AC and DC ELECTROMIGRATION IN ALUMINUM CONTACT JUNCTIONS

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ABSTRACT

Results are presented for experiments in which aluminum model contact asperity junctions are operated at current density up to 10^6 A/cm^2 with either DC or AC square wave current. Application of current as a square wave eliminates the possible influence of cyclic thermal stresses which could have been a factor in a previous study. Electromigration failure, observed as a relatively abrupt increase of resistance, occurs in both AC and DC specimens. Conditions under which electromigration deterioration may occur in practical aluminum power connections are discussed. Keywords: Aluminum Contacts, Aluminum Connections, Electromigration, Aluminum Contact Failure, Qualification Testing.

INTRODUCTION

Current flow across an aluminum contact interface occurs only at metallic junctions where there is no insulating aluminum oxide film.[1][2] The actual conductive metallic area in a practical aluminum connection is a strong function of surface preparation of the aluminum and mechanical disruption of the insulating oxide that may be imparted while making the connection.

Several methods of aluminum surface preparation are utilized to deal with the insulating oxide. Examples are abrasion, sand blasting, plating, and cladding.[3][4][5][6] Cost factors being important, considerable effort has gone toward the development of connectors for aluminum conductors that might provide safe long-term service without special preparation of the conductor surface.

Provided that there is some penetration of the oxide, the actual amount of metallic conducting area at the contact interface has not generally been considered to be important in achieving that objective. The key requirements for a connector for aluminum are thought to be: 1) establishing and maintaining adequate normal force, 2) resistance to contact interface motion, and 3) corrosion resistance. Recent studies indicate, however, that the amount of metallic conducting area at the contact interface may in fact be a key determinant of contact life, because of the phenomenon known as electromigration.[7]

Electromigration within a conducting contact asperity junction is the drift of atoms within the solid metal due to electrical current flow. Also referred to as "bulk electromigration", it is essentially a current-induced diffusion that is driven by the momentum of the electrons (the so-called "electron wind") and the potential gradient. It is this phenomenon that is referred to in this paper as electromigration. For aluminum, it can become significant when the current density is above 10^5 A/cm^2.

For a practical aluminum wire connection made without special preparation of the wire surface, whether or not current density reaches those levels depends on the effectiveness of the connector in penetrating the aluminum oxide film. Where a connector imposes substantial distortion or wiping of the aluminum wire surface, relatively large areas of metallic contact are created. This occurs, for example, under the screw head in a binding-head screw terminal or under the spring in a twist-on connector splice where the screw head or connector spring scrapes the alumninum wire surface during tightening.

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Under application of normal force alone, relatively tiny areas of metallic contact are established through the aluminum oxide film.[8][9] This is the case at the wire-to-plate contact of a binding head screw terminal or at the wire-to-wire contact in a twist-on connector splice. Experimental data and current flow path analysis are available for these two types of connections.[10][11] Using that data, it is demonstrated (below) that current density well above 10^5 A/cm^2 can occur in the aluminum conducting spots of these connections at the intended current-carrying interface (wire-to-plate, wire-to-wire) within rated current loading.

Electromigration effects in aluminum have been studied. The major focus of aluminum electromigration investigations has dealt with microscopic aluminum conductors on the surface of semiconductor chips. Runde has extended the electromigration theory to conditions that exist at an electrical contact interface.[12] Experimentally, the phenomenon has been studied for both AC and DC current flow.[13][14]

Previous experimental results, presented at the 1995 Holm Conference, demonstrated failure of model aluminum contact asperity junctions at high current density with both AC and DC current.[14] Current in that experiment was applied as a 60 Hz sine wave for the AC specimens and as unfiltered full-wave rectified 60 Hz sine wave passing through the DC specimens. At the presentation of that paper, it was pointed out that the experimental results did not unambiguously demonstrate electromigration, since all or part of the effect noted could have been attributed to fatigue from thermally-induced stresses in the model asperity.[15] The applied current, it was noted, imparted a 120 Hz temperature oscillation at the tiny model asperity junction in both AC and DC specimens that could be a significant influence.

The objective of the present experiment is to investigate bulk electromigration effects at a model asperity junction under AC and DC current flow while eliminating the 120 Hz oscillating temperature of the previous experiment. This is accomplished by applying the AC current as a square wave rather than as a sine wave. The heat generation (I^2R loss) at the model asperity, and therefore the temperature, is constant for both AC and DC specimens when a square wave is employed. Additionally, relative to the previous work, refinements in the experimental method have been made to permit operation at higher current density and to facilitate electron microscope examination of the specimens.

