

FAILURE OF ALUMINUM CONNECTIONS IN RESIDENTIAL APPLICATIONS

J. Aronstein
Consulting Engineer
Poughkeepsie, NY

ABSTRACT

Failures of aluminum connections in various residential electrical applications are examined. Specific examples are provided, including aluminum bus bar contacts, aluminum-bodied connectors, and aluminum-shell lamp sockets. Design factors of the failed connections are discussed in terms of criteria for successful long-lived contact to aluminum. Deficiencies of the designs and the applicable qualification standards are discussed. Key words: Aluminum Contacts, Aluminum Connections, Aluminum Busbar, Connection Failure, Qualification Standards.

INTRODUCTION

Reliable and safe use of aluminum for current-carrying components of electrical apparatus depends on the ability to make long-lasting low-resistance connections to the aluminum surface. In many such applications it has been found that specialized connectors and/or installation practices are required. When adequate consideration was not given to the particular properties of aluminum relative to the requirements of the application and the application environment, serious problems have occurred. Examples include aluminum power transmission lines, service entrance cable, branch circuit wire, signal wire, and railroad locomotive cable.[1][2][3][4][5]

Aluminum connection problems generally appear after some time in service. In the examples noted above, short term or inadequate testing, together with insensitive acceptance criteria, failed to reveal the problems that were later encountered in actual service. In each instance, strengthening of acceptance testing and criteria was attempted after substantial field problems became evident. The long-term consequences have been costly, involving lost markets as well as litigation of personal injury, fire damage, and business losses.

The principal advantage of aluminum is lower cost relative to copper for the same current-carrying cross-section. Principally specified as a cost reduction, and in spite of the known connection interface difficulties relative to copper, aluminum has become common in many residential electrical applications. With time in service, field failures have become evident in various types of equipment and devices using aluminum current-carrying components. This paper examines aluminum connection failures in

three types of aluminum residential electrical components: service panel busbars, wire and cable connectors, and lamp sockets.

EXAMPLES OF ALUMINUM CONNECTION FIELD FAILURES

Aluminum Busbar Connections to Circuit Breakers

Molded case circuit breakers for residential applications have their input connection made to the panel's power distribution busbar by spring pressure contact. This simplifies insertion and removal of the circuit breakers. The spring contact in many instances is made to an aluminum surface, either directly to the busbar or its extensions. Figures 1 and 2 show the spring contact of a representative residential circuit breaker.

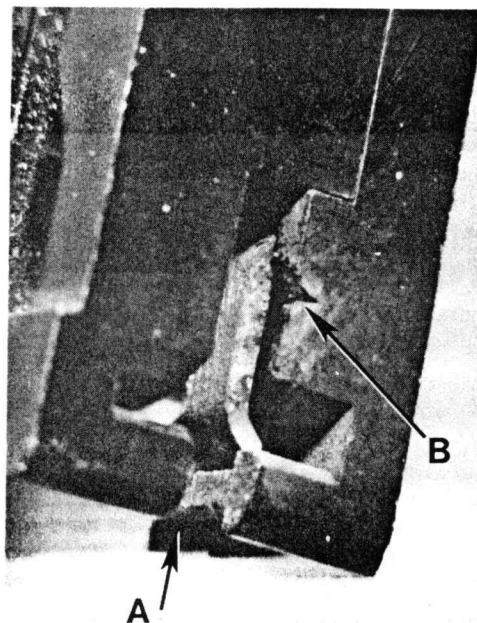


FIGURE 1 - CIRCUIT BREAKER SPRING CLIP CONTACT

(Arrow "A" shows direction of insertion of aluminum busbar finger. Arrow "B" shows case material charred from heat generation at the spring clip contact to aluminum busbar.)

