Impact of Assembly Cycles on Copper Wrap Plating

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Abstract:
The PWB industry needs to complete reliability testing in order to define the minimum copper wrap plating thickness requirement for confirming the reliability of PTH structures. Predicting reliability must ensure that the failure mechanism is demonstrated as a wear-out failure mode because a plating wrap failure is unpredictable. The purpose of this study was to quantify the effects of various copper wrap plating thicknesses through IST testing followed by micro sectioning to determine the failure mechanism and identify the minimum copper wrap thickness required for a reliable PWB.

Minimum copper wrap plating thickness has become an even a bigger concern since designers started designing HDI products with buried vias, microvias and through filled vias all in one design. PWBs go through multiple plating cycles requiring planarization after each plating cycle to keep the surface copper to a manageable thickness for etching.

The companies started a project to study the relationship between Copper wrap plating thickness and via reliability. The project had two phases. This paper will present findings from both Phase 1 and Phase 2.

Introduction:
Figure 1 shows an illustration of the wrap around requirement as defined in IPC –A -600 section 3.3.18 (IPC-6012D Section 3.6.2.11.1). The copper wrap plating requirement was put in to ensure that the plated copper that wraps around the base copper makes a reliable connection and prevents butt joint types of failures.

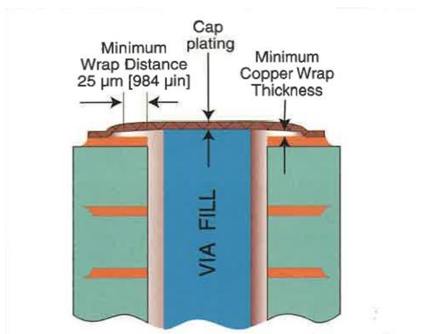


Figure 1 [1]

Customer's quality assurance requires PWB manufacturers to expose IPC A/B coupons to various numbers of thermal stress cycles followed by visual examination of the conformance to the plated wrap layer at the knee of the PTH barrel, as per IPC 6012D (amended). Copper plated wrap requirement is classified as Class 1 (AABUS), Class 2 (5µm) and Class 3 (5µm as per amended spec. and 12µm prior to amendment).

The purpose of the Phase 1 study was to find any correlation between failure modes as related to copper wrap plating thickness. Phase 1 testing had an extremely low failure rate at very high IST cycles and the failure mode was related to barrel cracking and not related to copper wrap plating. Since some level of failure was desired to draw conclusions, the test method for Phase 2 was changed from IST cycles to assembly cycles, using IST testers to simulate assembly cycles.

Design:

This project was carried out in two phases.

- Phase 1 – A quick study using available IST Coupons from previously build designs.
- Phase 2 – Build product with controlled wrap thickness.

Phase 1
All our high Reliability customers require their IPC coupons to be stored for an extended period of time. This is done to make sure coupons are available for testing in case there is any field failure. Part numbers that required copper wrap plating and IST testing were identified and stored IST coupons were pulled for testing. Eighty four coupons from identified parts

were randomly selected. In addition 20 coupons were selected for the panels which were rejected for not meeting the IPC 6012 Class 3 requirement.

Table 1providesthe details of the coupons.

Table # 1

IST Test Coupon Details						
Part Number	**Material 173 ^{0} C - Tg**	**# of coupons**	**Wrap meeting IPC6012D(non-amended) Class 3**	**Surface Finish**	**Via Fill Material**	**IST - Hole Size - µm (mil)**
32531	Laminate A	20	Yes	ENIG	Via Fill Material A	300 (11.8)
30007		39	Yes	ENIG	Via Fill Material A	250 (9.8)
32383		9	No	ENIG	Via Fill Material A	200 (7.9)
31995		6	No	ENIG	Via Fill Material A	571 (22.5)
31652		6	No	ENIG	Via Fill Material B	450 (17.7)
31641		24	Yes	HASL	Via Fill Material A	250 (9.8)

Test Method (Phase 1)

Coupons from different part numbers were mixed together and were given a different identification number. Multiple testers were used in order to eliminate the tester as an influencing factor which allowed testing of coupons from the same part on different testers. The following were the test parameters:

- Preconditioning to 6x@260^{0} C.
- IST test temperatures - from Ambient to 150^{0} C.
- Acceptance criteria - 1,000 cycles or 10% change in resistance, whichever came first.

