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DIELECTRIC MATERIAL DAMAGE VS. CONDUCTIVE ANODIC FILAMENT FORMATION

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ABSTRACT:

It should be noted that this is an overview paper that represents the early stages of an ongoing investigation into the causes and effects between conductive anodic filament (CAF) formation and printed wiring board (PWB) material damage. Our belief is that certain or specific types of material damage can increase the propensity for CAF formation. The preliminary data collected suggests is that there is no statistical correlation between the general definition of material damage (cohesive failure) and CAF. The resulting dichotomy is that we find no CAF failures in some coupons that have obvious material damage and we find CAF failures in coupons that don't exhibit material damage.

Since the advent of the European Union's legislation for Restriction on Hazardous Substances (RoHS) lead (Pb) was removed from solder in surface finishes and pastes used in the component assembly process. The alternative metals and alloys to traditional tin/lead (Sn/Pb) solder required that the assembly temperatures be increased to achieve the higher melting point of the lead free solders. The traditional assembly temperature reached a level of 230°C, lead-free can require up to a maximum of 260°C, although most assembly houses are using a more modest 245°C. Multiple exposures to the additional 15°C to 30°C has demonstrated a negatively impact to the integrity of the FR4 and halogen free dielectric material used in PWB substrates. Quantification of material damage is now possible through new techniques that utilize capacitance measurements to identify specific levels of bulk capacitance change that signify degradation within the resin system. This technique was employed to non-destructively identify both the locations within the construction and the magnitude of the change, traditional microsectioning was completed to confirm the results of the capacitance testing. This new technique, including equipment used is described

Many of the commercially available materials have not demonstrated sufficient robustness when exposed to multiple lead-free assembly and rework thermal excursions. The reality is that these higher assembly and rework temperatures are increasing the risk of material damage. One would naturally expect that the increasing levels of material damage would produce an opportunistic path that would provide an increased possibility for CAF growth. In order to understand this very complex environment it is necessary to lay the ground work for how and effective quantification can be determined. This paper reviews the results of some initial work, our strategy for improved test vehicles design, including features for measuring material damage and CAF formation, the assembly and rework environments, the material and CAF testing methodology and the protocols that will be used. Our ultimate objective is to establish whether correlation can be found between the various types of material damage and the propensity to CAF failure.

Key words: PWB, IST, CAF, DELAM, Material Damage

INTRODUCTION:

The materials used in the initial studies were all FR4 types of materials. The resin systems included halogen free, high Tg and low loss (high speed) materials that are advertized to be lead free compatible. All material types were constructed into 20 layer test panels that included both Interconnect Stress Test (IST) and CAF coupons. Each of 12 different material types were constructed with two different resin contents (58% or 69%) for a total of 24 sets of test panels. The same glass style and resin content stack-up was specified to each material supplier. The two resin content constructions are essentially the same thickness, 2.94 mm (.116") for the 58% resin and 3.0mm (.118") thick for the 69% resin construction. The effect of resin content was evaluated independently. The 58% resin content construction is shown in figure 1; the 69% resin content construction is shown in figure 2. The labeling convention for each material type used a single letter (E.g. "A") for 58% resin content and a double letter designation (E.g. "AA") for the 69% resin content. It should be noted that the identification of these specific materials is being withheld.

