Presented at IPC Printed Circuits Expo®
SMEMA Council APEX®
Designers Summit 04

Lead Free and Other Process Effects on Conductive Anodic Filamentation Resistance of Glass Reinforced Epoxy Laminates

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Abstract
Conductive Anodic Filamentation is a subsurface failure mode for woven glass reinforced laminates (FR4) materials, where a copper salt filament allows bridging between via walls or other copper conductors. In this study FR4 laminates, in the form of high via density multi-layer test circuits, are exposed to different manufacturing conditions and assessed for resistance to Conductive Anodic Filamentation (CAF). CAF performance was assessed using high temperature and humidity conditions to promote failures, with a voltage applied across adjacent vias. By application of a range of voltages and via geometries a performance map for laminates can be obtained to compare materials for performance. The changes due to exposure of laminate to lead-free temperatures and other processing steps are then examined using the technique.

Introduction

Conductive Anodic Filamentation (CAF) is a failure phenomenon seen within the bulk of glass reinforced epoxy printed circuit board laminate, used for the manufacture of circuit assemblies. This distinct electro migration failure mode was first reported in 1979.[1] Although the existence of the CAF mechanism has been known for some time; currently there is an increase in concern about these effects.

There are three main drivers for this concern:

- Continued requirements for increased circuit density, smaller via geometries and increased layer counts in multi-layer boards
- The increased use of electronics in harsh environments and for high reliability and safety critical applications (Automotive, Avionics, Medical)
- The impending implementation of lead-free processing in Europe (but effecting global market place) before July 2006, which may effect laminate stability and materials choices

In this study a range of materials, board layout configurations, thermal events, and processing steps are investigated. The data allows guidelines for design and material choices to be compiled.

The CAF Mechanism

There are sources describing the mechanism for CAF formation, (for example[1]), but brief overviews of the steps that take place in the formation of a CAF are described here.

Initiation – Where copper, under bias and part of a glass reinforcement fiber come into the same locality. In dense multi-layer PCB's this can often occur at the via wall where the drilled hole has been seeded and plated, although fibers protruding through the surface of PCB's to the locality of surface tracks has also been reported.[3]

Separation of glass and epoxy - If glass preparation is of poor quality separation of the epoxy resin and glass fibers can be more likely. Bonding can also be lost due to hydrolysis of the glass finish, or due to residual stress in the weave being relieved.[1] The absorption of moisture into the laminate accelerates these processes and the de-lamination can then provide a pathway for CAF growth.

Electrochemical Reaction - With moisture present as an electrolyte and a pathway established current may begin to flow setting up an electrochemical process. The mechanism involves oxidation and dissolution of copper at the anode, and if copper anions reach the cathode they are reduced back to copper metal. Other ions present from processing or materials such as chloride, sulphur or other metals may also take part in this process.

Salt deposition - As the electrochemical dissolution of copper continues, a pH gradient is produced due to the H^+ ions produced at the anode and OH^- ions at the cathode. In Figure 1 this is represented by a schematic of two vias, where the anode via wall is the initiation site. The formation of this pH gradient is key to the mechanism of CAF growth since the solubility of copper is dependant on pH and the electrical potential applied. At the cathode Cu metal remains stable, however at the anode, a positive potential and an acidic pH, makes the copper as Cu^{2+}. As the filament grows (Cu ions migrate) along the glass fibre/epoxy interface towards the cathode, an environment of neutral pH is reached. Thus copper precipitates as an insoluble copper salt and it is this build up that forms the conductive path.

