Investigating Hole-Wall to Hole-Wall Filament Growth Induced by PCB Design Features

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Abstract
The physical reliability of a printed circuit board (PCB) is often seen as more important than having the best dielectric performance. Hence, a great deal of research and development has been put into testing various dielectric materials' ability to survive in high-humidity, high-temperature testing without allowing copper to migrate between closely spaced features such as hole-walls. When copper migration does happen, it often occurs as dendritic type growths that form filaments, where a single filament can cause a short between two closely spaced copper features. This type of short is known as a conductive-anodic filament (CAF) [1] failure, or simply CAF for short. It is often assumed that anytime failures occur during high-temperature, high-humidity CAF testing, it is because of some shortcoming of the host resin system. However, in this study, we aim to show that an otherwise CAF-resistant resin system can be made to fail CAF testing if poor design choices are made and executed when building a test vehicle or other stack-up.

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Introduction
In today's market for high-performance dielectric materials, there is an expectation across the industry that copper-clad laminate (CCL) and prepreg suppliers will offer "CAF resistant" materials; that is, materials which, when exposed to high temperatures and high humidity environments, will not allow copper to migrate through the material and potentially cause a point of failure. Often, we see the request for "CAF resistant" materials made as though such a feature is an unusual or special request. However, in the marketplace of electronic substrate materials, any material that is not "CAF resistant" would very likely be disqualified from any Original Equipment Manufacturer (OEM) material testing protocol; hence, being "CAF resistant" is a de facto standard requirement lest a material become unmarketable. So, if any substrate that is presented to the high-performance dielectric materials market must be "CAF resistant," then we must have a widely accepted definition for CAF failures that occur because of the inherent material properties during testing. Likewise, we must be able to differentiate when a CAF failure occurs because of other flaws in a test vehicle, such as poor design (material choice(s), test vehicle stack, etc.) or poor fabrication quality of said test vehicle or its specific material lot.

Turbini [2] defines a CAF failure as "*a failure mode in printed wiring boards (PWBs) which occurs under high humidity and high voltage gradient conditions*" and goes on to specify that the filament "*grows from anode to cathode along the epoxy -glass interface.*" Turbini's definition is backed by research on the topic dating from the 1970s, when this failure mode was first discovered, and through the turn of the millennia as industry knowledge on the subject grew. With this definition in mind—and modifying it to account for more modern resin systems—it is clear true material-caused CAF failure will occur along the glass bundles in a CCL that has been built into a circuit board or test vehicle (see Image 1). Other modes of failure, such as along the surface of the test vehicle, or through voids formed during construction, should not be considered a shortfall of the dielectric resin system present in the substrate, but rather as a defect in either the design or construction process by which a product or test vehicle was made.

The IPC test method IPC-TM-650-2.6.25 Conductive Anodic Filament describes how to make and test coupons to determine a material's resistance to CAF formation, it defines a failure as a decade drop in resistance after the 96 hour temperature and humidity conditioning without bias. If we consider that a true material-caused failure occurs between the glass-resin interface, then we must consider what phenomenon will degrade the glass-resin bond. Thermal cycling, hydrolysis of the silane treatment on the glass fibers, and mechanical stress are three ways that the glass-resin bond can be degraded. Of those three modes of degradation, thermal cycling and mechanical stress are two modes that can easily be caused by either poor test vehicle design or careless construction techniques. It is not difficult to imagine a fabrication line that features multiple laminations at high temperatures (thermal cycling) or perhaps a design that minimizes resin near important vias prior to sequential laminations, a design containing significant low-pressure areas resulting from high thickness differential of stacked copper versus non-copper areas, high copper layer count, heavy stacked copper weight, or a combination of these design characteristics (mechanical stress points).

To illustrate what true CAF failure looks like, we have a "real world" example from an ultra-low loss resin system that was first treated onto fiberglass cloth to make prepreg, and then further processed to make laminates that were built into CAF test coupons. In Image 1 below, we can see that indeed, a conductive filament comprised of electrochemically formed copper salts has grown along the path of least resistance: the low-resin area in-between the glass fibers. Upon first review of these images, we of course hoped the failures were caused by the low-pressure areas that might have formed between the copper features that can be seen extending above the resin plane. Sadly, failure analysis confirmed that the failure did occur along the glass bundles, at the resin-glass interface; it was rather a classic Turbini-an case of CAF failure from degradation of the glass-resin bond.

