# 1.0 Introduction

David Chapman

### 1.1. About this Guide

Busbars are used within electrical installations for distributing power from a supply point to a number of output circuits. They may be used in a variety of configurations ranging from vertical risers, carrying current to each floor of a multi-storey building, to bars used entirely within a distribution panel or within an industrial process.

The issues that need to be addressed in the design of busbar systems are:

- Temperature rise due to energy losses
- Energy efficiency and lifetime cost
- Short-circuit current stresses and protection
- Jointing methods and performance
- Maintenance.

This book provides the information needed to design efficient, economic and reliable busbar systems.

In any electrical circuit some electrical energy is lost as heat which, if not kept within safe limits, may impair the long term performance or the safety of the system. For busbar systems, the maximum working current is determined primarily by the maximum tolerable working temperature, which is, in turn, determined by considerations such as safety, the retention of mechanical properties of the conductor, compatibility with mounting structures and cable connections. '2.0 Current-Carrying Capacity of Busbars' discusses how to estimate the working current and temperature.

A higher working temperature means that energy is being wasted. Designing for lower energy loss requires the use of more conductor material but results in more reliable operation due to the lower working temperature and, because the cost of lifetime energy losses is far greater than the cost of first installation, lower lifetime costs. The process of assessing the life cycle cost of a busbar system is described in '3.0 Life Cycle Costing'.

Because of the large currents involved, short circuit protection of busbar systems needs careful consideration. The important issues are the temperature rise of the busbar during the event and the magnitude of the forces generated by the high current, which may cause deformation of the bars and the failure of mountings. The design of the mounting system is an important factor and one that is becoming more important with the increase in harmonic currents, which can trigger mechanical resonances in the busbar. '4.0 Short-Circuit Effects' discusses these issues.

It is usually necessary to joint busbars on site during installation and this is most easily accomplished by bolting bars together or by welding. For long and reliable service, joints need to be carefully made with controlled torque applied to correctly sized bolts. A properly designed and implemented joint can have a resistance lower than that of the same length of plain bar. The design of efficient joints is discussed in '6.0 Jointing'.

The remainder of this Introduction presents reference material giving mechanical and electrical properties of copper that are required for design purposes.

### 1.2 Materials for Busbars

#### 1.2.1 Material Requirements

To achieve a long and reliable service life at the lowest lifetime cost, the conductor material needs the following properties:

- Low electrical and thermal resistance
- High mechanical strength in tension, compression and shear
- High resistance to fatigue failure
- Low electrical resistance of surface films
- Ease of fabrication
- High resistance to corrosion
- Competitive first cost and high eventual recovery value.

This combination of properties is best met by copper. Aluminium is the main alternative material, but a comparison of the properties of the two metals shows that, in nearly all respects, copper is the superior busbar material.

### 1.2.2 Material Choice

Busbars are generally made from either copper or aluminium. For a complete list of mechanical properties and compositions of copper used for busbars, see BS EN 13601: 2013 Copper rod, bar and wire for electrical purposes. Table 1 below gives a comparison of some electrical and mechanical properties. It can be seen that for conductivity and strength, high conductivity (HC) copper is far superior to aluminium. The only disadvantage of copper is its higher density, which results in higher weight. The greater hardness of copper compared with aluminium gives it better resistance to mechanical damage, both during erection and in service. Copper bars are also less likely to develop problems in clamped joints due to cold metal flow under the prolonged application of a high contact pressure. The higher modulus of elasticity of copper gives it greater beam stiffness compared with an aluminium conductor of the same dimensions. The temperature variations encountered under service conditions require a certain amount of flexibility to be allowed for in the design. The lower coefficient of linear expansion of copper reduces the degree of flexibility required.

