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Review of Interconnect Stress Testing Protocols and Their Effectiveness in Screening Microvias

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Abstract
The use of microvias in Printed Circuit Boards (PCBs) for military hardware is increasing as technology drives us toward smaller pitches and denser circuitry. Along with the changes in technology, the industry has changed and captive manufacturing lines are few and far between. As PCBs get more complicated, the testing we perform to verify the material was manufactured to our requirements before they are used in an assembly needs to be reviewed to ensure that it is sufficient for the technology and meets industry needs to better screen for long-term reliability. The Interconnect Stress Testing (IST) protocol currently used to identify manufacturing issues in plated through holes, blind, or buried vias are not necessarily sufficient to identify problems with microvias. There is a need to review the current IST protocol to determine if it is adequate for finding bad microvias or if there is a more reliable test that will screen out manufacturing inconsistencies.

The objective of this research is to analyze a large population of PCB IST coupons to determine if there is a more effective IST test to find less reliable microvias in electrically passing PCB product and to screen for manufacturing deficiencies. The proposed IST test procedure will be supported with visual inspection of corresponding microvia cross sections and Printed Wiring Assembly (PWA) acceptance test results. The proposed screening will be shown to only slightly affect PCB yield while showing a large benefit to screening before PCBs are used in an assembly.

The test vehicles will be production-built hardware from multiple suppliers over a 4-year time period, of 2010 to 2014, of polyimide and epoxy constructions. Both 152-µm and 203-µm diameter microvias will be reviewed. It will be shown that the initial IPC-TM-650 Number 2.6.26 DC Current Induced Thermal Cycling Test, dated May 2001 default conditions were not sufficient to adequately screen for microvia manufacturing inconsistencies and that, with a few changes to the current testing, high-reliability product could be screened quickly for current technology.

Introduction
The initiation of this research resulted from a PWA anomaly discovered during developmental testing. This testing evaluates the system performance in a simulated dynamic environment in order to provide test data to stakeholders that can be used to evaluate system performance as well as provide information to aid in future test profile development. The system consists of a number of PWAs in the in multiple sub-system components. During one of these dynamic tests, a 15-V monitoring circuit within the sub-system from one PWA to another PWA exhibited an out-of-family condition. These two PWAs were disassembled from the system and retested on a PWA acceptance test station. One PWA was exonerated. The other PWA also passed testing, but when the data were closely scrutinized, it was determined to be a false pass. Individual data points exceeded test specification limits for this 15-V monitoring circuit, but the test station software was averaging all the data points rather than reporting the maximum value detected.

The resistance in this circuit is only allowed to vary by 10 Ω, and an absolute resistance greater than 100 Ω would constitute a failure. An exhaustive troubleshooting procedure was undertaken to determine the root cause of the monitor circuit problem. Setup for the test isolated the trace by removing all parts, leaving only the suspect trace. The removed parts were then inspected and tested with no anomalies noted. Thermal cycling showed that the resistance of this circuit (two microvias and buried trace) spiked randomly up to, but not over, 500 Ω during the ramping of the temperature during thermal cycling. A bare board was used as a control unit during this thermal cycling. The resistance of the monitor circuit on the control unit changed in a linear and predictable manner consistent with the thermal changes. The conclusion is that there is a disturbance in the trace that could be attributed to a microvia failure and that this disturbance is isolated to one location, preventing full performance of the module. After this bench testing, a destructive physical analysis was conducted. The locations of interest can be seen in Figure 3 and Figure 4.

