013% (130 ppm), making them more resistant to hydrogen embrittlement while maintaining conductivity above 91.5% IACS.

Cu-DHP (CW024A) and Cu-DXP (CR025A) contain 0.015 to 0.060% phosphorus to ensure freedom from residual oxygen and are readily joined by all welding and brazing techniques. They are not intended for electrical applications, having a conductivity of about 80% and 70% IACS respectively – they are mentioned here only to differentiate them from the electrical grades above and so that they can be avoided. Cu-DHP is the preferred material for tubes for heat exchangers and for the most severe deep drawing operations on sheet.

Table 7 – Unwrought* and Wrought# High Conductivity Coppers – Designations and Applications

Material Designation			Characteristics and Uses
Symbol	Number		
	Unwrought	Wrought	
Copper Cathode			
Cu-CATH-1	CR001A		Refined coppers made in the form of cathodes by electrolytic deposition. The basic raw materials for most melting and casting purposes. Cu-CATH-1 is the higher grade. Copper cathodes are too brittle to fabricate.
Cu-CATH-2	CR002A		
Coppers ex Cu-CATH-1			
Cu-ETP1	CR003A	CW003A	Used for re-draw to wire. Suitable for high speed annealing and enamelling.
Cu-OF1	CR007A	CW007A	Oxygen-free version of Cu-ETP1 for use in reducing atmospheres and cryogenic temperatures.
Cu-OFE	CR009A	CW009A	Oxygen-free and low phosphorus coppers of high purity; the final 'E' of the symbol indicates suitability for use in electronic vacuum devices.
Cu-PHCE	CR022A	CW022A	
Other Unalloyed Coppers			
Cu-ETP	CR004A	CW004A	Used for most conductors and fabricated electrical components.
Cu-FRHC	CR005A	CW005A	Little fire-refined high conductivity copper is now made.
Cu-OF	CR008A	CW008A	Oxygen-free version of Cu-ETP for use in reducing atmospheres.
Cu-FRTP	CR006A	CW006A	Fire-refined tough pitch copper is rarely made in wrought form. Ingots provide feedstock for castings.
Phosphorus-containing Coppers			
Cu-PHC	CR020A	CW020A	Phosphorus deoxidised coppers for applications where brazing or welding is required.
Cu-HCP	CR021A	CW021A	
Cu-PHCE	CR022A	CW022A	
Cu-DLP	CR023A	CW023A	
Cu-DHP	CR024A	CW024A	Cu-DHP is the preferred material for copper tubes for heating and plumbing applications. Cu-DHP and Cu-DXP is not generally used for electrical applications.
Cu-DXP	CR025A	CW025A	
Silver-bearing Coppers			
Tough Pitch			
CuAg0,04	CR011A	CW011A	Increasing additions of silver give increase in creep strength and resistance to softening in elevated service temperatures. Good creep resistance to 250°C (short times at 350°C) provides suitability for electrical motor parts, semiconductor components and etching plates.
CuAg0,07	CR012A	CW012A	
CuAg0,10	CR013A	CW013A	
Phosphorus Deoxidised Silver-bearing Alloys			
CuAg0,04P	CR014A	CW014A	
CuAg0,07P	CR015A	CW015A	
CuAg0,10P	CR016A	CW016A	
Oxygen-free Silver-bearing Alloys			
CuAg0,04OF	CR017A	CW017A	
CuAg0,07OF	CR018A	CW018A	
CuAg0,10OF	CR019A	CW019A	

* Unwrought coppers in EN 1976 – Cast Unwrought Copper Products and EN 1978 – Copper Cathodes

\# BS 6017 (confirmed 1989)

Table 8 – Unwrought* and Wrought High Conductivity Coppers – Compositions and Properties