EXPERIMENTAL METHOD

Test Specimens

The test specimen is a two-dimensional model of a contact asperity junction that is made in a sheet of 99.5% minimum purity aluminum foil 0.025mm (0.001in) thick. At the minimum constriction, the width of the current path is 0.1mm (0.004in). The asperity model dimensions and most of the specimen fabrication details are the same as in the previous work.[14] The specimen assembly configuration and assembly method are somewhat different from those previously used, however.

Rectangular specimen blanks 64x24mm (2.5x0.95in) are all cut from the same sheet of foil, oriented in the same direction. Two 0.15mm (0.006in) holes on 0.25mm (0.010in) centers are drilled through the blanks at the center. A foil specimen is then placed on a beryllia (beryllium oxide ceramic) plate 1.5mm (0.062in) thick that has a thin coating of a low melting point wax. Another beryllia plate is placed over the foil. The stack is clamped together, heated to 100C, and allowed to cool under the clamping pressure. The clamp and upper beryllia plate are then removed, leaving the foil bonded to the lower beryllia plate. The ends of the foil specimens protrude beyond the beryllia plates.

Slots are cut from the outer side of the holes to the edges of the specimen, leaving a single constricted current path bridge of the solid parent metal between the two halves of the specimen. Figure 1 shows the mounted specimen at this stage of construction.

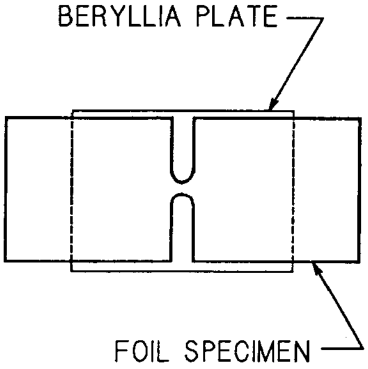

FIGURE 1 - SPECIMEN MOUNTED TO HEAT SINK

A small amount of grease is applied at the constriction bridge to provide thermal coupling to the upper beryllia plate. The upper beryllia plate is placed over the specimen. This subassembly is then placed between copper plates 3mm (0.12in) thick.

The assembly is held together firmly by a spring clamp bearing on the copper plates but electrically insulated from them. Each protruding end of the aluminum foil specimen is then abraded under a film of inhibitor, and is connected to one of the copper plates by pressure of screw fastenings holding a copper clamping bar. Two solder lugs under the screw heads at each end provide connections for applying current and sensing potential drop. Figure 2 shows a completed specimen assembly.

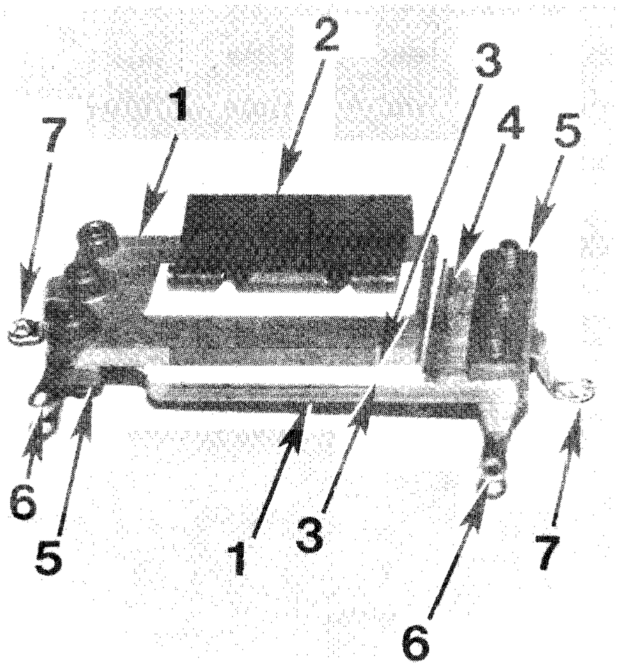

FIGURE 2 - SPECIMEN ASSEMBLY

1. Copper Plate
2. Spring Clip
3. Beryllia Plate
4. Connection End of Foil Specimen
5. Copper Clamping Bars
6. Instrument Connection
7. Power Connection

Specimens are tested in sets of six, cooled by fan-forced room air. The specimen assemblies are supported by their power connection lugs, which are bent to provide a compliant mounting. This minimizes horizontal shear forces that may develop from differential thermal expansion of the specimen assembly relative to the mounting frame.