**Table 1 – Properties of Typical Grades of Copper and Aluminium**

| Property (at 20°C) | Copper (C101) | Aluminium (1350) | Units |
|---|---|---|---|
| Electrical conductivity (annealed) | 101 | 61 | % IACS |
| Electrical resistance (annealed) | 17.2 | 28.3 | nΩ mm |
| Temperature coefficient of resistivity | 0.0039 | 0.004 | per °K |
| Thermal conductivity | 397 | 230 | W/m°K |
| Specific heat | 385 | 900 | J/kg °K |
| Coefficient of expansion | $17 \times 10^{-6}$ | $23 \times 10^{-6}$ | per °K |
| 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 | kN/mm$^2$ |
| Density | 8910 | 2700 | kg/m$^3$ |
| Melting point | 1083 | 660 | °C |

#### 1.2.2.1 High Conductivity

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

**Table 2 – Properties of 100% IACS Copper**

| | |
|---|---|
| Volume conductivity, $\sigma_v$ | 58 MS/m |
| Density, $d$ | 8890 kg/m$^3$ |
| Temperature coefficient of resistance, $\alpha$ | 0.00393/°C |

It follows from the first two of these values that:

**Table 3 – Implied Properties of 100% IACS Copper**

| | |
|---|---|
| Volume resistivity, $\rho_v$ ( = $1/\sigma_v$ ) | 1.7241 mΩcm |
| Mass conductivity, $\sigma_m$ ( = $\sigma_v / d$ ) | 6524 Sm²/kg |
| Mass resistivity, $\rho_m$ ( = $1/\sigma_m$) | 153.28 μΩkg/m² |

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

Aluminium has a lower conductivity than copper (61% IACS), so an equivalent resistance conductor would have a cross-sectional area which is a factor of 1.6 times greater than one made from copper.  Taking into account the difference in density, the aluminium conductor would have half the weight of copper.  Copper will therefore allow a more compact installation and, in many systems, space considerations are of greater importance than weight.  Greater weight may make installation slightly more difficult but, since the electromagnetic stresses set up in the bar are usually more severe than the stress due to its weight, the mounting design is largely unaffected.

Although busbar systems should normally be designed for lowest lifetime cost – which means a lower working temperature to reduce waste energy costs – the ability of copper to maintain its mechanical properties at higher temperatures provides extra capacity and safety during short circuit conditions.  Copper also allows the use of higher peak operating temperatures in special circumstances.

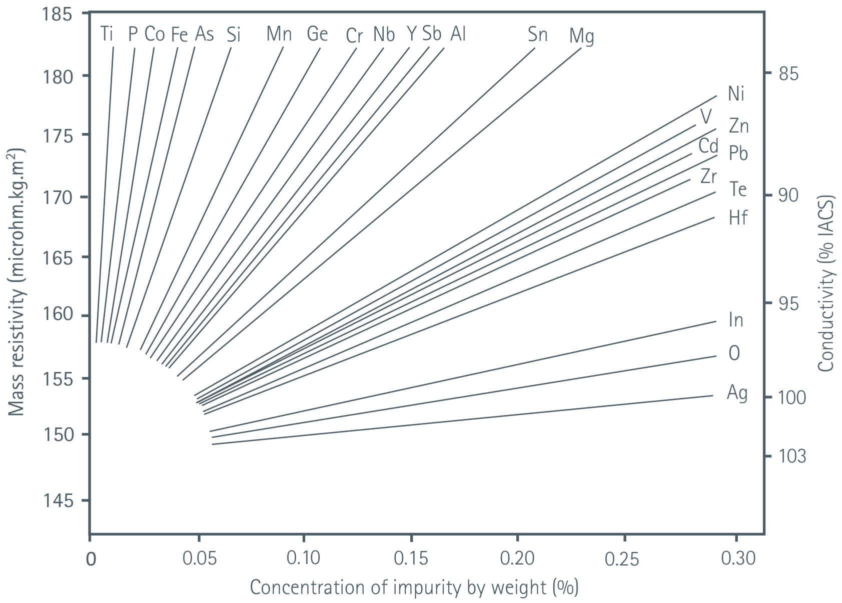

**Figure 1 – Effect of small concentrations of impurities on the resistivity of copper**

The degree to which the electrical conductivity is affected by an impurity depends largely on the element present, as illustrated in Figure 1.  For example, the presence of only 0.04% phosphorus reduces the conductivity of HC copper to around 80% IACS.  Normally, the purest copper is used for bulk conductors.  In particular, oxygen-free copper is usually specified, not only for its high conductivity but also because it can be welded without the risk of hydrogen embrittlement.

