

ELECTROCHEMICAL MIGRATION ON HASL PLATED FR-4 PRINTED CIRCUIT BOARDS

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ABSTRACT

As the current trends toward miniaturization take hold, proper cleanliness levels become more difficult to achieve. In addition, effective cleaning requirements may not be in place. The smaller spacing between conductors also yields a larger electric field, which in conjunction with insufficient cleaning can lead to dendritic growth. This paper investigates the effects of chloride contamination and electric field on the migration behavior of hot air solder level (HASL) plated FR-4 printed circuit boards. It was found that chloride contamination level and electric field influence which failure mechanism is occurring, electrochemical migration or electrolytic corrosion. This study concludes that current industry specifications for cleanliness may be inadequate for the next generation of electronic assemblies.

Key words: electrochemical migration, dendritic growth, electric field, contamination

INTRODUCTION

Electrochemical migration can be a vexing problem in electronic assemblies. It may cause electrical shorts and/or intermittent operation of equipment. In most cases, with proper cleaning measures in place, dendritic growth can be eliminated. However, as spacings on circuit boards and component lead pitch decrease, effective cleaning becomes more difficult. The reduction in spacing also increases the electric field, which is a primary driver of dendritic growth.

Dendritic growth is defined as “the growth of conductive metal filaments on or through a printed circuit board (PCB) through an electrolytic solution under the influence of a DC voltage bias” [1]. This definition encompasses the phenomenon known as conductive filament formation (CFF) in addition to electrochemical migration (ECM). For the purposes of this investigation, ECM will refer specifically to migration over the surface and CFF will refer specifically to migration below the surface.

The definition given by IPC requires two components external to the PCB itself: an electrolytic solution and a DC voltage bias. The electrolytic solution is provided from humidity present in the operating environment. Water adsorbs to the surface of the circuit board, eventually connecting two oppositely biased conductors. The amount of water necessary to provide a sufficient path is approximately 20 monolayers thick [2]. The presence of contaminants, especially chlorine, in the water serves to exacerbate the situation.

Halide ions act as catalysts in localized corrosion, with chloride ions having the strongest effect of the halides [3]. However, the minimum levels necessary to induce corrosion are uncertain, with several sources specifying a range of recommended contamination limits, from 2 $\mu\text{g}/\text{in}^2$ to 10 $\mu\text{g}/\text{in}^2$ [4 – 8]. Bromide ions, which are also known to be a problem, have reported ranges from 15 $\mu\text{g}/\text{in}^2$ to 20 $\mu\text{g}/\text{in}^2$ [4 – 8]. The combination of chloride and bromide may also prove harmful, but this effect has not been covered in the literature.

In addition to halide contamination, the role of a DC voltage bias is of interest. The voltage bias allows for calculation of the electric field, which in turn is directly proportional to the force applied on a charged particle (e.g., a metallic ion) within the field. The force applied on a charged particle may affect the time it takes an ion to move through the electrolytic solution. The electric field can be calculated from the applied voltage and the geometry of the structure under consideration,

$$E = V/d$$

where E is the electric field, V is the applied voltage, and d is the distance separating two oppositely biased conductors.

Zou and Hunt determined voltage is a factor that affects dendritic growth. They specified the relationship between dendrite formation and e -field as an increase in probability of dendrite formation with an increasing e -field [10]. Peck also suggested a role of voltage in his model, but left the voltage relationship undefined [11]. The role of voltage was

defined for a conductive filament formation (CFF) model given by Rudra [14]. This model was recently verified by Sun Microsystems [12]. The model is

$$t_f = \frac{af(1000L_{\text{eff}})^n}{V^m(M - M_t)}, \quad M > M_t$$

where t_f is the time to failure in hours, a is the filament formation acceleration factor, f is a multi-layer correction factor, n is a geometry acceleration factor, V is the applied voltage bias in volts, m is a voltage acceleration factor, M is the percentage moisture content, and M_t is the percentage threshold moisture content. L_{eff} is

$$L_{\text{eff}} = kL$$

where L_{eff} is the effective length between conductors, k is a shape factor, and L is the spacing between conductors in inches. The voltage is inversely proportional to the time to failure assuming m is positive.

