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Creep Corrosion of PWB Final Finishes: Its Cause and Prevention

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Abstract
As the electronic industry moves to lead-free assembly and finer-pitch circuits, widely used printed wiring board (PWB) finish, SnPb HASL, has been replaced with lead-free and coplanar PWB finishes such as OSP, ImAg, ENIG, and ImSn. While SnPb HASL offers excellent corrosion protection of the underlying copper due to its thick coating and inherent corrosion resistance, the lead-free board finishes provide reduced corrosion protection to the underlying copper due to their very thin coating. For ImAg, the coating material itself can also corrode in more aggressive environments. This is an issue for products deployed in environments with high levels of sulfur containing pollutants encountered in the current global market. In those corrosive environments, creep corrosion has been observed and led to product failures in very short service life (1-5 years). Creep corrosion failures within one year of product deployment have also been reported. This has prompted an industry-wide effort to understand creep corrosion although minimal progress has been made in this effort. This lack of progress has been primarily due to the inability of reproducing creep corrosion in the lab using realistic accelerated aging tests. In this paper, we will demonstrate that creep corrosion on a PWB is highly surface sensitive. Neither clean FR4 nor clean solder mask surfaces support the creep corrosion. In general, the board assembled with rosin wave soldering fluxes and solder paste containing rosin flux is also resistant to the creep corrosion. However, residue left on the solder mask surface by organic acid flux is highly active and supports the creep corrosion of copper sulfides. The proper choice of the assembly flux can eliminate product failure due to creep corrosion associated with the ImAg plated circuit boards deployed in highly corrosive global environments. Furthermore, mixed flowing gas testing (MFG) provides a realistic accelerated test for simulating the creep corrosion in the laboratory without requiring condensing conditions.

1. Introduction
Lead-free PWB final finishes have been developed with the primary design objective of providing a solderable and coplanar surface for the component attachment during electronic circuit assembly. While the short-term corrosion resistance of the board finishes is important for the purpose of maintaining shelf-life for solderability (up to 12 months), long-term corrosion resistance was neither required nor considered [1-3]. The long-term corrosion resistance in the field during the service life of the device has not been an issue for the traditional board finish, hot air solder leveling (HASL), as it offers excellent corrosion protection of underlying copper due to its thick coating and inherent corrosion resistance. Extensive testing and reliability assessments have been performed on the lead-free PWB finishes. However, very little attention has been paid to the corrosion resistance of the lead-free PWB finishes once they are field deployed. Recently, the corrosion resistance of lead-free PWB finishes has generated considerable interest due to premature field failures observed in various parts of the world. Works on the product failure in the field due to corrosion and simulating those failures in the lab have been published [4-7].

Two types of failures have been identified: creep corrosion and flaking of corrosion products [6]. In both cases, the semi-conducting to conducting corrosion products can cause either intermittent or permanent short circuits in the electronic products.

Mixed flowing gas containing H_2S, SO_2, NO_2 and Cl_2 has been widely used to simulate the field environmental conditions and perform accelerated tests on electronic devices. While the flaking of corrosion products can be easily reproduced in the MFG test, creep corrosion has not been consistently reproduced. For instance, samples prepared using clean IPC-B25 comb patterns showed minor to no creep corrosion after extended MFG exposures using the international condition [6], even though severe flaking of corrosion products was observed. Fig.1 shows samples with Cu trace only (right) and ImAg plated Cu trace (left) after 40 days MFG exposure using international condition [6]. Thick corrosion products (mostly copper sulfide) as well as flaking of the corrosion products were observed in both cases but no signs of creep corrosion across the FR-4 surface between the traces were seen in either case. However, creep corrosion readily occurs in the MFG test if certain types

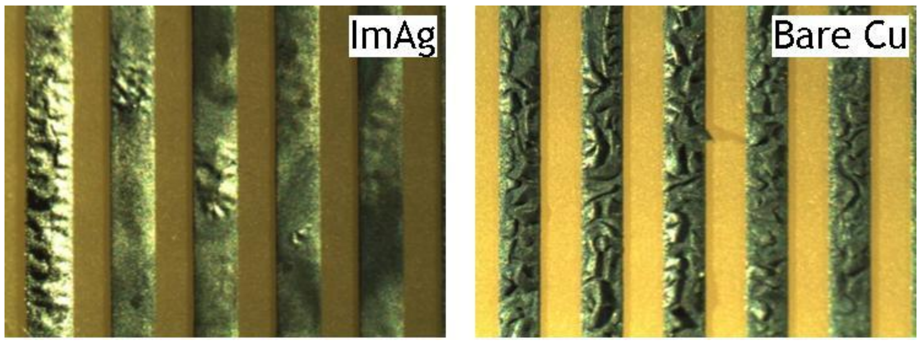

Figure 1 – Samples after 40 days MFG test using international conditions [6]

of contamination were present on the surface. This is demonstrated in Fig. 2, which shows an ImAg-plated IPC-B25 comb coupon after only 2 days MFG exposure. In the majority of the areas, no creep corrosion was observed, although severe localized corrosion was seen on ImAg plated traces. Interestingly, in the middle of the coupon, creep corrosion was observed within a droplet-shaped area and a short circuit of 1.3kohm was measured. This result indicates that creep corrosion is highly surface specific and sensitive to surface chemical properties. The clean FR-4 surface does not support creep corrosion, while the contaminated FR-4 surface does support creep corrosion. Apparently, certain surface characteristics are required for the corrosion product to creep on those surfaces.

