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Reliability of power connections

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Abstract: Despite the use of various preventive maintenance measures, there are still a number of problem areas that can adversely affect system reliability. Also, economical constraints have pushed the designs of power connections closer to the limits allowed by the existing standards. The major parameters influencing the reliability and life of Al-Al and Al-Cu connections are identified. The effectiveness of various palliative measures is determined and the misconceptions about their effectiveness are dealt in detail.

Key words: Power connections, Deterioration mechanisms, Palliative measures
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INTRODUCTION

The primary purpose of an electrical connection is to allow the uninterrupted passage of electrical current across the contact interface, which can only be achieved if a good metal-to-metal contact is established. The processes occurring in the contact zone are complex and not fully explained within the limits of present knowledge. Although the nature of these processes may be different, they are all governed by the same fundamental phenomena, the most important being the degradation of the contacting interface and the associated changes in contact resistance, load, temperature, and other parameters of a multipoint contact.

Experimental evidence and various reports of service problems strongly suggest that reliable power connections are not obtained by routine application of established practices and methods. The degradation rate of power connectors in service cannot be determined precisely, which makes maintenance scheduling difficult.

There are two main reasons for this: first, there is a general lack of awareness of the problem, since connection deterioration is a time-related process; and second, the specific features of connection deterioration are not readily recognizable, because the failure of a power connection is usually associated with thermal runaway, thus making identification of the degradation mechanism difficult. The adverse consequences of this situation are reflected in the materials specifications for electrical joints, their usage and maintenance, and thus reliability of the entire power network.

The necessity of developing reliable electrical contact dates back to the beginning of the 19th century when the first electrical machines were used. First contacts were made of copper. As electric engineering evolved, the metal-carbon-graphite material became the most common material presently widely used in sliding contacts such as many types of electric machines and current pick-offs.

Progress in power engineering, the development of new electronic circuits and automatics and telecommunication devices prompted extensive applications of separable, breaking, and sliding contacts of new kinds such as: relay contacts, low-voltage and high-voltage electrical apparatuses, rheostats, potentiometers, electronic circuit joints, etc. Currents and voltages at which the contacts operate can vary by ten and more orders of magnitude and their operating conditions include space, vacuum and high temperatures (hundreds of centigrade).

In the 21st century, electric energy still remains as one of the most basic need for civilization. A huge number of various electrical contacts are being used in the process of energy production, transmission, distribution, and usage. The trend of the extensive utilization of microprocessor devices, automatic control systems of technological processes, communication equipment, speedy electric transport, and the modular telecommunication device design increases the number of contact joints reaching thousands and tens of thousands in one article. For instance, a motherboard of a PC unit may comprise up to 20000 contacts.

Because of some intrinsic problems with electrical contacts such as noise, constricted current transfer across the contact interface, numerous attempts are being made to use electronic non-contact circuits as an alternative in some electrical/electronic devices.

However, the ability of these non-contact replacements may be compromised and their cost prohibitive. Consequently, any notion that in the future the application field of electrical contacts will become narrower or even obsolete is unjustified.

The variety of types of contacts and operating requirements prompted the use of a great number of conducting materials from graphite to rhenium. The world consumption of only noble metals used in the fabrication of materials and coatings for contacts is in thousands of tons. On the other hand, not only noble metals but also common contact material, such as copper, is becoming more and more deficient. Therefore, the replacement of copper with aluminum with improved connectability and reliability is an important step towards a wider use of aluminum in electrical devices.

ELECTRICAL CONTACT REQUIREMENTS

Different types of contacts should satisfy different set of requirements depending on their stability and reliability. These problems can be addressed and solved by careful consideration of the application, design, and operating conditions of electrical contacts. Since the main function of an electrical contact is to enable transmission of the electric current from one contacting member to another with a minimal impact on the transmitted signal, the following set of requirements should be met: (1) Electrical: low power losses, no signal distortion, no overheating; (2) Mechanical: stable contact force during closing and opening, high wear resistance; (3) Ecological: resistance to environment factors, minimal pollution to the environment under fabricating, operating, and recycling conditions; (4) Ergonomic: simplicity of design and fabrication, simple maintenance repair and replacement, possibility of combining units; (5) Economical: minimal content of noble and deficient non-ferrous metals.

In view of the above set of requirements, the reliability has become one of the most important characteristics of any electric/electronic device. Hence, as the requirements on the connectors increase, the development process becomes substantially more complex.

FACTORS AFFECTING RELIABILITY

One of the most important problems in providing reliability to electrical contact is the discrete nature of the interface. An electrical contact between solids is formed at discrete areas within the contacting interface and these areas (*a*-spots) are the only current conducting paths.

The formation of the real and conductive contact areas controls the reliability and efficiency of the electrical contact. These processes depend on a great number of independent or interrelated factors. The variety of the factors can be conventionally divided into the performance factors governed by the operating conditions and the design-technological factors determined by the fabrication characteristics of a contact unit. The performance factors (parameters) are divided basically into two groups: internal and external (Fig.1).

The internal factors are the mechanical (the contact load, the type and characteristics of motion such as slip, the sliding velocity, and reciprocation) and electric (type and strength of current, operating voltages) factors. The external factors may be temperature-time variation, humidity, atmospheric pressure, and effect of aerosols, etc., which are often uncontrollable. The performance factors affect the properties of contact materials and surface films, the occurrence of physical and chemical processes in the contact zone, and the wear particle formation, which influence the state of the interface and, finally, the contact resistance and reliability of electrical contacts.