The current trend toward finer pitch and high density/high impedance designs have resulted in conductor spacings in the range of 50 to 200 μm [11 – 13]. Assuming no reduction in line voltage, these factors contribute significantly to higher e-fields than have been experienced previously in more mature technology.

Some other models have used current density to describe metallic growth mechanisms. Current density is of primary concern in corrosion rate. Using a probabilistic approach, DiGiacomo derives a time to failure equation based on current density as given in the Butler-Volmer equation [16]. The Butler-Volmer equation relates applied potential to corrosion current density, from which the general corrosion (dissolution) rate can be calculated. All other steps of ECM are accounted for through probability. If dissolution rate is the rate limiting step, DiGiacomo's model may apply to ECM. However, there is no evidence in the literature to verify what the rate limiting step, dissolution, ion transport, or deposition.

EXPERIMENTAL PROCEDURE

IPC-B-25 HASL plated printed circuit boards were used as the test vehicle. The IPC-B-25 board has three comb structures with one at 6.25 mil spacing, one at 12.5 mil spacing, and one at 25 mil spacing. See Figure 1. The comb structures were copper 1.8 mils thick with HASL plating 0.6 mils. The test board measured 18 inches squared in area.

All boards were cleaned by boiling submerged in a solution of 75% isopropyl alcohol, 25% de-ionized water by volume at 80°C for one hour. After the hour period, the boards were removed and allowed to dry for 24 hours at 25°C and 50% RH.

Ion chromatography grade 1000 ppm Cl standard solution was diluted to 18, 45, 90, 180, and 450 ppm solutions. Using an application amount of 2 mL per board, an atomizing spray was used to cover one side of each board with solution, which gives applied contamination levels of

2, 5, 10, 20, and 50 $\mu\text{g}/\text{in}^2$ Cl. (These levels were used based on information found in the literature [4 – 9].) A control group with no applied contamination was prepared. (The no applied contamination group will be referred to as “0” $\mu\text{g}/\text{in}^2$ Cl.) Four boards were prepared at each contamination level, including the control group.

One of the four boards was chosen at random for the chloride contamination level to be verified through ion chromatography. All boards tested were within $\pm 10\%$ of the applied chloride contamination levels.

The other boards were suspended vertically in an ESPEC LHL-112 environmental chamber and ramped to 85°C/ 85% RH at 1°C/min. The boards were allowed to stabilize for one hour, then a 10 V DC voltage bias was applied to each test for 168 hours. All boards were removed at the end of this period and examined and documented using an optical microscope with digital camera attachment. Boards were then examined using an environmental scanning electron microscope.

RESULTS

Two failure mechanisms were present on the test specimens: ECM and uniform corrosion. Boards at each contamination level had some evidence of ECM and/or uniform corrosion.

Dendritic Growth

Dendritic growth was found on boards ranging all contamination levels, including the “0” $\mu\text{g}/\text{in}^2$ Cl boards. At the lower contamination levels (“0” and 2 $\mu\text{g}/\text{in}^2$ Cl), dendritic growth was mainly found on the 6.25 mil spacing comb structure, with infrequent appearances on the 12.5 mil comb structure, and no occurrence on the 25 mil comb structure. See Figure 2. At 5 $\mu\text{g}/\text{in}^2$ Cl to 20 $\mu\text{g}/\text{in}^2$ Cl, dendritic growth was found on both the 6.25 and 12.5 mil spacing comb structures, with infrequent appearance on the 25 mil spacing comb structure. See Figure 3. At 50 $\mu\text{g}/\text{in}^2$ Cl, dendritic growth was no longer distinguishable due to the presence uniform corrosion products. See Figure 4.

Uniform Corrosion

There was no other corrosion product visible at the “0” and 2 $\mu\text{g}/\text{in}^2$ Cl levels. However, at the 5 $\mu\text{g}/\text{in}^2$ Cl level general corrosion product began appearing. The corrosion product seen on the 5 $\mu\text{g}/\text{in}^2$ Cl was mainly on the conductor ends on the 6.25 mil spacing comb structure, with some corrosion product on the 12.5 mil spacing comb structure. See Figure 5. The occurrence of the corrosion product got progressively worse with contamination level. By 50 $\mu\text{g}/\text{in}^2$ Cl and 6.25 mil spacing, conductors were drastically reduced in line width due to the corrosion. Refer to Figure 4.