Material Designation			Composition % (Range or max.)		Electrical Properties at 20°C (Unwrought)		Typical Mechanical Properties			
Symbol	Number									
	Unwrought	Wrought	Copper (incl. 0.015 max. Ag)	Max. of 19 listed elements other than Copper #	Mass Resistivity Ω.g/m^2	Min. Conductivity % IACS	0.2% Proof Strength N/mm^2	Tensile Strength N/mm^2	Elongation %	Hardness HV
Copper Cathodes										
Cu-CATH-1	CR001A		Rem.	0.0065	0.15176	101.0				
Cu-CATH-2	CR002A		99.90 min.	0.03 excl. Ag & O	0.15328	100.0				
Coppers from Cu-CATH-1										
Cu-ETP1	CR003A	CW003A	Rem.	0.0065 excl. O 0.040 max. O	0.15176	101.0	Properties similar to those for Cu-ETP			
Cu-OF1	CR007A	CW007A	Rem.	0.0065 excl. O	0.15176	101.0				
Cu-OFE	CR009A	CW009A	99.99 min.	15 elements listed individually	0.15176	101.0				
Cu-PHCE	CR022A	CW022A	99.99 min.	P 0.001-0.006 plus 14 elements listed individually	0.15328	100.0				
Other Unalloyed Coppers										
Cu-ETP	CR004A	CW004A	99.90 min.	0.03 excl. Ag & O	0.15328	100.0	50-340	200-400	50-5	40-120
Cu-FRHC	CR005A	CW005A	99.90 min.	0.04 excl. Ag & O	0.15328	100.0	Properties similar to those for Cu-ETP			
Cu-OF	CR 008A	CW008A	99.95 min.	0.03 excl. Ag	0.15328	100.0	50-340	200-400	50-5	40-120
Cu-FRTP	CR006A	CW006A	99.90 min.	0.05 excl. Ag, Ni & O			50-340	200-400	50-5	40-120
Phosphorus-containing Copper										
Cu-PHC	CR020A	CW020A	99.95 min.	0.03 excl. Ag & P P 0.001-0.006	0.15328	100.0	Properties similar to those for Cu-DLP			
Cu-HCP	CR021A	CW021A	99.95 min.	0.03 excl. Ag & P P 0.002-0.007	0.15596	98.3	50	200	30	45
Cu-DLP	CR023A	CW023A	99.90 min.	0.03 excl. Ag, Ni & P P 0.005-0.013		Approx. 91.5	50-340	200-400	50-5	40-120
Cu-DHP	CR024A	CW024A	99.90 min.	P 0.015-0.040		Approx. 80	50-340	200-400	50-5	40-120
Cu-DXP	CR025A	CW025A	99.90 min.	0.03 excl. Ag, Ni & P P 0.04-0.06		Approx. 70	Properties similar to those for Cu-DLP			

Silver-bearing Coppers – Tough Pitch							
CuAg0,04	CR011A	CW011A	Rem.	0.03 excl. Ag & O Ag 0.03-0.05, O 0.040 max.	0.15328	100.0	Properties similar to those for Cu-ETP at ambient temperatures
CuAg0,07	CR012A	CW012A	Rem.	0.03 excl. Ag & O Ag 0.06-0.08, O 0.040 max.	0.15328	100.0	
CuAg0,10	CR013A	CW013A	Rem.	0.03 excl. Ag & O Ag 0.08-0.012, O 0.040 max.	0.15328	100.0	
Phosphorus Deoxidised Silver-bearing Copper							
CuAg0,04P	CR014A	CW014A	Rem.	0.03 excl. Ag & P Ag 0.03-0.05, P 0.001-0.007	0.15596	98.3	
CuAg0,07P	CR0015A	CW015A	Rem.	0.03 excl. Ag & P Ag 0.06-0.08, P 0.001-0.007	0.15596	98.3	
CuAg0,10P	CR016A	CW016A	Rem.	0.03 excl. Ag & P Ag 0.08-0.12, P 0.001-0.007	0.15596	98.3	
Oxygen-free Silver-bearing Copper							
CuAg0,04(OF)	CR017A	CW017A	Rem.	0.0065 excl. Ag & O Ag 0.03-0.05	0.15328	100.0	
CuAg0,07(OF)	CR018A	CW018A	Rem.	0.0065 excl. Ag & O Ag 0.06-0.08	0.15328	100.0	
CuAg0,10(OF)	CR019A	CW019A	Rem.	0.0065 excl. Ag & O Ag 0.08-0.12	0.15328	100.0	

* Unwrought coppers in EN 1976 - Cast Unwrought Copper Products and EN 1978 - Copper Cathodes.

