Reliability Testing of PWB Plated through Holes in Air-to-Air Thermal Cycling and Interconnect Stress Testing after Pb-free Reflow Preconditioning

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Abstract
The High Density Packaging Users Group Consortium investigated plated through hole reliability of printed wiring board test vehicles constructed with 20 different Pb-free capable printed wiring board materials. The study contained a total of 27 different constructions built by three PWB manufacturers. The materials were tested using both air-to-air thermal cycling and Interconnect Stress Testing (IST) methodologies. The test vehicles combined both via reliability and materials analysis testing capabilities, using two specially designed IST coupons with via to via spacing of both 0.040" (1mm) and 0.032" (0.8mm), All products were constructed with 20 layers, laminated to an average thickness of 0.115" (2.92mm), and drilled with 0.010" (0.254mm) vias, producing an aspect ratio of 11.5 to 1. Seven of the 20 materials were investigated with two different glass styles and resin contents. The materials were IST tested on the two coupons types, both as built and after 6X Pb-free (260°C) reflow. The air-to-air thermal cycling tested a single configuration after 6X Pb-free reflow only. Materials in the test included eight high Tg, filled FR4 materials, six high Tg halogen-free FR4 materials, and six high speed materials. Correlations between the air-to-air thermal cycling results and IST results are detailed, as are the correlations of these results to independently measured and supplier listed material properties.

Introduction
A previous HDPUG consortium study identified significant challenges in complex multilayer applications with printed wiring board materials ability to survive multiple exposures through Pb-free assembly reflow [1-3]. This behavior was specifically related to the detrimental impact of higher temperatures on plated through hole (via) reliability [4,5] and the onset of material delamination. One of the key influences previously noted was the effect of via to via spacing on the materials ability to survive through Pb-free assembly [1]. Additionally, in one of these earlier studies, difficulties were experienced in correlating IST to air-to-air thermal cycle testing [1], primarily due to fundamental differences in test vehicle design.

The industry has recently released improved materials that better address Pb-free assembly applications and there was much interest in the consortium to evaluate these materials. The Alcatel-Lucent Material reliability test vehicle (MRT-3) used for this study contained multiple upgrades to previous versions. Major design changes to the test vehicle included;

- Adding a specific area for Dynamic Mechanical Analysis (DMA) testing
- Implementing an innovative IST coupon that utilizes capacitance measurements to determine product construction, estimated dielectric spacing, and determines if material damage was caused during assembly
- Consistency in the geometries and layout between the IST and air-to-air thermal cycle test vehicles
- Expanding the focus of the IST and air-to-air thermal cycle designs to address via pitch in more detail
- Adding custom designed IBM style WIC-20 coupons for material analysis investigations and moisture sensitivity testing.

The goals for this testing were to;

- Characterize the performance of a number of recently released Pb-free compatible materials using the MRT-3 test vehicle
    - Focusing on 20 layer constructions only, with some materials produced with both 58% and 69% resin content configurations
    - Identifying materials that are robust through Pb-free assembly reflow at 1mm and 0.8mm pitch via to via spacing
    - Including new High Tg (glass transition temperature) halogen free materials
    - Including mid-level electrical performance and very high speed materials

- Focus on those FR4 and halogen free materials that are expected to be more thermally robust and have better electrical performance characteristics while remaining cost effective materials.
- Evaluate the IST MAT coupon design to determine if the methodology provides an effective non-destructive capability for understanding how to use capacitance measurements to confirm consistency of product construction, dielectric thickness and presence of material damage.
- Determine the effectiveness of the improved IST coupon heating elements distribution used throughout the construction (not just on the traditional outer 3 layers), with the anticipation that this would enhance the ability to achieve a statistical correlation between the IST and the air-to-air thermal cycling methods.
- Understand, using the WIC-20 coupons, the effect of moisture on material survivability through Pb-free assembly.

This paper reports the results of material survivability through Pb-free assembly reflow and the correlation between the IST and air-to-air thermal cycle test methods. Reported separately [6-10] are the Conductive Anodic Filament (CAF) tests, moisture sensitivity testing, stress vs. temperature relationships, electrically quantifying the consistency of product construction, dielectric thickness and material damage through assembly and characterization of the electrical characteristics of each laminate.

MRT-3 Printed Circuit Board Design

The printed circuit board design used for this study is shown in Figures 1 and 2. The two IST coupons are specifically designed material analysis coupons (PWB Interconnect part numbers MAT20006A-32 and MAT20005A-40) having 0.25mm (.010 inch) diameter drilled via holes. One coupon has 1mm (.040 inch) via to via spacing and the other has a 0.8mm (.032 inch) via to via spacing. The air-to-air thermal cycling section has four sets of vias arranged in eight chains of 50 vias each. The first three sets of eight chains of 50 vias have 0.25mm (.010 inch) drilled via holes with via spacing of 2.54mm (.100 inch), 1mm (.040 inch), and 0.8mm (.032 inch) respectively. The fourth set of eight chains uses a 0.66 mm (.026 inch) drilled hole size on a 2.54 mm (.100 inch) via to via spacing. The via chains on 1mm and 0.8mm pitch in both the IST and air-to-air thermal cycling sections are designed identically such that they use the same hole sizes, including the use of non-functional pads, etc. Complete design details are reported separately [11].

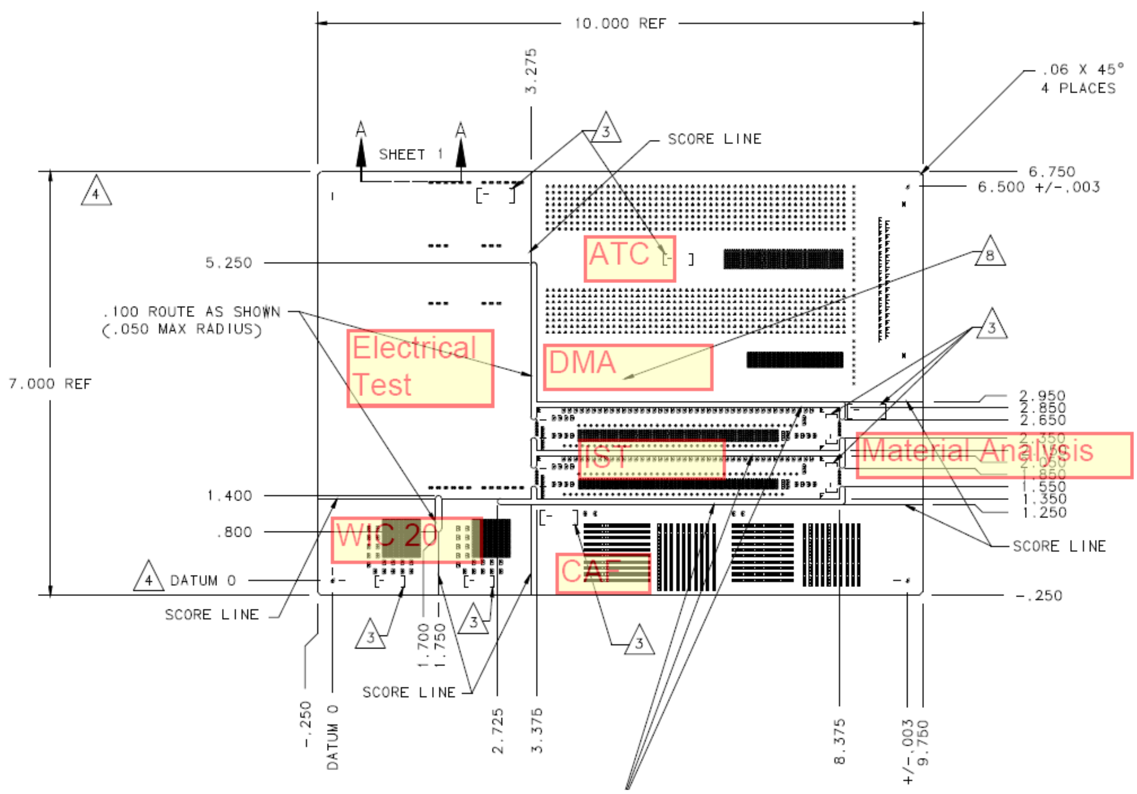

Figure 1: MRT 3 Test Board

The MRT-3 test board was stepped and repeated 4 times (2 by 2) onto a 24” (610mm) x 18” (457mm) production panel, see Figure 2 for production panel lay-out. For this study a minimum quantity of six production panels were produced for each material, resulting in a minimum of 24 boards of each material type. Subsequent testing was carried out on 12 non-stressed (as received) and 12 stressed (6x 260°C Reflow) boards, this effectively results in 12 “coupons” of each type for each test condition. For the purposes of increased statistical confidence a higher number of coupons (18+) is recommended, the lower quantity was determined by considering a compromise between statistical validity and containing the escalating costs associated to all types and levels of testing.

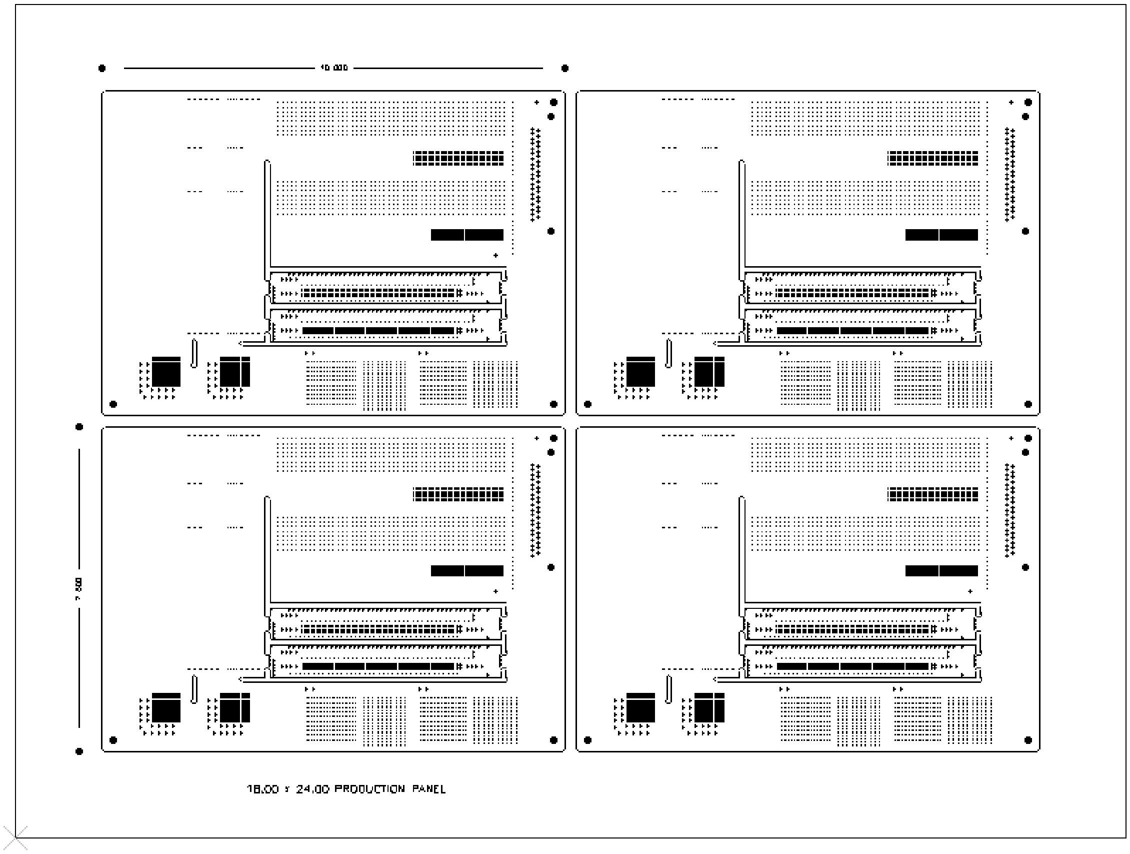

Figure 2: PWB Fabricator Production Panel

Following the production of panels for each of the 27 different material types the production panels were pre-routed and scored to enable easier removal (singulation) of certain coupon types and then profile routed into individual 254mm (10.00 inch) x 178mm (7 inch) test boards. Figure 3 shows a pre-routed and scored individual test board.

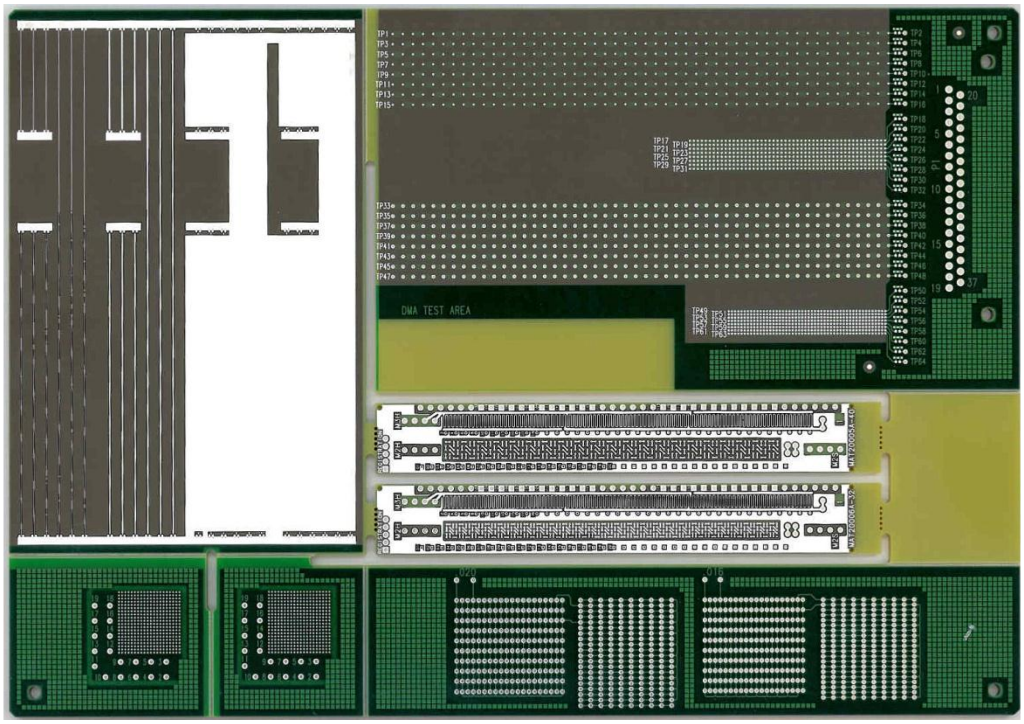

Figure 3: Picture of an actual MRT-3 test board

Material Stack-ups

All material types tested used the same material stack-ups with the same glass styles and resin contents for each given stack-up, regardless of material supplier. This enables the materials to be directly compared to one another. For the 20 layer constructions, both the standard and high resin content constructions are essentially the same in overall thickness, measuring 2.95 mm (0.116 inches) and 3.0mm (0.118 inches) thick respectively. Using similar constructions enables the ability to compare the effect of resin content independently of layer count and board thickness. The standard 20 layer construction was designed with an overall resin content of 58% and is considered typical for a board of this thickness, as shown in Figure 4. The high resin content construction has an overall resin content of 69% and represents very complex and worst case constructions that would typically have higher layer counts (such as 26 or 28 layers) in a similar thickness. This 69% resin content stack-up is detailed in Figure 5.

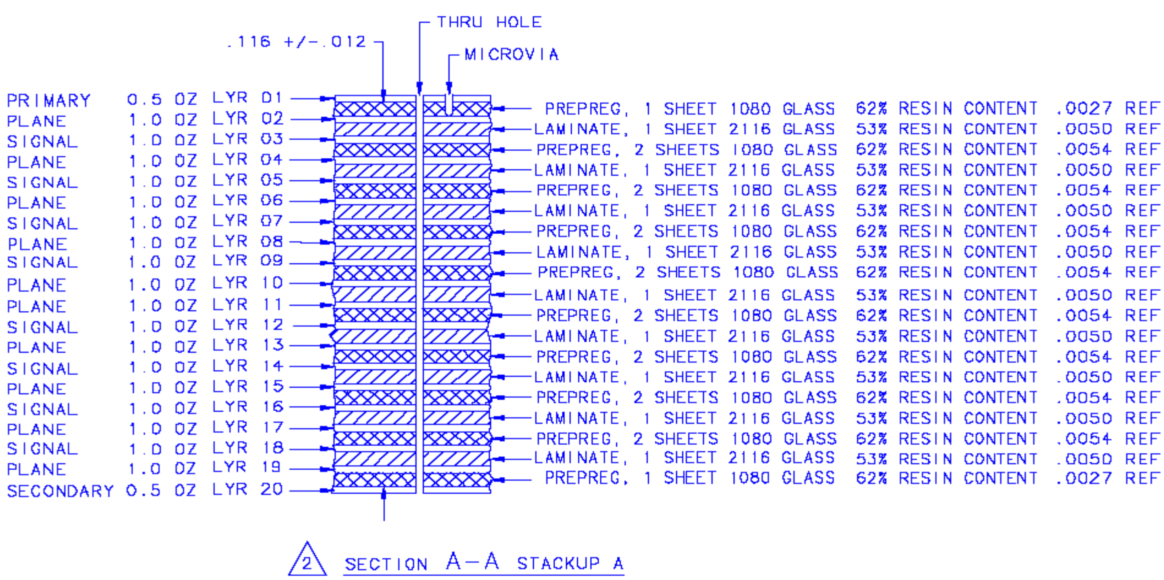

Figure 4: 20 layer standard stack-up, 58% resin content

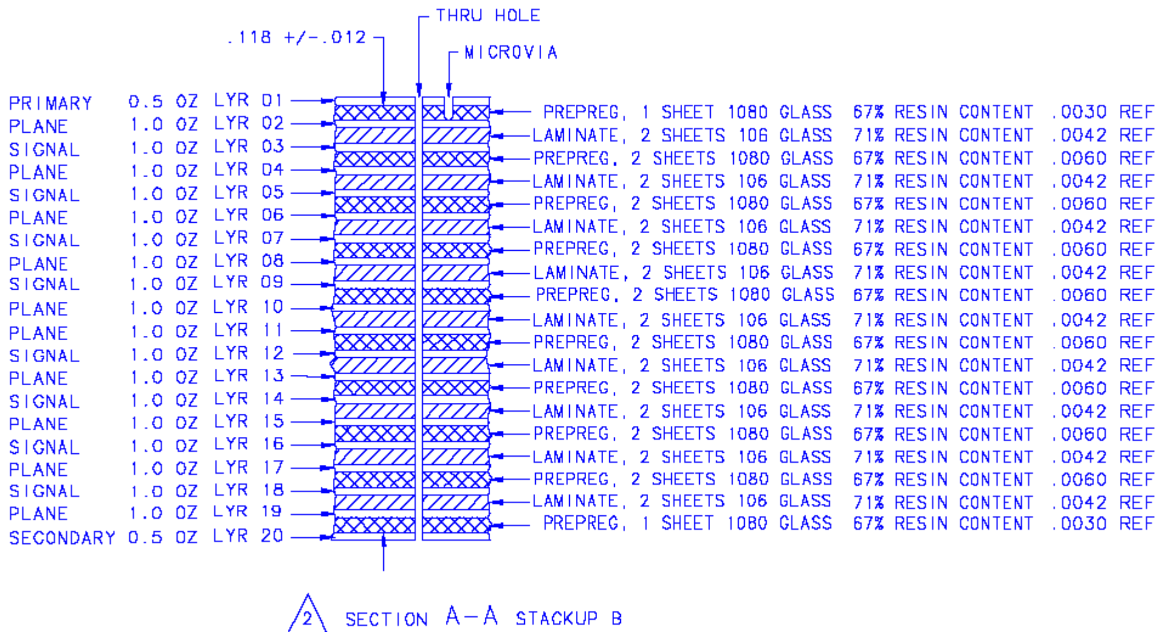

Figure 5: 20 layer high resin content stack-up, 69% resin content

PCB Surface Finish

The PCB finish chosen for this testing was immersion silver. The actual finish used was not critical, provided it remained solderable after 6X reflow at 260ºC and did not include a nickel under-layer, as a nickel underlayer could potentially affect many of the results [4, 12].