Electric Field

With a constant voltage of 10 V applied to the comb structures, the electric field varied due to the geometry of the three differently spaced comb structures on the board. Refer back to Figure 1. This yields an electric field of 1.6

V/mil, 0.8 V/mil, and 0.4 V/mil for the 6.25, 12.5, and 25 mil spacings, respectively. Away from the ends of the conductors (or points where the geometry changes significantly), the electric field can be assumed constant.

DISCUSSION

Current cleanliness standards recommend chloride levels to under $2 \mu\text{g}/\text{in}^2$ [4 – 8], so the presence of dendrites on the “0” $\mu\text{g}/\text{in}^2$ Cl boards prompted further investigation into other contaminants that could be present. One of the “0” $\mu\text{g}/\text{in}^2$ Cl boards was taken for ion chromatography analysis after the visual inspection. Of primary interest was possible presence of bromide on the board due to the dissociation of bromide (used in the flame retardant) at elevated temperatures [17]. Prior to environmental testing, there was less than $0.1 \mu\text{g}/\text{in}^2$ Br present on the boards. This is well below the recommended levels of $15 - 20 \mu\text{g}/\text{in}^2$ Br in the literature [4 – 8]. However, after the exposure to the $85^\circ\text{C}/85\%\text{RH}$, the bromide level was found to be close to $12 \mu\text{g}/\text{in}^2$ Br. Such a dramatic increase in surface concentration of bromide indicates that dissociation should be considered as a possible root cause.

Current spacing trends can yield spacing between printed circuit board traces as small as $48 \mu\text{m}$ (1.92 mils) [12]. Common applied voltages can be close to 5V, creating an electric field of approximately 2.5 V/mil. This is close to 1.5 times the maximum electric field tested. As the electric field increased from 0.4 V/mil to 1.6 V/mil, the occurrence of dendrites increased. Fundamentally, this may be due to the forces on a charged particle being directly proportional to e-field. So, as the e-field increased, the force on the metallic ions increased.

Applying this to current spacing and applied voltage trends, an electric field of 2.5 V/mil may have ECM issues at lower contamination levels than previously considered. The “0” $\mu\text{g}/\text{in}^2$ Cl boards at an electric field of 1.6 V/mil showed the presence of ECM with contamination amounts under the currently recommended standards for bromine contamination. Chloride is widely accepted as a stronger catalyst than bromine [3, 4]. The effects of chloride and bromide together have not been investigated in the literature.

Halide ions serve as catalysts in the dissolution of metallic ions [3]. Due to this behavior, at lower contamination levels less metal is dissolved and taken into bulk solution. With less metal in the bulk solution, the forces on the metallic ions are driven by the electric field. The electric field vector has a direction toward any deformities on the surface of a conductor. In theory, conductor planes are smooth and without defects, which allows for calculation of the electric field as given above. However, in reality, there are surface dislocations and other defects, which can cause localized focusing of the electric field. The electric field will be higher at the defect location, driving the metallic ions to this defect and causing dendritic growth.

As metallic ions are dissolved at a faster rate due to increased chloride concentration, uniform corrosion occurs. This may be due to the concentration of metal ions overcoming the resistive properties of the electric double layer. Also, with the presence of an electrochemically active species (Na^+ ions in this case), the resistance of the electric double layer drops further, allowing for uniform corrosion to occur.

The results also indicate a threshold contamination level above which, ECM will transition to uniform corrosion. This threshold may be dependent on electric field as well. At low contamination levels (“0” and $2 \mu\text{g}/\text{in}^2$ Cl), no uniform corrosion was found. However, between 5 and $20 \mu\text{g}/\text{in}^2$ Cl, both ECM and uniform corrosion were found. At $50 \mu\text{g}/\text{in}^2$ Cl, no ECM was found. This means that a failure mechanism threshold occurred between 20 and $50 \mu\text{g}/\text{in}^2$ Cl. There is also a minimum threshold for uniform corrosion to occur, which is below $5 \mu\text{g}/\text{in}^2$ Cl.

