Galvanic Compatibility of Immersion Gold and Immersion Silver Printed Wiring Board Finishes with Aluminum

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Abstract
Numerous industry studies have been performed examining the compatibility between new plating finishes and other metals used in printed wiring assemblies. The transition to the new printed wiring board finishes has been driven by global lead-free legislation and a desire for more coplanar surfaces. The most commonly examined metals have been immersion finishes, such as immersion silver, immersion tin, and electroless nickel / immersion gold (ENIG). The industry studies have demonstrated the producibility, testability, and reliability of these three immersion finishes; however, very little investigative data can be found concerning the galvanic compatibility between these finishes and other metals used for structural interconnects (e.g. aluminum). This paper documents a galvanic compatibility examination between these three common finishes and aluminum, using both temperature/humidity and salt spray test environments with an applied electrical potential. The test results illustrate that these three immersion finishes are galvanically compatible with aluminum when best practice material considerations are applied.

Background
Galvanic corrosion/degradation of dissimilar metallic surfaces in contact with each other is a well recognized phenomena. Considerable industry resources have been expended to assist the design community with understanding galvanic corrosion. Fontana and Greene[1] classified galvanic corrosion as one of eight forms of corrosion. The Department of Defense issued a military handbook, MIL-HDBK-729 "Corrosion and Corrosion Prevention Metals", in an effort to provide basic, fundamental information on corrosion and corrosion prevention.[2] Forman and Verchot[3] expended considerable funding and resources for the US Army Missile Command to characterize and develop a practical galvanic series of metal combinations for missile systems designers. Galvanic corrosion is defined as "accelerated corrosion of a metal because of an electrical contact with a more noble metal or non metallic conductor in a corrosive electrolyte".[4] The less corrosion resistant metal undergoes oxidation (e.g. becomes the anode), thus losing electrons to the corrosive electrolyte and the more corrosion resistant metal undergoes reduction (e.g. becomes the cathode), thus gaining electrons from the corrosive electrolyte. To aid designers in the selection of compatible metallic couples the Galvanic Series Chart was created. The Galvanic Series Chart is a listing of potential differences between metals as measured in a specific electrolyte. The standard Galvanic Series Chart used by the electronics industry, illustrated in Figure 1, is for a sea water electrolyte, using pure metals, and measured at room temperature (e.g. 25ºC).

The Galvanic Series Chart is very useful for estimating first order effects but a number of caveats must be considered during its use. The assessment of metallic couple galvanic compatibility needs to consider the following parameters:

A. <u>Potential Difference Between Metals</u>
The potential difference between two metals in a solution at a given temperature is called the electromotive force or the EMF series. The standard EMF series is referenced against a hydrogen electrode to create an arbitrary zero baseline. A comparison of the absolute EMF potential differences between two metals can be used to predict corrosion behavior. However, environmental factors can affect the EMF potential values. A classic environmental impact on a galvanic couple is the reaction of zinc and steel in an aqueous environment.[1] Normally zinc behaves as anodically when coupled with steel in water. However, in some water supplies zinc behaves cathodically and the steel becomes anodic when the temperatures exceed 82ºC (180ºF). This potential reversal is due to the corrosion products on the zinc making the zinc surface noble in relation to the steel surface. Additionally, the composition of the use environment atmosphere (i.e. salt spray, acid rain) and the influence of having a metal alloy rather than pure metals should be a consideration.

Noble or cathodic

Platinum
Gold
Graphite
Titanium
Silver
- Chlorimet 3 (62 Ni, 18 Cr, 18 Mo)
- Hastelloy C (62 Ni, 17 Cr, 15 Mo)

- 18-8 Mo stainless steel (passive)
- 18-8 stainless steel (passive)
- Chromium stainless steel 11-30% Cr (passive)

- Inconel (passive) (80 Ni, 13 Cr, 7 Fe)
- Nickel (passive)

Silver solder
- Monel (70 Ni, 30 Cu)
- Cupronickels (60-90 Cu, 40-10 Ni)
- Bronzes (Cu-Sn)
- Copper
- Brasses (Cu-Zn)

- Chlorimet 2 (66 Ni, 32 Mo, 1 Fe)
- Hastelloy B (60 Ni, 30 Mo, 6 Fe, 1 Mn)

