AN UPDATED VIEW OF THE ALUMINUM CONTACT INTERFACE

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Abstract - **The properties and behavior of aluminum in electrical power connections have been extensively studied for more than 50 years. This paper provides an overview of several key aspects of the aluminum contact interface. Examined in the light of experimental and theoretical information available today, some popular concepts of the aluminum contact interface that were developed many years ago are seen to be incorrect. The topics addressed are the wide variability of the oxide film, "self healing", "glowing" connections, and the effect of high current density at the metallic conducting spots within the contact.**

Keywords: Aluminum contact interface, self healing, glowing connection, electromigration, intermetallic compounds.

I. INTRODUCTION

In the United States, starting in the 1950's, the use of aluminum increased markedly, as a replacement for copper and brass, in a wide variety of common electrical applications. For example, in addition to wire and cable, aluminum was substituted for copper as bussbar in circuit breaker panels, cable connectors, and lamp sockets. Lower cost was the principal reason underlying the substitution of aluminum for copper and brass.

The lower material cost was achieved. In many applications, however, this saving was made at the expense of resolving product reliability and safety problems which resulted from overheating and burnouts at the aluminum electrical connections. The frequency of occurrence and serious consequences of the problems that were encountered stimulated a substantial amount of investigation of aluminum connections and the nature of the aluminum contact interface. In spite of more than one-half century of intensive investigation and testing of aluminum connection performance and contact properties, however, the long-term reliability and safety of products involving aluminum conductors or aluminum current-carrying components is not assured by present practices and standards.

Contributing to the problem is an often repeated - but erroneous - concept of the nature and behavior of the aluminum contact interface. This common concept envisions a very thin, brittle, and highly insulating aluminum oxide through which conducting metallic junctions are easily formed by the application of normal contact force. Once the contact is established, according to this model, it is immune to degradation mechanisms as long as the contact force is reasonably maintained. Further, according to this concept, in the event that overheating does start to occur, progressive deterioration to destruction is precluded by a phenomenon called "self healing", which reestablishes a low-resistance contact. This idealized model of an aluminum contact interface has been demonstrated to be wrong in many ways, by a large body of published studies from a diverse population of investigators.

This paper presents an up-to-date overview of the aluminum contact interface, one that is more consistent with the present body of investigative results and field experience. The concepts that are brought together here exist in isolation in the details of the related literature, much of which is essentially inaccessible and unknown to the average applications engineer. The discussion applies primarily to the contact interface of pressure connections in electrical power (as opposed to signal) applications.

II. ALUMINUM SURFACE FILM

Bare aluminum surfaces vary widely with respect to film thickness, composition, and conductivity. The often-pictured self-limiting thin (30 Å or so) and totally insulating oxide may grow on a fresh metallic surface of high-purity aluminum at room temperature, but those conditions do not generally apply for commercial aluminum products. Practical aluminum conductor and electrical component surfaces have a surface film of unique - and uncertain - characteristics. The actual thickness and properties of the surface film vary according to the composition of the aluminum and the specific thermal, environmental, and mechanical processing conditions to which the particular sample has been exposed, prior to, during, and subsequent to manufacturing.

The surface film on practical aluminum surfaces must therefore be considered as an unknown wide-ranging variable rather than the older model's extremely thin and pure (insulating) aluminum oxide film. Large variations in both thickness and conductivity must be expected, and are commonly reflected in the wide range of contact resistance (vs. force, non-wiping) results obtained on non-abraded aluminum specimens.[1][2]

III. ESTABLISHING METALLIC CONTACT THROUGH THE SURFACE FILM

The common concept envisions a surface film on aluminum that is easily disturbed and penetrated, such that a large number of minute metallic conducting "a-spots" are formed even when there is no wipe (lateral scraping) between the surfaces. This type of non-wiping surface engagement actually exists at many of the intended current-carrying interfaces of aluminum conductor splices and terminations as well as in flat bussbar connections. For example, it occurs at strand-to-strand contacts in splices made with "twist-on" connectors, at the strand-to-strand interface in multi-strand conductor terminations, and also between the conductor strand(s) and connector body in many types of pressure terminals.

The idealized easily-penetrated film on aluminum exists only as the extreme best case within a wide range. The oxide cracking envisioned in this best-case model is often based on the studies of Tripp and Williamson, who studied crack patterns that developed in spherical painted-clay asperity models pressed against glass plates or against each other.[3] Radial and circumferential cracks appeared in the paint film as engagement continued, and general crazing appeared after heavy deformation. For an aluminum-aluminum interface, with a surface film on each member, metallic junctions can occur only where a crack on one surface intersects or coincides with a crack on the other. Bond demonstrated cracking patterns of aluminum oxide under various surface engagement conditions.[4]

These studies defined conditions under which cracking occurs and allows contact to be established through the relatively brittle surface film. At a practical aluminum contact interface, the extent to which those specific conditions are met determines the amount of actual metallic conducting area that is established through cracks in the surface films. Surface roughness, the thickness of the surface film(s), the physical properties of both the film and the underlying metal, and surface lubrication are the major variables.