Materials

The materials selected for this study were selected from a large group of candidates to keep the total to a manageable number, 27. Initially, FR4 materials were prioritized based on their advertised material properties and pricing. Some lower cost materials with promising properties made the first cut. After this, certain FR4 materials were further eliminated based on electrical performance and consortium team preferences. A range of material thermal properties were considered important to this effort. The halogen free and high speed selections were based on materials recently made available to the electronics industry. The choice of materials was considerably less here, and certain materials were excluded if previous testing had already been completed, or was presently in progress. All materials were fabricated using stackup “A” (Figure 4).

A subset of materials was chosen to be fabricated using a second stack-up “B” (Figure 5). The initial intention was to select the lowest and highest pre-Tg CTE Z in each category, if it was practical. For the phenolic FR4 materials, material F and G was chosen because this material had one of the lower advertised pre-Tg CTE Z (ppm) and the lowest overall CTE Z % from 50-260°C. Material A and B was also chosen since it has the highest post Tg CTE Z (ppm) and the highest overall CTE Z% from 50-260°C in the phenolic FR4 group. In the halogen free FR4 materials, material K and L had the lowest pre-Tg CTE Z (ppm) and material M and N had the highest Pre-Tg CTE plus a lower Tg. For the high speed materials the lowest CTE Z (ppm) pre-Tg was material S and T. For the High CTE pre-Tg, two materials were selected. Material V and W and material Y and Z both have very high pre-Tg CTE Z (ppm), plus the material Y and Z has a very low overall expansion rate of 1.5%. The selected materials could be used to determine whether the pre-Tg CTE Z dominates or influences the reliability results. Table 1 summarized the conditions and configurations associated to each tested material.

Table 1: Materials Evaluated

Coding	Stackup	Resin Content (%)	Description
FR4			
A	A	58	Filled Phenolic FR4
B	B	69	Filled Phenolic FR4
C	A	58	Filled Phenolic FR4
D	A	58	Filled Phenolic FR4
E	A	58	Filled Phenolic FR4
F	A	58	Filled Phenolic FR4
G	B	69	Filled Phenolic FR4
H	A	58	Filled Phenolic FR4
I	A	58	Filled Phenolic FR4
J	A	58	Filled Phenolic FR4
Halogen Free FR4			
K	A	58	Filled Halogen Free FR4
L	B	69	Filled Halogen Free FR4
M	A	58	Filled Halogen Free FR4
N	B	69	Filled Halogen Free FR4
O	A	58	Filled Halogen Free FR4
P	A	58	Filled Halogen Free FR4
Q	A	58	Filled Halogen Free FR4
R	A	58	Filled Halogen Free FR4
High Speed Materials			
S	A	58	High Speed Material
T	B	69	High Speed Material
U	A	58	High Speed Material
V	A	58	High Speed Material
W	B	69	High Speed Material
X	A	58	High Speed Material
Y	A	58	High Speed Material
Z	B	69	High Speed Material
AA	A	58	High Speed Material

PWB Fabrication

PWB fabrication for all 27 material types was coordinated between three different manufacturing sites; Viasystems, Meadville (TTM), and Multek. All facilities are located in China. In all cases, the material suppliers were available on-site to review the critical process steps that ensured that the PWB fabricator met their specific requirements prior to product fabrication. In each case a pilot run was completed prior to the production run to resolve any potential processing issues. All subsequent testing was done only on the material used from the production runs. When possible, all material types produced at a single facility were plated as a single lot, in order to reduce potential variability of the performance critical electrolytic plating operation. This was not always possible, but in all cases efforts were made to minimize any plating variability between material types. Plated through hole wall copper thickness was targeted at 0.025 mm (.001" inch) minimum. Subsequent microsection analysis confirmed that the plating specification was achieved and the copper was evenly distributed through the barrel. Some of the low flow materials had some process related resin voiding in the areas with no or low levels of copper (low pressure areas in the stackup). Where possible these areas were avoided during any subsequent testing.

Board Preconditioning – Simulated Pb-free Assembly

All boards were preconditioned at Celestica's Suzhou China facility. A BTU Pyramax150N 10 zone forced convection oven was used for pre-conditioning.

Preconditioning Profile

The following parameters were used to create the reflow profiles.

Table 2: Target Reflow Profile Parameters

Profile Elements	***10 Zone Convection Oven Recommended***
Ramp Rate to 217°C Peak	Linear Ramp desired. Can have a small soak period. Usually 1 to 5°C/sec. No more than 2°C/sec
Pre-heat Temperature	Usually measured from 150°C to 200°C. Times within this temperature range are usually 60 to 120 seconds
TAL (Time above 217°C Liquidus)	Target 60 to 90 seconds
Time Within 5°C of Max Peak Temp.	10 to 20 seconds ok. Usually will be lower time.
Target Peak Temperature	**260°C Minimum +5°C / -0°C**
Ramp Down Rate	Target from 1.5°C/sec to 2.5°C/sec with normal oven cooling configuration
Reflow Atmosphere	Run all samples in air. (Worst case scenario)
Total Time in Oven	Usually 4 to 6 minutes
Thermocouples Attachment	Require minimum of 3 T/C's to properly profile raw card. (Leading Edge + Centre of Card +Trailing edge) are recommended locations.

One single profile card was generated for both stack-up configurations. A picture of the profile board, with three thermocouple attachment locations is shown in Figure 6 and the resulting profile is shown in Figure 7.

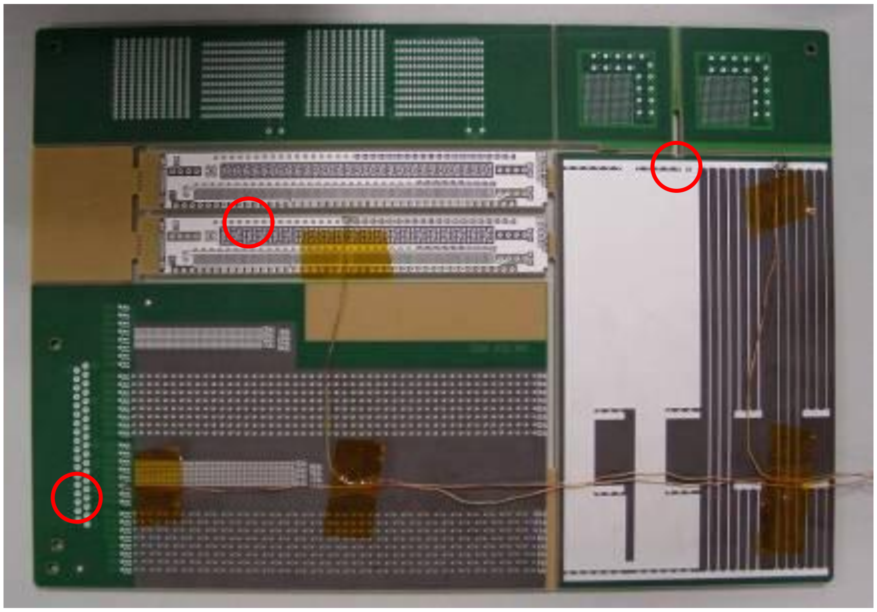

Figure 6: Reflow Oven Profile Board

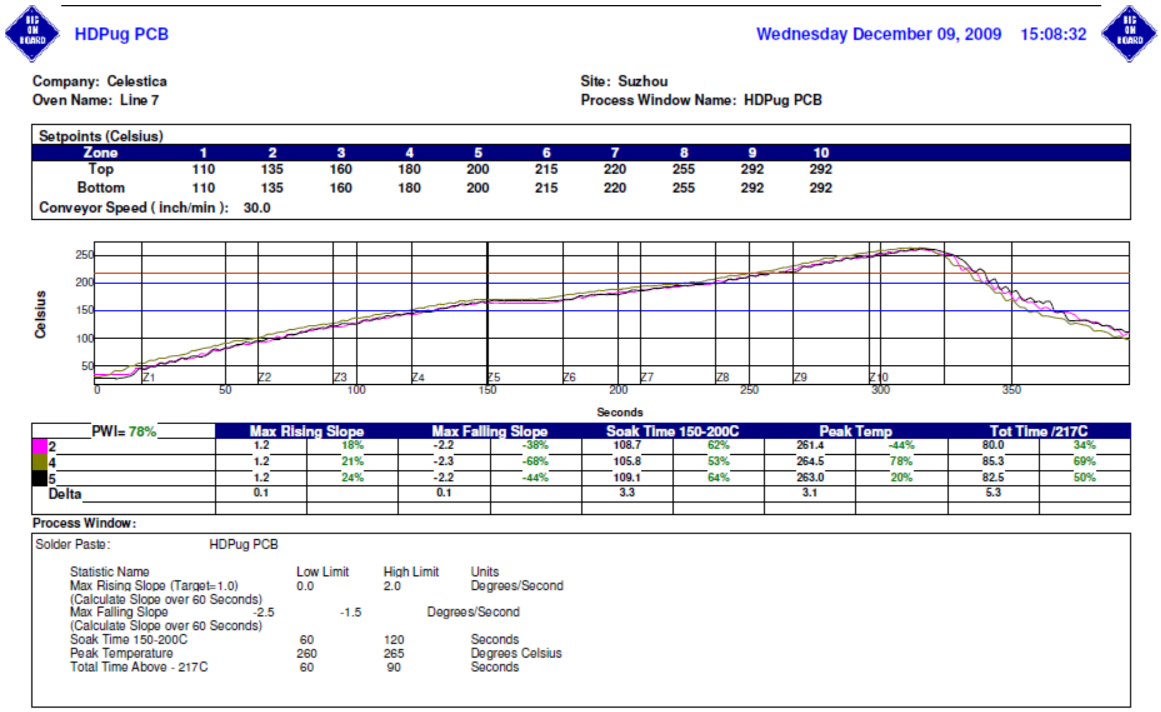

Figure 7: Profile Used for Preconditioning

Pre-conditioning Procedure

Boards were not baked prior to reflow. Panels (a single board including all coupon types as shown in Figure 6) were taken out of the packaging material and pre-conditioned as received. Prior to the start of each pre-conditioning run, the profiles were verified again to validate that nothing had changed between when the profiles were generated and when the actual board pre-conditioning run took place. During the actual runs, the cards were introduced into the oven to guarantee a minimum board spacing of at least two zones. This was required to ensure that there were no thermal interactions between cards. Each card was cooled to room temperature after each reflow cycle, to guarantee that each card experienced the same thermal excursion between profile runs. All "stressed" panels received six cycles of pre-conditioning. Small labels with the numbers "1 to n" were attached near each dash number box on each coupon on the panel. This was done to ensure traceability back to the original panel once all the coupons were broken out of the panel at the end of the pre-conditioning.

A tracking sheet was used to manually track and record all boards through the process.

Prior to start of the preconditioning, a photograph was taken of one panel from each dash number. After all subsequent reflow cycles the panels were inspected for any defects. All defects were recorded in the tracking sheets and photographed noting the defect location, type and run number. After the completion of 6X reflow cycles, one panel from each dash number was photographed for comparison purposes to the incoming board condition.

After each cycle through the reflow oven each panel was visually inspected to determine if surface material delamination was present. On the majority of materials (24 out of 27) no visual delamination was found after six reflow cycles to 260°C. Material V and W exhibited severe signs of visual blistering and delamination during the pre-conditioning; it was subsequently removed from any further testing. Material Y did exhibit low level delamination on one panel, this panel was eliminated. The remaining panels were accepted for further testing. Table 3 lists the materials that exhibited material damage following pre-conditioning.

Table 3: Summary of Results after 6X Reflow Preconditioning – Showing only the Board types with Material Damage

Coding	Stackup A = (58%) B = (69%)	Comments
V	A	Major Delamination even after 1X Reflow
W	B	Major Delamination even after 1X Reflow
Y	A	Minor delamination on 1 board sample after 1X reflow

Laminate Integrity using 6X Thermal Stress (Solder Float) Methodology

Table 3 summarizes the laminate integrity results by material and construction as determined by visual inspection after 6X reflow cycles at 260°C. Table 4 provides an overview of the results of traditional cross-sections completed after both 6X reflow at 260°C and 6X thermal stress at 288°C (IPC-TM-650 Method 2.6.8 Condition A). Entries color coded red confirm a condition (damage) that is rejectable per IPC 6012C (class 3) criteria. The magnitude of the damage was separated into two categories; major ("MAJ") and medium ("MED"). The typical failure mode was material delamination as shown in Figures 8 and 9 for major delamination and Figure 10 for medium delamination. Cross sections that showed "eye-browing" without other major defects present as shown in Figure 10 are specifically highlighted as "EB" in the table. As there is no clear industry agreement as to whether this is a real defect, the decision whether or not to consider this a valid failure mode rests with the product's customer.

The authors of this paper believe that, at least in the specific cross-sections examined, eye-browing is an actual separation of the glass to resin bond and is not caused by the pulling out of a glass fiber during sample preparation. Other damage identified, highlighted as yellow, is significant material degradation that may or may not be rejectable per IPC criteria. Examples of this include medium "cigar" voids as shown in Figure 11 or other zone "A" degradation or damage. Hole wall separation that exceeds 20%, though not an IPC defect, is also highlighted as yellow and specifically noted as "HWS", when no other defects or degradation are noted in the cross sections.

Table 4: Material Damage Summary

Coding	Stackup	Resin Content (%)	Visual Delam after 6X Reflow	Cross-sections after Thermal stressing											
				Internal Material Damage after 6X 260C reflow						Internal Material Damage after 6X 288C thermal shock					
				1mm ATC	0.8mm ATC	1mm IST	0.8mm IST	CAF - 16 mil HW-HW	CAF - 20 mil HW-HW	1mm ATC	0.8mm ATC	1mm IST	0.8mm IST	CAF - 16 mil HW-HW	CAF - 20 mil HW-HW
	FR4:														
A	A	58	No	No	No	No	No	HWS	HWS	No	MAJ	No	No	No	No
B	B	69	No	No	No	No	No	HWS	HWS	No	MAJ	No	No	No	No
C	A	58	No	No	No	No	No	MAJ	No	No	No	No	No	No	No
D	A	58	No	No	No	No	No	HWS	EB	No	No	No	No	No	No
E	A	58	No	No	No	No	No	No	HWS	No	MAJ	No	No	No	No
F	A	58	No	No	No	No	MED	EB	No	No	MAJ	No	No	MAJ	MAJ
G	B	69	No	No	No	No	MAJ	No	No	No	MAJ	No	No	No	No
H	A	58	No	No	No	No	No	No	HWS	No	MAJ	No	No	No	No
I	A	58	No	No	MAJ	No	MED	No	HWS	No	MAJ	No	No	No	No
J	A	58	No	No	MAJ	No	MAJ	MED	No	MAJ	MAJ	MAJ	MAJ	No	No
	Halogen Free FR4:														
K	A	58	No	No	No	No	MED	HWS	HWS	No	MAJ	No	No	HWS	No
L	B	69	No	No	No	No	No	HWS	HWS	No	MAJ	No	No	HWS	No
M	A	58	No	MED	MAJ	MAJ	MAJ	MAJ	MAJ	MED	MAJ	MAJ	MAJ	MAJ	MAJ
N	B	69	No	MED	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ
O	A	58	No	No	MAJ	No	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ
P	A	58	No	No	No	No	No	No	No	No	No	No	No	No	No
Q	A	58	No	No	MAJ	No	MAJ	HWS	HWS	No	MAJ	No	MAJ	HWS	No
R	A	58	No	No	No	No	No	HWS	No	No	No	No	MAJ	No	No
	High Speed Materials:														
S	A	58	No	No	No	No	No	No	No	No	MAJ	No	MAJ	No	No
T	B	69	No	No	No	No	No	No	No	No	No	No	No	No	No
U	A	58	No	EB	MAJ	MAJ	MAJ	EB	EB	MAJ	MAJ	EB	MAJ	EB	EB
V	A	58	Yes	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ
W	B	69	Yes	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ	No	MAJ	MAJ	MAJ	MAJ	MAJ
X	A	58	No	EB	MAJ	No	MED	EB	No	No	MAJ	No	No	HWS	No
Y	A	58	No	EB	EB	EB	MAJ	EB	No	EB	EB	EB	MAJ	EB	EB
Z	B	69	No	No	EB	EB	MAJ	No	No	No	EB	No	MAJ	EB	No
AA	A	58	No	No	No	No	No	No	No	No	No	No	No	MAJ	No
				HWS	Hole Wall Separation > 20% is only defect found (note - <20% not listed)										
				Damage in Zone A only not listed											
				MAJ	Major - Delamination, Cigar voids beyond zone A or Snake Delam										
				MED	Medium damage - May or may not be rejectable (example - medium cigar void)										
				EB	Eyebrow cracks beyond Zone A										

A number of key points are notable in Table 4:

1) Many materials had multiple levels of rejectable internal damage not detectable in surface visual inspection. This issue was identified and previously discussed in detail in reference 1 for a previous series of similar tests. This specific subject will be detailed in the work completed with the IST MAT (material damage) test vehicle, covered in a separate paper [8].
2) The through hole via pitch has a major impact on material survivability in Pb-free assembly with the tighter 0.8mm pitch considerably more susceptible to damage compared to 1mm pitch. This also agrees with the data in references 1 and 8.
3) In the majority of cases, the 6X thermal shock at 288°C test condition was more severe than the 6X reflow cycles at 260°C. Considering the complexity of the product (20 layers, 0.115" thick, 11.5:1 aspect ratio) it is accepted that the six solder float thermal excursions is a very challenging requirement. Despite this situation the 288°C thermal stress methodology is both easy to implement at the PWB fabricator and a valuable tool for looking at first article, or as a production check on an actual design. It is recommended to use both the combination of reflow soldering and solder float testing when material and product qualification is important.
4) Hole wall separation was caused much more often after 6X reflow at 260°C than after 6X thermal shock at 288°C. This is believed to be a function of the longer time at temperature associated with the reflow oven compared to the very short duration of the thermal stress test. The presence of hole wall separation indicates that plastic deformation of copper occurred during the reflow cycles, confirming that the tensile strength of the copper was exceeded. The

resulting shear stress separates the interface between the copper plating and the resin/glass sidewall of the barrel and the resulting separation would potentially affect the levels of strain being applied to the copper barrel. The influence of hole wall separation on product reliability is not fully understood, but a hypothesis is as follows: If structural damage (copper crack initiation) was caused during the 260°C reflow cycles, this could propagate during the subsequent thermal cycling and lead to premature (earlier) cycles to failure. If no structural damage was caused, the copper barrel could experience lower levels of strain (stress relieving) and would perform with extended cycles.

