Introduction

Aluminium for Busbars

There are only two materials suitable as conductors of electricity. These are aluminium and copper. The materials are quite different, and both have advantages and disadvantages. It is inevitable that users of copper will compare the material that they are familiar with to aluminium. For this reason, where applicable, comparisons are provided.

High voltage transmission lines are almost exclusively aluminium for reasons of weight and cost. Bus ducts are normally available in copper or aluminium. However, the choice for busbars in switchboards and motor control centres is largely dependent on location rather than the merits of the material. Some countries use aluminium (unless otherwise specified), where others normally use copper.

The main considerations for both materials are:
- Mechanical Properties
- Electrical Properties
- Reliability
- Cost
- Availability

The primary concern in the use of aluminium busbars is the jointing between aluminium, and to dissimilar metals such as plain and plated copper. This is addressed by the application of a patented plating process. (Described on page 9) It is this process that allows aluminium to be considered as a viable alternative where copper is predominant.

Reliability

Aluminium conductors have been used successfully for electrical purposes for more than 100 years.

The first aluminium busbars in the U.S.A. were made by ALCOA in 1895. these were rated at 20,000A and installed at ALCOA’s Niagara works.¹

In 1962, the Indian Government banned the use of copper for power cables, followed by busbars for the simple reason that India had very little copper deposits, but bauxite (from which aluminium is derived) was plentiful. As a result, India has had around 40 years of experience in the use of aluminium busbars.²

Finland is another example of a country using only aluminium for busbars.

Internationally recognised companies manufacturing switchboards with type-tested aluminium busbars include SCHNEIDER, LARSON AND TOUBRO, and ELSTEEL.

Provided that the busbars are sized according to thermal rating, arranged and supported according to short-circuit rating and properly connected, copper and aluminium are equally reliable. Faulty connections are the leading cause of electrical failures, regardless of the conductor material.

Properties

Aluminium and Copper Specifications

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Aluminium</th>
<th>Copper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relevant Standards</td>
<td>IEC 60105 ISO 209-1,2</td>
<td>IEC 60028</td>
</tr>
<tr>
<td>Grade</td>
<td>6101</td>
<td>100% IACS</td>
</tr>
<tr>
<td>Physical Properties</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemical Composition</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific Heat gcal/ºC</td>
<td>0.092</td>
<td>99% pure</td>
</tr>
<tr>
<td>Density g/cm²</td>
<td>2.91</td>
<td>8.89</td>
</tr>
<tr>
<td>Melting Point ºC</td>
<td>660</td>
<td>1083</td>
</tr>
<tr>
<td>Mechanical Properties</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultimate Tensile Strength kgf/mm²</td>
<td>20.5/25</td>
<td>22-26</td>
</tr>
<tr>
<td>Ultimate Shearing Strength kgf/mm²</td>
<td>15</td>
<td>16-19</td>
</tr>
<tr>
<td>Elastic Modulus kgf/mm²</td>
<td>6,700</td>
<td>12,000</td>
</tr>
<tr>
<td>0.2% Tensile-proof Strength kgf/mm²</td>
<td>16.5/22</td>
<td>60-80% of tensile strength</td>
</tr>
<tr>
<td>Electrical Properties</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific Resistance µΩcm</td>
<td>3.133</td>
<td>1.7241</td>
</tr>
<tr>
<td>Volume Conductivity µΩmm²</td>
<td>31.9</td>
<td>58</td>
</tr>
<tr>
<td>Conductivity % IACS</td>
<td>57</td>
<td>100</td>
</tr>
<tr>
<td>Co-efficient of expansion mm/m²/ºC</td>
<td>2.3 x 10⁻⁵</td>
<td>1.73 x 10⁻⁵</td>
</tr>
</tbody>
</table>

Definitions

Specific Heat: The heat required to raise the temperature of its unit by mass by 1ºC. (This is a physical property)

Density: This is its mass per unit volume. This is defined as mass divided by volume.

Melting Point: The point at which it changes state from a solid to a liquid.

Ultimate Tensile Strength: The maximum stress value as obtained on a stress-strain curve.

Ultimate Shearing Strength: The force that will shear the material, and act in the plane of the area at a right angle to the area subjected at such force.

Elastic Modulus: The ratio of the unit stress to the unit strain within the proportional limits of a material in tension or compression.

0.2% Tensile-proof Strength: (yield strength) The point between 60– 80% of the ultimate tensile strength of the material where a 0.2% permanent deformation will occur.

Coefficient of Expansion: This is the fractional change in length per degree of temperature change.

IACS: International Annealed Copper Standard.
Aluminium Busbar Specifications

Pure aluminium has a conductivity of about 65% IACS (International Annealed Copper Standard)

Alloy 6101. This heat treatable wrought alloy is recognised internationally as providing the optimum combination of strength and electrical conductivity for busbars.

Temper T6. This is solution heat treated and artificially aged to maximum mechanical property levels.

<table>
<thead>
<tr>
<th>CHEMICAL COMPOSITION</th>
<th>Silicon</th>
<th>Iron</th>
<th>Copper</th>
<th>Manganese</th>
<th>Magnesium</th>
<th>Chromium</th>
<th>Zinc</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.30-0.70</td>
<td>0.35</td>
<td>0.10</td>
<td>0.10</td>
<td>0.45-0.90</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>Total of other elements</td>
<td>0.10.</td>
<td>Remainder is aluminium</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Thermal Capacity

The thermal storage capacity of aluminium is 0.214 cal/gram/°C. For copper it is 0.092 cal/gram/°C. Therefore aluminium has a thermal storage capacity of more than 2-3 times that of copper. This is used to advantage in wound transformers, as aluminium can withstand more surge and overload currents.