When enhanced mechanical properties - such as increased strength or wear resistance - are required, a silver-bearing (up to 0.12%) copper can be used at the expense of a small increase in resistivity.  Many other electrical alloys are available, but they are intended for special purposes, such as contacts or terminals, and are not used as bulk conductors.

### 1.2.2.1.1 Effect of Temperature on Conductivity

Conductivity varies with temperature so it is important that the correct value is used for the actual working temperature. The resistance of a copper conductor at temperatures up to 200°C can be calculated from:

$$R = R_{20}(1+\alpha_{20}\Delta T)$$

where:

$R_{20}$ is the conductor resistance at a temperature of 20°C, in $\Omega$

$\alpha_{20}$ is the temperature coefficient of resistance at 20°C, per K. $\alpha = 0.0039$ for copper

$\Delta T = T_k - 20$ is the temperature difference, in degrees K

$T_k$ is the final temperature, in K.

Note that $\alpha$ is temperature dependent; the value given will yield sufficiently accurate results up to 200°C. An alternative equation, which gives sufficiently accurate results for engineering purposes over a wide temperature range, is:

$$R = R_{20}\left(\frac{T}{T_{20}}\right)^{1.16} = R_{20}\left(\frac{T}{293}\right)^{1.16}$$

where:

$R$ is the resistance at temperature $T$

$R_{20}$ is the resistance at 20°C (293°K)

$T$ is the temperature in °K, i.e. temperature in °C + 273.

### 1.2.2.1.2 Effect of Cold Work on Conductivity

The conductivity of copper is decreased by cold working and may be 2 to 3% less in the hard drawn condition than when annealed. Thus standards for hard drawn HC copper products should stipulate a minimum conductivity requirement of 97% IACS compared with 100% IACS for annealed products.

An approximate relationship between tensile strength of cold worked copper and its increase in electrical resistivity is:

$$P = F/160$$

where:

$P$ is % increase in electrical resistivity of cold worked copper over its resistivity when annealed

$F$ is tensile strength, N/mm².

### 1.2.2.2 Mechanical Strength

The mechanical strength of the busbar material is important to ensure that the material is not deformed during transport and assembly, does not sag over an extended working life at maximum temperature, does not creep under pressure leading to loosened joints and does not permanently distort under short circuit loads.

The mechanical properties are influenced by the production processes employed. Most busbar materials will have been extruded and drawn resulting, typically, in a 'half-hard' material. The effect on the mechanical properties of cold work by rolling (to reduce the thickness) is shown in Figure 2. Cold working of the material has the effect of raising the tensile strength, proof strength and hardness, but reducing its elongation.

### 1.2.2.2.1 Tensile Strength

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

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

For the usual sizes of busbar conductors in the hard-condition, tensile strengths from 250 N/mm² up to 340 N/mm² can be obtained depending on the cross-sectional area.

### 1.2.2.2.2 Proof Strength

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

As with the tensile strength, the proof strength varies with the amount of cold work put into the material (see Figure 2).

