Creep corrosion of electronic assemblies in harsh environments

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Abstract

Creep corrosion occurs in electronics assemblies and it is reminiscent to electromigration but does not require electrical field to drive the reaction. Corrosive elements and moisture must be present for creep corrosion to occur. Sulfur is the most prominent element to cause creep corrosion in environments such as paper mills, rubber manufacturing, mining, cement manufacturing, waste water treatment etc., also including companies and locations nearby such industries. The main part of printed circuit board assembly (PCBA) to be affected is the PCB surface finish. Especially immersion silver is prone to creep corrosion, but it sometimes occurs in NiPd (lead frames), and to a lesser extent in ENIG and OSP surface finishes. As the use of immersion silver is increasing as PCB surface finish and electronics are more and more used in harsh environments, creep corrosion is a growing risk. In this paper we will present the driving forces and mechanisms as well as suitable tests and mitigation strategies against creep corrosion

Key words: immersion silver, creep, corrosion, lead-free

Introduction

Creep corrosion occurs in electronics assemblies and it is reminiscent to electromigration. However, creep corrosion does not require electrical field to drive the reaction but corrosive elements and moisture must be present for creep corrosion to occur. Sulfur is the most prominent element to cause creep corrosion and it is readily available in environments such as paper mills, rubber manufacturing, mining (smelting) and cement/asphalt manufacturing, waste water treatment etc., also including companies and locations nearby such industries. The increasing usage of electronics in such environemts makes creep corrosion a growing risk.

The Restriction Of Hazardous Substances (ROHS) directive in the European union and similar activities in other parts of the word have lead the PCB industry to explore new solderable surface finishes. One cost effective solution is immersion silver. Immersion silver is especially prone to creep corrosion, but it sometimes occurs in NiPd (lead frames), and to a lesser extent in electroless nickel/immersion gold (ENIG) and Organic solderability preservative (OSP) surface finishes [1, 2]. As the use of immersion silver is increasing as PCB surface finish and electronics are more and more used in harsh environments, creep corrosion is a growing risk.

When increasing the usage of immersion silver it was expected that it would tarnish in the presence of sulfur (Ag_2S forms on the surface) but this was only a cosmetic concern. Previous studies showed that electrochemical migration was not a problem [3]. Typical mixed flowing gas (MFG) testing also did not show creep corrosion [4]. Therefore, it was a surprise to the industry when electronics in high sulfur industrial environments would fail rather quickly, some within four weeks in service; replacement systems would do the same. Most failures would occur in 2-4 months. Product tracking indicated that if failures did not take place within 6 months, they typically would not fail later from this mechanism. Thus there seemed to be a threshold of sulfur and humidity below which creep corrosion did not occur. High airflow appears to increase creep corrosion, as it is most severe in the direct path of air intake - likely due to more sulfur being made available for reaction.

Analysis of creep failures revealed the corrosion product to be fairly resistive, so bridging of two conductors does not cause immediate failure. As the corrosion product increases in thickness, the resistance decreases until functional shorting occurs. For this reason, there are a multitude of symptoms that can take place as a result of creep corrosion (depending on which two conductors are the first to bridge). Additionally, it was found that many corrosion failures passed electrical testing upon arrival from the field (termed CND – cannot duplicate). Upon exposure to high humidity, the failure symptom would reoccur. Resistance measurements showed that when exposed to high humidity, the resistance of the corrosion product dropped from over 10 MΩ to below 1 MΩ. Due to the nature of this failure mechanism it is difficult to identify corrosion failures without close inspection of each board.

In this paper we shall discuss creep corrosion mechanism in more detail. In addition, suitable test methods and countermeasures for creep corrosion will be covered.

Mechanisms of creep corrosion

A typical creep corrosion failure is shown in Figure 1 and Figure 2 provides an EDX spectrum of the corrosion product. It is primarily copper sulfide (Cu_2S) with a small amount of silver sulfide (Ag_2S). Studies have shown that high amounts of Cu_2S typically indicate the presence of active sulfur compounds such as elemental sulfur, hydrogen sulfide (H_2S), or organic sulfur compounds [5]. Creep appears to begin by growth of dendrites. However, this is not electro-chemical migration (voltage potential driven) dendritic growth, since creep takes place equally in all directions and does not require the board to be powered. Rather it appears that Cu_2S is being formed in a layer of moisture on the surface and precipitates out of solution as it forms (since Cu_2S is insoluble in water).