\# Ag, As, Bi, Cd, Co, Cr, Fe, Mn, Ni, O, P, Pb, S, Sb, Se, Si, Sn, Te & Zn

3.0 Copper Alloys

While the properties of copper make it the best choice for bulk conductors, some applications require enhanced properties, such as higher tensile strength, increased softening temperature, lower creep, better wear resistance or easier machinability.

The effect of most impurities in, or intentional additions to, copper is to increase the strength, hardness and resistance to softening but to decrease the conductivity. The effects on both electrical and thermal conductivity can usually be taken as proportional, the effect on electrical conductivity usually being easier to measure. The extent of the effects depends on the extent to which the addition is soluble in copper and the amount by which the copper crystal lattice structure is distorted and hardened by the solute. A very wide variety of possibilities exists for single and multiple additions of elements to attain properties suitable for different applications.

3.1 Types of Alloys

3.1.1 Non Heat-treatable Alloys

Small amounts of an alloying element added to molten copper will completely dissolve and form a homogeneous microstructure, i.e. a single phase. At some point, depending on the solid solubility of the particular element in copper, additional amounts of the alloying element will not dissolve. When that solid solubility limit is exceeded, two distinct microstructures form with different compositions and hardnesses. While pure copper is relatively soft compared with common structural metals, the addition of tin, to form bronze, or zinc, to form brass, results in an alloy which is stronger and harder than any of the pure constituent metals. It should be noted that neither 'brass' nor 'bronze' is a well-defined technical term, each referring to a wide range of alloys. Aluminium, manganese, nickel and silicon can also be added to strengthen copper.

3.1.2 Heat-treatable Alloys

Many of the high strength, good conductivity, copper alloys require special processing after, and perhaps during, fabrication in order to achieve full strength. The alloy is manufactured as a supersaturated solution which is easily worked but, because of internal strain, has reduced conductivity. Following fabrication the alloy is 'aged' during which the excess solute precipitates, forming a second phase which improves the mechanical properties. The ageing process can be performed using relatively inexpensive and unsophisticated furnaces but care must be taken to avoid excessive oxidation.

3.2 Common Non Heat-treatable Alloys

3.2.1 High Conductivity Copper Alloys

The low alloyed copper alloys (Table 8) have already been discussed.

3.2.1.1 Copper-cadmium

The addition of cadmium to copper increases its strength but has comparatively little effect on conductivity, as can be seen in Figure 1. Historically, it has been used extensively for overhead collector wires for the catenary systems of railways and tramways and for overhead wires for telephone systems. Because of the general toxicity of cadmium vapour during melting and casting operations (including during recycling), the manufacture and use of this alloy is discouraged or forbidden in many countries and it is no longer included (or is included but not recommended) in international standards. A large quantity of copper-cadmium remains in installations and it is important to ensure that proper measures are taken in the recycling process. Copper-silver, copper-magnesium or copper-tin alloys are usually selected as an alternative.

3.2.2 Free-machining Coppers

Although tough pitch, deoxidised and oxygen-free coppers can all be machined without great difficulty, their machinability is less than that of free-machining brass - the standard by which all metals are compared. Being relatively soft, copper may tend to stick to and build up on the cutting edges of drills and other tools, although recent developments in the design of tool geometry can minimise this. The addition of an insoluble second phase can give much improved machinability without a greatly deleterious effect on conductivity. Sulphur and tellurium are examples of possible additions. Lead is used at a concentration of 0.1%. Selenium and higher concentrations of lead are no longer used for environmental reasons and because they reduce scrap value.

An addition of approximately 0.5% tellurium or sulphur raises the machinability rating from 20% to 90%, based on a scale where free-machining brass is rated at 100%. The particles of copper telluride or copper sulphide act as chip breakers leading to excellent machinability without substantially affecting the electrical conductivity which is rated at 93% IACS (see Table 9). Free-machining copper is used where a large amount of repetitive machining at high rates is required. Applications include screws, fasteners, contacts, connectors, clamps and bolts.

3.3 Common Heat-treatable Alloys

Many of the high strength, good conductivity copper alloys owe their properties to the fact that their composition is controlled to be just outside the solid solubility limits of the added alloying additions. These alloys require a process consisting of solution, quenching, cold working and precipitation to reach full conductivity and strength.