Anode:	$Cu_{(s)} \rightarrow Cu^{n+}_{(aq)} + n^{e-}$
	$H_2O \rightarrow \frac{1}{2}O_{2(g)} + 2H^+_{(aq)} + 2^{e-}$
Cathode:	$2H_2O + 2e^- \rightarrow H_{2(g)} + 2OH^-_{(aq)}$
	$Cu^{n+}_{(aq)} + ne^- \rightarrow Cu_{(s)}$

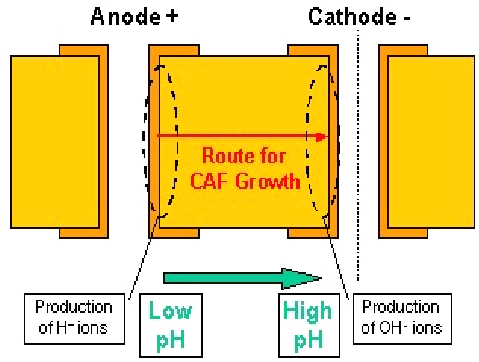

Figure 1 - Mechanism for CAF Growth (Initially Proposed by Bell Labs)

Completion of conductive pathway - Catastrophic electrical failure occurs when the filament of copper salts bridge the anode and cathode in question. Under humid conditions the salts are conductive and will allow a massive increase in current flow between the previously well-isolated copper areas.

Test Vehicle Design

The board has ten-layers and over 6,000 vias with a 32-tab connector layout allowing connection to a test rack system for application of bias voltage and monitoring of leakage currents.

In-line test combs – These comprise of a series of alternate rows of vias with a voltage applied across the comb. They represent the most common failure sites where CAF can occur; between via walls. The vias are in line with one another, essentially forming a grid oriented with the glass fibre weave.

Staggered Combs - The construction of staggered combs is similar to that the in-line combs, however the via pairs are arranged at 45º to the glass warp and weft. This means that the most likely route for potential CAF growth is longer since the orientation of the glass fibres may only permit growth in the horizontal and vertical directions

Anti-Pad Combs - These combs represent the potential failure site when a CAF may grow between a ground plane in a multi-layer board, and a nearby via wall. There is a surrounding copper plane at a potential to each via.

Conditioning Effects and Variables Investigated

Thermal Shock - Thermal shocks were provided by the use of a dual silicone oil bath system. The baths were held at -15°C and +120°C and the coupons were transferred between the baths by a robotic arm. Selected samples were exposed to 250 thermal shock cycles.

Laminate suppler - The company providing the base laminate materials (pre-preg layers, cores etc) to the board house.

Board House - The manufacturing site for the PCB's, where the Gerber data is used to etch, drill and plate copper foils. The materials are placed in a press cycle to bond all the layers together forming the multi-layer board. There a plethora of chemical preparation, etching, drilling, alignment, masking and development stages which take place during the construction of a multi-layer PCB, the intention in this work was not to investigate them all but to understand any significance of where boards are produced.

Glass transition temperature (Tg) - Tg marks the onset temperature of segmental mobility for a polymer (the temperature below which the polymer segments do not have sufficient energy to move past one another). In practice for FR4 composites rigidity and co-planarity can be affected once the Tg is exceeded by a large margin, and so some may consider high Tg materials to reduce flex in lead-free production.

CAF Resistance - Suppliers can offer laminates that use resin cure systems marketed as CAF resistant. A known contributor to the problem is the curing agent dicyandiamide (DICY), which is often eliminated from such materials.

Weave - The make up of the glass fibres woven in the composite. There are two generic glass weave types used in this study (2116, 2113) and a commercial unknown weave style. Variables include fibre diameter and number of fibres per bundle, and can be different for the warp and weft directions.

Board solderable surface finish - In this study the following finishes were used:

- NiAu – Around 10µm of Ni as a protective barrier with around 0.1µm of Au to aid wetting
- Ag – 0.2µm of silver covers the copper
- HASL – (Hot air solder levelling)
- OSP – (Organic Solderable Preservative)

Reflow - Three different reflow conditions are applied:
Reflow Exposure - Selected test coupons were exposed to three passes through a 5 zone forced convection reflow oven. The boards were allowed to return to room temperature after each pass before being passed through the oven again.[2]

- No Reflow – As a control condition
- SnPb Reflow – Typical of that used to reflow SnPb solder paste (eutectic 183ºC)
- Lead-Free Reflow - Typical of that used to reflow SnAgCu solder paste (eutectic ~217ºC).