Conductivity

When the density of copper (8.89 gm/cm³) is compared to aluminium (2.91gm/cm³) and taking into consideration the conductivity ratio of aluminium to copper of 57% for grade 6101 aluminium, aluminium has approximately 1.85 times that of copper. Copper has a greater conductivity on an equal volume, cross sectional area basis.

Mechanical Strength

Aluminium does have a lower tensile strength (37%) than copper for the same cross section of material. However, approximately 66% greater cross-section of grade 6101 aluminium is required to carry the same amount of current as would be required for a copper conductor, so the larger cross-section of aluminium approaches the tensile strength of copper for a given ampacity.

Weight

Aluminium is approximately 30% of copper of the same size. The charts on page 13 show weights per metre for standard rectangular aluminium and copper bars.

Metallurgy

As aluminium and copper are used for busbars, and both for terminations on switchgear, the various forms of corrosion are described for each. This includes issues of interconnection. (The section under Electroplating shows the remedies for corrosion etc.)

Corrosion

Corrosion is a chemical or electrochemical reaction between a metallic component and the surrounding environment causing detectable changes that lead to a deterioration of the component material, its properties and function. It begins at an exposed metal surface altering progressively the geometry of the affected component without changing the chemical composition of the material or its microstructure. Degradation initiates with the formation of a corrosion product layer and continues as long as at least one of the reactants can diffuse through the layer and sustain the reaction. The composition and characteristics of the corrosion product layer can significantly influence the corrosion rate. Among the many forms of general corrosion that could potentially affect the power equipment metallic components, atmospheric, localized, crevice, pitting and galvanic are probably the most common.

The composition and characteristics of the corrosion product layer can significantly influence the corrosion rate. The environment is an essential ingredient in corrosion rate.

For the purposes of this publication, the most relevant is galvanic corrosion.

Galvanic corrosion is accelerated corrosion occurring when a metal or alloy is electrically coupled to a more noble metal in the same electrolyte. In a bimetallic system, this form of corrosion is one of the most serious degradation mechanisms. Whenever dissimilar metals are coupled in the presence of solutions containing ionized salts, galvanic corrosion will occur. The requirements for galvanic corrosion are: 1) materials possessing different surface potentials, 2) common electrolyte, and 3) a common electrical path.

The driving force behind the flow of electrons is the difference in potential between the two metals with the direction of flow depending on which metal is more active. The more active (less noble) metal becomes anodic, and corrosion occurs while the less active metal becomes cathodic.

In the case of aluminium-to-copper connections, aluminium (the anodic component) dissolves and is deposited at the copper cathode in the form of a complex hydrated aluminium oxide, with a simultaneous evolution of hydrogen at the cathode (copper).

The dissociation of the electrolyte also supplies the oxygen which is a key ingredient in the formation of the metal oxide.

The process will continue as long as the electrolyte is present or until the aluminium has been consumed, even though the build-up of corrosion products may limit the rate of corrosion at the surface.

The aluminium-to-copper connection is affected by corrosion in two ways: either the contact area is drastically reduced, causing an electrical failure, or the connector is severely corroded, causing a mechanical failure. In most instances, failure is due to a combination of both effects. The factors that influence the degree or severity of galvanic corrosion are numerous and complex but probably the most important is humidity.

To limit the detrimental effect of galvanic action in corrosive environments and maintain a low contact resistance, various palliative measures such as plating with a metal of small differences in anodic indexes, contact aid-compounds, and transition washers have been employed.
Metallurgy

Oxidation

This is a chemical process that increases the oxygen content of the base metal, with the result of losing electrons. For bare copper, copper oxide is formed.

In the presence of oxygen-bearing atmospheres, the continuous oxidation of the metal-metal contacts by oxidation can cause rapid increase in the contact resistance to a high value after remaining relatively low for a considerable length of time. The oxides of copper grow, flake and spall off from the base metal. Copper oxides are softer as compared to aluminium oxides and more easily disrupted by the applied contact force. They are also semiconducting and copper contacts with an initially high resistance, as a result of poor surface preparation, can show a steady decrease in contact resistance with time as a result of the growth of semiconducting layer over a large area.

In the presence of a sulphur-bearing atmosphere, tarnishing of the copper surface is normally observed because of sulphide formation from hydrogen sulphide in the atmosphere. The growth of tarnished film is strongly dependent on the humidity, which can reduce it if a low sulphide concentration prevails or increase it if sulphide concentration is high.

For aluminium, alumina is formed.

In this case, it is generally considered a less likely mechanism of degradation because oxide growth is self-limiting and reaches a limiting thickness of about 10nm (nanometres) within a very short period of time. This is very much less than the diameter of the contact spots, generally considered being much more than 10nm for rough surfaces.

Aluminium oxide is hard, tenacious, and brittle, with a high resistivity. It is also transparent so that even the bright and clean appearance of an aluminium conductor does not assure that a low contact resistance can be achieved without appropriate surface preparation. In electrical contacts having one or both contact members of aluminium, the current flow is restricted to the areas where the oxide film is ruptured.