Figure 1 - PWA Top

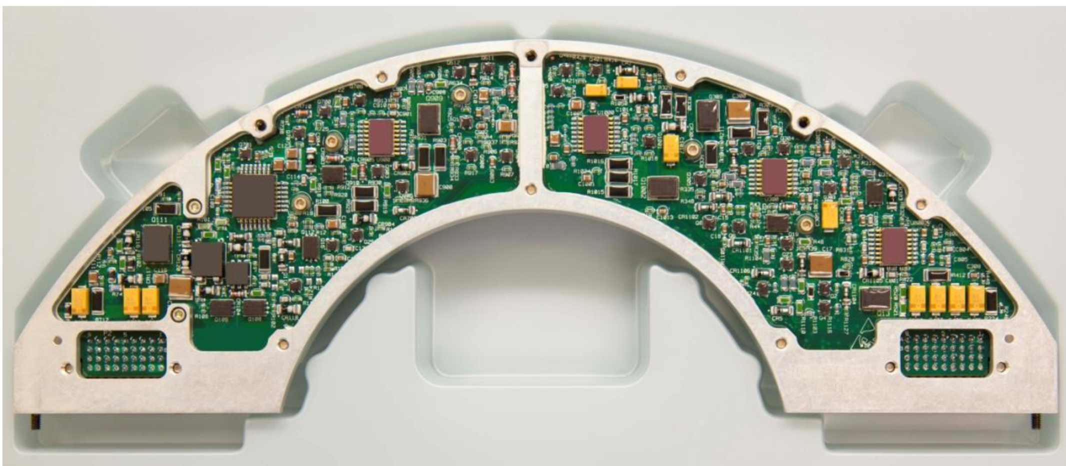

Figure 2 - PWA Bottom

The site was removed and mounted for microsection analysis. Before getting to the first vias of interest, leads on the microcircuit (top side) were used to align the polishing plane. This minimized the need for polishing all the way to the sites of interest. Most sites encountered had good via to target pad connection. Of the 2 suspected failed vias, both had evidence of fine line separation at the via to target pad location. An example can be seen in Figure 5 and Figure 6. At a magnification of 200x, the fine line separation is hardly visible, but at 400x, it is much more pronounced. The single via between the two suspected (then confirmed) vias, also had fine line separation. Of 17 microvia sites examined, 3 would have failed the program's internally developed criteria for target pad integrity, which requires a minimum connection of 140-µm, with no fine line separation.