5) Hole wall separation was noted more often in the CAF sections compared to the 1mm and 0.8mm pitch IST and air to air test vehicles. An important consideration is that the non functional lands were removed in many cases from the CAF test vehicles; this could potentially reduce the number of "anchor points" for the attachment between the plated copper and the materials. The CAF sections also have larger drilled hole sizes and have increased volumes of copper compared to the smaller holes in the reliability test vehicles. The stronger barrels would re-distribute more of the stress toward the surface layers and subsequently increase the shear at the sidewall. The added copper could also maintain the material temperatures higher (through thermal conduction) for a longer period of time compared to the small hole size vias.
6) Comparing the results to a similar study conducted two years ago [1], the laminate integrity performance of this set of materials after 6X reflow cycles at 260°C is demonstrating definite improvement, showing that the materials industry is learning and maturing relative to the materials' ability to survive multiple cycles through Pb-free assembly.

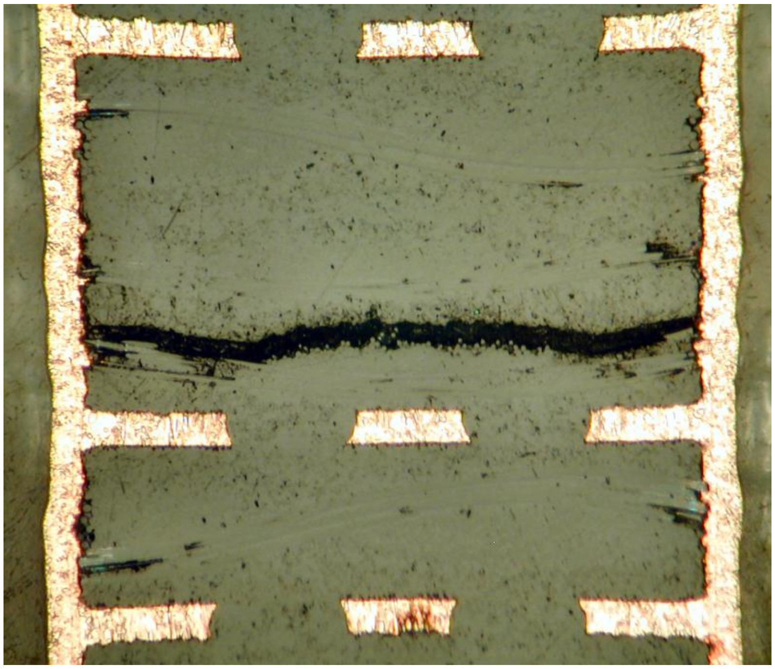

Figure 8: Example internal longtitudinal cohesive delamination

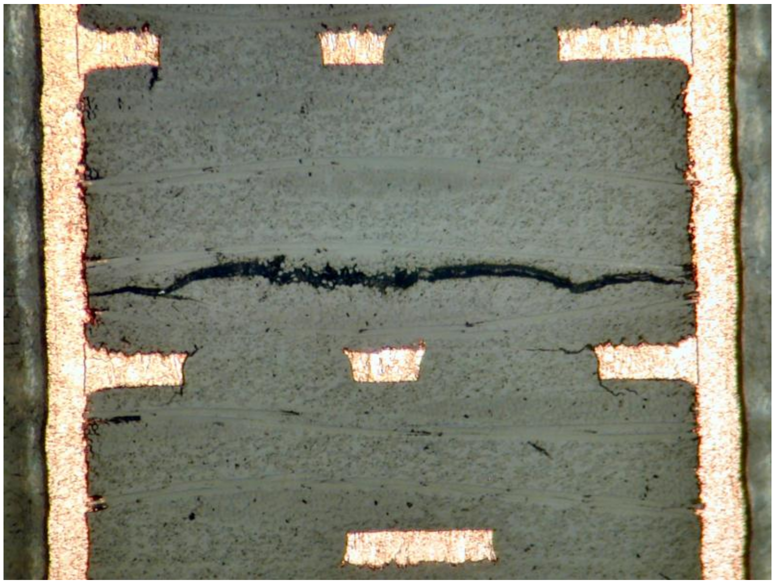

Figure 9: Example Snake Delamination

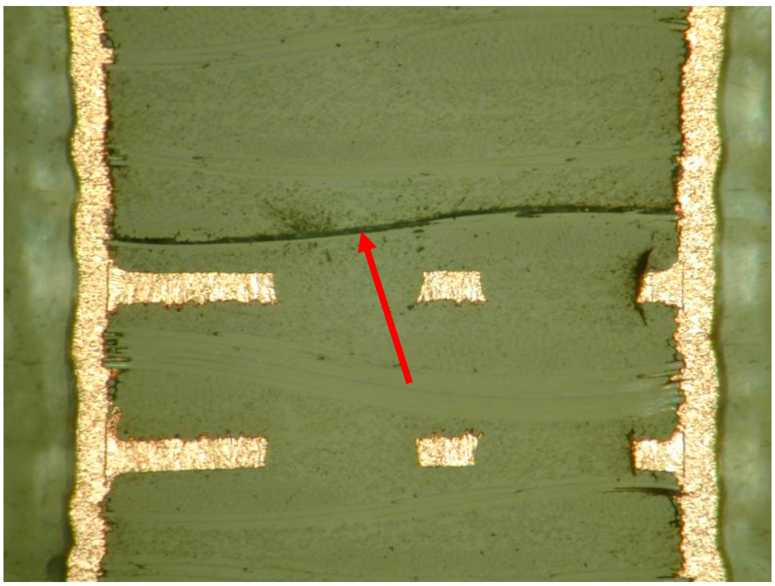

Figure 10: Example of Eyebrowing

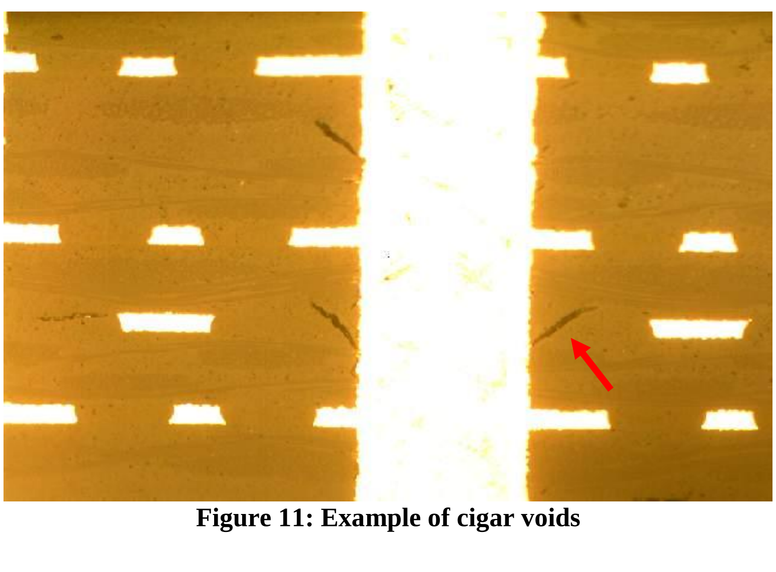

Figure 11: Example of cigar voids

Testing Methodologies and Protocols

After 6X reflow at 260°C, twenty five of the original twenty seven materials were tested in both air-to-air thermal cycling from -40 to +135°C as measured on the boards with 10 minute dwell and ramp times (Figure 12) and IST Testing from ambient (23°C) to 150°C with three minute heating ramps, two minute cooling ramps (Figure 13), and no dwell at either temperature extreme. Testing was initially continued to a maximum of 3000 cycles, and then extended to 6000 cycles on certain materials that proved to be very robust.

Air-to-air Thermal Cycling

For materials that exceeded a 63% failure rate (20 out of the 32 nets) the test vehicles were removed from the thermal cycle chambers after that failure rate was reached. Materials that did not reach the failure criteria were continued to 6000 thermal cycles. In this test, because of the large number of materials, only the 0.25 mm (.010") drilled hole sizes were tested for each material. The goal was to test the 1mm pitch daisy chains on all materials and the 0.8mm pitch daisy chains on selected materials. IST capacitance screening identified a number of materials, Material L, 69% Resin content, both constructions of material V and W, and material X, that were potentially delaminated in the 1mm pitch arrays. For these materials the via chains tested were on 2.5 mm (.100 inch) pitch where delamination is less likely based on previous testing [1]. Differences between 1mm and 2.54 mm (.100 inch) pitch on thermal cycle test results are generally small based on other testing of this coupon design provided that the laminate integrity is good. Material A and B and material Y and Z were chosen to test via chains on both 0.8mm and 1mm pitch.

For the air-to-air thermal cycling a failure was defined as a measured circuit bulk resistance threshold of 11 ohms (virtually open). This was based on previous testing that identified this threshold to give the cleanest Weibull plots on this test circuit [4].

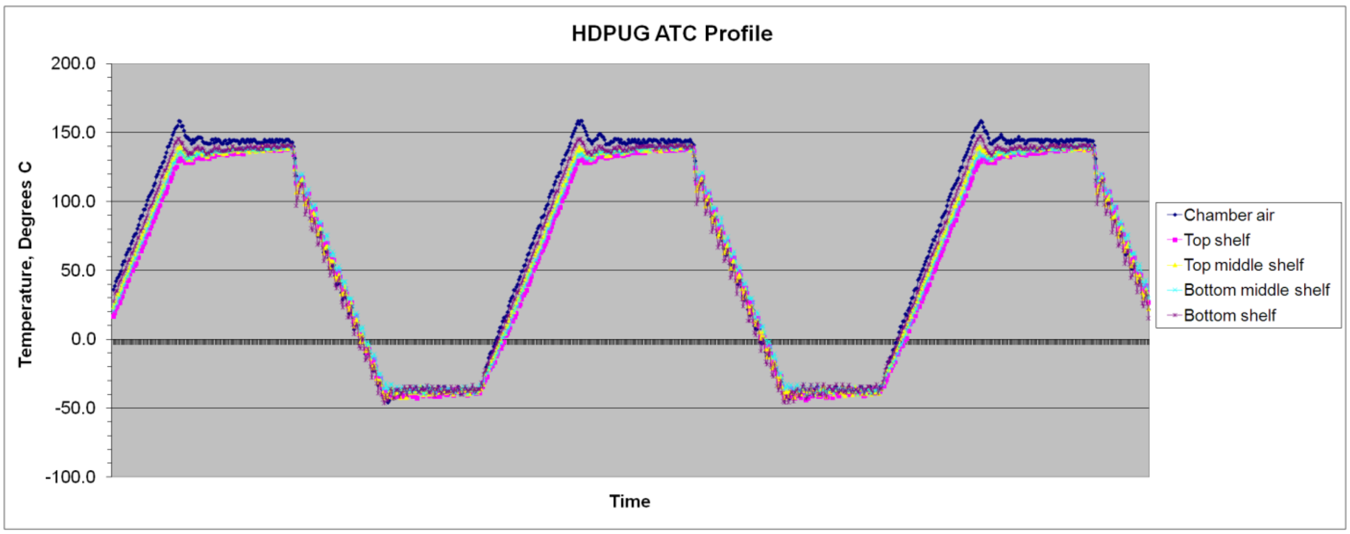

Figure 12: Air-to-Air Thermal Cycle Profile

IST Cycling

The IST coupons were cycled per the IPC-TM-650 Method 2.6.26 using single sense testing, heating from ambient to 150°C in 3 minutes, and cooling back to ambient in 2 minutes. The failure criteria used for IST is that the coupon testing stops at 10% increase in resistance (as per IPC Standards). This capability identifies a further advantage of the IST methodology in the fact that each coupon is individually stopped during testing, permitting precise understanding of the damage accumulation when the product reaches a point of elevated resistance, usually caused by a cylindrical barrel crack. This greatly enhances the ability to determine the root cause during the failure analysis stage because "non-relevant" damage that can commonly confound the ability to understand premature product failures is not present.

All of the materials with the exception of material V and W were tested both as built and after six assembly reflows to 260°C as detailed above. Material V and W was not tested due to obvious gross delamination of the reflowed material. Both the 0.8mm pitch and the 1mm pitch coupons were tested for each material. The test duration used for this testing was initially set to 3000 cycles, or until everything fails, whichever came first. For the purposes of generating data for correlation to air-to-air thermal cycling any material that did not fail at 3000 cycles of specific materials testing was extended to 6000 cycles.

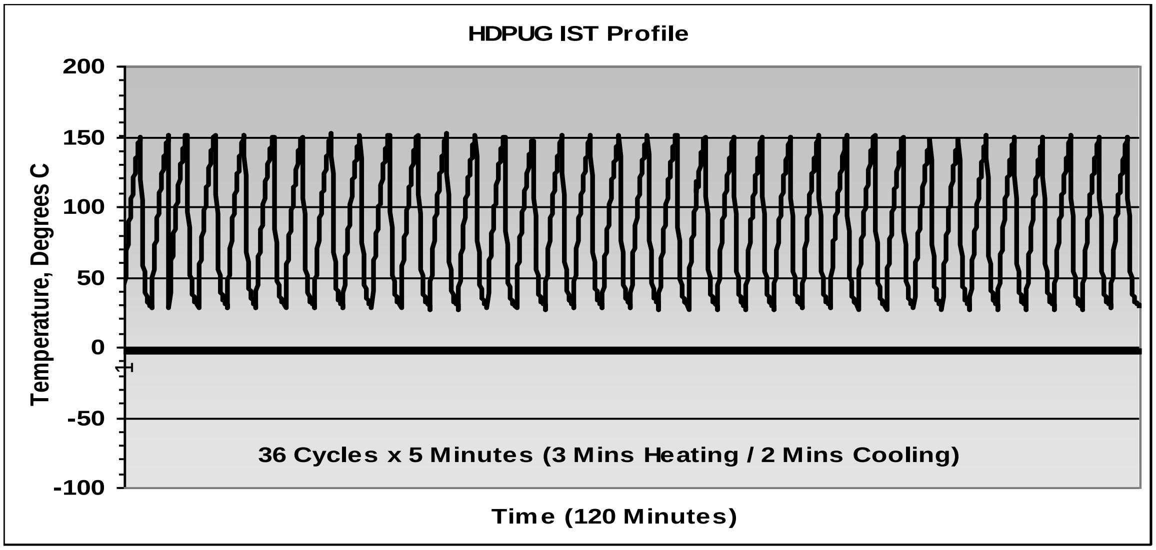

Figure 13: IST Thermal Cycle Profile

One of the major advantages of the IST methodology is the rapid time to results. For this study the effective cycle time ratio is eight IST Cycles to one Air to Air Cycle. Table 5 illustrates the potential time savings relative to the required number of cycles. In today's fast-paced technology changing industry the capability to make rapid, statistically valid decisions on product reliability cannot be emphasized enough.

Table 5: Cycle Time in Days

Cycles	250	500	750	1000	2000	3000	4000	5000	6000
IST	0.9	1.7	2.6	3.5	6.9	10.4	13.9	17.4	20.8
Air to Air	6.9	13.9	20.8	27.8	55.6	83.3	111.1	139	166.7

Results of Air to Air Thermal Cycling (ATC) and Interconnect Stress Testing (IST)

A direct comparison of each material's performance based solely on the ATC and or IST results should consider the following three factors:

1) The boards were fabricated in three different PWB manufacturing locations
2) Though each fabricator made great efforts to plate with exactly the same conditions, different plating runs were required for at least a few materials at the various fabricators.
3) Material damage, as noted above, will impact the results. Delamination can result in either early failures of the plated through holes or may artificially extend the life of the plated through hole due to stress relief associated with the delamination.