<table>
<thead>
<tr>
<th>Metal</th>
<th>Ambient</th>
<th>Product</th>
<th>Characteristic Features</th>
<th>Thickness (nm) at 10^4h</th>
<th>Thickness (nm) at 10^5h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>Air</td>
<td>Cu_2O</td>
<td>Oxide forms immediately. Temperature dependent.</td>
<td>20°C 2.2 4.0</td>
<td>100°C 15.0 130.0</td>
</tr>
</tbody>
</table>

Metallurgy

Fretting

The process is defined as accelerated surface damage occurring at the interface of contacting materials subjected to small oscillatory movements. Two basic conditions necessary for fretting to occur are relative movement or slip and amplitude of motion sufficient to cause the damage. Experimental evidence shows that amplitudes of the order of 10^6 cm (<100nm) are sufficient to produce fretting. Thus, from a practical standpoint, there appears to be no minimum surface slip amplitude below which fretting will not occur.

Vibration is a major contributor to fretting.

Aluminium to Copper Bolted Joints:

Because the coefficient of thermal expansion of aluminium is 1.36 times that of copper, and when a bolted aluminium-copper joint is heated by the passage of current, aluminium will tend to expand relative to copper.

Aluminium to Aluminium Joints:

The deleterious effects of fretting are of particular interest in aluminium connections since aluminium exposed to the atmosphere rapidly oxidises, forming an oxide film within a very short time. Hence, under fretting conditions, accumulated wear debris and oxides cannot be effectively removed from the contact zone and a highly localized, thick insulating layer is formed, leading to rapid increase in contact resistance and, subsequently, to virtually open circuits.

Fretting will occur, to some degree in any bolted connection regardless of the material. For connections that include aluminium, fretting can be reduced by:

- The use of disk-spring (Belleville) washers to allow for the difference in Expansion.
- A contact lubricant to reduce adhesion, friction and wear rate and to reduce or eliminate oxygen inclusion.
- A plated surface (such as nickel) to prevent oxide forming on the aluminium resist fretting and whiskering and provide a low resistance connection even on dissimilar metals. (Tin is susceptible to fretting and whiskering.)

It is worth noting that some manufacturers use nickel plated aluminium for connection tags on their MCCB’s and ACB’s.

Whiskering

In the search for an alternative coating material, tin was used as substitute plating in many applications. However, it became apparent that in addition to susceptibility to fretting, the additional problem when using tin is its propensity to whisker formation. A whisker is typically a single crystal, mechanically strong, metallic filaments that can spontaneously nucleate and grow protruding from the surface of a metal.

This phenomenon is also found in silver based connections. The main concern is that the growth of whiskers, being conductive may lead to shorting.
Electroplating
Both copper and aluminium are subjected to oxidisation when exposed to the atmosphere.

The coating of aluminium or copper by different metals is one of the most common commercial practices used to improve the stability, and to suppress the galvanic corrosion of aluminium-to-copper connections. The most widely used coating materials are tin, silver, copper, cadmium, and nickel.9

On aluminium bars, the natural oxidisation away from the joint area is not an issue as this protects the conductor from further corrosion in most environments. However, it is more practical to have the bars already plated than plating the connection area after fabrication.

Tin Plating
Although tin is widely used in the electrical industry, there is mounting evidence indicating that tin neither effectively prevents galvanic corrosion nor ensures the stability of aluminium-to-copper connections. Tin plating, traditionally used to suppress the adverse effects of galvanic corrosion, requires no special surface preparation prior to assembly and improves the performance of joints at elevated temperatures. However, there is mounting evidence that the use of tin-plating is not as advantageous as previously thought for two main reasons. First, tin-plating contacts are very susceptible to fretting, which causes severe degradation of contact interfaces and leads to an unacceptably high contact resistance, instability and, ultimately, an open circuit. Second, tin easily forms intermetallic phases with copper even at room temperature, rendering the contact interface very brittle, highly resistive, and susceptible to the influence of the environment. Furthermore, galvanic corrosion is not eliminated by tin coating, and therefore the lubrication of bolted busbars is essential for reducing the corrosion damage in a saline environment.9

Silver Plating
Silver is an excellent conductor and is widely used in joints for high-temperature operations in enclosed-type switchgear assemblies. Although the silver plating of electrical contacts is beneficial in maintaining a low electric resistance, it has a potential disadvantage: silver, like copper, is cathodic to aluminium and may, therefore, cause the galvanic corrosion of aluminium. Furthermore, due to the sensitivity of silver to tarnishing, the use of silver plating in environments with sulfurized contaminants has to be avoided. The coatings should be uniform and relatively thick. The use of protective contact aid compounds for the optimum performance is essential for silver-coated joints that are exposed to a high humidity or moisture. Of course, where no moisture or other contaminants exist, silver-coated joints are not subject to deterioration.10

Electroplating
Nickel Plating
Recent studies have clearly demonstrated that the nickel-coated connections, as manifested by their stable contact resistance behaviour under the simulated service conditions, were superior in the performance to other plating materials. From the available data, nickel appears to be the best practical coating material from the point of view of both its economy and the significant improvements of the metallurgical and contact properties of aluminium-to-copper connections.11

The superiority of nickel to other coating materials is confirmed by current-cycling tests on tin-, silver-, and nickel-plated copper busbars bolted to 1350 grade aluminium. The nickel coatings on copper connections showed an excellent stability and low initial contact resistance. The poor performance to tin- and silver-plated connections is attributed to the effect of differential thermal expansion between the substrates of aluminium and copper that promote progressive loss of the contact spots, leading to deterioration of the contact.11