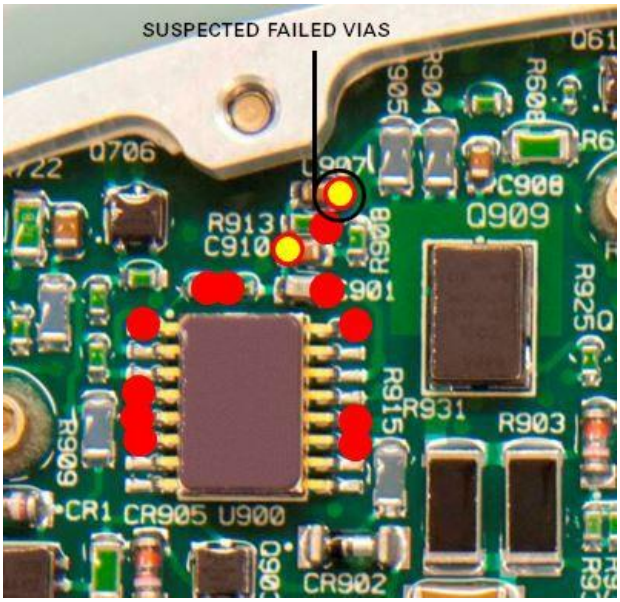

Figure 3 - Top Side of Interest

Figure 4 - Bottom Side of Interest

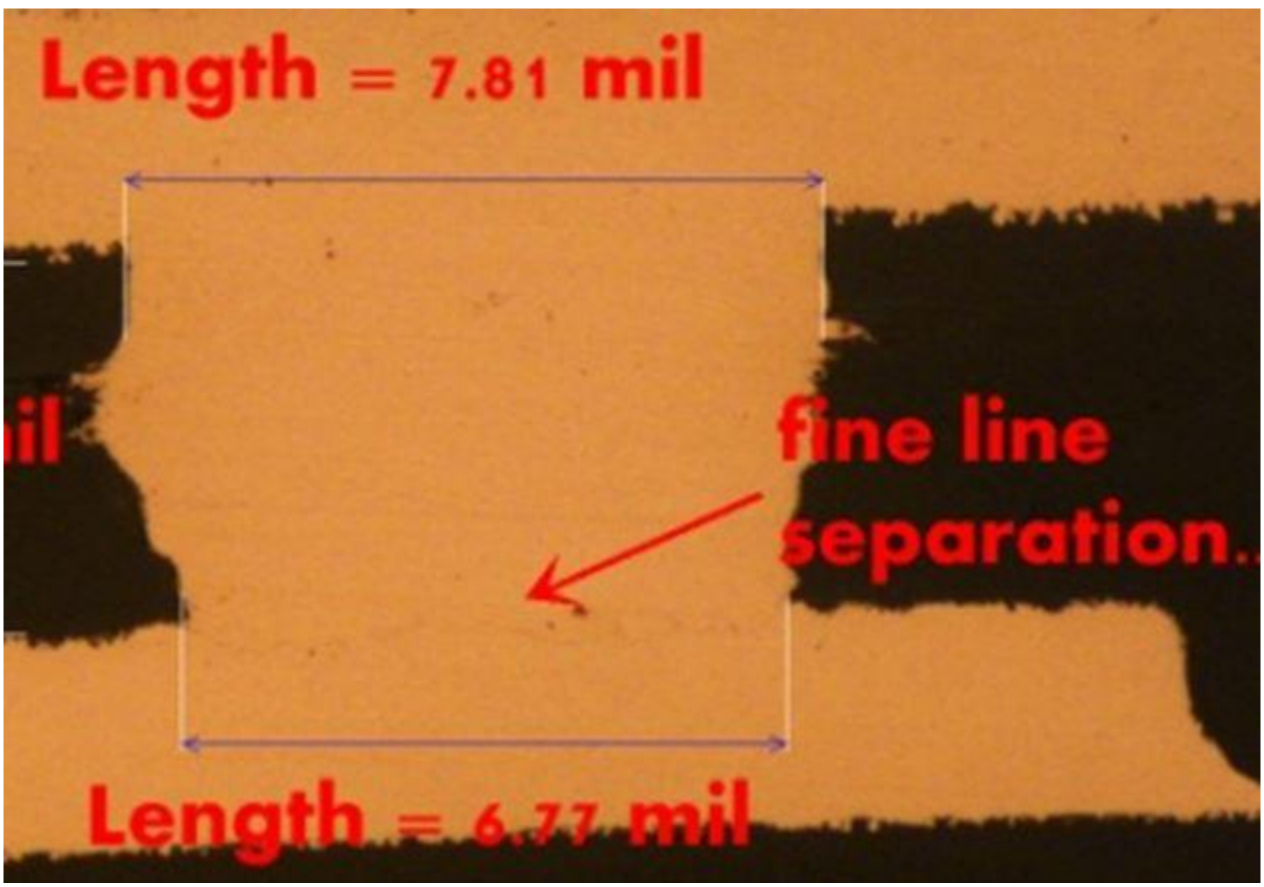

Figure 5 - Via C907 Fine Line Separation 200x

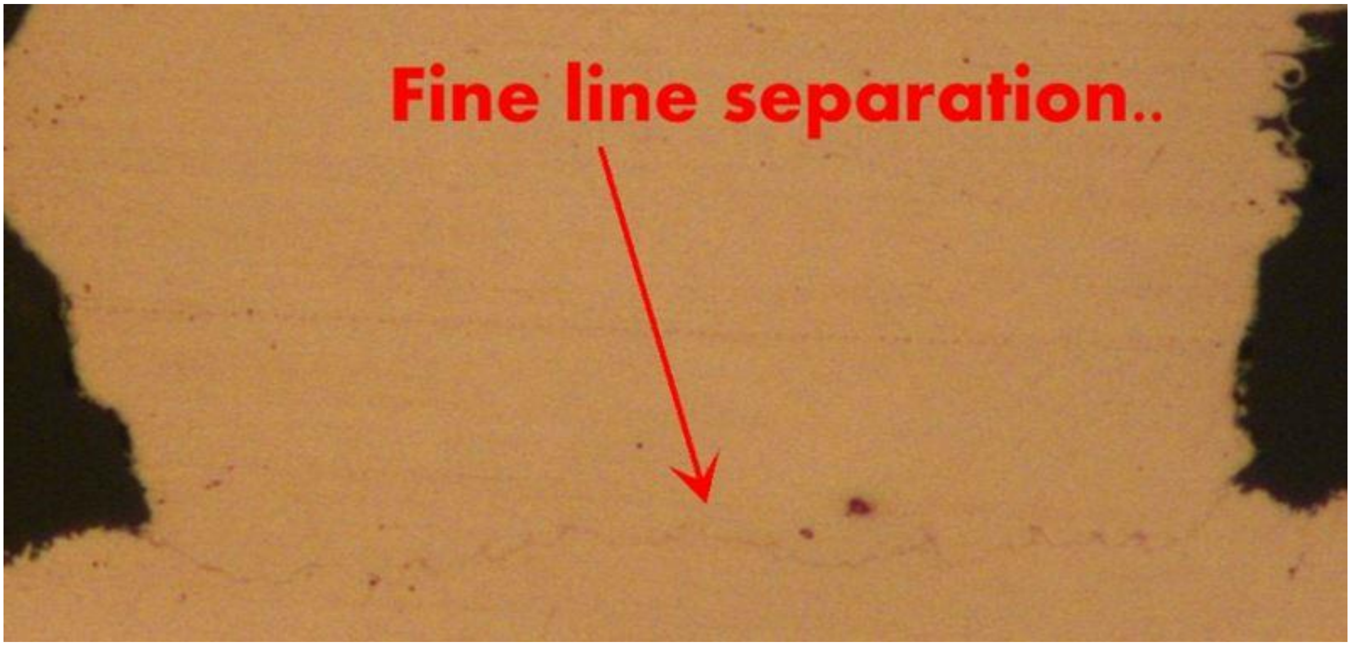

Figure 6 - Via C907 Fine Line Separation 400x

Historical records were reviewed for the date code of the PCB lot in question as well as a date code of a lot produced several weeks later. Results of four PWB lot acceptance results showed that of 64 microvia sites reviewed, 2 of those sites, as indicated by the supplier, would not meet the fine line separation criteria. Note that 2 of those sites were indicated by the supplier to be in the same general location as the failed sites determined above. That PCB had been scrapped at the factory. Some of the supplier-determined acceptable microvias were later found by our team's expert independent qualifying source to have fine line separations that would not have met the existing requirements at a higher magnification.

During the evaluation of the above item, multiple PWAs of a different part number experienced failures during factory testing. These were related to two panels from the same PCB production lot from a different supplier than above. At least one of these PWA failures was tied to a microvia visual failure. Again, our independent qualifying source examined the acceptance coupons from these panels and found fine line separation did not meet our internally developed criteria.