- Inconel (active)
- Nickel (active)

Tin
Lead
Lead-tin solders
- 18-8 Mo stainless steel (active)
- 18-8 stainless steel (active)

Ni-Resist (high Ni cast iron)
Chromium stainless steel, 13% Cr (active)
- Cast iron
- Steel or iron

2024 aluminum (4.5 Cu, 1.5 Mg, 0.6 Mn)
Cadmium
Commercially pure aluminum (1100)
Zinc
Magnesium and magnesium alloys

Active or anodic

Figure 1 -Typical Galvanic Series [1]

B. Polarization Effects

Polarization can be divided into two types: 1) activation polarization where the reaction is metal/electrolyte controlled; 2) concentration polarization where the reaction is electrolyte diffusion rate controlled. Environmental effects can have a significant impact on the polarization affects thus controlling the corrosion rate. Increased agitation of the electrolyte due to environmental conditions will increase the corrosion rate for concentration polarization situations. The formation of oxide films can shift the polarization curves from an active/corrosive rate to an inactive/passivated rated. Figure 2 illustrates shifting polarization curve behavior due to oxide film formation.

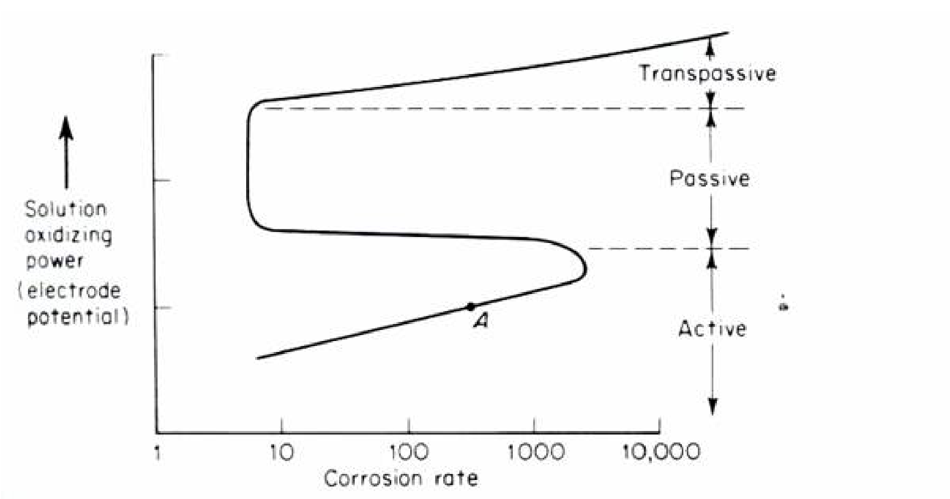


Figure 2 - Active/Passive Metal Corrosion Characteristics Due to Oxide Film Formation[1]

C. <u>Area Effects</u>
One rule of thumb utilized in minimizing the galvanic coupling of metals is keeping the surface area ratio of the anode to cathode as large as possible. Having the anode surface area (i.e. the corroding surface) large results in a much smaller driving EMF potential as the metallic couple is polarized against an accelerated corrosion rate. The application of an organic coating over the cathodic member of a galvanic couple will result in the same effect.

D. <u>Distance Effects</u>
The closer the physical connection of two dissimilar metals the greater the corrosive attack. The distance effect follows standard electrical formuli – the length of a conductive path increases the resistance to current flow thus the longer the conductive path, the lower the corrosion rate. However, the electrolyte solution conductivity does play a confounding role on distance effect considerations and should be considered when predicting corrosion behavior.

E. <u>Geometry Effects</u>
Physical geometry effects are very similar to the distance effect. Electrical current takes the path of least resistance so bends, corners, and other potential long, non-linear paths/shapes will tend to lower current flow and reduce the corrosion rate. However, the creation of electrolyte trap space due to geometry has the opposite impact and increases corrosion rates.