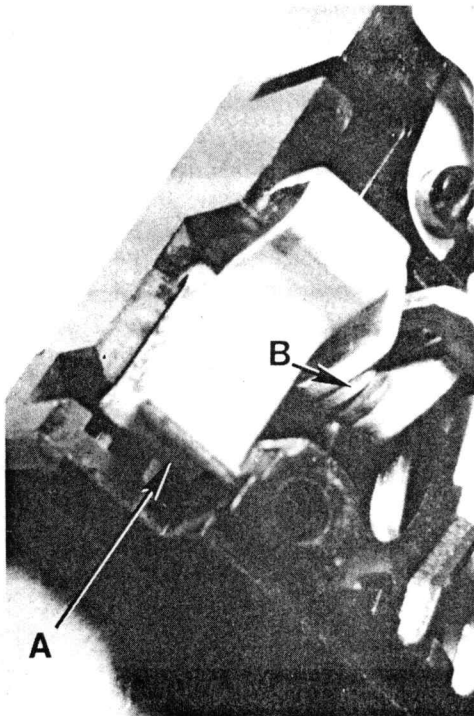


FIGURE 2 - CIRCUIT BREAKER SPRING CLIP CONTACT
Case opened to show construction.

(Arrow "A" shows direction of insertion of aluminum busbar finger. Arrow "B" shows make-break contacts.)

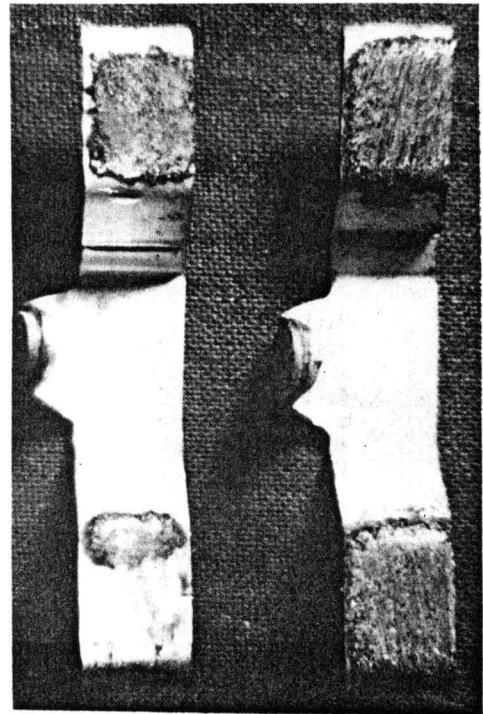


FIGURE 3 - CIRCUIT BREAKER SPRING CLIP CONTACTS
(Bent open to show areas of contact to the aluminum busbar.)

Inserting the breaker into the panel, the spring clip engages a mating finger on the bus bar, engaging it in the direction shown by the arrow "A". Contact is established on both sides of the busbar extension, with normal force generated by the spreading apart of the spring clip. Note in Figure 2 that the breaker's stationary make-break contact is constructed as an integral part of the clip (Fig. 2, "B"). This design is cost-effective in manufacturing but has serious deficiencies in terms of contact performance when used in combination with aluminum mating contact members.

Failures of circuit breaker spring contacts to aluminum busbar (or busbar extensions) are common. The failures involve increasing contact resistance and consequential abnormal heat generation. The spring contact of the breaker shown in Figure 1 is failing, and has overheated in service to the extent that the plastic case material has started to char in the area labelled "B".

Figure 3 shows two representative failing spring clip (to aluminum) contacts from relatively small (15 and 20 A) circuit breakers of the same type previously shown. The spring clips have been bent open so that the contact areas can be seen. These circuit breaker contact clips are from a residential installation in service for 20 years. Figure 4 is a closeup view of one of these contact areas. Note that the apparent area of contact is relatively large and it has been seriously eroded.