It is important to note that of 39 PCBs in the system, 13 have microvia technology. The construction of these 13 covers epoxy as well as polyimide PCBs. Of those 13, all have microvias from layers 1 to 2 and layers n to n minus 1. The number of microvia sites range from 101 for the smallest PCB to 2,233 for one of the largest PCBs. Now that we had discovered at least 2 similar failures, and with the number of microvia PCBs in the system, we needed to determine if there was a systemic issue, and if so, how we could mitigate or eliminate the risk of microvia failures in the future.

Original Test Method

At the time of construction of the PCBs related to the microvia failures, the following requirements were in place. All product was built to MIL-PRF-31032/1C and supplemented by IST testing. At the beginning of our investigation, the IST defaults set in IPC-TM-650 Number 2.6.26 were followed with a few modifications for our high reliability product. All IST coupons were baked for no less than 4 h at 123°C ± 2°C, preconditioning was set at 3 cycles at a temperature of 220°C where the maximum power circuit temperature was set to 205°C to 230°C and the pre-cycle time window was fixed at 10 s maximum. IST testing was done at 150°C with a 10% resistance change failure threshold, but the test cycles were set to 500, up from the default of 250.

Testing using the method above was done on both polyimide and epoxy constructions, which included 152-µm and 203-µm microvias. Each PCB panel required two coupons to pass for panels equal to or less than 457.2 x 609.6-mm (18x24) in and three per panel for panels greater than 457.2 x 609.6-mm, with the third coupon located in the center of the panel. As these coupons could also test other via types in parallel; the power for the microvia test was applied to the P-circuit.