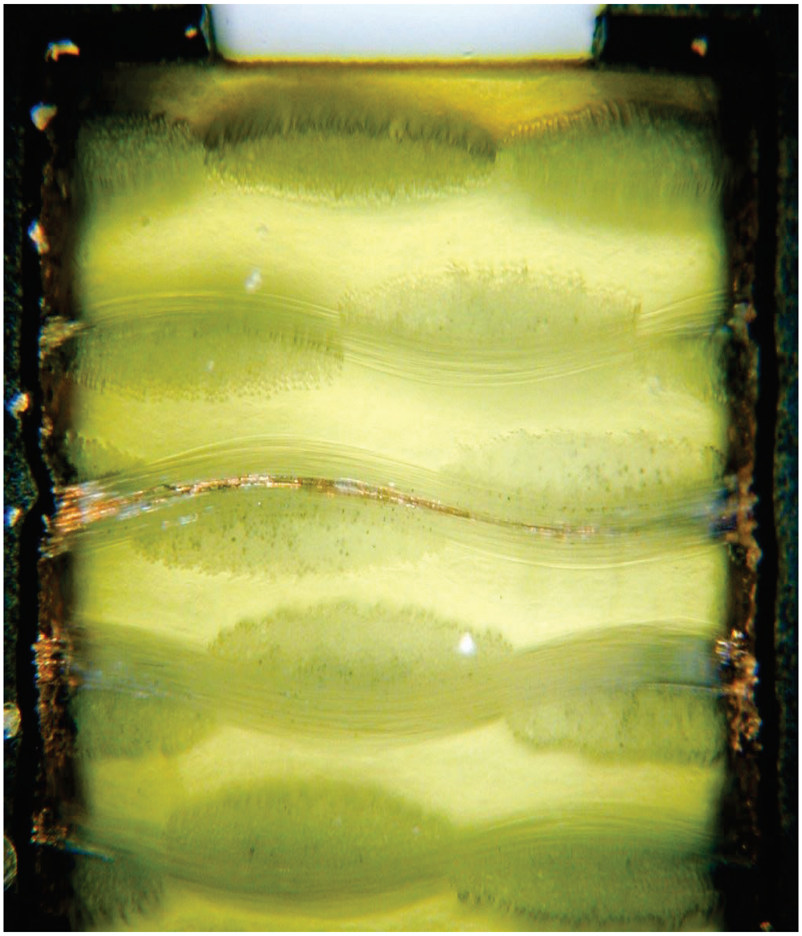

Image 1: This image shows a cross-section of a CCL with CAF growing along a bundle of glass fibers. The glass fiber bundles can present a low-resin area that allows for Cu migration that leads to CAF failure.

Over the course of this study, we will show several examples of CAF failures that do not occur along the glass-resin interface. Some failures occur along the test vehicle surface, where the resin has been coated by another material designed to aid the soldering process. This type of failure parallels those investigated by Ready et al [3] and others, where Ready was focused on CAF failures that were promoted by water-soluble fluxes, while our case seems to be CAF promoted by the solder mask or final finish processes. Other sources of failure include low-resin areas where minimizing the amount of resin present in a layer has allowed conductive features to be closer together, thus enhancing the chance of CAF, as was also predicted by Ready and Turbini [4]. Overall, the goal of this work is to spark more discussion in the PCB industry about how CAFs are formed and how we can further innovate together to help make them less likely to occur in high-performance materials.