Table 6 summarizes the ATC results after 6X reflow at 260°C using Weibull analysis. Note that better statistical fit to this data is log normal rather than Weibull and the failure mode, barrel cracking, is better represented by the log normal distribution. However, Weibull analysis is reported here as it is much easier to compare and understand the spread of the data (Weibull slope or beta) than comparing the log normal distribution statistics (log normal slope shape factor SigF). Key items to note include the following:

1) There is a wide range of performance in the various tested materials, with characteristic life of the failure distributions ranging from as low as 354 thermal cycles to greater than 6000 cycles for four specific materials (five constructions).
2) As expected based on previous work [1], the lower resin content constructions, which also have lower z-axis coefficients of thermal expansion, last considerably longer without failure in thermal cycling compared to the same materials used in the higher resin content constructions. This difference is very significant, ranging from the lower resin content outperforming the higher resin content by a factor of 1.28 times as long, to as much as 4.07 times as long. In a few cases, internal material damage may be affecting these results.
3) The 0.8mm pitch vias out-performed the 1mm pitch vias in thermal cycling. This is consistent with other data on this test coupon. The sample size in this testing is limited to only four constructions tested with both pitches and material damage may be impacting some of the results.

4) The average Beta (slope of the Weibull distribution) is roughly 5.2, but the range of this value is significant, from a low of approximately 2.3 and a high of 11.1. This variation is primarily driven by material characteristics combined with plating characteristics.

Tables 7 and 8 summarize the IST coupon results both as built (no preconditioning) and after 6X reflow cycles at 260°C, using Weibull analysis. In the tables the data highlighted in yellow represent data sets where there were 50% or fewer failures. Due to the small sample size of only six coupons and the limited number of failures, this data cannot be considered statistically significant and hence may be inaccurate.

The data highlighted in orange represents cells where five of six coupons have failed. All others materials were taken to 100% failure completed during IST testing. Key items to note in this data include the following:

1) As with the ATC data, there is a wide range of performance in these failure distributions, with characteristic life as built ranging from as low as 312 cycles to greater than 3000 IST cycles. For the after assembly reflow coupons the characteristic life ranges from as low as 164 to greater than 6000 IST cycles. Some of the after reflow data is affected by material degradation as noted previously.
2) For the IST tests done without reflow preconditioning, in all except two cases, material K and L, and material M and N, the low resin content constructions outperform the high resin content constructions. In general, this is consistent with the ATC results and the difference in coefficient of thermal expansions of the materials. For the exceptions noted, the materials also have a Tg by DMA Storage Modulus below 150°C that affects these results. This is discussed in more detail in the comparison of ATC to IST following.
3) For the IST testing done after reflow preconditioning, in all except two cases, material F and G and material K and L 0.8mm pitch only, the low resin content constructions outperform the high resin content constructions. In general, this is consistent with the ATC results and the differences in the coefficients of thermal expansion of the materials. The exception in the case of the material F and G may be explained by the material damage noted on the IST coupons after reflow preconditioning as indicated by the failure analysis. Material K and L has a Tg by DMA Storage Modulus below 150°C that affects these results. This is discussed in more detail in the comparison of ATC to IST following.
4) The average Beta (slope of the Weibull distribution) is approximately 4.5 for the as built IST coupon results, approximately 4.3 for the 0.8mm pitch IST coupons and 5.1 for the 1mm pitch IST coupons after reflow preconditioning. The range of this value is significant, from a low of approximately 1.7 and a high of 10.7 for the as built coupons, and from a low of approximately 1.7 to a high of 13.3 for the coupons after reflow preconditioning. This variation is driven by material characteristics combined with plating characteristics. The slightly larger range of beta in IST compared to ATC is driven primarily by the smaller sample sizes of IST testing. For materials with significantly lower beta in ATC compared to IST, this is typically a result of how a failure is recorded. IST records a failure as an increase of 10% from the baseline resistance. The ATC data was taken at an 11 ohm failure threshold. In most cases, this is not significant, as the failures at 11 ohms occur only a few cycles after the 10% failure point is reached. However, in cases where the resistance increase is very slow, IST will pick up the failures earlier. A sampling was done on the ATC data using a 5 ohm threshold (roughly a 25% increase in resistance) for a few materials that experienced this slow resistance increase and the Weibull slopes were reduced on these materials.
5) On average, there were only minor differences between the characteristic life of the IST coupons at 0.8mm pitch and 1mm pitch, both as built, and after reflow preconditioning. However, for individual materials, this difference could be significant.

Table 6: Summary of ATC Results

		ATC					
		After 6X Reflow @260C					
		0.100 Inch Pitch		1.0mm Pitch		0.8mm Pitch	
Apex Coding	**Resin Content %**	**Eta**	**Beta**	**Eta**	**Beta**	**Eta**	**Beta**
FR4:							
A	58	NA	NA	1362	5.932	1399	8.09
B	69	NA	NA	578.5	10.55	636.8	11.14
C	58	NA	NA	>6000		NA	NA
D	58	NA	NA	3211	4.794	NA	NA
E	58	NA	NA	1059	6.464	NA	NA
F	58	NA	NA	2566	4.81	NA	NA
G	69	NA	NA	3292	3.698	NA	NA
H	58	NA	NA	1723	4.933	NA	NA
I	58	NA	NA	439.6	5.362	NA	NA
J	58	NA	NA	1677	6.585	NA	NA
Halogen Free FR4:							
K	58	NA	NA	5432	4.264	NA	NA
L	69	1646	5.622	NA	NA	NA	NA
M	58	NA	NA	603	5.617	NA	NA
N	69	NA	NA	354	6.035	NA	NA
O	58	NA	NA	814.2	3.157	NA	NA
P	58	NA	NA	>6000		NA	NA
Q	58	NA	NA	698.6	4.677	NA	NA
R	58	NA	NA	1137	4.978	NA	NA
High Speed Materials:							
S	58	NA	NA	>6000		NA	NA
T	69	NA	NA	>6000		NA	NA
U	58	NA	NA	846.8	5.835	NA	NA
V	58	1787	3.794	NA	NA	NA	NA
W	69	1205	5.868	NA	NA	NA	NA
X	58	439.6	6.295	NA	NA	NA	NA
Y	58	NA	NA	1508	3.319	3485	2.27
Z	69	NA	NA	370.7	2.869	512.7	3.481
AA	58	NA	NA	6515	3.917	NA	NA

Table 7: Summary of IST Results as Built

Apex Coding	Resin Content %	IST As Built			
		0.8mm Pitch		1.0mm Pitch	
		Eta	Beta	Eta	Beta
FR4:					
A	58	>3000		>3000	
B	69	2554	40.04	2452	13.84
C	58	>3000		>3000	
D	58	>3000		>3000	
E	58	2021	2.796	2103	2.774
F	58	>3000		>3000	
G	69	5841	1.085	2391	1.58
H	58	2181	2.654	2548	9.078
I	58	752.2	9.9	781	6.026
Halogen Free FR4:					
J	58	2294	2.151	1971	3.606
K	58	1329	2.687	1613	4.122
L	69	1596	9.28	3858	2.293
M	58	363.6	3.639	338.6	2.853
N	69	331.1	3.337	421	3.974
O	58	600.9	3.017	437.1	2.912
P	58	>3000		>3000	
Q	58	526.4	3.109	408.2	5.32
R	58	1172	3.175	1270	3.403
High Speed Materials:					
S	58	>3000		>3000	
T	69	>3000		>3000	
U	58	624.1	4.504	888.5	3.458
V	58	NA	NA	NA	NA
W	69	NA	NA	NA	NA
X	58	1186	3.737	1337	4.032
Y	58	722.7	4.048	607.3	10.03
Z	69	312.2	10.68	338.5	3.635
AA	58	>3000		>3000	
(yellow)	**Limited fails - significantly less than 50% failure rates**				
(orange)	**Limited data set (5 fails only)**				

Table 8: Summary of IST results after 6X reflow at 260°C

Apex Coding	Resin Content %	IST After 6X Reflow @ 260C			
		0.8mm Pitch		1.0mm Pitch	
		Eta	Beta	Eta	Beta
FR4:					
A	58	1976	2.791	2204	4.577
B	69	1009	6.413	809.5	13.17
C	58	>6000		>6000	
D	58	2718	10.82	3379	9.344
E	58	663.1	3.591	874.9	7.667
F	58	1204	1.729	1431	2.035
G	69	1808	3.96	2566	3.516
H	58	920.8	5.166	1545	10.9
I	58	381.5	4.538	385.4	3.532
Halogen Free FR4:					
J	58	1217	1.949	1348	4.587
K	58	559.1	3.285	1666	5.919
L	69	645	5.753	1407	3.594
M	58	266.3	5.597	270.7	3.585
N	69	254.7	4.097	252.8	3.31
O	58	253.3	2.076	164	2.2
P	58	>6000		>6000	
Q	58	300	4.274	363.3	2.328
R	58	568.1	4.249	816.2	2.899
High Speed Materials:					
S	58	1366	1.868	2237	1.687
T	69	581.6	3.029	1114	2.637
U	58	528.5	2.392	363.1	1.883
V	58	NA	NA	NA	NA
W	69	NA	NA	NA	NA
X	58	483.2	2.888	315.2	3.551
Y	58	666.7	8.887	729.9	6.608
Z	69	275.4	5.91	234.7	13.27
AA	58	7112	4.656	>6000	
	Limited fails - significantly less than 50% failure rates				
	Limited data set (5 fails only)				

Comparison of ATC to IST

Air-to-air thermal cycle results were compared to IST thermal cycle results after the 6X assembly reflow using regression analysis (Figures 14a and b). To ensure that this was a valid comparison, only the 1mm pitch results from each test were compared. Additionally, any materials that were found to have major delamination defects in the cross-sections detailed above in the 1mm ATC and IST sections were excluded from this data, as major defects could produce misleading results.

The data for coupons without failures through 6000 ATC or IST cycles was entered as N50=6000 for this correlation analysis. As noted in the introduction, significant changes were made in the design of the IST coupons to more evenly distribute the heat in these coupons compared to previous similar testing [1] with the expectation that this would allow for a good correlation between these two tests. With the exception of the three outliers circled in Figure 14a, material K at 58% resin content, and material S and T at both resin contents, this goal has been achieved. When these three outliers are removed, the correlation coefficient between ATC and IST is greater than 0.95 as shown in Figure 14b. Even with the outliers removed, there is still a significant amount of scatter in the data around the best fit line. Some scatter is expected due to the smaller sample size of the IST coupons and the resulting variation in the spread of the data, plus normal variability associated with different locations of the boards on the fabrication panels.

The three outliers are unique in that these are three of five materials in this data set with the Tg by DMA storage modulus, at approximately 150°C or lower as measured on the multilayer board after 6X reflow. ATC testing peak temperature is 135°C compared to the 150°C peak temperature of IST. Thus the IST testing for these materials is at or above the Tg. All others have a Tg significantly higher than 150°C. The other two materials in this data set with a Tg by DMA storage modulus of 150°C or lower are also circled in Figure 14a. Though not obviously noted as outliers the materials O and Q had a similar result where ATC significantly outperformed IST by more than a 2:1 ratio. Figure 15 is the regression analysis and plot with all of these materials removed. Since the IST peak temperature is 150°C and is at or above the Tg by DMA storage modulus, this data suggests that for long term reliability testing, the peak temperature of the IST testing should be reduced to below the Tg of the finished multilayer board (10°C reduction in the peak test temperature appears to be an adequate reduction based on the data). Otherwise, the plating reliability will be judged to be much lower than it actually is for typical applications where the operating temperature does not approach the Tg of the material. For applications with high peak operating temperatures, such as some automotive applications, the Tg (DMA Storage Modulus) appears to be a critical material parameter affecting long term plating reliability and higher Tg materials may be required.

In summary, after accounting for the issues noted above associated with the Tg of the material, IST testing using these newly designed IST material analysis coupons with distributed internal heaters, correlates well to ATC testing and can be used for long term reliability estimates.

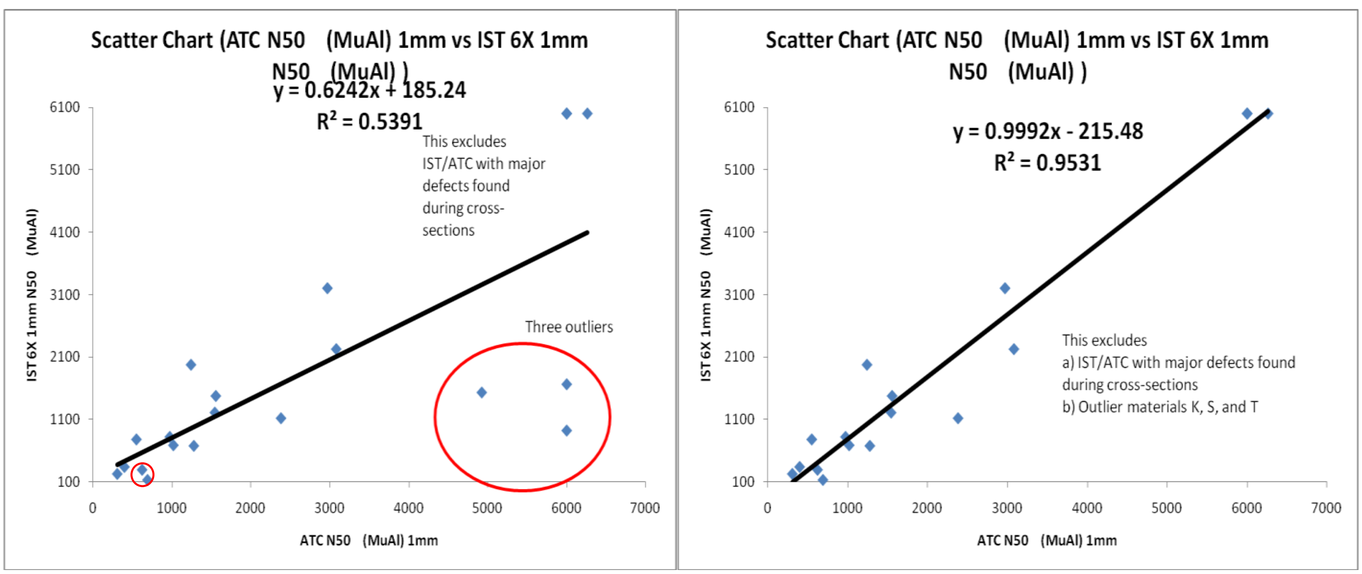

Figure 14a (left) and b (right): IST vs. ATC after 6X reflow. a) includes all data without major laminate defects in the samples b) same data with the 3 outliers removed. This data is from the 50% failure rate (N50, MuAl) as defined by the log normal distribution.

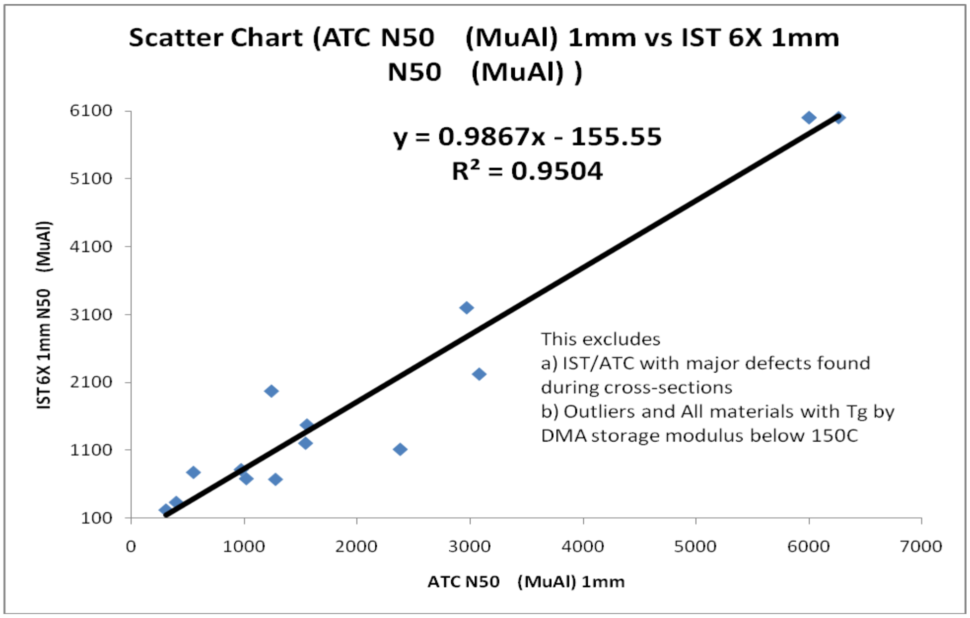

Figure 15: IST vs. ATC after 6X reflow after removing major defects and outliers with Tg by DMA storage modulus below 150°C.

Comparison of ATC to CTE Z

Previous work [1] showed the correlation of ATC performance to the Z-axis coefficient of thermal expansion (CTE) below the glass transition temperature (Tg) as measured on the finished multilayer printed circuit boards (not the bare laminates). In this work, with three different fabricators and multiple plating runs, there are challenges in replicating the correlation due to plating differences among suppliers and plating runs. After eliminating any data from boards with internal laminate damage, there were sufficient boards fabricated at Viasystems for this correlation study. There were two separate plating runs at Viasystems, with a different plating current density in each one (6.1 Amperes/square foot (ASF) for 240 minutes and 8.5 amperes/square foot for 180 minutes). Figure 16a is the plot and regression analysis for the two plating runs combined. For this analysis, the materials with no failures after 6000 cycles were entered as having an N50 failure rate of 6000 which makes the regression somewhat inaccurate. Even with this entry, the correlation coefficient is 0.93. Figure 16b reduces the sample set to the 8.5 ASF plating run only. In this run, there were no materials that did not fail before 6000 cycles. The correlation coefficient is identical to the combined data set, but as expected the equation describing the fit is different as it is not influenced by suspensions. This data confirms the direct relationship of the Z-axis CTE below the Tg ($\alpha 1$) as measured on the finished multilayer printed circuit board and the plated through hole reliability in thermal cycling. Given this information, once a fabricator's plating reliability has been qualified, the effect on thermal cycle reliability of changes to the board materials can be estimated by the resulting change in the Z-axis CTE. This can be extended across multiple designs.