In addition to IST testing, visual inspections were performed on the acceptance (A/B) coupons, which had been 3x solder floated per IPC-TM-650 Number 2.6.8E condition C for each panel, and a premicroetch inspection was performed to determine if there was any fine line separation. Inspection criteria for microsection defaulted to MIL-PRF-31032/1C, which calls out inspection magnification per IPC-TM-650 Number 2.2.5A. IPC-TM-650 Number 2.2.5A allows magnifications of microsections "…that allows clear viewing of the areas containing the attributes to be measured". Also, MIL-PRF-31032/1C allows referee inspections to be performed in accordance with MIL-PRF-31032/1C from 200x to 400x magnification. Without a very specific requirement passed down to our suppliers, the premicroetch inspection magnification was interpreted as anywhere from 50x to 400x.

Experiments

Once multiple failures were identified, it was clear that the IST testing and visual inspections in place were not sufficient. Our revised test method was developed over multiple months and many tests. Initially, it was believed that additional cycles would provide a higher degree of confidence in the prescribed IST results. Coupons were taken from one of the failed polyimide lots that had been exposed to the original test method. All setup parameters remained the same except that additional cycles were added in 500-cycle increments up to 1500 cycles. Eight coupons were tested and there were no failures. The follow-on experiment took two coupons from the same lot, whose visual examination at 200x and 400x showed fine line separation for 500 cycles at 190°C. Both coupons passed the initial 500 cycles and they were subsequently tested for an additional 500 cycles. One coupon passed, while one coupon failed at the 521st cycle.

Material glass transition (Tg) temperatures were reviewed for the polyimide in the design under test, and the next iteration of testing was performed at 210°C (closer to the material Tg) to test the theory that the current 150°C temperature was not sufficiently stressing the microvia. Seven coupons were tested at 210°C for 100 cycles and all passed. The same seven coupons were then tested an additional 400 cycles and three of seven coupons failed the 10% resistance criteria before the 500 total cycles were completed. Coupons continued to be tested for an additional 500 cycles and one of the four coupons failed before 1000 cycles.

The same experiment was run on the lot of IST coupons from the PW that had the original anomaly. Being an epoxy design, the test temperature was adjusted to 190°C closer to its Tg. Testing was conducted up to 1000 cycles on five coupons. All five coupons passed at 100 cycles, and four of the five failed before the 500th cycle, and five of five failed before 1000 cycles.

With the temperatures set at 210°C for polyimide and 190°C for epoxy, hundreds of coupons were run to collect our data set, which will be called data set A. After data set A was complete, the optimum IST setup parameters were validated by testing hundreds of additional coupons, which will be called data set B. It is important to note that for the collection of data set A and data set B, the power was applied to the microvia sense circuit and only the microvias were monitored. In addition to IST testing, some A/B compliance coupons from each panel went through microsection inspection, which had been 3x solder floated per IPC-TM-650 Number 2.6.8E condition C, and a premicroetch inspection was performed to determine if there was any fine line separation. Inspection criteria for microsection defaulted to MIL-PRF-31032/1C, which calls out inspection magnification per IPC-TM-650 Number 2.2.5A. For the purpose of these experiments, all coupons were inspected at 400x magnification for indications of microvia separation.

Results

Data set A consists of a total of 324 IST coupons. Coupons were a mix of previously tested (150°C, three precondition cycles at 220°C, 10% resistance threshold) and untested coupons that we ran through six precondition cycles at 220°C before testing. Coupons were run for 1000 total cycles with post-test data analysis performed to look at 100 and 500 cycle results. . Failure rates were reviewed at 4% and 10% resistance change thresholds.

Data set B consists of production material that all passed the original program IST criteria and was assumed to be known good product. This data set is made up of 477 panels that equate to 980 coupons. The two lots used to develop the test method were eliminated from the results. In order for a panel to pass, either 2 or 3 coupons, depending on panel size, were required to pass.