The table below shows that nickel plating significantly enhances the stability of aluminium-to-copper connections (the lowest INDEX), while tin and silver coatings show the poorest performance (the highest INDEX) under different operating and environmental conditions.11

<table>
<thead>
<tr>
<th>CONTACT PAIRS</th>
<th>INDEX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium (nickel-plated)- Copper (nickel-plated)</td>
<td>0.7</td>
</tr>
<tr>
<td>Aluminium (copper-plated)- Copper (bare)</td>
<td>1.0</td>
</tr>
<tr>
<td>Aluminium (bare)- Copper (nickel-plated)</td>
<td>1.3</td>
</tr>
<tr>
<td>Aluminium (bare)- Copper (silver-plated)</td>
<td>2.0</td>
</tr>
<tr>
<td>Aluminium (bare)- Copper (bare)</td>
<td>2.4</td>
</tr>
<tr>
<td>Aluminium (bare)- Copper (tin-plated)</td>
<td>2.7</td>
</tr>
</tbody>
</table>

In summary, for added assurance of satisfactory performance on routine installations and for additional protection against adverse environmental effects, connections should be thoroughly sealed with a suitable contact aid compound to prevent the penetration of moisture and other contaminants into the contact zone.11
Electroplating

Nickel Sulfamate

The nickel which is electroplated onto the ALBUS INDUSTRIES aluminium busbars is deposited using a nickel sulfamate based solution.

This is a rapid electrodepositing process having very low bar tensile stress on the base metal. It has advantages over other (normally brittle) types of nickel plating.

- Ductile (bends without fracturing)
- Prevents galling and fretting.
- High tensile strength.
- Low weight factor.
- High temperature resistance (melting point 1450°C)
- Excellent corrosion resistance.
- Minimises loss of fatigue strength of the base metal.
- Excellent adhesion.

Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness</td>
<td>175 to 230 Hv200</td>
</tr>
<tr>
<td>Elongation in 50mm</td>
<td>15 to 25%</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>620 MPa</td>
</tr>
<tr>
<td>Internal stress</td>
<td>3.4 – 620 MPa</td>
</tr>
<tr>
<td>Deposit appearance</td>
<td>Semi-matt</td>
</tr>
<tr>
<td>Deposit thickness</td>
<td>10 microns</td>
</tr>
</tbody>
</table>

Organic Coating

Nickel sulfamate electroplating marks through handling and aging in the same way as plain copper. To resist this, the bars have an organic coating. This also provides additional protection against corrosion, and also has a 48 hour salt spray protection rating. The organic solution is free from hazardous materials such as hexavalent chrome.

This treatment does not alter the appearance of the plating, nor have any affect on surface conductivity.

Current Ratings

Current Carrying Capacity

The current carrying capacity of a busbar is determined by its maximum continuous operating temperature.

According to AS/NZS 3439.1 (IEC 60439-1) this is 90°C for aluminium bars and 105°C for copper. (This limitation for aluminium does not take plating into account, in which case the temperature may be higher.)

These temperatures are chosen to limit the amount of oxidisation, leading to possible overheating of joints. The oxidisation of aluminium is self limiting to about 10nm (nanometres), but is highly resistive. This is one of the reasons that aluminium should be electroplated. Copper is much more temperature dependent than aluminium, and its oxide is not self limiting.

There are a number of factors affecting the thermal rating of a busbar. These are common to either material.

- Conductor material
- Enclosure size and location
- Ventilation
- Skin effect
- Proximity effect
- Enclosure material
- Emissivity

Conductor Material

Aluminium (grade 6101) has 57% of the conductivity of copper. Therefore, the cross sectional area of these aluminium busbars should be around 63% greater than copper for the same current rating in the same circumstances.

Enclosure Size and Location

A metal clad switchboard assembly diffuses its heat through the external surfaces. The size of the compartment containing the busbars should be as large as is practical to permit the maximum amount of air circulation. The frequent pressure to make switchboards as small as possible reduces the surface area, and space available for bars and switchgear, often leading to overheating.

The location of the switchboard should be taken into account. These factors include ambient temperature, and ventilation of the room in which the switchboard is installed.

Positioning the main busbars in an enclosure on top of the switchboard assembly maximises the radiation surface, does not contribute to the heat output within the assembly, and simplifies accessibility.

Ventilation

Ventilation will improve the thermal ratings of busbars. However, this may be constrained by the specified IP rating or fault containment certification.
Current Ratings

Skin Effect

Alternating current in a busbar creates an alternating magnetic flux around it, and induces a back e.m.f., having an inductive effect. This is greater at the centre of the conductor, and this causes an uneven distribution of current through the cross-section of the conductor. The current therefore tends to flow in the path of least resistance, which is towards the outside of the conductor. The size and shape of the conductor (rectangular, circular, hollow etc) and numbers of bars per phase also influences the skin effect.

For more than one bar per phase, the skin effect will cause the outer bars to carry most of the current.

The skin effect causes an increase in resistance, and therefore contributes to the heating of the bar.

The skin effect is somewhat reduced in an aluminium busbar, due to its increased size for the same current compared to copper.

The skin effect becomes significant from around 2000A and above.