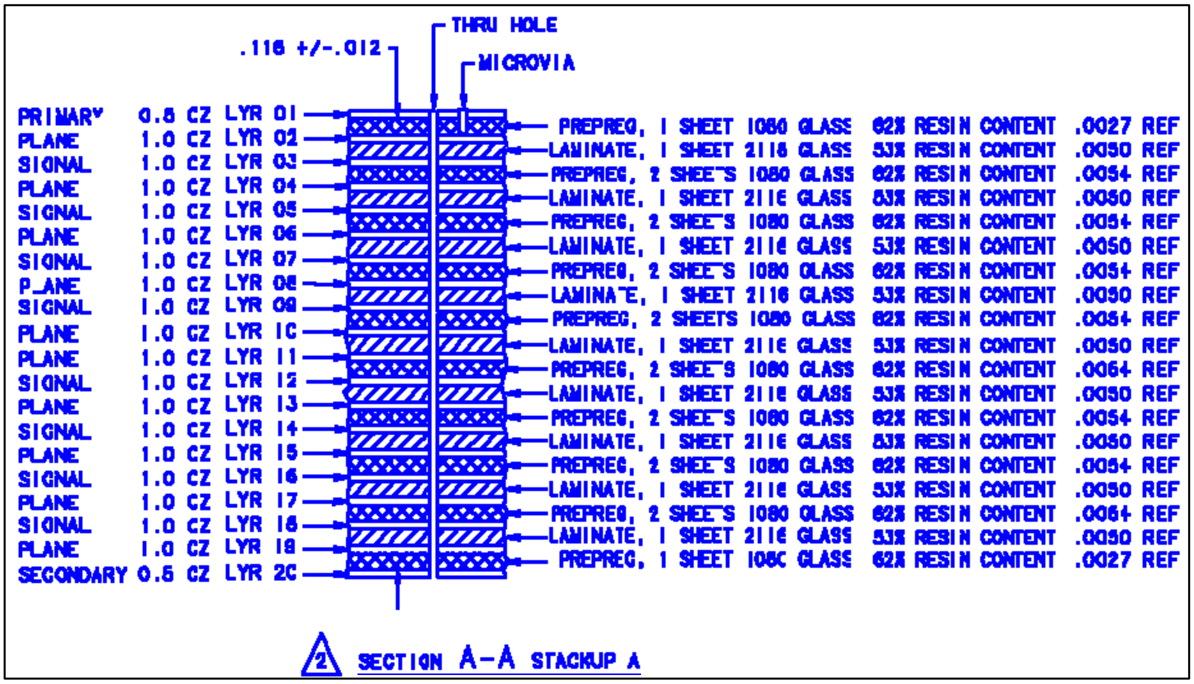


Figure 1. 20 Layer Standard Stackup - 58% resin content

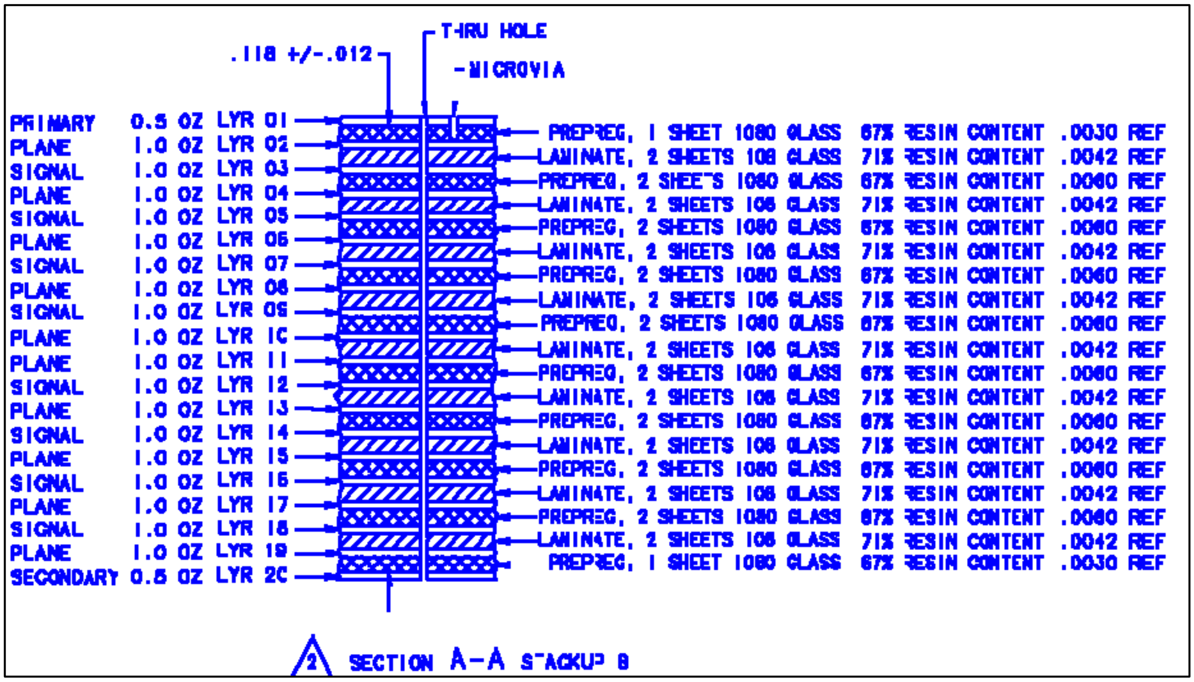


Figure 2. 20 Layer High Resin Stackup - 69% resin content

CAF Testing Methodology And Protocol Definition

CAF testing was performed as per ***IPC 650 Test Methods Manual – Procedure 2.6.25A Conductive Anodic Filament (CAF) Resistance Test: X-Y Axis*--5/12.** This test determines if a material is prone to growing a conductive path between adjacent conductors. The test was done using a temperature humidity chamber, set at 87% relative humidity and a temperature of 85°C +/- 2°C. The coupons were subjected to a bias of 100 VDC applied between two isolated groups of adjacent holes within each test circuit.

CAF is an "electrochemical failure mode of electronic substrates involves the growth of a copper containing filament subsurface along the epoxy-glass interface, from anode to cathode." [1]

After the 96 hour stabilization period, any test board nets measuring less than 10 MΩ (7.0 log ohms) were excluded from the test analysis. This is due to the fact that these failures aren't due to CAF but poor copper plated through hole PTH quality or laminate capability. As a result of the applied bias, the test circuit is considered failed if the insulation resistance is dropped by a decade.

This test was monitored on a daily basis (24 hour recordings) using a micro-volt meter, until testing stopped at 1000 hours. After completion of the test, the test coupons were grounded before removal from the environmental chamber. Visual examination at 100X magnification was completed to discern evidence of surface insulation resistance failure (i.e., discoloration, corrosion), the examination also considered handling or processing defects other than CAF. Any coupon results with these conditions found were excluded from the test. There was a total of one coupon per material type tested.

CAF testing was completed using an IST coupon design (MAT20006A). This coupon has three sections M1, M2 and M3 that have different functions. The section that was used for the CAF evaluation was the M2 section. The M2 section was designed to enable both IST and CAF testing. It contains a test circuit configured of PTHs connected on the outer layers; this enables the bias to applied for the full construction of the dielectric material.

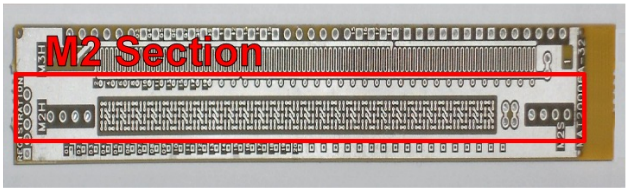


Photo 1. IST coupon showing M2 Section

In order to facilitate CAF testing a trace in the daisy chained was cut at one end of the via reliability test circuit. Individual wires were soldered into each side of the now open test circuit. In Figure 3 the lower (red) traces are the anode and the upper (blue) traces are the cathode. Note that there are approximately 200 holes that are adjacent to one another within this configuration.

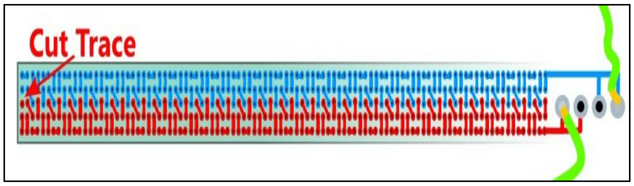


Figure 3. The M2 section configuration of the CAF coupons

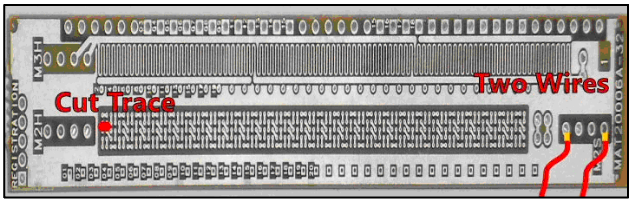


Photo 2. Example of actual IST coupon configured for CAF testing.