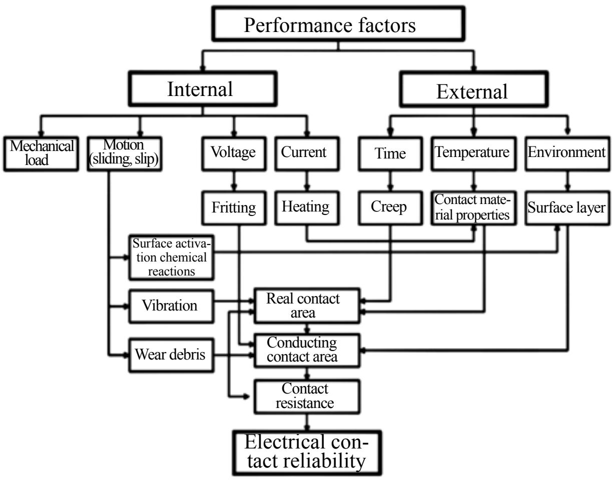


Fig.1 Effect of performance factors on the reliability of electrical contacts

Fig.2 shows schematically the influence of the design-technological factors on the reliability and quality of electrical contacts. The selected kind of contact materials, the contact geometry, the intermediate layers separating the contacting surfaces, the quality of the deposited coatings and the contact surface microrelief determine the apparent contact area, the size, number, and distribution of contact spots. This, in its turn, influences the real and electrical contact areas, the constriction and surface film resistances, and, finally, the electrical contact reliability.

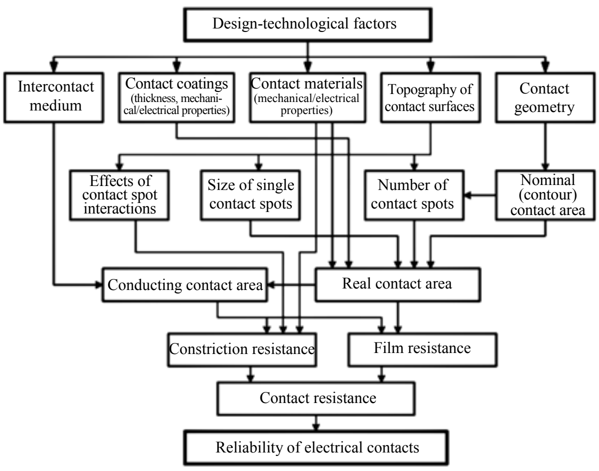


Fig.2 Effect of design-technological factors on the performance of electrical contacts

The widespread use of aluminium in a variety of electrical applications has prompted numerous studies into the processes occurring in aluminium connections. Published experimental evidence and various reports of trouble in service suggest that reliable aluminium connections cannot be obtained by routine application of the practices and methods established for joints with copper conductors.

The complexity of failure mechanisms in aluminium power connections is best described in the form of a cycle as seen in Fig.3. Breaking this cycle requires a thorough understanding of the parameters affecting various properties of aluminium and other conductor and contact materials subjected to different load and environmental conditions.

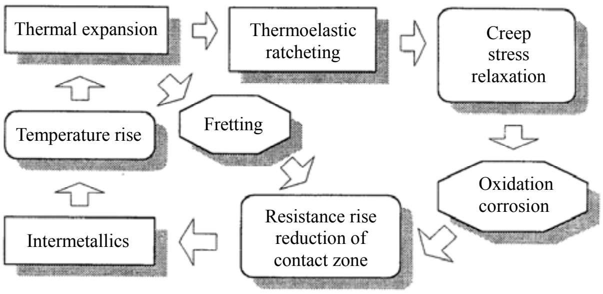


Fig.3 Schematic of degradation mechanisms in aluminium connections

Contact area

It has been established (Holm, 1967) that real surfaces are not flat but comprise many asperities. Hence, when contact is made between two metals, surface asperities of the contacting members will penetrate the natural oxide and other surface contaminant films, establishing localized metallic contacts and, thus, conducting paths. As the force increases, the number and the area of these small metal-metal contact spots will increase due to the rupturing of the oxide film and extrusion of metal through the ruptures. These spots, termed *a*-spots, are small cold welds providing the only conducting paths for the transfer of electrical current. Current passing across a contact interface is thus constricted to flow through these *a*-spots as seen in Fig.4.

Hence, the electrical resistance of the contact due to this constricted flow of current is called "constriction resistance" and is related to the basic properties of metals such as hardness and electrical resistivity. The constriction resistance for a single *a*-spot of the

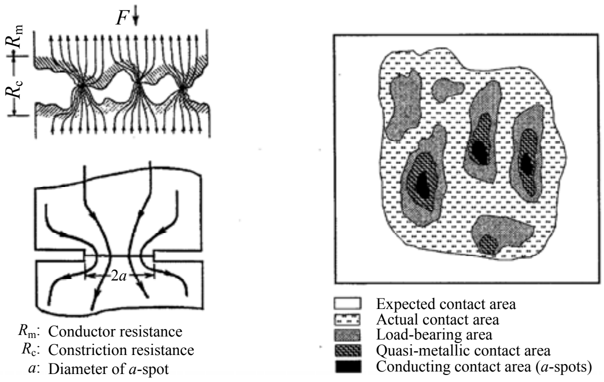


Fig.4 Schematic of real contact area and current constriction

same two contacting metals can be expressed as (Holm, 1967):

$$R_c=\rho/(2a), \quad (1)$$

where ρ is the resistivity of the contacting metals, a is the radius of the metal-to-metal contact area. Since the metals are not clean, the passage of electric current may be affected by thin oxide, sulfide and other inorganic films usually present on metal surfaces. Hence, the total contact resistance of a joint is a sum of the constriction resistance (R_c) and the resistance of the film (R_f):

$$R=R_c+R_f, \qquad R_f=\sigma/(\pi a^2), \quad (2)$$

where σ is the resistance per area of the film. In most practical applications, the contribution of these films to the total contact resistance is of minor importance, since the contact spots are usually created by the mechanical rupture of surface films.

Increasing the number of electrical current paths and more uniform distribution of current can be achieved by increasing the surface roughness thus increased probability to establish many metal-metal contacts at much lower loads than with smooth surface. Hence, the contact surfaces finished with rough abrading will have appreciably lower contact resistance than those smoothly machined (Naybour and Farrell, 1973a; Oberg and Olsson, 1992).