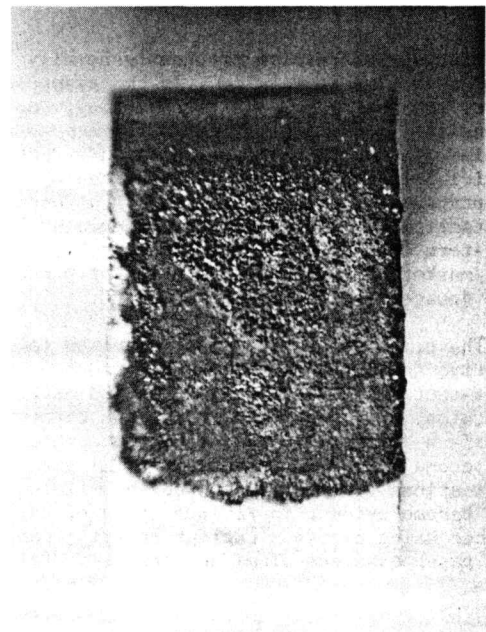


FIGURE 4 - SPRING CLIP CONTACT AREA
(Upper left area in Fig. 3)

Figure 5 shows the contact area to an aluminum busbar from a failing spring contact of a 200 A main circuit breaker. In this instance, the contact is single-sided. Severe erosion of the contact surface is again apparent.

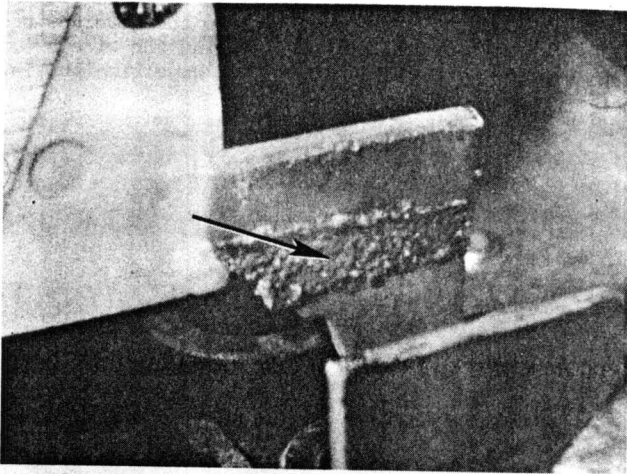


FIGURE 5 - ALUMINUM BUSBAR CONTACT TO 200 AMP MAIN BREAKER.

(Arrow indicates area of contact.)

Fuse Contacts to Aluminum Busbar

Some residential service panels utilizing fuses also have pressure contacts to aluminum busbar. One type of design uses cartridge fuses clipped into holders that in turn clip onto the busbar. Another design uses Edison base fuses which screw into a socket in the same manner as a lamp, but with the center contact bearing directly against the aluminum busbar. Figure 6 shows a representative configuration, with a failing contact at the fuse position on the right. An enlarged view of the eroded area of contact on the aluminum bus bar is shown in Figure 7.

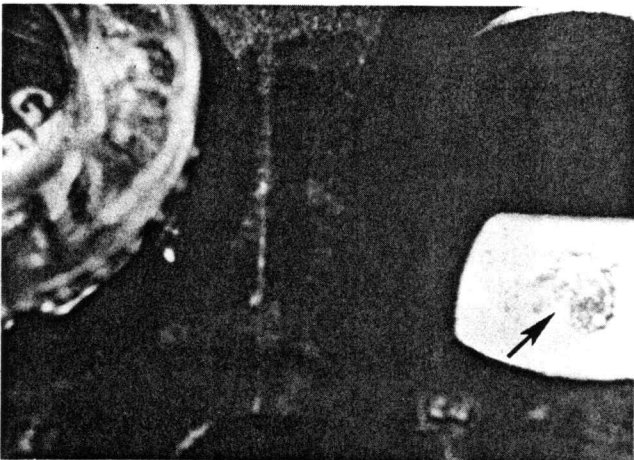


FIGURE 6 - FUSE SOCKETS IN SERVICE PANEL

(Edison-base fuse makes direct contact to aluminum busbar visible at right with fuse removed. Canadian.)