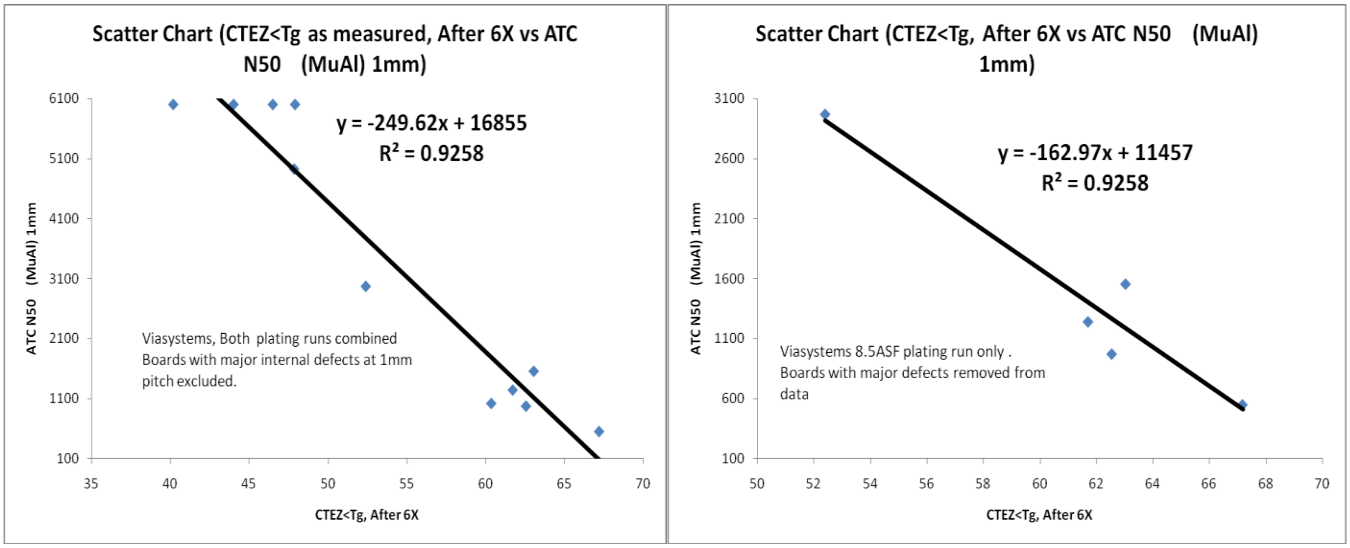

Figure 16 a and b: Comparison of ATC performance to Z-axis CTE as measured on the multilayer board, a) Left, all boards plated at Viasystems b) Right, Single plating run at Viasystems (8 Amperes/square foot current density) only.

Comparison of IST to CTE Z

A regression analysis similar to that done for the ATC case was completed comparing IST results to the Z-axis CTE prior to Tg for the Viasystems boards with the results as shown in Figure 17. The results obtained by combined both plating run results (not shown) had very poor correlation. This was driven by the materials that had a Tg as measured by DMA Storage Modulus at or below 150°C as discussed above in the ATC to IST comparison. When only the 8.5ASF plating run data is used, which did not include any of these materials, the correlation coefficient is 0.86 and the results are very comparable to ATC. This confirms that IST testing using these specially design material analysis IST test coupons in addition to ATC can also be used for plating qualification and the affects of material changes on plating reliability can be assessed by changes in the Z-axis CTE of the finished printed wiring board.

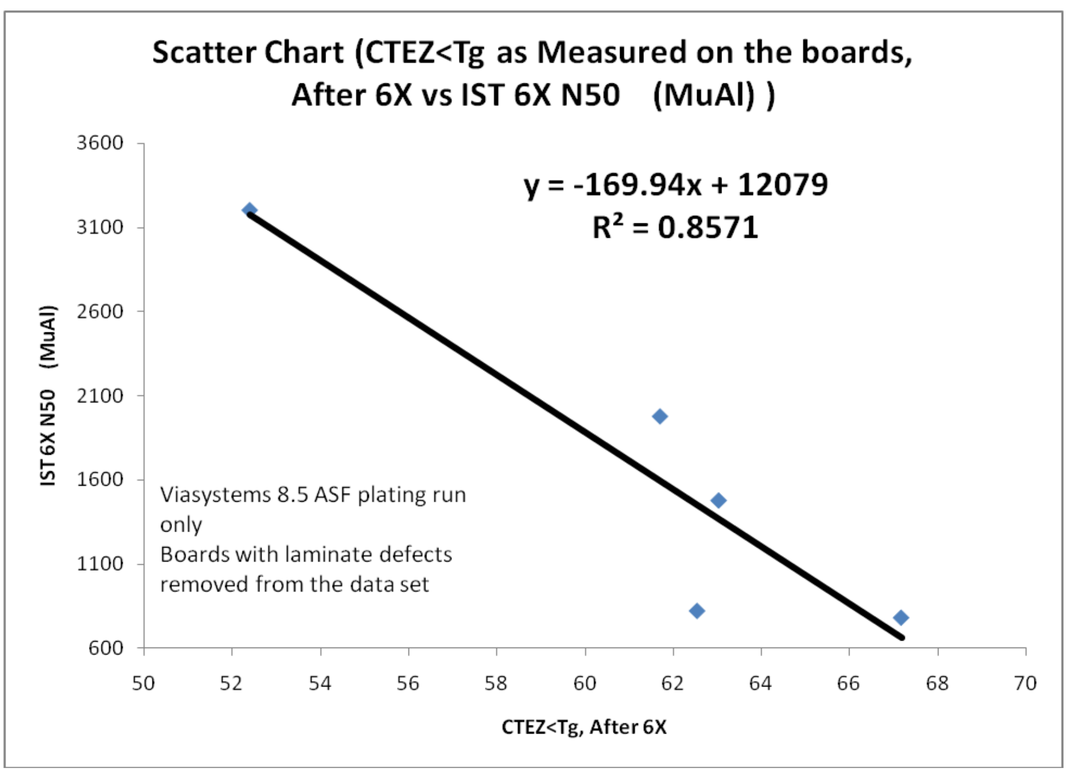

Figure 17: Comparison of IST performance to Z-axis CTE as measured on the multilayer board

Comparison of Supplier CTE Z to Measured CTE Z

Previous work [1] showed a very poor correlation between suppliers advertised CTE Z below the Tg (α1) and measured CTE Z below Tg on actual boards with identical stackups. Because these are multilayer boards, and the supplier data is taken on individual laminates, differences are expected. However, there should be a good correlation between these. Figure 18 is the regression analysis comparing the Z-axis CTE prior to Tg as built and measured by TMA on the 58% resin content boards only (to ensure that this is a valid comparison) to supplier advertised Z-axis CTE Z prior to Tg at 50% resin content. All TMA measurements were done by the same lab at the same location on every board material type to minimize any variations.

As can be seen in Figure 18, the correlation between suppliers advertised data and data on actual boards is nearly non-existent. Also, the supplier data in many cases is quantized to the nearest five parts per million. This is a major flaw in many supplier data sheets. The observed lack of correlation can only be due to suppliers' inconsistent sample selection for this testing or inconsistent measuring techniques confounded by rounding the data to the nearest five parts per million. Another possibility is that some suppliers may overstate the capability of their products for marketing purposes. Considering the importance of this data to the reliability of end user products, industry standards need to be reviewed to ensure that the methods for sample selection (including thickness, glass style and resin content), preparation and measurement are clear, and reporting requirements need to be to the nearest part per million and not rounded.

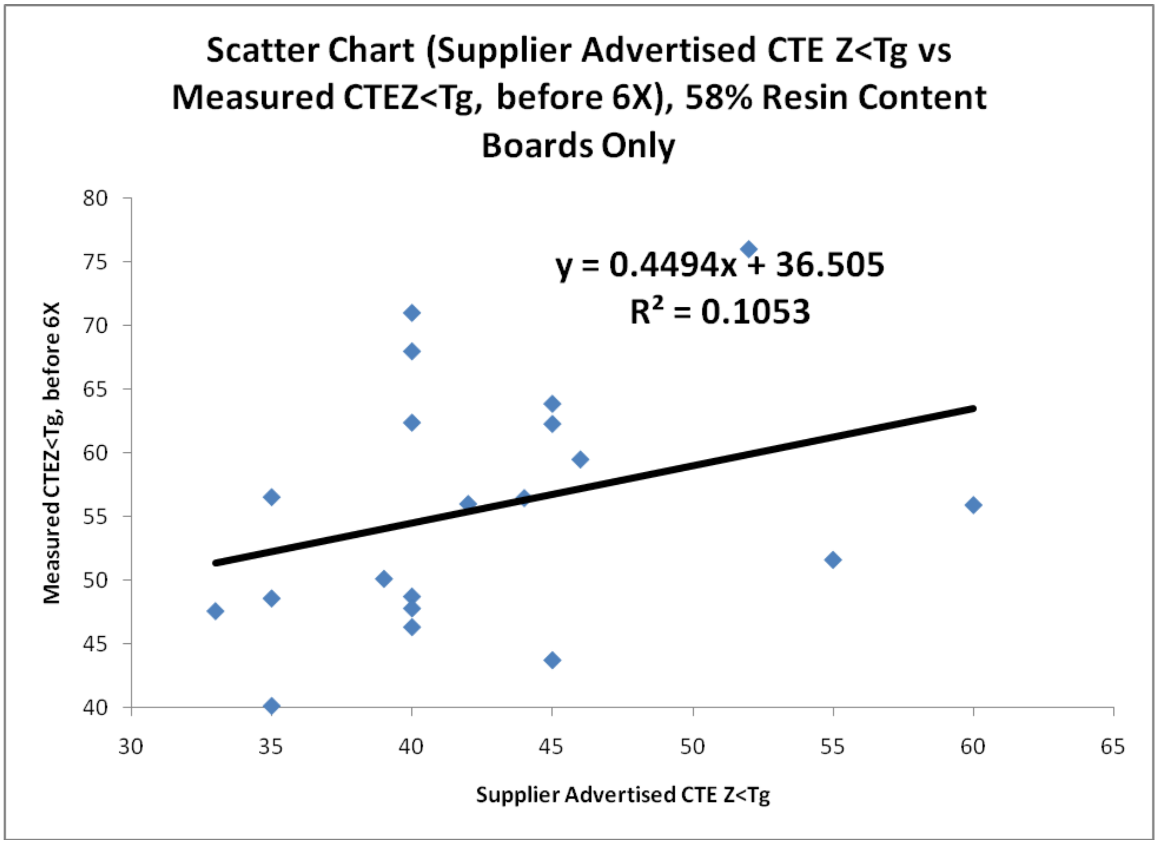

Figure 18: Comparison of Supplier Advertised Z-axis CTE below Tg to Measured Z-Axis CTE below Tg as built on the 58% resin content constructions.

Failure analysis

After completion of ATC and IST, cross-sections were done to determine the failure modes and to help in identification of any anomalous results. All the failures identified were barrel cracks as shown in the example in Figure 19. Also noted in the cross-sections after ATC was that there was a significant increase in eyebrow cracks compared to the after 6X reflow cross-sections as shown in Figure 20.

Figure 19: Typical Fatigue Crack

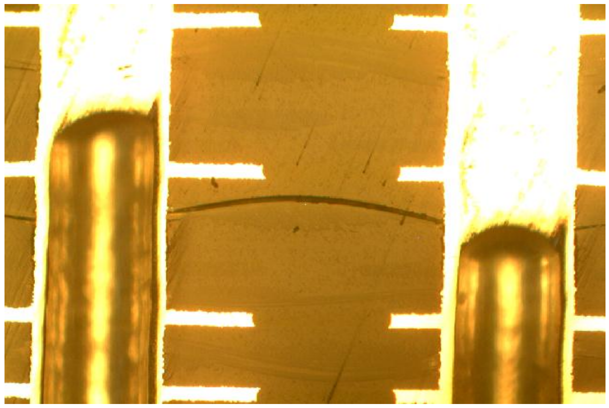

Figure 20: Example Eyebrow Crack

Summary

Material properties alone are insufficient to ensure a high quality and reliable finished printing wiring board. Testing and evaluation of multilayer product is required.

Material suitability in a multilayer printed wiring board for Pb-free assembly reflow cannot be determined by visual inspection alone. Cross-sections of the materials are required at arrays of via holes at various pitches to determine the survivability of these materials.

Through hole via pitches of 0.8mm are more susceptible to internal material damage during Pb-free reflow or other thermal stresses than 1mm or greater via pitch. Because of the closer pitch of the vias at 0.8 mm, the stresses built up during Pb-free assembly resulting from the CTE differences between the copper plated through holes and the laminates, plus any vapor pressure generated during reflow, are less able to be distributed across the material between the vias. In the worst case this results in severe internal delamination of the materials.

When evaluating Pb-free survivability, in the majority of cases, the 6X thermal stress at 288°C test condition was more severe than the 6X reflow cycles at 260°C. The 288°C thermal stress methodology is both easy to implement at the PWB fabricator and a valuable tool for looking at first article, or as a production check on an actual design. It is recommended to use both the combination of reflow cycling and solder float testing when material and product qualification is important.

As a general observation, the laminate integrity of the Pb-free materials after 6X reflow cycles at 260°C was significantly better than a similar study conducted two years ago, showing that the materials industry is learning and maturing relative to materials ability to survive multiple cycles through Pb-free assembly.

In both air to air thermal and IST cycling there is a wide range of performance among various materials. While this is partially a function of plating, Z-axis CTE is a key factor. Materials with lower CTE-Z below Tg ($\alpha 1$) provide the highest plated through hole reliability. Lower resin content constructions, which also have lower z-axis coefficients of thermal expansion, last considerably longer in thermal cycling without failure compared to the same materials used in the higher resin content constructions.

In air-to-air thermal cycling, 0.8mm pitch vias out-perform the 1mm pitch vias.

When the material Tg, specifically as measured by DMA Storage Modulus, is below the testing temperature of both IST and ATC, then IST and ATC correlate very closely and IST can be used to as an alternative to air-to-air thermal cycling for field life predictions. For thick boards, as in this study, the IST design must have heating elements distributed through the material stackup to ensure even heating of the IST coupon and good correlation to the ATC testing. For materials where the Tg as measured by DMA Storage Modulus is below 150°C, the peak temperature in IST should be reduced when using IST to assess the plated through hole reliability for applications where the peak operating temperature is below the Tg. A 10°C reduction appears to be sufficient based on this data. For end user applications where the temperatures equal or exceed the Tg as measured by DMA Storage Modulus, IST or ATC testing should be sure to test to the peak temperature of the end user application.

IST and ATC performance, with proper coupon design and identical plating, both correlate well to the Z-axis CTE below Tg ($\alpha 1$). Given this information, once a fabricator's plating reliability has been qualified, the effect on thermal cycle reliability as measured by either ATC or IST of changes to the board materials can be estimated by the resulting change in the Z-axis CTE. This can be extended across multiple designs.

Supplier advertised data on Z-axis CTE below Tg ($\alpha 1$) does not correlate with measured data on actual multilayer constructions and hence, cannot be considered valid. This can only be due to inconsistent sample selection for this testing or inconsistent measuring techniques confounded by rounding the data to the nearest five parts per million. Considering the importance of this data to the end user reliability, industry standards need to be reviewed to ensure that the methods for sample selection (including thickness, glass style and resin content), preparation and measurement are clear, and reporting requirements need to be to the nearest part per million and not rounded.

Acknowledgements
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[7] Freda, M., Shi, J., Lopez, L., "Use of Lead-Free Laminate DMA and TMA Data to Develop Stress versus Temperature Relationships for Predicting Plated Hole Reliability", IPC/APEX, Las Vegas NV, 2011
[8] Birch, B., Furlong, J. "Electrically Quantifying Material Damage Through Assembly and Validating PWB Product Construction", IPC/APEX, Las Vegas NV, 2011
[9] HDPUG Consortium Internal Data
[10] Morton, K, Smetana, J., Qin G., "The Effects of Reflow on Conductive Anodic Filament (CAF) Performance of Materials", IPC/APEX, Las Vegas NV, 2011
[11] Smetana, J., Birch, B., Rothschild, W., "A Standard Multilayer Printed Wiring Board for Material Reliability Evaluations", IPC/APEX, Las Vegas NV, 2011.
[12] K.T. Knadle and M.G. Ferrill, Failure of Thick Board Plated Through Vias with Multiple Assembly Cycles, The Hidden BGA Threat, Proceedings of Surface Mount International Conference, April 1997, pp. 109-115.

Reliability Testing of PWB Plated Through Holes in Air-to-Air Thermal Cycling and Interconnect Stress Testing after Pb-free Reflow Preconditioning

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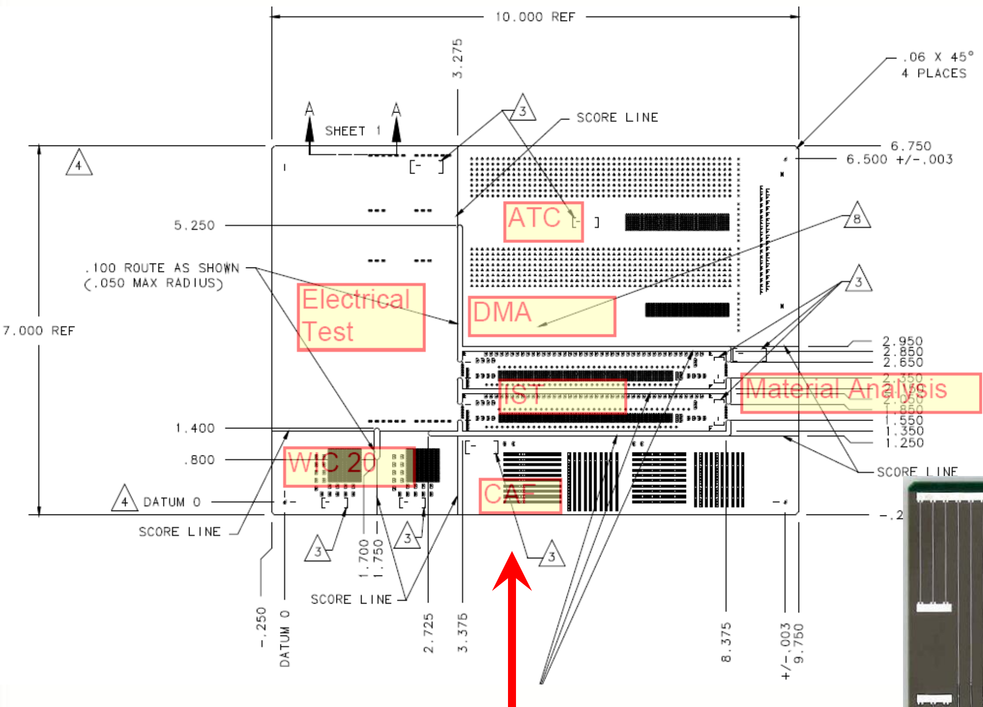
Introduction

- Follow-on project to prior HDPUG Pb-free materials project reported at APEX 2009
- Primary Goal: Characterize the performance of a number of newer Pb-free compatible materials using the MRT-3 test vehicle (an update from the MRT-1 test vehicle used in phase 1)
  - 20 layer constructions only
    - 58 and 69% Resin constructions
    - Better understand the effect of resin content/z-axis expansion on reflow survivability
  - Hopefully identify materials that survive 6X@260C reflow
    - At 1mm pitch in high resin content construction
    - At 0.8mm pitch in either construction
  - Include Hi-Tg Halogen Free Materials
  - Include newer high speed Materials
  - Focus on thermally robust FR4's and better electrical performing materials
    - Cost effective materials
  - New IST coupon designs
    - Will heat more evenly (heating elements are distributed throughout the layers, and not just on the outer 3 layers – also they are not dependent on the PTH copper).
      - Enable correlation of ATC to IST? (Not achieved in phase 1).
    - New DELAM Test methods (reported separately)
  - Understand moisture effect on material survivability through Pb-free reflow. (reported separately)
  - CAF Evaluations (reported separately)
  - Electrical performance and effect of Pb-free reflow (reported separately)

This paper focuses on material survivability through Pb-free assembly reflow and the Air-to-Air and IST thermal cycle performance.