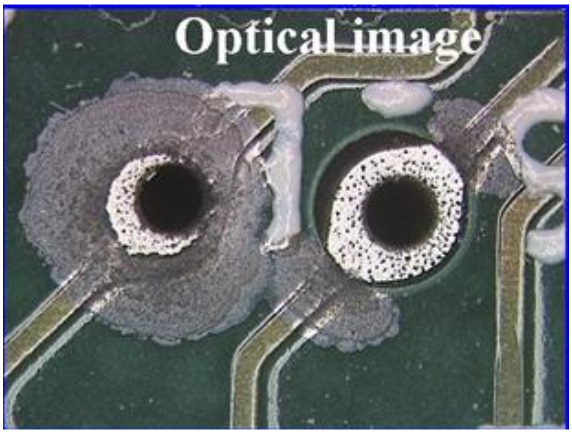
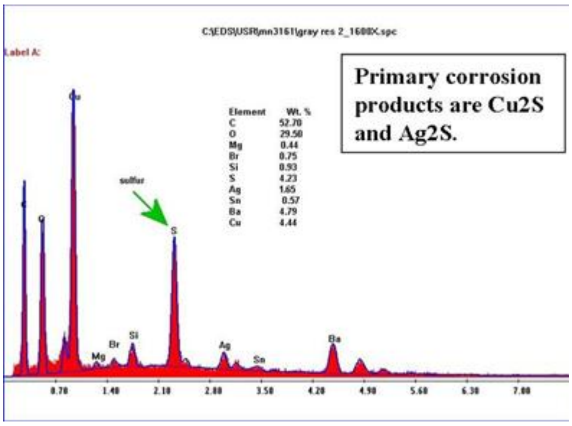


Figure 1: Creep corrosion on pad

It is known that sulfur compounds can dissolve readily in water to create a weak sulfuric acid that can in-turn reduce the copper oxide and expose the underlying copper to attack [6]. It requires only about 50% RH to form a thin film of water on a surface. This film is thicker if the surface has hydrophilic properties (polarized to attract water).

Xu et al. have studied creep corrosion on immersion silver PCBs and have found that it is highly sensitive to the surface condition [2]. Based on their results, clean FR4 nor clean solder mask surfaces do not support creep corrosion. In addition, PCBAs assembled with rosin fluxes (both wave and reflow soldering) are relatively resistant to creep corrosion. Some organic acid fluxes will leave the surface in a condition which promotes the initiation and progress of creep corrosion.



Element	Wt. %
C	52.70
O	29.50
Mg	0.44
Br	0.75
Si	0.93
S	4.23
Ag	1.65
Sn	0.57
Ba	4.79
Cu	4.44

Primary corrosion products are Cu2S and Ag2S.

Figure 2: EDX spectrum of creep corrosion product

If the primary corrosion product is copper sulfide, one might wonder why this creep corrosion is predominantly observed on copper with Immersion silver finish. It seems the electrode potential difference of the two metals plays a significant role (Galvanic driven corrosion). Copper is anodic with respect to silver, and thus in its presence would be attacked much more aggressively in an electrolyte solution (whereas, copper by itself would be attacked significantly slower). This attack of the anode is greatly enhanced when the surface area of the anode is small with respect to the exposed area of the cathode (as one will see is indeed the case in this situation).

A similar galvanic corrosion mechanism was implicated as the source of microvoids in solder joints when Immersion silver surface finish is used [7]. This excellent study revealed that the interaction between silver and copper during the silver plating process caused cavities in the copper (the source of the microvoids upon reflow). These cavities formed under the silver coating and under the edge of the soldermask where copper was most exposed. Incomplete silver coverage at the soldermask edge enabled the Immersion silver plating solution to attack the copper galvanically.

Data show that this same type of behavior (exposed Cu at edge of soldermask) is the primary reason most creep corrosion seems to emanate from soldermask defined features. Cross sections of heavily creep corroded vias are shown in Figure 3. A large amount of copper is etched from beneath the soldermask and converted to Cu_2S. The full area of silver coverage (cathode) is much larger than the small exposed copper region (anode), thus helping to drive this aggressive galvanic corrosion in the presence of sulfur and moisture. Any pinholes in the Immersion silver film would also result in a similarly etched Cu region.