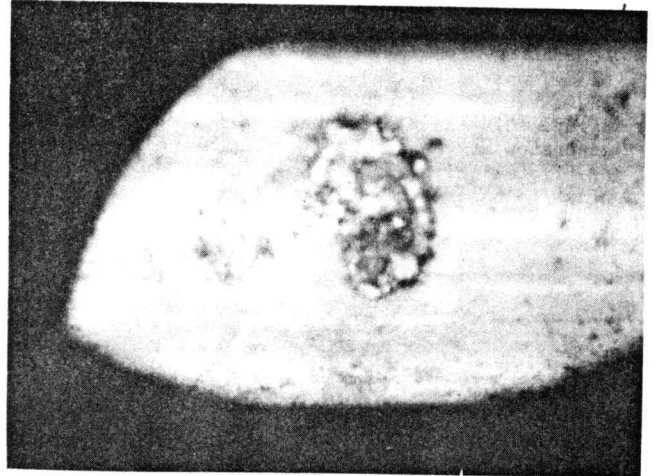


FIGURE 7 - CLOSE-UP VIEW OF CONTACT AREA OF RIGHT-HAND FUSE POSITION OF FIG. 6.

Aluminum Busbar Interconnections

Busbars in residential panels often consist of several parts, typically secured by steel screw fasteners with lockwashers. Similar connections are used to fasten terminal lugs to the busbar, the tang on the terminal lug serving as an extension of the busbar. Figure 8 shows one such design, in which a failing aluminum busbar interconnection has overheated in service to the extent of burning the insulating separator between the busbar and the back of the panel enclosure.

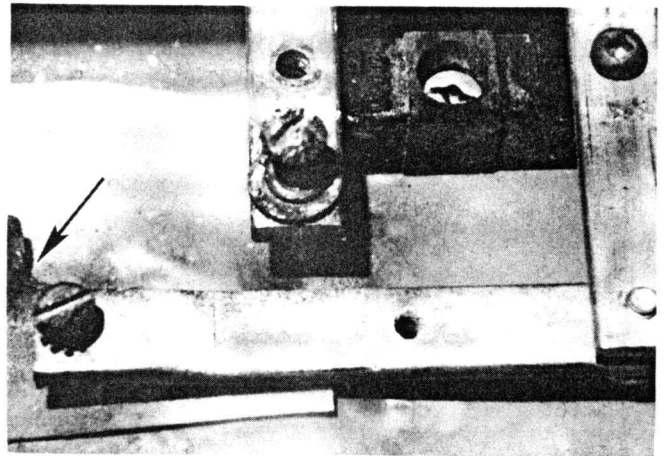


FIGURE 8 - SCREW CONNECTIONS OF ALUMINUM BUSBAR

(Arrow points to burned portion of plastic insulating barrier. Canadian.)

Figure 9 shows a different type of busbar interconnection. In this instance the bus link assembly consists of two posts and a short link, all of which are made of aluminum. Each post subassembly is held together by an 8-32 steel screw. The bus link assembly is used in a residential panel to carry current across from one breaker insertion position

to another. (Current is fed from a cable welded to the left-hand breaker insertion plate.) In the actual panel installation, most of the bus link assembly visible in Figure 9 is within and behind a plastic insulating block. The backside of the insulating block, corresponding to point on the bus link indicated by the arrow in Figure 9, is shown in Figure 10. The plastic had ignited due to heat generated at the contact between the aluminum post and the flat aluminum link. Smoldering combustion of the plastic insulator is indicated by the white ash residue.

