Copper Development Association

High Conductivity Coppers

For Electrical Engineering

CDA Publication 122, 1998

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For Electriacl Engineering

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Copper Development Association

Copper Development Association is a non-trading organisation sponsored by the copper producers and fabricators to encourage the use of copper and copper alloys and to promote their correct and efficient application. Its services, which include the provision of technical advice and information, are available to those interested in the utilisation of copper in all its aspects. The Association also provides a link between research and user industries and maintains close contact with other copper development associations throughout the world.

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Introduction

The Vital Metal

Copper has made possible the continued, efficient development of the electrical industry because it has the highest conductivity of the commercial metals. In addition, it has ideal mechanical properties at low, ambient and elevated temperatures, is easily fabricated or cast to shape and can be readily machined. It has excellent resistance to oxidation and corrosion. The thin oxide layer that does form is conductive, meaning that good joints have a long service life. From high voltage transmission cables to microcircuits, and from megawatt generators to computers, in every aspect of electricity generation, transmission and use, copper is the vital, energy efficient metal.

Copper is mined in many places throughout the world so that new metal is in plentiful supply, but it has also the enormous advantage of being readily recycled. It is easily separated from other scrap and can be reused economically thus preventing further depletion of the Earth's natural resources.

Its use in our homes and industries provides no health risk. Indeed it is an essential trace element in our diets.

The vast majority of electrical applications require the use of conventional high-conductivity copper and this forms the major tonnage produced. However, modern electronic and computer technology has created requirements for extremes of service conditions that demand materials specially produced to meet these needs. For example, tensile strengths up to 1400 N/mm2 can be achieved in heat-treatable alloys. Copper’s high electrical conductivity is paralleled by excellent thermal conductivity. This makes it the first choice for heat exchanger applications, including the newly developed copper-brass automobile radiators which are fully competitive with aluminium counterparts.

This booklet describes the way in which coppers of all types have been developed and improved to meet the design requirements of electrical engineers. Information is given on the way in which British Standards are adopting agreed European (CEN) standards without modification as the new BS EN series of standards. The new designations are linked to the historic British Standards and information is given on the properties most often required.

The materials described are the commercially pure coppers, low alloy coppers and the copper alloys with good elevated temperature properties used for special purposes. Materials, such as the brasses, nickel silvers, phosphor bronzes and aluminium bronzes also used in electrical applications such as switchgear, contacts and terminations are covered in other CDA publications.

The New BS EN Standards

The old British Standards are being replaced by a new BS EN series of standards for copper and copper alloys that offer a selection of materials to suit a very wide variety of end uses. They represent a European consensus agreement on those most frequently ordered by consumers. The previous series of standards were prepared during the late 1960’s to meet the demand for metrication and had not been substantially revised since then.

Materials popularly used from the previous BS standards will of course continue to be available but the new designations should be used. Compositions, properties, tolerances and other requirements will conform to the standard quoted.

Commencing in the late 1980’s, drafting of European Standards for Copper and Copper Alloys became a major activity for national standards’ organisations and their industrial partners. The majority of the ratified versions of the new standards, published or due during the period 1996-1998, caused, or will cause, withdrawal of conflicting national standards such as the BS287x series.

Because a large number of national preferences have needed to be taken into account against the background of a pan-European agreement to develop tight product standards, the new BS EN standards (the British implementation of European standards) are more complex than the historic BS standards. Furthermore, the BS EN standards tend to cover narrower fields than BS standards. There are therefore more materials in the BS EN series than in the previous BS standards.

More information about relevant standards, material designations and conditions is given in Section 6.

Ordering Information

This technical note gives an introduction to the reasons for the selection of high conductivity coppers for a wide variety of applications. The information given, the examples of applications shown and the literature in the bibliography will all help indicate the way in which materials may be chosen to suit particular end uses. Manufacturers' literature should also be used as this can give a better indication of the types of material most easily available in suitable size ranges. The advice of manufacturers regarding the suitability of their products for given applications should also be sought, particularly if significant quantities of material are being considered and the most economic whole life cost is to be achieved.

Small quantities of materials commonly available can best be obtained from a stockist.

In ordering material the correct use of the 'Ordering Information' details given in Section 6 and in the requirements of the appropriate British Standard documents for compositions, properties and tolerances will be of benefit. Any other special requirements may also be negotiated at the time of ordering so that the optimum use may be made of the properties of high conductivity coppers.

Why Choose Copper?

Of the materials now available, only copper has the very valuable combination of high conductivity allied with good strength, ductility, machinability and durability together with good resistance to oxidation, corrosion, creep and fatigue. Ease of joining is another of the many other properties that are of interest and can be tailored during production to suit special applications.

High conductivity copper is the most common form of the metal available. Improvements in production techniques have kept quality, availability and price ahead of commercial demand. It is first choice for the manufacture of conductors of all types. Though copper is frequently unseen in the finished products, it is essential. It is impossible to imagine modern life without electrical services to provide lighting and power in its most convenient form. Copper is easily recycled; the economics of the industry have been based for many centuries on the use of both primary and recycled secondary supplies of copper and copper alloys.

Making Copper Conductors

Primary copper is refined electrolytically to make cathodes that are the main feedstock for vertical shaft furnaces. These give a controlled flow of high quality molten copper that is fed in to a mould formed by a water-cooled steel belt and rotating copper grooved wheel. The section formed is then continuously fed in to the rod mill for reduction in size by hot rolling to form wire rod that is typically 9mm diameter. The coiled of wire rod are cut to lots of around five tons each and passed to a wire mill to be drawn down to sizes ranging from large power conductors down to ultra-fine enamelled winding wires (magnet wires).

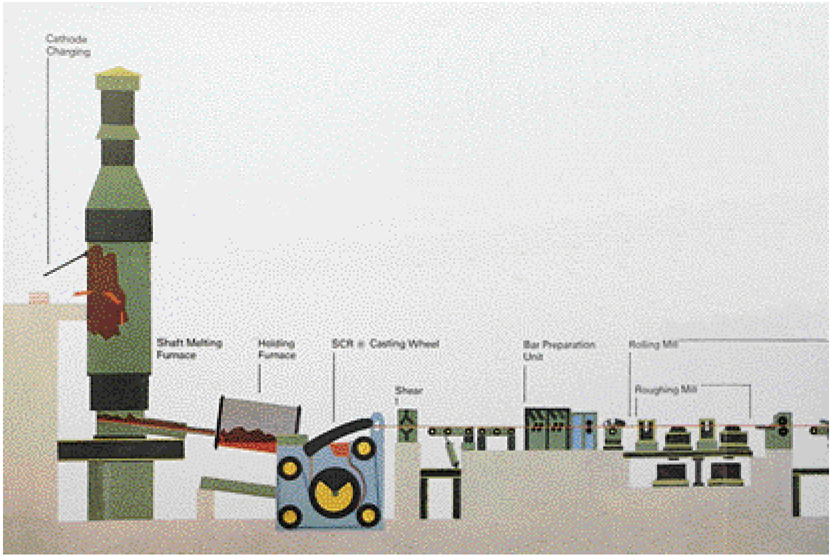

Plate 1 - Photo/ diagram – Southwire Rod Plant

Wire rod is now made in a continuous process by melting copper cathode in a shaft furnace into a holding pot from which it is fed down a launder and into a mould formed by a rotating grooved high conductivity copper alloy wheel and a steel belt. The wheel and belt are water cooled so that the metal solidifies rapidly. In red hot form it is fed directly to a multistand rod mill.

The wire rod can also be rolled or drawn to give rectangular strips suitable for windings. Larger conductor sections are formed by extrusion of cast billet to shape. Complex shapes can be made by casting. More details of production processes are found later in this book and in other CDA publications.

Wire and Cables

Copper wire has long been the preferred conductor material in the majority of cables used for power and telecommunications. Having high conductivity combined with a ductility that makes it easy to draw down to close-tolerance sizes, it can also be readily soldered to make economic, durable connections. It is compatible with all modern insulation materials but good oxidation resistance means that it can also be used bare.

Insulation can be of lacquer or enamel types used for winding wires or of polymers used for heavier duties. Lacquers permit close spacing of windings to give best efficiency in the coils of motors, transformers and chokes. Polymers and other coverings are used for flexible message cables and power cables where voltage differences are larger and abrasion is likely in service.

Conductor sizing considerations are dealt with in Section 3.

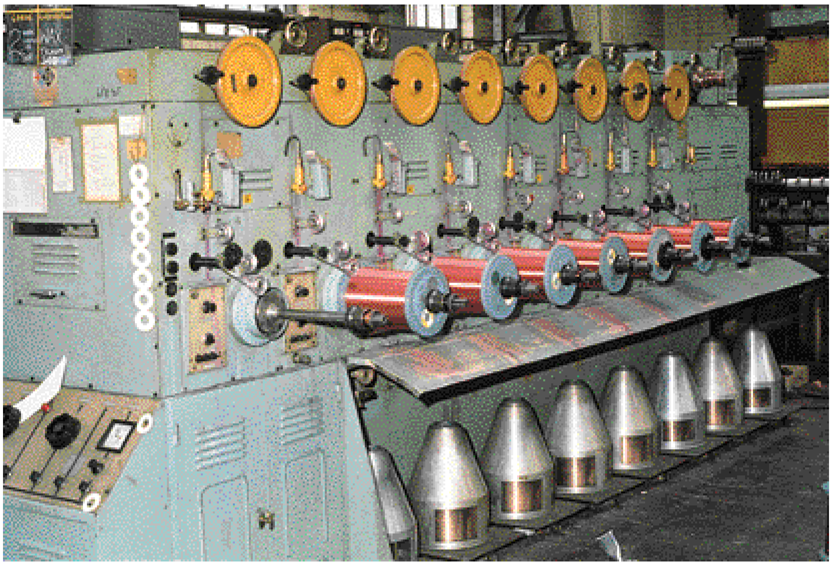

Plate 2 - Fine wire drawing machines

High purity copper from the rod mill is drawn down to size through a succession of dies and high-speed interstage continuous annealing without breakage. Fine wires are then passed through a multistage enamelling plant to make winding wires for small motors, transformers, coils and chokes.

Transformers

The high conductivity copper used for the manufacture of transformer windings is in the form of wire for small products and strip for larger equipment. For small products the wire must be strong enough to be wound without breakage yet limp enough to give close-packed windings. Strip products are necessarily of good surface quality so that insulating enamels do not break down under voltage. Good ductility is essential for the strip to be formed and packed yet good strength is needed to withstand the high electro-mechanical stresses set up under occasional short-circuit conditions. Where windings have to withstand severe loading, winding strip is ordered with a controlled proof stress. All aspects of transformer design are covered in M. J. Heathcote's 'J & P Transformer Book', now in 12th edition.

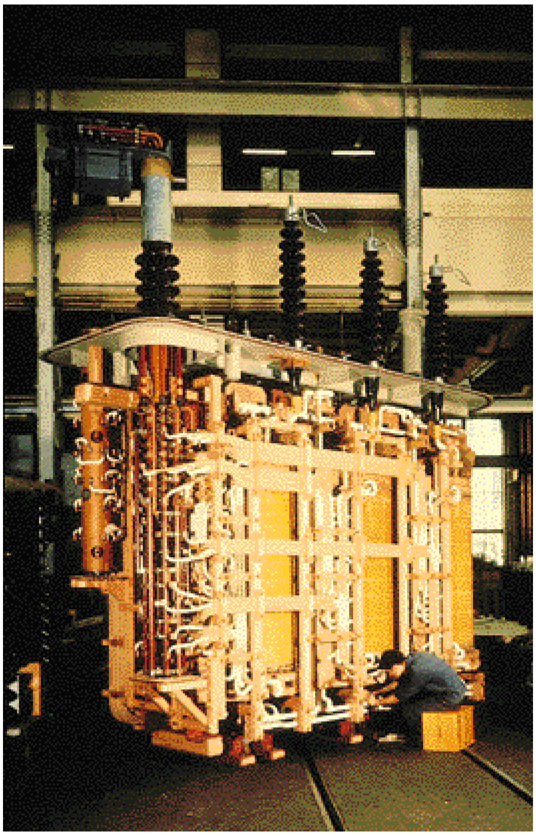

Plate 3 - Transformer windings

Transformers are designed to operate continuously for many years without maintenance. They rely on copper windings that are finished to close tolerances on size and corner radius so that the insulation on the windings is not broken. A uniform good strength is needed so that the windings can be formed in to shape easily yet withstand the severe mechanical stresses that are present in the event of a short circuit.

Busbars

Because of its good conductivity, strength, ductility and resistance to oxidation, copper is the most obvious material to specify for the manufacture of busbars. Most busbars are manufactured from high conductivity copper by the hot extrusion of billet to rectangular cross section followed by drawing to finished size. Angled sections are formed from rolled or extruded strip. Detailed consideration of busbar system design is reviewed in Section 3 and described at length in CDA Book 22 ‘Copper for Busbars’.

Commutators

Under very high centrifugal forces at operating temperatures, the commutators used in electric motors pick up from the brushes the electricity needed to activate the rotor. This duty they perform for a very long service life without oxidising to produce arcing and wear. The sections used are made from extruded and drawn sections to close tolerances on the size and taper needed to ensure reliable assembly. For most applications high conductivity copper is used but for heavy duty work it is usual to use a silver-bearing copper to obtain increased creep strength at operating temperature.

For more information, consult the brochures of manufacturers such as Thomas Bolton.

Motor windings

The properties needed for motor windings are similar to those needed for transformers but with the additional requirement to withstand centrifugal forces at working temperatures. For best efficiency, windings are tightly packed in the magnetic susceptor slots of the stators and rotors.

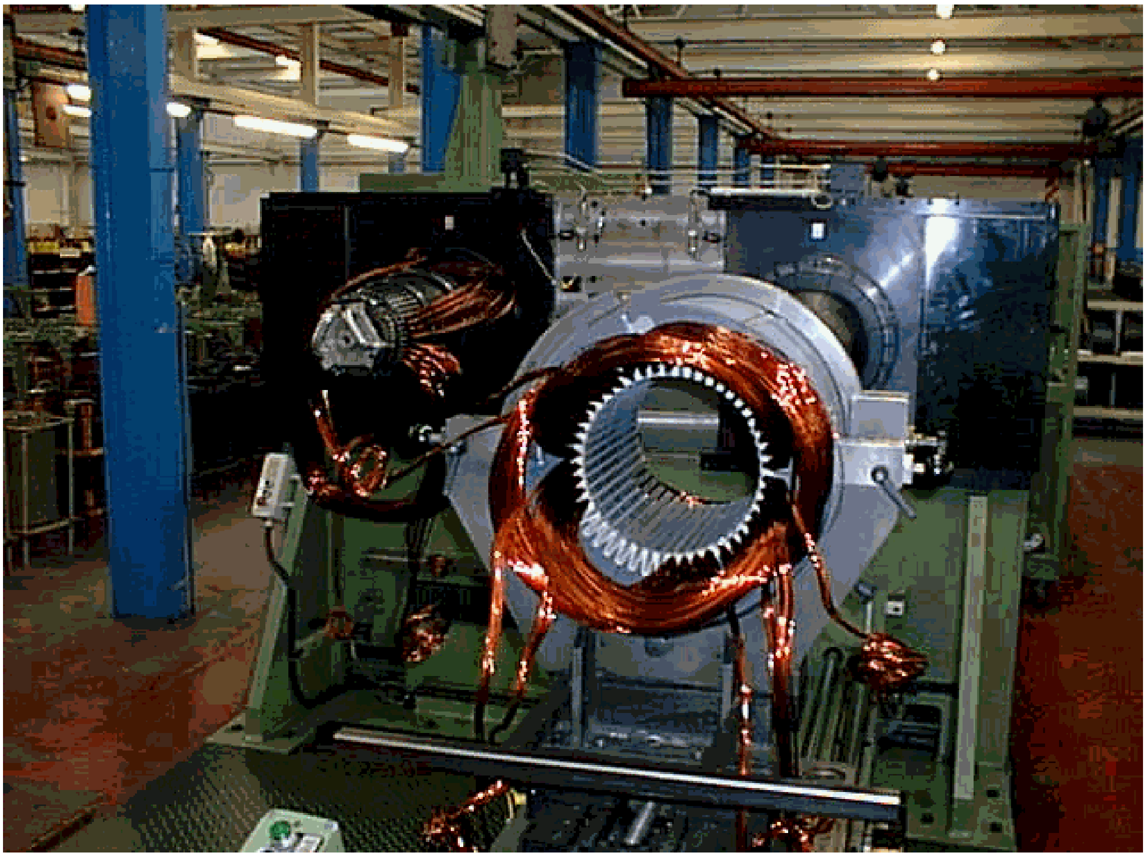

Plate 4 - Three tier, two pole machine winding with first two tiers inserted (Brook Hansen)

Welding electrodes

Most car bodies and central heating radiators depend on spot and seam welding of steel components to make them strong, reliable and cheap to produce in large numbers. Spot welding between pairs of rod electrodes must give local fusion at the steel-to-steel interface without impairing the life of the electrodes.

High electrical and thermal conductivity is essential so that the welding amperages can be carried without overheating the electrodes or causing arcing at the contacts. The rods must have high strength and hardness at operating temperatures to resist the 'mushrooming' tendency of deformation under pressure whilst the weld is being made. They must also be made from materials that are relatively easy to form and machine to finished shape. Many designs require drilling of the electrodes to provide passages for water-cooling. Copper-chromium alloys are usually preferred.

Similar conditions apply to electrode wheels used for seam welding, though these usually have to maintain their strength and contact life without the benefit of water-cooling.

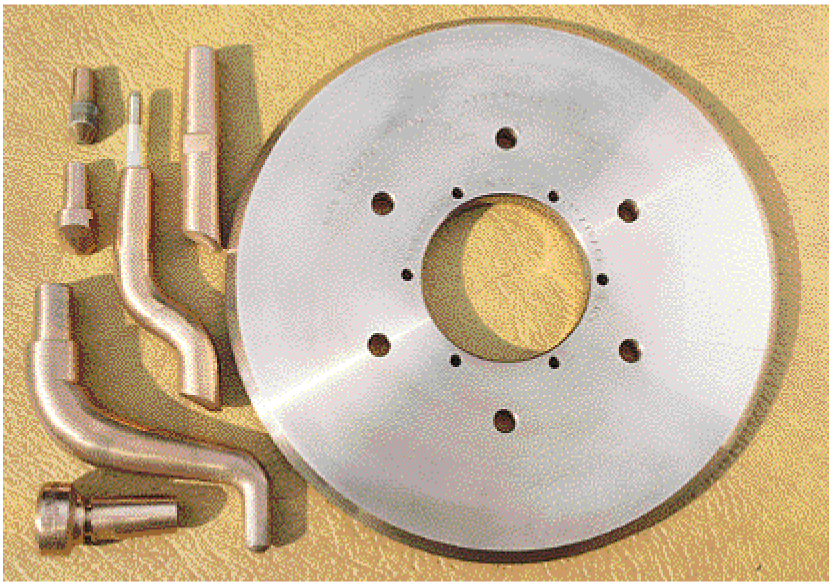

Plate 5 -Spot welding electrodes (Delta Enfield Metals Ltd)

As a quick, economic method of permanently joining steel and other metals, resistance welding is the standard method used for the assembly of car bodies, central heating radiators and similar products. The electrodes are used to clamped together the components while a high current is passed between them to cause local fusion welding.