The designed hole to hole spacing (grid size) was 0.8 mm (.032"). The holes were drilled at 0.25 mm (.010") leaving a maximum of 0.55mm (.022") of dielectric material. The pads were designed to be 0.5 mm (.020"), leaving a distance of 0.3 mm (.012") between adjacent pads. There is approximately 0.1 mm (.004") of spacing between the pads and the copper of internal copper planes for a total distance of 0.2 mm (.008") that needs to be bridged by CAF propagation (see photo 3)

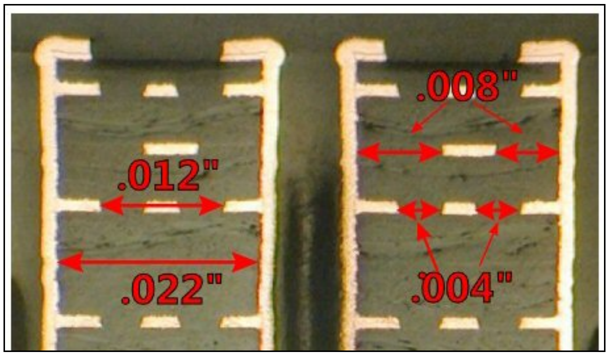
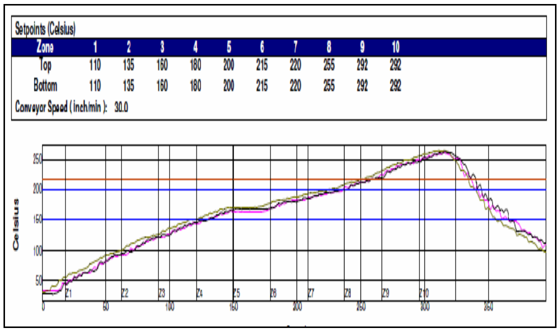


Photo 3. Coupon features and geometries"

Test Conditions (Non-stressed Vs Stressed)

In this study the 24 configurations were CAF tested, the conditions were "as received" (non-stressed) compared to 24 configurations following exposure to six reflow oven thermal excursions to 260°C (6X260°C), required to simulate standard assembly and rework. Three thermal excursions are considered a simulation of standard assembly which would be twice down a reflow oven, (one time for each side) and one time to simulate hand soldering. Three additional thermal cycles were added to simulate possible rework, for example, a ball grid array (BGA) removed and replaced, (two thermal excursions), and a possible hand soldering touch up, (the third thermal excursion).

Figure 4 is a plot of the thermal profile created in a 10 zone SMT convection oven used to precondition the coupons to a maximum of 6 cycles to 260°C.



Setpoints (Celsius)

Zone	1	2	3	4	5	6	7	8	9	10
Top	110	135	160	180	200	215	220	255	292	292
Bottom	110	135	160	180	200	215	220	255	292	292

Conveyor Speed (inch/min): 30.0

Figure 4. The assembly profile

CAF Definition

CAF requires a number of factors to be present in order to propagate. For CAF to “grow” one must have moisture present, a source of ionic contamination, adjacent conductive features (traces or vias), a power bias, and a pathway (between the glass fibres and the resin system interface). If one of these conditions is removed then CAF cannot form. With all five present CAF is likely to form.

What appears to happen is that a very thin branching conductive path will form between two adjacent conductors until it produces an electrical path. Once the salts form a conductive path that path is initially very weak and it is destroyed by the arching of electricity. The short destroys some of the conductive path but not all of it. The path then reforms a more robust connection until the short forms again. This continues until a ‘hard” short is formed at which time the copper can melt and the circuit board may catch on fire. Figure 5 illustrates how CAF (shown in red) can migrate along a glass bundle from the drilled hole wall across to an adjacent feature.

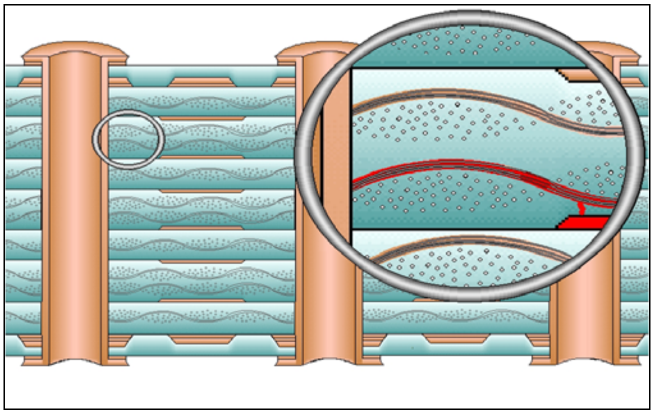


Figure 5. CAF shorting along a crazing type delamination

Photo 4 is an extreme example of a short that occurred in a circuit board that failed for CAF. The board was in use when it burnt up. It is obvious that a CAF formed between the internal power layer and the PTH, the short circuit was robust enough to melt the plated copper and scorch the dielectric material.