Introduction
The electronics industry has swiftly implemented three alternative printed wiring board surface finishes as substitutes for the traditional hot air solder leveled (HASL) tin/lead surface finish. Legislative pressures such as the Restriction of Hazardous Substances (RoHS) directive in Europe have provided incentives for surface finish substitutions. Producibility pressures such as the demand for improved surface finish coplanarity for area array components have fueled implementation activities. The three predominate alternative finishes are: immersion silver over copper, immersion tin over copper and immersion gold over electroless nickel over copper. It is typical industry practice to connect the printed wiring board to a cast aluminum or a sheet metal housing using aluminum standoffs or in direct contact using fasteners. Aluminum is a common housing material due to weight and heat dissipation characteristics. An inspection of the Galvanic Series Chart shown in Figure 1 reveals that aluminum is one of the more anodic metals in the table. Figure 1 also indicates that an immersion tin surface finish and a HASL surface finish occupy similar table locations. The EMF potentials of tin, lead and aluminum (6061-T6 alloy) are -0.281 volts, -0.316 volts and -0.493 volts respectively (Forman and Verchot.[3] The EMF potential of tin-plate and tin/lead solder per the SAE Aerospace Recommended Practice specification 1870 is listed as -0.50 volts.[5] A commonly used EMF comparison rule is that the absolute EMF value difference should be no greater than 0.300 volts to minimize corrosion problems. Using this figure of merit, an aluminum versus tin or tin/lead couple is less than 0.300 volts and would be an acceptable metallic couple. Therefore, the immersion tin surface finish was not included in the study.

The EMF potentials for silver and gold are +1.50 and +0.800 respectively (ASM Handbook).[4] The reader should realize that these EMF potentials are based on pure metals and not for gold or silver plating thus the values are slightly inflated. However, even if the EMF potentials were adjusted down the absolute EMF value comparison would dictate that a gold or silver coupling to aluminum would result in a high corrosion rate. Electronics manufacturers have used immersion gold surface finishes for over 20 years.[6] The authors were not able to find any reported cases of galvanic corrosion issues associated with immersion gold surface finishes and aluminum housings in the industry literature. The lack of industry data on potential problems with immersion gold prompted the authors to develop and execute a series of conditioning tests to understand the potential/possible issues of using either immersion gold or immersion silver surface finishes on printed wiring boards in aluminum housings.

Objectives
Determine the degree of corrosion between a precious metal surface finish (e.g. silver or gold) and aluminum galvanic couple:

- the degree of corrosion between bare aluminum and gold galvanic couple.
- the degree of corrosion between aluminum and silver galvanic couple.
- the degree of corrosion between aluminum and tin/lead galvanic couple (baseline data).
- the effect of zinc plated hardware and a zinc/gold/aluminum galvanic couple.
- the degree of corrosion between a precious metal surface finish (e.g. . silver or gold) and aluminum using best practices material/finish selections (e.g. in a best case scenario or real world application).

Test Methodology
Test Vehicles
In the course of this experiment three test vehicles were used. An electroless nickel - immersion gold (ENIG) board was tested. To increase the galvanic potential of the system a five volt bias was placed between internal circuit planes of the board. Bias wires were soldered to the bare board as illustrated in Figure 3A.

Attached to the board were eight aluminum hex posts (located per Figure 3B). The posts were held in place on one side with one stainless steel pan head screw and one stainless steel flat washer per post. On the other side of the post was a piece of aluminum sheet metal simulating an aluminum housing or chassis. The perimeter outline of the sheet metal was the same as the circuit board. The sheet metal was predrilled to allow the screws to connect to the posts. At all times there was continuous contact between the sheet metal, post, and gold. Figure 4 illustrates the setup of hardware used on all test vehicles.