By a solution treatment, typically at about 900-925°C dependent upon alloy and section size, followed by a water quench, the alloying elements are retained in solid solution. In this state the alloys can most easily be fabricated but, because of high internal strain, the conductivity is lowered. Precipitation treatment (ageing) is effected at about between 400-425°C dependent upon the type of alloy, section size and time at temperature. These heat treatments are generally carried out in air furnaces, there being no requirement for close control of the atmosphere. Excessive oxidation should, of course, be avoided.

The best conductivity values are obtained with the material after full solution and precipitation heat treatments. For optimum mechanical properties to be obtained, it is usual for 10 to 30% of cold work to be required while the material is in the solution-treated state. For the highest tensile properties further cold work can be carried out after ageing.

Fabrication of these alloys by welding or brazing, at temperatures above that for ageing, results in loss of mechanical properties. The full cycle of solution and precipitation heat treatment will not restore original properties if it is not possible to include the required deformation by cold work between treatments.

The optimum heat treatment conditions for these alloys depend upon the properties required, the size of the components and the extent of any cold work. Advice should be sought from the manufacturers.

3.3.1 Copper-beryllium Alloys

Beryllium vapour is well known to be toxic and the inhalation of beryllium in a finely divided form can cause a serious lung condition. Precautions must therefore be taken in melting, casting, machining and welding of beryllium copper. However, in service, copper-beryllium is perfectly safe to handle and use, but it must be separated from other alloys for recycling at end of life. Copper-beryllium should only be specified where its unique combination of properties is essential. It can be replaced by copper-nickel-tin in many applications.

Copper-beryllium has excellent fatigue resistance and has been traditionally used for springs, pressure responsive diaphragms, flexible bellows, connectors, contacts and relays, all of which are subject to cyclical loading. Copper-beryllium is non-sparking and non-magnetic. It has long been used for non-sparking tools in the mining, gas and petrochemical industries and its anti-galling properties, high strength and good corrosion resistance have led to the widespread use of copper-beryllium for down-hole drilling tools for the oil and gas industry.

In the fully heat treated and cold worked condition copper-beryllium is the hardest (HV 100-420) and strongest (tensile strength 410-1400 N/mm^2) of any copper alloy. It is similar in mechanical properties to many high strength steels but, compared to steels, it has better corrosion resistance (approximately equivalent to nickel-silvers), higher electrical conductivity (16-65% IACS) and higher thermal conductivity (210 W/mK).

The most important of the copper-beryllium alloys contains from 1.6 to 2.1% beryllium. For the most extensively wrought materials such as springs and pressure-sensitive devices, the lower end of the range is preferred but for dies the extra hardness attained at the upper end of the range is exploited. To improve properties an addition of nickel and/or cobalt is also commonly made. These alloys are used because of their great strength and hardness which is attained by combinations of heat treatment and cold work. As can be seen from Table 9, the conductivity of the material is 30% IACS, but it is preferred for many specific applications.

For some applications a low beryllium alloy is preferred. This contains around 2.5% cobalt (plus nickel) and only 0.5% beryllium. The strength obtained is not quite so high but it remains a good compromise material for some purposes requiring strength but greater ductility. Since the precipitation hardening temperature is about 100°C higher, it can also be used at higher temperatures (up to 350-400°C) without risk of over-ageing. The electrical conductivity is also slightly better.

3.3.2 Copper-chromium

This type of alloy is the most frequently used high strength, high conductivity material. The chromium content is usually between 0.5 and 1.2%. Other elements such as silicon, sulphur and magnesium may be added to help to improve the properties further or to improve machinability. Copper-chromium alloys can be made in all fabricated forms but are mostly available as rod, bar or forgings. In the molten state the added chromium, like many other refractory metals, oxidises readily, increasing the viscosity of the liquid. Careful processing is necessary to avoid inclusions in castings.

Copper-chromium alloys are commonly used in rod form for spot welding electrodes, as bars for high strength conductors and as forgings for seam welding fabricated parts such as wheels and aircraft brake discs. As castings (CuCr1, CC140C, with up to 90% IACS) they find applications as electrode holders and electrical termination equipment where the shape required is more complex than can be economically machined.