Contacts

Heavy duty circuit breakers must operate reliably at operating temperature for many years and break circuit when pulled without suffering undue damage from arcing. Good strength, conductivity and resistance to oxidation and creep are essential in components that are often of complex shape. Under operating temperatures as high as allowed by the regulations, the stress on the contacts is high and good creep strength is essential to avoid relaxation of contact pressure. Choice of material depends on design but will be between conventional high conductivity copper and some of the high conductivity copper alloys described later.

Contact springs

Contact springs are still essential in much electrical equipment, especially in switchgear and sockets. Good strength at operating temperature, resistance to oxidation and reasonable conductivity affect choice of materials. Design of springs is covered in CDA TN12 ‘Copper Alloy Spring Materials’ available on http://www.cda.org.uk/ .

Printed circuit boards

Early printed circuit boards were manufactured from copper clad SRBP (synthetic resin bonded paper) by etching away unwanted copper to leave the required conductor pattern on the board, which was then drilled to accept component leads. Later, fibre glass was used as the substrate, clad on both sides by a reduced thickness of copper. Processing involved etching away unwanted copper and simultaneously depositing extra copper to form the required conductor pattern. The substrates were pre-drilled to accept component leads and the holes were ‘plated through’ to interconnect the layers and improve the integrity of the soldered joints. In modern practice the substrate is built up in a number of layers, with a copper conductor layer added at each stage; a 1.6mm thick board might have 24 copper layers (including the outside surfaces). At the same time, the lead-pitch of components has reduced from 2.54mm to less than 0.5mm, making PCB manufacture a high precision operation. Manufacturing techniques have developed to such an extent that six or eight layer boards are economically viable for low cost consumer applications.

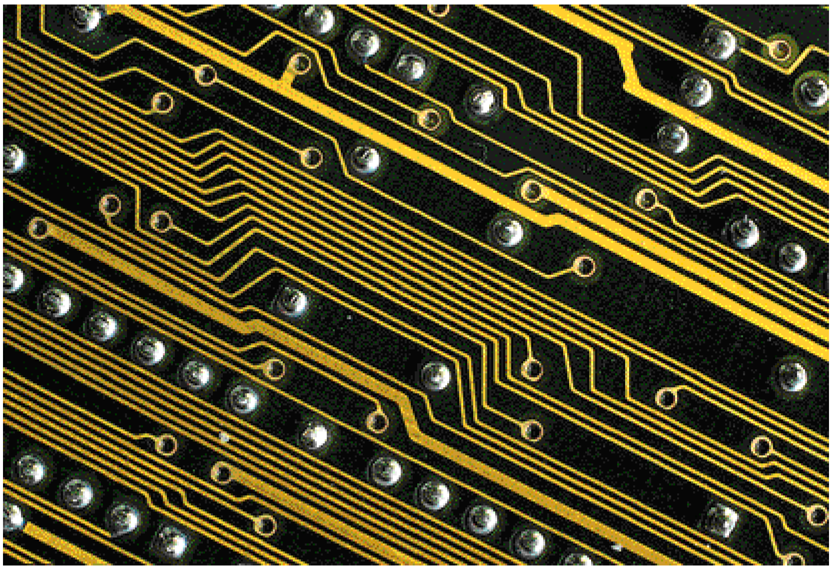

Plate 6 - Printed circuit board

All the connections on a printed circuit board depend on copper for ease of solderability, high conductivity and resistance to tarnishing and corrosion. The copper can be easily plated with tin or gold in critical areas to improve surface properties still further.

Semiconductors

Developments in semi-conductor technology are expected to continue to lead to the doubling of the power and complexity of microchips every eighteen months. Copper alloys have played an important part in keeping microchips reliably connected to their bases for many years, as is described in the section of this publication dealing with leadframe materials.

Now copper is becoming increasingly important as one of the interstitial layers in the build-up of the chips. Copper conducts electricity and heat better than aluminium and is now being used to help increase the power and speed of chips without size having to be enlarged. Product developments have established techniques for obtaining full compatibility between the copper layers and the silicon semi-conducting gates. This gives a performance gain of 30% and permits miniaturisation of current channel lengths to 0.12 microns, allowing up to 200 million transistors to be packed into a single chip.

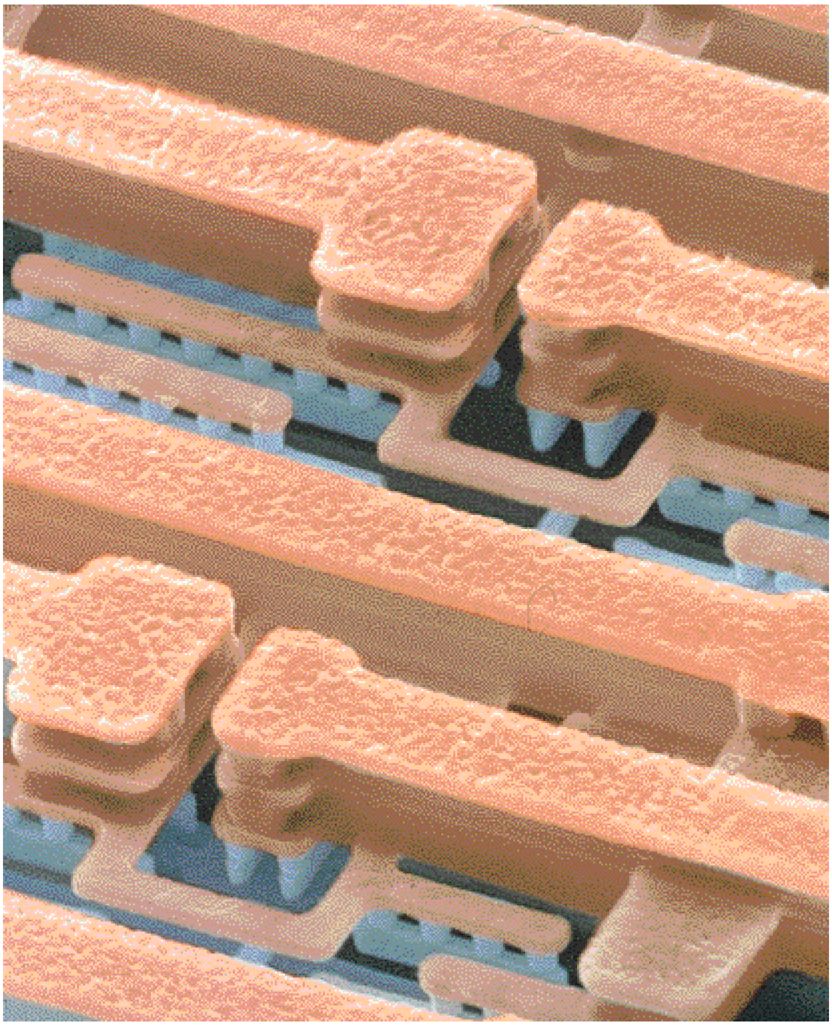

Plate 7 - New technology microchip (Fred Perkins and IBM Corporation)

High vacuum and other electronic devices

These devices include thermionic valves, transmitters and many semi-conductors. Besides the highest possible conductivity, the extra properties required for these devices include freedom from dissolved gases and the ability to form strong vacuum-tight glass-to-metal seals. Specially certified oxygen-free copper is usually specified since this has been melted and cast in vacuum. It will therefore, when heated, not give off slight traces of dissolved gases that might impair the performance of high-vacuum devices. Hydrogen does not diffuse through copper at ambient and slightly elevated temperatures. When heated, this copper forms a dense black oxide of integrity suitable for the formation of glass-to-metal seals using, of course, glass of similar expansion coefficient.

Tuyeres

One of the most demanding of applications for copper in heavy industrial applications is that of the tuyeres (or nozzles) used to blow high pressure oxygen in to converters containing molten steel. There is a removable cap that fits on the end of a multiple concentric oxygen pipe that includes provision of water-cooling to pipe and tuyere. Lifetime must be predictable as failure can cause a catastrophic leakage of the water in to the white-hot liquid steel. Many manufacturing techniques have been tried in order to make the complex high conductivity copper component. Copper-chromium is the preferred high-strength high conductivity material but it is not easy to obtain perfect castings nor to fabricate. Lengthening the service life of these components remains an ongoing challenge.

Plate 8 - Tuyeres (BSC Engineering, Cumbria)

Samples of five types of tuyeres cast in copper-chromium alloy

Heat exchangers

With thermal conductivity allied to high electrical conductivity, copper is ideal for the manufacture of heat exchangers of all types. It is easily fabricated, easily joined and has excellent corrosion resistance. Typical applications are:

- · Radiators, oil coolers and air conditioning units in transport
- · Heat sinks for electrical equipment
- · Calorifiers for domestic and industrial water heating
- · Refrigeration units.

Electrolytic high conductivity copper is ideal for most electrical applications but when welding or brazing assembly processes are to be used, especially for pressure vessels and plumbing tubes, phosphorus deoxidised copper is frequently selected.

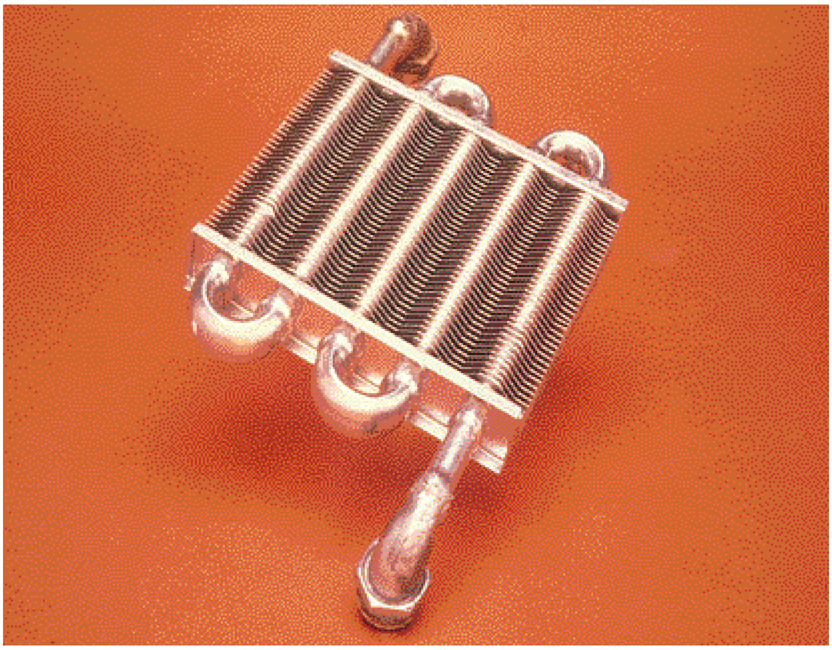

Plate 9 - Heat Exchanger (International Copper Association)

The finned tube product is made by inserting the tube through a stack of regularly spaced and pierced thin copper fins. The assembly is then hot dip soldered to ensure long life of the good thermal joints.

Cables and Busbars

Cables

There are many reasons why copper should be regarded as the preferred material for cables. The conductivity of copper is 65% higher than that of aluminium which means that the conductor size of similarly rated cables is proportionally smaller. Correspondingly less expense is then incurred in providing for insulation, shielding and armouring the cables. Transport of the less bulky cables is easier and so is installation. In limited spaces in cable ducts, the smaller volume and better ductility of copper cables can have an even larger benefit.

Copper cables are easily jointed because copper does not form on its surface a tough non-conducting oxide, as does aluminium. The oxide film that does form is thin, strongly adherent and electrically conductive, causing few problems. Cleaning and protection of copper is easy and if joints are made as recommended, they will not deteriorate to any great extent with age, thereby saving on maintenance costs.

For the same nominal current rating, the cable with the aluminium conductor is significantly larger in diameter, carries a proportionally greater volume of insulation and is not so easily installed because of being less flexible. Aluminium is notoriously difficult to joint reliably. The following table compares aluminium and copper conductors for equivalent current ratings.

Characteristic	**Conductor Material**	
	Copper 300mm^2	**Aluminium 500mm^2**
Overall diameter (mm)	66.5	83.9
Minimum bending radius (mm)	550	700
Max.dc resistance/km at 20^{o}C	0.0601	0.0617
Approx. voltage drop/A/m (mV)	0.190	0.188
Continuous current rating, drawn into duct (amp)	496	501

Table 1 - Comparison of Aluminium and Copper Concuctors

(Cable : to BS 5467 (and IEC 502) 4-core, stranded conductors, XLPE insulation, PVC bedding, steel wire armour, PVC oversheath, rated at 0.6/1.0 kV)

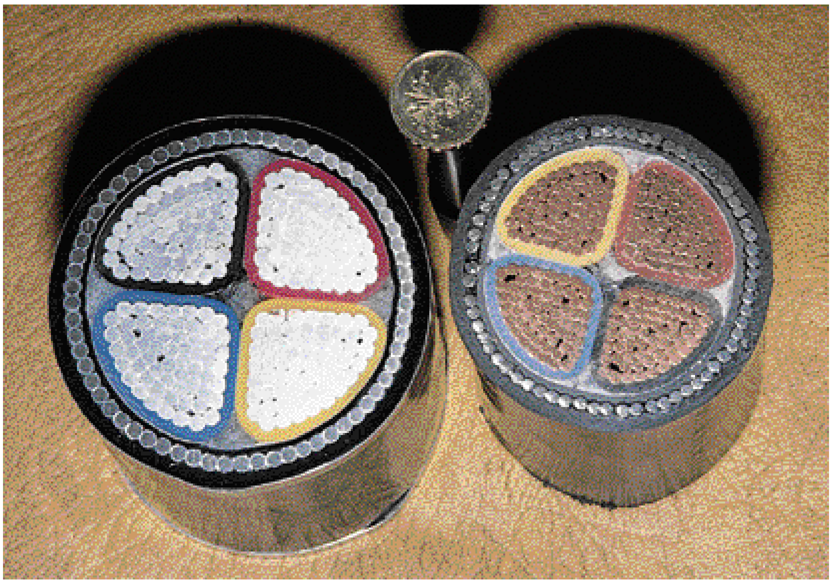

Plate 10 - Copper and Aluminium Cables Sizes Compared

Shown side by side, these cables have similar current carrying capacity. The extra size of conductor and consequent increase in volume of insulation are significant factors in selection.

In recent years, the development of elastomeric high voltage cables, insulated with Cross-Linked Polyethylene (XLPE) and Ethylene Propylene Rubber (EPR), has provided alternatives to oil-filled cables at voltages up to 132 kV. More generally, distribution cables for area boards, and industrial and domestic purposes have insulators ranging from Compound Impregnated Paper, through Plastic (PVC) to the newer XLPE and EPR types.

'Electrical Energy Efficiency – CDA Publication 116'

Since the cost of electricity is one of the biggest expenses of many organisations, this publication is very valuable. Aimed at financial decision-makers and electrical engineers, it has four main sections, each backed up by appendices that give comprehensive explanations. These are:

- Financial appraisal, including the recognition of money-saving possibilities not generally recognised and the techniques of calculating return on capital.
- Energy efficient motors, recognising that an electric motor can take only three weeks to use electricity equivalent in cost to its purchase price.
- Transformers, including methods of specifying them for minimum economic losses.
- Power cables, that can be forgotten energy wasters connecting transformers to motors and other equipment.

'Earthing Practice' – CDA Publication 119

A long-needed overview of good earthing principles and practice including:

- Standards and legal framework for safe, reliable operation.
- Methods of earthing covering the common electrical techniques.
- Earth conductors, their requirements, electrode forms and bonding needs.
- Installation methods giving practical guidance on correct practice with rods, plates and horizontal electrodes, connection techniques and backfill procedures.

- Performance considerations dependant on contact resistance and soil resistivity.
- Design of earth electrode systems relative to site considerations.
- Earthing design within buildings.
- Lightning protection.
- Prevention of electrical interference.
- Avoidance of corrosion risks.
- Maintenance of earthing systems.

'Electrical Design – A Good Practice Guide' – CDA Publication 123

Based on considerations of good design practice to ensure adequate performance throughout service life, this publication discusses many topics and makes suitable recommendations for design, sizing and layout of power cable systems.

- Overview of electricity supply and cost of failure.
- Reliability in electrical power systems including importance of estimating probable time to failure, basic concepts and application of problem-reducing designs.
- Power quality survey results showing the many on-site causes of poor power quality, their effects and suitable remedies.
- Harmonic problem descriptions, causes, measurement and avoidance.
- Earthing and current leakage as designed into control equipment.
- Avoidance of electrical noise.
- Energy efficiency as part of the design concept.

Busbars

As with cables, currently there are only two commercially available materials suitable for busbar purposes, namely copper and aluminium. The following table gives a comparison of some of their properties.

Property	Copper (Cu-ETP)	Aluminium (1350)	Units
Electrical conductivity (annealed)	101	61	%IACS
Electrical resistivitry (annealed)	1.72	2.83	μΩ cm
Thermal conductivity at 20°C	397	230	W/mK
Coefficient of expansion	17×10^{-6}	23×10^{-6}	/°C
Tensile strength (annealed)	200-250	50-60	N/mm^2
Tensile strength (half-hard)	260-300	85-100	N/mm^2
0.2% proof strength (annealed)	50-55	20-30	N/mm^2
0.2% proof strength (half-hard)	170-200	60-65	N/mm^2
Elastic modulus	116-130	70	N/mm^2
Fatigue Strength (annealed)	62	35	N/mm^2
Fatigue Strength (half-hard)	117	50	N/mm^2
Specific heat	385	900	J/kgK
Density	8.91	2.70	g/cm^3
Melting Point	1083	660	°C

Table 2 - Physical and Mechanical Properties of Copper (Cu-ETP) and Aluminium (1350)

For conductivity and strength, high conductivity copper is clearly superior to aluminium. For a given current and temperature rise, an aluminium conductor would be lighter than its copper equivalent, but larger, and space considerations are often of greater importance than weight. Where conductors are jointed by welding, the properties considered should be those for the annealed state, irrespective of the original temper.