Experimental Methodology

Laminate Creation

Prepreg and dielectric laminates investigated in this study were made by first creating a resin dispersion, coating the resin dispersion on glass cloth to make "prepreg", and then laminating the prepreg under vacuum using a heated hydraulic press. First, a curable composition was prepared by dissolving the soluble resin components in compatible solvent (*e.g.* methyl-ethyl ketone, toluene, dimethyl formamide, etc.). Next, the insoluble materials such as solid flame retardant and silica or mineral fillers were added and dispersed in the resin varnish using a combination of low and high-shear mixing techniques (*e.g.* Cowles blade, rotor-stator, or milling). Then, the resin dispersion was poured into a suitable vessel and a glass cloth was impregnated with the curable composition by pulling through a gap of pre-determined width set between two metal bars. The coating thickness was adjusted by changing the gap width. The prepreg was dried with air flow at room temperature for 10 minutes and then heated up to 130-160°C to form a dried prepreg. Two to twelve layers of prepreg were laminated with copper foil on the outside of the prepreg layers (*i.e.* the copper forms the top and bottom of the stack) to form a laminate. The laminate was cured at 200-225 °C for 1-3 hours at 350-450 psi.

CAF Testing

The test procedure followed the IPC Test Method IPC-TM-650 2.6.25C Conductive Anodic Filament (CAF) Resistance Test: X-Y Axis. Several OEM's have developed various CAF test board designs for their specific CAF evaluation needs. The test vehicles used in this study have been fabricated with two to twelve plies of prepreg and finished with a solder mask. The CAF coupons used in this study were designed to evaluate In-Line Hole to Hole CAF formation at various pitch distances. The pitch distance includes 0.406 mm (0.016 in) and 0.508 mm (0.02 in) in both with-grain and cross-section (Weft and Warp) directions. The circuit design includes ten sets of daisy chains for each pitch distance and each grain direction as seen in the Figure below.

A Hewlett Packard 4339A High Resistance Meter was used to determine the "As-Received" resistance for each daisy chain and check each net for defects or opens. The test coupons were wired using insulated copper wires soldered directly to the test board at the daisy chain connection points. Each coupon went through a cleaning process using Isopropyl Alcohol to remove any ionic contamination they may have been caused by surface salt formation or solder flux. The wires were then plugged into an ESPEC AMI Ion Migration Evaluation System Model AMI-025-U-5 and the CAF Coupons were placed into an ESPEC Environmental Chamber Model EPL-2H in a vertical position such that the airflow is parallel to the direction of the test coupons.

The CAF coupons were first pretested after installation into the environmental chamber to ensure there was still a solid connection and to measure initial insulation resistance. A preconditioning phase is applied to the coupons in a bias-free state (without electrical potential) for a minimum of 30 minutes at 23°C and 50% relative humidity. The insulation resistance is noted before and after the preconditioning phase. A Stabilization Profile is performed for 96 hours at 85°C and 85% relative humidity with no applied bias. The insulation resistance is monitored throughout the stabilization profile and noted upon completion. A first 500 hour applied bias profile is performed by applying 100V to the test coupons for the entire 500 hours. Insulation resistance is measured and recorded every 24 hours until the profile is completed. An additional 500 hours for (1096 hours total) may be performed under the same conditions: bias, temperature, and humidity if it is agreed upon by the testing requirements. As noted in the IPC 2.6.25C document, a CAF failure is determined by a decade drop in resistance at any point during the applied bias profiles from the original insulation resistance measured after the Stabilization Profile.

Dielectric Measurements

Dk and Df were measured using a split post dielectric resonator (QWED Technologies) at 10 GHz connected to an Agilent Technologies N5230A PNA Series Network Analyzer. Dk and Df against different frequencies were measured via Balanced Type Circular Disk Resonator (BCDR; Keysight) from 14 GHz to around 100 GHz.

Results & Discussion

As stated in the Introduction, we will now explore several examples where test vehicles or boards experienced CAF failure that were not caused by the glass-resin bond failing to resist the copper ion migration, but instead were failures induced by some other cause. Failures like those listed below are easy to dismiss as a flaw in the resin-glass chemistry, but closer inspection often reveals the true cause lies elsewhere.