3.3.3 Copper-chromium-zirconium

Some improvement in the softening resistance and creep strength of copper-chromium may be gained by the addition of 0.03 to 0.3% zirconium. Although not generally available cast to shape, the alloy is available as wire in addition to the wrought product forms similar to those of copper-chromium alloys and is used in similar applications. Copper-magnesium is an alternative material, with a conductivity of 74% IACS (compare this with the conductivity of copper-chromium-zirconium, 75-85% IACS).

3.3.4 Copper-chromium-magnesium

While copper-chromium is an excellent material for use under the arduous conditions associated with resistance welding applications, it can show poor creep ductility due to cavitation effects at grain boundaries when used continuously at moderately elevated temperatures under tensile stress. An addition of magnesium has been found to avoid the problem and this type of alloy is now specified for some special applications such as rotor bars for heavy duty electric motors. It has not been included in EN standards but properties are similar to copper-chromium.

3.3.5 Copper-zirconium

The addition of a small amount (0.05-0.15%) of zirconium to copper results in a heat-treatable, medium strength alloy with an increased softening temperature (500°C) compared to pure copper, whilst maintaining excellent electrical (95% IACS) and thermal conductivity. Copper-zirconium is available as rod, strip, wire, profiles and forgings.

3.3.6 Copper-nickel alloys

The usual 90/10 and 70/30 copper-nickel alloys with their combination of strength, corrosion and biofouling resistance are in considerable use in heat exchangers and marine seawater piping systems. Copper-nickel alloys are used for resistance heating elements because of their high resistivity and low temperature coefficient of electrical resistivity. CuNi44 is the preferred material for resistance elements since it has high resistivity (~3.5% IACS) and a near-zero coefficient of resistance.

3.3.7 Copper-nickel-silicon

These alloys have three nominal compositions of 1.3, 2.0 and 3.5% nickel, with silicon rising from 0.5 to 1.2% and are available as castings, forgings, rod and bar with good strength and reasonable conductivity. Applications exploit the wear resistance of this alloy and include electrode holders, seam welding wheel shafts, flash or butt welding dies and ball and roller bearing cages. The alloy with 2.0% nickel and 0.6% silicon (CuNi2Si/CW111C) has the widest availability.

3.3.8 Copper-nickel-phosphorus

This alloy has a nominal 1% nickel and 0.2% of phosphorus. It is not as hard or strong as the copper-nickel-silicon alloy but has better conductivity and ductility, so is sometimes used for electrode holders, clamps and terminations in cast and wrought forms.

3.3.9 Copper-nickel-tin

Copper-nickel-tin alloys can replace copper-beryllium alloys in many applications.

Copper-nickel-tin alloys undergo a spinodal decomposition reaction in which the original alloy decomposes into two chemically different phases with identical crystal structures. Each phase in the spinodally hardened alloy is on the nanoscale and is continuous throughout the grains up to the grain boundaries. This results in alloys of very good strength and wear resistance, coupled with excellent corrosion resistance. They retain high strength at elevated temperature and have high resistance to stress relaxation, making them ideal for contact carriers.

Two American compositions are standardised, UNS No C72700 with 9% nickel and 6% tin, and C72900 with 15% nickel and 8% tin. Both are available as strip which is fabricated by the user and then heat treated. The Unified Numbering System (UNS) is an alloy designation system widely used in North America.

