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Conductive Anodic Filament (CAF) Formation: An Historic Perspective

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Abstract
Conductive Anodic Filament (CAF) is a failure mode in printed wiring boards (PWBs) which occurs under high humidity and high voltage gradient conditions. The filament, a copper salt, grows from anode to cathode along the epoxy-glass interface. First identified by Bell Labs in 1976, this failure mode had also been investigated by Der Marderosian at Raytheon who termed it the "punch through" phenomenon. Early studies of CAF were confined to unprocessed PWBs, but in the 1990's Jachim identified the effect of solder fluxes in enhancing this failure mode. This presentation will review the history of CAF from its identification in the 1970's, to the statistical analysis of its failure mode and the factors that enhance its formation.

Introduction

In the mid-1970's Bell Laboratory researchers were concerned about potential failures of printed wiring boards intended for high voltage switching applications. They reported[1] on accelerated life testing of flexible PWBs coated with UV cured resin, and identified two new failure modes: (a) conductive bridges between conductors on the surface and (b) conductive shorts through the substrate. At the same time, Aaron Der Marderosian at Raytheon used accelerated conditions to study measling, crazing and delamination in multilayer boards and reported a failure he termed "punch thru". Both of these research groups independently discovered an unexpected failure mode associated with the growth from the anode of a conductive filament, which today is known as CAF. This paper will highlight the history of CAF.

AT&T Bell Labs' test vehicle (Figure 1) was a flexible epoxy-glass PWB. 0.005" to 0.007" thick with comb patterns of 0.008" lines and 0.009" spaces. Some combs were biased on the surface and some were biased through the substrate. Processed boards, coated with conformal coating were tested from 35oC to 95oC, 25% to 95% RH and DC voltages up to 400V. For accelerated testing at 85oC, 80% RH, 78V bias, failures occurred within 2-5 days.

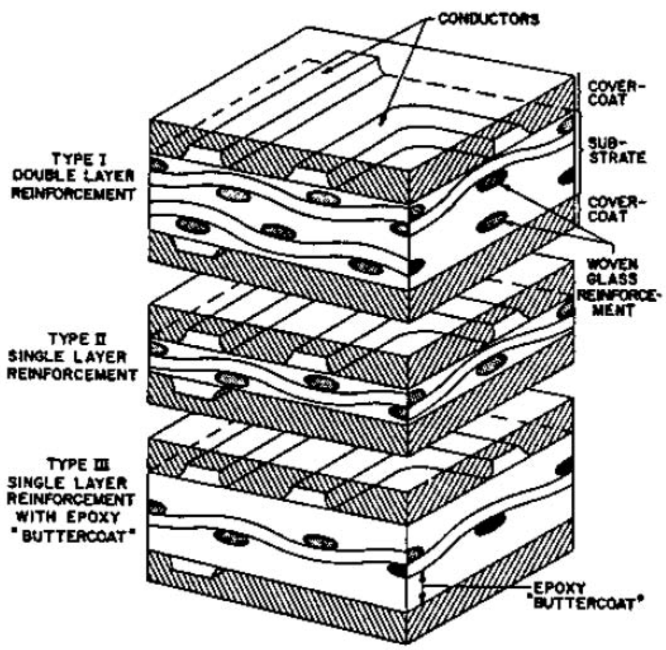


Figure 1 – AT&T Test Vehicle Compared (a) Double Layer of Glass Reinforcement, (b) Single Layer of Glass Reinforcement, and (c) Single Layer of Glass Reinforcement with Extra "Buttercoat"[1]

They identified two major failure modes that they described as causing "catastrophic loss of insulation resistance due to the formation of conductive bridges between conductors". The first failure mode – *through substrate shorts* – only occurred above 75oC and 85% relative humidity, and thus was not considered to be a problem at use conditions (Figure 2). The second mode involved shorts between conductors on the same side of the board in which conductive material accumulates between the glass bundles and the epoxy (Figure 3). Delaney and Lahti[2] noted that the thicker the buttercoat, the more this failure is reduced. They also observed a failure, which they termed – *anodic eruption failure mode* – in which corrosion products emerged from the anode to the covercoat surface, charring the surface, and then growing back through the covercoat to the cathode where it shorted (Figure 4).