Data Collection and Analysis (Phase 1)

Out of 104 coupons tested only eight coupons failed below 1,000 cycles. Cycles to failure for these eight coupons were:

- One coupon at 417 cycles
- One coupon at 672 cycles
- Three coupons between 800-900 cycles and
- Three coupons between 901-999 cycles

All coupons met IPC650 - 2.6.26, section 5.2.2's default acceptance criteria of 250 cycles. Ninety two percent of the coupons passed 1,000 cycles. At that time a decision was made to continue testing to failure or 4,000 cycles, whichever came first. Table # 2 below shows the statistical data for Phase 1 testing.

Table # 2 -Data Summary

Part Number	Mean	Std. Dev.	Min.	Max.
31995	3896	232	3378	4000
30007	2910	544	417	4000
32383	2712	498	1695	3270
32531	3572	642	1951	4000
31641	1866	865	802	4000
31652	4000	0	4000	4000

Sections of the coupon that failed at 417 cycles showed that the failure was due to barrel cracking. No butt joint anomaly was observed (see Figure 2).

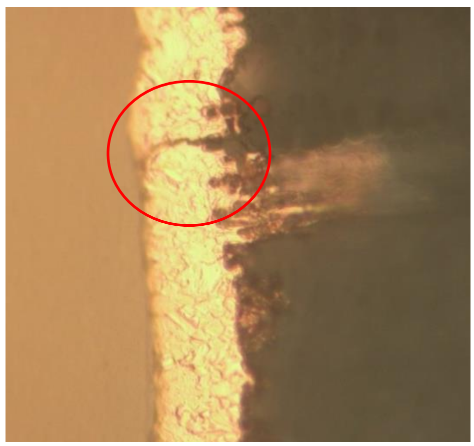
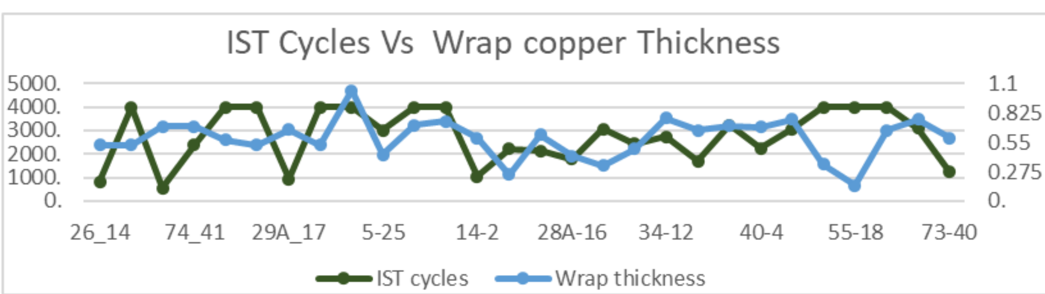


Figure 2 – After 417 cycles

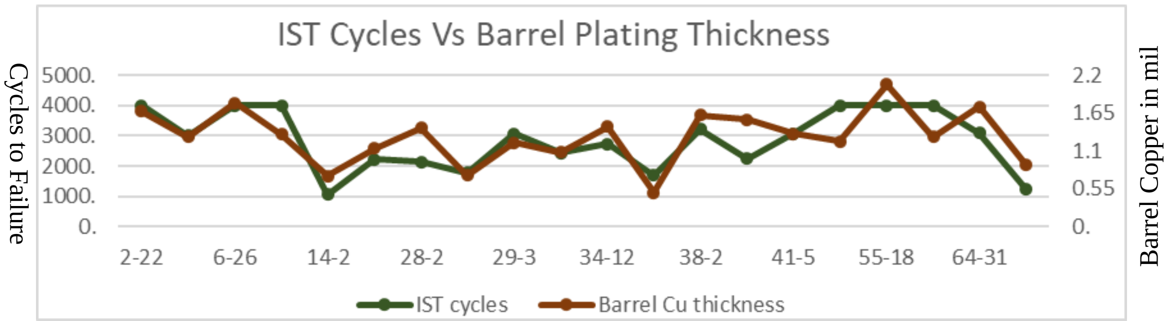
In addition, twenty eight of the tested coupons with various cycles to failures were sectioned. Copper wrap thickness and barrel copper plated thickness was measured on these coupons. IST cycles and plated wrap thickness data were plotted against each other (Plot#1) and likewise, IST cycles and copper plating in the barrel of the via was plotted against each other (Plot # 2). It was also noted that the coupons for the same part number with thicker barrel copper plating had higher cycles to failure. A clear correlation between barrel copper plated thickness and IST cycles was observed.