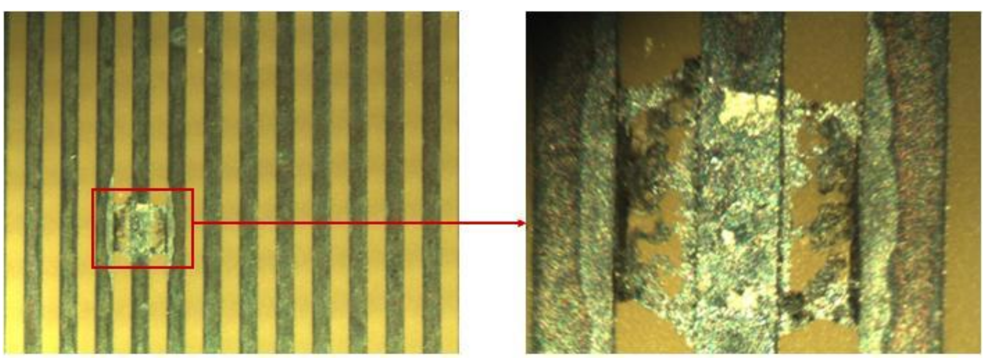

Figure 2 – Creep corrosion over contaminated surface resulting in short circuit of 1.3kΩ

In the assembly of circuit boards, flux residues are a common surface contaminant. This bears the question: "do flux residues promote creep corrosion (as in the case of certain types of surface contamination)?" If this is true, it may explain the difference between the creep corrosion observed on the assembled circuit boards in the field and inconsistent evidence of creep corrosion on lab samples, which have not seen the assembly fluxes. To examine the possible effect of flux residues on the creep corrosion, we have purchased an ImAg plated populated circuit board used in consumer electronics. The board was assembled with selective wave soldering, as the flux residues on the board clearly indicate. The board was subjected to MFG exposure in our lab. Fig. 3 shows the result after 5 days MFG exposure using the international condition. Three distinctly different areas were observed. (1) In the right top corner, the vias were selectively soldered and completely covered by the solder. No corrosion was seen in this area. (2) The left bottom corner was not soldered and the Ag finish on the vias is completely exposed. Severe corrosion was observed in this area but no creep corrosion was seen. (3) The boundary area between the unsoldered area and wave-soldered area. Severe creep corrosion was seen in this boundary area and short circuits due to the creep corrosion were also observed. The pattern of no corrosion in the soldered area, creep corrosion in the boundary area and corrosion without creep in the non-soldered area was repeatedly observed across the entire circuit board.

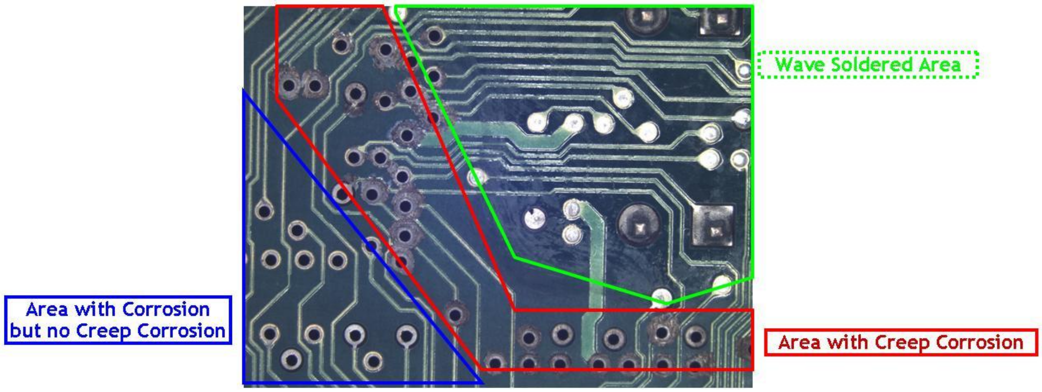

Figure 3 – ImAg board from a consumer product after 5 days MFG exposure using international condition [6]

Apparently, flux has migrated from the soldered area to the adjacent boundary area during the selective wave soldering and left residues in the boundary area. The combination of exposed Ag and flux residues in the boundary area allows the Ag to corrode and then provides a transport media for the corrosion products to migrate on the flux residue covered solder mask surface. The Ag plated vias in areas far away from the soldered area were corroded but did not show signs of creep corrosion, as the clean solder mask surface does not support the creep of the corrosion products. This result further demonstrates that creep corrosion is highly surface specific and only certain types of surfaces can support creep corrosion. The “wrong” combination of solder mask, fluxes, and process conditions can produce a “creepable” surface for ImAg plated circuit boards. Searching for creep corrosion resistant ImAg or other PWB final finishes should be done on an assembled board with solder mask and fluxes. The MFG test provides a viable and realistic accelerated aging test for creep corrosion.