Electrical Power Circuit

Half of the specimens under test are operated with DC current and the other half with AC. DC specimens are connected directly in series with the output of a variable current-regulated DC power supply. Also in series in the DC section of the circuit is a calibrated shunt used for current measurement.

Downstream in the same circuit, in series, is a square-wave generator that feeds the AC specimens. DC and AC specimens therefore pass exactly the same current at any given moment, except that the current direction for the AC specimens alternates as a 60 Hz square wave.

The square-wave generator is constructed using a full bridge of FET power transistors. The gates of the corresponding pairs of the transistors are powered according to the complimentary outputs of a flip-flop that is triggered by a clocking circuit synchronized to the primary AC power line. Figure 3 shows the essential elements of the power circuit.

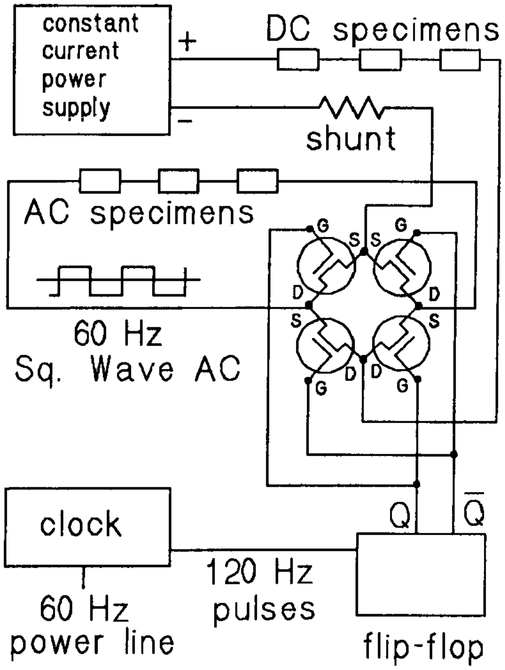

FIGURE 3 - TEST CIRCUIT

Once a new set of specimens is started on test, current is applied continuously. A latching relay system shunts each specimen on command of the control system. The shunt path resistance is about equal to that of the specimen. Shunting of a specimen that has electrical continuity reduces the specimen current by about 50%, effectively minimizing additional specimen deterioration.

Applied Current and Current Density

Specimens are tested at 24 and 25.8A, the latter value corresponding to 1x10^{6}A/cm^2.

Instrumentation

A PC-based data logging and control system records elapsed time, specimen potential drop, circuit current, and ambient temperature. When the potential drop of any specimen exceeds 10mV above its initial value, the system actuates the corresponding shunting relay and logs the time of that event.

Local ambient temperature and current are recorded to assure that the experimental conditions are in control. Measurement resolution for potential drop in this system is 1mV.

Specimen Temperature

Steady state temperature of the specimen at the constriction bridge is determined at a single current level by use of a temperature indicating paint. The material used dries to a smooth thin film, adheres to the aluminum, and makes a permanent color transition from pink to lavender at 104C (220F). The paint is applied locally to the region of the constriction bridge of a specimen that is adhered to the lower beryllia plate. When the paint is thoroughly dry, the upper beryllia plate is put in place (without any grease), and the specimen assembly is completed as previously described. The specimen assembly is then installed in the system.

After being run at a preselected current for one hour, the specimen is removed from the system and the upper portion is disassembled. The temperature indicating paint is inspected under a microscope. If there is no color change, the specimen is reassembled and run at a higher current level for one hour. The process is repeated until the minimum current at which there is a detectable point of color transition at the constriction bridge is determined. Maximum constriction bridge temperature at other current levels can then be calculated.

EXPERIMENTAL RESULTS

Specimen Life vs. Current

Table 1 summarizes the experimental results. Figure 4 shows the potential drop of two representative specimens as a function of time. Specimen behavior is similar to that previously observed.[14] The specimens operate at a relatively stable potential drop until near the end of life. In these experiments, a few millivolts rise of potential drop relative to the initial value has been found to be a reliable signal of an impending runaway increase that would end with an open-circuit failure of the constriction bridge. For the present experiment, a 10mV potential drop increase is taken as the end-of-life signal, at which time open circuit is imminent. The specimens are shunted at that time to suppress further deterioration.