The electromagnetic stresses set up in busbars are usually more severe than the stresses introduced by their weight. The ability of copper to absorb the heavy electromagnetic and thermal stresses generated by overload conditions gives a considerable factor of safety. The data in Table 3 shows that high conductivity aluminium exhibits evidence of significant creep at room temperature, whereas a similar rate of creep is only shown by high conductivity copper at 150°C - above the usual operating temperature of busbars.

Material	**Testing Temperature °C**	**Min Creep Rate %/1,000h**	**Stress N/mm^2**
Al	20	0.022	26
Cu-ETP	150	0.022	26
CuAg0.086	130	0.004	138
CuAg0.086	225	0.029	96.5

Table 3 - Comparison of Creep Properties of High Conductivity Copper and Aluminium

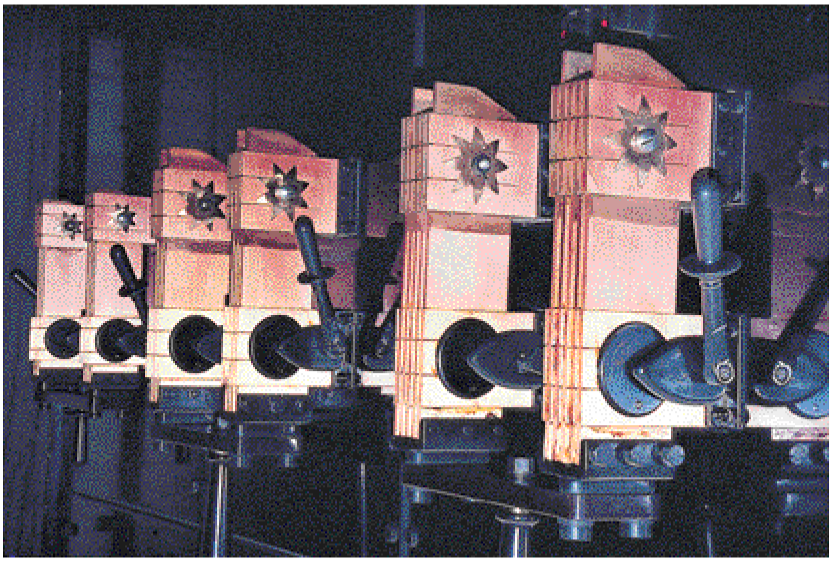

Plate 11 - Copper Busbars (Thos Bolton.)

These busbars are typical of many in industrial environments that carry high currents at elevated operating temperatures for many years without significant maintenance. The resistance of copper to corrosion is essential. The thin film of black oxide that forms improves dissipation of heat by radiation.

High conductivity coppers are ductile and will withstand the severe bending and forming operations conducive to best busbar design practice. As a general guide to bending, copper in the half-hard or hard temper will bend satisfactorily round formers of the following radii:

Thickness mm	Minimum bend radius
Up to 10	1t
11-25	1.5t
26-50	2t

Table 4 - Minimum Bend Radii of Copper bar of thickness t

‘Copper for Busbars’ – CDA Publication 22

Long accepted as the standard reference work on busbar design, this book was first published in 1938 and has been updated and metricated to suit common practice. The main topics covered are:

- The principles governing the current carrying capacity of busbars controlled by maximum permissible temperatures and governed by rates of loss of heat.
- Alternating current phenomena such as skin effect, proximity effect and the effect of high frequencies on current penetration.
- Effect of busbar geometry.
- Effect of arrangements of multiple busbars.
- Short-circuit effects.
- Jointing techniques.
- Mechanical strength requirements.
- Busbar impedance, including considerations of voltage drop, inductance formulae, capacitance formulae and geometric mean distance formulae.

Which Forms Of Copper?

Table 5 shows the general availability of product forms commonly used for electrical purposes.

Table 6 shows the standard designations now used together with the previously standardised equivalents.

Table 7 shows the new BS EN standards for coppers and copper alloys for both non-electrical (general purpose) and electrical purposes. Generally, similar materials have similar mechanical properties in both standards but the materials for electrical purposes have a conductivity requirement and there may be other clauses that are relevant.

Materials other than those listed may also be available from specialist stockholders or directly from the manufacturers. If a manufacturer is unable to supply quantities from stock, he may be able to recommend stockists known to hold stocks of specified products or their equivalents. Note that Cu-ETP may be commonly referred to as "electro" copper and Cu-DHP as "deox" or "DONA". (A glossary of terms is included in CDA introductory publication No.121 'Copper – The Vital Metal'[6].) The BS EN Standard designations should be quoted when ordering to the standard appropriate to the wrought form required.

Further details of the new standards are included in Section 6. More details, especially those related to materials for purposes other than electrical, are in CDA Publication 120 'Copper and Copper Alloy Compositions, Applications and Properties'[7].

Wire	Plain, tinned or enamelled in a large number of superfing, fine and larger mm size. Wound on spools or packed in drums.
Sheet	In width and length modules of 300mm (or 1ft) up to 1800 x 900mm (6ft x 3ft) in a variety of mm (or SWG) thicknesses/
Strip and Foil	Sheared to width as required in a variety of mm (or SWG) thicknesses.
	Maximum coil weights in kg/mm width by arrangement.
Plate	By arrangement
Tube	In OD and wall thicknesses selected from the appropriate sections.
	Thick-walled tube for busbars by arrangement.
Rod	Straight lengths in a variety of mm sizes up to 100mm dia.
Rectangular bar or strip	In preferred sizes, with or without radiused edges.
Hexagonal bar	In a variety of sizes up to 75mm across flats.
Profiles	Extruded sections up to 100mm wide depending on geometry.
Forgings	Open or closed die forgings by arrangement.
Wire rod	Supplied as redraw stock for the manufacture of wire, over 6mm dia in coils of up to 5 tons on formers or in packs.
Castings	Sand, shell-moulded, diecast, etc. as available, in copper and, notably, copper-chromium which is used for resistance welding electrodes and other heavy duty applications.

Table 5 - General Guidance on the Available Forms of Coppers

Material designation		Nearest old BS Equivalent	Characteristics and uses
Symbol	**Number**		
HEAT-TREATABLE ALLOYS			
CuBe1.7 CuBe2 CUBe2Pb	CW100C CW101C CW102C	CB101 - -	High strength beryllium coppers for springs, pressure sensitive devices and injection mould parts. CW102C is the free machining version
CuCo1Ni1Be CuCo2Be CuNi2Be	CW103C CW104C CW110C	- C112 -	Beryllium containing alloys with lower strength and better conductivity and ductility than beryllium copper; also higher service temperatures. Hot riveting dies and plunger tips in diecasting machines.
CuCr1	CW105C	CC101	Resistance welding electrodes, electrode holders, welding dies and shafts for seam welding electrode wheels. Rotor rings for high-performance electric motors. Good conductivity at elevated temperatures.
CuCr1Zr	CW106C	CC102	Zr increases softening temperatures and increases life at higher working temperatures.
CuNi1P	CW108C	C113	Electrode holders, seam welding wheel shafts, welding dies and bearing cages.
CuNi1Si CuNi2Si CuNi3Si1	CW109C CW111C CW112C	- - -	As silicon content is raised, strength and wear resistance increase and conductivity decreases. Anti-friction bearing applications in motor construction. Valve guides and seats in internal combustion engines. Heavy duty switchgear.
CuZr	CW120C	-	Special applications at elevated temperatures.
NON HEAT-TREATABLE ALLOYS – FREE MACHINING			
CuPb1P CuSP CuTeP	CW113C CW114C CW118C	- C111 C109	Free machining coppers with machinability index about 80% used for current carrying components made by extensive machining.
NON HEAT-TREATABLE ALLOYS - OTHER			
CuFe2P	CW107C	-	Special tube products and strip for lead frames (see BS EN 1758)
CuSn0.15	CW117C	-	Strip for lead frames (see BS EN 1758)
CuZn0.5	CW119C	-	Strip for radiator fins.

Table 6 - Wrought Low Alloyed Copper Alloys - Designations and Applications

Material designation			**Inclusion in the following BS EN numbers with indicated material conditions (2)**														
Symbol	Number		1652	1653	1758	12163	12165	12166	12167	12449	12451	1977	133/60	133/61	133/62	133/63	133/66
	Unwrought	Wrought	Plate Strip Sheet Circles (3)	Plate Sheet Circles (4)	Strip for Lead Frames	Rod for General Purposes	Forging Stock	Wire	Profiles Rectan-gular Bar	Tubes for General Purposes	Tubes for Heat Exchang -ers	Copper Drawing Stock (Wire Rod)	Copper Plate Sheet Strip	Seamless Copper Tubes	Copper Rod Bar Wire	Drawn Round Copper Wire	Copper Profiles
Copper cathode												(for electrical purposes)					
Cu-CATH-1	CR001A –	-															
Cu-CATH-2	CR002A -	-															
Coppers ex Cu-Cath-1																	
Cu-ETP1	CR003A	CW003A														AR	
Cu-OF1	CR007A	CW007A										E				AR	
Cu-OFE	CR009A	CW009A										E					
Cu-PHCE	CR022A	CW022A										E			DRH		
Other unalloyed coppers																	
Cu-ETP	CR004A	CW004A	RH				MH							DRH	DRH	AR	DRH
Cu-EFHC	CR005A	CW005A												DRH	DRH	AR	DRH
Cu-OF	CR008A	CW008A	RH				MH					E		DRH	DRH	AR	DRH
Cu-FRTP	CR006A	CW006A	RH			MRH											
Phosphorus-containing coppers																	
Cu-PHC	CR020A	CW020A										E		DRH			DRH
Cu-HCP	CR021A	CW021A					MH					E		DRH			DRH
Cu-DLP	CR023A	CW023A	RH	R	RH	MRH			MRH						DRH		
Cu-DHP	CR024A	CW024A	RH	R		MRH	MH	MRHG	MRH	MRH	RH						
Cu-DXP	CR025A	CW025A															

Table 7 - Unwrought and Wrought Coppers - Relevant Standards

Material designation			**Inclusion in the following BS EN numbers with indicated material conditions (2)**														
Symbol	Number		1652	1653	1758	12163	12165	12166	12167	12449	12451	1977	133/60	133/61	133/62	133/63	133/66
	Unwrought	Wrought	Plate Strip Sheet Circles (3)	Plate Sheet Circles (4)	Strip for Lead Frames	Rod for General Purposes	Forging Stock	Wire	Profiles Rectan-gular Bar	Tubes for General Purposes	Tubes for Heat Exchang -ers	Copper Drawing Stock (Wire Rod)	Copper Plate Sheet Strip	Seamless Copper Tubes	Copper Rod Bar Wire	Drawn Round Copper Wire	Copper Profiles
Silver–bearing coppers																	
CuAg0.04	CR011A	CW011A													DRH		DRH
CuAg0.07	CR012A	CW012A													DRH		
CuAg0.10	CR013A	CW013A												DRH	DRH		DRH
CuAg0.04P	CR014A	CW014A										E			DRH		DRH
CuAg0.07P	CR015A	CW015A										E			DRH		DRH
CuAg0.10P	CR016A	CW016A										E		DRH	DRH		DRH
CuAg0.04(OF)	CR017A	CW017A										E			DRH		DRH
CuAg0.07(OF)	CR018A	CW018A										E			DRH		
CuAg0.10(OF)	CR019A	CW019A										E		DRH	DRH		DRH

Table 7 - Unwrought and Wrought Coppers - Relevant Standards (continued)

1 Unwrought coppers in BS EN 1976 - Cast Unwrought Copper Products and BS EN 1978 - Copper Cathodes

2 A - mandatory elongation
D - as drawn
E - mandatory hydrogen embrittlement test
G - mandatory grain size
H - mandatory hardness
M - as manufactured
R - mandatory tensile strength

3 For General Purposes

4 For Boilers, Pressure Vessels and Hot Water Storage Units

How to Make it in Copper

Copper and most of the high conductivity copper alloys can be worked both hot and cold very readily; details are shown in the following table.

	Material Designations									
	Cu-ETP							CuCr1		
	Cu-FRHC	Cu-DHP	Cu-OF	CuSP	CuAg	CuBe2	CuCo2Be	CuCr1Zr	CuNi2Si	CuNi1P
	Cu-FRTP		Cu-OFE	Cu-TeP						
Casting temperature, ^{0}C	1120-1200	1140-1200	1120-1200	1140-1200	1120-1200	1030-1100	1120-1200	1160-1250	1130-1200	1130-1200
Heat treatment temperatures ^{0}C:										
Stress relieving	150-225	200-250	150-200	225-275	250-350					
Annealing	200-650	250-650	200-600	400-650	350-650					
Solution treatment	-	-	-	-	-	600-750	750-825	700-850	650-725	750-825
Precipitation treatment	-	-	-	-	-	740-800	900-960	950-1000	750-850	900-980
Hot formability	Good	Good	Good	Good	Good	Good	Good	Good	Excellent	Good
Hot working temperatures	750-950	750-900	750-900	750-850	750-950	625-800	700-900	750-900	800-900	700-900
Cold formability - annealed	Excellent	Excellent	Excellent	Good	Excellent					
Max. cold reduction %										
between anneals	95	95	95	70	90	40	50	75	75	75
solution treated	-	-	-	-	-	Good	Good	Good	Good	Good
precipitation hardened	-	-	-	-	-	10	30	35	20	60
Machinability as % of free machining brass										
as manufactured	20	20	20	80	20					
solution treated	-	-	-	-		30	30	30	20	30
precipitation hardened	-	-	-	-	-	20	30	30	30	30
Joining methods:										
Soldering	Excellent	Excellent	Excellent	Excellent	Excellent	Good	Good	Good	Good	Good
Brazing	Good	Excellent	Excellent	Good	Good	Good	Good	Fair	Good	Good
Oxyacetylene welding	x	Good	Fair	x	Fair	x	x	x	x	Good
Carbon-arc wld	Fair	Good	Fair	x	Fair	x	x	x	x	Good
Gas Shielded-arc-wld	Fair	Excellent	Good	x	Fair	Good	Fair	Fair	Good	Good
Coated metal arc wld	x	x	x	x	x	Fair	Fair	x	Fair	x
Resistance welding:										
spot and seam	x	Fair	x	x	x	Good	Good	Fair	Good	Good
butt	x	Good	x	x	x	Fair	Fair	Fair	Good	Good

Table 8 - Fabrication Properties of Coppers and High Conductivity Copper Alloys

The information given in Table 8 is for general guidance only since many factors influence fabrication techniques. For closer information regarding specific applications consult the manufacturers or the CDA.

Further details of design considerations and fabrication processes are included in CDA Publication No 97 'Design for Production'

Hot working

The ranges of hot working temperatures quoted for materials are those which are commonly used. The part of the range to be selected depends on the size of the material, the type of operation, and the extent of working required. It will generally be possible to continue working below these temperatures but the resultant product, having been worked "warm" rather than "hot", will retain a distorted internal structure giving higher strength and hardness.

A controlled atmosphere can be used in preheating furnaces to reduce oxidation but care must be taken when heating coppers containing oxygen so that they are not embrittled by hydrogen or other reducing gases. Following hot working, a water quench may be used with most materials to help remove excess oxide scale.

Copper and copper alloy hot forgings are used extensively in heating, refrigeration and electrical components, offering designers and specifiers unique combinations of economy and properties. There are three die configurations in common use and choice is left to the manufacturers to use their wide experience and state-of-the-art skills to optimise metal usage, die life and ultimately the finished component cost. More details are to be found in CDA Publication 103 "Hot Stampings in Copper Alloys".[9]

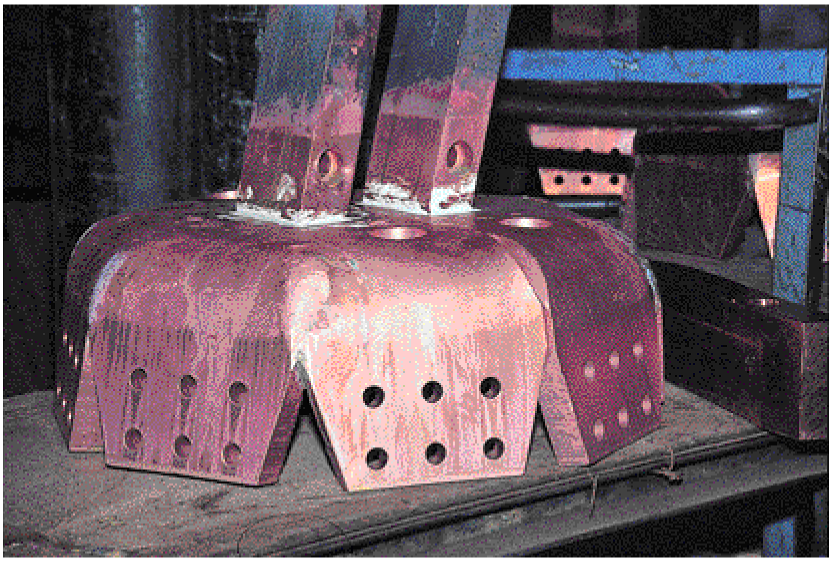

Plate 12 - Heavy Duty Fabrication (Thomas Bolton)

This electrode holder cap carries the current to a steelmaking arc furnace.

Cold working

All the materials show some degree of cold ductility. Naturally the extent of any deformation achieved will depend upon the material, the form in which it is supplied and the type of cold working process used. The elongation values quoted in Tables 13 and 14 in Section 7 give a guide to ductility in tension as required for drawing operations. For cold rolling or similar processes involving compression, greater strain can be achieved. Figure 1 shows the change of strength, hardness and elongation of electrolytic high conductivity copper strip with the extent of cold work. Note that the relationship between tensile strength and hardness is not linear.