The flux residue assisted creep corrosion is not only limited to ImAg plated circuit boards. Similar results are also observed for Organic Solder Preservatives (OSP) [8]. Fig.4 compares two circuit boards after 5 days MFG exposure using the

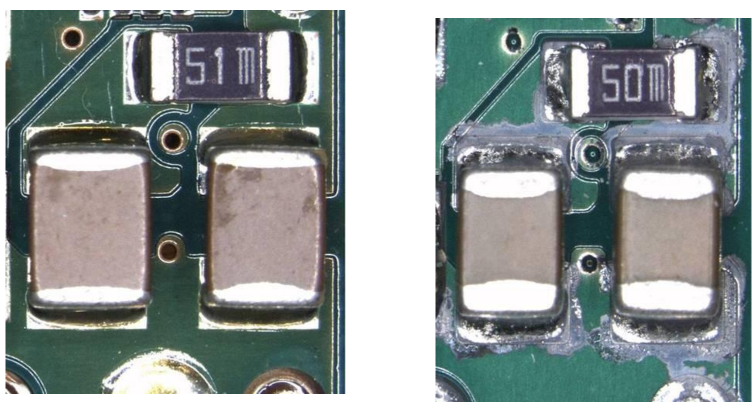

Figure 4 – OSP boards after 5 days MFG exposure using international condition [6]

international condition [6]. Both circuit boards have OSP final finishes but were assembled with different types of solder pastes. The board on the left side was assembled with a solder paste containing organic acid flux, while the board on the right side was assembled with a solder paste containing rosin-based flux. After 5 days MFG exposure, severe creep corrosion was observed on the board assembled using the paste containing organic acid flux. On the other hand, the board assembled using the paste containing rosin-based flux only showed localized corrosion in the exposed OSP areas without any significant creep corrosion. Furthermore, the degree of the creep corrosion depends on the cleaning operation after the assembly and correlates with the cleanness of the board. This drastic difference between boards assembled with different type of fluxes demonstrates the important role which flux residues have on the creep corrosion. To further delineate the effect of various assembly fluxes on the creep corrosion, a systematic study involving eight different wave soldering flux and six different solder pastes was conducted and the results are reported in this paper.

2. Experimental

2.1 Test vehicle

Figure 5 shows images of the top and bottom sides of the test vehicles used in this work. It contains nine trace comb patterns (seven on the top side and two on the bottom side) with varying line width and spacing. Five of the nine trace patterns have solder mask stripes across the traces for creating maximal areas of ImAg and solder mask interface for creep corrosion. There are four comb patterns of through-holes with two having solder mask defined vias and two having non-solder mask defined vias on each sides. A pattern for QFP component is also included on the top side. The middle area of the bottom side is masked for selective wave soldering (see image on the right).

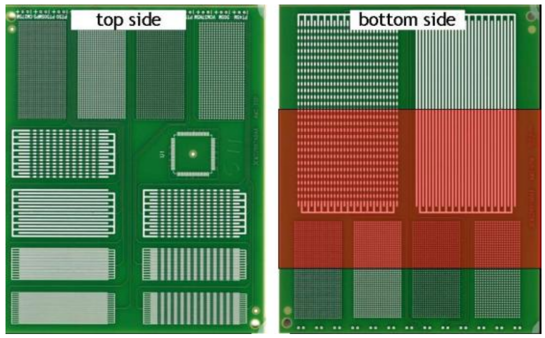

Figure 5 – Test vehicle

2.2 Test Condition

Based on literature survey and extensive internal testing within Alcatel-Lucent both in the field and the lab [9-16], the parameters of mixed flowing gas (MFG) test were chosen to simulate the worst field conditions which can be encountered in the current worldwide marketplace. As both Battelle and Telcordia MFG test conditions were designed largely for simulating North American environment, a significantly higher H_2S concentration has to be used for simulating the high corrosion rate (copper sulfide as the main components of the corrosion products in the field) in more aggressive environments. The concentration of corrosive gases is summarized in Tab.1. The temperature was 40^oC and the humidity was between 70-75% RH. The corrosion rate in the chamber was monitored using Cu coupon weight gain and was determined to be ~500 nm/day (equivalent copper sulfide thickness). Similar thickness of corrosion products have been observed for Cu coupons deployed for one year in some field locations [15-16] in the world. Thus, one year filed deployment of the equipment in those locations can be simulated by one day exposure in MFG chamber. For comparison, the typical corrosion rate in North American is 60-90nm/year for indoor and 180-270nm/year for outdoor environment [13].