While working with an industry partner to qualify a new dielectric material, we encountered some CAF coupons that were failing during testing. After examining the coupons under a microscope (100-200x magnification), and carefully looking at all the available images, it became clear that the copper had migrated through a clearance ring between a via pad and an adjacent plane (Image 2). This clearance ring acted as a low-pressure area in a multi-layer stack (>12 layers) and likely subjected the layer above to mechanical stress. It was also noticed that the anti-pad was slightly off-center, which might be within tolerance, but as observed by Karavakis and Bertling [5] the spacing of features affects the likelihood of CAF formation to occur. So, it is not surprising to see that after meticulous sanding, polishing, & observation under 100-200x magnification revealed the filament formed adjacent to the degraded area where the copper-copper spacing was minimized. If the design had called for a higher resin content and/or perhaps used a task-targeted fill layer, then perhaps this failure might have been avoided.

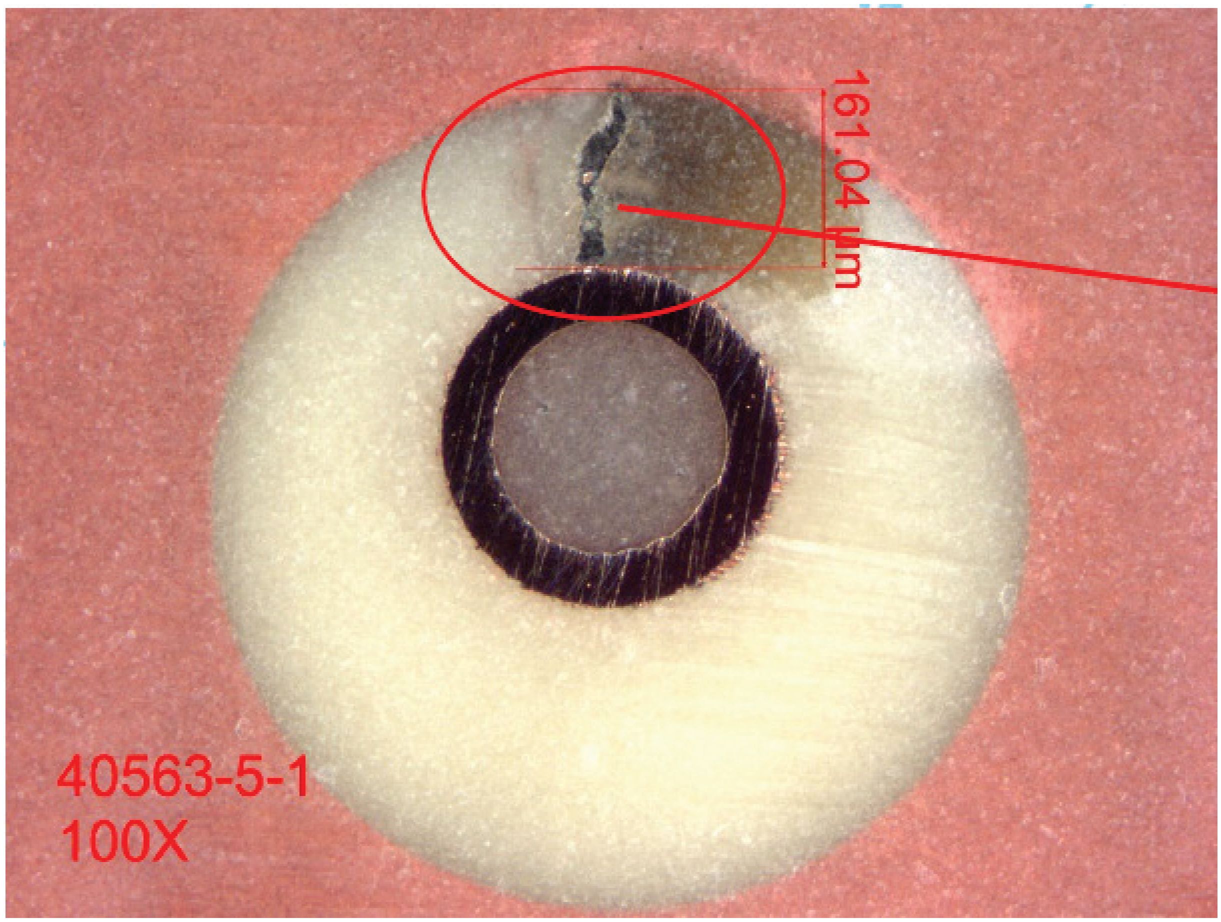

Image 2: This image shows a slightly off-center clearance ring with degraded polymer and a copper filament that formed in the area where the Cu-to-Cu feature distance was at a minimum.