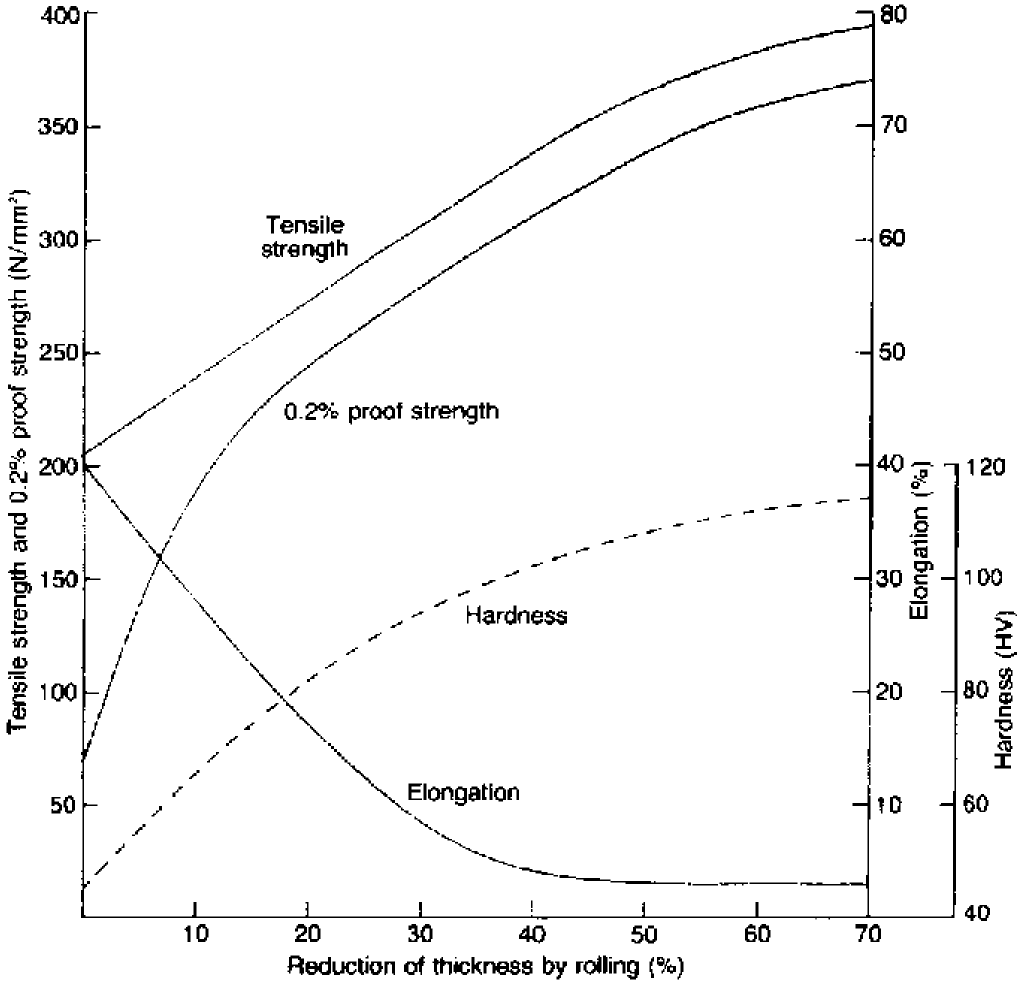

Figure 1 - Effect of cold rolling on mechanical properties and hardness of high conductivity copper strip

If the extent of cold work required is severe, interstage annealing may be required. 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 "orange peel" effects or even embrittlement.

For deep drawing, phosphorus deoxidised copper is normally considered to be the best material amongst those described here. Sheet required for this purpose should be ordered to "deep drawing quality". This will ensure that there has been close control of the composition, working and annealing of the material to give non-directional mechanical properties with a high ductility. The unevenness during drawing which causes "ears" at the edges of pressings will then be minimised.

Annealing

Although the high conductivity coppers are extremely ductile and can be cold worked considerably, an anneal may be required to resoften the metal. The temperature to be used 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.

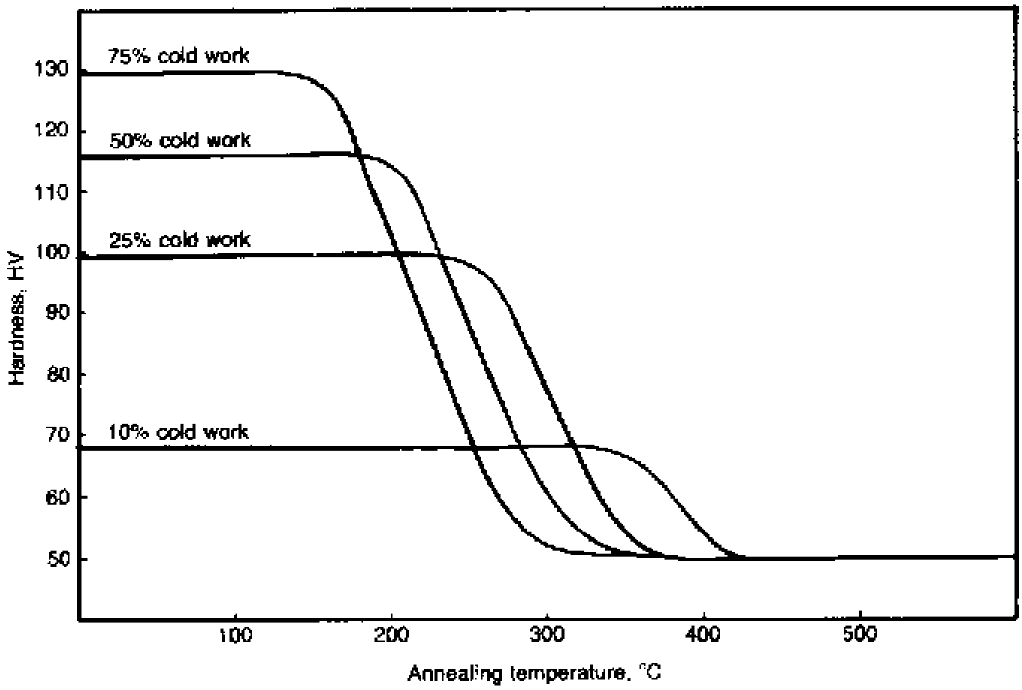

Figure 2 - Typical effect of the extent of previous cold work on the annealing behaviour of tough pitch copper Cu-ETP.

The annealing time in each case is 1 hour

In Figure 2 the effect that various amounts of prior cold work have on the annealability of electrolytic, high conductivity tough pitch copper is shown. It will be noted that the more cold work present, the more readily is the copper annealed. Similar effects will be found with the other materials. For any given material, the lower the temperature, the longer it will take to soften, as is shown in Figure 3.

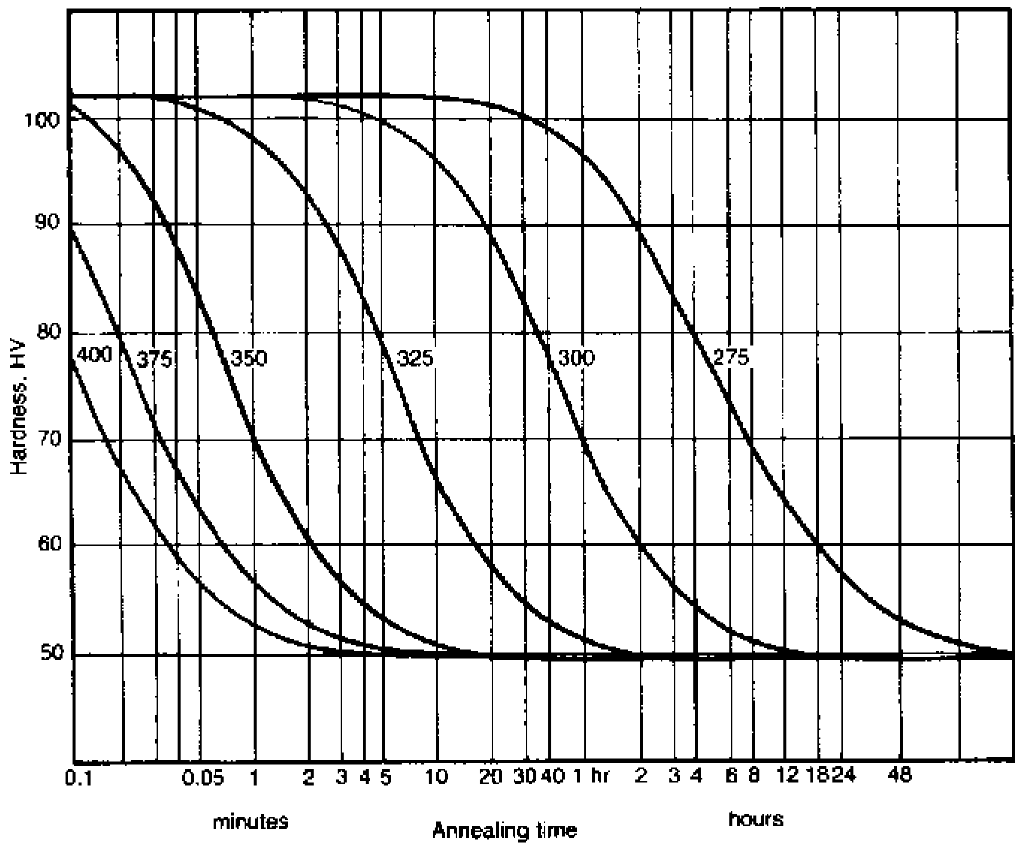

Figure 3 - Typical effect of annealing temperature (°C) on the annealing behaviour of tough pitch copper Cu-ETP.

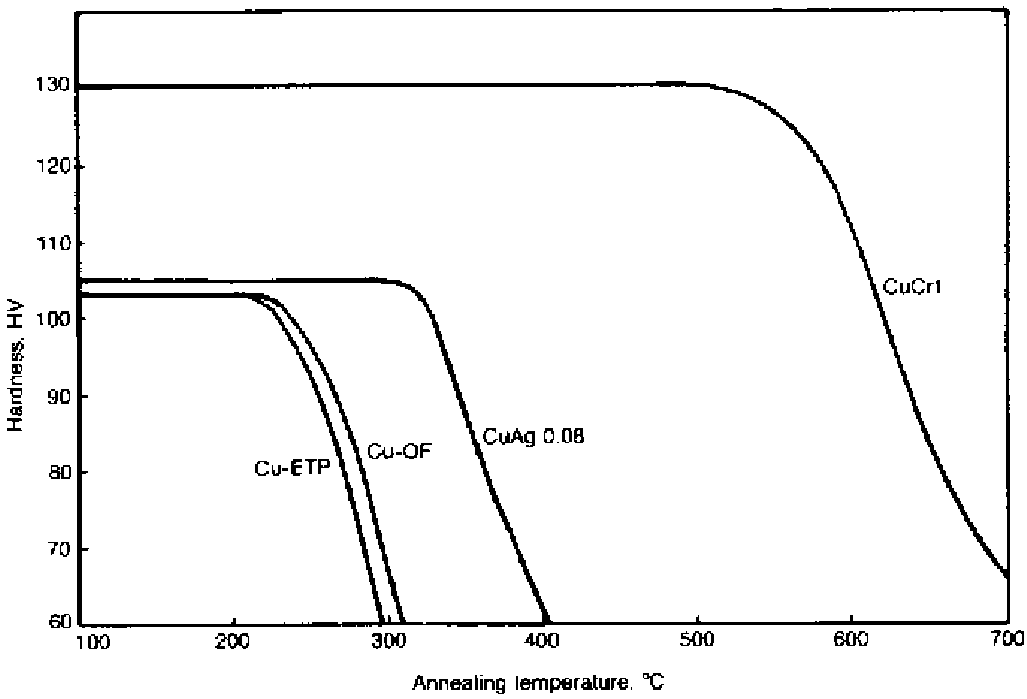

Figure 4 - Change of hardness of various materials after 30 minutes at temperature

The results of annealability tests on four different materials are shown in Figure 4 which emphasises the effect of alloying on elevated temperature behaviour. The interrelationship of temperature with time is shown in Figure 5 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.

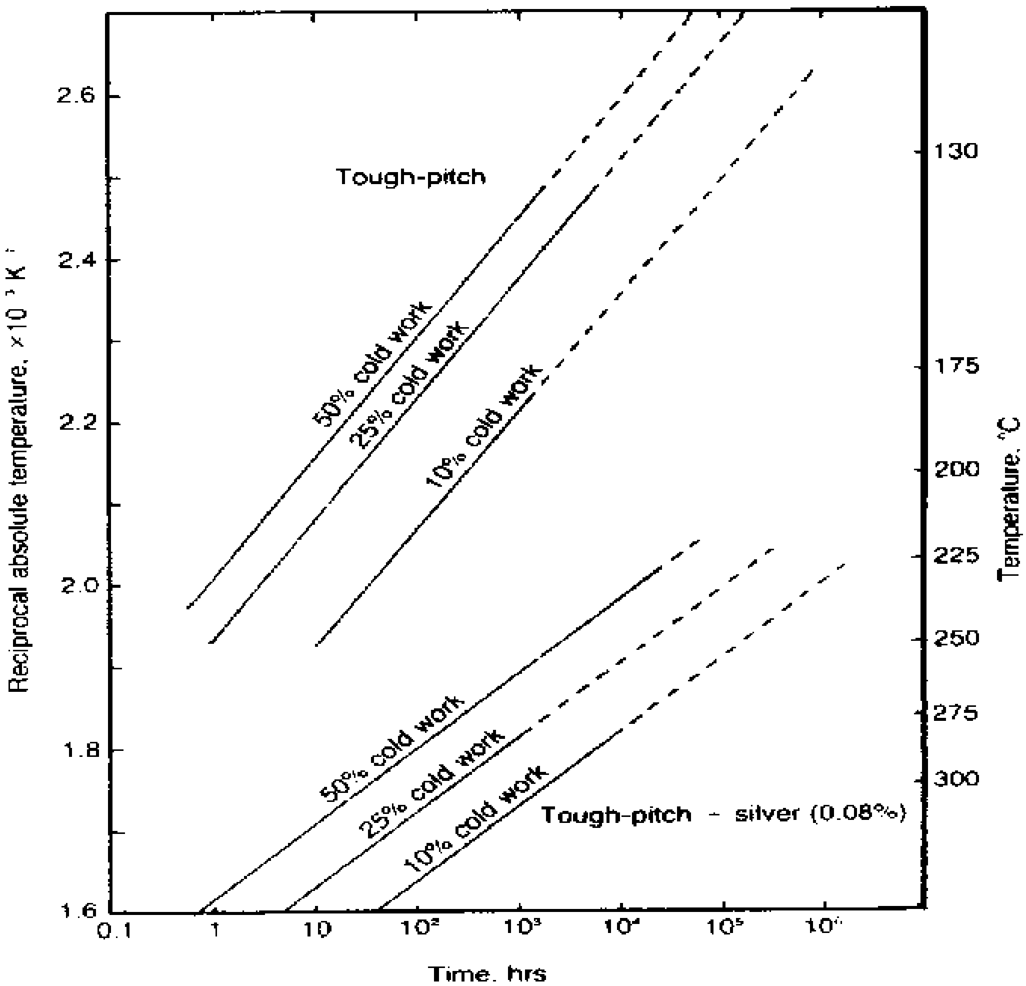

Figure 5 - Relationship between time and reciprocal absolute annealing temperature to produce 50% softening of cold-worked Cu-ETP and CuAg0.08

In Table 8, temperature ranges are shown for each composition for both stress relieving and full annealing. The former treatment may be employed if components are likely to be used in an aggressive environment to reduce susceptibility to stress corrosion or corrosion fatigue. This practice is, however, not frequent. The wide range of temperatures quoted for annealing is caused by the factors mentioned previously, all of which must be taken into account when specifying an annealing treatment. Generally, it is good practice to use moderate temperatures and times in order to restrict oxidation and also the grain growth caused by over-annealing.

Unlike the brasses, it is not normally practicable to "temper anneal" high conductivity copper reproducibly to a hardness intermediate between hard and annealed. Such intermediate tempers are produced by cold work from the soft condition. This does not apply though to the heat treatable alloys where prolonged heating at or above the precipitation hardening temperature will result in progressive "overaging" and a gradual loss of hardness and, eventually, conductivity.

The principles upon which the solution and precipitation treatments for the heat treatable alloys depend have been briefly described previously. The recommendations of the manufacturers of these alloys regarding times and temperatures suitable to particular products should be sought and followed in order to obtain optimum properties.

For most annealing operations, closely controlled atmospheres are not essential because any oxide film produced may usually be removed during a water quench or subsequent pickle in dilute sulphuric acid.

"Bright" annealing in a controlled atmosphere is possible but, as mentioned elsewhere, care should be taken when annealing any tough pitch copper that there is not available sufficient hydrogen to reduce the oxides in the copper to steam and thus embrittle it (also called "gassing").

For more information on all the mechanical and physical properties of the high conductivity coppers at ambient, elevated and cryogenic temperatures see CDA Technical Note TN 27, High Conductivity Coppers - Technical Data. This is included on the CD-ROM 'Megabytes on Coppers II' and summarises many references and includes much information only previously published in the comprehensive CIDEC Data Sheets.

Machining

As shown in Table 8, the easiest of the coppers to machine are the special free machining grades which approach the ease of machining of the standard brass. The machining properties of all the materials vary and it is suggested that for best results the tool angles, cutting speeds and lubricants should be selected from those recommended in the CDA publication TN44 "Machining Brass, Copper and Its Alloys" [10].

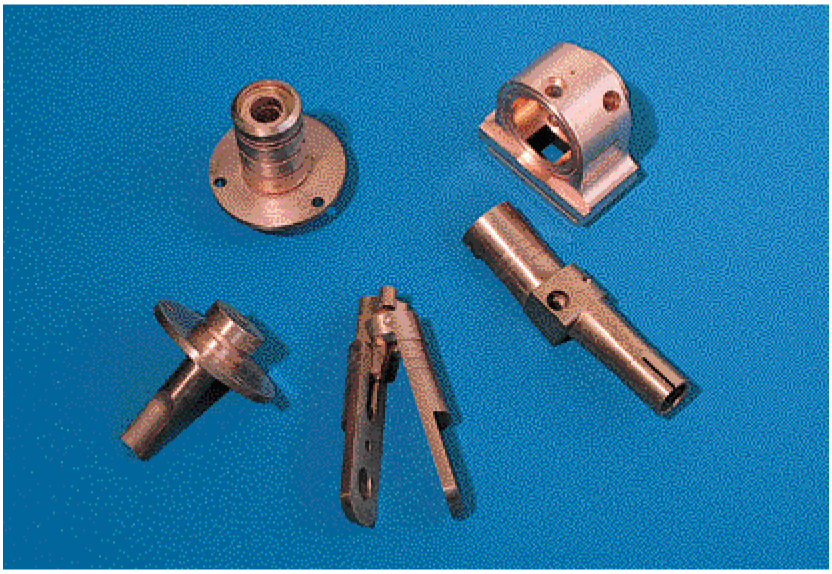

Plate 13 - Free Machining Copper (Thomas Bolton)

The cost of these components for the electrical engineering industry is minimised by making forgings and castings near to the final shape in a free-machining grade of copper and then finishing to close tolerances.

Electrodeposition

Copper is frequently plated onto other metals, notably steels, leaded brasses and free-machining coppers as a substrate prior to finish plating with nickel and chromium. To obtain the required smooth finish, the composition of the plating bath and current densities used are different from those used in tankhouses of electrolytic refineries.

Large quantities of copper wire are tin coated by electrolytic means or vacuum inert gas tinning (a hot dip process) to provide corrosion resistance and to enhance solderability.