Test Method
The samples were placed in an environmental chamber at steady state conditions of 85°C and 85%RH for 1000 hours. The temperature was increased ahead of the relative humidity to prevent any condensation onto the samples. Throughout the exposure the insulation resistance (IR) of each comb pattern was measured and logged every 20 minutes. The resistance measurement system was a 256 channel Auto-SIR using a current limiting resistor of 10^6Ohms.

After failures had been established using the electrical monitoring technique, selected combs were sectioned to locate and identify CAF. The area between the failed vias was cut with a slow speed wet diamond saw, close to the anode via wall. Sequential polishing with 5 to 1 µm particle polish was then used to move through the sample towards the cathode until the CAF was located. A high-resolution optical image of the CAF cross section was acquired the polished CAF sample was carbon coated and mounted for EDAX analysis. (See Figure 2.)

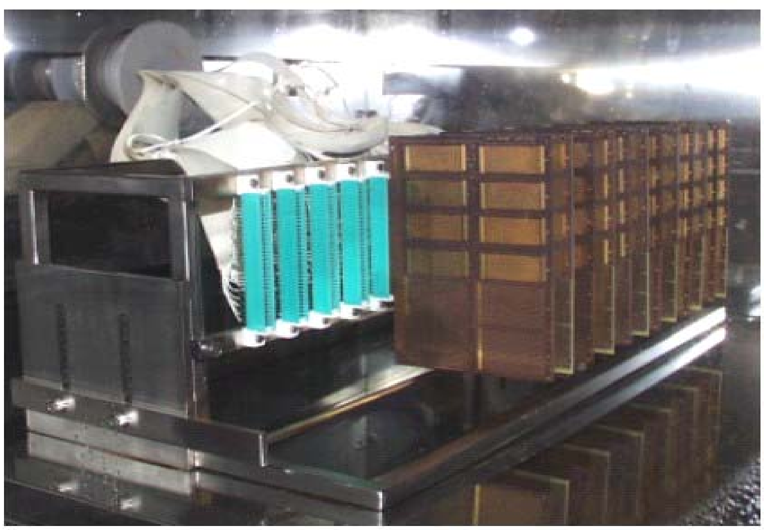

Figure 2 – CAF Coupons in Test

A typical IR vs. time curve for a failed comb, measured during the 1000 hours artificial ageing, is shown in Figure 3. The decrease in IR as moisture permeates the laminate material can be seen in the first 10-20 hours of the test. At about 170 hours (in this example) the sudden catastrophic loss in insulation between the vias in the comb is seen. The IR does not drop below 10^6Ohms due to the use of a current limiting resistor. Two parameters can be noted from the IR-time curve for each comb tested in this work, the final IR (log Ohm) and the time to failure (hours), as indicated.

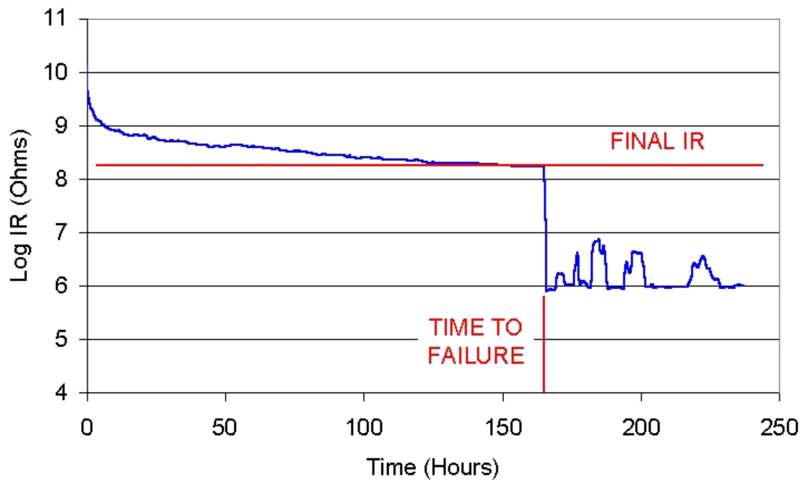

Figure 3 - Typical IR vs. Time Curve for a CAF Failed Comb

Normalisation of Data for Trend Analysis

In order to see the effect of a particular parameter (for the example below 'surface finish') on CAF resistance the following procedure is applied.