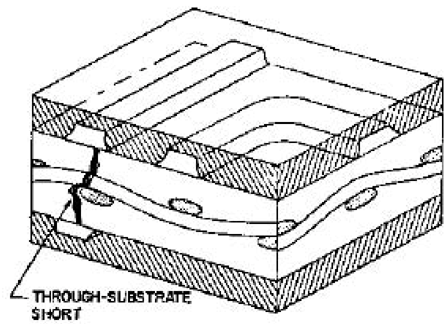


Figure 2 – Through-Substrate Short

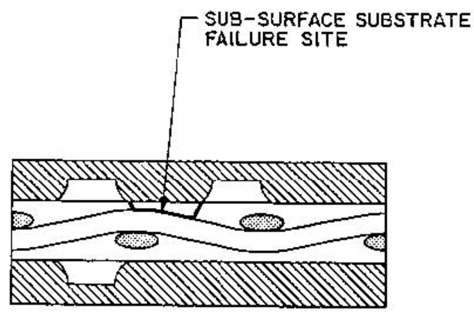


Figure 3 – Subsurface Substrate Failure

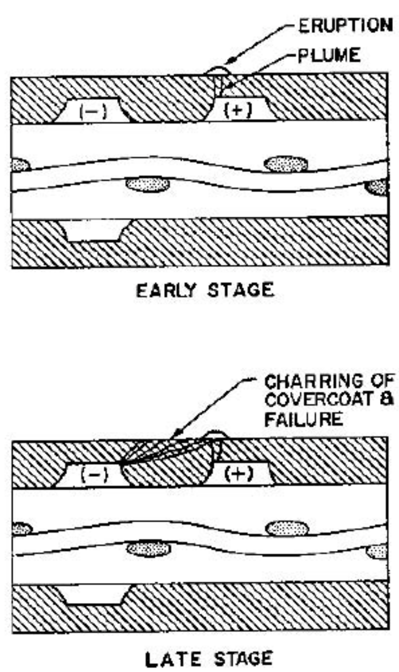


Figure 4 – Anodic Eruption Failure Mode

In 1976 Der Marderosian of Raytheon examined[3] the reliability of multilayer PWBs using a bias between ground planes and conductor traces (Figure 5). Test coupons were biased at 100V and aged at 65oC and 95% RH for 10 days. Der Marderosian defined the failure mode he observed as the "punch through" phenomenon. To study this failure further, he obtained test coupons from 3 different vendors. Some coupons were biased at 100V DC, others were at 100V AC and some were unbiased.

Punch through was only observed when the 100V DC was applied. Thus, Der Marderosian concluded that this failure was due to electrochemically initiated metal migration. He reported that the number of incidents of punch through decreased as aging voltage was decreased from 100V to 75V to 50V. The addition of a urethane conformal coating appeared to accelerate, not suppress the problem.

Punch-thru is an electrical failure which eventually manifests itself in a rupture of the insulation between two layers of copper metallization. In the early stages, Der Marderosian observed conductive CuO deposits along the glass fibers eventually shorting to the cathode and creating carbonization of the epoxy, which causes it to be more conductive. Epoxy "blow out" then ruptured the glass fibers. In the later stages he observed melting of the metal traces.