A considerable tonnage of copper wire is plated with silver or nickel for stranded conductors in high performance electric and high temperature cables. It is also woven into mesh and cloth and a substantial volume is used in the manufacture of musical instrument strings.

Vitreous Enamelling

Copper and its alloys are ideal for vitreous enamelling and a large range of attractively coloured frits is available. Most products are exclusively used for the manufacture of enamelled badges and jewellery and a large range of enamelled decorative ware.

Winding Wires - Enamelling

It is generally accepted that the enamelling process represents the most important phase in the manufacture of winding wires. This process involves taking wire from the final wire-drawing stage, dipping it in liquid enamel and passing it up through an enamel baking oven. Several stages of this process add successive coats to give an even, pore-free baked enamel coating to the required specification. The enamel baking temperature is similar to that needed to anneal the wire to the soft, limp state in which it is ideal for forming tight coils. Commercially available enamels include the following:-

Solderable Enamels - these consist generally of an isocyanate mixed with a polyester or polyurethane resin: they are particularly suitable for high speed enamelling of ultra-fine wire and are solderable at 320°C to 340°C. These insulations withstand abuse from high speed winding machines in applications such as shavers, vacuum leaners and fans. Other uses include coils where high "Q" or D.C. insulation resistance is a design factor and random wound coils where, at temperature, pressure between turns is severe, for example in stators and armatures.

PVF Enamels - the possibility of developing these for the superfine wire market is not high. There are difficulties in build-up and they have little resistance to humidity.

Polyester and Polyester-imide Enamels - these are easy to apply but do not solder easily.

Polyamide Enamels - this class of enamel is not particularly suitable for superfine wires but does have good flow properties.

Amide-imide and Polyamide Enamels do, however, possess valuable features relating to thermal classification and resistance to atmospheric factors and chemical attack. Although there are difficulties in soldering, their other properties make it possible to manufacture wires having excellent electrical performance in high stress conditions. For example, a polyester winding wire with an amide-imide linear polymer top coat has exceptional ductility, surface toughness and heat-shock resistance even at 260°C. Solvent and hydrolysis resistance are excellent. Applications for these wires include hermetic motors, dry and oil transformers, D.C. and universal armatures, and all types of random wound coils.

It has been shown that for refrigerant-resistant enamelled wires, which have high requirements regarding softness and ductility, tough pitch copper is preferred to oxygen free copper for ease of annealing. The enamelling process itself and high speed winding are factors that decrease elongation and increase springback.

Plate 14 - Copper coils for motors, transformers and chokes (Delta Winding Wires)

These components are made at relatively low cost because of the ease with which copper can be insulated by a thin coat of enamel and wound closely to give a reliable, energy-efficient lifetime of service.

Winding Wires -Textile Covered

An insulation of synthetic paper produced from aromatic polyamide fibres is suitable for continuous use at 220°C and will withstand thermal shocks above 300°C. Such coatings are compatible with all commonly used resins, solvents and transformer oils and meet the demands of the electrical repair industry and the manufacturers of transformers and large electrical equipment.

A composite of resin-rich mica/paper tape gives a Class 155 thermal rating and provides high dielectric strength without the need for vacuum impregnation. Such insulation is suitable for high voltage windings and field coils.

Glass fibre coverings have superseded cotton insulation as thermal properties have increased in importance. They will withstand relatively high temperatures and have good moisture resistance and are therefore suitable for the most demanding service conditions, provided space is not a problem. Applications include rotor and stator windings for heavy duty motors and generators.

Un-impregnated electrical paper lapped conductors should be subsequently impregnated before use in oil filled transformers to preserve electrical properties and to protect them from contamination.

Lacquering

Any lacquers applied to preserve the lustre of copper should be selected from those specially recommended by the manufacturers for the purpose. Tarnish can easily occur under simple nitro-cellulose lacquers and the finish can then only be restored by stripping off the lacquer prior to repolishing. For exterior used, lacquers should contain a corrosion inhibitor such as benzotriazole ('Incralac'). CDA book No 41 'Clear Protective Coatings for Copper and Copper Alloys' can be recommended for further information.

Inhibitors

The cheap, nitro-cellulose clear lacquers often used to preserve the bright appearance of small domestic decorative items afford adequate protection for the purpose but underfilm tarnishing usually becomes apparent after a year or so of indoor exposure. Superior performance is obtained from lacquers based on cellulose acetate or acrylic resins without inhibitive additions but these also fail, after perhaps a couple of years, by tarnishing spreading beneath the lacquer film from pinholes or scratches. This problem can be overcome by the incorporation of benzotriazole in the lacquer. Incralac (so named after the International Copper research Association, which sponsored the research in the UK and USA that produced the inhibited lacquer formulation) is an air-drying acrylic ester lacquer containing benzotriazole, together with ultraviolet absorbing agents and anti-oxidants to extend its life in outdoor service.

Incralac is manufactured under licence in most countries and has been used commercially throughout the world for the past 30 years. It can be relied upon to provide protection to copper, gilding metal, bronze, brass and nickel silver for 3-8 years outdoors and for much longer periods indoors. The usual precautions concerning cleaning of the metal surface before lacquering must of course be observed and a minimum dry film thickness of 25µm (0.001") is recommended. This normally requires the application of two coats since a single coat will provide about 13µm. Since, even after long periods of service, the bta still prevents any extensive tarnishing of the metal, it is easy to remove the lacquer with solvent and respray after a minimum of re-preparation when its general appearance is no longer considered satisfactory.

More detailed information on protection by lacquers and on plated coatings, which are treated briefly in the next section, was presented at a CDA Seminar on "Surface finishes on copper and copper alloys" and in an Institute of Metal Finishing paper. It has since been published as CDA Book No 41 ‘Clear Protective Coatings for Copper and Copper Alloys’[11]

Joining

A full description of the processes, joint design and techniques recommended is contained in CDA Publication No.98 "Joining of Copper and Copper Alloys[12]".

Soldering

Copper is one of the easiest of metals to solder and for this reason, combined with its conductivity, finds many applications where good joint integrity is essential. That applies not only in the electrical industries but also in plumbing and heat exchangers where joints must be easy to make and permanent.

Fluxes are used to prevent oxidation during soldering. Their compositions are specified in BS 5625 and recommendations for use vary according to the expected cleanliness of the joint and the type of application. "Protective" fluxes will maintain copper in an oxide free condition for soldering under gentle heating conditions. For dealing with conditions where the copper may be slightly tarnished initially and when using direct blow torch heating, an "active" flux is required. The residues from this flux should be removed as recommended by the manufacturer to eliminate any danger of subsequent corrosion. Many of these fluxes are now easily washed off in water.

Hard Soldering and Brazing

Carried out at a higher temperature than soldering, brazing similarly entails "wetting" the materials to be joined with a filler metal, though with a much greater strength. The techniques involve the use of fluid metal with good capillary penetration between close joint clearances. Alternatively, a fillet jointing operation "bronze welding" can be carried out generally on heavier sections than for the former methods.

"Silver Solders" are a family of alloys based on copper-silver alloys. They require the use of a suitable flux and the silver content makes them initially expensive but the limited quantity of filler used and the good integrity of fill of well designed joints frequently keeps this material economic.

A self-fluxing action is found in the copper-phosphorus alloys which also contain some silver. At brazing temperatures the phosphorus reduces any oxides formed during heating and a good joint can therefore be made.

Welding

All coppers can be welded using recommended techniques. Basic details of the suitability of the many welding processes available are shown for each material in Table 8. When suitable for the application, phosphorus deoxidised copper (Cu-DHP) is normally specified for fabricated assemblies not requiring the highest of conductivities. For full details CDA publication No.98 'Joining of Copper and Copper Alloys' is again recommended.

The BS EN Standards

Following many years of co-operative committee work, the European CEN TC133 'Copper and Copper Alloys' committee has nearly completed preparation of a series of new material and product standards that replace all similar individual national standards.

Standards' Titles and Numbers

Table 9 shows BS EN standards' titles, categorised by product type, and the BS standards that are replaced. Late in the standardisation process but before national implementation, an EN number is allocated; at this stage drafts are identified with the prefix 'pr'. In due course, the BS EN implementation uses the same number.

This publication lists the BS EN numbers, even if still 'pr EN' at publication. When the number is still not known, the CEN Technical Committee 133 Work Item Number is given, i.e. 133/xx. Further details are included in CDA Publication No 120 [13] which supersedes publication TN10 [14]

Table 10 shows BS historic standard numbers in numerical order and their replacement BS EN standards.

BS EN Number	Title	Nearest old BS equivalent
Unwrought products		
1978	Copper cathodes	6017
1977	Copper drawing stock (wire rod)	6926
1976	Cast unwrought copper products	6017
1982	Ingots and castings	1400
1981	Master alloys	-
Rolled flat products		
1652	Plate, sheet, strip and circles for general purposes	2870, 2875
1653	Plate, sheet and circles for boilers, pressure vessels and hot water storage units	2870, 2875
1654	Strip for springs and connectors	2870
1172	Sheet and strip for building purposes	2870
1758	Strip for lead frames	-
13148	Hot dip tinned strip	-
(133/18)*	Electrolytically tinned strip	-
Tubes		
12449	Seamless, round tubes for general purposes	2871 pt.2
12451	Seamless, round tubes for heat exchangers	2871 pt.3
1057	Seamless, round copper tubes for water and gas in sanitary and heating applications	2871 pt.1
12452	Rolled, finned, seamless tubes for heat exchangers	-
12735	Seamless, round copper tubes for air conditioning and refrigeration Part 1: Tubes for piping systems, Part 2: Tubes for equipment	
(133/26)*	Seamless, round copper tubes for medical gases	-
12450	Seamless, round copper capillary tubes	-
133/29	Pre-insulated copper tubes: Tubes with solid covering	-

Table 9 - BS EN Standards For Copper And Copper Alloys

BS EN Number	Title	Nearest old BS equivalent
Rod/bar, wire, profiles		
12163	Rod for general purposes	2874
12164	Rod for free machining purposes	2874
12165	Wrought and unwrought forging stock	2872
12166	Wire for general purposes	2873, 2874
12167	Profiles and rectangular bar for general purposes	2874
12168	Hollow rod for free machining purposes	-
(133/52)*	Rod and wire for welding and braze welding	1453, 1845, 2901
Electrical purposes		
(133/60)*	Copper plate, sheet and strip for electrical purposes	4608
(133/61)*	Seamless copper tubes for electrical purposes	1977
(133/62)*	Copper rod, bar and wire for general electrical purposes	1433, 4109
(133/63)*	Drawn round copper wire for the manufacture of electrical conductors	4109, 6811
(133/65)*	Products of high conductivity copper for electronic tubes, semiconductor devices and vacuum applications	3839
(133/66)*	Copper profiles for electrical purposes	-
Forgings and fittings		
12420	Forgings	2872
1254 pts 1 to 5	Plumbing fittings	864
Test methods		
12893	Determination of spiral elongation number	DD79
12384	Determination of spring bending limit on strip	-
13147	Determination of residual stresses in the border area of strip	-
1971	Eddy current test for tubes	-
723	Combustion method for determination of carbon on the inner surface of copper tubes or fittings	-
(133/64)*	Test methods for assessing protective tin coatings on drawn round copper wire for electrical purposes	-
(133/110)*	Methods of chemical analysis (to be based on existing ISO standards)	-
ISO 196	Detection of residual stress - mercury(1) nitrate test (ISO 196 : 1978)	-
ISO 2624	Estimation of average grain size (ISO 2624:1990)	-
ISO 2626	Hydrogen embrittlement test (ISO 2626:1973)	=5899
ISO 4746	Scale adhesion test (for Cu-OFE)	=5909
IEC 468	Mass resistivity	=5714
Miscellaneous		
1655	Declarations of conformity	-
1412	European numbering system	-
1173	Material condition or temper designation	-
10204	Metallic products-types of inspection documents	-
12861	Scrap	

*When the BS EN number is not yet available the number is expressed as: CEN Technical Committee Number / Work Item Number, e.g. (133/61).

Table 9 - BS EN Standards For Copper And Copper Alloys (continued)

Old BS Standard		BS EN Standards
DD79	Spiral elongation test for HC copper	12893
1400	Copper & copper alloy castings	1982
1432	HC copper rectangular conductors	133/60
1433	HC copper rod and bar	133/62
1434	HC copper for commutator sections	133/66
1453	Filler materials for gas welding	133/52
1845	Filler metals for brazing	133/52
1977	HC copper tubes	133/61
2870	Sheet. Strip and foil	1172, 1652, 1653, 1654
2871 Pt 1	Tubes for water, gas and sanitation	1057
Pt 2	Tubes for general purposes	12449
Pt 3	Tubes for heat exchangers	12451
2872	Forging stock and forgings	12165, 12420
2873	Wire	12166
2874	Rods and sections	12163, 12164, 12167
2875	Plate	1652, 1653
2901	Filler rods for gas-shielded arc welding	133/52
3839	Oxygen-free copper for electronic tubes and semi-conductor devices	133/65
4109	HC copper wire	133/63
4608	HC sheet, strip & foil	133/60
6017	Copper refinery shapes	1976, 1978
6811	Enamelled winding wires	133/63
6926	HC copper wire rod	1977

Table 10 - Listing of old BS Standards Replaced by BS EN Standards

Material Designations

Material Designations (individual copper and copper alloy identifications) are in two forms, symbol and number. As with many other existing European national standards, symbols are based on the ISO compositional system (e.g. CuCr1 is a copper-chromium alloy containing a nominal 1% of chromium). ISO and EN symbols may be identical but the detailed compositional limits are not always identical and cannot be assumed to refer to unique materials.

Numbering System

A new numbering system has therefore been developed to offer a more user- and computer-friendly alternative. The system is a 6-character, alpha-numeric series, beginning C for copper based material; the second letter indicates the product form as follows:-

B - Materials in ingot form for re-melting to produce cast products

C - Materials in the form of cast products

F - Filler materials for brazing and welding

M - Master alloys

R - Refined unwrought copper

S - Materials in the form of scrap

W - Materials in the form of wrought products

X - Non-standardised materials

A three-digit number series in the 3rd, 4th and 5th places is used to designate each material and can range from 001 to 999; with numbers being allocated in preferred groups, each series being shown below. The sixth character, a letter, indicates the copper or alloy grouping as follows:-

Number Series	Letters	Materials
000-099	A or B	Copper
100-199	C or D	Copper alloys, low alloyed (less than 5% alloying elements)
200-299	E or F	Miscellaneous copper alloys (5% or more alloying elements)
300-349	G	Copper – aluminium alloys
350-399	H	Copper – nickel alloys
400-449	J	Copper – nickel – zinc alloys
450-499	K	Copper – tin alloys
500-599	L or M	Copper –zinc alloys, binary
600-699	N or P	Copper – zinc lead alloys
700-799	R or S	Copper – zinc alloys, complex

Symbol Designations

- The symbols used are based on the ISO designation system (ISO 1191 Pt1).
- The principal element, copper, is first.
- Other alloying elements are included in decreasing order of percentage content.
- Where contents are similar, alphabetical order may be used.
- The numbers after elements represent nominal compositions.
- No number is normally used if the nominal composition is less than 1%

Material Condition (Temper) Designations

A number of designations are defined in BS EN 1173; in product standards only one designation is allowed for a single product.

The first letter indicates the designated property, as follows:-

A - Elongation

B - Spring Bending Limit

D - As drawn, without specified mechanical properties

G - Grain size

H - Hardness (Brinell or Vickers)

M - As manufactured, without specified mechanical properties

R - Tensile strength

Y - 0.2% proof strength

Beside the designating property, other properties may be mandatory; check the standard document for full details.

A minimum of three digits follow, where appropriate, to indicate the value of the mandatory property with the possibility of a final character, ‘S’, for the stress relieved condition. Normally the value refers to a minimum for the property. Sometimes, as with grain size, it refers to a nominal mid-range value.

Table 7 shows not only the existence of copper or copper alloys in particular standards but also the material conditions available as mandatory properties within those standards.

Typical Properties

In Table 13 and Table 14 in Section 7, typical properties are usually shown as ranges. For materials available in both soft condition, for example as forging stock, and very hard, for example as spring wire, then the ranges are very wide. It is vital that designers and purchasers consult with suppliers to clarify what property values and combinations are available in the desired product form.

Metallurgy And Properties

High Conductivity Copper

There is an enormous range of electrical applications for which high conductivity copper is used, and there are a number of different coppers which may be specified, but for the majority of applications the appropriate choice will be Electrolytic Tough Pitch Copper, (Cu-ETP). This is tough pitch (oxygen bearing) high conductivity copper which has been electrolytically refined to lower the impurity levels to total less than 0.03%. CR004A is the number for the cast material and the equivalent number for wrought material is CW004A. This copper is readily available in a variety of forms and can be worked both hot and cold. It is not liable to cracking during hot working (called 'hot-shortness') because the levels of lead and bismuth which cause such cracking are subject to defined limits.

A higher grade, designated Cu-ETP1, with number CR003A as cast and CW003A when wrought, is available for use by manufacturers with advantage in modern high speed rod breakdown and wire drawing machines with in-line annealing. It makes excellent feedstock for many wire enamelling processes where a copper with a consistently low annealing temperature is needed to ensure a good reproducible quality of wire. Very low impurity levels in this product are ensured by using high grade cathode (Cu-Cath-1) and minimising contamination during processing.

Standard Compositions

The standard compositions and typical properties of Cu-ETP1 and Cu-ETP are set out in Table 13 along with other coppers.

The new standards stipulate the purity of coppers together with some minimum conductivity requirements. The requirements clearly define the maximum total of 19 listed impurities. This total has had to be defined with cautious regard for existing standard and the accuracy tolerances of referee analytical methods. It is believed that in fact most commercial coppers are significantly purer than specified.

The oxygen content is not specified, but is particularly important and is carefully controlled during manufacture. 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 rather than in solution in the copper. Their effect on conductivity and ductility of the copper is then minimised.

When copper is molten it normally picks up some hydrogen, typically from the furnace atmosphere. The presence of some oxygen during solidification ensures that the two gases combine to give steam and the possible embrittling effect of the hydrogen is avoided. The microporosity generated by the steam counteracts the shrinkage which would otherwise occur during solidification and this leads to the required level set.

Improved melting practice with better control of the melting atmosphere results in a lower pickup of hydrogen. Many refinery shapes are also now cast continuously. The constant head of liquid metal during this process ensures good feeding of any shrinkage cavities. Oxygen contents have in consequence been reduced from about 0.06% to 0.02% or less and this, together with the drop in impurity levels resulting from improvements in refinery techniques, has had a beneficial effect on the electrical properties of the coppers as originally defined in 1913 by the International Electrotechnical Commission (IEC).