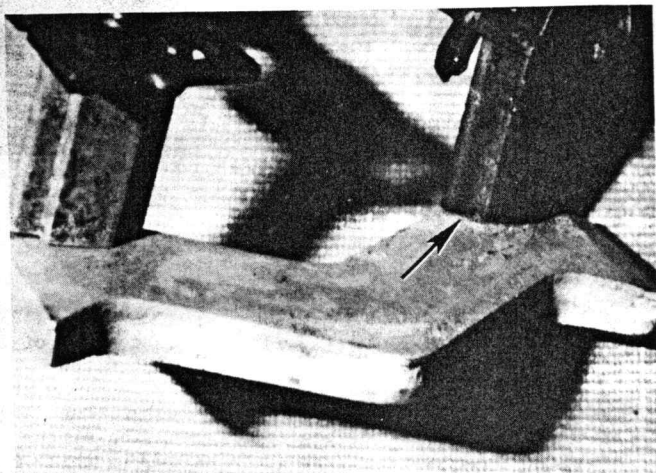


FIGURE 9 - ALUMINUM BUSBAR LINK ASSEMBLY

(Arrow shows contact between busbar and post that was originally mounted in the portion of the insulating block shown in Fig. 10.)



FIGURE 10 - INSULATING BLOCK IN WHICH THE ALUMINUM BUSBAR LINK ASSEMBLY OF FIGURE 9 WAS MOUNTED.

Aluminum Busbar Wire Terminal

The neutral side of the branch circuit wiring in a residential service panel is generally connected to screw terminals incorporated in a busbar, made of aluminum in most residential service panels today. Figure 11 shows the aluminum neutral bus of a residential service panel, with wires connected to it with steel binding head screws. One of the terminations of the copper wire to the aluminum busbar has failed to the extent of damaging the wire's insulation (arrow) as a result of excessive heating at the connection.



FIGURE 11 - WIRE TERMINALS ON ALUMINUM BUSBAR

(Arrow indicates insulation damage due to overheating termination, copper wire to aluminum busbar, steel screw.

Aluminum Body Connector to Copper Cable

Aluminum bodied connectors are widely used in residential electrical systems, for both copper and aluminum conductors. Failures of copper cable terminations at aluminum-bodied connectors occur, as for example that illustrated in Figure 12. Overheating at the connection has resulted in insulation damage on the cable.

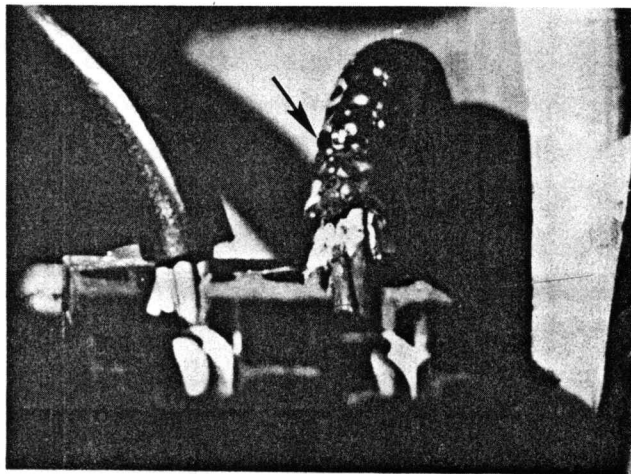


FIGURE 12 - INSULATION DAMAGE DUE TO OVERHEATING OF COPPER CABLE IN ALUMINUM-BODIED CONNECTOR.

Aluminum Lamp Socket Components

Aluminum is commonly utilized for lamp socket components. An example is the aluminum shell of the socket shown in Figure 13. Failure occurred at the contact between the aluminum screw shell and a brass eyelet (or tube) which is headed over to provide the current path to the wire terminal inside the socket assembly. Sufficient excess heat was generated at this failing connection to destroy the insulation on the wire at the screw termination on the other end of the eyelet.