GROUP	TIME (seconds) TO +10mV POTENTIAL DROP CHANGE		
	MINIMUM	MEDIAN	MAXIMUM
24A AC	7,320	15,240	21,840
24A DC	2,040	18,210	48,360
25.8A* AC	186	1,284	4,140
25.8A* DC	414	1,887	3,738

TABLE 1 - DATA SUMMARY
6 data points per group

* 10^6 A/cm^2

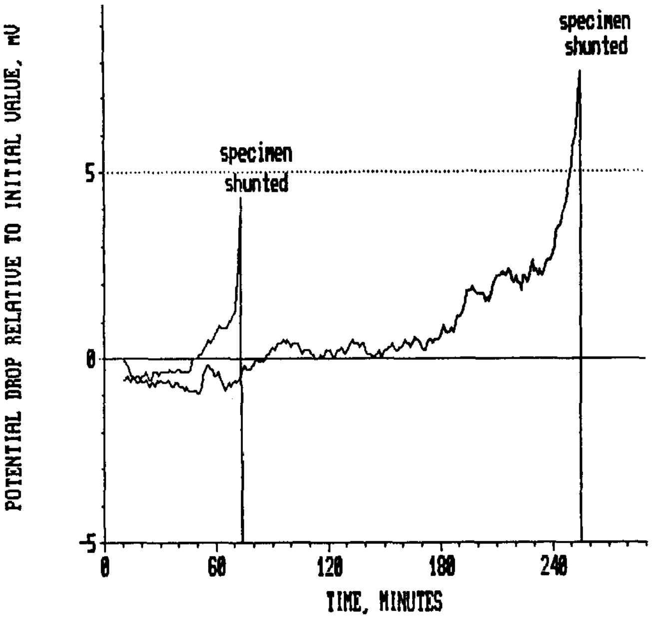

FIGURE 4 - POTENTIAL DROP CHANGE

(24A AC specimens, moving average of 10 data points.)

All specimens tested, AC and DC, demonstrate end-of-life behavior similar to that shown in Figure 4. Specimens are relatively stable, at potential drop close to the initial value, until the runaway end of life increase begins. Low-order trends that may occur in the early stages of a test cannot be positively identified in this experiment. Limitations are the 1mV instrument resolution as well as systematic variations of the same magnitude that occur due to specimen assembly temperature change and instrument drift. The relatively large and rapid potential drop increase near end of life is unambiguous, however.

Specimen Temperature

The current at which color transition of the indictating paint is first detected microscopically on the surface of the constriction bridge is 17.8A. For calculation purposes, a lower current, 17.6A, is taken as that which yields the indicated temperature (104C) as a maximum in the center of the constriction bridge. Since the heat-conducting grease is not used in the experimental temperature determination, this is considered to be a high-limit estimate of the temperature of actual test specimens.

A temperature-current curve is then calculated on the basis that the steady state temperature rise is proportional to the power dissipation (I^2R). Resistivity change of the aluminum with temperature is factored into the calculation according to the formula: $\rho=2.56\times10^{-6}(1+0.0045T+1.03\times10^{-6}T^2)$ Ω-cm.[16] The result is shown in Figure 5. The calculated maximum constriction bridge temperature at each current level tested, 24A and 25.8A, is determined to be 265 C and 375 C respectively.

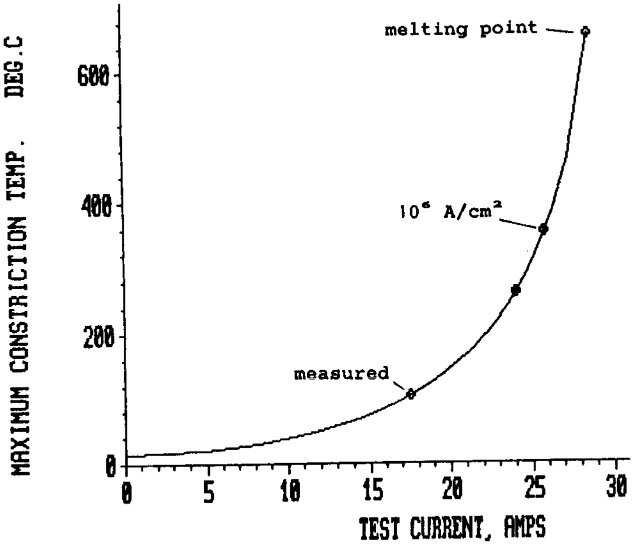

FIGURE 5 - MAXIMUM TEMPERATURE AT THE CONSTRICTION BRIDGE

Specimen Examination

After testing is completed, the upper heat sink assembly is removed. The specimen is examined microscopically and is then submitted for independent investigation by analytic electron microscopy (AEM).