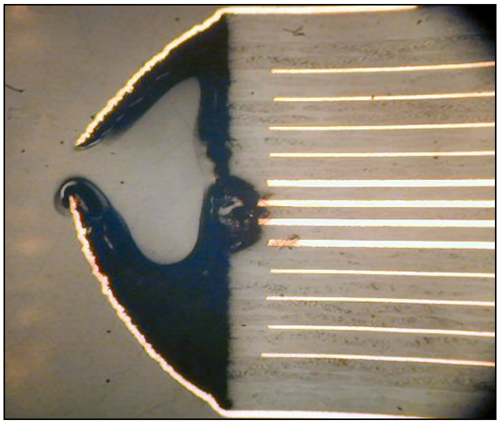
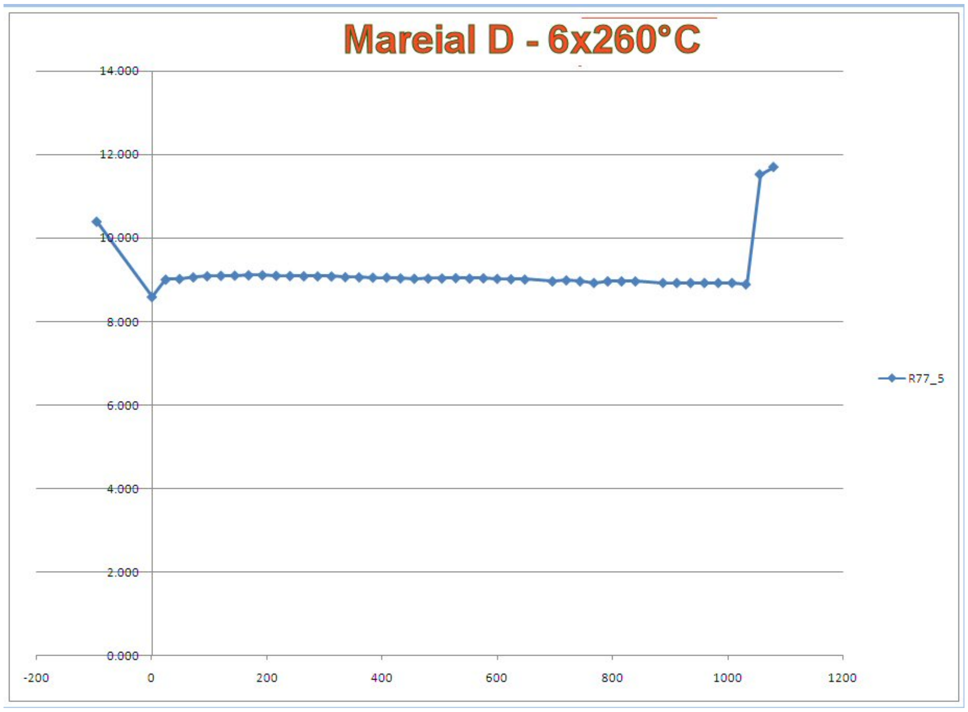


Photo 4. Example of a CAF Short

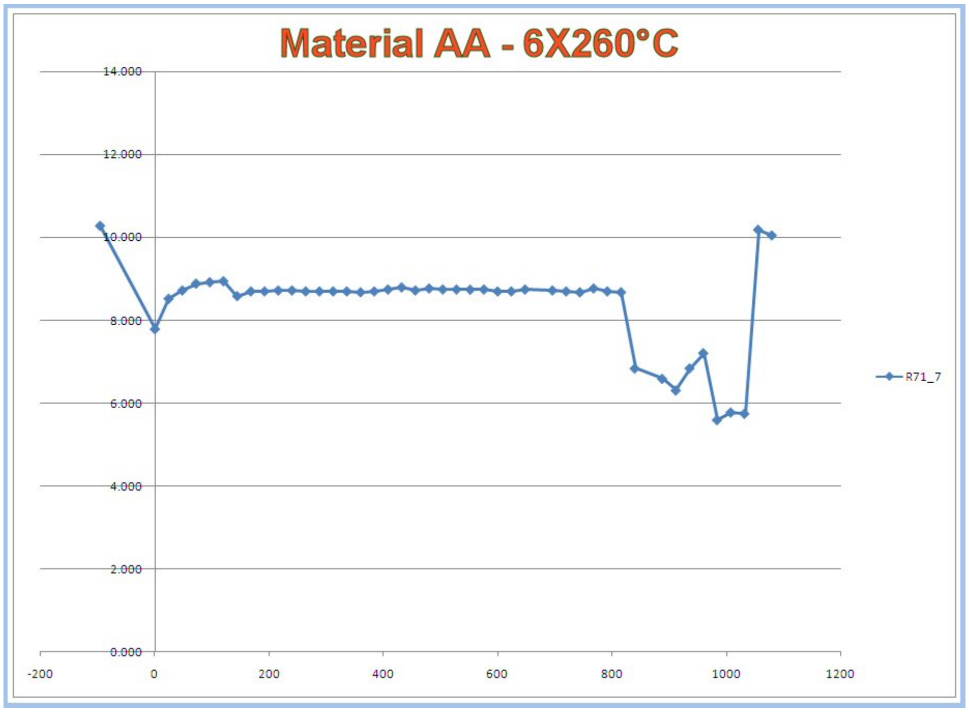
CAF Test Results

The CAF results between the non-stressed and stressed samples showed a great deal of variability. One would expect that if a coupon had fail the non-stressed condition then that same material would also fail after exposed to 6X260°C (stressed). Materials EE, F, FF, GG, H and K had CAF formation in the as received coupons but none in the coupons that had 6X 260°C preconditioning.

The graph 1 below represents material “D” which did not have a failure after 1000 hours in the humidity chamber. The graph 2 is of material “AA” which demonstrates a CAF failure some time after 800 hours.



Graph 1. Material D – No Failure



Graph 2. Material AA –Failed 800 Hours

CAF Results of IST Coupons - Unstressed

Table 1

Coupons	Insulation Resistance Measurement (log ohms)				Result
	0 hours	96 hours	510	1012	
AA_4	12	8.552	9.195	8.619	**Pass**
AAA_6	12	8.419	9.145	9.027	**Pass**
AB_6	12	8.584	8.92	8.677	**Pass**
ABB_9	6.733	3.835	3.604	3.57	**Excluded**
AC_9	12	7.428	8.958	8.92	**Fail**
ACC_7	12	7.227	8.299	8.43	**Fail**
AD_9	12	8.677	9.255	9.093	**Pass**
ADD_3	12	8.335	8.973	8.92	**Pass**
AE_6	12	8.133	8.92	8.92	**Pass**
AEE_2	12	8.698	8.265	7.264	**Fail**
AF_5	12.097	8.567	4.084	3.912	**Fail**
AFF_9	12.155	8.536	4.653	5.655	**Fail**
AG_1	11.959	5.277	4.426	5.677	**Excluded**
AGG_2	12.097	8.219	5.789	5.53	**Fail**
AH_4	12.046	8.242	4.89	3	**Fail**
AHH_6	12	8.567	7.305	7.762	**Pass**
AI_5	12.097	4.443	3	1	**Excluded**
AII	N/A				
AJ_6	6.589	7.27	4.607	6.091	**Fail**
AJJ_3	12	8.657	3.604	2.955	**Fail**
AK_3	12.097	8.72	7.396	7.734	**Pass**
AKK_2	5.786	5.833	5.561	5.353	**Excluded**
AL_2	12.398	7.88	8.795	8.823	**Pass**
ALL_1	12.097	8.619	8.637	8.29	**Pass**