Table 1 Concentration of corrosive gases in MFG chamber

Gas	Concentration (ppb)
H_2S	1500
NO_2	200
Cl_2	20
SO_2	200

2.3 Test Samples

Test vehicles were fabricated by six different board houses using various type of ImAg and solder mask. The boards were then assembled at four different EMS locations using eight different wave soldering fluxes (four ORL0, three ROL0 and one ROM1 fluxes) and six different solder pastes (four containing ROL0 fluxes and two containing ROL1 fluxes). The samples were then subjected to MFG test using the condition described in table 1. The primary difference in creep corrosion was observed between the different types of the fluxes and will be the focus of the discussion of this paper. Only minor difference was observed between the boards fabricated at different board houses (different ImAg and solder mask combination) and will be the focus of a future work.

3. Experimental results

All samples were initially exposed to MFG for 5 days. If severe creep corrosion was observed, the MFG test was terminated. For samples exhibiting only minor or no creep corrosion after 5 days MFG exposure, the MFG test was extended to 10, 15 and 20 days.

In addition to the assembled test boards, bare boards were also collected from all six fabricators. 11 bare boards were subjected to the MFG test along with the assembled test vehicles.

No or very minor creep corrosion was seen for all the bare boards, even after 20 days MFG exposure. As the creep corrosion on the assembled boards occur mostly in the areas of through-hole patterns (see below), we will focus our discussion on those areas throughout this paper. Fig. 6 shows images taken from two of the through-hole patterns on the bottom side (wave soldering side). The image on the left was taken from the as-received sample, while the image on the right was from a sample after 20 days MFG test. As it can be clearly seen from the image, the exposed Ag surface is completely corroded but no creep corrosion on to the adjacent dielectric surface (solder mask or FR-4 surfaces) is observed. This result is consistent with the previous observation that clean solder mask and FR-4 surfaces do not support creep corrosion.

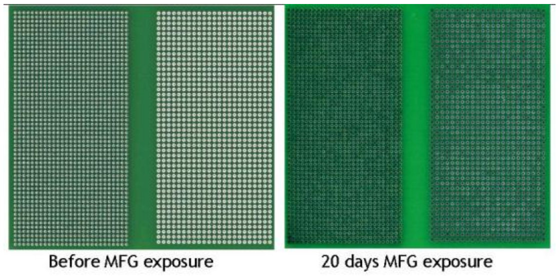

Figure 6 – Bare boards

3.1 Effect of wave soldering flux on creep corrosion

Eight different wave soldering fluxes were evaluated in this work. Four of the eight fluxes are classified as ORL0 according to IPC J-STD-004 standard and contain organic acid as the key active ingredient. Among the four ORL0 fluxes, three fluxes are water-based and the fourth one is solvent based. The other four of the eight fluxes are rosin type of fluxes (RO). Three of the four rosin fluxes have low activity and contain no halides (ROL0) and the fourth one has a moderate activity and contains 0.5-2% halides (ROM1). A strong dependence of creep corrosion was observed on the type of the fluxes used for the assembly. For facilitating the discussion, we divided samples into three groups based on the degree of the creep corrosion observed: 1) poor (moderate creep corrosion to severe creep corrosion) 2) marginal (creep corrosion in small isolated areas due to flux residues) and 3) good (no/minor creep corrosion, or localized creep corrosion due to apparent contamination other than flux residues, such as fibers).

3.1.1 Poorly performing samples

The worst creep corrosion was observed on samples assembled with organic acid wave soldering flux (Type ORL0). Fig. 7 shows results for test board assembled with solvent based ORL0 flux. Both images were taken on the bottom side (wave soldering side) of the test boards, with the picture on the left being taken before MFG exposure and the picture on the right being taken after 5 days MFG exposure. In both pictures, two through-hole patterns were included, with bottom half of the two patterns having been selectively wave soldered. Due to the process variation, the pattern on the left shows only partial wetting by the solder, while the through-holes in the right pattern are completely covered by the solder. After 5 days MFG exposure, all exposed ImAg (not covered by solder) was completely corroded. The top half of the two patterns showed no creep corrosion, even though localized corrosion was observed on exposed ImAg surface. Conversely, severe creep corrosion was observed in the selective soldered areas, except the areas which are completely covered by the solder. Furthermore, creep corrosion was also observed in the boundary areas between soldered and non-soldered areas. This is more clearly seen in the images shown in Fig.8, which provides a close up view of the two through hole patterns: solder mask defined vias in the left and non-solder mask defined vias on the right.