Optical microscopic examination reveals surface roughness at the constriction bridge of many specimens. Some specimens also have an irregular furrow across the constriction bridge that is suggestive of the early stages of a crack of the type seen in the previous work at open-circuit failure.[14]

The present specimen assembly procedure permits transfer of the intact foil specimen to a more conventional mount for further examination. An independent in-depth AEM study of specimens from this experiment has been undertaken by T.Hare, the results of which are reported separately.[17]

DISCUSSION

General

The experimental results have demonstrated, to a greater degree of certainty than the previous work, that electromigration can cause deterioration of aluminum contact junctions operating at high current density with either AC or DC current. There are no substantive differences in specimen behavior between the AC and the DC specimens. The range of time to end of life is of the same order in either case.

In all respects, the present results are consistent with the previous work.[14] Direct comparison is not possible, however, because of differences in specimen mounting and the applied current waveform. Changes in the specimen mount assembly, specifically the use of thicker beryllia heat sink plates and increased clamping pressure, have enabled these tests to be run at almost double the applied current of the previous work. At the highest curent now applied, 25.8A (current density 10^6 A/cm^2) the estimated maximum temperature of a new specimen at the constriction bridge is 375 C, well below the melting point of the aluminum (660 C). No comparative values (obtained by the same measurement and calculation techniques) are available for the previous experiments.

The use of pure DC and square-wave AC, from the rectified and unrectified AC sine wave used previously, is the most significant change. The change eliminates the 120 Hz temperature oscillation at the constriction bridge, and therefore the results obtained in this present experiment are free of any possible thermal stress fatigue effect. This strengthens the conclusion that electromigration is responsible for the observed end-of-life failures in both the AC and DC specimens.

Electromigration is essentially an atomic diffusion process in the bulk material, driven by the electric field gradient and the so-called "electron wind". At a contact interface, the conducting metallic "a-spots" are the regions of highest temperature and maximum current density.[18] Because of this, the probability of an atomic jump is higher in the contact a-spot than it is for atoms in neighboring regions either upstream and downstream in the electron flow. Both thermotransport and electromigration are maximized at the a-spot. Analysis demonstrates that, at current density of the order of 10^5 A/cm^2 and higher, atomic drift due to electromigration is at least an order of magnitude higher than drift due to thermotransport.[12][14]

At high current density, atomic drift out of the constriction zone is in the downstream direction of the "electron wind". More atoms move downstream out of the a-spot than move into the a-spot from upstream, resulting in a net flow out of the a-spot. On reversal of the current, as in an AC contact, the process continues, except that the net flow out of the a-spot is in the opposite direction. There are still more atoms leaving the a-spot than entering. The process ultimately leads to the development of voids and increasing resistance in both AC and DC contacts, continuing until the a-spot fails (opens).

Current Density and Contact Resistance

Whether or not electromigration is significant in a practical aluminum connection at a given current depends on the actual amount of metallic contact and on the a-spot distribution. Because aluminum oxide is essentially an insulator, the conducting a-spots in an aluminum-aluminum contact are purely metallic. For that case, upper and lower limits for the actual conducting area can be estimated using known relationships for contact resistance of individual and multiple a-spots in a contact.[18][19][20] Re-arranging Holm's equation for contact resistance of a single circular a-spot ($R_c = \rho/2a$)[18], the radius of a single circular a-spot that yields a given contact resistance is:

$$a = \rho/2R_c \tag{1}$$

where a = a-spot radius (cm)
ρ = resistivity (Ω-cm)
R_c = contact resistance (Ω)

A number of identical a-spots sufficiently remote from each other may be considered to be conducting in parallel without interaction. The radius of the a-spots in such a cluster of "n" spots that yields a given contact resistance is then:

$$a = \rho/2nR_c \tag{2}$$

The conducting metallic area of each a-spot is πa^2 sq.cm, and so the total metallic conducting area is $n\pi a^2$ sq.cm. The current density at the a-spots is then:

$$I/A = I/(n\pi a^2)$$

$$= I/[n\pi(\rho/2nR_c)^2]$$

$$I/A = 4nIR_c^2/\pi\rho^2 \tag{3}$$

where I = applied current (amps)
A = total metallic conducting area, (cm^2)