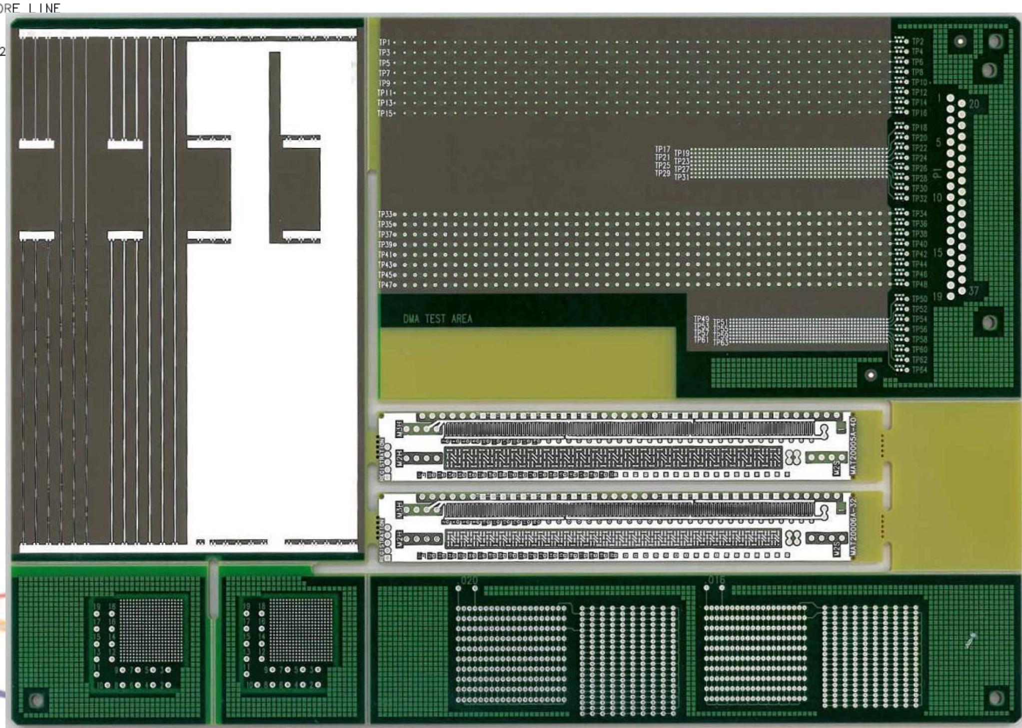
Test Vehicle Design



Complete Details of the test vehicle are reported separately

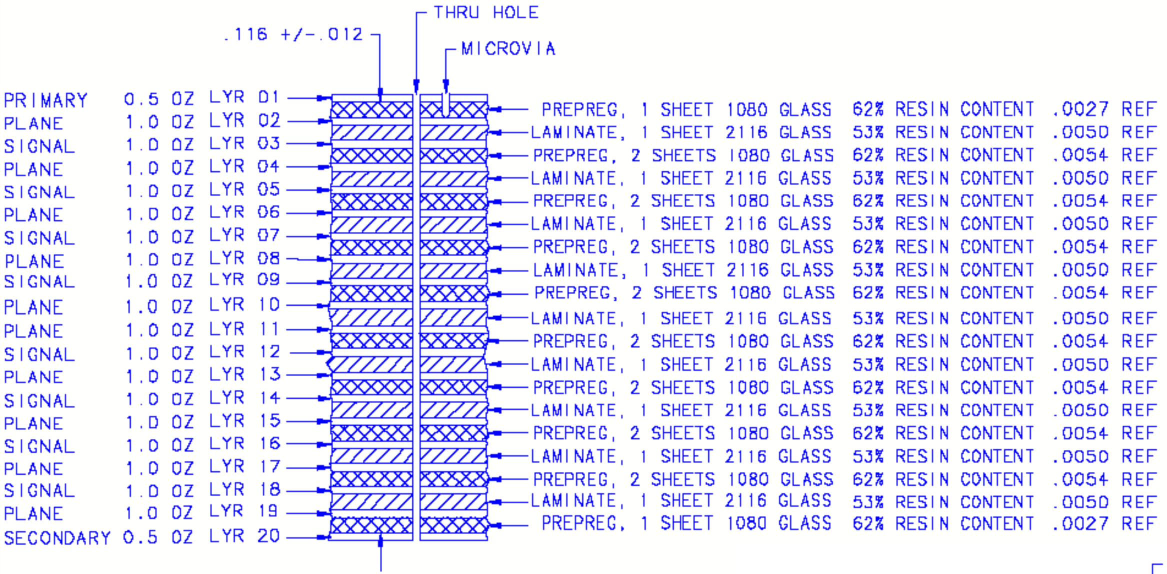
Test vehicle below-

7 sections on new Test Vehicle



Material Stackups

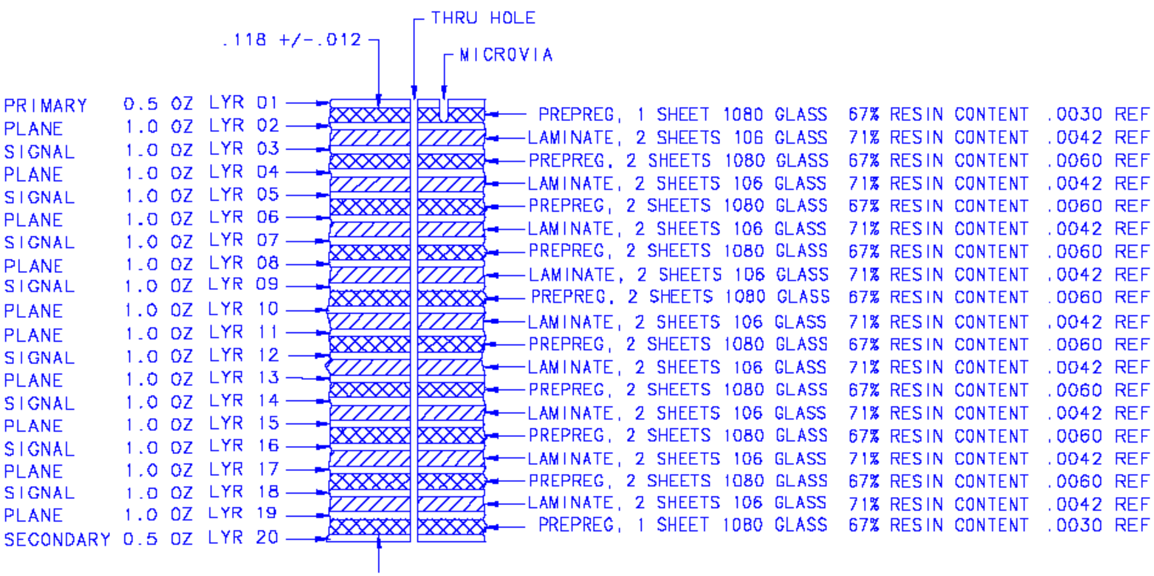
Fully detailed stackups. Same for every material type to ensure we have valid comparisons



2 SECTION A–A STACKUP A

Stackup A: 20L, 58% RC, .116” thick

Stackup B: 20L, 69% RC, .118” thick (represents Higher Layer count in same thickness)



2 SECTION A–A STACKUP B

20 Materials, 27 Constructions

Coding	Stackup	Resin Content (%)	Description
Hi Tg Phenolic FR4			
A	A	58	Filled Phenolic FR4
B	B	69	Filled Phenolic FR4
C	A	58	Filled Phenolic FR4
D	A	58	Filled Phenolic FR4
E	A	58	Filled Phenolic FR4
F	A	58	Filled Phenolic FR4
G	B	69	Filled Phenolic FR4
H	A	58	Filled Phenolic FR4
I	A	58	Filled Phenolic FR4
J	A	58	Filled Phenolic FR4
High Tg Halogen Free FR4			
K	A	58	Filled Halogen Free FR4
L	B	69	Filled Halogen Free FR4
M	A	58	Filled Halogen Free FR4
N	B	69	Filled Halogen Free FR4
O	A	58	Filled Halogen Free FR4
P	A	58	Filled Halogen Free FR4
Q	A	58	Filled Halogen Free FR4
R	A	58	Filled Halogen Free FR4
High Speed Materials			
S	A	58	High Speed Material
T	B	69	High Speed Material
U	A	58	High Speed Material
V	A	58	High Speed Material
W	B	69	High Speed Material
X	A	58	High Speed Material
Y	A	58	High Speed Material
Z	B	69	High Speed Material
AA	A	58	High Speed Material

7 of the 20 materials (highlighted in grey) were tested in both constructions/ resin contents

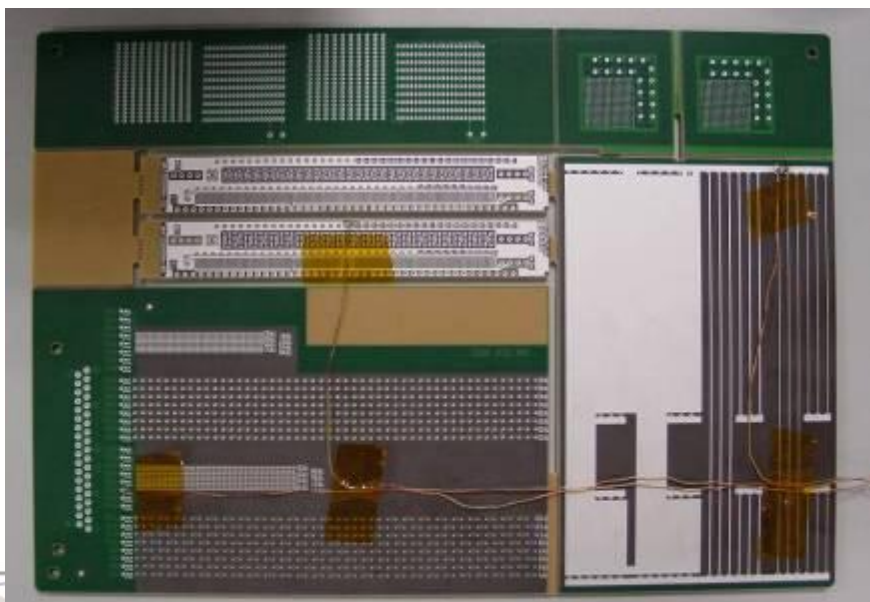
Board Fabrication

- Coordinated between 3 manufacturing locations:
  - Viasystems China
  - Meadville (TTM) China
  - Multek China
- In all cases, material suppliers on-site to review the critical process steps prior to fabrication
- Pilot run was completed prior to the production run
  - Resolve any potential processing issues
  - Testing was done only on the production runs
- Plated in a single run when possible
  - Cu thickness target 1 mil minimum

Board "Assembly" (Pb-free reflow – 6X)

Profile Elements	*10 Zone Convection Oven Recommended*
Ramp Rate to 217° C Peak	Linear Ramp desired. Can have a small soak period. Usually 1 to 5° C/sec. No more than 2° C/sec
Pre-heat Temperature	Usually measured from 150° C to 200° C. Times within this temperature range are usually 60 to 120 seconds
TAL (Time above 217° C Liquidus)	Target 60 to 90 seconds
Time Within 5° C of Max Peak Temp.	10 to 20 seconds ok. Usually will be lower time.
Target Peak Temperature	**260° C Minimum +5° C / -0° C**
Ramp Down Rate	Target from 1.5° C/sec to 2.5° C/sec with normal oven cooling configuration
Reflow Atmosphere	Run all samples in air. (Worst case scenario)
Total Time in Oven	Usually 4 to 6 minutes
Thermocouples Attachment	Require minimum of 3 T/C's to properly profile raw card. (Leading Edge + Centre of Card +Trailing edge) are recommended locations.

Reflow at Celestica Suzhou China



Peak Temps achieved: 261-264ºC

HDPug PCB — Wednesday December 09, 2009 15:08:32

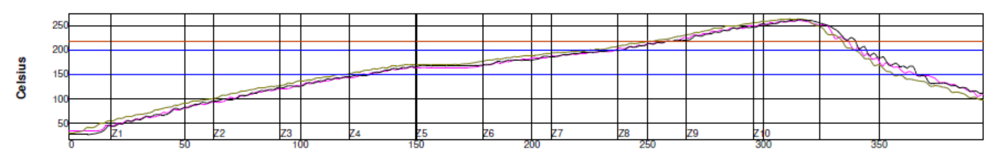
Company: Celestica
Oven Name: Line 7

Site: Suzhou
Process Window Name: HDPug PCB

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



PWI= 78%	Max Rising Slope		Max Falling Slope		Soak Time 150-200C		Peak Temp		Tot Time /217C	
2	1.2	18%	-2.2	-38%	108.7	62%	261.4	-44%	80.0	34%
4	1.2	21%	-2.3	-68%	105.8	53%	264.5	78%	85.3	69%
5	1.2	24%	-2.2	-44%	109.1	64%	263.0	20%	82.5	50%
Delta	0.1		0.1		3.3		3.1		5.3	

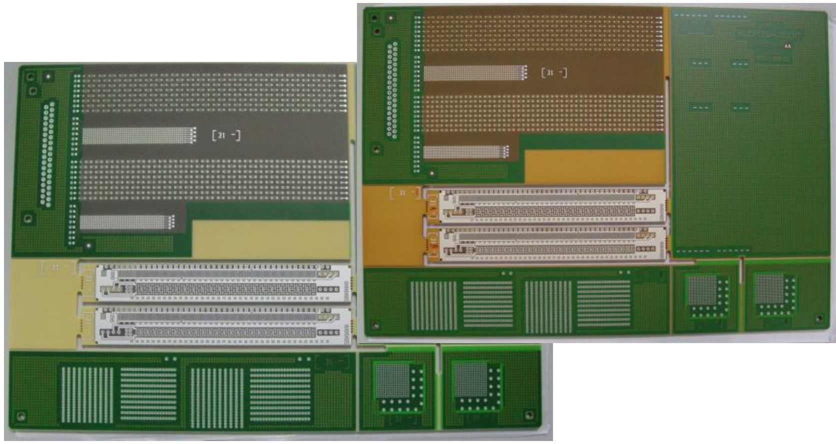
Process Window:

Solder Paste: HDPug PCB

Statistic Name	Low Limit	High Limit	Units
Max Rising Slope (Target=1.0) (Calculate Slope over 60 Seconds)	0.0	2.0	Degrees/Second
Max Falling Slope (Calculate Slope over 60 Seconds)	-2.5	-1.5	Degrees/Second
Soak Time 150-200C	60	120	Seconds
Peak Temperature	260	265	Degrees Celsius
Total Time Above - 217C	60	90	Seconds

Reflow

- Reflow completed 6X@260ºC
  - Note we intentionally did NOT bake the boards prior to reflow to reflect how we will really use boards in real life.
    - The WIC20 Moisture testing is reported separately
  - Visual Inspections at a minimum after 3 and 6X reflow
  - Before and after photos to show visible changes
  - Capacitance Measurements were made on the IST coupons prior to reflow, and after 6X reflows.
    - PWB Interconnect completed all the capacitance measurements using the as built coupons to baseline the data prior to reflow.