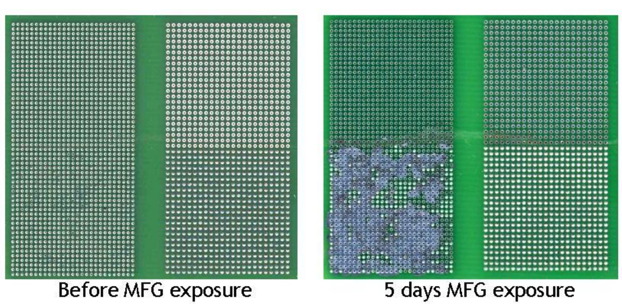

Figure 7 – Board assembled with solvent based ORL0 wave soldering flux

In both cases, only localized corrosion was observed in the non soldered areas (left side of each images), while severe creep corrosion was seen for the selectively soldered areas and the boundary areas

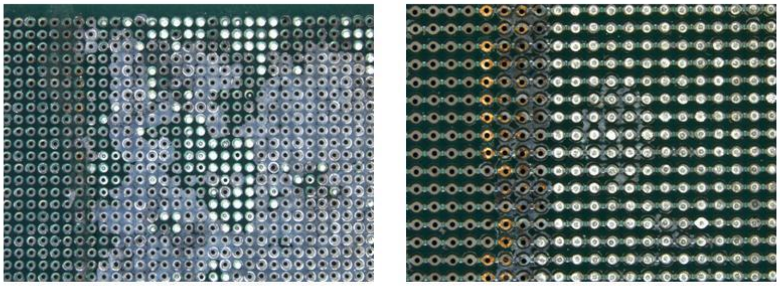

Figure 8 – Board assembled with solvent-based ORL0 flux after 5 days MFG test

between the soldered and non-soldered areas. Additionally, it is worthy to note that the creep corrosion occurs preferentially over the solder mask covered areas for the non-solder mask defined vias. This result suggests that the combination of flux and solder mask provides a surface for the creep corrosion to occur. Similar results were also observed for the top side of the test board. Fig. 9 shows the image taken on the top side of the same sample after 5 days MFG exposure. The through holes on the left side of the image showed only localized corrosion, while the soldered area on the right and the boundary area between soldered and non-soldered areas showed severe creep corrosion. Apparently, the wave soldering flux has flowed through the through-hole during the wave soldering and left residues on the surface of the top-side, which in combination with the solder mask provides a surface for the creep corrosion to occur.

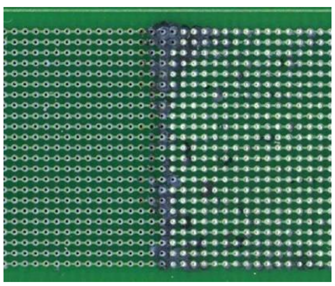

Figure 9 – Top side of the board assembled with solvent- based ORL0 flux after 5 days MFG test

Severe creep corrosion was also observed for the boards assembled with two of the three aqueous ORL0 of fluxes, while the board assembled with the third aqueous ORL0 showed some creep corrosion but far less than the other two. Fig.10 shows the top-side of one sample before (left) and after 5 days MFG test (right). Interestingly, severe creep corrosion was seen in both soldered and non-soldered through-holes.

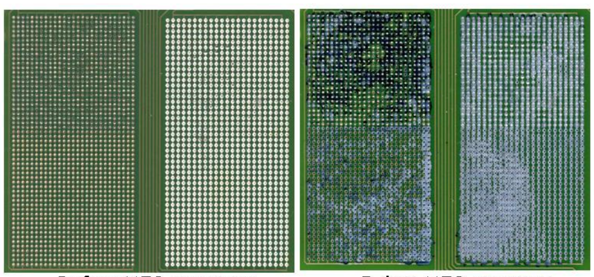

Figure 10 – Board assembled with aqueous based ORL0 wave soldering flux

Apparently, the wave soldering flux has reached the topside through the through-holes in the soldered areas and then migrated from the soldered areas to non-soldered areas during the wave soldering.

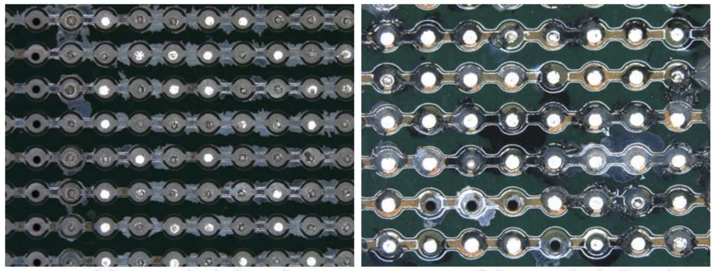

Figure 11 – Board assembled with aqueous ORL0 flux after 5 days MFG test

This conclusion is supported by the fact that the non-soldered area on the bottom side (protected by the mask during wave soldering) did not show any creep corrosion. Fig.11 shows the close-up view of the solder mask defined (right) and non-solder-mask defined (left) through-holes of a sample after 5 days MFG test. Severe creep corrosion was observed in both areas. Again, there is a clear preference for creep corrosion to occur on the flux-contaminated solder mask surface than the flux-contaminated FR-4 surface for the non-solder mask defined through-holes.