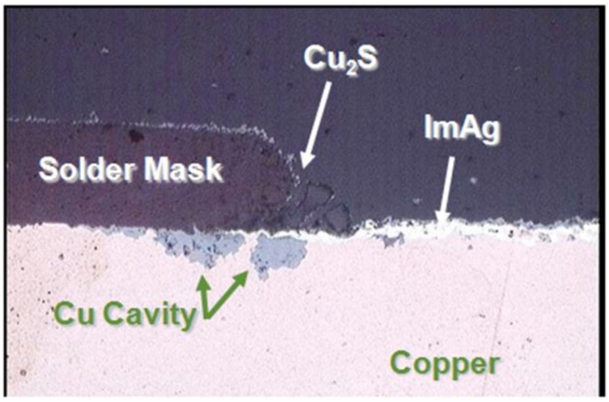


Figure 3: Cu cavity at the edge of solder mask

This does not to imply, however, that bare copper cannot creep corrode on its own (without an Immersion silver coating). PCB cards with OSP finish have been known to fail from creep corrosion when used in severe sulfur environments with high humidity (ink stripping room in a paper mill). An example is shown in Figure 5. In this case, copper was exposed through the residual OSP coating and was attacked. Cross sections show this attack does not occur under the solder mask edge (as with Immersion silver) but is more uniform. In extreme cases it consumed the full thickness of copper.

Figure 4: Corroded Cu with OSP finish

Test methods

When the creep corrosion issue was first encountered in late 2005, a test method did not exist that would reproduce the creep corrosion on a consistent basis. Therefore, initial analysis of various surface finish alternatives was performed at industrial locations where creep corrosion had occurred. It is not practical to use industrial environments to perform field testing each time one investigates a new variation in surface finish or design. The industry requires a test method that will consistently produce creep corrosion on Immersion silver control samples in a way that is observed in the high sulfur industrial environments. Several test methods are currently being explored by various groups in the industry.

A test method investigated by Schueller [1] utilized the high sulfur clay used in modeling studios to drive the creep corrosion. Testing is performed by placing the clay into a plastic container with a clamp down lid. A small amount of water (1-2 ml) is used to wet the clay and the container with clay is placed in a microwave oven and heated until the clay starts to become soft and workable (~50°C). PCBA samples are placed in a vertical position within the container and the lid is replaced. To achieve aggressive creep corrosion, 2-4 pounds of clay is used and the PCBA is cooled in a refrigerator for 5 minutes prior to placing in the container (to enhance the condensation). The PCBA remains in the container at room temperature for 11-13 hours at which point the process is repeated (2 cycles per day).

Creep corrosion on Immersion silver PCBAs is typically visible after 2 days and is quite pronounced after 5 days. This aggressive test was also found to create creep corrosion on some PCBAs with OSP surface finish. Thus it seems this test method was simulating a harsh class GX environmen. It is worth noting that when preassembled bare PCBs with OSP coating were subjected to this aggressive test environment, no creep corrosion or even discoloration, was observed. It appears that the degree of creep on OSP coated PCBAs is dependent on the amount of OSP remaining on the pads after assembly, as well as the aggressiveness of the environment. Lead-free HASL holds up quite well to this extreme test but if there is exposed copper on the lead-free HASL boards they may show some creep corrosion as well. Less severe versions of the test were developed to better represent the more typical G2 or G3 industrial environments (in which OSP finish does not creep corrode).

Mixed flowing gas (MFG) test has been used for simulating the corrosive elements. A new test has been developed by Alcatel-Lucent to simulate more aggressive environments, with considerably high sulfur (H_2S) concentration [2]. The main reason for high sulfur concentration are that copper sulfide formation has been determined the main component of the corrosion products in the field. Moreover, copper sulfide formation increases with increasing H_2S concentration.

Prevention of creep corrosion

While the physics behind the creep corrosion has been identified, it is difficult to decide what surface finish to use. This is difficult, since assembly of lead free products involves many complexities that must be considered and worked through. Some key options will be briefly discussed below.

High Temperature OSP: As mentioned previously, PCBs with OSP finish survived all but the worst high sulfur industrial environments. OSP is the least expensive surface finish but this cost advantage can be lost in the assembly process. Its wetting properties are not as good as Immersion silver so achieving IPC standard hole fill is a challenge for double sided boards over 0.062 inches thick. The OSP can break down on the second pass through the surface mount oven, so achieving hole fill in wave solder may require more flux, higher preheat temperature, slower line speed and/or more costly wave solder alloys. Incircuit test is also a significant challenge. Testing directly through the OSP coating is not recommended, so solder paste is deposited onto test pads and test vias. Flux residue on the solder can quickly build up on the probes causing false failures. Solder paste deposited on test vias will tend to flow slightly down into the hole, resulting in a dimple on the top that collects even more flux residue. These test challenges must be overcome.