1. Only data for samples in which **all other material and processing parameters are identical** are used in the calculation. This means the effects of processes other than the key variable 'e.g surface finish' do not influence trends.
2. For each style of comb pattern separately the time to failure (TTF) data is normalised against the average TTF. Equation XX shows this calculation, where A_x is the normalised TTF for comb design A for condition (e.g. surface finish) x, $TTFA_x$ is the TTF for comb design A for condition x, and $TTFA_{mean}$ is the mean TTF for comb design A across all conditions.

$$A_x = \frac{TTFA_x - TTFA_{mean}}{TTFA_{mean}}$$

3. The normalised data is then averaged across all combs to give a mean normalised TTF for each condition.

Effect of Via to Via Gap

Figure 4 shows the normalised TTF data across all the samples for different in-line comb geometries. Comparing the vertically aligned combs A to D the increase in via to via gap from 300 to 800µm shows an increase in TTF. The same trend is seen between the horizontally aligned combs E and G. Thus larger via to via gaps are, unsurprisingly, more resistance to CAF growth.

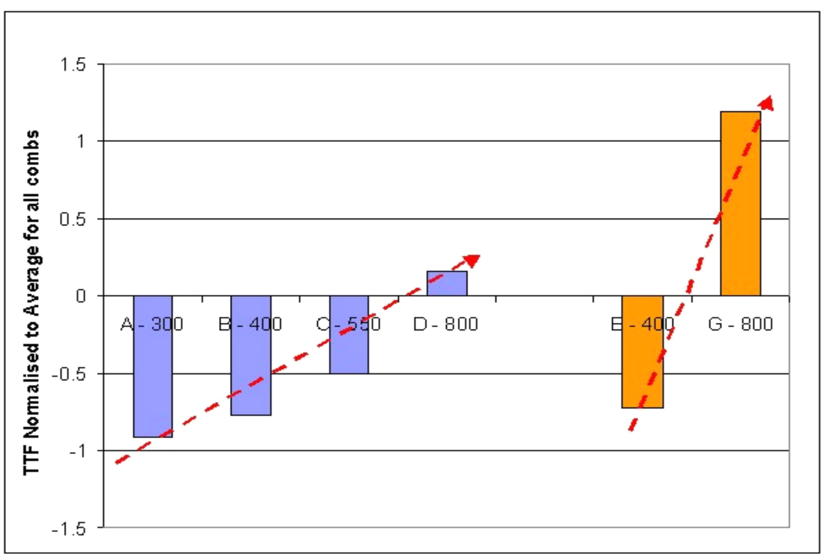

Figure 4 - Effect of Gap between Via Walls

Effect of Reflow Conditions
Earlier NPL studies indicated that it was high peak reflow temperature that reduced CAF performance, not thermal shock. This suggests that the mechanism for damage in the laminate is not based on TCE mismatch between the materials in the composite FR4, but perhaps a chemical or physical breakdown at a certain temperature. An investigation of reflow conditions was therefore undertaken and the normalised TTF data is plotted for five laminate types exposed to different reflow conditions are shown in Figure 5. A significant trend for lower CAF performance after exposure to lead-free reflow conditions compared to tin-lead reflow exposure can be seen. Whilst the reflow conditions used can be considered worse case this could be a concern for those manufacturing high reliability multi-layer product, especially with high via densities as they switch to lead-free production.