When the current is confined to flow through the conducting spots (a-spots), the temperature of the point of contact (T_c) may be higher than that of the bulk (T_b). Hence, the increase in constriction resistance over the resistance that would exist if the metal-metal contact were continuous across the entire contact area can be expressed as:

$$R_c=R_c(0)[1+2/3(T_c-T_b)]. \quad (3)$$

The term (T_c-T_b) is called the super-temperature and is related to the voltage drop across the contact interface (U) as:

$$T_c^2-T_b^2=U^2/(4L), \quad (4)$$

where L is the Wiedemann-Franz Lorenz number (2.45×10^{-8} V^2/K^2). Hence, a small increase in the contact voltage (U) can raise the super-temperature high enough to produce metallurgical changes such as softening or even melting of the conducting areas.

In a good connection, the temperature of the interface is only slightly higher than the bulk temperature but in a poor connection the super-temperature is higher than the bulk temperature and accelerates deterioration of the contact areas, causing higher resistance. The deterioration is cumulative resulting in increasingly higher temperatures and ultimate failure of the connection.

The deterioration of a connector proceeds slowly at a rate determined by the nature of different processes operating in the contact zone and in the environment. This initial stage persists for a long time without any noticeable deterioration until the final stages of the connector life when a self-accelerating deterioration, resulting from the interaction of thermal, chemical, mechanical and electrical processes is triggered causing the contact resistance to rise abruptly (Williamson, 1968).

Oxidation

The oxidation of the metal-metal contacts within the contact interface is widely considered as the most serious degradation mechanism occurring in mechanical connectors. In the copper connections and 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. From about 40 °C to about 200 °C in air, there is a continual temperature dependent thickness growth of the Cu_2O oxide. At about 200 °C and above, other copper oxides form while continually consuming metal. Copper oxides are softer as compared with aluminium oxides and more easily disrupted by the applied contact force and are also semiconducting. The electrical resistivity of Cu_2O is 10^{10} μΩ·cm.

In the aluminium contacts, however, oxidation is generally considered as a less likely mechanism of degradation since the oxide growth is self-limiting to a thickness of about 10 nm within a very short period of time. When exposed to the oxygen-containing atmosphere, aluminium oxide Al_2O_3 forms as a duplex film which is hard, tenacious, and brittle with a high resistivity of 10^{24} μΩ·cm.

The hardness and tenacity of the Al_2O_3 film makes it difficulty to establish a good contact through this film as compared with the relative ease of forming metal-to-metal contacts in copper through a Cu_2O film. As a result, in the electrical contacts having one or both contact members of aluminium, the current flow is restricted to flow through the areas where the oxide film is ruptured.

The hardness of the oxide film can be significantly reduced by segregation of solute or impurities to the free surface. Thermal cycling of an Al-0.5 at.%Mg alloy was found to cause impurities to segregate to free surfaces and thus reduce the hardness and contact resistance (Braunovic *et al*., 1977). The solute surface segregation made the oxide more brittle, thus creating more cracks through which the contacting materials extruded to form conducting paths.

Galvanic corrosion

Whenever dissimilar metals are coupled in the presence of solutions containing ionized salts, galvanic corrosion will occur. The metal with the most negative electrolytic potential is anodic and will be consumed by galvanic action. In the Al-Cu 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 process will continue as long as the electrolyte is present or until all the aluminium has been consumed, even though the build-up of corrosion products may limit the rate of corrosion at the surface.

The Al-Cu 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.

Dust corrosion

This type of corrosion occurs due to presence of water-soluble salts in the dust. Such solutions form electrolyte and cause metal to corrode. This problem has been extensively studied by Lin and Zhang (2004) and Wan *et al*.(1999) who have shown that the relative humidity and the pH factor are the most important parameters affecting dust corrosion. Corrosion of dust particle increases almost linearly with the relative humidity as seen in Fig.5 whereas the typical appearance of corrosion product around the dust particle is shown in Fig.6.

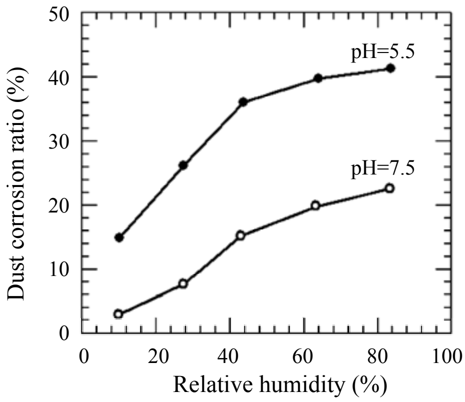


Fig.5 Corrosion ratios of dust particles with different pH as a function of relative humidity

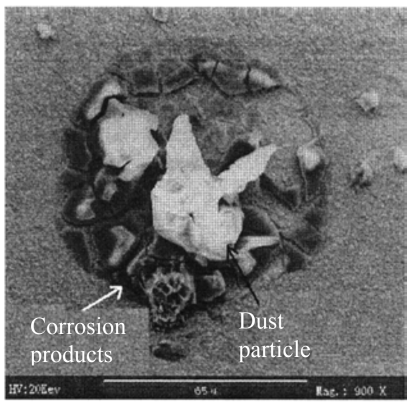


Fig.6 SEM images of the corrosion product around dust particle

Thermal expansion

When exposed to an increase in temperature, aluminium expands at a greater rate than copper and causes large lateral movements in the contact zone, which shears the metal-contact bridges thus reducing the contact area and increasing the contact resistance so causing the connection temperature to rise. At higher temperatures, the stresses may be relieved by recovery in the matrix.

On cooling, however, the thermal stresses build up again and further interfacial shearing occurs since at lower temperatures there will be very little recovery in the matrix and thus little stress relief. When the process is repeated many times, considerable plastic deformation in the contact zone will take place if the thermal stresses generated are greater than the yield stress of the aluminium. The result is a cascading effect, which accelerates the degradation of the connection until failure.

Another result of the greater thermal expansion of aluminium is thermoelastic ratcheting. In a bolted Al-Cu joint when a steel bolt is used, excessive tightening of the bolt can plastically deform the aluminium and copper conductors during heating which cannot regain their original dimensions during cooling. Repeated heating and cooling can thus cause loosening of the joint, which, in turn, will increase the joint temperature and contact resistance.