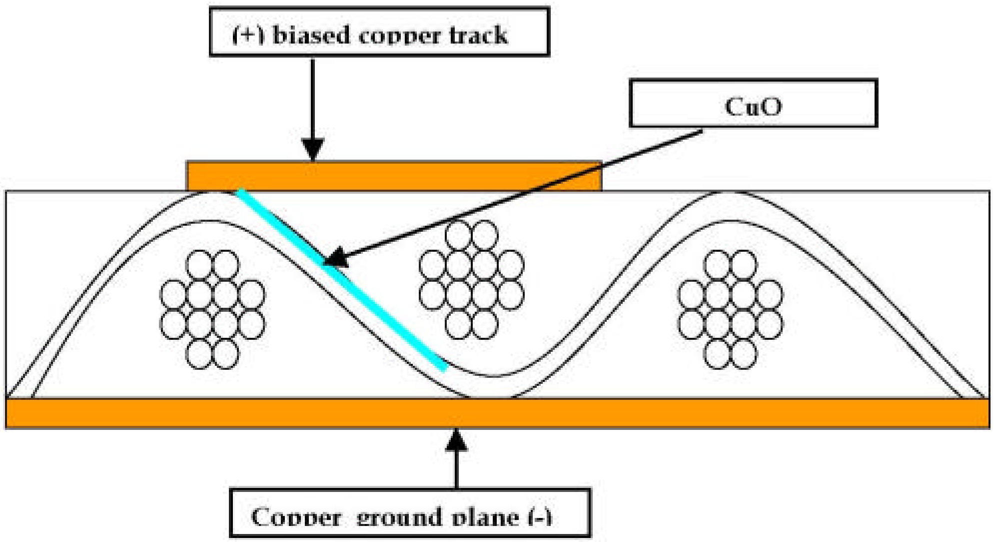


Figure 5 – Raytheon Test Coupon with "Punch Through" from Anode Trace to Copper Ground Plane.

At 95% RH, punch through was observed at 45°C. At 75% to 85% RH, punch through was observed at 65°C. The equation below represents Der Marderosian's concept of the production of CuO and Cu(OH)2 at the anode. He noted that copper hydroxide decomposes to copper oxide above 60oC. At the cathode, reduction takes place yielding copper and hydrogen gas.

3Cu + 3H2O = CuO? + Cu(OH)2? + 2H2?+ Cu?
anode cathode

Lando *et a*[4] first used the term –*conductive anodic filament* (CAF)– to describe this failure in 1979. They evaluated several different conductor configurations: line-to-line (L-L), hole-to-line (H-L) and hole-to-hole (H-H) and showed that susceptibility to CAF is H-H > H-L > L-L. Lahti *et al*[5] showed that the smaller the spacing between conductors and the greater the proximity of the glass fibers to the copper conductors, the faster the CAF growth. They noted that for a multilayer board failure initiated in the most deeply buried layers.

They defined the mechanism of CAF formation as a two-step process: (1) degradation of the epoxy/glass interface followed by (2) the electrochemical reaction.

Anode: Cu = Cun+ + ne-
H2O = ½ O2 + 2H+ + 2e-

Cathode: 2H2O + 2e - = H2 + 2OH-
H2O + ½ O2 + 2e - = 2OH-
Cun+ + ne- = Cu

In 1980, Welsher *et al*[6] reported that CAF was potentially a serious reliability problem for closely spaced conductors with a mean time to failure (MTTF)

$$MTTF = a(H)^b \exp\left(\frac{E_a}{RT}\right) + d\frac{L^2}{V}$$

where
H = Humidity
Ea = activation energy
T = temperature in Kelvin
L = conductor spacing
V = voltage
and a, b, Ea and d are material dependent.

They noted that additional work was needed to determine the exact dependence of CAF on conductor spacing and humidity. They also reported that glass-reinforced triazine is CAF resistant. In 1981 they expanded their view of the MTTF and reported it as:

$$MTTF = \alpha\left(1 + \beta\frac{L^n}{V}\right) \cdot H^\gamma \exp\frac{E_a}{kT}$$

where
a, ß = Material dependent constants
? = Humidity dependent constant
n = Related to the orientation of the conductors
L = Spacing
V = Voltage
H = Humidity
Ea = Activation Energy
k = Boltzman's constant
T = Temperature in Kelvin

The CALCE group[7, 8] studied the physics of failure and used the term conductive filament formation (CFF), which they defined as "an electrochemical process that involves the transport (usually ionic) of a metal through or across a non-metallic medium under the influence of an applied electric field." This definition is not specific to CAF but can include surface dendrites, CAF and copper plating in hollow glass fibers (which occurs during the board plating process). They defined the time to failure as:

$$t_f = \left(\frac{a \cdot f \cdot [1000 \cdot k \cdot L]^n}{V^m \cdot [M - M_t]}\right)$$

where
a = filament formation acceleration factor
f = multilayer correction factor
k = shape factor
L = spacing between the conductors
n = geometry accelerating factor
M = fraction moisture content
Mt= threshold fraction moisture content
m = voltage accelerating factor
V = voltage

Work by Jachim et al[9] and Ready et al[10] showed that the use of certain water-soluble fluxes or fusing (HASL) fluids could increase CAF formation. In examining a catastrophic field failure (Figure 6), Ready et al extracted the flux residues from an inner layer of the multilayer board and used ion chromatography to match the residues with the constituents of the flux used.