Color changes (oxidation) typical after reflow

Visible Damage after Reflow

Coding	Stackup A = (58%) B = (69%)	Comments
V	A	Major Delamination even after 1X Reflow
W	B	Major Delamination even after 1X Reflow
Y	A	Minor delamination on 1 board sample after 1X reflow

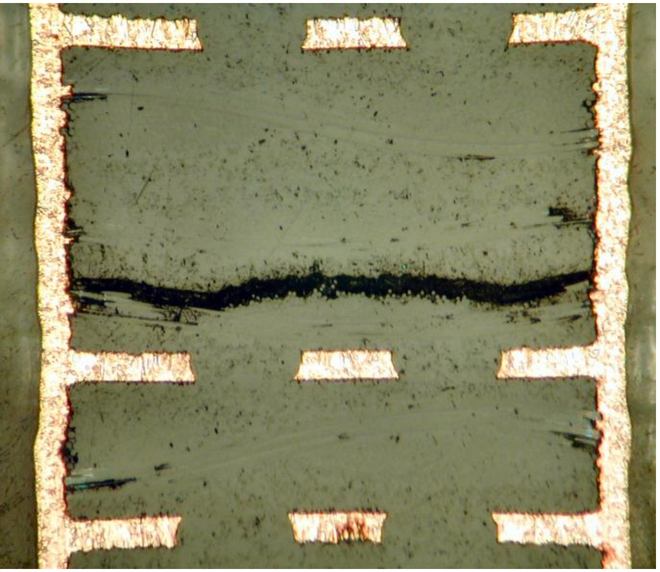
Internal Material Damage – 2 Conditions, Compared to Visual

				Cross-sections after Thermal stressing											
				Internal Material Damage after 6X 260C reflow						Internal Material Damage after 6X 288C thermal shock					
Coding	Stackup	Resin Content (%)	Visual Delam after 6X Reflow	1mm ATC	0.8mm ATC	1mm IST	0.8mm IST	CAF - 16 mil HW-HW	CAF - 20 mil HW-HW	1mm ATC	0.8mm ATC	1mm IST	0.8mm IST	CAF - 16 mil HW-HW	CAF - 20 mil HW-HW
	FR4:														
A	A	58	No	No	No	No	No	HWS	HWS	No	MAJ	No	No	No	No
B	B	69	No	No	No	No	No	HWS	HWS	No	MAJ	No	No	No	No
C	A	58	No	No	No	No	No	MAJ	No	No	No	No	No	No	No
D	A	58	No	No	No	No	No	HWS	EB	No	No	No	No	No	No
E	A	58	No	No	No	No	No	No	HWS	No	MAJ	No	No	No	No
F	A	58	No	No	No	No	MED	EB	No	No	MAJ	No	No	MAJ	MAJ
G	B	69	No	No	No	No	MAJ	No	No	No	MAJ	No	No	No	No
H	A	58	No	No	No	No	No	No	HWS	No	MAJ	No	No	No	No
I	A	58	No	No	MAJ	No	MED	No	HWS	No	MAJ	No	No	No	No
J	A	58	No	No	MAJ	No	MAJ	MED	No	MAJ	MAJ	MAJ	MAJ	No	No
	Halogen Free FR4:														
K	A	58	No	No	No	No	MED	HWS	HWS	No	MAJ	No	No	HWS	No
L	B	69	No	No	No	No	No	HWS	HWS	No	MAJ	No	No	HWS	No
M	A	58	No	MED	MAJ	MAJ	MAJ	MAJ	MAJ	MED	MAJ	MAJ	MAJ	MAJ	MAJ
N	B	69	No	MED	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ
O	A	58	No	No	MAJ	No	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ
P	A	58	No	No	No	No	No	No	No	No	No	No	No	No	No
Q	A	58	No	No	MAJ	No	MAJ	HWS	HWS	No	MAJ	No	MAJ	HWS	No
R	A	58	No	No	No	No	No	HWS	No	No	No	No	MAJ	No	No
	High Speed Materials:														
S	A	58	No	No	No	No	No	No	No	No	MAJ	No	MAJ	No	No
T	B	69	No	No	No	No	No	No	No	No	No	No	No	No	No
U	A	58	No	EB	MAJ	MAJ	MAJ	EB	EB	MAJ	MAJ	EB	MAJ	EB	EB
V	A	58	Yes	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ
W	B	69	Yes	MAJ	MAJ	MAJ	MAJ	MAJ	MAJ	No	MAJ	MAJ	MAJ	MAJ	MAJ
X	A	58	No	EB	MAJ	No	MED	EB	No	No	MAJ	No	No	HWS	No
Y	A	58	No	EB	EB	EB	MAJ	EB	No	EB	EB	EB	MAJ	EB	EB
Z	B	69	No	No	EB	EB	MAJ	No	No	No	EB	No	MAJ	EB	No
AA	A	58	No	No	No	No	No	No	No	No	No	No	No	MAJ	No
				HWS	Hole Wall Separation > 20% is only defect found (note - <20% not listed)										
				Damage in Zone A only not listed											
				MAJ	Major - Delamination, Cigar voids beyond zone A or Snake Delam										
				MED	Medium damage - May or may not be rejectable (example - medium cigar void)										
				EB	Eyebrow cracks beyond Zone A										

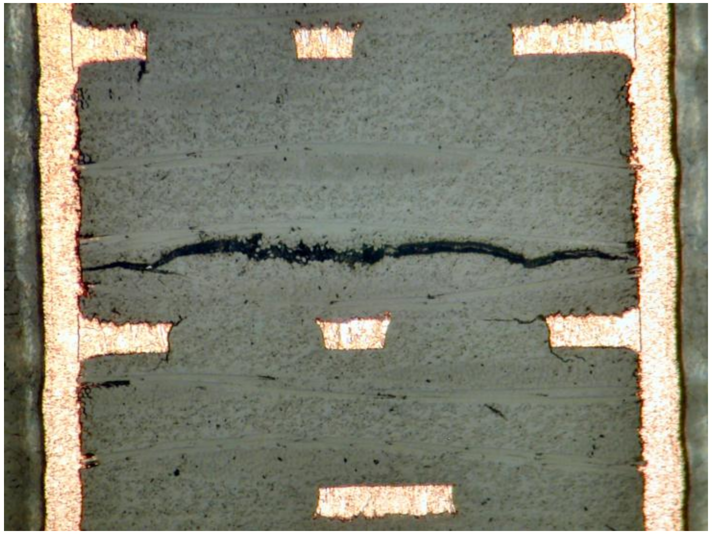
The 6X 260ºC samples are the same boards taken through Assembly reflow.

The 6X 288C thermal stress solder floats are from identical boards as received

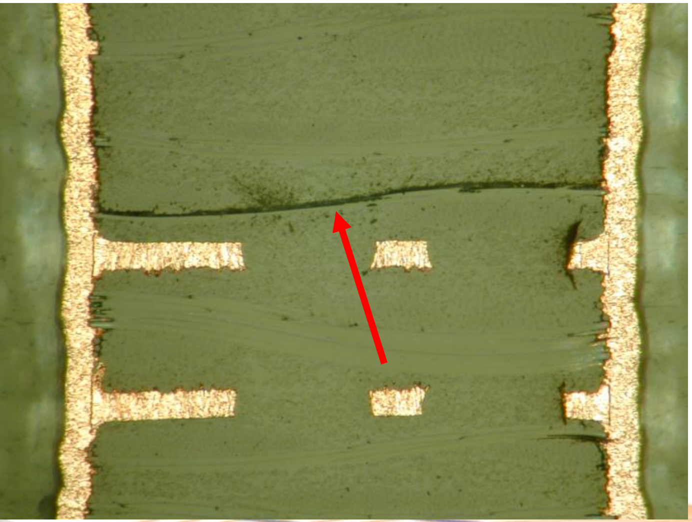
Defect Examples



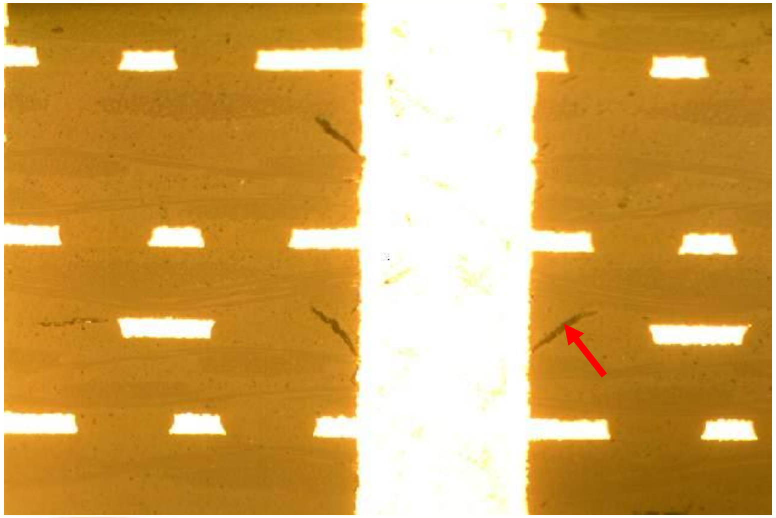
Longitudinal cohesive delamination



Snake Delamination (Partially in resin, partially along glass)



Eyebrowing (separation along glass)



Cigar voids

Key Observations (1)

- Many materials had multiple levels of rejectable internal damage not detectable in surface visual inspection.
- Through hole via pitch has a major impact on material survivability
  - 0.8mm pitch considerably more susceptible to damage than 1mm pitch.
- In the majority of cases, the 6X thermal shock at 288° C test condition was more severe than the 6X reflow cycles at 260° C.
  - Complex product (20 layers, 0.115" thick, 11.5:1 aspect ratio) → 6X@288ºC very challenging
  - But 288° C thermal stress methodology is both easy to implement at the PWB fabricator and a valuable tool for looking at first article, or as a production check on an actual design.
  - **Both** reflow and 288ºC thermal stress recommended when doing material and product qualification

Key Observations (2)

- Hole wall separation was caused much more often after 6X reflow at 260°C than after 6X thermal shock at 288°C.
  - Believed a function of the longer time at temperature associated with the reflow oven compared to the very short duration of the thermal stress test.
    - Indicates that plastic deformation of copper occurred in reflow → tensile strength of the copper was exceeded. The resulting shear stress separates the interface between the copper plating and the resin/glass sidewall of the barrel and the resulting separation would potentially affect the levels of strain being applied to the copper barrel.
    - Influence of hole wall separation on product reliability is not fully understood → could improve or reduce thermal cycling performance.
      - Could either be crack initiating or stress relieving

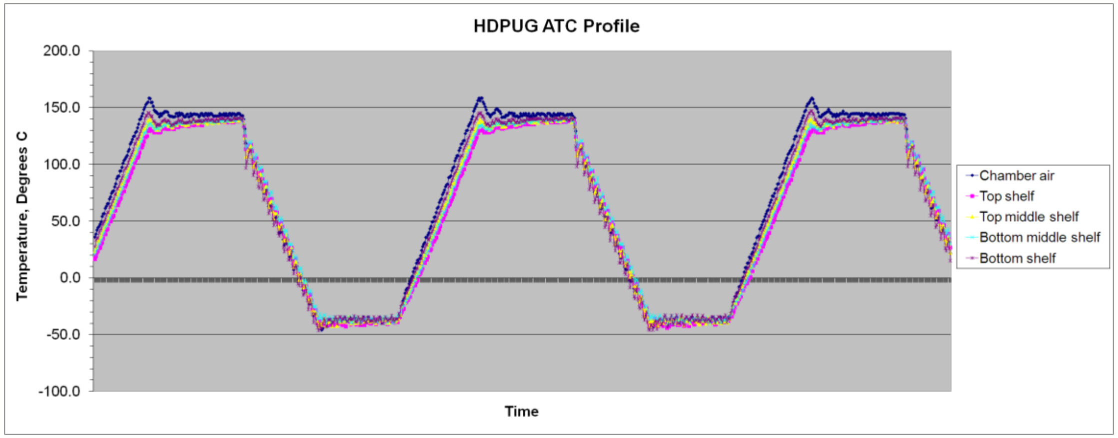
Key Observations (3)

- Hole wall separation was noted more often in the CAF sections compared to the 1mm and 0.8mm pitch IST and air to air test vehicles.
  - Non functional lands were removed in many cases from the CAF test vehicles; this could potentially reduce the number of “anchor points” for the attachment between the plated copper and the materials.
  - The CAF sections also have larger drilled hole sizes and have increased volumes of copper compared to the smaller holes in the reliability test vehicles.
    - The stronger barrels would re-distribute more of the stress toward the surface layers and subsequently increase the shear at the sidewall.
    - The added copper could also maintain the material temperatures higher (through thermal conduction) for a longer period of time compared to the small hole size vias.
- Comparing the results similar study reported in 2009 the laminate integrity performance of this set of materials after 6X reflow cycles at 260° C is demonstrating definite improvement
  - Materials industry is learning and maturing relative to the materials’ ability to survive multiple cycles through Pb-free assembly.

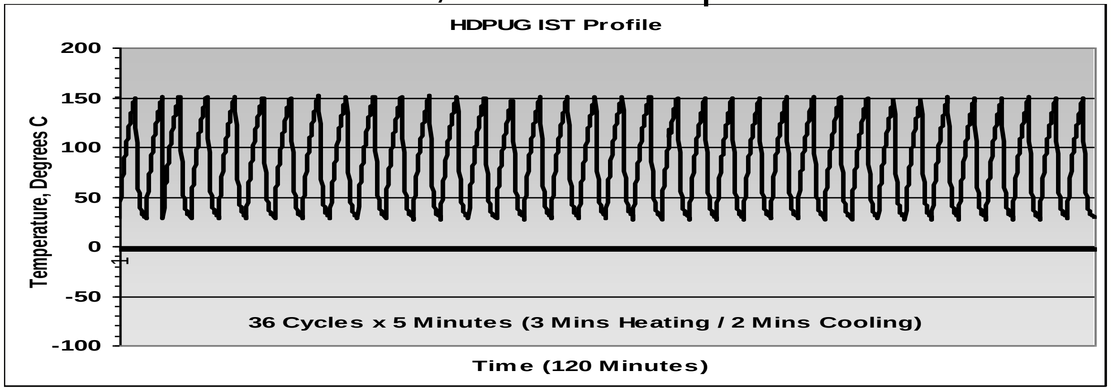
Air-to-Air (ATC) and IST Thermal Cycling

- ATC: -40 to +135ºC, 10 min dwell and ramp
  - After 6X reflow only,
  - 10 mil drill, 1mm pitch focus, 0.100” pitch in a few cases. 0.8 mm pitch for selected materials.
  - Sample size 32 chains of 50 vias (4bds) per material
  - Used 11 ohms as the failure criteria
  - Stopped after 63% failure or 6000 cycles
- IST: 25 to 150ºC, 3 min heating, 2 min cooling
  - Both As built and After 6X reflow tested.
  - 10mil drill, 1mm and 0.8mm pitch tested
  - Sample size: 6 IST coupons per condition
  - Used 10% resistance increase as the failure criteria
  - Stopped after all fail or 3000 cycles for as-built samples or 6000 cycles for after 6X reflow samples

Thermal Cycle Profile Comparison



-40 to +135ºC, 10 min ramps and dwells



25 to 150ºC, 3min heating, 2 min cooling, no dwell

For small sample sizes, IST has a much shorter test time. ATC takes 8X longer.

For large numbers of samples, ATC can test them all at once compared to IST testers limited to 6 or 18 samples depending on machine.

Cycle Time in Days

Cycles	250	500	750	1000	2000	3000	4000	5000	6000
IST	0.9	1.7	2.6	3.5	6.9	10.4	13.9	17.4	20.8
Air to Air	6.9	13.9	20.8	27.8	55.6	83.3	111.1	139	166.7

Thermal Cycle Data Considerations

- The boards were fabricated in three different PWB manufacturing locations
- Though each fabricator made great efforts to plate with exactly the same conditions, different plating runs were required for at least a few materials at the various fabricators.
  - Plating chemistries and other factors, not just Cu thickness will affect the results
    - Must be careful in comparisons
- Material damage can impact the results.
  - Delamination → early failures or
  - Delamination → “falsely” better due to stress relief associated with the delamination.
- In comparisons following, comparing only materials without rejectable defects unless otherwise noted.

Summary of ATC results

- Wide range of performance in the various tested materials
  - Characteristic life ranging from as low as 354 thermal cycles to greater than 6000 cycles for four specific materials (five constructions).
- Lower resin content constructions, which also have lower z-axis coefficients of thermal expansion, last considerably longer without failure in thermal cycling compared to the same materials used in the higher resin content constructions.
  - Very significant →lower resin content outperforms the higher resin content by a factor of 1.28 to 4.07 times as long.
    - In a few cases, internal material damage may be affecting these results.
- The 0.8mm pitch vias out-performed the 1mm pitch vias in thermal cycling.
  - This is consistent with other data on this test coupon.
  - The sample size in this testing is limited to only four constructions tested with both pitches and material damage may be impacting some of the results.
- The average Beta (slope of the Weibull distribution) is roughly 5.2, but the range of this value is significant
  - From a low of approximately 2.3 to a high of 11.1.
  - Variation is primarily driven by material characteristics combined with plating characteristics.
- See paper for complete Weibull Statistics

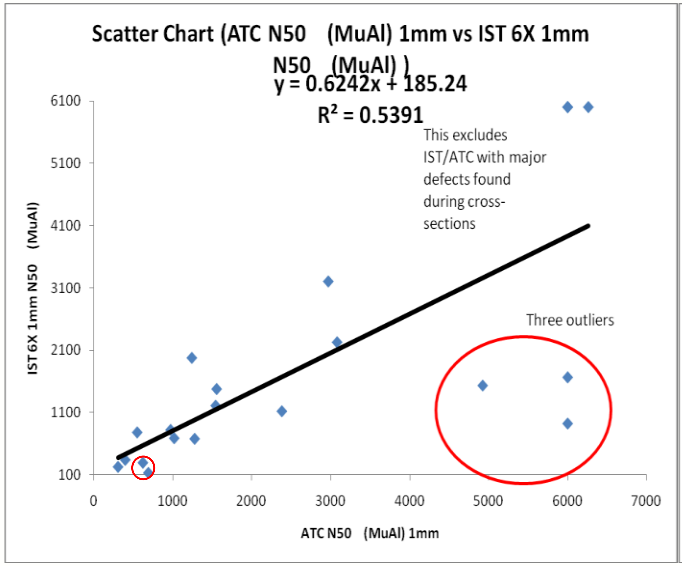
Summary of IST results (1)

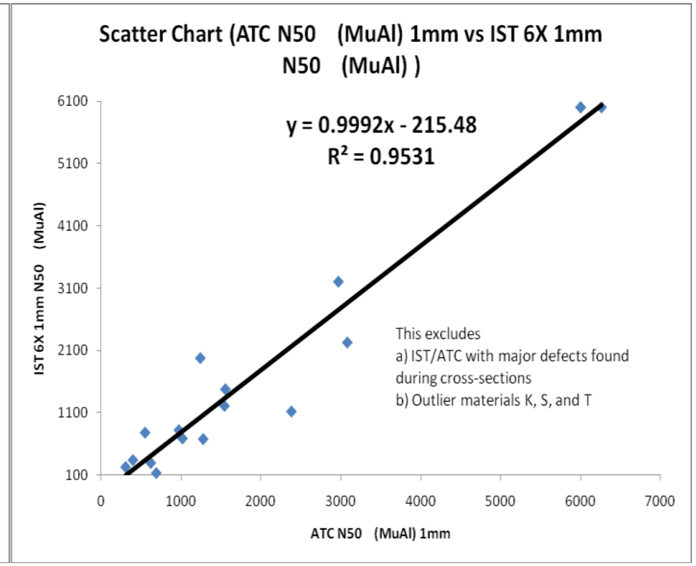
- Similar to ATC data, wide range of performance.
  - As Built characteristic life from 312 cycles to greater than 3000 IST cycles. (Testing stopped at 3000 cycles)
  - After 6X Reflow characteristic from 164 cycles to greater than 6000 IST cycles (Testing stopped at 6000 cycles
  - Some of the after reflow data is affected by material degradation.
- IST As built in all except two cases, the low resin content constructions outperform the high resin content constructions.
  - Consistent with ATC results and the difference in coefficient of thermal expansions of the materials.
  - Exceptions have a Tg by DMA Storage Modulus below 150° C that affects these results. This is discussed in more detail in the comparison of ATC to IST following.
- IST after 6X Reflow in all except two cases, the low resin content constructions outperform the high resin content constructions.
  - Consistent with the ATC results and the differences in the coefficients of thermal expansion of the materials.
  - Exception in the case of the material F and G may be explained by the material damage noted on the IST coupons after reflow
  - Exception in case of Material K and L has a Tg by DMA Storage Modulus below 150° C that affects these results. This is discussed in more detail in the comparison of ATC to IST following.