For our in-house CAF testing, we switched from 4-layer to 2-layer coupons to minimize the number of lamination bond-lines in the test vehicles. The often substandard construction quality of the coupons consistently lead to CAF formation along these bond lines (Image 3), thereby hampering the goal of testing the resin system's viability of withstanding CAF judged solely on the basis of its chemical makeup. Poor bond-line quality in the sample gives a pathway for moisture adsorption, which in turn leads to copper ion migration. Despite attempting a few rounds of troubleshooting with our coupon fabricator, the easiest way to exclude the unwanted influence of the sample fabrication process was to simply eliminate the extra bond lines by using a 2-layer construction.

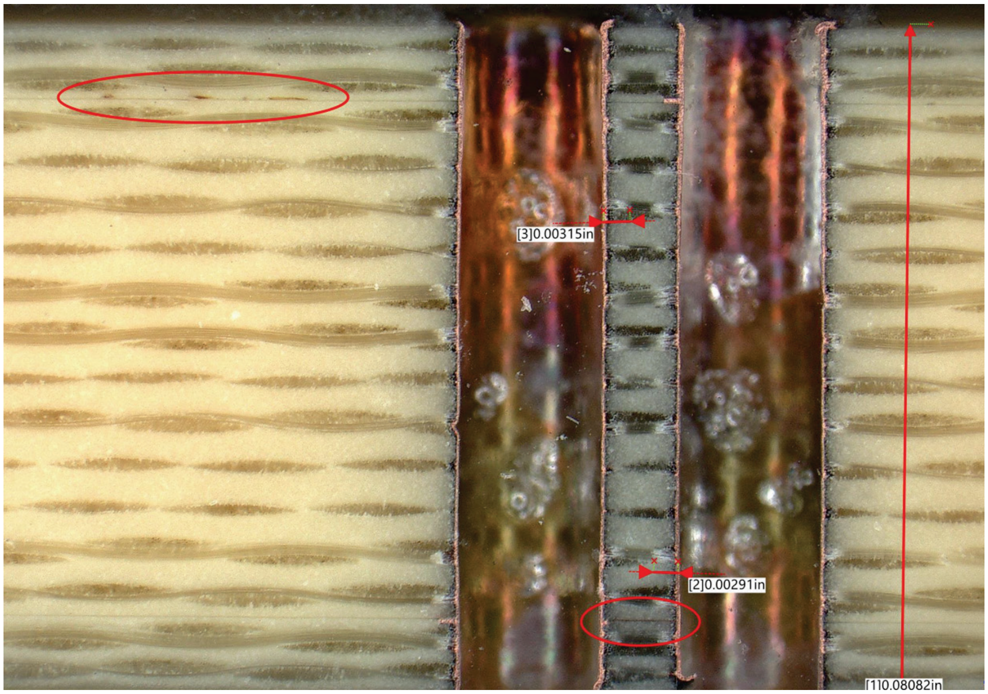

Image 3: The image shows a cross-section of a 4-layer CAF coupon; the lamination bond line has allowed CAF formation (circled in red near the top left) between the first and second layers in the stack.

Another interesting case of suspected material-caused CAF failure happened when inter-connect defects were found within a set of test vehicles. While examining cross-sections, we found delamination from the copper in the middle of the stack due to low resin content (Image 4). In the image below, the dark areas are voids that occurred due to the design calling for low-resin content materials. Although there is often a need to hit certain thickness targets, minimizing resin content makes any design vulnerable to the defect(s) presented below. It is interesting to note there were multiple hole diameters in the design (0.2, 0.25, & 0.30 mm) but only the smallest hole diameter saw defects. After heat shock, multiple low-resin areas showed cracking at the heavy copper non- hole drill areas, and as observed elsewhere, the low-resin areas presented low-pressure areas which coincided with CAF formation.