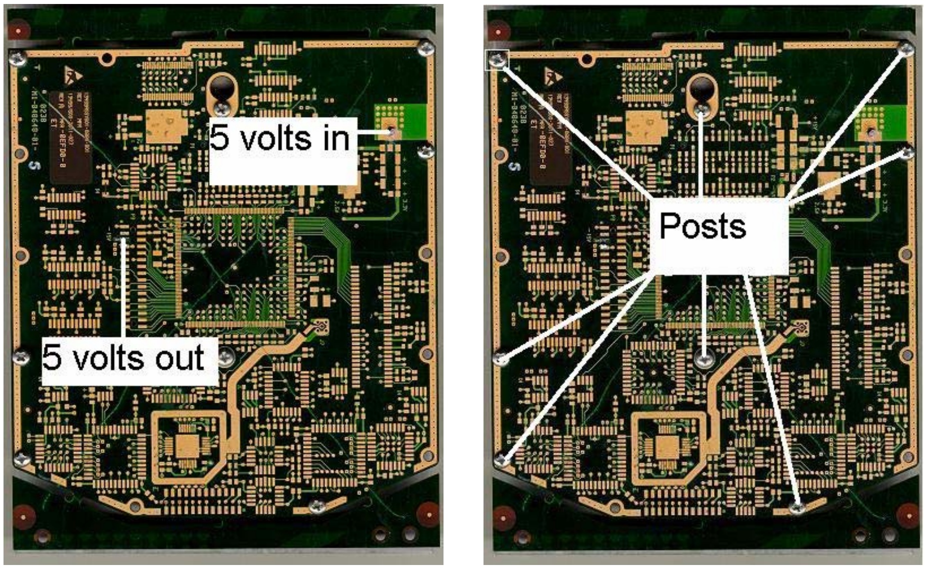


Figure 3A/3B – ENIG PWB Bias and Post Locations

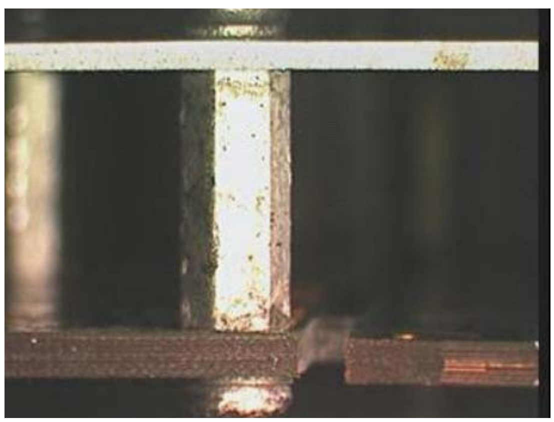


Figure 4 - Hardware Configuration

An immersion silver board was plated using the Sterling™ immersion silver plating process. The MacDermid Printed Circuit Laboratory performed the plating. This test board, unlike the ENIG test board, could not be biased on internal planes. Instead, parallel surface traces were utilized. Jumper wires were soldered in position as illustrated in Figure 5.

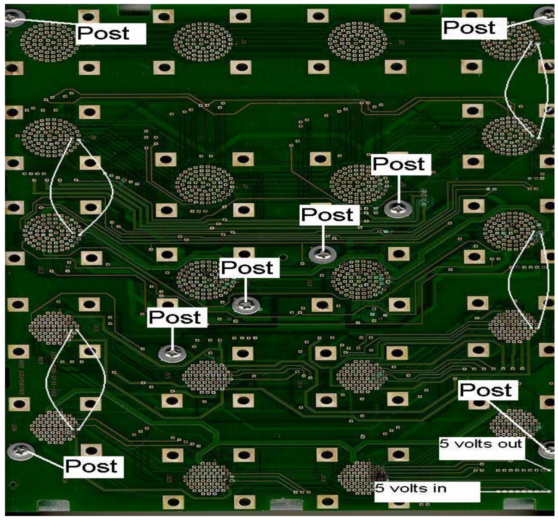


Figure 5 - Immersion Silver PWB Bias and Post Locations

The immersion silver test board was attached to aluminum sheet metal, using the same setup as the ENIG test board, with eight aluminum hex posts. This board used larger posts, screws, and washers due to hole sizes.

The third test vehicle was a tin/lead finish board. Wires were soldered onto this board as illustrated in Figure 6A. The tin/lead board utilized the same hardware configuration scheme as the immersion silver and ENIG test boards. The hex post positions are illustrated in Figure 6B. Each board had a similar size piece of sheet metal attached by six posts in the same fashion as the previous boards.

Figure 6A/B – Tin/Lead PWB Bias and Post Locations

Conditioning Environments

A set of the ENIG and immersion silver test boards were subjected to a temperature/humidity test environment. The humidity chamber parameters were 85ºC / 85% RH for 270 hours with a 5 volt bias on each test board. Test boards were placed in the chamber such that each board was not touching the other, nor were they allowed to come into contact with the walls of the chamber. A sheet of aluminum foil was placed on the top shelf of the chamber to prevent to possibility of having condensation drip on the boards.