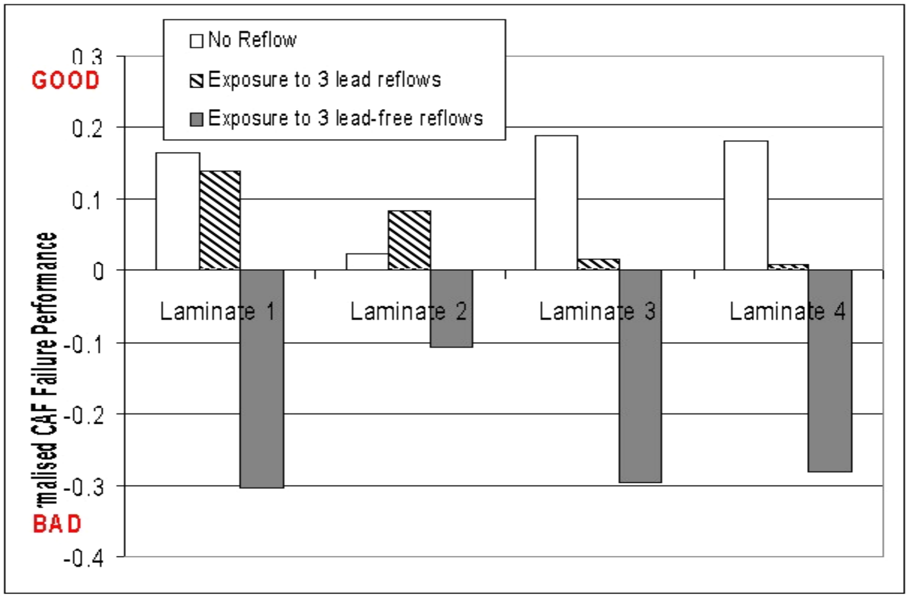

Figure 5 - Effect of Reflow Exposure to CAF Performance

Effect of Orientation of Vias to Glass Weave
Thus study was able to demonstrate staggered vias being more resistant than those in-line, and horizontal combs being more resistant than vertical. This supports earlier work with the improvement in CAF resistance for staggered combs coming from the lack of direct glass fibre contact between the two via walls. It is also important to note that the properties of the warp and weft fibres are different.

Effect of Inner Layer Pads and Via Polarity
Figure 6 gives normalised TFF data for the anti-pad combs. Firstly it is clear that if the via is anodic (+ve bias) then the CAF resistance of the system is dramatically reduced compare to a cathodic via system. Put another way the CAF grows much quicker from a via anode initiation site than from a copper plane anode.

Secondly one can see that there appears to be no significant change in CAF performance as a result of the presence of inner layer pads for CAF growing from the via wall (Combs J and L).

This suggests that the CAF grows from the via wall (associated with the ends of the glass fibres) and not the edge of the inner layer pad (held in between the reinforced pre-preg layers away for the fibres). For the case where CAF grows from the copper planes (combs I and K) the failures are earlier for the configuration with inner layer pads. This is because in this instance the effective distance for the CAF to grow is reduced by the presence of the pads. (See Figure 7).