In data set A, with a 4% resistance change failure threshold, 4 of the 324 coupons failed before 100 cycles. Three of the 4 failures were in precondition or upon power up, with the fourth failure occurring at 13 cycles. Eighteen of the 324 failed between 100 and 500 cycles, and 18 additional coupons failed before 1000 cycles. As seen in Table 1, at 500 cycles, there was a 7% cumulative failure rate, and at 1000 cycles there was a 12% cumulative failure rate. The same coupons were reviewed by microvia size/material and both materials had similar failure rates.

Per Table 1, 100 cycles had a 1% failure rate, although 3 of the 4 failures were before cycling began, and if eliminated, bring the rate close to zero. As failure cycles were recorded, the data were reevaluated with the number of failures that would have occurred with a 250 limit. At 250 cycles, data set A showed only a 2% failure rate, including the failures before cycling per Table 2. Reviewing the original failure lot, only one of the five coupons failed before 250 cycles.

Table 1 - Data Set A –

Mix of previously tested coupons (original protocol) and untested with 6 precondition cycles which were retested to new temperature limits and cycles to define new protocol.

All Coupons	324		
IST cycles 190°C(epoxy) & 210°C (Polyimide)			
Cycle Range	Fails	Failure Rate	**Cumulative Failure Rate**
0-100	4	1.23%	**1%**
101-500	18	5.56%	**7%**
501-1000	18	5.56%	**12%**
152-µm microvia Polyimide Coupons	217		
Cycle Range	Fails	Failure Rate	**Cumulative Failure Rate**
0-100	4	1.84%	**2%**
101-500	8	3.69%	**6%**
501-1000	11	5.07%	**11%**
203-µm microvia Epoxy Coupons	107		
Cycle Range	Fails	Failure Rate	**Cumulative Failure Rate**
0-100	0	0.00%	**0%**
101-500	10	9.35%	**9%**
501-1000	7	6.54%	**16%**

Table 2 - 250 Cycle Failure Rate

All Coupons	324	
Cycle Range	Fails	**Failure Rate**
0-250	7	**2%**

Data set A was also designed to record the cycles to failure based on a 4% and a 10% resistance change threshold rate for 500 and 1,000 total cycles. Table 3 gives the average number of cycles coupons failed at between 0 and 500 cycles and 501 to 1000 cycles at the 4% and 10% resistance threshold limits. As expected, the average number of cycles is greater for a 10% failure rate than for a 4% failure rate.

Table 3 -: Resistance Threshold Comparisons – Average Cycles to Failure

		Cycles to Failure	
		0-500	**501-1000**
Resistance Change Threshold Percentage	**4%**	261	**756**
	10%	282	**785**

At the completion of gathering data set A, program requirements were redefined. All coupons were baked for no less than 4 hours at 123°C ± 2°C, preconditioning was set at six cycles at a temperature of 220°C where the maximum power circuit temperature was set to 205°C to 230°C and the pre-cycle time window was fixed at 10 s maximum. Testing was done at

190°C for epoxy and 210°C for polyimide microvias with a 4% resistance change failure threshold. Test cycles were set at 500, and each PCB panel required two coupons to pass for panels equal to or less than 18x24 and three coupons to pass for panels greater than 18x24, with the third coupon located in the center of the panel.

The effects and benefits of a proper set of test limits can be seen in data set B. Data set B is all production-built material excluding the original two lots used to develop test methods The following criteria were used to designate a Pass or Fail. To Pass IST, a panel must have two or three coupons, depending on panel size, pass 500 cycles at 190°C or 210°C for epoxy or polyimide, respectively. An IST fail was counted if any of the coupons failed before 500 cycles or if any coupon failed during precondition or power on before cycling of the microvia circuit.

A smaller subset of data set B was also visually inspected. When the visual data of compliance A/B coupons were reviewed with the IST data, the following Pass/Fail criteria was used. A panel pass required that both (a) IST testing be successful for all coupons and that (b) there be no fine line separation causing our minimum target pad length, 140-µm and 101-µm for 203 µm and 152 µm vias, respectively, to be violated. A fail could be due to either (a) or (b). This subgroup required both IST and visual testing to be performed.

Reviewing data set B, Table 4 identified that of the 477 production panels that were tested, 8% of the material that was previously accepted as known good product under the original test method failed the new criteria. The same data set was also re-reviewed by microvia size/material, and both materials had similar failure rates. The 477 panels were made up of 57 lots of material. In the review of lots, only 5 of the lots were complete failures, 43 of the lots were found to be good-goods, and 9 of the lots had between 1-3 panels fail.