A second set of ENIG and immersion silver test boards were tested per the ASTM B117 Salt Fog specification. A 5 volt bias was placed on each board. The salt fog test was run for a total of 48 hours. During the test, boards were placed in the chamber at an approximate angle of 15º, with no board overlapping the other. The tin/lead test boards were processed as a second salt fog test run after the ENIG and immersion silver test board exposure was completed. After completion of the salt fog testing, all hardware was removed and cleaned with DI water, light brushing, and Isopropyl Alcohol (IPA) in accordance per the specification requirements. All boards were cleaned with the same process.

Test Results

Humidity Test

The humidity tests results revealed little to no effect on the posts and no effect on the gold or silver finishes on the boards. Visual inspection focused on any areas of corrosion attack (e.g. pitting), corrosion product buildup or surface discoloration. Discoloration was defined as a visual appearance change with no physical corrosion attack for this study. The humidity test produced no corrosion evidence; however it did result in the discoloration of the finishes.

All of the ENIG test boards had discoloration of the surface finish after the humidity exposure. Figures 7 and 8 are illustrations of the typical ENIG test board. In addition to the potential galvanic reaction between the test board finish and the simulated aluminum housing, there also was a potential galvanic reaction between all stainless steel washers and each finish, this couple having a lower (e.g. less severe) EMF potential. Neither the post nor washer sites showed any signs of pitting or corrosion product buildup.

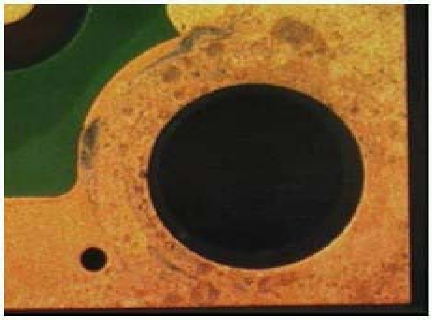
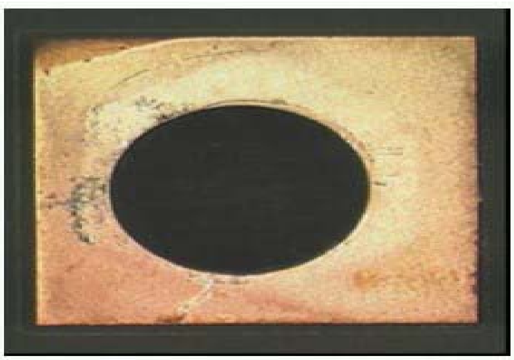


Figure 7 - ENIG Post Site **Figure 8 - ENIG Washer Site**

Figure 9 (a post site) and Figure 10 (a vacant site, i.e. no hardware) show the effect of humidity observed on the immersion silver surface finish. Visual examination of the immersion silver test boards revealed no corrosion but some evidence of surface finish discoloration.



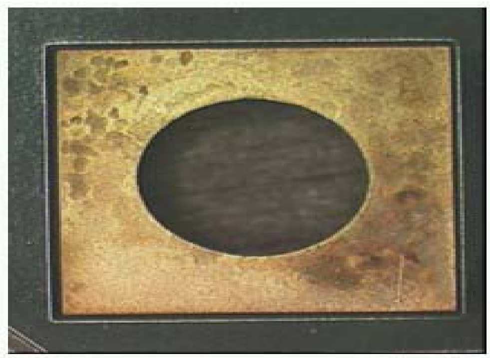


Figure 9 – Immersion Silver Post Site **Figure 10 – Immersion Silver Vacate Site**

Salt Fog Test
The salt fog test was considered much more severe than the humidity test for galvanic corrosion. The post test visual examination confirmed that belief. None of the surface finishes tested were corroded by the salt fog environment in the mating area of contact between the post and the finish. These areas did undergo severe discoloration of the surface finish. Figure 11 illustrates this contact area. However, examination of the posts themselves shows the effect of a galvanic corrosion reaction. Figure 12 shows the corrosion attack on the post.