Cycles to Failure



Wrap Copper in mil

Plot #1



Plot #2

Covariance analysis between IST cycles and barrel plating thickness, and between IST cycles and copper wrap plating thickness was performed. Covariance between IST cycles and copper wrap plating thickness was 0.0517 whereas the covariance between IST cycles and barrel copper plating thickness was 0.694, indicating that barrel copper plating thickness has significant influence on IST cycles to failure. Minimum copper wrap plating thickness on the twenty coupons was 3.63µm (143µin) and this coupon did not show any failure at 4,000 IST cycles. None of the coupons sectioned had zero copper wrap plating (Class 1) as such reliability of the Class 1 (no wrap) condition could not be established.

Phase 2

The IST coupon design was as follows:

- 10 layer 1.57mm (0.062”) thick FR4 laminate construction.
- 0.254mm (0.010”) Buried from layer 2 to 9 and 0.254mm (0.010”) and 0.4mm (0.016”) through vias from layer 1 to 10.
- Buried vias were filled with Via Fill Material A
    - With cap plating and
    - Without cap plating
- Through vias were also filled with Via Fill Material A and capped.

Two IST coupons (see Figure3) were designed to meet the above via and layers criteria. Twenty four of these pairs were placed on a panel. The location of each coupon was identified to see if the location on the panel made any difference. Manufacturing of these coupons was controlled to achieve IPC 6012D (non-amended) Class 1 (No Wrap), Class 2 (5µm wrap) and Class 3 (12µm wrap).

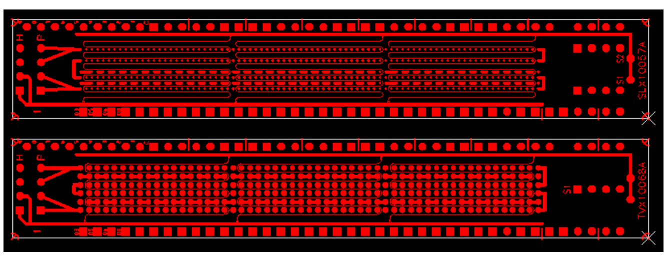


Figure 3

Figure 4

Test Method (Phase 2)

Phase 1 testing had shown that as long as there is some copper wrap plating the coupons will pass 1,000 IST cycles. It was decided to change the test method with the objective to take the IST coupons to failure. Figure5 shows a typical board movement at different assembly cycle temperatures. There is substantial z-axis expansion during leaded and lead-free assembly and it is believed that using assembly cycling to failure could give more comparative results. A lead-free assembly temperature of 245^0 C was selected because it is believed that multiple assembly cycles at 260^0 C could do more damage to material and give us false results. IST testers similar to the one shown in Figure 4 were used for the assembly simulation. Test data collected was used to compare the reliability between all wrap classes.

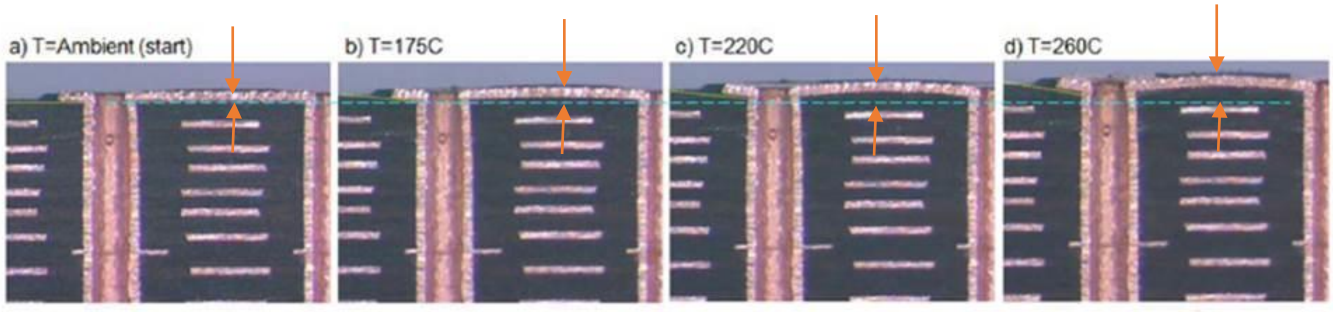


Figure 5

The following provides the details of Phase 2 testing:

- Sample size – Eight samples per panel per wrap level and for all designs
    - 384 coupons for lead-free assembly cycles
    - 32 coupons for leaded assembly
- Test conditions
    - Lead-free Assembly - Ambient to 245^0 C in 3 minutes
    - Leaded assembly – Ambient to 230^0 C in 3 minutes
- Rejection criteria – 10% change in resistance for both buried and through vias
- Heating Circuit – External – superheat (no vias)

Testing, Data Collection and Analysis:

Pre-screening showed that Panel # 6 had manufacturing related issues in the through vias. As a result, sixteen coupons related to through via for Panel # 6 were removed from the test samples. The balance of the 368 IST coupons were subjected to lead-free assembly cycles @ 245^0 C to failure.