At any given contact resistance, equation 3 demonstrates that the lowest current density possible occurs when there is one conducting a-spot. For clusters of smaller a-spots, yielding the same contact resistance, the current density is always higher. How much higher depends on the size, and therefore the number, of a-spots in the cluster. At a given a-spot size, if the a-spots are too close to be truly non-interacting, the current density will be in between that of the non-interacting case and the single spot, for the same contact resistance. Figure 6 shows current density per amp as a function of contact resistance for several values of "n":

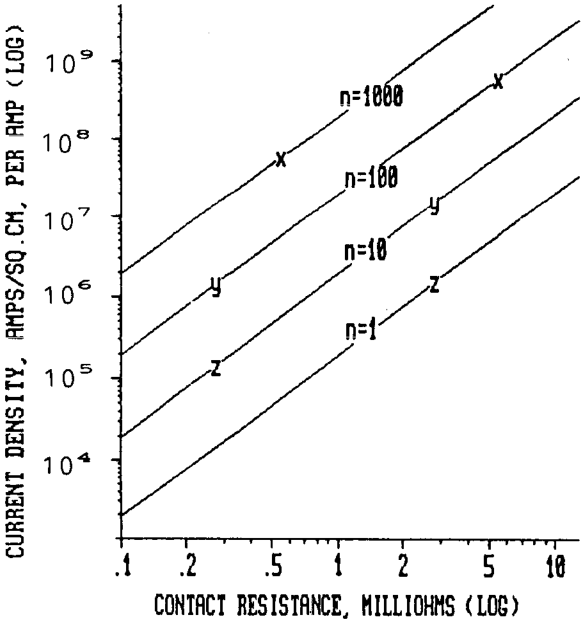

FIGURE 6 - CURRENT DENSITY PER AMP AS A FUNCTION OF Rc FOR VARIOUS VALUES OF "n"
(for aluminum-aluminum contact)

$a = 0.025\times10^{-4}$ cm for points "x"
$a = 0.5\times10^{-4}$ cm for points "y"
$a = 5.0\times10^{-4}$ cm for points "z"

The points marked "x" in Figure 6 are calculated based on a representative reported a-spot size for aluminum contacts, $0.025\text{x}10^{-4}$cm radius.[16] A cluster of 1,000 such a-spots, non-interacting, will yield contact resistance of about 0.5 mΩ. Figure 6 shows the current density at that point to be $5\text{x}10^{7}$A/sq.cm per amp (i.e. for a contact carrying one amp). For an actual contact of that configuration passing 10A, the current density is $5\text{x}10^{8}$A/sq.cm.

If the a-spots are close enough to interact, the resistance per spot increases. Therefore, it would take a larger number of a-spots (of the same size) to achieve the same contact resistance. The total conducting area would be larger and therefore the current density would be lower.

Assuming the a-spots to be ever closer, and increasing the number to maintain the same contact resistance, the low limit is reached. No matter how tightly packed, a cluster of small a-spots yielding an effective contact resistance of 0.5 mΩ cannot operate at a lower current density than that of the single larger a-spot (n=1 in Fig. 6), which is $5\text{x}10^{5}$A/sq.cm. at 10A.

Establishing large a-spots and low contact resistance are seen to be the keys to avoidance of electromigration deterioration. For example, if the contact resistance of a practical aluminum-aluminum connection rated for 10 A is of the order of 0.1 mΩ or above, the current density in the a-spots is likely to be high enough to initiate electromigration deterioration.

Effect of A-Spot Size Distribution

Actual contacts have a-spots that vary in size. The relationship between current density and a-spot diameter within a given contact can be developed. Considering the applied voltage (IR drop) to be the same across all a-spots at the contact interface, the following relationships are developed:

(4) $I_nR_n = IR_c$

where the subscript "n" refers to the n^{th} a-spot

(5) $I_n = IR_c/(\rho/2a_n)$

(6) $I_n/A_n = IR_c/[(\rho/2a_n)(\pi a_n^2)]$

(7) $I_n/A_n = 2IR_c/\pi\rho a_n$

Equation 7 shows that, within a given contact, the current density for individual a-spots is inversely proportional to the a-spot radius. Consequently, it would be anticipated that the smaller a-spots in a contact will fail earlier than the larger a-spots when electromigration deterioration is active.

Consider, as a basic example, a contact consisting of two isolated circular a-spots, the smaller being 1/2 the diameter of the larger. The resistance of the smaller contact is double that of the larger. Based on the parallel resistance rule, the current passing through the smaller a-spot is 1/2 that of the larger a-spot, but its area is 1/4 that of the larger. The current density in the smaller a-spot will therefore be double that of the larger.