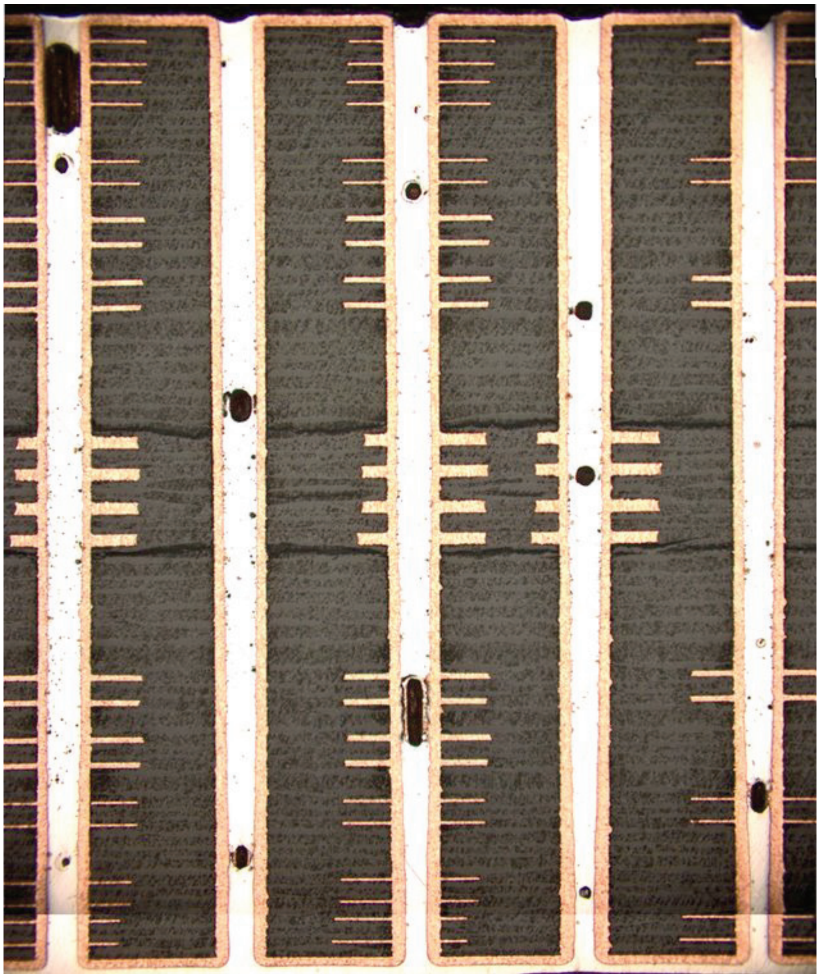

Image 4: This image shows a cross-section of a test vehicle where voids have appeared due to low resin content in the middle of the stack; the voids are the dark areas. These voids served as low-pressure areas that led to inter-connect defects during lamination.

In the next example, we see the classic dendritic growth pattern exhibited by the migration of copper ions forming a filament (Image 5). However, these filaments are not seen growing between the glass-resin bond inside the body of the test vehicle, but rather they are migrating across an over-coated surface that was treated with a solder mask product. The OEM who tested these coupons examined them internally and did not report CAF growth through the glass-resin system. It seems the choice of solder-mask product may have been incompatible with the high-humidity, high-voltage test environment presented by the CAF test procedure.