CAF Results of IST Coupons – 6X260°C

Table 2

Coupons	Insulation Resistance Measurement (log ohms)				Result
	0 hours	96 hours	504	1008	
R A_7	10.276	7.789	8.744	5.784	**Fail**
R AA_3	10.229	7.337	6.138	3.718	**Fail**
RB_1	10.301	7.845	6.158	5.47	**Fail**
RBB_1	7.525	6.323	5.33	5.525	**Excluded**
RC_3	10.337	7.812	6.581	6.51	**Fail**
RCC_1	10.284	7.64	6.399	6.731	**Pass**
RD_5	10.387	8.584	9.026	8.92	**Pass**
RDD_4	10.108	4.443	4.475	6.649	**Excluded**
RE_5	10.319	8.077	5.483	2	**Fail**
REE_6	10.276	7.51	7.261	7.326	**Pass**
RF_9	10.276	4.673	4.475	2.301	**Excluded**
RFF_1	10.337	7.912	6.613	7.403	**Pass**
RG_5	10.237	8.637	8.958	8.853	**Pass**
RGG_7	10.377	8.507	8.958	8.29	**Pass**
RH_3	10.42	8.853	8.853	8.769	**Pass**
RHH_10	10.42	8.257	8.677	8.619	**Pass**
RI_9	7.673	8.705	4.263	4.054	**Fail**
RII_5	10.337	8.419	3.604	3.958	**Fail**
RJ_5	10.319	4.222	3.302	3.205	**Excluded**
RJJ_6	10.337	5.186	3	2.903	**Excluded**
RK_1	10.409	8.795	4.585	4.89	**Fail**
RKK_6	9.475	8.375	5.109	3.848	**Fail**
RL_6	8.385	8.355	8.885	8.823	**Pass**
RLL_4	10.319	4.12	4.084	5.62	**Excluded**

Material Damage (Capacitance) Testing

The technique used to determine the presence and location of material damage uses an acronym of DELAM (Dielectric Estimation and Laminate Analysis Measurement) test method. This method measures the capacitance between power layers inside the circuit board. The DELAM tester automatically measures the bulk capacitances between the layers and records that data in a files on the computer. This system greatly reduces the time is take multiple capacitances and reduces the risk of human error related to data entry.

The DELAM testing is determined in the same location (M2) of the IST coupon design. The coupon is designed with ground planes that correspond to ground planes of a representative circuit board. The M2 section contains capacitance planes on layers 2, 4, 6, 8, 10, 11, 13, 15, 17 and 19 (see photo 5). There is a heating circuit (super heat) on layers 3, 7, 14, and 18 (that were not used in this part of the study). There are no layers or pads in the M2 section of the coupon on layer 5, 9, 12 or 16.

Capacitance is measured between adjacent layers 2/4, 4/6, 6/8, 8/10, 10/11, 11/13, 13/15, 15/17 and 17/19 on the "as received" coupons and then compared the reading of those same coupons during and after exposure to 6X260°C. If a capacitance change greater than -4% is measured it is a strong indication that material degradation has initiated. Once we identified coupons with a -4% decrease it was selected for microsection analysis, to confirm, or refute the presence of material damage. All coupons that measured a -4%, or greater reduction in capacitance were confirmed to have material damage during microscopic examination. The correlation between DELAM testing and microsection results are shown in Table 3.

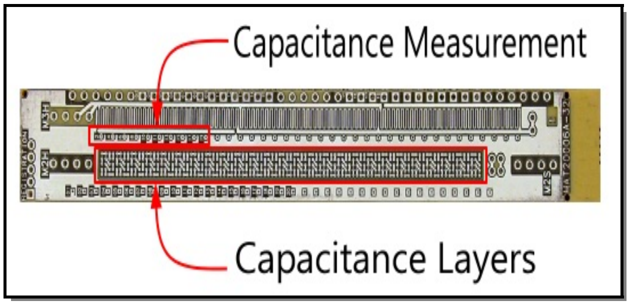


Photo 5. MAT20006A coupon

DELAM Tester

The DELAM tester uses a bed of nails that corresponds to the capacitance holes in the IST coupon. Photos 6 through 8 are images of the DELAM tester and fixture.