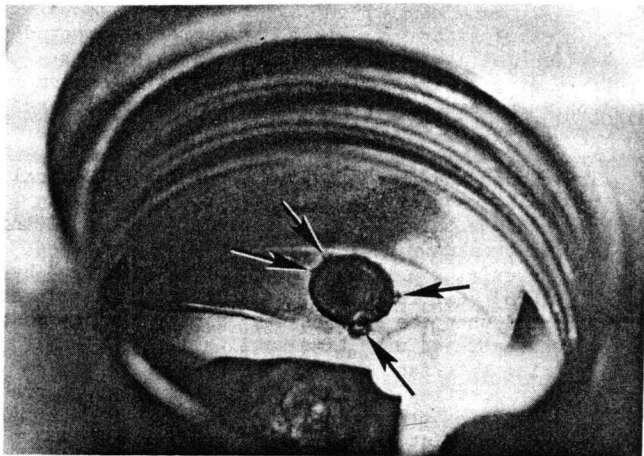


FIGURE 13 - ALUMINUM LAMP SHELL CONTACT

(Arrows indicate pitting of failing contact between aluminum shell and brass eyelet.)

DISCUSSION

The failing connection types illustrated above all involve aluminum as at least one of the contacting members. Operating current ranged approximately from 1 A to 200 A. The failures occurred in time under normal current and operating conditions.

The designs employed in the examples shown have for the most part evolved from those developed originally utilizing copper and copper alloy components. It is generally recognized that long lasting mechanical connection to aluminum can be made if: a) adequate normal force is established and maintained, b) microscopic motion at the contact interface is prevented, and c) the metallic contact areas are protected from air, moisture and atmospheric contaminants.[6] On examination, each of the designs is deficient with respect to one or more of these important requirements for permanent mechanical pressure connections to aluminum.

Aluminum Busbar Connections to Circuit Breakers

The circuit breaker spring clip connections to aluminum busbar have sufficient force and wiping action to establish low resistance contact when first engaged. The spring clip design permits relative motion of the contacting members at the interface, exposing the contact to deterioration due to fretting.[7][8] Microscopic interfacial motion in the circuit breaker spring clip contact results from mechanical disturbance and from differential thermal expansion and contraction effects.

Mechanical disturbance of the circuit breaker spring clip contact interface can occur from such action as removal or installation of other breakers on the same busbar, opening or closing the cover door on the panel, and operation of the breaker's make-break contacts. Closing of the breaker's contacts involves a snap action mechanism that causes the moving contact to impact the contact on the spring clip.

Thermal expansion and contraction also contribute to the interfacial motion between the spring clip and the aluminum busbar. The thermal expansion mismatch between the aluminum and the copper-based mating component causes differential motion in the plane of the contact interface. The relatively large dimensions of the contact area of these connections (Fig. 4 and 5) results in differential interface motion of the same order as the size of the contacting asperities under the normal range of temperature fluctuations. Additional contact interface motion can result from thermal expansion and contraction of the breaker itself and the structure on which it is mounted.

Considering the lack of resistance to contact interface motion, deterioration by fretting is believed to be the most likely initiating factor in the failure process of the circuit breaker spring clip contacts to aluminum busbar. Contacts involving aluminum, plated or unplated, are not resistant to deterioration by fretting.[8]

Fuse Contact to Aluminum Busbar

Fretting is considered to be a major factor in the failure of the fuse contact to the aluminum busbar. Thermal expansion and contraction of the mounting structure is a principal contributor to interfacial motion in this instance. Because of the relatively small dimension across the contact area, differential thermal expansion of the mating contact materials is considered to be less important.

The design is unable to assure that normal force initially established is maintained. The busbar is essentially a flat beam supported between every second fuse. A fuse screwed into place deflects the busbar. When the adjacent fuse, in the same span of the busbar, is screwed into place, the contact force on the first fuse is decreased, increasing the probability of failure.