Production of High Conductivity Copper

Copper is extracted and refined in many places throughout the world as Plate 15 shows. The large number of sources now being worked ensures continuity of supply.

There is also an important industry in the recycling of copper scrap. Scrap arises inevitably as a by-product of all fabrication processes, for example as machining swarf and surplus cable ends. This is known as industrial or new scrap and forms about two-thirds of the world's secondary copper supply. The rest comes from old scrap which is material salvaged from obsolete equipment. Organisations such as the telecommunications industries are big producers of old scrap as installations are continually being up-dated and replaced, also old buildings which are pulled down for redevelopment yield large quantities of copper wire. All this scrap finds its way back to refineries for secondary processing and at present it forms about 50% of the total amount of copper produced.

The output from a refinery is in a variety of forms depending on the type of semi-finished wrought material to be made. Copper Cathodes are the product of electrowinning, direct from leach solutions or following solvent extraction, or of electrolytic refining. They must be remelted before being usable and may then be cast to different "refinery shapes".

The shapes are billets for extrusions and cakes for rolling into flat plate. Wirebars used to be made for rolling to rod but these have been largely superseded by wire rod continuously cast and rolled as feedstock for wire drawing.

Plate 15 - World map showing the location of copper producers.

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 to fabricate 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 1200 x 900mm in size, weighing 100-300kg each. For primary refineries the trace impurity levels depend on the ore being worked and the precise control of the refining process.

Hydrogen can be introduced to cathode copper by organic additives, such as glue and urea , which are used to refine the grain structure. This hydrogen can significantly affect subsequent hot rolling.

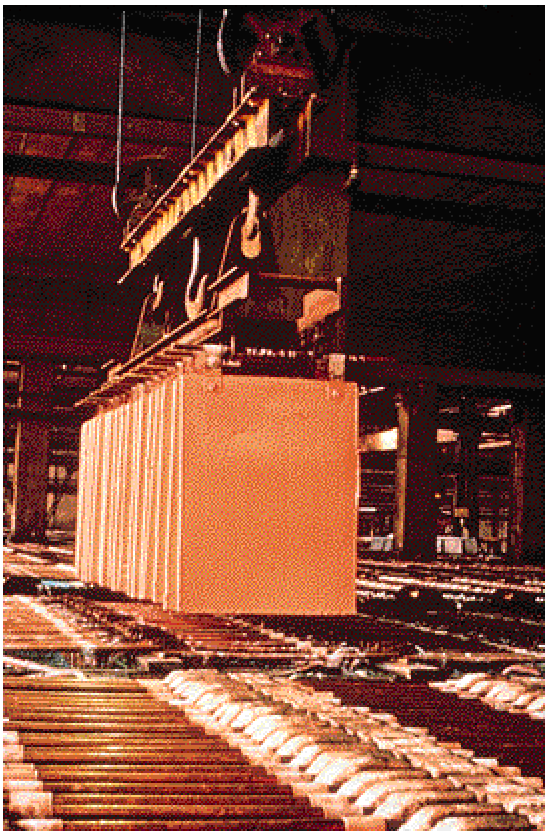

Plate 16 - Copper Cathodes ((DKI))

This batch of cathodes are being lifted out of the deposition bath in the electrolytic refinery. Typically the impurities are less than 0.0065%. Precious metals are recovered from the anode slime deposited at the bottom of each tank.

Refinery Shapes

Billets, usually about 200mm diameter, are cast for subsequent extrusion to rod and bar. Normally these are cut to no more than 750mm 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 previous static casting methods. Copper is commonly hot rolled from, 150 mm thickness down 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 35mm diameter (typically 9mm) which provide the starting stock for wiredrawing. At one time these were limited in weight to about 100kg, 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, Contirod and Up-cast. 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 does require a consistently high quality of copper.

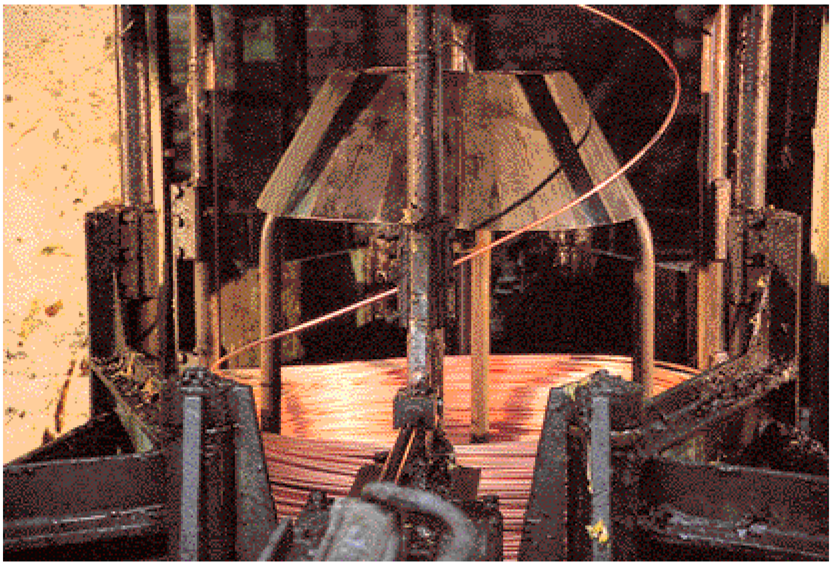

Plate 17 - Copper Wire Rod (Vin Callcut)

This five ton coil is typical of the high quality rod now economically made in continuous rod mills.

These stringent quality demands are needed to provide the reproducibility of performance which permits the economic production of magnet wires and superfine wires down to 0.01mm diameter for enamelling and tinning.

Physical Properties

The physical properties for the wrought material, Cu-ETP/CW004A, are shown in Table 15 at the end of Section 7. These are also typical for similar coppers.

Electrical and Thermal Properties

Besides corrosion resistance, one of the most useful properties of copper is its high conductivity for both electricity and heat. The standard by which other conductors are judged is the International Annealed Copper Standard on which scale copper was given the arbitrary value of 100% in 1913.

As the standard metal for electrical conductors, copper has many economic advantages. Size for size, conductors made from copper are smaller than others. This means that insulation costs are significantly reduced and that, in electrical machines, more windings can be installed in a given area which results in greater electrical efficiency and less need to waste energy driving cooling systems.

For standard values and detailed consideration of factors affecting the electrical conductivity and resistivity and thermal conductivity see Section 11.

Effect of Impurities and Minor Alloying Additions on Conductivity

The effect of some added elements on electrical conductivity of copper is shown in Figure 6. This is only approximate since the actual effects are varied by the thermal and mechanical history of the copper, by oxygen content and by 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 largely insoluble in copper have little effect on conductivity. Since they are present as discrete particles they are intentionally added to improve the machinability of high conductivity copper.

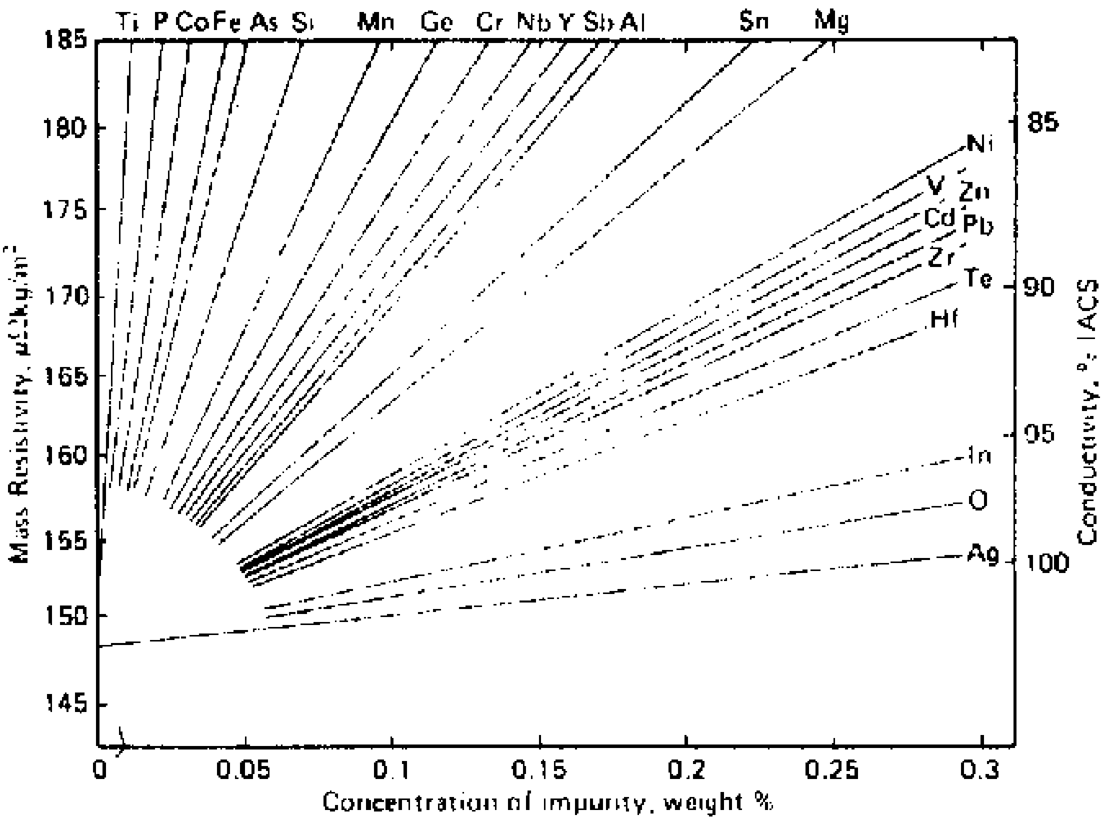

Figure 6 - Approximate effect of impurity elements on the electrical resistivity of copper

The effect of oxygen is beneficial since some impurities are then present as insoluble complex oxides rather than being in solid solution in the metal. The reduced levels of impurities in primary coppers produced by modern tankhouses means that, as previously mentioned, the oxygen content of the coppers made from their cathode need now be only around 0.02% or less.

At lower concentrations than those shown, the effect of individual impurities on conductivity is less easily measured because of the difficulty of eliminating inter-element effects and an increased effect of prior mechanical and thermal treatment on the extent to which elements may be in solution. The curves shown should not therefore be extrapolated backwards towards "parts-per-million" figures.

Effect of Impurities on Annealability

Since high-speed production plant relies on reproducible materials, manufacturers now use several quality control tests to check wire rod before release. One of these is the Spiral Elongation Test described in BS 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.

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.

Commercial electrolytic tough pitch copper (Cu-ETP) has the high conductivity typical of pure copper because it contains enough oxygen to ensure that residual impurities are present as oxides rather than in solution. If dissolved in the copper they would have a much more adverse effect than they do on conductivity.

If heated for a significant time in a reducing atmosphere containing hydrogen, the oxide is reduced as hydrogen diffuses in to the metal. As it converts to steam there is a build-up of pressure that can rupture the copper. Normal hot working procedures avoid this potential problem by keeping the atmosphere with an oxidising potential.

Coppers and Copper alloys for Electrical and Thermal Applications

Table 13 shows a comparison of commercially available "pure" coppers with typical mechanical and electrical properties. Table 7 in Section 4 shows the wrought forms in which all these materials are available and the relevant BS EN Standards for coppers and some products commonly made from copper are listed in Table 6.

Other Coppers Available

Cathode copper (Cu-Cath-1 and Cu-Cath-2)

As previously explained, 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 described, high speed wire drawing and modern enamelling plants need the reproducibility of the higher specification.

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.

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 number (CW006A) for the material in wrought form it is rarely made.

Phosphorus deoxidised copper (Cu-DHP)

Numbered CW024A in wrought form, Cu-DHP is the preferred material for tubes for heat exchangers and commonly called 'Deox' copper. It was previously also known as 'DONA' copper (phosphorus deoxidised non-arsenical). It contains 0.015 to 0.040% phosphorus to ensure freedom from residual oxygen and is readily joined by all welding and brazing techniques. For the most severe of deep drawing operations on sheet, Cu-DHP is preferred to tough pitch copper.

If copper containing oxygen is heated in a reducing atmosphere containing hydrogen, severe "gassing" embrittlement can result if the hydrogen diffuses into the copper and reduces the oxides forming high pressure steam. Deoxidised copper is therefore used where such conditions are likely to be encountered, as in many types of welding and brazing fabrication techniques. Phosphorus is the most commonly used deoxidant for copper but does have a deleterious effect on the conductivity of the copper which will be around 92% IACS at a phosphorus content of 0.015%, reducing to about 78% at 0.05%.

Some specifications allow a phosphorus content lower than 0.013% to reduce the loss in conductivity. During casting of this copper, great care has to be taken to avoid residual oxygen and a hydrogen embrittlement test is therefore carried out on such material in the wrought form to check that it is absent. Boron (added as calcium boride) or lithium are also occasionally used as deoxidants that do not have such an effect on conductivity.

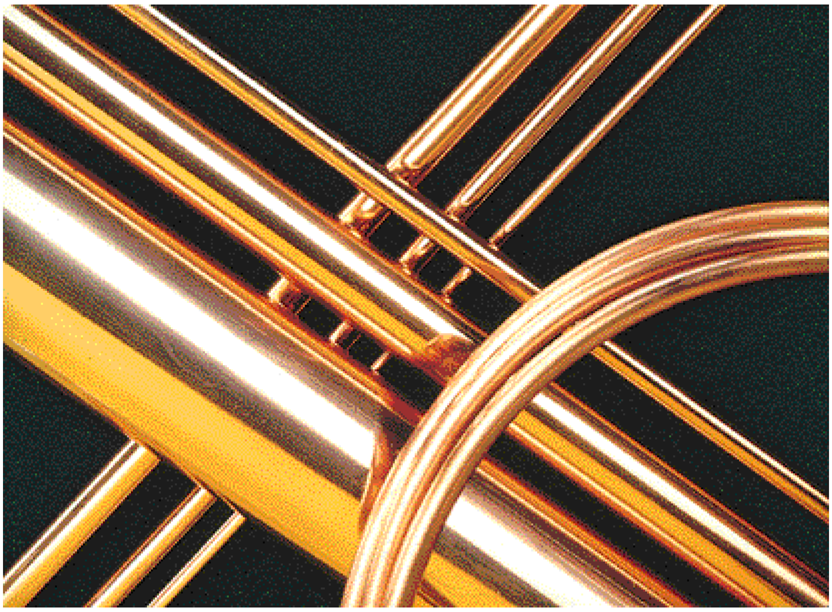

Plate 18 - Copper Tubes

Copper is the standard material for tubes when small sizes are needed for water supplies, central heating and for water-cooling. They are made from phosphorus-deoxidised copper and are strong yet ductile and easily joined by soldering, brazing or welding.

Oxygen-free copper (Cu-OF-1 and Cu-OF)

Copper can be melted under closely controlled inert atmosphere conditions and poured to give metal substantially free from oxygen and residual deoxidants. In wrought form, Cu-OF is numbered CW008A and is suitable for high conductivity applications involving processing at elevated temperatures in reducing atmospheres. Since the effect of most impurities on conductivity is greater in the absence of oxygen, it is important that they be kept to a minimum.

Cu-OF-1 is a higher grade than Cu-OF with lower impurity levels and higher conductivity.

Plate 19 - Components machined from High Conductivity Copper, Electronic Grade (Dawson Shanahan)

The products in the foreground are semiconductor heat sinks for use in diodes and thyristors for heavy current operations. Those with the narrow slots are for interupters for emergency power switching. The accurately machined slots control the electric arc that forms as the contact is broken.

All these applications demand the purest form of copper easily available. Because it is not a free-machining grade, high precision machining techniques have been developed by the specialist manufacturer.

Oxygen-free copper - electronic grade (Cu-OFE)

For applications in high vacuum where no volatiles can be tolerated, this high purity "certified" grade of oxygen-free high conductivity copper is used. Its special requirements are covered by BS EN(133/65) and in wrought form is numbered CW009A. The oxide film on this copper is very strongly adherent to the metal which makes it a suitable base for glass-to-metal seals.

Copper-silver (CuAg)

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.

Previously the silver addition was agreed between supplier and purchaser but it is now possible to select from three ranges of preferred additions for suitable applications (0.03-0.05%; 0.06-0.08%; 0.08-0.12%). A minimum of 0.03% of silver facilitates the production of transformer and other winding strips with a controlled proof stress. Also, where a significant increase in creep properties is required with minimal additions of silver, the 0.03% minimum should be selected and this is frequently specified for heat exchanger strip. For applications requiring good softening resistance during hard soldering, such as commutators, 0.06-0.08% silver is required. The 0.08-0.12% grade gives very good resistance to creep and it is therefore suitable for use in highly stressed rotor winding strips.

The three ranges of silver are available in tough pitch, phosphorus deoxidised and oxygen-free coppers. Where embrittlement resistance is also required, without the loss of conductivity caused by deoxidants, the oxygen-free coppers should be selected. 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.

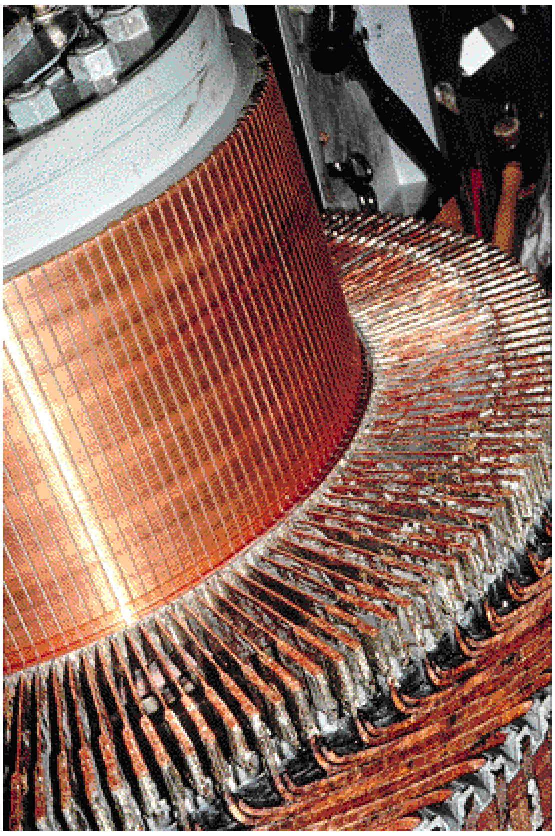

Plate 20 - Commutator for a Large DC Motor. (Lawrence Scott and Electromotors.)

The commutator segments are made from tapered sections of silver-bearing copper with good creep resistance to the centrifugal forces at high speed and operating temperature. The motor has already seen many years of service in a marine environment.