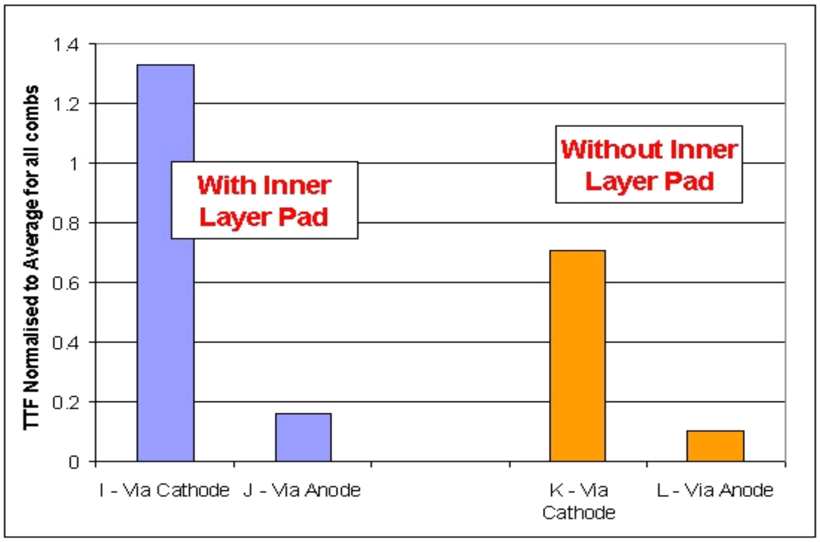

Figure 6 - TTF Data for Anti-pad Combs

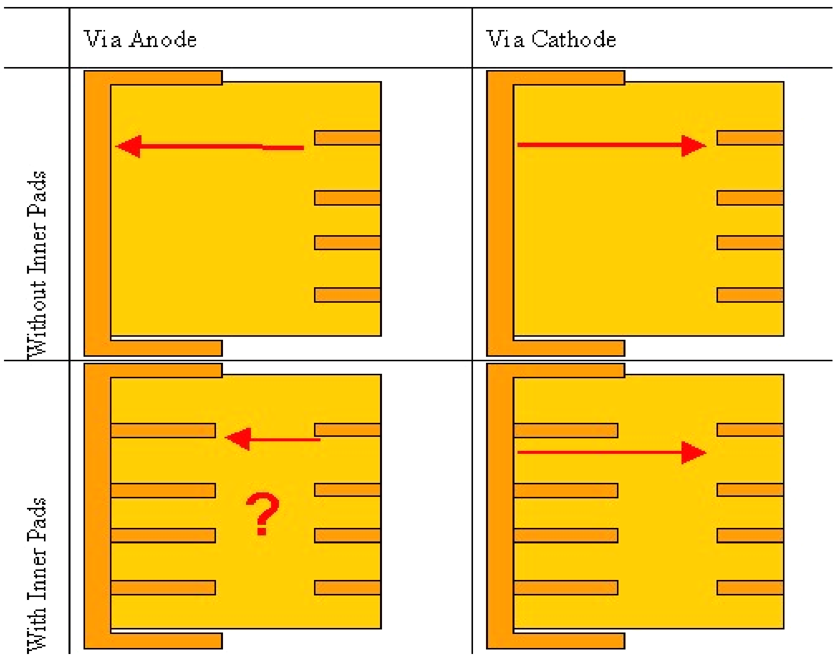

Figure 7 - Schematic showing CAF Growth for Anti-pad Layout Designs

Summary of Findings for All Variables

There is not enough space to detail results for all parameters tested in the study, so a summary of the conclusions is given here although the full report is available.[3] The test method used in this study has proven to be sensitive to changes in CAF resistance for laminates.

The following parameters have a significant effect upon CAF resistance:

- Design Geometries
  - Via to Via Gap
    - Vias closer together are more susceptible to CAF, even at the same voltage gradient
  - Via and ground planes
    - Anodic vias fail faster than geometrically identical cathodic vias
  - Inner Layer Pads
    - Reduce CAF resistance for geometries where CAF growth is initiated from copper plane, which have an intrinsically higher resistance in any case
  - Alignment to reinforcement

  - Warp and weft directions can show markedly different resistances to CAF, both must be examined
  - Via staggered at 45º to the lay-up have a resistance to CAF greater than those aligned with warp or weft with the same gap
- Voltages
  - Higher voltages decrease time to failure at the same geometries
- Laminate System
  - 'CAF resistant' (DICY free) resins reduce the risk of CAF formation
  - Identically specified laminate from different suppliers can have different CAF performance
- Reflow Conditions
  - Peak temperatures of 250ºC in reflow are potentially harmful to the CAF performance of laminate
- Manufacturing
  - Processing of laminate at board houses has a significant effect upon CAF performance

The following parameters had less significance with regards to CAF performance:

- Boards Solderability Surface Finish
- Drill feed rate during via drilling
- Presence or size of inner layer pads
- High/Low T_g designation of laminate
- Thermal Shock of laminate

Acknowledgements

The work was part of a project in the Materials Processing Metrology Programme of the UK Department of Trade and Industry. NPL gratefully acknowledges the work of the industrial partners: Alcatel Submarine Networks, TRW Automotive Group; Graphic Plc, Prestwick Circuits, Invotec, Isola and Polyclad.

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