Proximity Effect

The inductance of the skin effect is further affected by adjacent bars of other phases. This adds to the distortion of current distribution, further adding resistance, impedance and altering the heating pattern set by the skin effect. Bars of the same phase will therefore operate at different temperatures. In the case of more than one bar per phase, the current rating is set by the highest temperature. As for the skin effect, the size and shape of the conductors influences the proximity effect. The layers and different directions of busbars in close proximity to each other in a switchboard also compound these effects.

Due to this, charts showing current ratings for busbars can only be taken as a guide. Actual tests on typical busbar arrangements in a switchboard are the only definite means establishing current ratings. This applies equally to copper and aluminium busbars. As a general rule, increasing the distances between the bars reduces the proximity effect. This also dramatically improves the short-circuit strength of the structure. The distance between the outer surfaces of each phase bar (or group) should be at least 300mm to negate the proximity effect. However, space is always a concern in switchboard design.

The switchboard enclosure is also part of the proximity effect. (See Enclosure Materials page 12).

As the increased distance between the phases reduces the proximity effect, so does increasing the distance from the bars to the inside of the enclosure. The distance of around 300mm is the same as for the phase groups.

Although such relatively large clearances may not be practical, greater distances as possible improves the efficiency and the strength of the busbar arrangement.

Enclosure Material

The magnetic field surrounding the busbars induces currents in the structure or enclosure in which they are installed. These lead to resistance and magnetic losses.

Enclosures made from a non-magnetic material such as aluminium, copper or stainless steel only have resistance losses.

From 2000A, the magnetic losses in magnetic enclosures such as mild steel can be significant. Magnetic losses are made of eddy and hysteresis currents. These have a heating effect on the enclosure and adjacent structures. The enclosure in certain circumstances will generate heat rather than providing a means of dissipation.

Enclosures made of non-magnetic materials compared to magnetic metals can improve the current rating of the busbars by around 18%.

Emissivity

This is the relative ability of the surface of a material to emit energy by radiation.

The duller and blacker a material, the higher its emissivity. The more reflective a material is, the lower its emissivity.

<table>
<thead>
<tr>
<th>Surface Material</th>
<th>Emissivity Coefficient (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper- new</td>
<td>0.1</td>
</tr>
<tr>
<td>Copper- tarnished</td>
<td>0.5-0.7</td>
</tr>
<tr>
<td>Bright tin plate</td>
<td>0.04</td>
</tr>
<tr>
<td>Aluminium- new</td>
<td>0.9</td>
</tr>
<tr>
<td>Aluminium- nickel plated (2)</td>
<td>0.3</td>
</tr>
<tr>
<td>PVC Insulation (3)</td>
<td>0.08-0.09</td>
</tr>
</tbody>
</table>

(1) Values are approximate.
(2) Applies to nickel sulfate plating with passivation.
(3) Assumes a good bond between insulation and conductor.
(4) Although increasing emissivity ratings, aluminium and copper oxides are not good conductors of heat. Therefore, dull plating gives the best result.

Symmetry

It is important that bars carrying currents in excess of around 1200A are arranged symmetrically. Unequal distances between phases will generate high currents and temperatures.
### Current Ratings

**Standard Rectangular bars**

<table>
<thead>
<tr>
<th>Bar Shape</th>
<th>Bar size (mm)</th>
<th>Cross Section Area</th>
<th>Aluminium Bars per Phase (A)</th>
<th>Weight/m (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>6.35 x 25</td>
<td>156</td>
<td>226</td>
<td>397</td>
<td>-</td>
</tr>
<tr>
<td>6.35 x 32</td>
<td>200</td>
<td>270</td>
<td>467</td>
<td>-</td>
</tr>
<tr>
<td>6.35 x 40</td>
<td>250</td>
<td>338</td>
<td>580</td>
<td>813</td>
</tr>
<tr>
<td>6.35 x 50</td>
<td>315</td>
<td>410</td>
<td>700</td>
<td>980</td>
</tr>
<tr>
<td>6.35 x 63</td>
<td>398</td>
<td>500</td>
<td>864</td>
<td>1197</td>
</tr>
<tr>
<td>6.35 x 80</td>
<td>565</td>
<td>618</td>
<td>1055</td>
<td>1434</td>
</tr>
<tr>
<td>6.35 x 100</td>
<td>632</td>
<td>754</td>
<td>1298</td>
<td>1720</td>
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<tr>
<td>6.35 x 125</td>
<td>790</td>
<td>906</td>
<td>1546</td>
<td>2035</td>
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<td>6.35 x 160</td>
<td>1013</td>
<td>1136</td>
<td>1925</td>
<td>2514</td>
</tr>
<tr>
<td>10 x 40</td>
<td>400</td>
<td>447</td>
<td>787</td>
<td>1094</td>
</tr>
<tr>
<td>10 x 50</td>
<td>500</td>
<td>557</td>
<td>960</td>
<td>1318</td>
</tr>
<tr>
<td>10 x 60</td>
<td>600</td>
<td>650</td>
<td>1120</td>
<td>1504</td>
</tr>
<tr>
<td>10 x 80</td>
<td>800</td>
<td>800</td>
<td>1418</td>
<td>1882</td>
</tr>
<tr>
<td>10 x 100</td>
<td>1000</td>
<td>1000</td>
<td>1696</td>
<td>2218</td>
</tr>
<tr>
<td>10 x 120</td>
<td>1200</td>
<td>1158</td>
<td>1952</td>
<td>2566</td>
</tr>
<tr>
<td>10 x 160</td>
<td>1600</td>
<td>1478</td>
<td>2522</td>
<td>3309</td>
</tr>
<tr>
<td>10 x 200</td>
<td>2000</td>
<td>1780</td>
<td>3040</td>
<td>3940</td>
</tr>
<tr>
<td>10 x 250</td>
<td>2500</td>
<td>2150</td>
<td>3660</td>
<td>4230</td>
</tr>
</tbody>
</table>

1. Ratings from THE ALUMINIUM FEDERATION.
2. Based on a temperature rise of 55°C over 35°C ambient.
3. Ratings have been reduced by a factor of 0.64 for an indoor enclosure of magnetic material as recommended in AS 3000-1991 (table C3).
4. Ratings take into account the proximity effect. (ie. Phase centres approximately 150mm)
5. Ratings apply to bars arranged vertically.