CONCLUSIONS

The $12 \mu\text{g}/\text{in}^2$ Br is less than the current recommended standards of $15 - 20 \mu\text{g}/\text{in}^2$ Br, suggesting that these recommendation may be too lenient to prevent ECM. As spacings continue to be reduced, cleanliness standards must become more stringent. Due to the effect of electric field, as spacing reduces, for a given contamination level, the likelihood of ECM will increase. In addition, the effects of combinations of contaminants in relation to the reduced spacing trend, needs to be further investigated. For instance, the effects of bromide and chloride combined at their recommended minimum levels would be of interest.

The results clearly demonstrate that e-field has an effect on ECM. At higher electric fields, dendrites grew, while at lower electric fields dendrites infrequently grew. The force on the metallic ion in solution is proportional to the electric field. Applied voltage is of concern only in calculation of the electric field. The force due to the electric field may be a primary driver of ECM. The threshold electric field under which ECM will not occur is between 0.8 and 1.6 V/mil. The existence of a lower threshold must still be investigated.

As chloride contamination increases, the failure mechanism shifts from ECM to uniform corrosion. Lower chloride contamination levels may be a greater risk for ECM and as the contamination levels increase, the risk of uniform corrosion becomes higher. The occurrence of ECM at lower contamination levels may be due to the lower concentration of metal in solution. At higher contamination levels, the concentration of electrochemically active species overcomes the electrochemical corrosion resistance and uniform corrosion occurs. This mechanism shift occurs between 20 and $50 \mu\text{g}/\text{in}^2$. A lower threshold under which ECM will not occur must still be found.

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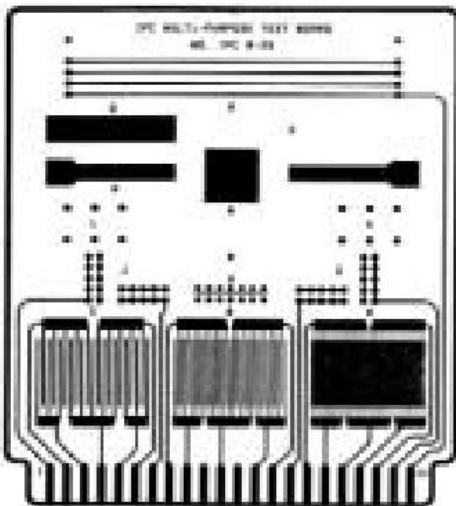


Figure 1. IPC-B-25 test board with comb structures spaced 6.25, 12.5, and 25 mils.

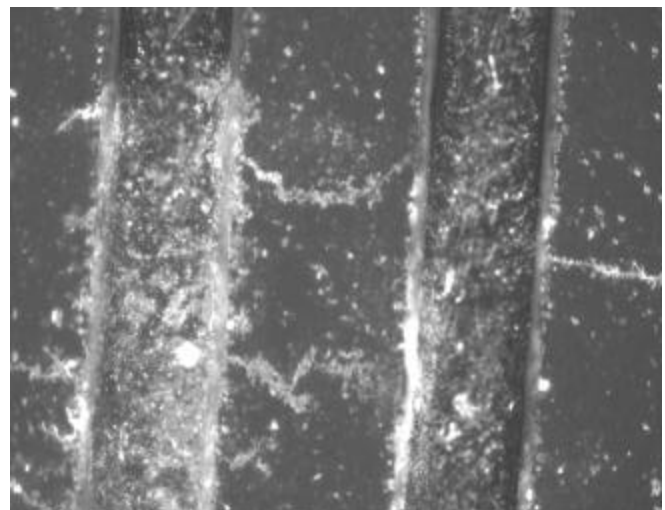
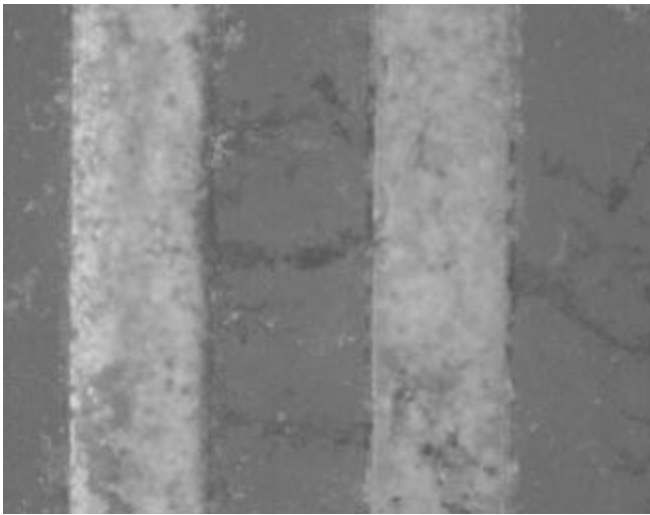
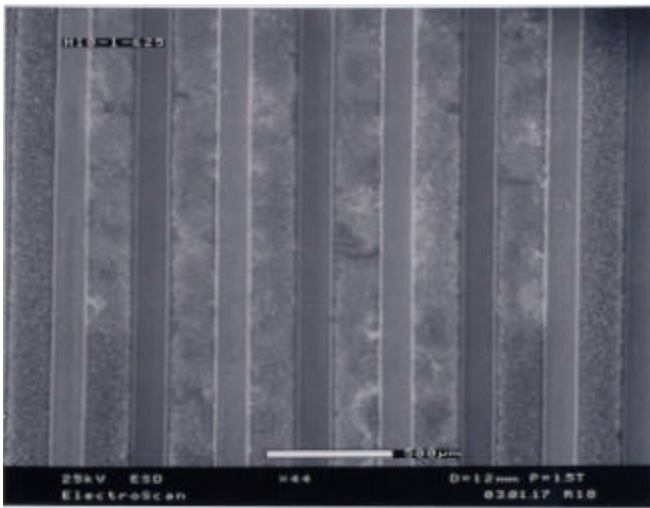