The effect of higher soldering temperature in weakening the epoxy-glass interface was clearly evident in data from Turbini et al[11] that demonstrated that the increased soldering temperature associated with lead-free alloys significantly increase the incidence of CAF.

Ready *et al*[12] studied the effect of voltage and spacing on CAF failures for a hole-to-hole test pattern (Figure 7). Using two different spacing (0.50mm and 0.75mm) and two different bias voltages, they were able to show the relation is L4/V2.

$$MTTF = c \cdot \exp\left(\frac{E_a}{kT}\right) + d\left(\frac{L^4}{V^2}\right)$$

In addition, they provided evidence for different CAF morphologies when different flux constituents were used (Figure 8).

They also identified the chemical nature of CAF as atacamite: Cu7Cl4(OH)10 H2O. An examination of the Pourbaix diagram for the copper-chlorine-water system reveals that copper hydroxy chloride is insoluble below pH 4 and thus this salt can grow from the anode, which is acidic. They also showed that the high conductivity of this salt, which causes catastrophic failure when it bridges to the cathode, suggests that it conducts through electrons and holes, i.e. it has semiconductor properties.

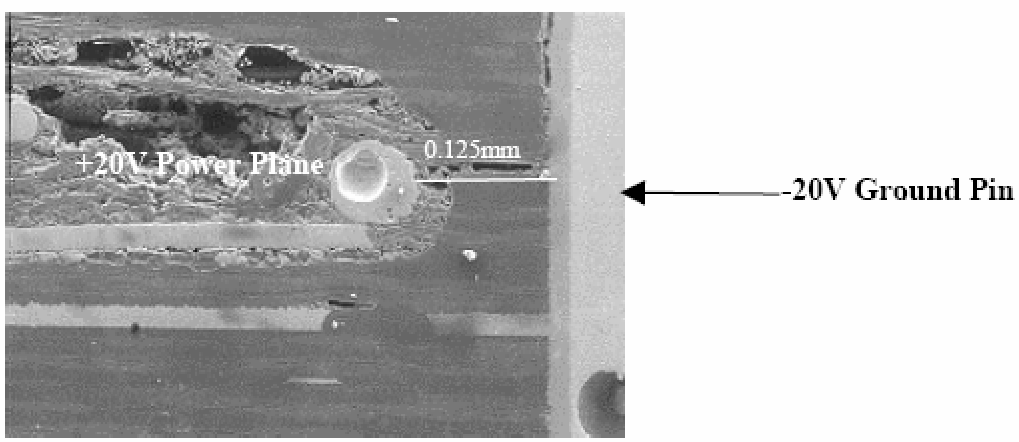
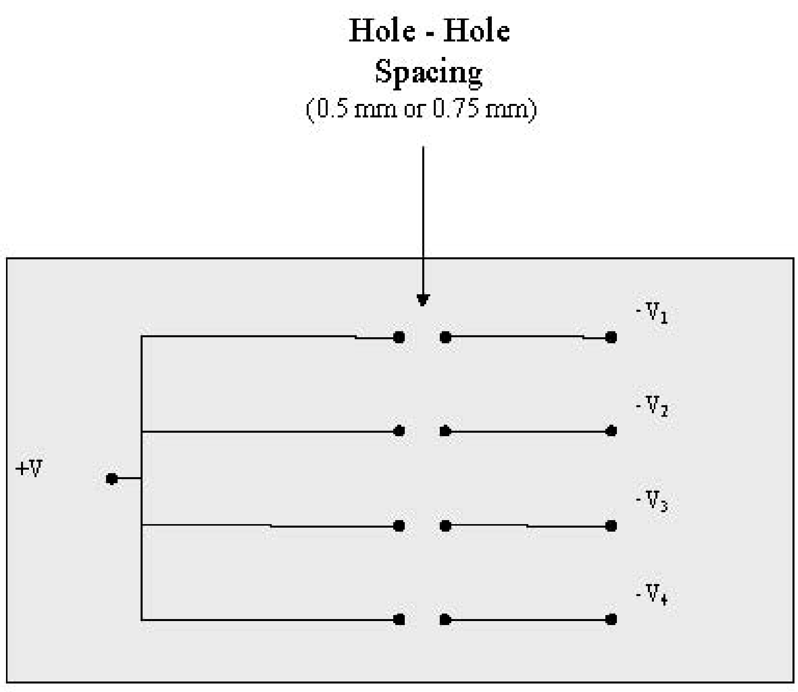