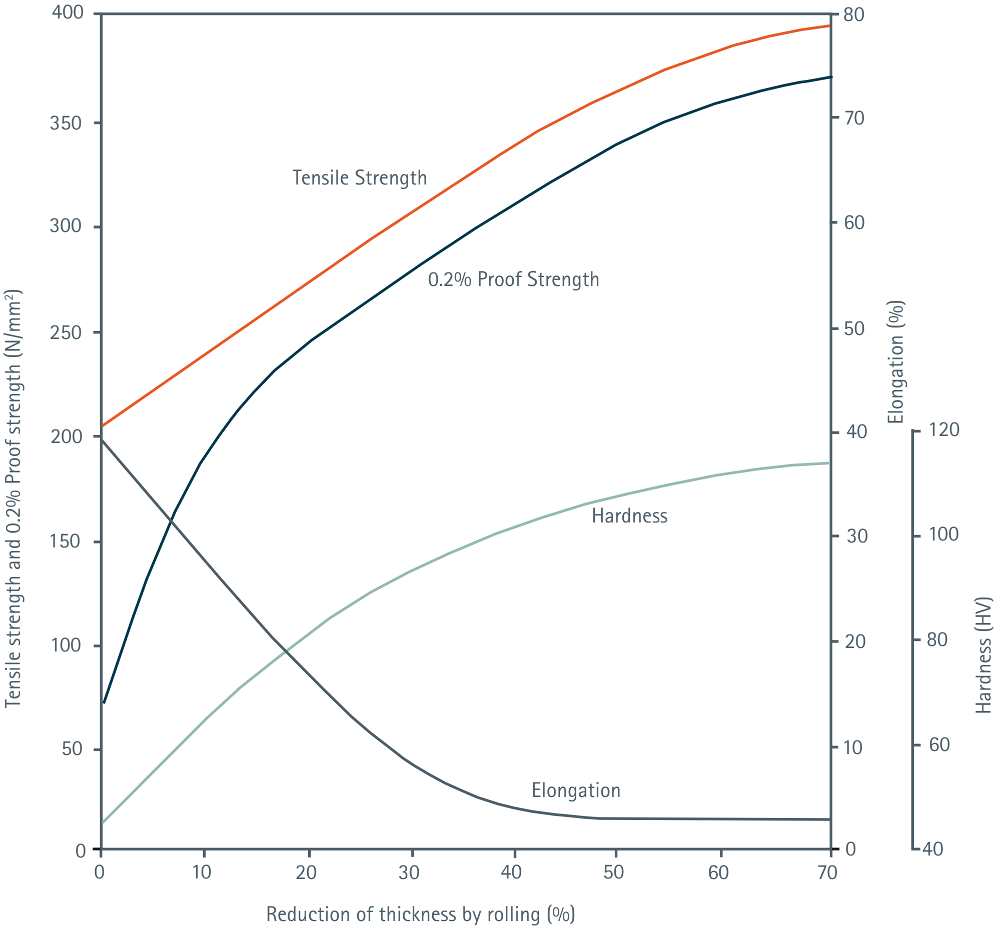

**Figure 2 – Effect of cold rolling on mechanical properties and hardness of high conductivity copper strips**

#### 1.2.2.2.3 Hardness

Standards applicable to busbar conductors do not specify hardness measurement as part of the testing requirements. It can however be more quickly and easily carried out than a tensile test and is therefore convenient as a guide to the strength of a conductor. The results have to be used with discretion for two reasons:

- Unlike ferrous materials, the relationship between hardness and tensile strength is not constant (see Figure 2).
- A hardness test is usually only a measurement of the outer skin of the material tested. If the conductor is of large cross-sectional area and has received a minimum amount of cold work, the skin will be harder than the underlying metal. Consequently, variations in hardness may be obtained dependent on where the measurement is made in relation to its cross-section.

As a guide, typical hardness figures of the temper range of conductors supplied are:

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

#### 1.2.2.2.4 Resistance to Softening

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

In the case of HC copper, this softening occurs at temperatures above 150°C. It has been established experimentally that such copper would operate successfully at a temperature of 105°C for periods of 20-25 years, and that it could withstand short-circuit conditions as high as 250°C for a few seconds without any adverse effect.

If hard drawn conductors are required to retain strength under operating conditions higher than normal, the addition of small amounts of silver at the melting and casting stage produces alloys with improved resistance to softening. The addition of 0.06% silver raises the softening temperature by approximately 100°C without any significant effect on its conductivity, at the same time appreciably increasing its creep resistance.