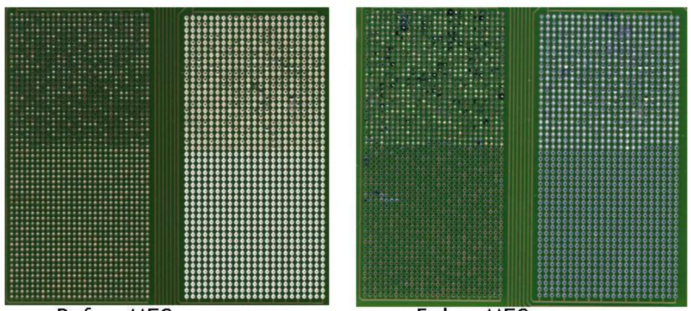

Figure 12 – Marginal board assembled with aqueous based ORL0 flux

3.1.2 Marginal samples

As mentioned above, the test board assembled with one of the three aqueous fluxes showed significantly less creep corrosion, although creep corrosion was also observed in this case. Fig. 12 shows pictures taken on the topside of the board before and after 5 days MFG test. Compared to images shown in Fig.10, significantly less creep corrosion was observed on this sample. The creep corrosion only occurred in selected areas. However, as demonstrated by the close-up view in Fig.13, in the areas where the creep corrosion was observed, it did create short circuit between the adjacent through-holes.

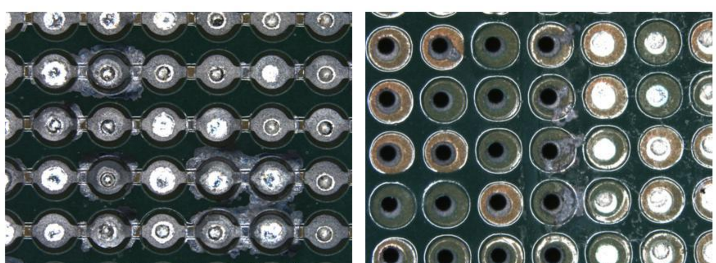

Figure 13 – Marginal board assembled with aqueous based ORL0 flux after 5 days MFG test

3.1.3 Good samples

In contrast to organic acid flux (OR), the rosin based fluxes (RO) in general do not promote creep corrosion. This is demonstrated in Fig.14, where images from boards assembled with ROL0 flux were shown. Both images show two through-hole patterns on the bottom side of the test vehicle. The left image was from the as-received sample, while right sample was taken from a sample after 5 days MFG test. No creep corrosion was seen in any areas of this sample. Fig. 15 shows a close-up view of one of the solder mask defined through-hole pattern. As it can clear be seen in this image, no creep corrosion was seen, even though the exposed Ag surface was severely corroded in both solder and non-soldered areas.

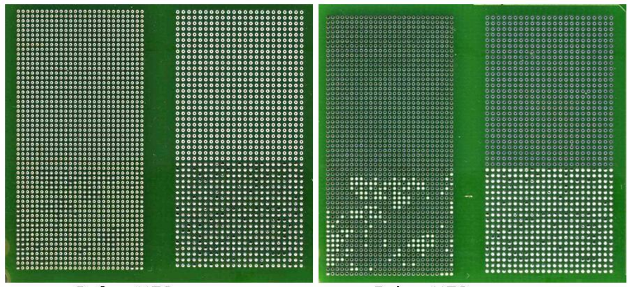

Figure 14 – Board assembled with ROL0 wave soldering flux

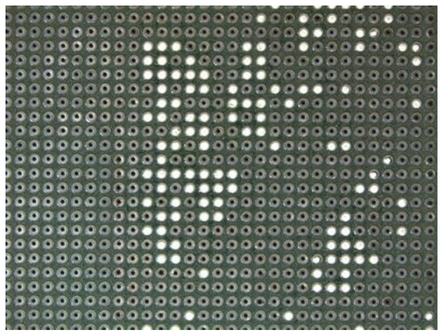

Figure 15 – Board assembled with ROL0 wave soldering flux after 5 days MFG test

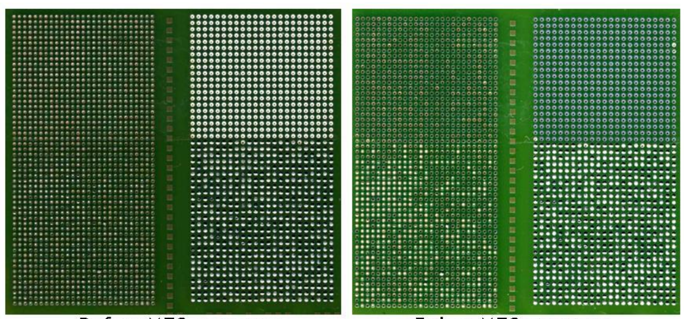

Figure 16 – Board assembled with ROM1 wave soldering flux

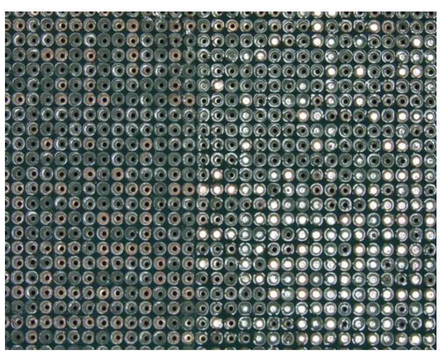

Figure 17 – Board assembled with ROM1 wave soldering flux after 5 days MFG test

Similar results were also observed for the rosin flux with a moderate activity and containing 0.5-2% halides (ROM1). This is demonstrated by the images in Figs. 16 and 17. Again, severe corrosion was observed on the exposed Ag surface but no creep corrosion was observed. The MFG test was also extended to 20 days for selected samples assembled with RO fluxes and still no creep corrosion due to the flux residues was observed.