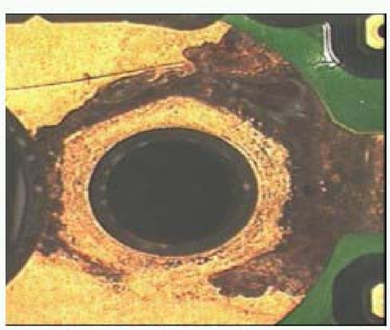


Figure 11 - ENIG Post Site **Figure 12 - ENIG Post Corrosion**

The EMF potential difference between the silver and aluminum is smaller than gold and aluminum so it would be a reasonable assumption that less corrosion would be observed. Additionally, the aluminum posts used on the immersion silver test boards inadvertently had a Class 3 conversion coating applied for improved corrosion resistance. The visual examination confirmed that the degree of corrosion was less severe for the immersion silver finish than observed on the ENIG finish. Figures 13 and 14 illustrate the amount of corrosion on the silver boards post site and post.

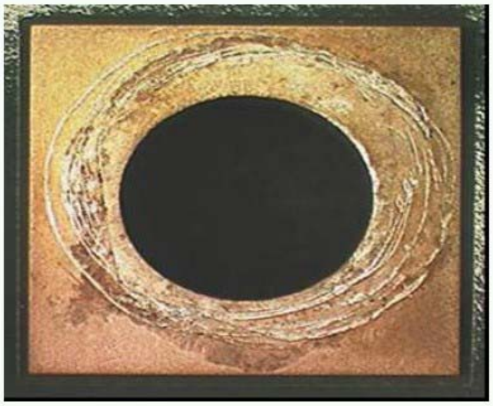


Figure 13 - Immersion Silver Post Site

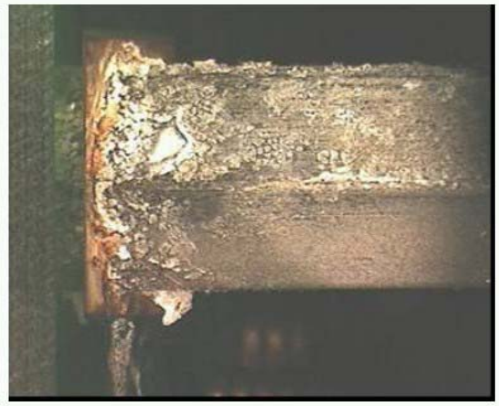


Figure 14 - Immersion Silver PWB Post

The potential difference between the tin/lead and aluminum is lowest of the three finishes tested thus it would be a reasonable to assume that the smallest amount of corrosion would be observed. However, the visual examination results show that the corrosion between tin/lead, immersion silver and ENIG finishes were very similar. These results demonstrate that the EMF potential (i.e. the galvanic reaction couple) can not always predict corrosion effects. Figures 15 and 16 illustrate the corrosion attack of the posts from the tin/lead test boards.

Figures 15-16 also demonstrate the corrosive attack of the post aluminum alloy grain boundaries even though there was an acceptable EMF potential difference present.

Figure 15 -Tin/lead - Post Cross Section (25X)

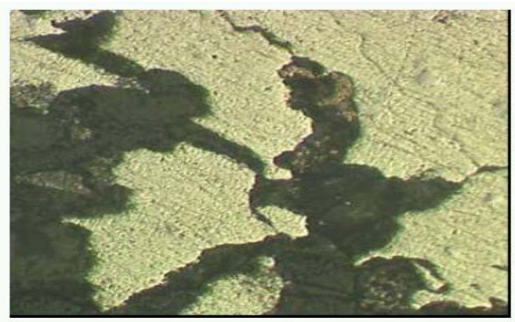


Figure 16 - Tin/lead - Post Cross Section (200X)

The issue of substituting zinc plated screws for the stainless steel screws and stainless steel washers in the hardware configuration was explored. A set of ENIG test boards was wired with a five volt bias and placed into salt fog test for 48 hours. The post test visual examination revealed an attack of the zinc plated screws. Once the zinc plating was compromised the underlying metal was exposed to the salt fog and severe corrosion occurred. This corrosion attack only occurred to the screws that were in contact with the gold finish. Figures 17-18 illustrate the affect of the potential difference in the galvanic couple between zinc, aluminum, and gold.