Summary of IST results (2)

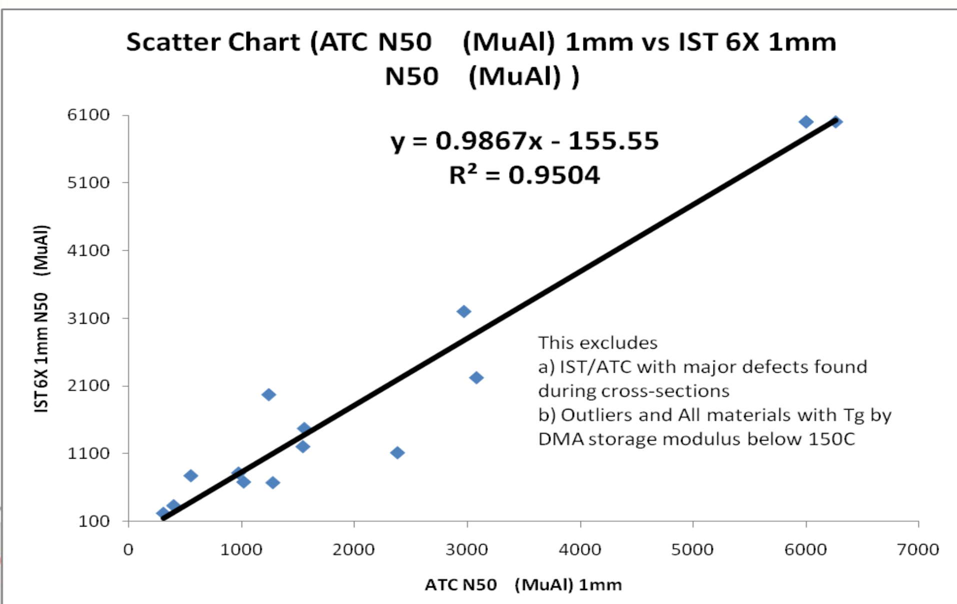
- Average Beta (slope of the Weibull distribution) is approximately 4.5 for the as built IST coupon results
- Average Beta (slope of the Weibull distribution) is approximately 4.3 for the 0.8mm pitch IST coupons and 5.1 for the 1mm pitch IST coupons after reflow preconditioning.
- Range of β is significant, from 1.7 to 10.7 for the as built coupons, 1.7 to 13.3 for the coupons after reflow preconditioning. T
  - Variation is driven by material characteristics combined with plating characteristics.
  - The slightly larger range of beta in IST compared to ATC is driven primarily by the smaller sample sizes of IST testing.
  - For materials with significantly lower beta in ATC compared to IST, this is typically a result of how a failure is recorded.
    - IST failure = 10% increase
    - ATC failure = 11 ohm failure threshold
      - Most cases, not significant, as the failures at 11 ohms occur only a few cycles after the 10% failure point is reached.
      - Where the resistance increase is very slow, IST will pick up the failures earlier.
      - A sampling was done on the ATC data using a 5 ohm threshold (roughly a 25% increase in resistance) for a few materials that experienced this slow resistance increase and the Weibull slopes were reduced on these materials.
- On average, there were only minor differences between the characteristic life of the IST coupons at 0.8mm pitch and 1mm pitch, both as built, and after reflow preconditioning. However, for individual materials, this difference could be significant.
- See paper for complete Weibull Statistics

Comparison of ATC to IST (6X Reflow, 1mm pitch)



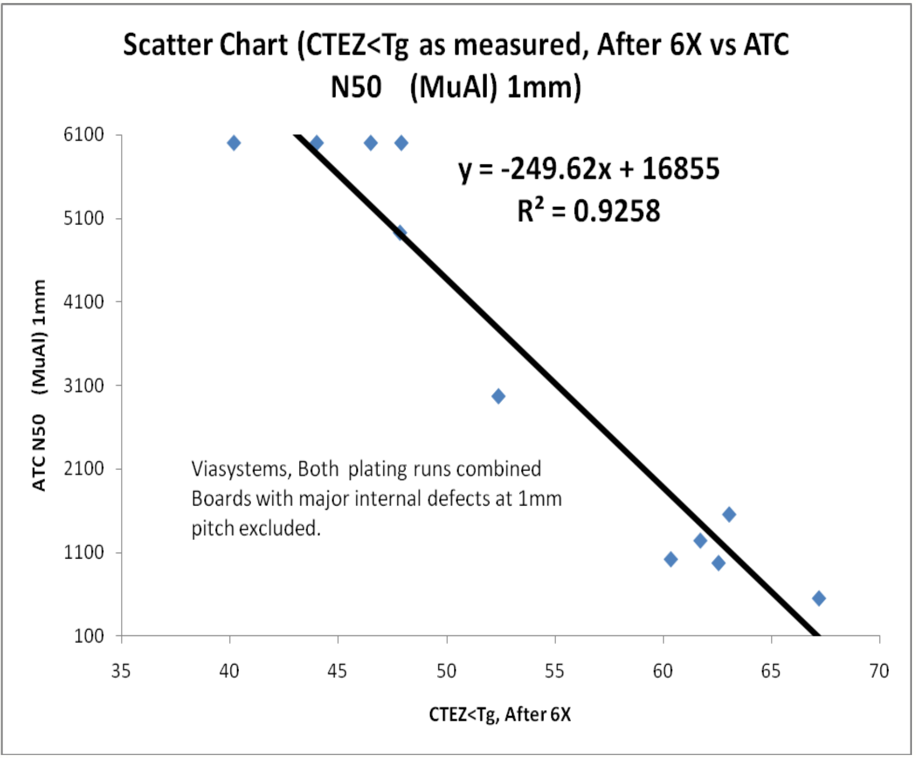


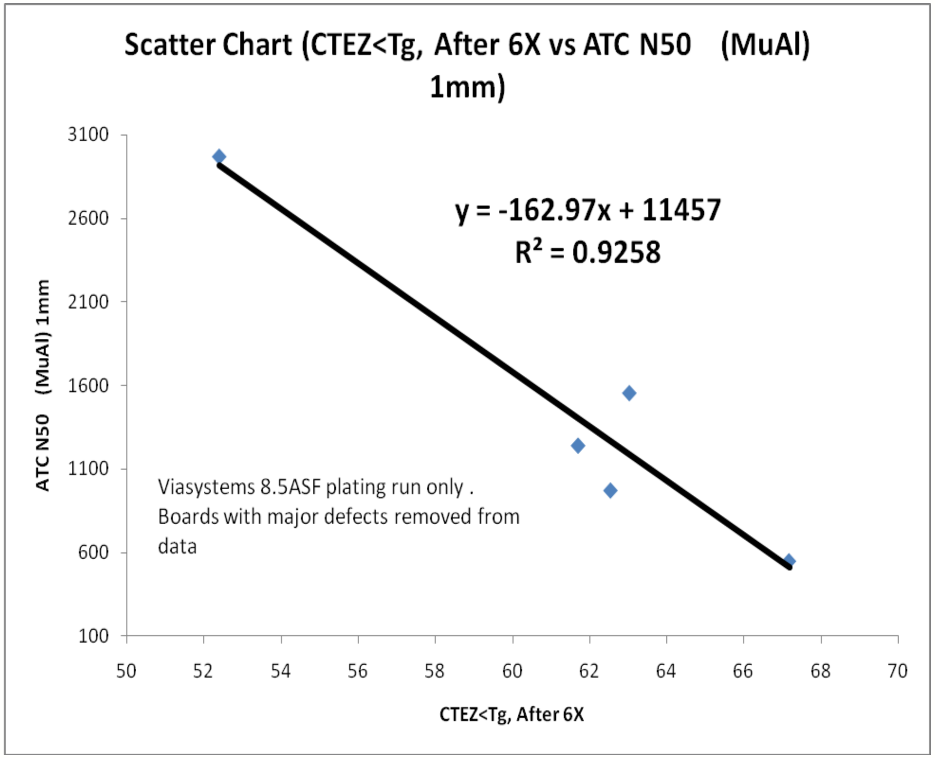
Scatter believed primarily due to smaller IST sample size



Outliers: Actually 5. Where ATC >> IST (>2:1 ratio) → Tg by DMA storage modulus or lower → Affect IST (peak temp 150ºC) but not ATC (peak temp 135ºC)

Comparison of ATC to CTE Z



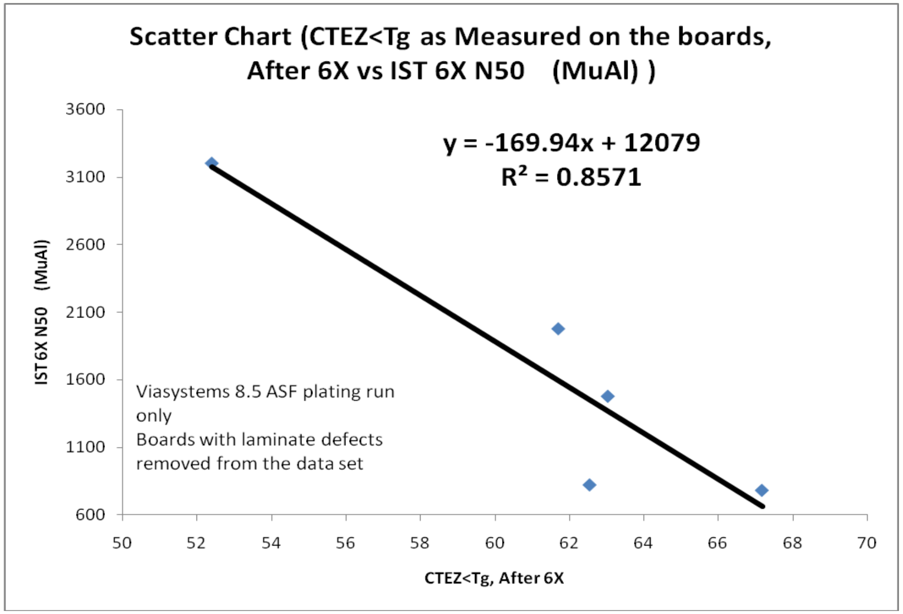


All boards plated at Viasystems **Single plating run at Viasystems(8 ASF)**

Data confirms previous results & direct relationship of the Z-axis CTE below the Tg (α1)

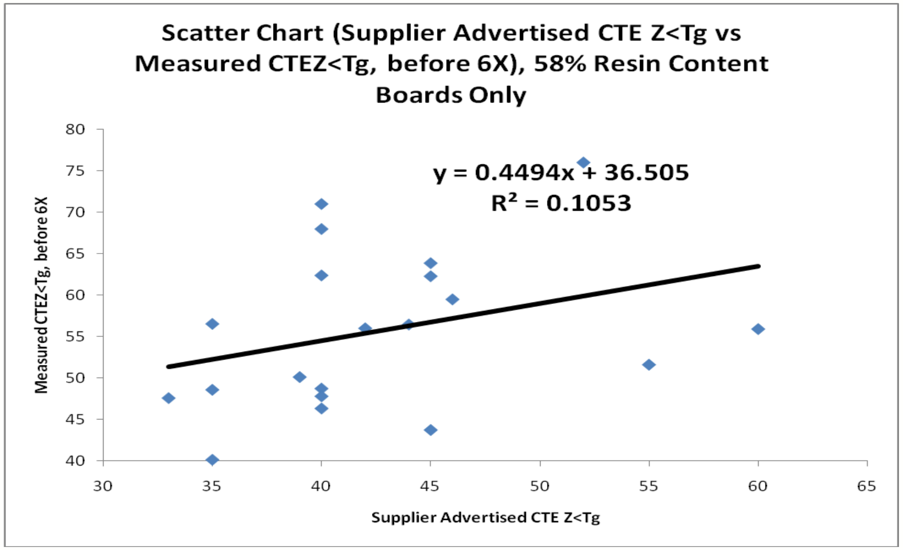
Given this, once a fabricator’s plating reliability has been qualified, the effect on thermal cycle reliability of changes to the board materials can be estimated by the resulting change in the Z-axis CTE. This can be extended across multiple designs

Comparison of IST to CTE Z



- Good correlation only occurs when you remove materials with Tg ≤ 150ºC
  - Same issue comparing ATC vs. IST
  - Confirms IST testing using these specially design material analysis IST test coupons in addition to ATC can also be used for plating qualification and the affects of material changes on plating reliability can be assessed by changes in the Z-axis CTE of the finished printed wiring board.

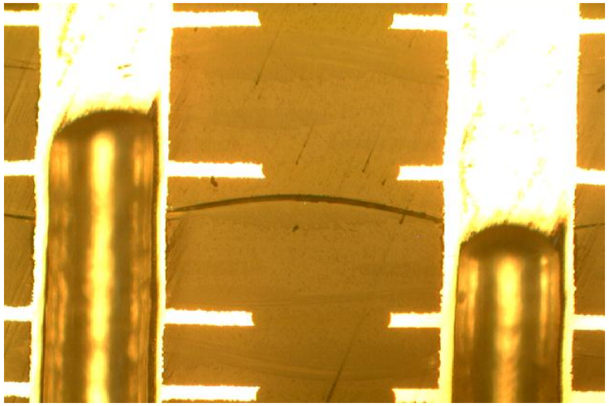
Comparison of Supplier CTE Z to Measured CTE Z



- Supplier Advertised data at 50% RC vs. Measured on identical 58% RC boards
  - Should be a difference, but should correlate → **Clearly Does NOT**!
  - Can only be due to suppliers' inconsistent sample selection for this testing or inconsistent measuring techniques confounded by rounding the data to the nearest five parts per million (or supplier "advertising")
- Considering the importance of this data to the reliability→ industry standards need to be reviewed to ensure that the methods for sample selection (including thickness, glass style and resin content), preparation and measurement are clear, and reporting requirements need to be to the nearest part per million and not rounded.

Failure Analysis

Typical Fatigue Crack



Eyebrow Crack

- All failures were barrel cracks
- Also noted in the cross-sections after ATC → significant increase in eyebrow cracks compared to the after 6X reflow cross-sections (no ATC).

Summary (1)

- Material properties alone are insufficient to ensure a high quality and reliable finished printing wiring board.
  - Testing and evaluation of multilayer product is required.
- Material suitability in a MLB for Pb-free assembly reflow cannot be determined by visual inspection alone.
  - Cross-sections of the materials are required at arrays of via holes at various pitches to determine the survivability of these materials.
- Through hole via pitches of 0.8mm are more susceptible to internal material damage during Pb-free reflow or other thermal stresses than 1mm or greater via pitch.
  - Because of the closer pitch of the vias at 0.8 mm, the stresses built up during Pb-free assembly resulting from the CTE differences between the copper plated through holes and the laminates, plus any vapor pressure generated during reflow, are less able to be distributed across the material between the vias. In the worst case this results in severe internal delamination of the materials.

Summary (2)

- When evaluating Pb-free survivability, in the majority of cases, the 6X thermal stress at 288° C test condition was more severe than the 6X reflow cycles at 260° C.
  - 288° C thermal stress methodology is both easy to implement at the PWB fabricator and a valuable tool for looking at first article, or as a production check on an actual design.
  - It is recommended to use both the combination of reflow cycling and solder float testing when material and product qualification is important.
- As a general observation, the laminate integrity of the Pb-free materials after 6X reflow cycles at 260° C was significantly better than a similar study conducted two years ago,
  - The materials industry is learning and maturing relative to materials ability to survive multiple cycles through Pb-free assembly.

Summary (3)

- In both ATC and IST cycling there is a wide range of performance among various materials. While this is partially a function of plating, Z-axis CTE is a key factor.
  - Materials with lower CTE-Z below Tg ($\alpha 1$) provide the highest plated through hole reliability.
  - Lower resin content constructions, which also have lower z-axis coefficients of thermal expansion, last considerably longer in thermal cycling without failure compared to the same materials used in the higher resin content constructions.
- In air-to-air thermal cycling, 0.8mm pitch vias out-perform the 1mm pitch vias.

Summary (4)

- When the material Tg (on the finished MLB), specifically as measured by DMA Storage Modulus, is below the testing temperature of both IST and ATC, then IST and ATC correlate very closely and IST can be used to as an alternative to air-to-air thermal cycling for field life predictions.
  - For thick boards, the IST design must have heating elements distributed through the material stackup to ensure even heating of the IST coupon and good correlation to the ATC testing.
  - For materials where the Tg as measured by DMA Storage Modulus is below 150˚ C, the peak temperature in IST should be reduced when using IST to assess the plated through hole reliability for applications where the peak operating temperature is below the Tg.
    - A 10˚ C reduction appears to be sufficient based on this data.
  - For end user applications where the temperatures equal or exceed the Tg as measured by DMA Storage Modulus, IST or ATC testing should be sure to test to the peak temperature of the end user application.

Summary (5)

- IST and ATC performance, with proper coupon design and identical plating, both correlate well to the Z-axis CTE below Tg ($\alpha 1$).
  - Given this information, once a fabricator's plating reliability has been qualified, the effect on thermal cycle reliability as measured by either ATC or IST of changes to the board materials can be estimated by the resulting change in the Z-axis CTE.
  - This can be extended across multiple designs.
- Supplier advertised data on Z-axis CTE below Tg ($\alpha 1$) does not correlate with measured data on actual multilayer constructions and hence, cannot be considered valid.
  - This can only be due to inconsistent sample selection for this testing or inconsistent measuring techniques confounded by rounding the data to the nearest five parts per million.
  - Considering the importance of this data to the end user reliability, industry standards need to be reviewed to ensure that the methods for sample selection (including thickness, glass style and resin content), preparation and measurement are clear, and reporting requirements need to be to the nearest part per million and not rounded.

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