3.1.4 Summary on the wave soldering fluxes

As discussed above, the creep corrosion shows a strong dependence on the type of wave soldering flux used for the assembly. Table 2 summarizes results after 5 days MFG. All eleven boards, which have not seen the assembly flux, showed no creep corrosion. This is consistent with the previous findings that clean FR-4 and solder mask surface do not support the creep corrosion.

Table 2. Summary of creep corrosion after 5 days MFG testing

	bare board	assembled with rosin flux	assembled with organic acid flux
bad	0	0	25
marginal	0	2	9
good	11	16	7

Sixteen of the eighteen test vehicles assembled with rosin flux showed no to minor creep corrosion. Only two out of the eighteen test vehicles assembled with rosin flux showed creep corrosion in localized areas and have been classified as marginal performing samples. Both of these two samples were assembled with the same flux and solder mask. It is not clear whether the creep corrosion observed on these two samples is due to the variation in the flux composition of this particular rosin flux or due to contamination other than flux residues. At this point, it is reasonable to conclude that the rosin flux residue does not promote creep corrosion.

In contrast, the organic acid flux leaves residues behind on the solder mask surfaces which provide a surface for the creep corrosion to occur. Twenty-five of the forty-one test vehicles assembled with organic acid flux showed severe creep corrosion and nine of them showed creep corrosion in some areas. This result shows strong tendency of organic acid flux residues for promoting creep corrosion. It is interesting to note that seven of the test vehicles assembled with organic acid flux showed no to minor creep corrosion. Four of the seven samples were from the 13 samples assembled with the marginal organic acid flux, while the other three were assembled with poorly performing organic acid. One possible explanation for this exception is that no active residues were left in the areas with exposed ImAg. Additional work is planned to understand this performance variation.

3.2 Effect of solder paste on creep corrosion

Six different solder pastes were included in this work. All six solder pastes were manufactured with rosin-based flux having low activity. Four of the six fluxes are halide-free (ROL0 according to IPC classification), while the other two contain less than 0.5% halides (ROL1 according to IPC classification). After 5 days MFG test, no creep corrosion due to the flux residues was observed on any samples. The test was then extended to 20 days for selected samples and still no creep corrosion due to the flux residues was observed. However, fiber-assisted creep corrosion was observed occasionally. Fig. 18 shows a sample assembled with solder paste containing ROL1 flux after 5 days MFG test. The image on the left shows severe localized corrosion on exposed ImAg-plated traces. The image on the right shows a fiber across the adjacent traces. The fiber is covered with copper sulfide and causes a short circuit of 132kΩ between the adjacent the traces. This result demonstrated again that the creep corrosion is highly surface sensitive. While the fiber surface is active for supporting the creep corrosion, neither clean solder mask nor the rosin flux residues provide a "creepable" surface.

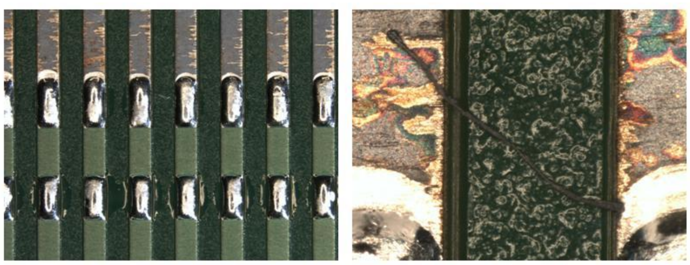

Figure 18 – Fiber assisted creep corrosion

4. Discussion

Creep corrosion is the mass transport process in which solid corrosion products (typically sulfide and chloride) migrate over a surface without the influence of an electric field. In contrast to electrochemical migration, creep corrosion does not require an electrical bias and a low-resistance electrolytic path between the anode and cathode. Although humidity can accelerate the corrosion of base metals and likely creep corrosion, the presence of an adsorbed/condensed water layer is not required for the creep corrosion. The creep corrosion could also occur on a "dry" surface. Unlike the electrochemical migration, which can occur on any surface with an adsorbed/condensed water layer under an electrical bias, the creep corrosion is highly surface specific and a given corrosion product can only migrate on a specific type surface. For instance, Ag_2S creeps readily on gold surface but does not creep on rhodium and palladium surfaces [17].