### Current Ratings

**Non-Standard Shapes**

The additional bulk of these bars-

- Provide ratings similar to copper bars of comparable height.
- Provide sufficient cross-sectional area to cope with the heat generated at various fault levels.
- Increase the mechanical strength compared to standard rectangular bars of the same area.

These are intended for ‘dropper bars’ in plug-in type switchboards and motor control centres. At 60mm phase centres there is 30mm clearance between bars.

<table>
<thead>
<tr>
<th>Bar Shape</th>
<th>Cross-Section Area</th>
<th>Rating (A)</th>
<th>Weight/m (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>663</td>
<td>790</td>
<td>1.80</td>
<td></td>
</tr>
<tr>
<td>1053</td>
<td>1260</td>
<td>2.86</td>
<td></td>
</tr>
</tbody>
</table>

These bars are intended for ‘main’ busbars. The bars are thickened to allow being run in parallel with allowance for insulation (when specified) up to 0.5mm wall thickness. The standard bar thicknesses of 6.35 and 10mm is retained each end so that standard supports may be used. This standard thickness is 40 and 60mm long respectively at one end for interleaving connection of bars of the same thickness.

<table>
<thead>
<tr>
<th>Bar Shape</th>
<th>Cross-Section Area</th>
<th>Bars per Phase (A)</th>
<th>Weight/m (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1160</td>
<td>1160</td>
<td>1860</td>
<td>2550</td>
</tr>
<tr>
<td>1569</td>
<td>1260</td>
<td>2000</td>
<td>2770</td>
</tr>
<tr>
<td>1605</td>
<td>1280</td>
<td>2040</td>
<td>2810</td>
</tr>
<tr>
<td>2365</td>
<td>1890</td>
<td>3020</td>
<td>4150</td>
</tr>
</tbody>
</table>
Current Ratings

Non-Standard Shapes—

Ratings for single bars have been extrapolated from the chart on page 13 and other published data on aluminium busbars in switchboards. This reveals a current density of:

- 1.1A/mm² to 700mm²
- 1.0A/mm² above 700 to 1200mm² and
- 0.8A/mm² above 1200 to 3200mm².

(As a comparison on the same bars, copper is:

- 1.5 A/mm² to 700mm²
- 1.3A/mm² above 700 to 1200mm² and
- 1.1A/mm² above 1200 to 3200mm².)

To determine the current ratings for 2 and 3 bars in parallel, the single bar has been multiplied by 1.6 and 2.2 respectively. This is consistent with the most conservative published charts on aluminium and copper busbars.

Typical Arrangements

6.35mm Type
Standard Interleaving

10mm Type
‘European’ style of take-off connection

10mm Type
Standard interleaving

10mm Type
As above but with standard rectangular centre bar

Short Circuit Effects

A short across busbars will draw on all the current that is available from the supply source, limited only by the relatively low impedance of the circuit. The duration is normally taken to be 1 second, although 3 seconds is sometimes specified. The busbars must be large enough to absorb the heating effects, and the system strong enough to withstand the electromagnetic forces.

Electromagnetic Forces

The excessive current caused as a consequence of a short-circuit creates powerful magnetic fields. These interact with each other, either repulsive or attracting adjacent bars of other phases depending on the direction of the current flow.

These forces are greatest at the start of the fault, at which point most damage is likely to occur to the bars or the support structure.

The electro-magnetic forces cause:

- Stresses between bars (attract and repulse)
- Vibrations
- Twisting of the bars
- Longitudinal stresses (ejecting forces)

The stress on the busbar arrangement is given by the fault current, duration and distance between phases. These forces are taken to be uniform over the length of the busbar system. The distance between supports is determined to limit the stress to 60-80% of the tensile strength of aluminium which is 2050 to 2500 kgf/cm². The mechanical strength of the busbar supports and fixings must also be calculated to be adequate.

The stresses on the bars are the same for aluminium and copper in the same circumstances. However, the higher elasticity of aluminium imposes less force on the busbar support system than copper. This advantage has been demonstrated by short-circuit tests on identical arrangements of aluminium and copper.
Short-circuit Effects

Thermal Effects

The duration of the fault, limited by the protective device to 1-3 seconds (approximately 6 cycles) is too short to allow the heat to dissipate from the bars, and will therefore be absorbed by the bars.

A maximum short-time temperature of up to 190°C is taken as a safe temperature for aluminium. (This limit is the same for copper in order to prevent damage to insulation and other parts of the same circuit).

The temperature rise of the busbars as a result of a short-circuit must be taken into account in the design of the busbar arrangement. In some cases, this may be the determining factor, rather than the continuous current rating.