High Conductivity Copper Alloys

High conductivity copper alloys (or 'low alloyed copper alloys') are used for a wide variety of applications needing their special combinations of such properties as electrical and/or thermal conductivity in conjunction with strength, hardness, corrosion resistance or ease of fabrication to the required shape. Compositions and typical properties of these alloys, including free machining coppers, are in Table 14. Further copper alloys are described in other CDA publications which give the compositions and properties of the brasses, nickel silvers, phosphor bronzes and others which have applications as springs, terminations, connections and other electrical components.

Addition of other elements to copper

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 being usually easier to measure. The extent of the effects depend 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 exist for single and multiple additions of elements to attain properties suitable for different applications.

A selection of equilibrium diagrams showing the phases formed in some of the binary copper alloy systems are included in CDA Publication No 94 'Copper Alloy Equilibrium Diagrams'[15].

Non Heat-Treatable Alloys

Free machining coppers

Full information on the machining of this and other coppers and copper alloys is available in CDA publication TN44 "Machining Brass, Copper and its Alloys"[16].

While tough pitch, deoxidised and oxygen free coppers can all be machined without great difficulty, their machinability is less than that of the standard by which all metals are compared, free machining brass. 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, tellurium, selenium and lead are examples of possible additions. Most of these are otherwise undesirable impurities and give a degraded scrap value. The preferred addition is sulphur, 0.3 to 0.6% being satisfactory for most purposes in a deoxidised copper with a low residual phosphorus. Copper-tellurium and copper-lead are also standardised but have limited availability.

With any of these additions the hot and cold ductility of the copper is reduced to some extent when compared to the more common coppers. The materials are available both as cast and in wrought form as rod, bar and forgings.

Copper-cadmium

The addition of cadmium to copper increases its strength but does not reduce the conductivity of copper as much as many other elements, as can be seen in Fig 6. Historically, it has been used extensively for overhead collector wires for the catenary systems of railways, for trolley wires and for tramways; also for telephone wires and, when rolled to a thin strip, for the fins of automotive radiators and other heat exchangers.

Because of the general toxicity of cadmium vapour during melting and casting operations, the manufacture of and use of this alloy is discouraged in many countries and it is not included in the new BS EN standards.

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. By a solution treatment, typically at about 1000°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 500°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.

Advice regarding the selection and fabrication of these alloys can be obtained from CDA Technical Note TN27 'High Conductivity Copper Alloys - Technical Data'[17] or, especially in the case of proprietary materials, from the manufacturers.

Copper-beryllium alloys

The most important of the copper-beryllium alloys contain 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 14, the conductivity of the material is reduced, but it is preferred for many specific applications. Along with the strength at ambient and elevated temperatures, very good fatigue resistance, spring properties and corrosion resistance are obtained.

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°) without risk of over-ageing. The electrical conductivity is also slightly better.

Plate 21 - Non-Sparking Tools

For use in hazardous industrial environments, these tools have the necessary resistance to the generation of dangerous sparks.

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 on these matters should be sought from the manufacturers.

Beryllium vapour is well known to be toxic and suitable precautions are employed when fume is likely to be generated, especially during the melting or welding of copper-beryllium alloys. Fabrication in the solid state may not involve such a hazard and nor may machining in an adequate supply of lubricant which prevents overheating. Where a hazard does exist, efficient fume removal and treatment facilities must be employed, see CDA Publication No 104 'Copper-Beryllium Health and Safety Notes'[18].

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 and causing possible inclusions in the casting, but the alloy can be readily cast by foundries with the required expertise.

Copper-chromium alloys are commonly used in rod form for spot welding electrodes, as bar for high strength conductors and as forgings for seam welding wheels and aircraft brake discs. As castings they find applications as electrode holders and electrical termination equipment where the shape required is more complex than can be economically machined.

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-chromium-magnesium

While copper-chromium is an excellent material for use under the arduous conditions associated with resistance welding applications, when used continuously at moderately elevated temperatures under tensile stress it can show poor creep ductility due to cavitation effects at grain boundaries. 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 BS EN standards but properties are similar to copper-chromium.

Plate 22 - Rotor Bars made of Copper-Chromium-Magnesium (Vin Callcut)

These are specially made for motors for the power industry that must run for very long periods without risk of failure.

Copper-zirconium

Copper-zirconium is an alloy with a different balance of properties from the copper-chromium alloys, the conductivity being not so good. Due to the extremely high affinity of zirconium for oxygen, it is not readily cast to cake or billet form without the use of a controlled atmosphere above the melt. It is therefore less generally available commercially but is used for some specialised applications.

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. Their use for electrical purposes is limited but specialised copper-nickel alloys can be described. All are heat treatable.

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.

Copper-nickel-phosphorus

This alloy has a nominal 1% nickel and 0.2% of phosphorus. It is not so 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.

Copper-nickel-tin

A particular group of copper-nickel-tin alloys undergoes a spinodal decomposition reaction which results in an alloy of very good strength and wear resistance coupled with excellent corrosion resistance. The alloys have been developed in America where they are used for hardwearing contacts in the telecommunications industry. Two compositions are specified, UNS No C72700 with 9% Ni and 6% Sn, and C72900 with 15% Ni and 8% Sn. Both are available as strip which is fabricated by the user and then heat treated.

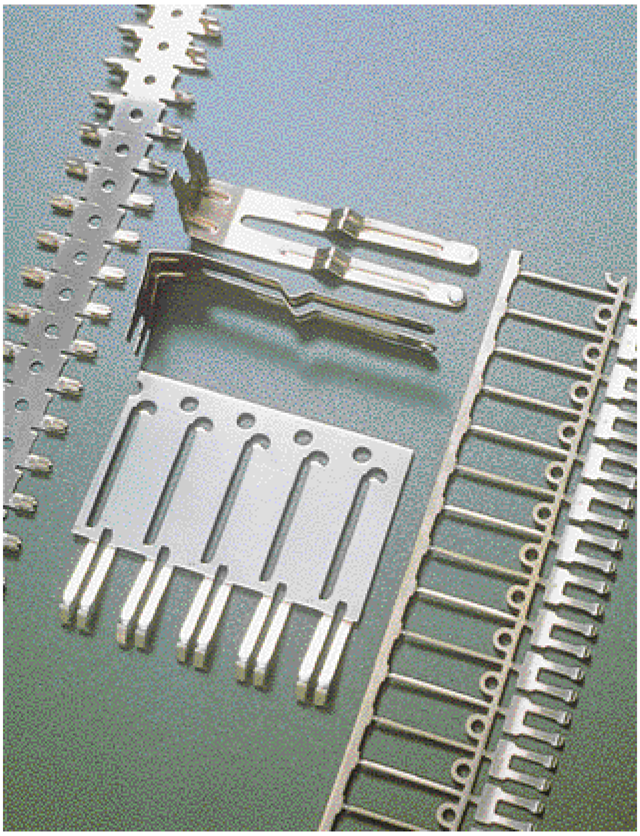

Plate 23 - Spring connectors stamped and formed from copper-nickel-tin strip.

Copper alloys for semiconductor leadframes

The development of more advanced microchips has required the production of copper alloys as leadframe 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 are many and varied, including such as silver, cobalt, chromium, iron, magnesium, nickel, phosphorus, silicon, tin, titanium, zinc and alumina; some of the materials developed are shown in Table 11. The ranges of tensile strength, ductility and conductivity achievable with these additions are shown in Figure 7. 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

Alloy No.	**Composition – per cent**											
	Ag	Co	Cr	Fe	Mg	Ni	P	Si	Sn	Ti	Zn	Al_20_3
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

Table 11 - Copper alloys for semiconductor leadframes

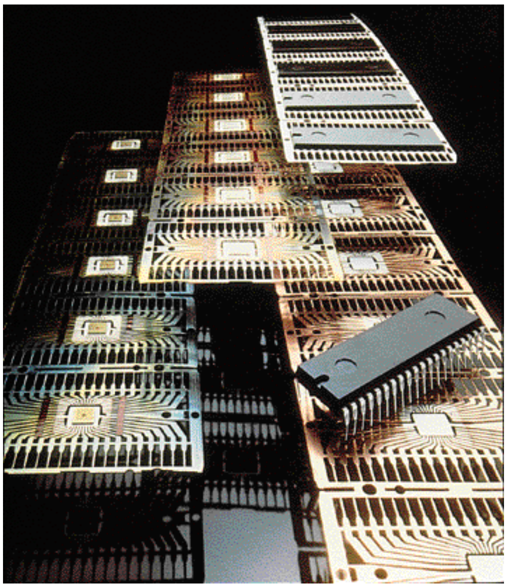

Plate 24 - Semiconductor Leadframes

Etching or stamping is used to make the basic shapes of these leadframes which are then bonded to the silicon chips at temperatures as high as 500°C. The pins are then bent to make the contact legs accurately. The material is chosen to meet the process requirements and still be reliable when fitted and in service.

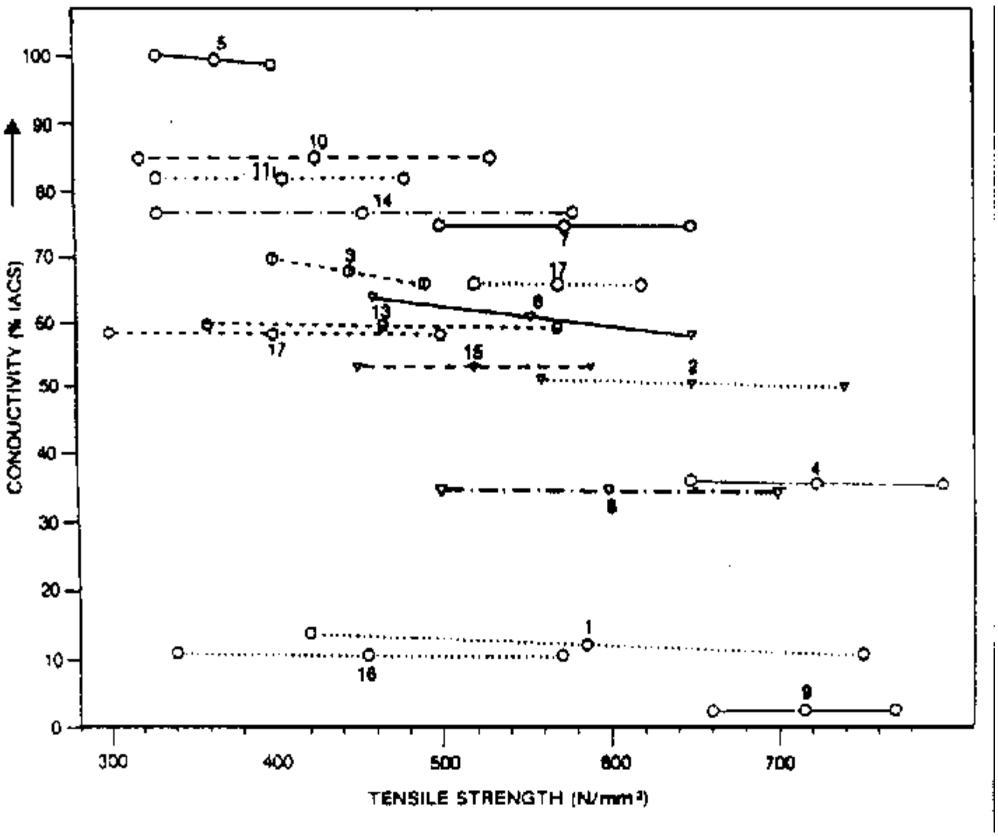

Figure 7 - Comparison of tensile strength and conductivity of various leadframe alloys after varying degrees of cold work (after Winkler Siemens)

Material designation			Nearest Old BS equivalent		Characteristics and uses
Symbol	Number				
	Unwrought	Wrought	Unwrought(#)	Wrought	
Copper cathode					
Cu-CATH-1 Cu-CATH-2	CR001A CR002A -		Cu-CATH-1- Cu-CATH-2	-	Refined coppers made in the form of cathodes by electrolytic desposition. The basic raw materials for most melting and casting purposes. Cu-CATH-1 is the higher grade - very low impurities. Copper cathodes are too brittle to fabricate.
Coppers ex Cu-Cath-1					
Cu-ETP1	CR003A	CW003A -	-	C100	Used for re-draw to wire. Suitable for high speed annealing and enamelling.
Cu-OF1	CR007A	CW007A	-	-	Oxygen-free version of Cu-ETPI for use in reducing atmospheres and cryogenic temperatures
Cu-OFE Cu-PHCE	CR009A CR022A	CW009A CW022A	Cu-OFE -	C110 -	Oxygen-free and low phosphorous coppers of high purity; the final "E" of the symbol indicates suitability for use in electronic vacuum devices.
Other unalloyed coppers					
Cu-ETP	CR004A	CW004A	Cu-ETP-2	C101	Used for most conductors and fabricated electrical components.
Cu-FRHC	CR005A	CW005A	Cu-FRHC	C102	.Little Fire-refined high conductivity copper is now made.
Cu-OF	CR008A	CW008A	Cu-OF	C103	Oxygen-free version of Cu-ETP for use in reducing atmospheres.
Cu-FRTP	CR006A	CW006A	Cu-FRTP	C104	Fire-refined tough pitch copper is rarely made in wrought form. Ingots provide feedstock for castings
Phosphorus-containing coppers					
Cu-PHC Cu-HCP Cu-DLP Cu-DHP Cu-DXP	CR020A CR021A CR023A CR024A CR025A	CW020A CW021A CW023A CW024A CW025A	- - - Cu-DHP	- - C106 -	Phosphorus-deoxidised coppers for general and chemical engineering applications, particularly when brazing or welding is involved. Cu-DHP is the preferred material for copper tubes for industrial and commercial heating applications and is a component of the new copper-brass car and truck radiators which easily out-perform aluminium units

Table 12 - Unwrought and Wrought High Conductivity Coppers - Designations and Applications*

Material designation			Nearest Old BS equivalent		Characteristics and uses
Symbol	Number				
	Unwrought	Wrought	Unwrought(#)	Wrought	
Silver-bearing coppers					
Tough Pitch					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, semi-conductor components and etching plates
CuAg0.04	CR011A	CW011A	Cu-Ag-2	C101	
CuAg0.07	CR012A	CW012A	Cu-Ag-3	C101	
CuAg0.10	CR013A	CW013A	Cu-Ag-4	C101	
Phosphorous Deoxidised					
CuAg0.04P	CR014A	CW014A			
CuAg0.07P	CR015A	CW015A			
CuAg0.10P	CR016A	CW016A			
Oxygen-free					
CuAg0.04OF	CR017A	CW017A	Cu-Ag-OF2	C103	
CuAg0.07OF	CR018A	CW018A			
CuAg0.10OF	CR019A	CW019A	Cu-Ag-OF4	C103	

Table 12 - Unwrought and Wrought High Conductivity Coppers - Designations and Applications (cont)*

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

(#) BS 6017 (confirmed 1989)

Metallography

Both copper oxide and copper phosphide are light blue when viewed under the microscope. However, while the phosphide is a solid colour, the oxide is transluscent. Under normal light it is possible to see the copper underneath the centre of each globule of oxide in annealed tough pitch copper. The oxide is only visible if the specimen has been carefully polished without any etchant, it is very easy to loose it and be left with apparent porosity.

Heat treatable copper alloys show the usual variations between solution treated and precipitation hardened conditions. For some materials, such as copper-chromium, the soluble phase does not always appear to dissolve. It takes a very long time to reach equilibrium conditions and there are also small particles of insolubles such as chromium and zirconium oxide frequently present.

Oxygen-free copper should present a featureless surface when unetched but in fact very small, harmless inclusions are frequently seen.

Details of microstructures are included in the CDA Publication No 94 'Equilibrium Diagrams[19]' and CDA Publication No 64 'Copper and Copper Alloys – selected Microstructures and Equilibrium Diagrams' (now out of print). Other illustrations are included on http://www.cda.org.uk/

Mechanical Properties

Typical mechanical properties of wrought coppers and high conductivity copper alloys are shown in Tables 13 and 14. These figures can only be taken as an approximate guide since they vary with the product form and the previous mechanical and thermal history. For actual minimum values to be specified the appropriate BS EN Standards or manufacturer's brochures 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. For further details of these properties, consult CDA publication ‘TN 27 High Conductivity Coppers – Technical Data’ (http://www.cda.org.uk/) or the literature quoted in the bibliography.