Experimental studies demonstrate that, without some sort of modification of the native oxide film on aluminum, there may be very few actual conducting metallic contact spots formed at aluminum non-wiping contact interfaces.[5] In contrast, a wiping or scraping action at the contact interface is much more effective in penetrating the aluminum oxide film. For example, in a binding-head screw termination of aluminum wire, the majority of the current may flow through the (scraped) interface under the head of the screw, rather than through the intended path directly from the wire to the contact plate.[6]

Similarly, it has been demonstrated that most of the current in many aluminum wire twist-on connector splices flows from wire to wire through the encompassing spring rather than directly from wire to wire. [7][8] The aluminum surface at the wire-to-spring interface is aggressively scraped in the process of making the splice, while the direct wire-to-wire interfaces are engaged without any wiping action.

In both of the above examples, the result is that substantial current flows through connector elements that are assumed to be - and designed to be - only clamping devices. These connector parts frequently are constructed with material and plating that are not capable of maintaining a reliable low-resistance contact to the aluminum conductor. In each instance, the current flow in the connection is not correctly predicted by the older concept of the aluminum contact interface. The present concept corrects this by recognizing that the oxide film on aluminum is a variable, and, on many practical conductor surfaces, is tough and difficult to penetrate.

IV. GLOWING CONNECTIONS

Among the anecdotal failure reports involving aluminum conductors in the 1970 time frame are some describing "glowing" devices and connections. The term is ambiguous in the context of electrical applications. In general "glowing" refers to the emission of visible light, which, in an electrical device, could be due to a plasma discharge, an arcing phenomenon, a semiconducting phenomenon, or a component hot enough to become incandescent.

Initial investigators attempted to achieve "glowing" in a short time by making intentionally loose contacts and manipulating or vibrating them while they were carrying current. Meese and Beausoliel managed to get some sort of relatively microscopic incandescence with certain combinations of materials by that method, and coined the phrase "glow phenomenon".[9] As it applies to the field reports of failing aluminum wire terminations and splices, this is seen to be an artifact of their experiment, and quite different from that more generally observed in failing aluminum contacts.

In long-term testing of field and laboratory samples within rated conditions, it was often observed that portions of a failing aluminum wire splice or termination would become hot enough to be incandescent simply from I^2R heating.[10][11]

This occurred at failing binding-head screw terminals operating at power dissipation of about 40W and above, and in failing twist-on connector splices at a somewhat lower level of power dissipation. The process of failure that was observed in the long-term experiments involves the progressive deterioration of a connection, resulting in substantial resistance increase. When this happens, the power dissipation at a given current also increases. A glowing (red-hot) binding-head screw termination of #10 AWG aluminum wire carrying 16 A (80% of circuit rating) will be operating at an average measured potential drop of about 2.5 V or more (connection resistance of 156 mΩ or more). The potential drop is not sufficient to cause malfunction of residential electrical equipment, even though the connection becomes dangerously hot. In contrast to the Meese "glow phenomenon" previously mentioned, red-hot connections (splice or wire terminal) within a wall receptacle box produce a macroscopic incandescence that emits enough light to be easily noticed by an occupant in a darkened room.

The red-hot high-resistance wire terminal or splice has a complex set of parallel and series interfaces in the current path. In a binding-head screw terminal, for example, there is more than just the aluminum wire to brass (or plated brass) contact plate interface. The current path also involves the screw, which may be made of brass (plated or non-plated) or steel (plated), and the screw-to-contact plate interface. The various material combinations utilized differ in the probability of deteriorating to the red-hot incandescent condition. Aluminum-wired terminals with steel screws, for instance, are more likely to become red-hot than those utilizing brass screws.

Irrespective of the screw and plating materials, it is clear that the aluminum contact interface is capable of deteriorating to become a resistor or insulator that is capable of relatively stable operation at elevated (red-hot) temperature. The potential drop across the aluminum interfaces in these red-hot connections can be sustained at levels an order of magnitude higher than the melting voltage at which "B-fritting" (asperity softening and enlargement) is assumed to occur.[12][13]. As the bulk temperature at the aluminum interface increases, thickening of the oxide and loss of force (from creep - or stress relaxation - and annealing) lessen the possibility of the occurrence of B-fritting.