Table 4 - Data Set B –

Production material that all passed the original program IST re-tested to new protocol by panel.

Upscreened to new criteria		Pass IST	Fail IST	**Failure Rate**
All Panels	477	440	37	**8%**
152-µm microvia Polyimide Panels	200	175	25	**13%**
203-µm microvia Epoxy Panels	277	265	12	**4%**
Total Lots	All Panels Failed in Lot	Some Panels Failed in Lot	No Panels Failed in Lot	
57	5	9	43	

A small set, 33 panels from data set B (**Error! Reference source not found.**) were reviewed against the IST results and visual examination at 400x magnification of the compliance A/B coupons for fine line separation. Due to the small dataset, the percentages are not believed to be significant, but were reviewed to correlate our assumptions. Testing indicates that there is a correlation between IST and visual. A passing IST was more likely to have a passing visual, and a failing IST was more likely to have a failing visual. From this sample of 33 that passed IST, 4 of 18 panels failed the visual criteria. Due to the small population, we are not claiming a 22% escape rate, but we do see indications that the visual should be done in conjunction with the IST. Additionally, there were 5 of 15 panels that failed the IST, but passed the visual criteria. This may seem somewhat contradictory. Recall that the visual is only performed on compliance A/B coupons, which accounts for such a very small sample of microvias on a panel. The initial suspect PWA panels were visually reexamined. Only 3 of 17 microvia sites would have failed the established criteria for fine line separation. It was not surprising to have some of the 33 panels that failed the IST pass the visual.

Table 5 - Data Set B IST & Visual Subset

33 Coupons: IST & Visual			
Pass Visual	Pass IST	Fail IST	
Fail Visual	14	5	
Total Panels	4	10	
	18	15	
Pass IST & Failed Visual			
Pass IST & Pass Visual	22%	67%	**Failed IST & Failed Visual**
	78%	33%	**Failed IST & Passed Visual**

Conclusions and Summary

Soon after the conclusion of this study, the IPC-TM-650 Number 2.6.26A dated May 2014 was released. This version included typical test temperatures more in line with the temperatures used in this study. However, due to the high reliability requirement of our program, we believe that the IST protocol needed for screening reduced reliability microvias in electrically passing PCB product needed to exceed some of typical test conditions listed in the revised test method. In our case, reducing the failure threshold from 10% to 4% and increasing the number of cycles to 500 were significant factors.

Our data indicate that 250 cycles will not consistently screen less reliable microvias, as was seen in the review of our original PWA lot to the 250 cycle count. The 10% resistance threshold will find many of the gross issues, but a finer requirement of 4% is still within the limits of the test equipment and screened defects with fewer cycles.

Very few PCB panel lots completely failed the new test protocol, and in most cases of failed panels, there was rarely more than a single failed panel in a lot. For this reason, it is very important to screen for microvias by panel and not by manufacturing lot. Our microvia IST coupon has 144 microvias. We dramatically increase the percentage of tested microvias vs. microvias on total deliverable PCBs in a lot by testing 2 IST coupons per panel. Due to what seems to be almost a random nature of manufacturing variability among microvias, multiple coupons should be tested per panel and pass both (a) IST protocol and (b) visual inspection (for compliance A/B) before the panel is accepted. As we learned in our experiments, not every panel will fail the IST criteria, even if its corresponding A/B coupons have deficient microvias.

Performing IST alone without a review of fine line separation at a suitable magnification may not limit the risk of a poor microvia escape. Our testing indicates that there is a correlation between a visual failure and an IST failure, but each was also seen with one failing while the other passed. We also determined that a very high magnification is required to reliably determine fine line separation in microsection coupons and have now integrated that in our specifications. Our testing showed escapes from the IST testing, so we believe the visual inspection should be done in conjunction with the IST testing when accepting product. When working with high reliability product or high dollar production assemblies, earlier screening for manufacturing defects in microvias in the PCBs can save high-dollar value PWAs in the long run.

Acknowledgments

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