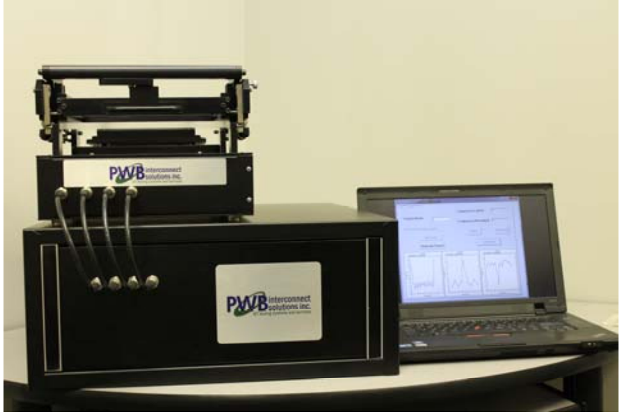


Photo 6. DELAM Tester

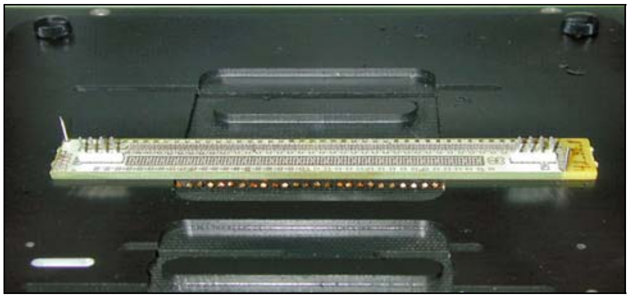


Photo 7. DELAM Tester Head

Photo 8. DELAM Tester Open

Definition Of Types Of Material Damage

Material damage can be grouped into four general types, which include adhesive delamination, cohesive cracks, "crazing" and material decomposition. Most often material damage is within the central zone of the construction, generally not visible on the surface of the substrate. To effectively find material damage one needs to process a microsection. Having the capacitance data enables an intelligent decision toward a suspect coupon that is expected to contain material damage rather than relying on random sections (hit or miss).

Adhesive Delamination

Adhesive Delamination is a separation between two laminated surfaces. It is usually between the B-stage and C-stage, B-stage and copper foil or between the glass bundle and the adjacent epoxy. This type of failure looks like a blister on microsection and usually ends in a single point that rarely branches. This is the only type of material damage that can respond to baking by driving down the amount of volatiles, like water, that are absorbed within the dielectric material. The problem is it is rare that baking will avoid the risk of delamination.

It is suggested that baking at 105°C for four hours is adequate to remove most of the latent moisture. Baking for a longer time or at a higher temperature can cause a degradation to the material that could increase the level of internal material damage.

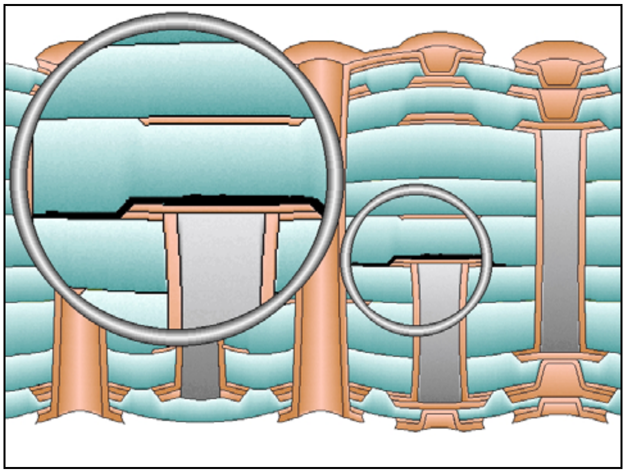


Figure 6. Example of Adhesive Delamination between B stage resin and copper plating

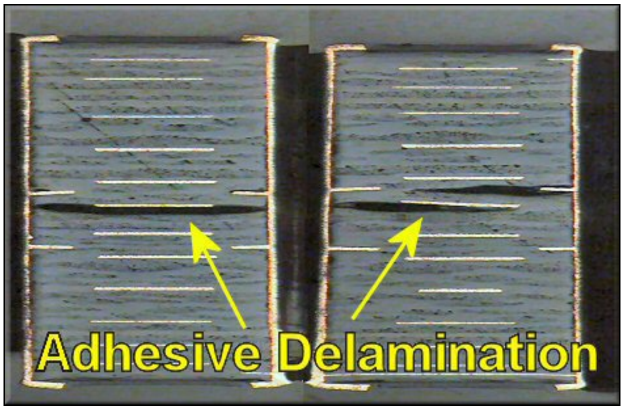


Photo 9. Microsection image of Adhesive Delamination

Cohesive Cracks

Cohesive cracks tend to produce cracks in the epoxy that go through the C-stage, B-stage layers and glass bundles. These cracks tend to go off on any direction and frequently branch, ending with multiple points. What appears to happen during multiple high temperature exposures is the material becomes over cross linked, shrinks, builds up stress and then ultimately cracks.

There are many factors that cause cohesive failure, like problems in lamination or material that is beyond its shelf life. One of the most common causes is lead/free assembly and rework. Assembly temperatures of 260°C are at the limit of what most modern, FR4, materials can withstand. Of the 24 material tested we had 15 that showed various degrees of material damage, cohesive cracking was the most prevalent in this study.

When confronted with cohesive failure one should consider changing the material to one that is more robust in your assembly environment. Also is would be prudent to limit the temperature and the number of thermal excursions that are used for assembly and reduce the need for rework cycles. The goal of the assembly profile is to achieve a reliable solder joint at the lowest temperature possible.

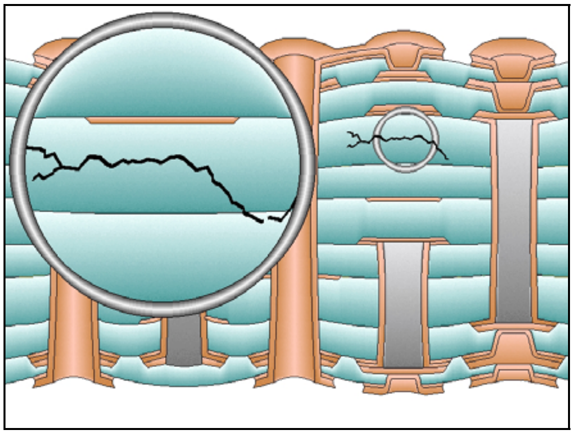


Figure 7. Cohesive Cracking Failure

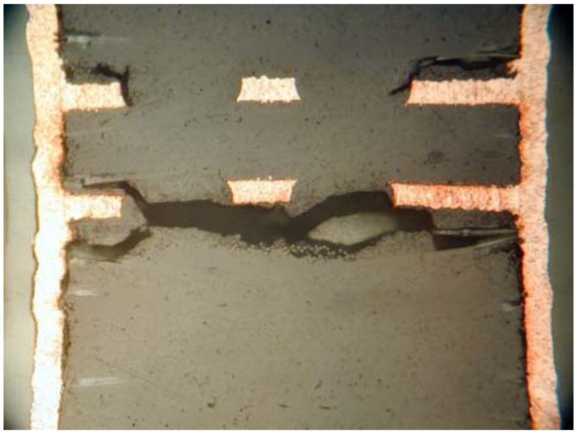


Photo 10. Example of a Gross Cohesive Failure (Material JJ)

Crazing

Crazing is a separation between the individual glass fibers within the glass bundle of the dielectric material. This type of material damage is not visible upon visual examination but it is seen in microsections as a silver separation running down groups of glass fibers. The silver sheen fluorescing from air gaps between the epoxy and the individual glass fibers. This type of material damage is particularly found when the grids size spacing is reduced to 0.6mm (.024”) or less. This type of material damage is a concern in CAF formation.