Fretting

Fretting is a common problem of significant practical importance that can affect a wide range of electrical equipment, incur costly component replacement and even more expensive equipment downtime. The process is defined as accelerated surface damage occurring at the interface of contacting materials subjected to small oscillatory movements that can be produced by mechanical vibrations, differential thermal expansion, load relaxation, and by junction heating as the power is switched on and off.

Fretting is generally concerned with slip amplitudes not greater than 125 μm. The nature of fretting depends on a large number of variables, and many theories have been proposed to account for the effects observed but no unified model for the process has yet emerged. A comprehensive review of fretting in power connections is given elsewhere (Braunovic, 1999). The examples of fretting damage in contacts of aluminium with copper and tin-plated contact are illustrated in Fig.7.

The reliability of bolted joints is generally attributed to high contact forces and large apparent contact areas with virtually no relative displacement between the contacting members. Although this may hold for copper-copper joints, it is certainly not the case of the Al-Cu connections.

The differential thermal expansion, generated by higher coefficient of thermal expansion of aluminium

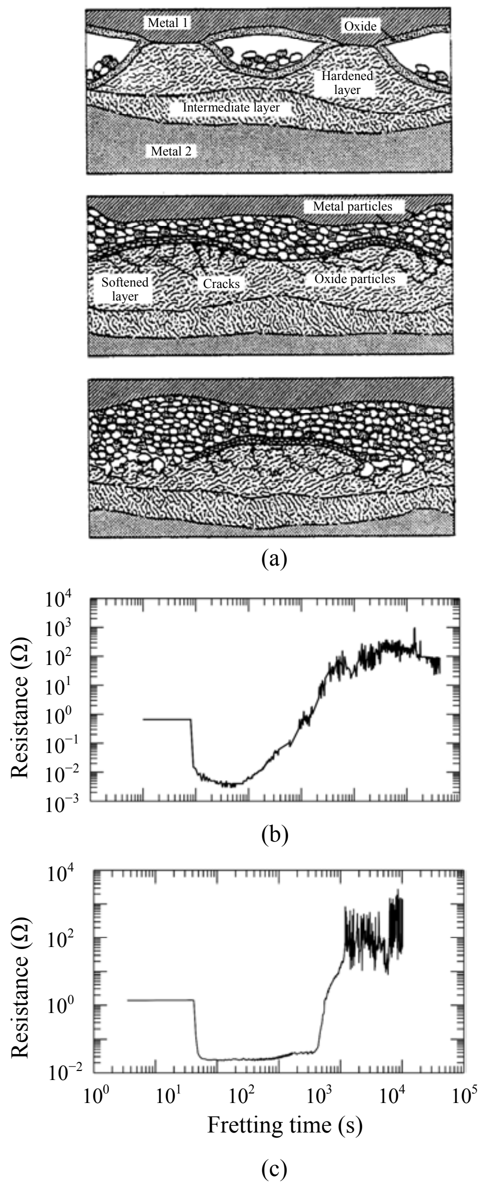


Fig.7 (a) Schematic of fretting damage evolution in electrical contacts. Effect of fretting on the contact resistance of (b) Al-Cu and (c) Al-Sn (tin-plated copper) contacts

(1.36 greater than copper), will cause displacement of the contact interface, shear the metallic bonds at the contact interface and induce significant joint degradation.

The fretting damage in the real life connectors has been reported in the case of tin-plated bolted joints commonly used for distribution transformers (Braunovic and Gervais, 1990). These connectors had been removed after 7~10 years of service due to either overheating, or unstable performance on the network under normal operating conditions.

Fig.8 shows a typical example of severe fretting damage in a connector as evidenced by a characteristic band of accumulated fretting debris and oxides formed in the contact zone around the bolt hole. The contact resistance of these zones was found to increase rapidly to very high values, and in some locations, an open-circuit conditions was developed (Fig.9).

More recently, the effects of fretting in copper-to-copper contacts under AC (60 Hz) and DC current conditions at fretting frequency 1 Hz, slip amplitude 100 μm and current 50 mA were investigated (Braunovic and Gervais, 1990). The results showed that the overall contact resistance behaviour of copper-to-copper wire-plate couples under AC and DC current was practically the same as illustrated in Fig.10.