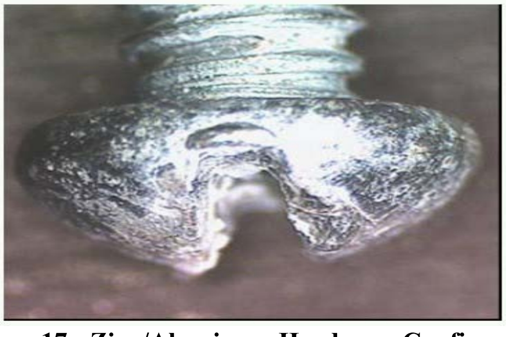


Figure 17 - Zinc/Aluminum Hardware Configuration

Figure 18 - Zinc/Gold Hardware Configuration

The corrosive attack of the zinc plated screws was so severe that corrosion product from the corroding base metal stained the board. Figure 19 illustrates the effect of zinc on the gold surface of the board (discoloration only). Figure 20 illustrates the interface between aluminum and gold. The discoloration seen in this picture is due to the presence of corrosion product buildup from the screw base metal.

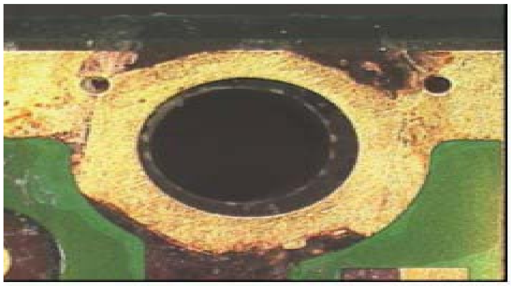


Figure 19 - Zinc/Gold Hardware Configuration

Figure 20 - Aluminum/Gold Hardware Configuration

Finally, a best case scenario was constructed to simulate a real world application of assemblies which utilized a best practices material system approach. This test board set was subjected to the salt fog test but used conversion coated aluminum posts, stainless steel screws/washers, conformally coated test board surfaces and the boards were not biased during the environmental exposure. The test boards used the same hardware configuration as the previous tests, however, the entire test board was placed in a 7"x 9"x 2" aluminum 5052 housing. The housing was modified attaching a 7"x 9" (5052 aluminum sheet) lid and cutting out a 7"x 2" area leaving open on one edge allowing salt fog to infiltrate from the bottom up. Figure 21 illustrates the setup (housing and test board) of the best case scenario.

Figure 21 - Best Case Scenario Configuration

The best case scenario results can be seen in Figures 22-23. Figure 22 illustrates the effect of the gold/aluminum couple on the aluminum post. There is very little corrosion/pitting on the posts or post sites in comparison to the corrosive attack on the posts for the non-optimized case (Figure 12). Figure 23 illustrates a post site where aluminum was in direct contact with gold. The visual examination revealed only discoloration and no corrosive attack.

Figure 22 - Best Case Scenario: Conversion Coated Post

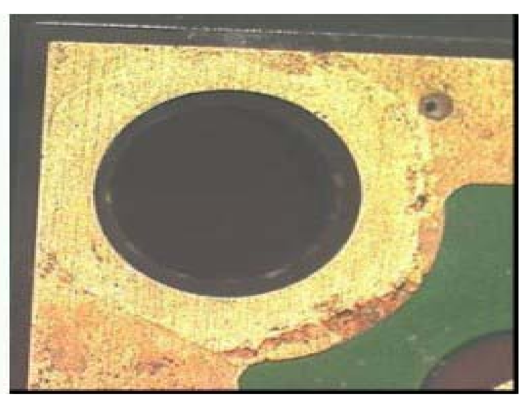


Figure 23 - Best Case Scenario: Post Site

Discussion

The humidity and salt fog testing conducted in this investigation demonstrated that a focus on the EMF potentials for gold/silver coupled to aluminum does not produce a realistic, predictive result in terms of corrosion susceptibility. Any material system which is subjected to a severe use environment without consideration of the overall material interactions is at considerable risk of degradation. Judicious application of materials, as demonstrated by the investigation's best case scenario, is the correct methodology for surviving a severe use environment.

Conclusions

This investigation showed that immersion silver and ENIG printed wiring board surface finishes are no more prone to a galvanic corrosion attack in a severe use environment than a traditional printed wiring board HASL finish if best practice material system methodologies are applied.

Acknowledgements

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