Crazing is usually associated with copper wicking at the drilled hole side wall (see photo 11). It appears that there is capillary action that aggressively draws water up the separation between the epoxy and the individual glass fibers.

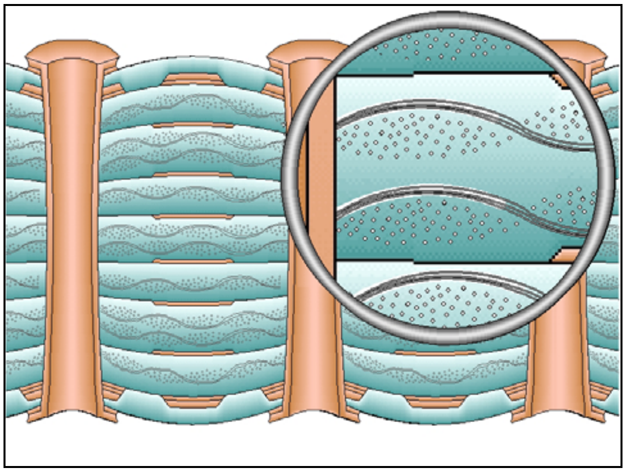


Figure 8. Crazing

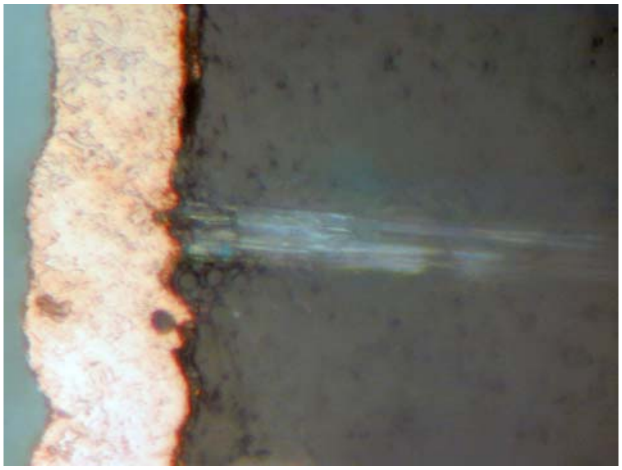


Photo 11. Example of Wicking (Material JJ)

Material Decomposition

Material decomposition is visually obvious in that it produces a blackening of the dielectric material and in extreme cases black balls of carbon on the surface of the PWB usually adjacent to holes. This occurs when one uses low end/cost material in a lead free application. This is a rare type of material damage. None of the materials in our study exhibited Material Decomposition.

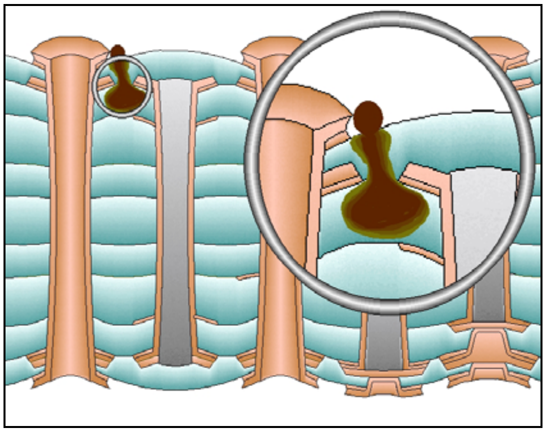
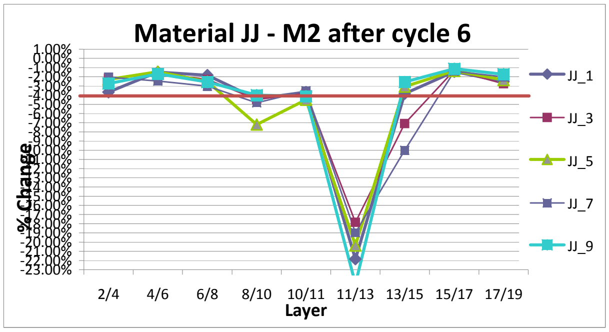


Figure 9. Material Decomposition

Photo 12. Example of Material Decomposition

Results Of DELAM Testing + Microsection Analysis

Graph 3 is a plot of capacitance percent change after 6X260°C preconditioning. Notice that on material "JJ" the majority of coupons measured material damage between layers 11/13.



Graph 3. Plot of Capacitance by Layer for Material JJ

Photo 13 is a view of a number of holes with material damage visible for material "JJ". The type of damage exhibited is most likely cohesive failure.

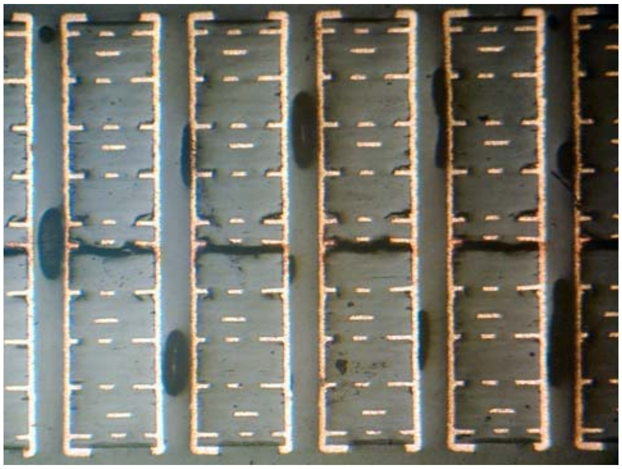


Photo 13. Material "JJ" cohesive failure

Photo 14 is a close up of cohesive failure found in material "JJ" coupon. Note that the material crack is not straight but branches on the left hand side and near the middle.