Table 9 – Wrought Low Alloyed Copper Alloys – Composition and Typical Properties

Material Designation		Nearest Equivalent	Composition % Range								IACS (%)	Typical Mechanical Properties			
Symbol	Number		Cu	Be	Cr	Ni	P	Si	Zn	Other		0.2% Proof Strength N/mm²	Tensile Strength N/mm²	Elongation %	Hardness HV
Heat-treatable Alloys															
CuBe1.7	CW100C	CB101	Rem.	1.6-1.8							30	200-1100	410-1300	40-1	100-400
CuBe2	CW101C		Rem.	1.8-2.1							30	200-1300	410-1400	40-1	100-420
CuBe2Pb	CW102C		Rem.	1.8-2.0						Pb 0.2-0.6	45	200-1300	410-1400	40-1	100-420
CuCo1Ni1Be	CW103C		Rem.	0.4-0.7		0.8-0.3				Co 0.8-1.3		135-760	250-900	25-1	100-250
CuCo2Be	CW104C	C112	Rem.	0.4-0.7						Co 2.0-2.8	45	135-900	240-950	25-1	90-260
CuNi2Be	CW110C		Rem.	0.2-0.6		1.4-2.4						135-900	240-950	25-1	90-260
CuCr1	CW105C	CC101	Rem.		0.5-1.2						80	100-440	220-500	30-5	80-180
CuCr1Zr	CW106C	CC102	Rem.		0.5-1.2					Zr 0.03-0.3	86	100-440	220-540	30-5	80-180
CuNi1P	CW108C	C113	Rem.			0.8-1.2	0.15-0.25				50	140-730	250-850	30-2	80-240
CuNi1Si	CW109		Rem.			1.0-1.6		0.4-0.7			29-60	100-620	300-700	30-3	80-220
CuNi2Si	CW111C		Rem.			1.6-2.5		0.4-0.8			25-51	100-620	300-700	30-3	80-220
CuNi3Si1	CW112C		Rem.			2.6-4.5		0.8-1.3			35-40	120-550	320-600	30-5	80-190
CuZr	CW120C		Rem.							Zr 1-0.2	85-95	80-350	250-450	35-5	60-160
Non Heat-treatable Alloys – Free Machining															
CuPb1P	CW113C		Rem.				0.003-0.012			Pb 0.7-1.5	75	200-320	250-400	10-2	80-120
CuSP	CW114C	C111	Rem.				0.003-0.012			S 0.2-0.7	93	200-320	250-400	10-2	80-120
CuTeP	CW118C	C109	Rem.				0.003-0.012			Te 0.4-0.7	90	200-320	250-400	15-1	80-120
Non Heat-treatable Alloys – Others															
CuFe2P	CW107C		Rem.				0.015-0.15		0.05-0.20	Fe 2.1-2.6		240-440	350-500	25-3	100-150
CuSi1	CW115C		Rem.					0.8-2.0				150-400	280-750	55-2	90-220
CuSi3Mn	CW116C	CS101	Rem.					2.7-3.2		Mn 0.7-1.3		240-850	380-900	50-2	90-220
CuSn 0.15	CW117C		Rem.							Sn 0.10-0.15	88				50-120
CuZn 0.5	CW119C		Rem.						-0.1-1.0		80	100-330	240-380	45-5	50-120

4.0 Appendix

4.1 Copper Alloys for Semiconductor Lead Frames

The development of more advanced microchips has required the production of copper alloys as lead frame materials with properties to suit the need for long reliable life at elevated temperatures. The pins that fit into the sockets:

- must be ductile enough to be bent to initial shape
- strong and rigid enough to be forced into the holder
- springy enough to conform to the holder geometry
- form an ideal base for the semiconductor components
- conduct away the heat generated under operating conditions without loss of properties over the many years of operating life expected.

This has meant that many alloys are now in commercial production to suit these needs and, again, a variety of combinations of properties is available as needed. The alloying additions made include silver, cobalt, chromium, iron, magnesium, nickel, phosphorus, silicon, tin, titanium, zinc and alumina; some of the materials developed are shown in Table 10. These specialist alloys are generally proprietary and frequently the subject of patents so are not at present included in British or other European national standards; only three alloys are included in BS EN 1758 - they are Cu-DLP/CW023A, CuFe2P/CW107C (Alloy 3 below), and CuSn0.15/CW117C. Material No 5, missing from the table, is oxygen-free high conductivity copper.

Table 10 – Copper Alloys for Semiconductor Lead Frames

Alloy	Composition (%)											
Number	Ag	Co	Cr	Fe	Mg	Ni	P	Si	Sn	Ti	Zn	Al203
1						9.0			2.0			
2		0.8	1.5		0.1	0.6						
3				2.4			0.03				0.12	
4						3.2		0.7	1.2		0.3	
6					0.01	2.0		0.4			0.2	
7			0.3						0.25		0.2	
8						1.5			2.0	0.25	0.5	
9			58.0		42.0							
10		0.28					0.08					
11	0.05				0.1		0.07		0.2			
12	0.6					0.05						
13				2.4	0.05		0.08				0.01	
14			0.3					0.02		0.15		
15			0.5			1.0			1.0	0.5		
16						9.0			2.0			
17				2.4			0.03				0.12	
18												1.1

4.2 Oxidation and Corrosion

Copper forms two oxides, both of which are conductive. Cuprous oxide (Cu_2O) is red in colour and first to form on a clean copper surface exposed to the atmosphere. At room temperature this will slowly darken to a thicker black layer of cupric oxide (CuO). Once formed, the black oxide film is tightly adherent and further growth is very slow provided the temperature does not exceed 200°C and other deleterious chemicals are not present.