Figure 2. Dendritic growth on 6.35 mil spacing at "0" mg/in² Cl.



(a)



(b)

Figure 3. (a)Dendritic growth on 12.5 mil spacing at 10 mg/in² Cl. (b)Dendritic growth and corrosion on 6.25 mil spacing at 10 mg/in² Cl.

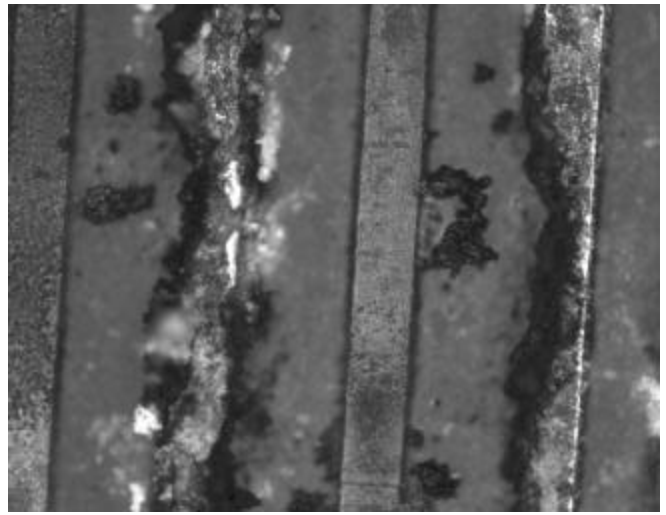


Figure 4. Uniform corrosion on 6.25 mil spacing at 50 mg/in² Cl.

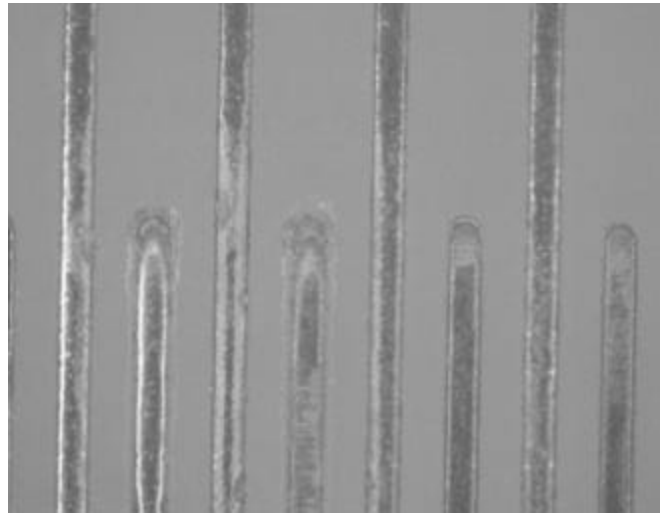


Figure 5. Uniform corrosion on 6.25 mil spacing at 5 mg/in² Cl.