#### 1.2.2.2.5 Creep Resistance

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

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

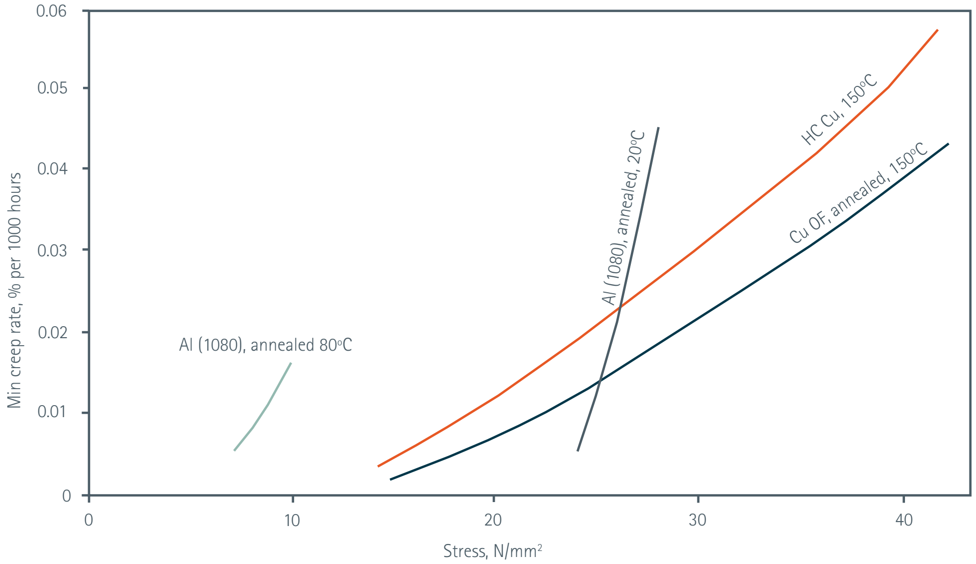

Figure 3 – Typical creep properties of commercially pure copper and aluminium

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

| Material | Testing Temp (°C) | Min Creep Rate (% per 1000h) | Stress (N/mm²) |
|---|---|---|---|
| Al (1080) annealed | 20 | 0.022 | 26 * |
| HC Cu annealed | 150 | 0.022 | 26 * |
| Cu-0.086% Ag 50% c.w. | 130 | 0.004 | 138 |
| Cu-0.086% Ag 50% c.w. | 225 | 0.029 | 96.5 |
| | | | * Interpolated from Figure 3 |

The creep resistance of oxygen-free HC copper is better than that of tough pitch HC copper. This is due to the very small amounts of impurities which remain in solid solution in oxygen-free copper, but which are absorbed in the oxide particles in tough pitch copper. Some typical observations are shown in Figure 3. Tough pitch copper creeps relatively rapidly under low stress at 220°C. The addition of silver to both oxygen-free and tough pitch coppers results in a significant increase in creep resistance.

### 1.2.2.2.6 Fatigue Resistance

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

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

| Material | | Fatigue Strength (N/mm²) | No of Cycles x $10^6$ |
|---|---|---|---|
| HC Aluminium | annealed | 20 | 50 |
| | half-hard (H8) | 45 | 50 |
| HC Copper | annealed | 62 | 300 |
| | half-hard | 115 | 300 |

Conditions for such failures can be set up in a busbar system rigidly clamped for support and then subjected to vibrating conditions. Where higher stresses or working temperatures are to be allowed for, copper containing small amounts of silver (about 0.1%) is used. The creep resistance and softening resistance of copper-silver alloys increase with increasing silver content.

In the conditions in which high conductivity aluminium and copper are used, either annealed (or as-welded) or half-hard, the fatigue strength of copper is approximately double that of aluminium. This gives a useful reserve of strength against failure initiated by mechanical or thermal cycling.

#### 1.2.2.2.7 Bending and Forming

The high conductivity coppers are ductile and, in the correct temper, will withstand severe bending and forming operations. As a general guide to bending, copper in the half-hard or hard temper will bend satisfactorily round formers of the following radii:

**Table 6 – Minimum Bend Radius of High Conductivity Copper**

| Thickness (t) | Minimum Bend Radius |
|---|---|
| Up to 10 mm | 1 t |
| 11-25 mm | 1.5 t |
| 26-50 mm | 2 t |

Material of thicknesses greater than 50 mm is not normally bent; however, it is possible to do so by localised annealing prior to bending.