At high enough current to initiate electromigration deterioration, the small a-spot will deteriorate substantially faster than the large a-spot, eventually opening completely. The larger a-spot then carries the full current. Current density in the larger spot is now 150% of the starting level, accelerating its electromigration deterioration.

As a consequence of the variation of current density with a-spot size, electromigration failure in an actual contact will progress in a manner that is a function of a-spot size distribution. The smallest a-spots in a contact will be the first to fail.

Temperature at the A-Spot

Heat generated in an actual conducting a-spot is efficiently dissipated into the surrounding metal and oxide. The maximum temperature at a-spots representative of those established in aluminum connections have been studied.[16] Results demonstrate that a-spots run well below the melting temperature at high current density.

For instance, the maximum temperature at an aluminum a-spot (or dense cluster) of radius $8\text{x}10^{-4}$cm that is carrying 30A current is about 140C (Ref.17, Fig.4). The current density for that set of conditions is at least $1.5\text{x}10^{7}$A/sq.cm. This example serves to demonstrate that current density sufficient to activate electromigration deterioration can be established at the contact interface at temperature well below the melting point of the aluminum.

Application to Practical Contacts

The analysis of a-spot current density can be extended to practical aluminum connections, given current path and contact resistance information. Based on available data, electromigration is demonstrated to be a probable contributor to the failure process for two types of residential aluminum connections, twist-on wire connectors and binding-head screw terminations.

The twist-on connector consists of a conical metal coil spring within a plastic insulator. They are hand-installed by holding the stripped wire ends together, pushing them into the open end of the connector, and twisting the connector on until it is tight.

Newly made, the average contact resistance at the wire-to-wire interface in a two-wire twist-on splice of #12 AWG aluminum wires is about 1 mΩ.[11] About 1/3 of the circuit current flows through this interface. The balance of the current flows from one wire to the other via sections of the surrounding spring, which is generally made of plated steel. At 12A applied current, which is only 80% of the circuit rating for the #12 aluminum wire, 4 amps flows directly through the wire-to-wire interface. The minimum current density through the a-spots at that 1 mΩ contact is 0.8×10^6A/sq.cm (based on Fig. 6, n=1). If the number of a-spots at that interface is assumed to be 10, then the current density is of the order of 10^7A/sq.cm for the average connection of this type.

In a binding-head screw termination, the wire is clamped against a brass contact plate by the presure of the tightened screw. Tests were made with #12 aluminum wire, newly connected to terminals of residential receptacles, with the screws uniformly tightened to 12 lb-in torque.[10] The results showed that as little as 1/4 of the current flowed through the wire-to-plate path of that connection, the contact resistance measuring as high as 1.7 mΩ. Allowing for the fact that the contact plate is brass, and neglecting film resistance on the brass (since the receptacles were new), the current density at the a-spots at the wire-to-plate interface is calculated to be of the order of 10^6 to 10^7A/sq.cm for the newly-made connections when the circuit current is 12A.

Both twist-on splices and binding-head screw terminations have been troublesome when used with aluminum wire. The above analysis demonstrates that electromigration is likely to be part of the failure process. Without special preparation of the aluminum wire surface, failure to consistently establish adequate metallic contact at the intended primary contact interface results in current density high enough for electromigration effects to be significant. In worst-case samples, the primary current path deteriorates at less than rated current. The greater portion of the circuit current flows through the available parallel secondary path, which is through sections of the connector spring in the twist-on connector, or through the screw itself in the binding-head screw terminal. Ultimately, all of the circuit current will pass through these secondary paths.

The contact interface to the aluminum wire in the secondary paths, at the wire-to-spring or wire-to-screwhead interface, is not initially subject to electromigration failure. This is because the agressive wiping action occurring at these interfaces when the connections are first made creates large areas of metallic contact relative to the area established at the wire-to-wire interface.After the primary contact interface fails, the next stage in the deterioration process is then caused by other factors, such as materials incompatibility (zinc plated steel connector spring, for instance). Electromigration may become significant again later in the failure process of these types of connections as the secondary contact interface to the wire deteriorates from other causes.