The mean data for all types from the 368 coupons is shown below in Table #3.

Table # 3 Mean Unleaded Assembly Cycles to Failure

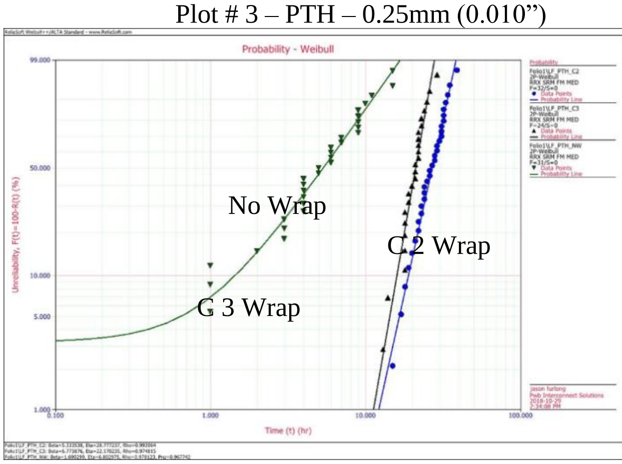
Panel #	Wrap Thickness	Through Via		Buried 0.25mm via	
		0.25mm	0.44mm	Cap	No Cap
1	Class 1 (No Wrap)	10.3	13.8	25.1	47.4
2		5.7	11.9	17.0	35.6
3	Class 2 Wrap	33.4	35.3	39.1	42.6
4		26.0	33.9	34.4	36.4
5	Class 3 Wrap	20.4	26.9	41.8	47.8
6		Not Tested		41.4	41
7	Class 1 (No Wrap)	2.9	2.3	20.6	47.6
8		4.6	6.0	15.0	41.7
9	Class 2 Wrap	22.5	39.9	29.0	42.1
10		24.4	40.1	30.8	37.1
11	Class 3 Wrap	21.0	34.0	37.0	49.6
12		20.9	33.4	42.9	38.8

For Class 1, the mean for through vias with no wrap was the lowest at 2.9 cycles and the mean for buried vias was 22.5 cycles. Some of the through vias with Class 1 (No Wrap) failed pre-screening. Both Class 2 and Class 3 wrap coupons performed much better and had a mean of 20.4 cycles. Statistical analysis was done to understand if there was a single cause or multiple cause for the failures.

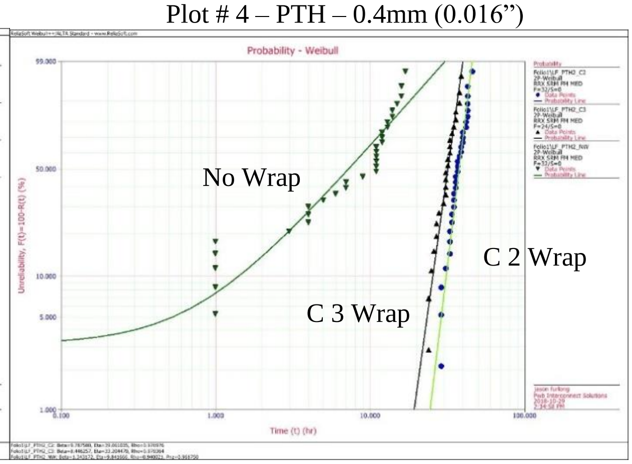
- PTH 0.25mm (0.010") – Plot # 3
- PTH 0.4mm (0.016") – Plot # 4
- Buried via 0.25mm (0.010") – Plot # 5
- PTH versus Buried via – Plot # 6
- PTH Class 2 versus Class 3 – Plot # 7
- Buried via Class 2 versus Class 3 – Plot # 8

Weibull Plots # 3 and #4 for 0.25mm (0.010") and 0.4mm (0.016") through vias showed that coupons with no wrap plating had butt joint and/or barrel cracking types of failure. Whereas Plot # 3 for 0.25mm (0.010") buried vias had barrel cracking failures. Weibull charts Plot #5, #6, #7 and #8 also showed that Class 2 samples for through vias performed better than Class 3 samples. Analysis of resistance plots showed that resistance for PTH vias with Class 2 wrap was lower than the resistance for Class 3 wrap vias. This can mean that the copper thickness for Class 2 wrap was higher than the panels with Class 3 wrap.