Lead-free HASL: SnPb HASL was the predominant surface finish prior to RoHS implementation. Lead-free HASL is similar in its excellent corrosion resistance and superior wetting properties. The concerns are 1) potential for laminate damage, 2) poor planarity, and 3) high copper dissolution. Experimental builds with SnCu as the lead-free HASL alloy have shown that points 2 & 3 are indeed an issue [1]. However, upon changing to SnCuNi alloy, excellent planarity was achieved (typically 2- 14 μm thickness range) and copper dissolution was very low (1-3 μm). This is consistent with the previous findings of Fellman [8]. Although laminate damage was not detected on 140T_g Dicy laminate, there was concern that damage may be possible due to the 270ºC solder bath temperature (leaded HASL was typically 255-260ºC). To add a margin of safety, a 150T_g phenolic laminate was introduced and has been successfully qualified. Assembly conditions do not require modification from those used for Immersion silver surface finish (essentially a drop in replacement). The cost of lead-free HASL is naturally higher than OSP on the bare board level, but the assembly cost can be lower. Overall total cost and quality should be considered.

Another factor to consider is wetting behavior of the surface finishes. A direct comparison can be made by studying solder paste printed on unused FET pads. The example in Figure 8 shows the least amount of wetting with OSP, a moderate amount with Immersion silver, and the most with LF HASL. These results are consistent with a more thorough investigation on this topic by Stevens et. al. [9]. A concern with poor wetting (in addition to hole fill) is a propensity for voiding in solder joints, especially under large thermal pads. Lead-free HASL appears to be a drop-in replacement; whereas OSP may require optimization of the surface mount conditions to reduce solder joint voiding.

Surface cleanliness: the studies at Alcatel-Lucent have shown that also surface cleanliness has a great effect on creep corrosion on PCBAs [2]. This requires careful consideration of materials (e.g. flux, solder mask) selection. A very important factor is also cleaning of the PCBAs after assembly has been completed. They also suggest that new cleanliness standards should be considered as the current ones have been developed to prevent electromigration.

PCB design: If immersion silver surface finish is to be used, there are several design changes that can be made to reduce the chance for corrosion failures. Solder mask defined metal features should be eliminated – at least those that will not get soldered during assembly. Non-test vias should be completely covered with solder mask (preferably fully plugged, as shown in Figure 9). Component pads should have rounded corners and the stencil designed to print paste to completely cover the pad. The same holds true for the passive component pads. Remaining unsoldered areas on a board might include test points (pads and vias). These should be non-solder mask defined and preferably separated by more than 2.5 mm to help reduce creep corrosion bridging and shorting.

Conformal Coatings: There are a variety of conformal coatings available for PCBAs. Most of these are difficult to apply and thus too costly to be practical for high volume consumer electronics. Such coatings could, however, be targeted for products going into known high sulfur environments. Spray on coatings are available, however, they only offer marginal protection since areas under components (not covered by the spray) will still creep corrode.

Improve Coverage of the Silver: If the silver film was not compromised to allow access to the underlying copper, the creep corrosion would not occur. Naturally the silver would still tarnish and form an Ag_2S film on the surface, but failure would not take place. The challenge is to achieve coverage under the edge of the soldermask. Preventing ingress of moisture beneath the mask would require improved adhesion of solder mask to copper. This is a challenge for the PCB shops and the soldermask manufacturers.

Conclusions

The transition toward immersion silver on high volume electronic products has resulted in creep corrosion when these products are exposed to high sulfur environments under elevated humidity. The creep corrosion product is primarily Cu_2S which is produced by galvanic driven attack of the copper beneath the edge of the soldermask. Test methods are being developed to replicate this creep corrosion so the mechanism can be better understood and the effectiveness of corrective actions can be tested prior to their implementation. Testing shows that lead-free HASL is resistant to this creep corrosion and high temperature OSP also appears to be effective in most industrial environments. In the event that immersion silver needs to be used, the chance for failure can be reduced through changes in the PCB layout. Design recommendations include: plugging all non-test vias with soldermask, use of non-soldermask defined test vias and pads, spacing these sufficiently far from each other, and using solder paste to cover all remaining metal features on the PCB.

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