In the presence of sulphur and hydrogen sulphide, copper sulphide, which is also black, will be formed.

Exposure of copper surfaces to rainwater, which normally contains dissolved carbon dioxide and oxides of sulphur and is consequently weakly acidic, will result in the formation of a green patina which is adherent and protective.

4.2.1 The Oxidation Laws

Figure 10 gives examples of the normal progress of oxidation. The logarithmic law applies mainly to highly protective thin films, formed at low temperatures. The parabolic law is widely obeyed at intermediate temperatures while the linear law applies to the initial stages of oxidation before the film is thick enough to be protective. Break-away effects are observed after disturbance of the film reduces its thickness. Repeated break-away on a fine scale can lead to linear oxidation.

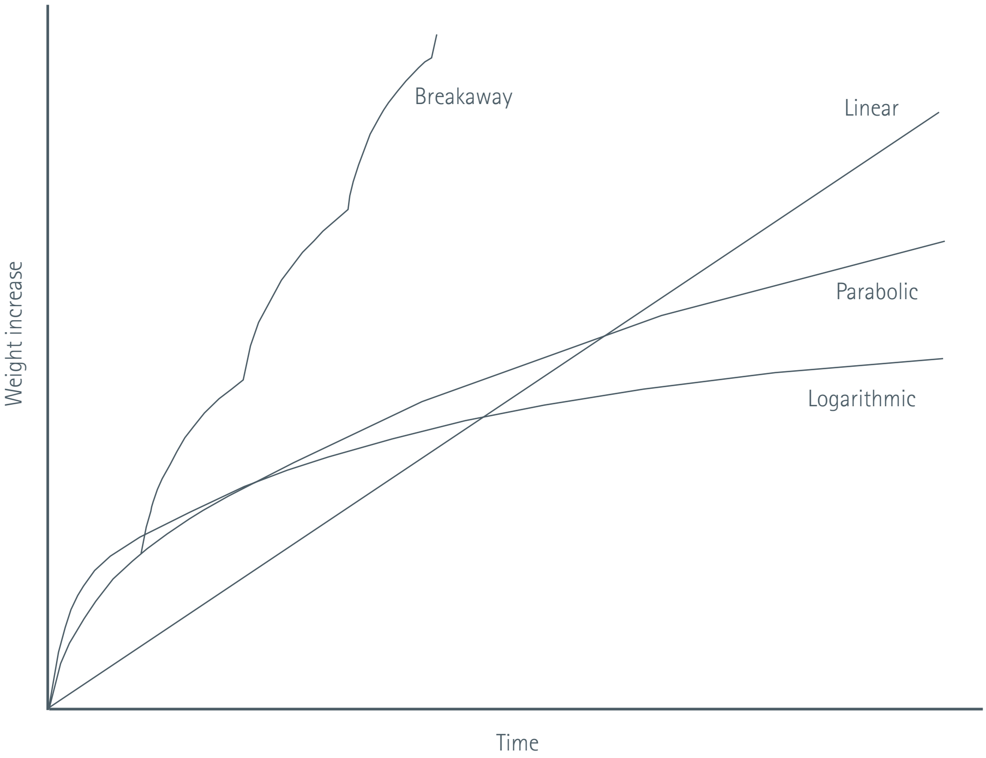

Figure 10 – The oxidation rate laws

At elevated temperatures, such as those used for annealing coppers, the oxide formed is mainly cupric oxide. Excess oxide tends to exfoliate and this removal may be assisted, if required, by water quenching after an annealing treatment.

Figure 11 shows the effect of temperature on the oxidation of copper.