V. "SELF HEALING"

B-fritting is the phenomenon underlying the behavior that Williamson called "self healing" of an aluminum contact interface.[14] Under this concept, as long as contact normal force is maintained, resistance increases are counteracted by decreases - "self healing" events - that are presumed to occur when, at elevated temperature, asperity softening and spreading or collapse results in additional cracking and penetration of the insulating oxide.

The term "self healing" implies that the contact resistance decrease is permanent, but that is not the case. The process is cyclic. Deterioration processes that cause the resistance to increase remain active, so that after a "self-healing" event the contact resistance again increases, and the process is repeated. Connections undergoing this process are erratic (sometimes relatively high temperature or potential drop, sometimes low), but, over the long term, the average power dissipation and temperature (at a given current) increase.

B-Fritting has been studied on constant-force probe-type contacts. That is not a valid model for a conducting metallic junction within a much larger load-bearing area, as generally exists in a typical aluminum contact interface. The softening of metal in the immediate vicinity of the tiny metallic contact spot does not result in any significant strain in the balance of the load-bearing area. B-fritting is not the mechanism that correctly accounts for "self healing" in a large-area aluminum contact.

For the B-fritting mechanism to activate, the potential drop must be close to the softening voltage, which, for aluminum, is 0.1 V.[15] Consider how this occurs in an actual contact: for example, a simple Al-Al crossed-wire (#12 AWG) contact, with initial contact resistance measuring 1 mΩ at a force of 2 kg. This is in the range of experimental results for aluminum crossed-wire contacts. [1][16][17] The actual load-bearing area in this contact is about $1.67\text{x}10^{-3}$ cm^2 (based on yield strength for the aluminum wire of 1200 kg/cm^2). The maximum possible conducting metallic contact area is that of a single a-spot, assumed to be circular, with a radius of $1.45\text{x}10^{-3}$ cm. The metallic conducting area is then $6.6\text{x}10^{-6}$ cm$^{2.}$. If conduction occurs though multiple a-spots,, the total metallic conducting area (for the same contact resistance) would be lower.[18] Initially, therefore, the metallic conducting spot is, at most, about 0.5% of the total load-bearing area. At 10 A current, the potential drop in this contact is 0.01 V (E=IR). The power dissipation, 0.1 W, results in a negligible bulk temperature increase of the aluminum wires.

Next, consider what happens if the deterioration over time reduces the metallic conducting area such that the contact resistance increases to 10 mΩ. The potential drop increases to 0.1 V, which is the softening voltage, meaning that the temperature at the metallic conducting junction is quite high. The power dissipation of the contact is only 1 W, however, and the bulk temperature rise is about 10$^{\text{O}}$C. At this point, the actual metallic conducting area has been reduced to $0.145\text{x}10^{-3}$ cm radius, and comprises only about 0.004% of the load-bearing area. The applied contact force has remained constant, as has the actual load-bearing area. There is no significant mechanical change in the contact interface that can be attributed to softening in a zone representing such a tiny fraction of the load-bearing area.

This conceptual picture is easily tested by considering the analogous effect of simply increasing the contact force by the same .004%, or even one or two orders of magnitude more. It is obvious that a drop in contact resistance, from 10 to 1 mΩ (to recover, or "self-heal", to the original value), is not likely to occur from a contact force increase of the order of 0.1%.

More likely, the explanation for the so-called "self-healing" behavior is that, when the potential drop becomes high enough, there is an electrical breakdown across the insulating film that results in a conducting metallic bridge at the point of breakdown. This is the mechanism that Holm called "A-fritting".[12] Evidence of A-fritting in aluminum contacts has been demonstrated by electrical means (oscilloscope) and by the resulting arc-pitted surface often encountered in failing aluminum contacts.[5][19]

"Self Healing" is a stage of the long-term failure sequence of aluminum connections that, in the long term, does not stop the progressive deterioration mechanisms that lead to eventual high-temperature catastrophic failure. If a medical term is to be used to describe this aspect of contact behavior, perhaps "temporary remission" imparts a more realistic concept of what is actually happening.

VI. CURRENT DENSITY

The common concept of the aluminum contact interface does not consider current density in the metallic junctions as a factor influencing contact life. The aluminum contact interface is assumed to be permanent and stable provided that normal force is maintained, that there is no interfacial motion, that it operates at reasonable (bulk) temperature, and that the ingress of corrosive agents is prevented. It is now known, however, that there are two deteriorating mechanisms, namely electromigration and growth of intermetallic compounds, that are influenced by current density.[20][21][22][23]

It is well understood that it takes very little conductive metallic area at the contact interface(s) to achieve low initial resistance in a practical aluminum connection. Contact resistance is not uniquely related to the actual area of metallic contact, however. At a given contact resistance, the actual area of conductive metallic contact, and with it the current density, may vary by orders of magnitude, depending on whether the metallic area consists of a few large spots or a larger number of substantially smaller spots. The native film on most practical aluminum surfaces favors the formation of very small a-spots, with a resulting high current density.