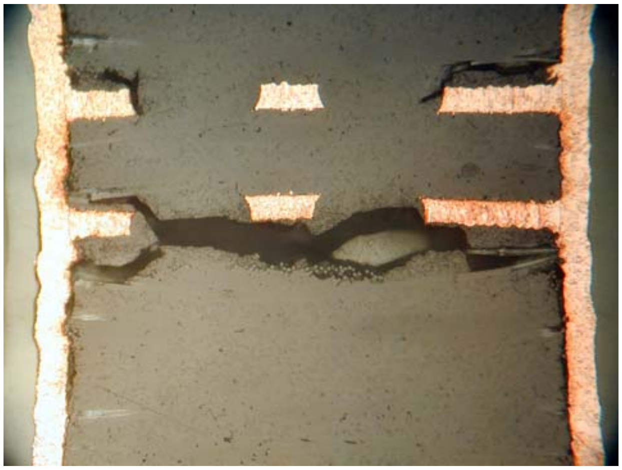


Photo 14. Material "C" cohesive failure

The results of DELAM testing are shown in table 3. Of the 24 materials tested there were 15 that showed material damage by capacitance changes of -4%, which were subsequently confirmed through microsection analysis. The cross sections confirmed the finding in all 24 materials. The type of delamination was predominately cohesive failures.

DELAM Results

Table 3

Coupon #	Damage .032" Grid	Type of Material Damage
A	None	None
AA	None	None
B	None	None
BB	None	None
C	Present	Cohesive Fracture
CC	Present	Cohesive Fracture
D	Present	Cohesive Fracture
DD	Present	Cohesive Fracture
E	None	None
EE	Present	Cohesive Fracture
F	Present	Cohesive Fracture
FF	Present	Cohesive Fracture
G	Present	Cohesive Fracture
GG	Present	Cohesive Fracture
H	None	None
HH	None	None
I	Present	Cohesive Fracture
II	Present	Cohesive Fracture
J	Present	Cohesive Fracture
JJ	Present	Cohesive Fracture
K	Present	Cohesive Fracture
KK	Present	Cohesive Fracture
L	None	None
LL	None	None
Damaged	15 out of 24 Materials	

DELAM vs. CAF Results

Table 4

Material		Damage	CAF		Expectation
Type	% Resin	.032" Grid	As Received	6X260°C	
A	58%	None	Pass	Fail	Not Expected
AA	69%	None	Pass	Fail	Not Expected
B	58%	None	Pass	Fail	Not Expected
BB	69%	None	Excluded	Excluded	N/A
C	58%	Present	Fail	Fail	Expected
CC	69%	Present	Fail	Pass	Not Expected
D	58%	Present	Pass	Pass	Not Expected
DD	69%	Present	Pass	Excluded	Not Expected
E	58%	None	Pass	Fail	Not Expected
EE	69%	Present	Fail	Pass	Not Expected
F	58%	Present	Fail	Excluded	Expected
FF	69%	Present	Fail	Pass	Not Expected
G	58%	Present	Excluded	Pass	Not Expected
GG	69%	Present	Fail	Pass	Not Expected
H	58%	None	Fail	Pass	Not Expected
HH	69%	None	Pass	Pass	Expected
I	58%	Present	Excluded	Fail	Expected
II	69%	Present	N/A	Fail	Expected
J	58%	Present	Fail	Excluded	Expected
JJ	69%	Present	Fail	Excluded	Expected
K	58%	Present	Pass	Fail	Not Expected
KK	69%	Present	Excluded	Fail	Expected
L	58%	None	Pass	Pass	Expected
LL	69%	None	Pass	Excluded	Expected
24		15	9	9	13

Comparing The CAF Results With Coupons Containing Material Damage

Material damage was found in 15 out of the 24 materials tested. A quantity of nine coupons (“as received” and preconditioned 6X260°C) failed the CAF test, but not necessarily from the same material type. There were five coupons that were excluded on the “as received” group and six from the group that had 6X260°C preconditioning, based on the IPC definition for exclusion.

Table 4 demonstrates the three data sets comparing the coupons with material damage with CAF results. Based on this results a determination of expectation was noted for each material type. 13 materials achieved results that were counter intuitive and 13 materials gave expected results.

It is obvious that there is no correlation in those coupons between material damage and CAF results.

CONCLUSIONS:

Based on these results there is no correlation between the presence of material damage and CAF failures during testing. This is a counter intuitive finding. What one would expect is that once there is an opportunity (path) that CAF should form relatively easily. Since we don’t find this to be the case it becomes problematic in understanding what is happening.

Various hypotheses are possible that explain the atypical results. It may be that the size of the material damage, or the type of material damage has a greater affect on CAF growth. It may be that crazing produces a more effective path for the formation of CAF, while adhesive delamination and cohesive failures do not provide an environment for CAF formation. It may be that adhesive delamination and cohesive failure produce cracks that are too large for conductive materials to “fill” the crack, while crazing produces a capillary action that readily moves water into the dielectric.

The uncertainty of root cause is sufficient grounds for further investigation; we are committed to developing the tools and techniques necessary to ultimately answer this question.

Future Work

This is an ongoing experiment that we plan on pursuing in the next round of testing. It is apparent that there needs to for bigger sample sizes on the CAF testing. A minimum sample size of six should give us more effective CAF data.

Another part of the investigation should include influence of different types of material damage. It would be critical to understand the influences of the differences in CAF formation between adhesive delamination, cohesive failures and crazing.

What is also needed are improved methods and equipment that allows us to confirm the presence of CAF in cross sectioning. This most would likely involve the procurement of a scanning electron microscope (SEM).

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