### 1.2.2.3 Connectivity

The surface of copper naturally oxidises, forming a thin hard layer on the surface which normally prevents further oxidation. This oxide film is conductive (under busbar conditions where it is sandwiched between two copper electrodes) so it does not affect the quality of bolted or clamped joints. On the other hand, exposed aluminium surfaces rapidly form a hard insulating film of aluminium oxide, which makes jointing very difficult and can lead to long term reliability problems. Terminals, switch contacts and similar parts are nearly always produced from copper or a copper alloy. The use of copper for the busbars to which these parts are connected therefore avoids contacts between dissimilar metals and the inherent jointing and corrosion problems associated with them.

### 1.2.2.4 Maintenance

The higher melting point and thermal conductivity of copper reduce the possibility of damage resulting from hot spots or accidental flashovers in service. If arcing occurs, copper busbars are less likely to support the arc than aluminium. Table 7 shows that copper can self-extinguish arcs across smaller separations, and at higher busbar currents. This self-extinguishing behaviour is related to the much larger heat input required to vaporise copper than aluminium.

**Table 7 - Self-extinguishing Arcs in Copper and Aluminium Busbars**

| | Copper | Aluminium |
|---|---|---|
| Minimum busbar spacing, mm | 50 | 100 |
| Maximum current per busbar, A | 4500 | 3220 |

Copper liberates considerably less heat during oxidation than aluminium and is therefore much less likely to sustain combustion in the case of accidental ignition by an arc. The large amounts of heat liberated by the oxidation of aluminium in this event are sufficient to vaporise more metal than was originally oxidised. This vaporised aluminium can itself rapidly oxidise, thus sustaining the reaction. The excess heat generated in this way heats nearby materials, including the busbar itself, the air and any supporting fixtures. As the busbar and air temperatures rise, the rates of the vaporisation and oxidation increase, so accelerating the whole process. As the air temperature is increased, the air expands and propels hot oxide particles. The busbar may reach its melting point, further increasing the rate of oxidation and providing hot liquid to be propelled, while other materials, such as wood panels, may be raised to their ignition temperatures. These dangers are avoided by the use of copper busbars.

Finally, copper is an economical conductor material. It gives long and reliable service at minimum maintenance costs and, when an installation is eventually replaced, the copper will have a high recovery value. Because of its many advantages, copper is still used worldwide as an electrical conductor material despite attempts at substitution.

### 1.2.3 Types of High Conductivity Copper Available

#### 1.2.3.1 Tough Pitch Copper, CW004A and CW005A (C101 and C102)

Coppers of this type, produced by fire-refining or remelting of electrolytic cathode, contain a small, deliberate addition of oxygen which scavenges impurities from the metal. The oxygen is present in the form of fine, well-distributed cuprous oxide particles only visible by microscopic examination of a polished section of the metal. Typical oxygen contents of these coppers fall in the range 0.02-0.05%. Between these limits the presence of the oxygen in this form has only a slight effect on the mechanical and electrical properties of the copper. It can, however, give rise to porosity and intergranular cracks or fissures if the copper is heated in a reducing atmosphere, as can happen during welding or brazing. This is a result of the reaction of the cuprous oxide particles with hydrogen and is known as 'hydrogen embrittlement'. Provided a reducing atmosphere is avoided, good welds and brazes can be readily achieved.

#### 1.2.3.2 Oxygen-free High Conductivity Copper, CW008A (C103)

In view of the above remarks, if welding and brazing operations under reducing conditions are unavoidable, it is necessary to use a different (and more expensive) grade of high conductivity copper which is specially produced for this purpose. This type of copper, known as 'oxygen-free high conductivity copper', is normally produced by melting and casting under a protective atmosphere. To obtain the high conductivity required it is necessary to select the best raw materials. The result is a high purity product containing 99.95% copper. This enables a conductivity of 100% IACS to be specified even in the absence of the scavenging oxygen.

### 1.2.4 Available Forms

HC copper conductors are obtainable in bar, strip, rod or tube form. For busbar applications, the most common forms supplied are bar, rod or tube and these are normally supplied in the hard condition. In this condition they offer greater stiffness, strength and hardness and have a better surface finish. Because of the practical difficulty of straightening uncoiled hard material, it is normally supplied in straight lengths, coiled material being limited to the smaller sizes.

The maximum length of material available with the advent of continuous casting methods is dependent on the capability of the supplier's plant.