Electromigration is an atomic diffusion phenomenon enhanced by current flow. It is tempting - but wrong - to consider electromigration as potentially active only with direct current (DC). At an a-spot in the aluminum contact interface, the current gradients are extremely steep, and the probability of an atom migrating out of the minimum constricted area toward the bulk metal is higher than the probability of it moving back in when the current reverses. With alternating current (AC) in a symmetrical contact (Al-Al), when current density is high enough to initiate electromigration, a net flow of atoms out of the narrowest part of the a-spot constriction occurs in both directions, toward the bulk metal on both sides. With time, in an a-spot undergoing electromigration, the metallic conductive area is continually reduced, increasing the current density and the rate of deterioration. The process continues, and accelerates, until the a-spot no longer conducts.

Bimetal connection systems involving aluminum in contact with other metals present conditions under which intermetallic compounds may form. Each of the various compounds that can form has a specific compositional ratio of the parent materials. In general, the intermetallic compounds that form at bimetallic contact interfaces have high resistivity relative to the parent materials and undesirable mechanical properties. When they form, the intermetallic compounds present a relatively brittle and high resistance layer in the conducting path. Resistance increases as the layer(s) thicken and also due to the formation of cracks. The nucleation and growth of intermetallic compounds is accelerated by elevated temperature and by current flow. The higher the current density at an a-spot in a bimetal contact, the greater the probability that intermetallics will form and the higher the rate of formation once the process starts.

This discussion has been presented in the context of a fixed and sealed aluminum contact interface in order to emphasize that, even in such a best-case contact, failure may occur if there is inadequate metallic conducting area at the interface. The conditions under which electromigration and intermettalic compound formation occur can exist within the normal operating range of practical aluminum connections when the metallic contact area is inadequate.[22][24] Low initial contact resistance, by itself, does not assure that the current density is low enough to preclude deterioration from these two mechanisms.

VII. OTHER FAILURE MECHANISMS

Practical aluminum contact interfaces are generally neither sealed nor fixed, and are thereby susceptible to additional failure mechanisms, including corrosion and fretting.[24] The potential for failure of aluminum connection systems from these processes is generally not recognized. This is most clearly demonstrated by the lack of relevant tests in the applicable qualification standards. The test that is generally performed under the standards, a so-called "heat cycle" test (actually a current-cycle test), as presently performed, is not capable of detecting susceptibility to the known aluminum connection failure mechanisms. An obvious example is the lack of environmental testing. Continued exclusive reliance on the heat cycle test reflects rejection of an extensive body of technical knowledge that has been developed over the years regarding the various failure mechanisms that may be active in aluminum connections.

VIII. DISCUSSION

The basic factors required to achieve high reliability and safety of aluminum terminations and interconnections have been established. The initial connection must have adequate metallic conducting area at the contact interface(s) in the intended current path(s), contact force must be reasonably maintained, motion of the interface must be prevented, and the interface must be sealed against ingress of atmospheric moisture and contaminants. It is the first of these conditions, the establishment of adequate metallic conducting area, reflecting the need to keep the current density low at the metallic conducting spots, that represents a major shift away from the older concepts.

Many of the early applications of aluminum became troublesome with time in service. From the mid-1960's to the early 1970's, the electrical industry was actively collecting information on field failures and trying to determine their underlying causes. That effort resulted in the introduction of the present type of heat cycle test into most of the applicable qualification standards. While the heat cycle test as generally applied does not specifically test for sensitivity to the known failure mechanisms, it has nevertheless been reasonably effective in screening out many of the poorest-performing connection types.

The result has been a plateau of performance, improved from the early days, but still at an undesirable level for the user. This is because there are some aluminum connection types in the market today that are prone to catastrophic failure in actual service even though they meet the applicable standards.[17][19][24] From the user's standpoint, the present standards do not adequately screen failure-prone connection types from the marketplace.

Progress towards more stringent qualification testing is, to a large extent, gated by the frame of reference adopted by those who create the products and their qualification standards. That frame of reference needs to be updated, to incorporate the technical understanding of the aluminum interface that has developed over the past several decades. The overview that has been presented here is, hopefully, a constructive step in that direction.

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