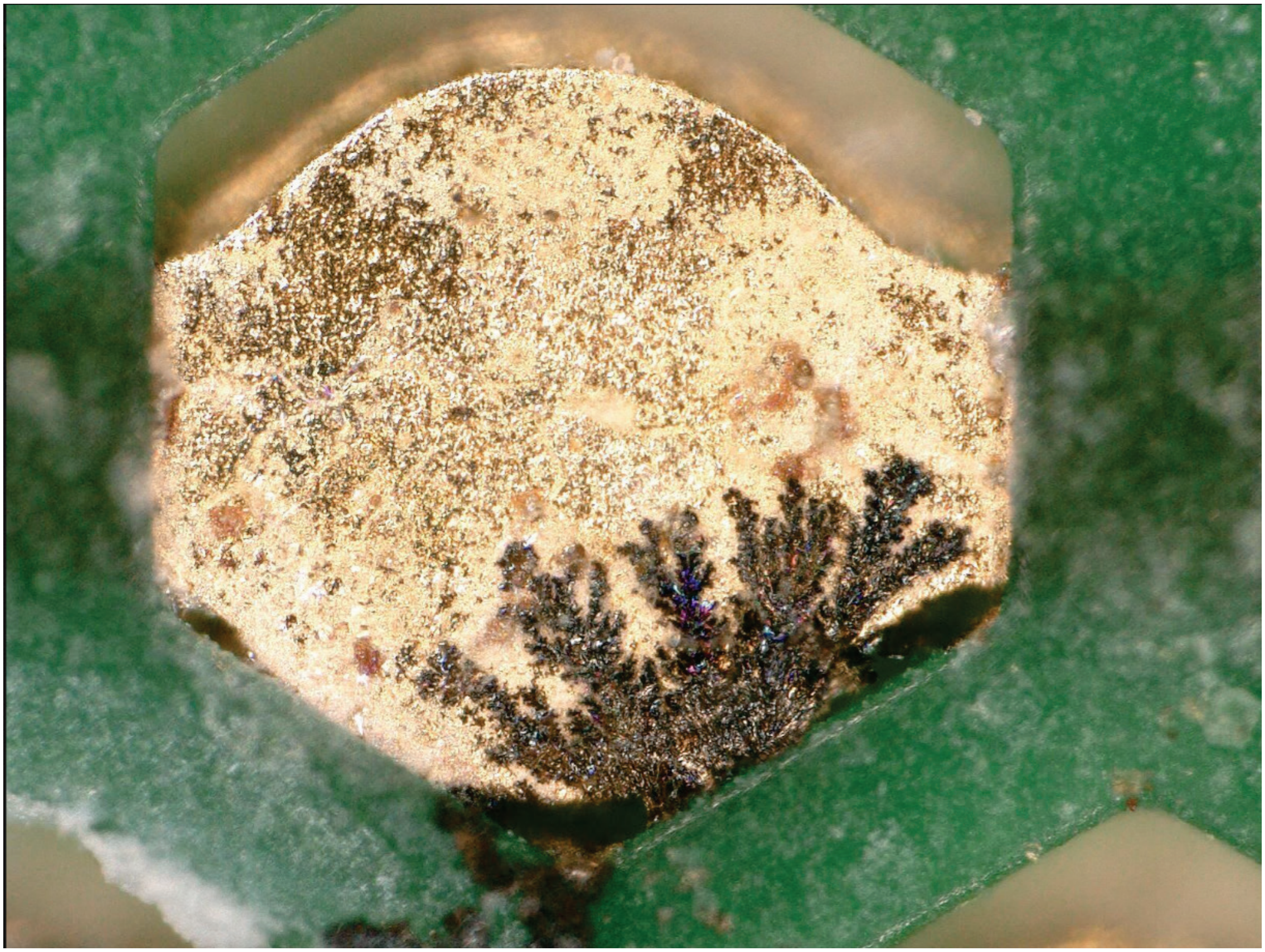

Image 5: This image shows dendritic growth forming on the surface of a test vehicle. Despite having the appearance of a classic CAF failure, since the filament does not form at the resin-glass interface, this is not considered a failure of the substrate resin system.

Below is another example of surface defects leading to failure during CAF testing that was not a true material-caused CAF formation (Image 6). The image shows surface contamination that is consistent with poor rinsing after the application of solder mask. This example illustrates the importance of meticulous construction and cleaning procedures.

Image 6: This image shows residue on a test vehicle that was left behind after insufficient rinsing following the application of solder mask. This residue can lead to a drop in resistance during CAF testing that mimics a true CAF failure.