Figure 6 – Catastrophic Field Failure of Military Hardware
(Conductive filament grew from the +20V ground plane to the –20V ground pin. Flux residues enhanced this failure rate.)



(not to scale, dimensions exaggerated for clarity)

Figure 7 – Hole-to-Hole Test Coupon was Used to Study[12] the Relationship of Voltage and Spacing on CAF Failure Rates

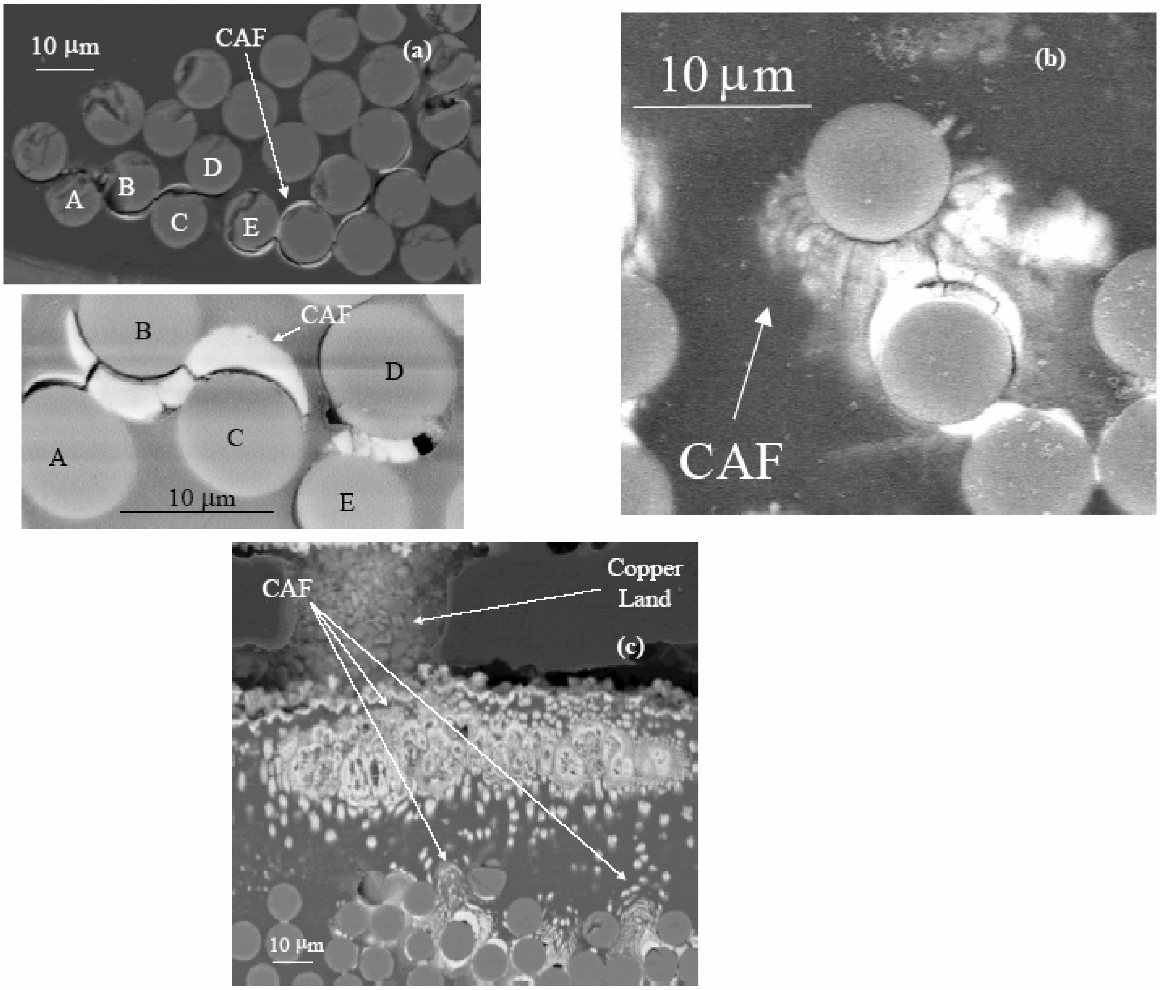


Figure 8 – Morphology of CAF Differs when Different Flux Constituents are Used

In (a) when no flux is used, CAF forms only a crystalline filament at the epoxy-glass interface; in (b) the flux contained polyethylene propylene Glycol (1800) and there appears to be copper-containing compounds in stratified layers within the matrix in addition to the filament at the epoxy-glass interface; and in (c) the flux contained a linear aliphatic polyether and one sees a copper-containing compound appearing in a striated morphology as well as in the filament at the interface.

CAF Resistant Materials

Lando, Mitchell and Welsher[4] compared FR-4 with several substrates: G-10 (a non-fire retardant epoxy/woven glass material), polyimide/woven glass (PI), triazine/woven glass, epoxy/woven kevlar™, and finally polyester/woven and chopped glass. Similarly, Rudra, Pecht, and Jennings[13] performed an extensive experimental comparison among the substrates: bismaleimide triazine (BT), cyanate esters (CE) and FR-4. In addition, Ready[14] compared the CAF susceptibilities of FR-4 with CEM-3 (a substrate similar to G-10 except with chopped glass) and MC-2 (a blended polyester and epoxy matrix with woven glass face sheets, and a chopped glass core). Of all materials tested by these investigators, the BT material proved to be most resistant to CAF formation (due to its low moisture absorption characteristics). Conversely, the MC-2 substrate proved to have the least resistance to CAF formation. The susceptibility of the materials follows the trend below and also depends on factors such as conductor configuration, conductor spacing, the presence of a conformal coating, etc.:

MC-2 >> Epoxy/Kevlar > FR-4 ˜ PI > G-10 > CEM-3 > CE > BT