The chart below shows the minimum cross-sectional areas for aluminium and copper for various fault ratings. These show temperature rise from 0°C, and a short-circuit occurring at the maximum continuous rating. This is 90°C for aluminium and 105°C for copper. (Some specifications limit the operating temperature of copper to less than 105°C) It can be seen that the final temperature is not the sum of the temperature rise and the operating temperature. This is an exponential factor due to the ever increasing resistance due to temperature.

<table>
<thead>
<tr>
<th>Base Temp</th>
<th>Short-Circuit (kA) (1 Sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40</td>
</tr>
<tr>
<td>Aluminium</td>
<td>0°C</td>
</tr>
<tr>
<td></td>
<td>90°C</td>
</tr>
<tr>
<td>Copper</td>
<td>0°C</td>
</tr>
<tr>
<td></td>
<td>105°C</td>
</tr>
</tbody>
</table>

1. Values show cross-sectional areas (mm²)
2. Refer to charts on pages 13 and 14 For cross-sectional areas of busbars.
3. Fault duration 1 second.

Installation

Installation Procedures

To ensure proper function of a joint, certain measures must be taken during installation. The most important items for proper bus connections include the correct selection of connecting hardware, surface preparation and applying the adequate contact force. For low-resistance connections, the surface preparation of the connection is as important as— if not more than— the selection of the proper joint compound. The measures to be taken to prevent the adverse effect of environment on the functioning of the joint depend upon the busbar material and the environment in which the busbars are installed.

The contact force required in bolted joints is attained with one or more bolts. By tightening the nuts to a given torque, the bolts are pre-tensioned and the required contact force is obtained in the joint. Maintaining certain pre-tension force is important not only for keeping the contact resistance low but also for preventing the nut and thus the joint from loosening when subjected to vibrations. If the bolts are tightened to less than the prescribed values, this will loosen the joint that will heat due to poor electrical contact. If the bolts are over tightened, however, the connection will be subjected to stress relaxation and creep, and eventually will fail.

Contact resistance is lowest near the bolts where the clamping force is highest. The majority of the current passes through these points of low contact resistance. If the contact zone is small, current density will increase that will generate heat at the contact interface. If the heat is not dissipated by radiation, a hot spot develops. The hot metal creeps toward the bolt holes at these high temperature and high pressure points. This gradual metal flow from the hot spots leads to a reduction in total clamping force over several heating-cooling cycles. A slight loss of clamping force can increase the joint resistance. The end result is a slow but progressive failure. To overcome this problem and ensure stable and low resistance operation, thick and large diameter flat washers are recommended.

However, despite deleterious effects of different degradation mechanisms to which the power connections are subjected under operating conditions, their reliable performance can be obtained and maintained providing the correct measures are applied and the installation procedures strictly followed.

Nickel plated aluminium - Nickel plated aluminium
- Bare, or tin or silver plated copper.
Remove dirt and grease with white spirit, solvent cleaner etc, apply thin layer of lubricant and bolt the joint.

Bare aluminium - Bare aluminium
- Tin or silver plated copper.
Remove dirt and grease with white spirit, solvent cleaner etc, apply thin layer of lubricant and bolt the joint.

Bare aluminium - Bare copper.
Not recommended due to galvanic action.
Installation

Thermal Expansion

Aluminium expands at a greater rate than copper when exposed to an increase in temperature. This can lead to lateral movement in the contact zone, or deformation concentrated in the area around the bolts where there is the greatest pressure. The amount of expansion is limited by the fact that the aluminium conductors are sized not to exceed 90ºC for continuous operation. It is also essential that bolts are not overtightened and that Belleville washers are used.

Stress, Relaxation and Creep

Creep, or cold flow, occurs when any metal is subjected to a constant external force over a period of time. The rate of creep depends on stress and temperature and is higher for aluminium than for copper. Stress relaxation also depends on time, temperature, and is evidenced by a reduction in the contact pressure due to changes in metallurgical structure.

Although stress relaxation cannot be prevented, the use of disk-spring (Belleville) washers together with thick washers will significantly improve the electrical and mechanical stability of the bolted joints, and thus minimise loosening of the joint during stress relaxation and exposure to current-cycling conditions.

The tendency to stress relaxation and creep is also reduced in the 6101 grades of aluminium compared to the relatively pure (and softer) 1350 grade.

Bolt Types and Belleville Washers

The recommended torque settings require at least 8.8 grade (high tensile) bolts. Spring-disc (Belleville) washers with thick flat washers should be used. For cumulative thicknesses of the joint above 35mm, a Belleville washer under the bolt head and nut is recommended.

Bolted Joints

Overlapping of joints:

The efficiency of an overlapped joint is dependent only on the ratio of the overlap to the thickness of the bars. An overlap of more than 6-7 times the thickness has very little effect on the resistance.

Therefore, for 6.35mm thick bars, a minimum overlap of between 40-45mm is sufficient.

For 10mm bars, 60mm is adequate.

Number of Bolts:

Where practical, connections should be made by more than one bolt. This is to reduce the risk of failure, and to distribute the contact pressure across as large an area as possible.

However, the common European practice of running 2–10mm thick bars in parallel and connecting the flat sides of the ‘take-off’ bars to the edges of the main bars with one or more bolts between the parallel bars appears to have stood the test of time, even though the overlap area is 20mm.