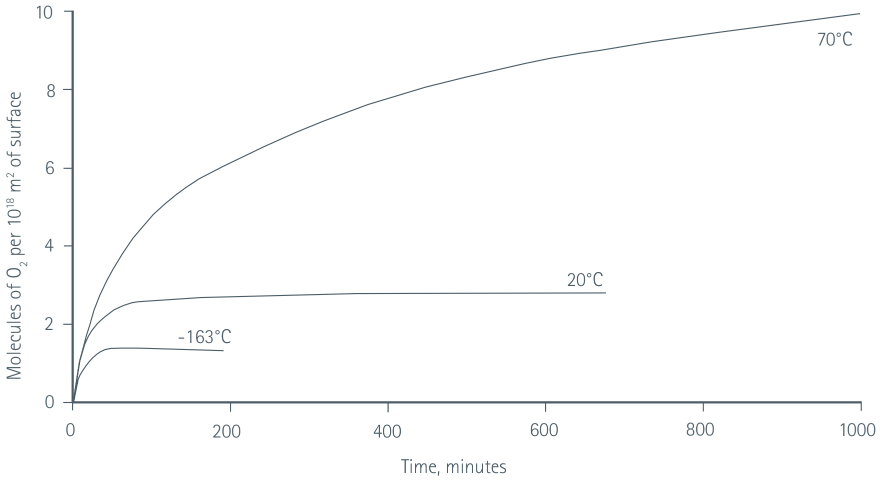

Figure 11- Effect of temperature on oxidation of copper

Less Noble (More susceptible to attack)

↑

- Magnesium and its alloys
- Zinc and its alloys
- Aluminium and its alloys
- Cadmium
- Mild steel
- Cast iron
- Stainless steel 13%Cr, Type 410 (active)
- Lead-tin solder
- 50/50 Stainless steel, 18/8, Type 304 (active)
- Stainless steel, 18/8/3% Mo, Type 316 (active)
- Lead
- Tin
- Brasses
- Gunmetal
- Aluminium bronzes
- COPPER
- Copper-nickel alloys
- Monel
- Titanium and its alloys
- Stainless steel 18/8, Type 304 (passive)
- Stainless steel, 18/8/3% Mo, Type 316 (passive)
- Silver
- Gold
- Platinum

↓

More Noble (Less susceptible to attack)

Figure 12 – Corrosion susceptibility of metals

Many of the applications of coppers rely on known corrosion resistance together with their other properties. Besides the good resistance to the atmosphere (including marine environments), coppers have a good resistance to organic acids and also to alkalis (with the exception of ammonia). Coppers can be buried underground in most soils without risk of corrosion, although there can be problems in certain acid soils and clays. The wide use of copper for heat exchanger purposes is indicative of its good resistance to corrosion by potable waters, both hot and cold, and to domestic wastes and sewage. In certain of these applications the strong resistance to biofouling is also a great advantage. All coppers are virtually immune to stress corrosion cracking.

4.2.2 Galvanic Corrosion

Figure 12 shows the corrosion susceptibility of copper compared with other metals and the way in which the behaviour of bimetallic couples in corrosive environments can be predicted. None of the alloying additions described has a deleterious effect on the good oxidation resistance of copper. In general, the effect is an improvement and this facilitates the use of some of these materials at temperatures higher than 200°C where creep resistance is also required.

As with all except the noble metals, the corrosion behaviour of copper is a function of the oxides. It will vary depending on the exposure conditions, such as turbulence and velocity of the media, the presence of traces of contaminants and, of course, any bi-metallic effects introduced in mixed metal systems in corrosive environments.

It can be seen from Figure 12, which represents the galvanic behaviour of metals in seawater, that brasses are more noble than other commonly used engineering metals. Where dissimilar metals are in bimetallic contact, the one higher in the table will corrode preferentially. Actual performance depends on the surface films formed under conditions of service. On exposed surfaces the free oxygen in the water ensures a passive film on many metals. In crevices at fastenings or under attached biofouling, oxygen may be depleted and passive films are not formed. Similar considerations apply in other media such as acids which may be oxidising or reducing in nature.

Further information can be obtained from *The Corrosion of Copper and its Alloys: A Practical Guide for Engineers*, Roger Francis, 2010 and *Guide to Engineered Materials*, ASM, Ohio, 1986.

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