To insure immunity to CAF, the laminate of preference is BT. However there is a cost penalty to consider.

In the late1990's, laminate suppliers began to develop new materials that they marketed as CAF resistant. To evaluate these materials, Sauter[15] developed a CAF test vehicle, which consisted of a multilayer board with daisy-chained hole-to-hole spacing of 0.25 mm, 0.375 mm, 0.50 mm and 0.625 mm. The holes were either (a) in-line with the glass fiber direction, or staggered. Accelerated aging was done at 65°C and 85%RH for 500 hours. His results show variations based on laminate material, manufacturer, and diagonal vs. in-line holes, with the former being more CAF resistant. He also defined a "readily conductive region" around the plated through holes, which must be considered in establishing design rules. This test vehicle and procedure has been developed as an IPC Test Method (IPC-TM-2.6.25) Conductive Anodic Filament (CAF) Resistance Test: X-Y Axis.

Summary

CAF is a conductive copper-containing salt created electrochemically that grows from the anode toward the cathode subsurface along the epoxy/glass interface. It can also grow from the anode on one layer to a cathode on another. CAF was first discovered in 1976 and was identified as a catastrophic failure mode. It is enhanced by high humidity during storage or use, by high voltage gradient between anode and cathode, by certain soldering flux ingredients, by hole drilling, multiple thermal cycles during processing, and by higher processing temperatures associated with lead-free solders. CAF is a copper hydroxy chloride salt and is a semiconducting material.

Our analytical tools today are far superior to those of these early researchers. Early data were obtained from chart recorders and manual plotting. Today we have computers for automated data collection and analysis and the sensitivity of the scanning electron microscope has improved significantly. The researchers of the 1970's and early 1980's characterized the basic factors associated with CAF and in many ways we are just repeating what they have done.

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