Creep corrosion is not only limited to metallic surface. It has been also observed on the plastic molding compound for IC package. In this case, the corrosion first takes place on the exposed lead-frame and the corrosion product migrates on to the adjacent encapsulate surface of the component and causes electrical short circuit between the adjacent leads and product failures in the field. Zhao [18] has systematically studied the creep corrosion on the plastic encapsulated microcircuit packages with noble metal pre-plated lead-frames and found that the Telecordia outdoor MFG testing is effective in producing creep corrosion on the plastic molding compound. As little as 5-day Telcordia outdoor MFG testing can induce creep corrosion over the mold compound.

Consistent with the previous results, we have also found that the creep corrosion on printed circuit boards is highly surface specific and sensitive to the surface chemical properties. Neither clean FR-4 nor solder mask surfaces showed signs of creep corrosion, even for samples exposed to MFG for 20 days at the international condition. However, extensive creep corrosion of Cu_2S was observed, if certain types of surface contaminations are present on the FR-4 or solder mask surfaces. The residues left behind by the organic acid wave soldering flux on the solder mask provide such a surface for the creep corrosion to occur. The combination of FR-4 surface and organic acid flux residues is far less active for the creep corrosion. Apparently, the solder mask surface has a high propensity for picking up the flux residues and provides a highly active surface for the creep corrosion to occur.

In contrast to the organic acid flux residues, the rosin flux residues in general do not promote creep corrosion. It is not clear at this point of time why such a drastic difference was observed between organic acid flux and rosin flux, even though the carboxylic acid function group is the active component for both types of fluxes. One possible explanation is that there is a higher concentration of carboxylic acid function group exposed on the surface after assembly with organic acid flux and those free carboxylic acid function group on the surface provide the active sites for the creep corrosion. In case of the rosin flux, the carboxylic acid function group is mostly imbedded in the rosin matrix and very little of them is exposed on the surface to be available for supporting the creep corrosion. Furthermore, the carboxylic acid group in the rosin is typically tied to the heavy organic molecule, while small and mobile organic acid molecule is often present in the organic acid flux. Further work is under way to understand this difference.

The mechanism of the creep corrosion is not well understood. For creep corrosion on metallic surface, the galvanic corrosion theory was first proposed by Conrad [19], whereby the difference in galvanic potential between different metals provides the driving force for the creep corrosion. This is clearly not applicable for the creep corrosion on dielectric materials such as solder mask surfaces. Phenomenologically speaking, the energy difference between replacing the “creepable” surface with the corrosion product surface (surface energy difference of the two surfaces) has to be compensated by the energy released by the interaction between the corrosion product and the “creepable” surface (the interfacial energy). In a microscopic sense, the driving force for the creep corrosion on PWB is probably provided by the interaction between copper sulfide and carboxylic acid function group present in the flux residues. For the clean FR-4 or solder mask surfaces, the interaction between the FR4/solder mask surface and the creeping copper sulfide is apparent not strong enough to compensate the surface energy difference between copper sulfide and FR-4/solder mask. The presence of the flux residues on the solder mask would likely increase the surface energy of the clean solder mask surface due to the active component of carboxylic acid in the organic acid flux. Furthermore, the carboxylic acid will also interact more strongly with the creeping species (copper sulfide) and generate a rather high interfacial energy between the creeping corrosion products and the “creepable” surface. Both increased surface energy of the flux-covered solder mask surface and the interfacial energy of the interface between the creeping corrosion products and the “creepable” surface could provide the thermodynamic driving force for the spontaneous creep corrosion. It is also important to point out that the interaction between the creeping species and the “creepable” surface can not be too strong. Otherwise, the creep corrosion would be “braked” by this strong interaction due to the kinetic effect.

The simulation of the creep corrosion in the laboratory has to take the highly surface sensitive nature of the creep corrosion into consideration. Mixed flowing gas testing can simulate the environmental conditions in the global market place and has been successfully used to generate creep corrosion on electrical contacts (metallic surface) and IC components (dielectric surface) previously. In this work, the creep corrosion was successfully reproduced on printed circuit boards using MFG test. The previous inconsistency in generating creep corrosion on PWB lies in the lack of recognizing the highly surface sensitive nature of the creep corrosion. Test vehicles containing only surface finishes and solder mask without going through assembly process are not the appropriate samples for understanding the creep corrosion. Searching for creep corrosion resistant ImAg or other PWB final finishes should be done on an assembled board with solder mask and fluxes. The MFG test provides a viable and realistic accelerated aging test for the creep corrosion.

Summary
The creep corrosion on printed circuit boards is highly sensitive to the surface chemical properties. Neither clean FR4 nor clean solder mask surfaces support the creep corrosion. In general, the board assembled with rosin wave soldering fluxes and solder paste containing rosin flux is also resistant to the creep corrosion. Residue left on the solder mask surface by the organic acid flux, on the other hand, forms a "creepable" surface and is highly active for supporting the creep corrosion of copper sulfides. The proper choice of the assembly flux can eliminate product failure due to creep corrosion associated with the ImAg plated circuit boards deployed in highly corrosive global environments. The corrosion test using mixed flowing gases provides a realistic accelerated test for the equipment to be deployed in global environments. No condensing condition is required for simulating the product failure due to the creep corrosion in the laboratory.

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