Installation

Tightening Torque

The correct contact pressure is essential in ensuring the reliability of a joint. Proper pressure minimises the contact resistance and eliminates localized heat. Loose contact pressure will lead to a high resistance joint. Over tightening will lead to deformation of the bars in time, causing a loose connection.

Average contact pressure for aluminium conductors is 40-55kg/cm².

<table>
<thead>
<tr>
<th>BOLT SIZE</th>
<th>TORQUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>M6</td>
<td>15N/m</td>
</tr>
<tr>
<td>M8</td>
<td>25N/m</td>
</tr>
<tr>
<td>M10</td>
<td>35N/m</td>
</tr>
<tr>
<td>M12</td>
<td>55N/m</td>
</tr>
</tbody>
</table>

Bending

The extruded bars can be bent edgewise at room temperatures to 90° without cracking, or evidence of slivers or other imperfections.

Up to 12mm thick- Radius 1.5 x thickness of bar

13 to 25mm thick- Radius 2.5 x thickness of bar.

Bus-Stab (Busplug) Connections

Bus-stab connections are subject to three modes of mechanical motion.

1. When the busbars change their length due to thermal expansion due to changes in electrical load. This results in a slow slide motion with respect to the contacts i.e. elongation of the stab-contact area along the busbar.

2. Electromagnetically induced vibrations.

3. Movement of the busbar due to both thermal and electromagnetically induced movement. This causes a transverse motion in the bus-stab contacts.

These forces are present in aluminium and copper bars, and it is recommended that the frequency of the busbar supports is not only determined by the fault-rating, but by the benefits of limiting the natural movement of the bars.

Bus-stab contacts should be silver-plated copper, and the aluminium bars nickel plated for durability.

Recommended contact forces for bus-stab contacts is at least 70N.

Frequent engagement of bus-stab contacts made of silver plated copper onto the nickel sulfamate plated alum. busbars causes the silver to rub onto the nickel sulfamate coating. There is therefore no contact between copper and aluminium.
Installation

Joint Resistances

Typical resistances based on 50 x 6.35mm aluminium bars with 50mm overlap, and 4–M8 steel bolts.

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>CONDITION</th>
<th>RESISTANCE ACROSS OVERLAP (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>Uncleaned surface</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Cleaned and lubricated and immediately joined</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Cleaned and lubricated and exposed 60 hours before joining</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>50 x 6.35 bar 1.8m long</td>
<td>5</td>
</tr>
</tbody>
</table>

Lubrication

It has been known for some time that the use of a suitable lubricant (contact aid compound) improves the performance of an electric contact. When the contact is made, the lubricant is squeezed away from the points of highest pressure and hence the metallic conduction through the contact is not disturbed. As a result, the oxidation of clean metal surfaces is virtually prevented and a high area of metallic contact, hence, low contact resistance, and protection of the contact zone from adverse environmental effects are maintained.16

It is a common practice that for both (unplated) aluminium and copper busbar connections, the contact surfaces should be abraded through the suitable contact aid compound with a wire brush or abrasive cloth. Due to a more rapid formation of initial oxide film on aluminium, this procedure is more important for aluminium conductors than for copper.16

However, when electrical equipment is supplied with plated terminals, the plated contact surfaces should not be scratched or brushed. It is recommended that such plated surfaces, before being bolted to aluminium or copper bus, be cleaned with cotton waste and then coated with a suitable compound to serve only as a sealer. Proper surface preparation combined with lubrication considerably reduces the contact resistance of bolted joints.16

The use of lubrication also considerably reduces the contact voltage fluctuations and provides for a relatively stable contact voltage along the wear track.16

In the case of all-copper connections, it is generally accepted practice not to use any contact aid compound. However, copper connections are also susceptible to degradation during their service life although their deterioration can proceed for a long time without any appreciable changes in their performance. This engenders a false sense of security, since experience has shown that the deterioration of copper connections occurs rather abruptly triggered by accelerated interaction of chemical, thermal, and electrical processes at the contact interface. Hence, to prolong the useful service life of copper connections, the use of contact aid compounds is highly recommended.16

Any lubricant should be able to withstand the operating temperatures of the busbar without running or drying out.16
Standards

AS2504-1981. As this was withdrawn without replacement, there is no current Australian Standard for Aluminium Busbars. This standard set out the requirements for chemical composition, physical properties and dimensions.

The busbars described in this publication conform to those specifications.

IEC 60105 Recommendation for Commercial Purity, Aluminium Busbar Material.


Acknowledgements

Much of the information on metallurgical issues has been derived from ‘Electrical Contacts, Fundamental, Applications and Technologies 2007.’ Extracts have been reprinted with permission. This is abbreviated to EC in the references section below.

Mr J. Webster, ASTC (Metallurgy) for reviewing the metallurgical and plating sections as a whole.

Further Reading

‘Electrical Power Engineering’ (K.C. Agrawal)
‘Alcoa Aluminium Bus Conductor Handbook’
‘Aluminium: Physical Properties, Characteristics and Alloys’ (R. Cobden)
‘Copper for Busbars’ Publication no 22.

References

1  Alcoa Aluminium Bus Conductor Handbook.
2  I.E.E.E. Vol CHMT-9 No 1.
3  EC pp212-214.
4  EC pp211-212.
5  EC pp214.
6  EC pp269.
7  EC pp271.
8  EC pp357.
9  EC pp102.
10  EC pp102-103.
11  EC pp103-105.
12  EC pp307-308.
13  EC pp247.
14  EC pp240.
15  EC pp276-277.
16  EC pp304.