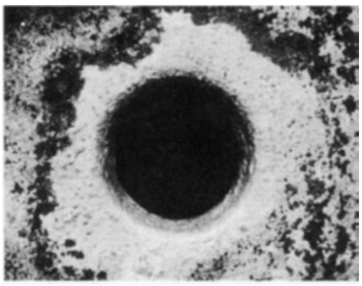


Fig.8 Fretting damage in a tin-plated connector removed from service

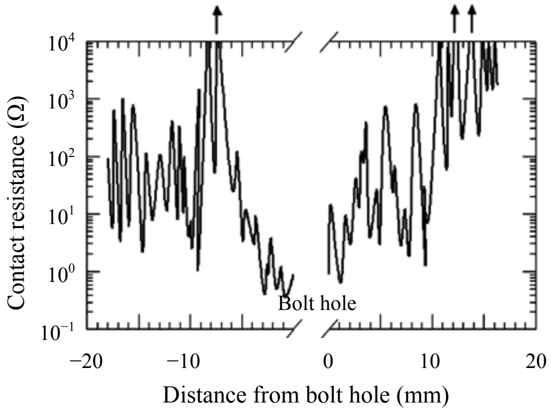


Fig.9 Contact resistance variations in contact zone damaged by fretting

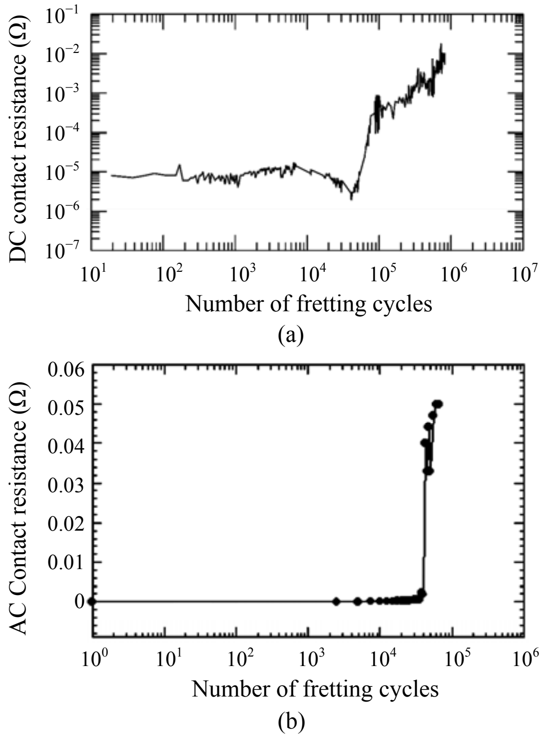


Fig.10 Effect of fretting on the DC (a) and AC (b) contact resistance of copper-to-copper wire-plate contacts. Fretting conditions: contact load 400 grf, fretting frequency 1 Hz, slip amplitude 100 μm current 50 mA

The characteristic feature of the samples under AC current conditions is a pronounced distortion of the contact voltage (Fig.11) and the presence of large amounts of flake-like fretting debris widely scattered around the contact zone (Fig.12). However, fretting debris in the samples fretted under DC conditions are compacted without the flake-like debris.

Intermetallic compounds

Bimetallic welds, particularly, Al-Cu are increasingly being used in a variety of electrical applications. Such joints, made by friction welding, pressure welding, diffusion and roll bonding, flash welding and explosion welding, are characterized by a relatively stable joint interface and negligible intermetallic formation. In service, however, frequent

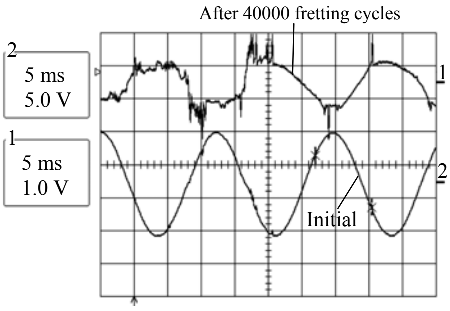
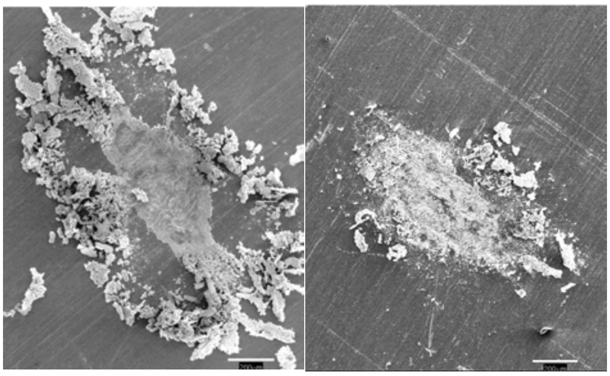


Fig.11 Contact voltage wave forms initial and after 40000 fretting cycles



(a) (b)

Fig.12 SEM images of the contact zones after 40000 fretting cycles under AC (a) and DC (b) current conditions

current surges on the network may generate favorable conditions for interdiffusion to occur and thus nucleation and growth of intermetallics at or near the initial interface. This, in turn, can seriously impair the overall electrical stability and mechanical integrity of bimetallic joints since intermetallic phases have much higher electrical resistance and lower mechanical strength.

Published experimental evidence of roll-bonded, hot-pressed and flash-welded aluminium-to-copper joints show that the mechanical and electrical properties are significantly affected by the formation and growth of intermetallics at the joint interface (Bauer and Lessmann, 1976; Timsit, 1986; Wallach and Davis, 1977; Braunovic and Alexandrov, 1994). When the total width of intermetallic phases exceeds 2~5 μm, the Al-Cu joint rapidly loses its mechanical integrity (Timsit, 1986).

The effect of electrical current on the kinetics of formation and morphology of intermetallic phases has recently been demonstrated in the case of friction-welded Al-Cu joints (Braunovic and Alexandrov, 1994). It was shown that the growth kinetics of intermetallic phases under the influence of electrical current is much higher than that under diffusion annealing in a temperature gradient. The deleterious effect of intermetallic phases is reflected in the greater brittleness of the contact interface (Fig.13a) and significantly higher contact resistance is found to increase linearly with the thickness of the intermetallic phases formed (Figs.13b and 13c).

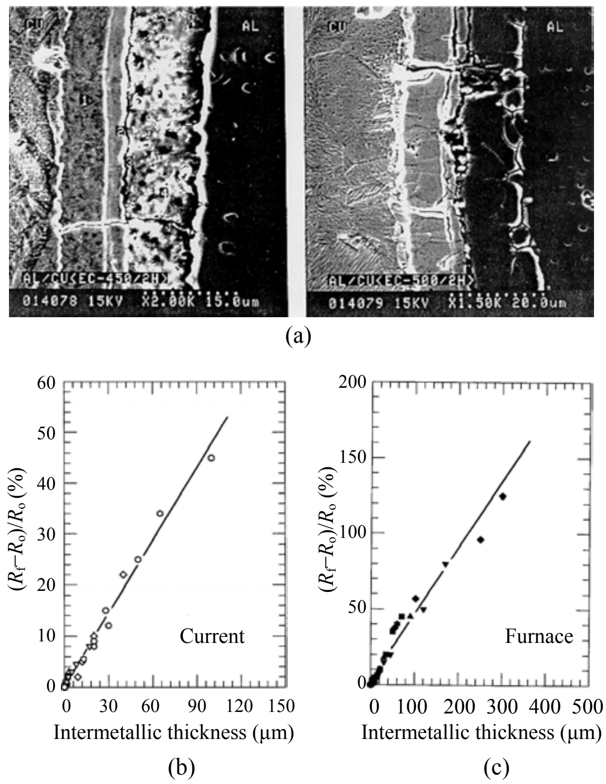


Fig.13 Formation of brittle intermetallics in Al-Cu bimetallic joints (a), and evolution of contact resistance in diffusion annealed Al-Cu joints in electric (b) and thermal gradient (c)

Stress relaxation and creep

Creep, or cold flow occurs when aluminum 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 stress but, unlike creep, is not accompanied by dimensional changes. It occurs at high stress levels and is evidenced by a reduction in the contact pressure due to changes in metallurgical structure.