Aluminum Busbar Interconnections

The aluminum busbar interconnection failures are attributed to failure to maintain normal contact force. The use of steel screws to fasten aluminum parts together leads to substantial normal force fluctuations as a result of differential thermal expansion and contraction between the aluminum and the steel. In the limit, yield strength can be exceeded during high temperature operation, resulting in a loose connection on return to low temperature. For the busbar interconnection shown in Fig. 9, for instance, calculations indicate that a temperature rise of 117°C results in complete loosening of the connection upon cooling to normal ambient temperature.[10]

Some designs have the steel screws threaded directly into the aluminum, as in the bus bars shown in Fig. 8. This compounds the problem, since the high stresses present in the threads in the aluminum lead to reduction of the contact normal force due to yielding and/or relaxation effects. Most aluminum busbar materials will yield and/or creep at substantially lower stress than the steel bolt at normal operating temperature.[10]

Self threading screws are used in some of these aluminum busbar interconnection applications, in which case the initial tension preloading of the screw is significantly lower than it would be with the same tightening torque applied to a screw engaging a lubricated pre-threaded hole.

The size of the screws is also important, and in some instances they are too small for the application. An example is shown in Fig. 9, in which an 8-32 screw holds the post to the bus bar link. This is inadequate for this interconnection, which in normal service may carry current in excess of 100 A. In terms of current per unit stressed area of the clamping bolt or screw, this connection exceeds recommended values.[10] Additionally, the contact area between the post and the busbar link is small, having a current density of about 700 amps per square inch, far above the recommended design guideline of less than 200 amps per square inch of contact area.[10]

As a general practice, cupped spring ("belville") washers are recommended for bolted connections with aluminum busbar when steel fasteners are used.[10] The spring washer maintains essentially constant contact interface normal force in spite of the difference in coefficient of thermal expansion between the aluminum and the steel. The busbar and busbar link assemblies that are failing do not have spring washers, but do employ a lockwasher to keep the screw from backing out by thermal ratcheting. The lock washer is not an effective substitute for a cupped spring washer in terms of maintaining contact interface normal force, however.

Wire and Cable Terminations to Aluminum

Field failures of copper wire and cable connected to aluminum busbar and aluminum-bodied connectors (Figures 11 and 12) demonstrate weakness in the connection design, in which aluminum and copper are connected together with contact force applied by means of steel screws.

When aluminum is utilized as wire and cable, it is generally recognized that the use of steel screws and copper-based connectors leads to poor performance.[11] Aluminum-bodied connectors were developed to provide compatibility with aluminum wire and cable, but connection performance with copper wire and cable may then be compromised. Additionally, because of the mismatch of both thermal expansion coefficient and electrochemical corrosion potential, the use of steel screws in connections of these types is considered to contribute to the probability of failure.

Lamp Socket

While the current may be low relative to the other aluminum connection applications, the lamp socket is subjected to relatively high temperature excursions due to heating from the lamp itself. Heating of the eyelet results in an indeterminate initial normal force in the contact with the aluminum lamp shell.

The structure through which the eyelet passes to contact the wire terminal on the backside may be plastic or ceramic, relatively massive and with a different thermal expansion coefficient than the brass eyelet. The failed lamp socket shown in Fig. 13 has a ceramic body. The coefficient of thermal expansion of a ceramic body is approximately 40% that of the brass eyelet, and so the connection tends to loosen as it heats up. While the loosening occurs whether the lamp socket shell is made of brass or aluminum, aluminum is failure prone under such conditions due to the effect called "contact breathing" by Holm.[12]

Plated Aluminum

Plated aluminum is utilized in some of the applications noted. The effectiveness of plating in overcoming the deficiencies of aluminum contact systems depends strongly on many factors, including the plating material(s), application process, thickness, porosity, and the mechanical and environmental factors of the application. For the failure examples previously shown, plating, where present, was not effective in counteracting the basic design deficiencies.

Failure Process

The aluminum connection failure examples shown were in service for many years, as normally expected in residential applications. The failure process occurred over a period of time, eventually becoming evident as a result of odor of burning material, intermittancy, or inspection.