One final example of a failure during CAF testing that was not a true CAF failure is shown below. In this example, a flip-drill procedure was not properly performed (Image 7). The initial hole was drilled, the test vehicle was flipped over, but proper alignment was not maintained. This led to the second hole being out of alignment with the first, causing a cascade of problems for the rest of the construction process. Even in a six-sigma process, defects like these are bound to occur, but this example serves as an illustration of the importance of following up on all "CAF failures" with proper failure analysis. Whether analyzed manually by cross-section & microscope, or non-invasively by X-ray or other imaging techniques, good failure analysis is paramount to revealing what really went wrong.

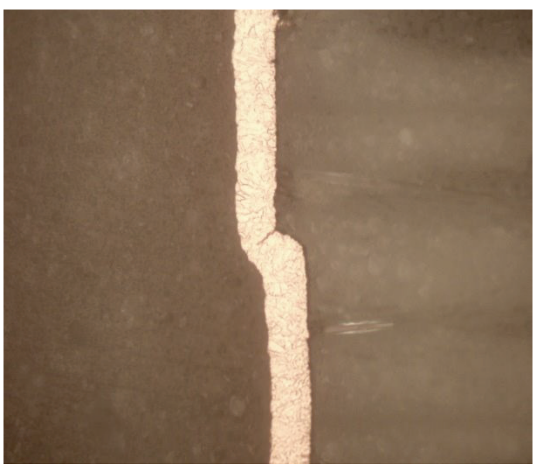

Image 7: This misaligned copper feature (hole wall) was caused by an error during a flip-drill procedure.

A trend that was noticed throughout the course of this work was the tendency for resin content to matter more as we approach copper thickness of 1 mm and above. Another observation is that there is a tendency for PCB designers to want to minimize the amount of resin in certain layers of their design. This could be for a variety of reasons: perhaps the cost of resin or the possibility of a CTE mismatch with copper comes into play. In the case of the latter, it should be noted that non-supported materials often target having a CTE that closely matches copper so they will give better reliability in high-density interconnects. It should be expected that anyone working with such resin systems could see the usefulness of adapting them to target supported materials where practical. Future studies of how much resin is actually needed to affect outcomes with >1 mm thick copper would also be helpful for both OEMs and PCB fabricators. Such studies could be done using modeling software or perhaps by design of experiments.

Conclusions

CAF is a major physical phenomenon that must be weightily considered and proactively accounted for at every step of the product design and manufacturing process. Material manufacturers would be well advised to continue their rigorous testing of new resin formulations and glass/filler products to assure that CAF is inhibited to the best possible extent for the greater cross-section of products manufactured within the electronics industry. Special product classifications, such as those meant to operate in high temperature, high humidity or high voltage environments, must be specially considered with targeted formulations that not only seek to control CAF, but can be tested and rated for their suitability for these environments. A selection of high-reliability defense, industrial, automotive and medical applications would undoubtedly profit from this effort, and indeed may not be possible without it.

However, as noted by the examples provided, there are many possible sources of CAF failures. From the investigations conducted it is clear process control within every primary and even secondary operation of the PCB manufacturing sequence is paramount for successfully controlling the incidence of CAF. In particular, cleanliness, mechanical precision, suitability of chemistries utilized, and material handling are just some of the factors which determine whether or not a manufactured PCB will be able to perform according to its designed function and for the intended duration without issue. The latency of the occurrence of failure with respect to the date of its actual origin is precisely the reason why the prerequisites for its occurrence must be rigorously and strictly controlled.

With the advent of AI and next-gen power products, -- thinner dielectrics, higher circuit densities, more and thicker copper features, more challenging SWAP, etc., -- there is every indication that CAF will become an even more central theme for product designers and substrate manufacturers in the decades to come. Undoubtedly there is fertile ground for the development of new tools that will help in abating the incidence and destructive influence of CAF, most notably for a new generation of design tools that optimize circuit layout for copper coverage, interconnect sizing, electrical parameters (especially voltage field), masking requirements and environmental conditions. AGC would welcome future project partners for such an endeavor.

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