The change from elastic to plastic strain has the effect of significantly reducing the residual contact pressure in the joints, resulting in increased contact resistance, possibly to the point of failure. The loss of initial contact pressure can be further accelerated at elevated temperatures, causing a loss of contact area in a relatively short time. Hence, excessive conductor deformation and high stresses produced by certain connector systems having no means of providing residual mechanical loading to the contact interface can cause accelerated stress relaxation and eventual failure of a joint.

The metallurgical state and temperature was found to exert strong effect on the stress relaxation of aluminum and copper (Naybour and Farrell, 1973b; Atermo, 1973). It was shown that, for electrical grade aluminum (EC-1350 grade), increasing the temperature and the amount of hardening augmented the rate of stress relaxation. It was also revealed that stress relaxation in hard-drawn EC-grade aluminum conductors was anisotropic, being much faster in the transverse than in the longitudinal direction, and much faster in hard-drawn than annealed wire. This is shown in Fig.14.

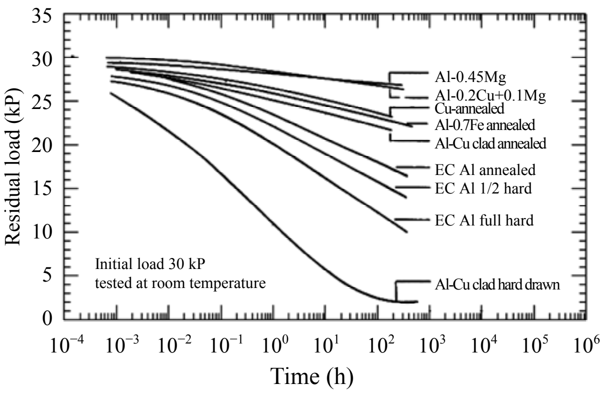


Fig.14 Effect of metallurgical state on the stress relaxation of aluminum

Mounting evidence indicates that mechanical properties such as creep, stress relaxation, flow stress can be significantly affected by the action of electric current. This so-called electroplasticity manifests itself in a dramatic increase in the ductility of a material. It is generally believed that the effect is a result of the interaction between electrons and dislocations, although some controversy still exists regarding the exact nature of this electron-dislocation interaction. A comprehensive overview of the electroplastic effect in metals was given by Sprecher *et al.*(1986).

Troitskii and co-workers (Troitskii, 1985) have used stress relaxation to study the electroplastic effect in a number of metals such as zinc, lead and cadmium under the influence of high-density (10^4 A/cm^2) current pulses. The frequency of the pulsing current was 100 Hz and the pulse duration 65 μs. They found that the application of current increases the rate of stress relaxation and significantly affects its onset. Fig.15a depicts stress relaxation dependence on time with and without current. Fig.15b illustrates the rate of stress relaxation with and without current as a function of applied stress. Note that the onset of stress relaxation with and without electric current is different: it is significantly lower for the samples under the influence of electric current.

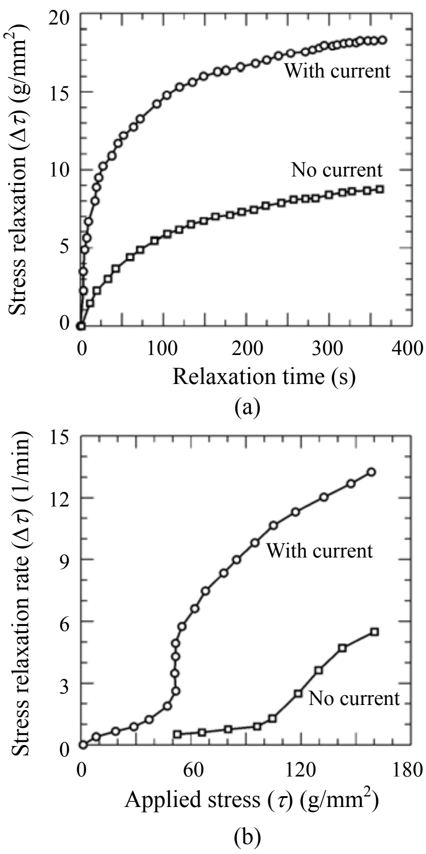


Fig.15 (a) Variation of stress relaxation with time with and without current; (b) Variation of the rate of stress relaxation with applied stress for samples with and without current

PALLIATIVE MEASURES

Contact area

The size of the contact area is generally determined by the hardness of the contacting members, applied force, and the rated current density. It should be sufficiently large to prevent the rise of the contact interface temperature under normal and emergency conditions. The contact temperature itself is not a critical parameter since it is a result rather than a cause of the processes occurring in a joint, being a function of the current density, the contact geometry and the voltage drop across the contact. The stability of the contact performance can only be assured when the changes in the contact temperature and voltage with the connector operating time remain very small.

Practice and published experimental evidence show that mechanical abrasion (brushing) is the simplest and most effective method of obtaining a large number of contact points. To serrate the connector contact surfaces is another efficient method when splicing conductors because the sharp serrated edges ensure a large contact surface area between connector and conductor. Examples of serrated contact surfaces are illustrated in Fig.16.