The eroded and/or pitted contact areas of several of the failed connections indicates that they had progressed to a point in the failure process involving dielectric breakdown of insulating material at the contact interface, a mechanism called "A-fritting" by Holm.[12][13] For this to occur, the metallic contact areas formed when the contact was originally made must have been destroyed with time until all of the load-bearing interface consisted of insulating oxide film and/or fretting debris. Conduction then occurred by the A-fritting process, deteriorating the contact areas point by point in essentially a microscopic arcing process.

Heat is generated at the contact interface according to the current flow and the potential drop. Hazardous levels of heat generation can be developed, as indicated in the examples shown by the insulation damage and burning.

The heat generation at failing aluminum connections of the types discussed generally accelerates the failure process. Thermal expansion mismatch, oxidation, and stress relaxation effects all become greater at higher temperature excursions. Springs or other metal members depended on to maintain contact normal force may anneal. Once started, the deterioration is progressive, leading eventually to the phase of failure known as "thermal runaway."

Qualification Standards

Safe long-term application of aluminum in residential electrical applications is possible provided that certain design and construction requirements are met, assuring adequate initial contact to the aluminum and long-term resistance to the known degradation mechanisms. The failed connection types examined above appear to violate conventional requirements for successful application of aluminum in pressure contacts. Considering the circuit breaker spring connections to the aluminum busbar or busbar fingers, for example, there is no technical basis to conclude that such designs will provide safe long-term service. Quite the opposite is true, since the opportunity for deterioration by fretting is immediately obvious.

Given the large number of variables in a connection system, however, and the substantial beneficial or detrimental effect that seemingly small changes in design and materials can have on an aluminum connection, it is generally not possible to predict with certainty, by inspection, theory, and initial condition tests alone, that a given construction will or will not provide satisfactory long-term service. Effective life tests are required.

Qualification standards for the types of products discussed above have been reviewed, and they permit qualification without life testing. With respect to the types of aluminum busbar, circuit breaker, and lamp socket interconnections discussed here, no life tests of any kind are required.[14][15][16] With respect to the copper wire and cable connections to aluminum busbar and aluminum-bodied connectors, the applicable standards permit such products to qualify under certain conditions without being life tested with copper conductor.[17][18] Aluminum bodied connectors are generally not subjected to the "heat cycle" testing (the only type of life testing in the two referenced standards) with copper conductor in the qualification procedure.[19] "Heat cycle" tests, actually current cycle tests in the referenced standards (since current is the controlled variable, not temperature), are required for connectors for use with aluminum wire and cable, however.[18])

Plating of the aluminum surfaces in these connection systems can have a beneficial influence on long-term performance. The qualification standards simply note that certain plating materials may be used, but there are no performance tests for the plating or criteria for minimum thickness, porosity and other significant factors. The contact interface is therefore essentially undefined in these connection types, and may be subject to wide variations.

Lacking definition of the contact surfaces and lacking mandatory life tests for these aluminum connection types, the present qualification standards are seriously deficient. As a minimum improvement, a form of the "heat-cycle" test is required for all types of connections involving aluminum. As defined in the connector qualification standards, however, this test has serious flaws and limitations.[20][21] Further improvement, including the addition of environmental testing, the application of more stringent pass/fail criteria, and the use of test sample groups large enough to assure statistical significance, are required to assure reliable and safe application of aluminum to the types of products discussed.

CONCLUSION

Hazardous failures are occurring in connections to aluminum components of various products in residential applications. The connection types that are observed to be failing are lacking in important design characteristics known to be required to achieve permanent stable contact to aluminum. The failures involve excess heat generation at the connections, leading to insulation degradation and possible fire ignition. Present qualification standards for the subject products are inadequate, and should be changed to incorporate effective mandatory life tests.

ACKNOWLEDGEMENTS

The author is grateful to the following for providing failed field samples and related information: F. Steubner (Lagrange Instruments), R. Schubert (Bellcore), D. Friedman (American Home Service), and G. Heighington (Citizens for Electrical Safety).

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