Aluminum Alloy Conductors

For electrical power connections, aluminum alloy conductors have often demonstrated improved performance in high-current tests. The alloys were developed to provide greater creep resistance while having almost the same electrical conductivity as EC grade aluminum. It is probable that in many connector types the demonstrated improvement is due to resistance to electromigration rather than resistance to creep. The two are related. Reduction of atomic mobility by addition of alloying elements and special heat treatment would reduce the electromigration rate along with the creep rate. Alloying of the aluminum is known to be part of the solution to the semiconductor chip electromigration problem.

Application to Qualification Testing

Present qualification standards for residential aluminum wire and cable connectors do not screen for possible electromigration effects. The performance test most generally used applies high current cycling (so-called "heat-cycle") and measures temperature rise of the connector. The pass-fail criteria of many connector qualification standards are quite liberal.[21] Connector types may pass the qualification tests even though they demonstrate significant excess initial resistance and obvious progressive resistance increase, both of which are indicators of inadequate metallic contact and possible electromigration deterioration.

Sensitivity to electromigration deterioration in an aluminum connection can be anticipated from initial contact resistance measurements and estimation of the current density at rated circuit load. Pass-fail criteria based on maximum contact resistance for aluminum connections have been proposed in the past.[22][23] Suitably selected, contact resistance limits can serve as an initial screen to reject connection types that may be prone to electromigration failure.

Present high-current cycling tests could be used to screen for electromigration sensitivity provided that suitable requirements for total current-on time and pass-fail criteria could be developed. The total time that a given test current is applied is a key parameter for detecting electromigration effects. This must be considered in evaluating the potential effectiveness of alternative qualification tests. Previously, it has generally been accepted that the total current-on time is not important provided that temperature equilibrium is reached. This would not be true for a connection type that is susceptible to electromigration deterioration.

A constant-current test may be used to screen for sensitivity to electromigration deterioration. Conceptually, an aluminum connection operating below the current density threshhold required for significant electromigration would be capable of continuous application of current in a non-corrosive constant-temperature environment without any measureable deterioration. Sensitivity to electromigration deterioration would be indicated by any significant progressive increase of connection resistance at constant high current.

Whether or not current density will be high enough for electromigration effects to be significant also depends on the aluminum conductor. Among aluminum conductors in actual use, there are wide variations in bulk material and surface oxide that have a large effect on a-spot size and number in some types of contact interfaces.[24] The ability of a particular connector design to consistently establish sufficient metallic contact at its intended primary current-carrying contact interface to avoid electromigration deterioration can be tested by measuring initial contact resistance with different conductors, including worst-case samples. There must be a tight sample-to-sample distribution at suitably low current density to assure that a connector will not fail in service from electromigration deterioration no matter which practical aluminum conductor it is applied to. If a connector cannot meet those criteria, abrasion of the aluminum conductor may be required as a necessary installation step for that connector type.

A simple and practical "acid test" to determine whether or not a connector can be used without surface abrasion of the aluminum conductor has been employed.[25] The acceptance criterion is that the initial resistance of the connection must be the same with or without abrasion of the aluminum conductor.

CONCLUSIONS

1. The experimental results demonstrate that electromigration is likely to be an active deterioration mechanism in both AC and DC aluminum connections

2. The minimum current density at the conducting metallic a-spots of an aluminum contact interface may be determined from the contact resistance of that interface and the applied current.

3. Current density sufficient to activate electromigration deterioration, of the order of 10^6 to 10^8 A/cm^2, exists at the conducting a-spots of aluminum contact interfaces at contact resistance levels frequently observed in aluminum connections operating within rated current.

4. Current density through the a-spots in a particular contact interface is inversely proportional to the a-spot radius. The progress of electromigration deterioration in a particular connection will be a function of the a-spot size distribution.

5. The temperature of conducting aluminum a-spots operating at current density high enough to induce electromigration deterioration is below the melting point.

6. Connection performance improvement reported for tests with aluminum alloy conductors may be due all or in part to enhanced resistance to electromigration rather than enhanced resistance to creep.

7. The primary contact interface of the most common residential aluminum wire connection types (twist-on connector splices and binding-head screw terminations) commonly operate at current density high enough to induce electromigration deterioration if made without special surface preparation of the aluminum.

8. Present qualification standards do not reliably reject connection types that are unable to consistently assure sufficient metallic aluminum contact area to preclude long-term deterioration by electromigration.

9. Practial tests exist that should be incorporated into qualification standards to screen connector types for electromigration sensitivity and to assure that a connector type can consistently establish the required level of metallic area at the primary aluminum contact interface if it is to be applied without special preparation of the aluminum conductor surface.

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