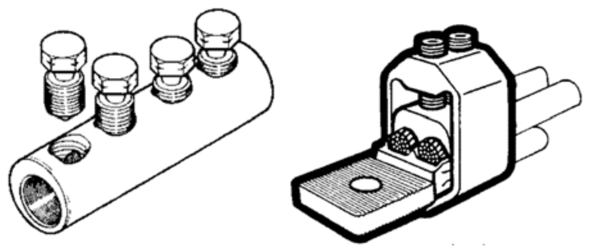
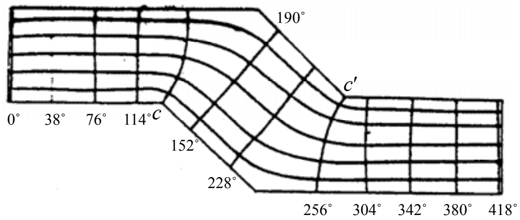


Fig.16 Examples of the serrated contact surfaces

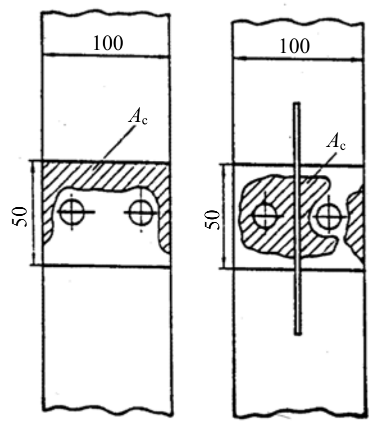
In a bolted joint, current lines are distorted at the joints as a result of which, the resistance of even a perfectly made overlapping joint (no interface resistance) is higher than that of a bar of the same length as the joint. This is known as "streamline effect" and is determined by the ratio between the overlap and busbar thickness. The current distortion can be minimized when the overlap length in a bolted joint is 5~7 times the busbar thickness. As a rule of thumb, the minimum overlap should be from 8 to 10 times the bar thickness. Furthermore, since the actual area of contact is much less than the total area of overlap, the current density in the contact surface should not exceed 1/3 to 1/4 of the current density in the busbar cross section.

Current distortion in the joint (streamline effect) can be substantially reduced by slanting the busbar ends under 45° (Fig.17a) which, in turn, will make the current distribution across the joint more uniform. The initial contact resistance of bolted joints with slanted ends is 15% lower than that without slanted ends. This is due to uniform current distribution at the contact interface, which eliminates localized overheating and thus improves the contact thermal stability.

Cutting the slots in the bus bars (Fig.17c) can enlarge the contact area by 1.5 to 1.7 times that without slots. The contact resistance of a joint configuration with slots in Fig.17c is 30%~40% lower than that of Fig.17b and is mechanically and electrically more stable. The beneficial effect of sectioning the bus bar is attributed to a uniform contact pressure distribution under the bolt which, in turn, enlarges the contact area (Boychenko and Dzektser, 1978).



(a)



(b) (c)

Fig.17 (a) Equipotential and current lines of an idealized joint with slanted bus bar ends; Schematic of bolted joints without (b) and with (c) slots

Contact pressure

A well-designed connector should have adequate mechanical strength to maintain its mechanical integrity under normal and overload conductor operating conditions and sufficient contact pressure to maintain an ample contact area, thus allowing uninterrupted passage of current across the contacting interfaces. The pressure, however, should never exceed elastic limits of the joint components since plastic deformation can increase stress relaxation and creep of the contacting members, which leads to eventual loss of a contact.

In a compression connector, there are definite relationships between the degree of compression and the resulting electrical and mechanical characteristics of the connection. In the initial stages of this deformation, the contact resistance is practically proportional to the deformation i.e. it decreases as the deformation increases. However, once the conductor is fixed firmly in the sleeve, the decrease in contact resistance levels off until no decrease is noticed with further deformation. At this point a satisfactory electrical connection has been established.

In the bolted joints, the use of contact force as an indicator of a satisfactory joint assembly is impractical, instead, tightening torque is almost entirely used in practical situations. Tightening torques depend upon the contact pressure required for the particular bus bar application. The amount of pressure for a given torque value varies over a wide range, depending upon whether threads are dry, lubricated, hot galvanized or otherwise treated. Hence, it is essential to maintain the tightening torque within the elastic limit of the bus bars since upon exceeding it, bus bars will undergo plastic deformation, which, in turn, will increase the stress relaxation and creep and thus cause loosening of a joint.

Mechanical contact aid devices

Although a bolted type connection is widely used method of joining aluminium and copper conductors, there are doubts concerning its reliability under the operating conditions, owing primarily to the fact that when two dissimilar metals are used, the difference in their physical, mechanical and metallurgical properties results in difficulties to make a satisfactory joint.

The heating and cooling of a bus joint as the result of normal changes in electrical load cause the corresponding increases and diminutions in the thickness of the bolted joint, varying in magnitude with the thermal expansion coefficient of the material. Moreover, the bolts are usually not heated by the current in the conductors to the same extent as the conductor itself resulting in a temperature differential of 10 °C or more between the bolt and the conductor, which tends to narrow over a period of time. During the hot portion of the load cycle, the differential expansion of the bus conductor and the bolts add additional stresses to the original stresses in the conductor and the bolt.

Studies of the effect of different types of mechanical contact devices on the performance of bolted Al-Al and Al-Cu joints under current cycling and stress relaxation showed that a combination of a disc-spring (Belleville) and thick flat washers assured the most satisfactory mechanical and electrical integrity of bolted joints under current-cycling and stress relaxation conditions (Braunovic and Marjanov, 1988).

The most important characteristics of disc-spring washers are their ability to elastically absorb deformation caused by an outside load. Fig.18 illustrates the preferred joint configurations for jointing aluminum or copper bus bar conductors. In all cases, in order to have a more uniform stress distribution in the bus bars under the washer and to avoid its buckling, it is recommended to use flat washers at least 3~4 mm thick.

When steel bolts are used, it is recommended to use disc-spring washers with a high spring constant and flat washers with thickness at least twice that of the disc-spring washer. Furthermore, the disc-spring has to have a very high spring constant to provide the required elasticity of a joint during temperature excursions caused by joint overheating, short circuit conditions and other causes impacting on the mechanical integrity of a bolted joint.

Failures due to differential thermal expansion can be avoided with the use of aluminium alloy bolts because the coefficients of expansion of the aluminium conductor and the bolts are essentially the same. An alternative method of joining Al-Al or Al-Cu is the use of a transition washer inserted between the contacting aluminium and copper surfaces. The sharp surface profile of these washers ruptures the oxide films without need for further cleaning and establishes substantially larger contact area that is more resistive to aging than the direct surface contact. It should be pointed out, however, that although these washers do not require surface preparation of the bus bar conductors, the use of contact aid compounds is essential.