Material designation			**Composition % (Range or max.)**		**Nearest Old BS Equivalent**		**Electrical properties at 20°C (unwrought)**		**Typical mechanical properties**			
Symbol	Number											
	Unwrought	Wrought	Cu (incl. 0.015 max Ag)	Max. of 19 listed elements other than Cu (2)	Unwrought (BS 6017)	Wrought	Mass Resistivity ($\Omega.g/m^2$)	Nominal Min. Conductivity (% IACS)	0.2% Proof Strength (N/mm^2)	Tensile Strength (N/mm^2)	Elongation (%)	Hardness (HV)
Copper cathode												
Cu-CATH-1	CR001A	-	Rem	0.0065 excl. O 0.040 max O	Cu-CATH-1	-	0.15176	101.0	-	-	-	-
Cu-CATH-2	CR002A	-	99.90 min.	0.03 excl. Ag, O;	Cu-CATH-2	-	0.15328	100.0	-	-	-	-
Coppers ex cu-cath-1												
Cu-ETP1	CR003A	CW003A	Rem	0.0065 excl. O 0.040 max O	Cu-ETP1	C100	0.15176	101.0	Properties similar to those for Cu-ETP			
Cu-OF1.	CR007A	CW007A	Rem	0.0065 excl. O	Cu-OF	C103	0.15176	101.0				
Cu-OFE	CR009A	CW009A	99.99 min.	15 elements listed individually	Cu-OFE	C110	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	Cu-ETP-2	C101	0.15328	100.0	50-340	200-400	50-5	40-120
Cu-FRHC	CR005A	CW005A	99.90 min.	0.04 excl. Ag & O	Cu FRHC	C102	0.15328	100.0	Properties similar to those for Cu-ETP			
Cu-OF	CR 008A	CW008A	99.95 min.	0.03 excl. Ag	Cu-OF	C103	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	Cu-FRTP	C104	-	-	50-340	200-400	50-5	40-120
Phosphorus-containing coppers												
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	-	-	-	-	50-340	200-400	50-5	40-120
Cu-DHP	CR024A	CW024A	99.90 min.	P 0.015-0.040	Cu-DHP	C106	-	-	50-340	200-400	50-5	40-120
Cu-DXP	CR025A	CW025A	99.90 min.	0.03 excl. Ag, Ni & P P0.04-0.06	-	-	-	-	Properties similar to those for Cu-DLP			

Table 13 - Unwrought and Wrought Coppers - Compositions and Properties

Material designation			Composition % (Range or max.)		Nearest Old BS Equivalent		Electrical properties at 20°C (unwrought)		Typical mechanical properties			
Symbol	Number											
	Unwrought	Wrought	Cu (incl. 0.015 max Ag)	Max. of 19 listed elements other than Cu (2)	Unwrought (BS 6017)	Wrought	Mass Resistivity ($\Omega.g/m^2$)	Nominal Min. Conductivity (% IACS)	0.2% Proof Strength (N/mm^2)	Tensile Strength (N/mm^2)	Elongation (%)	Hardness (HV)
Silver – bearing coppers Tough pitch												
CuAg0.04	CR011A	CW011A	Rem.	0.03 excl.Ag & O Ag 0.03-0.05, 0.040 max	Cu-Ag-2	C101	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, 0.0404 max.	Cu-Ag-3	C101	0.15328	100.0				
CuAg0.10	CR013A	CW013A	Rem.	0.03 excl. Ag & O Ag 0.08-0.012, 0.040 max.	Cu-Ag-4	C101	0.15328	100.0				
Phosphorus deoxidised												
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	CW0015A	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 P0.001-0.007	-	-	0.15596	98.3				
Oxygen Free												
CuAg0.04(OF)	CR017A		Rem	0.0065 excl. Ag & O Ag 0.03-0.05	Cu-Ag-OF2	C103	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	Cu-Ag-OF4	C103	0.15328	100.0				

Table 13 - Unwrought and Wrought Coppers - Compositions and Properties (continued)

(1) Unwrought coppers in BS EN 1976 - Cast Unwrought Copper Products and BS EN 1978 - Copper Cathodes

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

Material Designation		Nearest old BS equivalent	Composition, % Range								Approx condutivity % IACS	Typical mechanical properties (see section 6)			
Symbol	Number		Cu	Be	Cr	Ni	P	Si	Zn	Others		0.2% Proof S (N/mm^2)	Tensile Strength (N/mm^2)	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	75	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				100-620	300-700	30-3	80-220
CuNi2Si	CW111C	-	Rem			1.6-2.5		0.4-0.8			40	100-620	300-700	30-3	80-220
CuNi3Si1	CW112C	-	Rem			2.6-4.5		0.8-1.3				120-550	320-600	30-5	80-190
CuZr	CW120C	-	Rem							Zr 1-0.2	85-90	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

Table 14 - Wrought Low Alloyed Copper Alloys - Composition and Typical Properties

	Value	Units
Atomic number	29	
Atomic weight	63.54	
Lattice structure:	face centred cubic	
Density:		
IEC standard value (1913) Typical value at 20^{o}C at 1083^{o}C (solid) at 1083^{o}C liquid)	8.89 8.92 8.32 7.99	g/cm^3 g/cm^3 g/cm^3 g/cm^3
Melting point	1083	^{o}C
Boiling point	2595	^{o}C
Linear coefficient of thermal expansion at:		
-253^{o}C -183 ^{o}C -191 ^{o}C to 16 ^{o}C 25 ^{o}C to 100 ^{o}C 20 ^{o}C to 200 ^{o}C 20 ^{o}C to 300 ^{o}C	0.3 x 10^{-6} 9.5 x 10^{-6} 14.1 x 10^{-6} 16.8 x 10^{-6} 17.3 x 10^{-6} 17.7 x 10^{-6}	/^{o}C /^{o}C /^{o}C /^{o}C /^{o}C /^{o}C
Specific heat (thermal capacity) at:		
-253^{o}C -150 ^{o}C -50 ^{o}C 20 ^{o}C 100 ^{o}C 200 ^{o}C	0.013 0.282 0.361 0.386 0.393 0.403	J/g^{o}C J/g^{o}C J/g^{o}C J/g^{o}C J/g^{o}C J/g^{o}C
Thermal conductivity at:		
-253^{o}C -200 ^{o}C -183 ^{o}C -100 ^{o}C 20 ^{o}C 100 ^{o}C 200 ^{o}C 300 ^{o}C	12.98 5.74 4.73 4.35 3.94 3.85 3.81 3.77	Wcm/cm^{2o}C Wcm/cm^{2o}C Wcm/cm^{2o}C Wcm/cm^{2o}C Wcm/cm^{2o}C Wcm/cm^{2o}C Wcm/cm^{2o}C Wcm/cm^{2o}C
Electrical conductivity (volume) at:		
20^{o}C (annealed) 20^{o}C (annealed) 20^{o}C (fully cold worked) 20^{o}C (fully cold worked)	58.0-58.9 100.0-101.5 56.3 97.0	MS/m (m/Ωmm^2) % IACS MS/m (m/Ωmm$^{2)}$ % IACS
Electrical resistivity (volume) at:		
20^{o}C (annealed) 20^{o}C (annealed) 20^{o}C (fully cold worked) 20^{o}C (fully cold worked)	0.017241-0.0170 1.724-1.70 0.0178 1.78	
Electrical resistivity (mass) at 20^{o}C (annealed)		
Mandatory maximum	0.15328	μΩg/m^2
Temperature coefficient of electrical resistance (a) at 20^{o}C:		
Annealed copper of 100% IACS (applicable from – 100^{o}C to 200 ^{o}C Fully cold worked copper of 97% IACS (applicable from - 0 ^{o}C to 100 ^{o}C	0.00393 0.00381	/ ^{o}C / ^{o}C

Table 15 - Physical Properties of Copper

	Value	Units
Modulus of elasticity (tension) at 20 °C:		
Annealed Cold worked	118,000 118,000-132,000	N/mm^2 N/mm^2
Modulus of rigidity (torsion) at 20°C:		
Annealed Cold worked	44,000 44,000-49,000	N/mm^2 N/mm^2
Latent heat of fusion	205	J/g
Electro chemical equivalent for:		
Cu Cu	0.329 0.659	mg/C mg/C
Normal electrode potential (hydrogen electrode) for:		
Cu Cu	-0.344 -0.470	V V

Table 16 - Physical Properties of Copper

(Note: The values shown are typical for electrolytic tough pitch high conductivity copper (Cu-ETP). Values for other grades may differ from those quoted, see 'High Conductivity Coppers - Technical Data'.)

Oxidation and Corrosion

Copper forms two oxides, both of which are conductors. Cuprous oxide (Cu_20) is red in colour and first to form on the surface of polished copper exposed to the atmosphere. At room temperature this will slowly darken to a thicker black layer containing cupric oxide (CuO). The darkening will be faster in the presence of sulphur compounds due to the formation of black copper sulphide. Once formed the black oxide film is tightly adherent; further growth is very slow provided that the temperature does not exceed 200°C and that other deleterious chemicals are not present.

In outdoor conditions the exposed surfaces of copper are subject to rainwater containing dissolved carbon dioxide and oxides of sulphur. These form a weak acid solution and help to form the well known attractive green "patina' which is also adherent and protective.

The Oxidation Laws

Figure 8 gives examples of the usual rates 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 and 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.

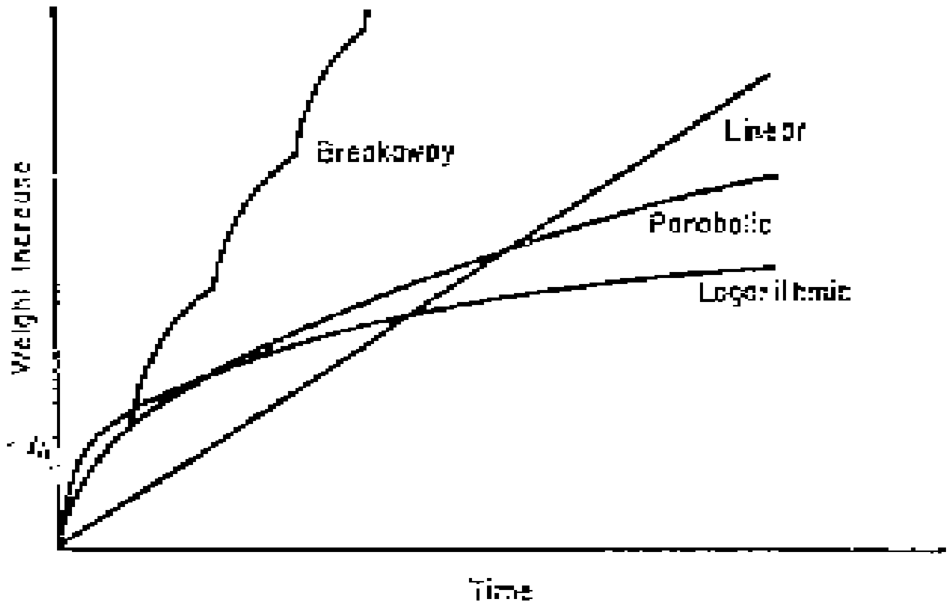

Figure 8 - The Oxidation rate laws ((Trans IMF, 1997, 75 (2))

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 anneal.

Figure 9 shows the effect of temperature on the oxidation of copper

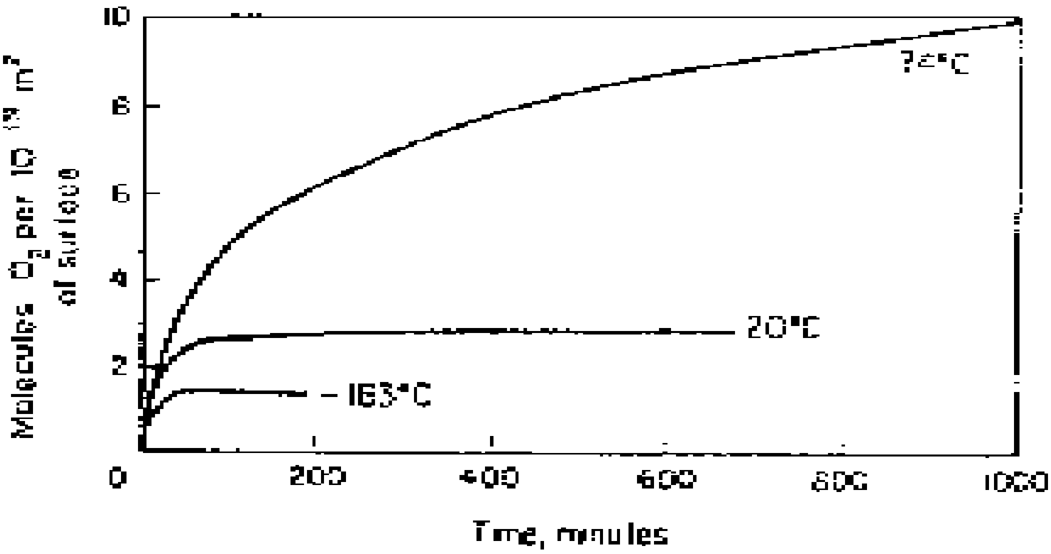

Figure 9 - The effect of temperature on the oxidation of copper ((Trans IMF, 1997, 75 (2))

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.

Galvanic Corrosion

Figure 10 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 10 that brasses are more noble than other commonly used engineering materials. The listing represents the galvanic behaviour of metals in seawater. 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 not formed. This explains the occasionally anomalous behaviour of stainless steels. Similar considerations apply in other media such as acids which may be oxidising or reducing in nature. (Ref: 'Guide to Engineered Materials', ASM, Ohio, 1986)

Corrosion susceptibility of metals

Most susceptible to corrosive attack (less noble) ↑

- Magnesium and its alloys
- Zinc and its alloys
- Aluminium and its alloys
- Cadmium
- Mild Steel
- Cast Iron
- Stainless steel, 135Cr, type 410 (active)
- Lead-tin solder, 50/50
- Stainless steel, 18/18 type 304 (active)
- Stainless steel, 18/18/3 Mo, type 316 (active)
- Lead
- Tin
- Brasses
- Gunmetals
- 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

Least susceptible to corrosive attack (more Noble) ↓

Figure 10 - Corrosion susceptibility of metals

Copper and Health

Human Health

Copper is one of a relatively small group of metallic elements which are essential to human health; an adult's body contains about a tenth of one gram. Copper combines with certain proteins to produce enzymes that act as catalysts to help a number of body functions. Research has suggested that copper deficiency is a factor leading to an increased risk of developing heart disease. Other research indicates that less than half the population of industrialised countries receive the amount of copper thought to be sufficient. Other indications are that copper is significant in medical anti-inflammatory preparations and treatments for convulsions and epilepsy. The efficacy of copper bangles to ward off the effects of arthritis is a well-known belief.

Hygiene

Copper is well known as a biocide. Advantage of this property is more often taken by inclusion of copper in alloys such as brasses and bronzes than by its use as a pure metal. Thus, door furniture such as knobs and finger-plates made in clean brass have been shown to be less likely to encourage the growth of the organisms causing nosocomal infections than similar items in other materials.

Health and Safety

In general, copper and copper alloys do not present unusual risks to health and safety. As with most materials, fume generated during casting and welding can have toxic properties but normal protective precautions are perfectly adequate. Components made from alloys containing beryllium can normally be fabricated and used with complete safety; however, if fumes or dust may be created it is vital that attention is paid to the comprehensive guidance available from manufacturers of copper-beryllium alloys.

Recycling of Copper

For thousands of years, copper and copper alloys have been recycled; indeed, the entire viability of the industry is dependent on the economic recycling of scrap arising from manufacturing process and surplus or redundant products. Only guaranteed uncontaminated process scrap or scrap that has been electrolytically refined may be used for production of grades of copper destined for electrical or enamelling purposes. Secondary grades of scrap are used for the types of copper appropriate for the manufacture of plumbing tube, roofing sheet and heat exchangers.

Contaminated copper scrap, for example after having been tinned, soldered or plated, finds a ready and economic home as feedstock for the alloy casting and wrought copper alloy industries.

More discussion of the subject can be found in CDA Publication 101 "Recycling of Copper." [20] and, together with comments on sustainability of supplies, in Book 121 'Copper - The Vital Metal'

Conductivity and Resistivity

The mandatory electrical property for high conductivity copper is now mass resistivity for which the unit Wg/m2 is used. This property is chosen because it can be the most accurately measured. It is shown in BS 5714 that the error in measurement of mass of small sections such as wire or strip is likely to be less than that for volume. The use of volume measurements quoted in IEC publication No. 28. (1913) assumes a standard density for copper in the wrought form used for the test of 8.89 grams per cubic centimetre (g/cm3 or gcm-3). This was valid when originally published in 1913 when oxygen contents were typically 0.06% but with modern coppers now containing only around 0.02% oxygen the density is nearer 8.91 g/cm3. For oxygen-free coppers 8.94 g/cm3 is more realistic.

Conductivity values are shown in Tables 13 and 14 in "per cent IACS (International Annealed Copper Standard)", this being the traditional way of comparing the conductivity of other metals and copper alloys with high conductivity copper. With the improvements in purity previously mentioned, most commercial high conductivity copper has a conductivity around 101.5% IACS in the annealed state. Work hardened material will have a lower value due to internal strain effects. Cast material also has a lower value due to grain boundary and porosity effects.

Volume resistivity

The resistivity of a conductor of a particular cross sectional area and length can be found from the equation

$$R = \rho \frac{l}{A}$$

where:

R = resistance in Ω

l = length in m

A = cross sectional area in m^2

ρ = specific resistivity in Ωm

The specific resistivity can be obtained from the mass resistivity by using

$$specific\,resistivity = \frac{mass\,resistivity}{density}$$

The specific resistivity is an inconvenient measurement with which to work because the cross sectional area of a conductor is normally measured in square millimetres rather than in square metres, so it is normal practice to quote the volume resistivity which has units $\Omega mm^2 m^{-1}$.

Effect of temperature on resistivity

The resistivity of copper increases with temperature according to the formula

$$\rho_{T2} = \rho_{T1}(1 + \beta_{t1t2}(T_2 - T_1))$$

where

T_1 and T_2 are the initial and final temperatures in °C

ρ_{T1} is the resistivity at temperature T_1

ρ_{T2} is the resistivity at temperature T_2

β_{t1t2} is the temperature coefficient of resistivity for the range of temperatures T_1 to T_2.

The value of ß itself changes with temperature, but for small temperature ranges its value at T1 may be taken to be constant from T1 to T2. The value of b for any temperature T above -200°C may be found from:

$$\beta_T = \frac{1}{233.54 + T}$$

Hence at 0°C

$$\beta_0 = \frac{1}{233.54 + 0} = 0.004282\, per\, {}^0C$$

and at 20°C, the reference temperature adopted by the IEC, the temperature coefficient of resistivity is:

$$\beta_{20} = \frac{1}{233.54 + 20} = 0.003947\, per\, {}^0C$$

Effect of temperature on resistance

Since the resistivity of the metal increases with temperature the resistance of a metallic conductor must increase with increasing temperature. The volume of the conductor also increases, and combining these two factors leads to the following formula for the change in resistance with temperature.

$$\rho_{T2} = \rho_{T1}(1 + \alpha_{t1t2}(T_2 - T_1))$$

where

T_1 and T_2 are the initial and final temperatures in °C

ρ_{T1} is the resistance at temperature T_1

ρ_{T2} is the resistance at temperature T_2

$\alpha_{t1\,t2}$ is the temperature coefficient of resistance for the range of temperatures T_1 to T_2.

The value of α changes with temperature, in a manner analogous to that described above for the temperature coefficient of resistivity, β.

The appropriate formula is:

$$\alpha = \frac{1}{234.45 + T}$$

Hence at 0°C

$$\alpha_0 = 0.004265 \, per \, °C$$

And at 20°C

$$\alpha_{20} = \frac{1}{234.45 + 20} = 0.00393 \, per \, °C$$

Effect of cold work on resistivity

The effect of retained stresses on resistivity is noticeable but not too great. Hard temper high conductivity coppers show a 3% increase in resistivity compared with annealed copper.

Thermal conductivity

The effects of all variables on electrical conductivity may usually be assumed to have similar effects on thermal conductivity properties.

Useful References

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(For the current list of CDA publications please visit www.cda.org.uk)

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16. See reference 8.

17. ‘High-Conductivity Coppers - Technical Data’, (Reprint of CIDEC Data Sheets) 1981, 200pp.

18. ‘Copper-Beryllium Health and Safety Notes’, CDA Publication No 104, 1994, 3pp.

19. ‘Equilibrium Diagrams – (see 15)

20. ‘Recycling of Copper’, CDA Publication No 101, 1994, 4pp.

Videos

AV7 "Copper - The Vital Metal" Describes briefly the essential role of copper in

industry and the home, including usage in electrical cables, motors, transformers and busbars. Running time -10 min.

AV8 "The Copper Connection" The electrical applications of coppers and copper alloy are highlighted with particular reference to energy efficiency. The extensive usage of coppers in all types of generation, transmission and operating equipment is discussed. Running time - 20 min.

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