Fig.19 shows examples of transition washers commonly used in Germany (Fig.19a) and Great Britain, France and Canada (Fig.19b). Although these washers do not require surface preparation of the bus bar conductors, the use of contact aid compounds is essential.

Coating (plating)

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

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 higher 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-plated contacts are very susceptible to fretting, which causes severe degradation of contacting interfaces and leads to unacceptably higher 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 lubrication is essential for reducing the corrosion damage in a saline environment (Bonwitt, 1948).

Silver is an excellent conductor and is widely used in joints for high temperature operation in the enclosed type switchgear assemblies. A plating thickness of 0.005 to 0.015 mm for coating switchgear and enclosed bus is generally considered adequate, or even thicker than necessary. Because of the porosity of silver plating, however, a thicker deposit is required where abrasion and weather resistance are factors.

Where the joint will be connected and disconnected many times during the life, for instance, of the

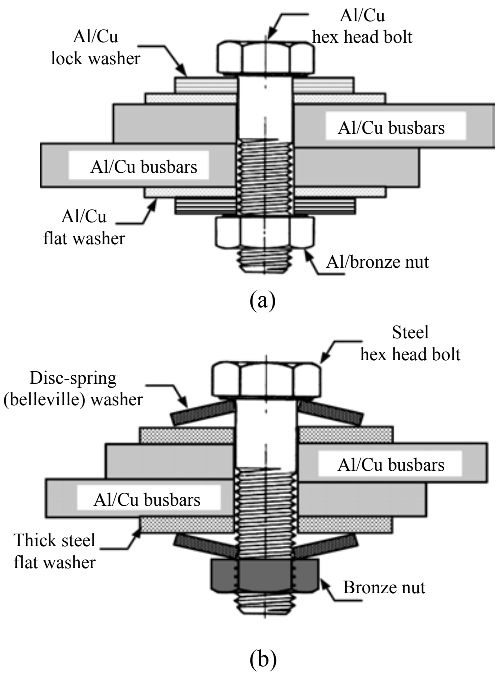


Fig.18 Recommended bolted joint configurations for (a) Al-Al; (b) Al-Cu and Cu-Cu busbar conductors

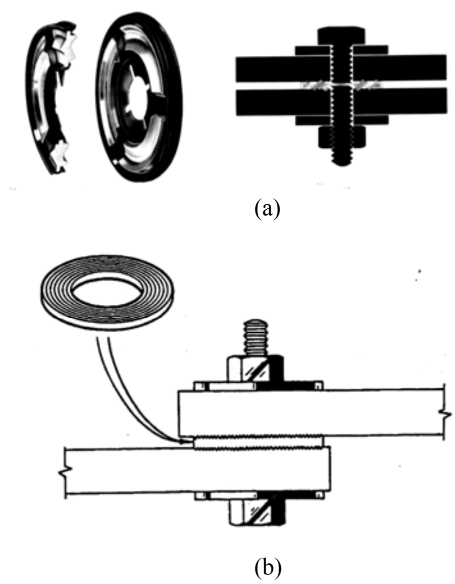


Fig.19 Transition washers made of (a) Al-Mg-Si alloy (used in Germany) and (b) brass (used in the UK, France and Canada)

disconnect switch, the silver plating must be thick enough to prevent exposure of the aluminium or copper through wear. Despite the advantages of silver plating of electric contacts in maintaining low electric resistance, it has a potential disadvantage: silver, like copper, is cathodic to aluminium and may, therefore, cause galvanic corrosion of aluminium.

Furthermore, due to sensitivity of silver to tarnishing, the use of silver-plating in environments where sulfurized contaminants are present has to be avoided. The coatings should be uniform and relatively thick. The use of protective contact aid compounds for optimum performance is essential for silver-coated joints that are exposed to high humidity or moisture.

The available data indicate that the nickel-coated connections show superior performance as compared with other plating materials. The superiority of nickel plating is manifested by its stable contact resistance behaviour under simulated service conditions and also from the point of view both of its economy and the significant improvements to the metallurgical and contact properties of Al-Cu connections (Bond, 1969; Jackson, 1982; Lefebre *et al.*, 1990; Bruel and Carballeira, 1986; Braunovic, 1990).

Lubrication (contact aid compounds)

It has been known for some time that the use of 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.

It is a common practice that for both aluminium and copper bus bar 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 aluminum, this procedure is more important for aluminum contacts than for copper. However, when electrical equipment is supplied with either silver- or tin-plated terminals, the plated contact surfaces should not be scratched or brushed. Only the contact surfaces of the aluminium or copper bus that are to be bolted to these surfaces should be prepared.

Recent studies have shown that the efficiency of a particular contact aid compound depends on its ability to protect the contact zones against corrosion and fretting, stability to thermal and UV degradation, spreading tendency, shear strength and the presence of metallic and/or nonmetallic particles added to improve their ability to shear the oxide films on the contacting surfaces (Braunovic, 1992).

It is now generally accepted practice to use contact aid compounds whenever aluminium is used. For all-copper connections, however, the use any lubricant is not a common practice since their deterioration proceeds for a long time without any appreciable changes in their performance. This is a false sense of security, since the experience has shown that the deterioration of copper connections occurs rather abruptly triggered by accelerated interaction of chemical, thermal, mechanical and electrical processes at the contact interface. Hence, to prolong the useful service life of copper connections, the use of appropriate contact aid compounds is strongly recommended.

It should be pointed out, however, that despite the protective benefits derived from the use of contact aid compounds, in some cases, the effectiveness of these compounds may be limited due to inadequate or improper application of the compound, loss of compound as a result of excessive operating temperatures and weathering characteristics of the compound.

CONCLUSION

The major parameters influencing the reliability and life of Al-Al and Al-Cu connections are identified and the effectiveness of various palliative measures are determined and the misconceptions about their effectiveness are dealt in detail.

It was shown that maintaining a large contacts area, adequate contact pressure and applying different mitigating measures such as lubrication, mechanical contact devices and coating are essential for assuring the reliability of power connections.

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