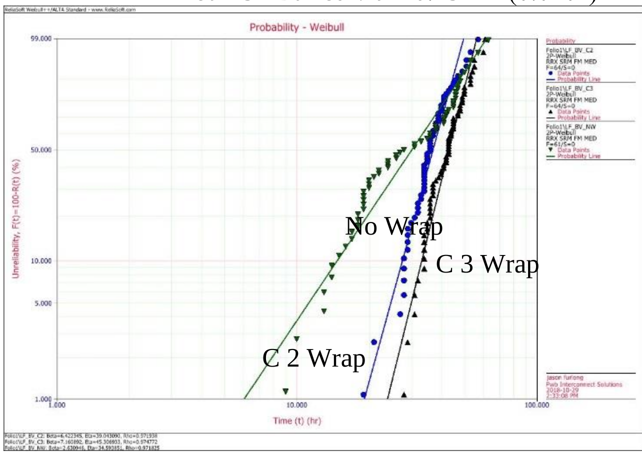
Plot # 3 – PTH – 0.25mm (0.010")



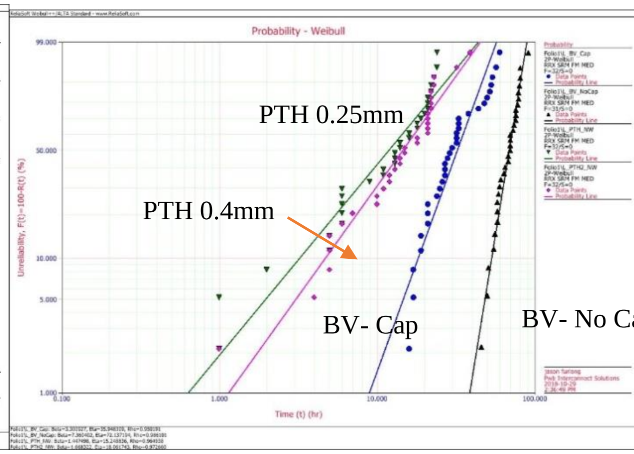
Plot # 4 – PTH – 0.4mm (0.016")



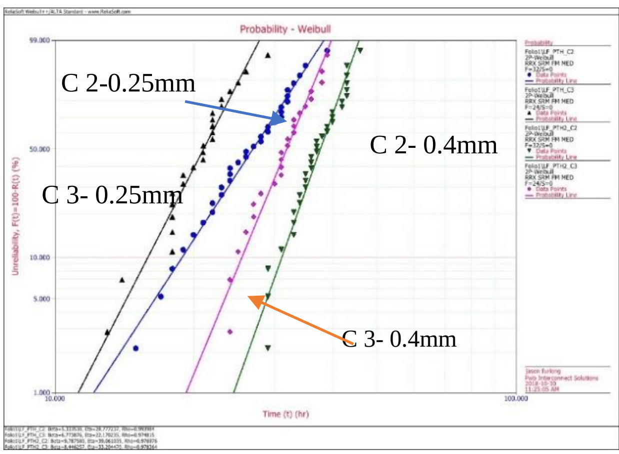
Plot # 5– Buried via – 0.25mm (0.010")



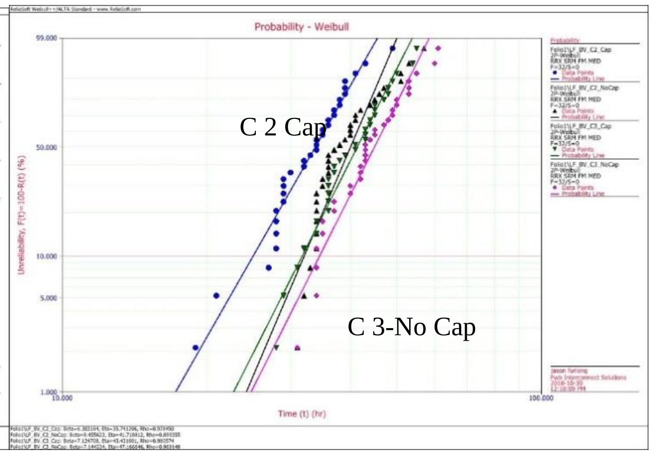
Plot # 6 – PTH vs Buried



Plot # 7 – PTH – Class 2 vs Class 3



Plot # 8 – Buried – Class 2 vs Class 3



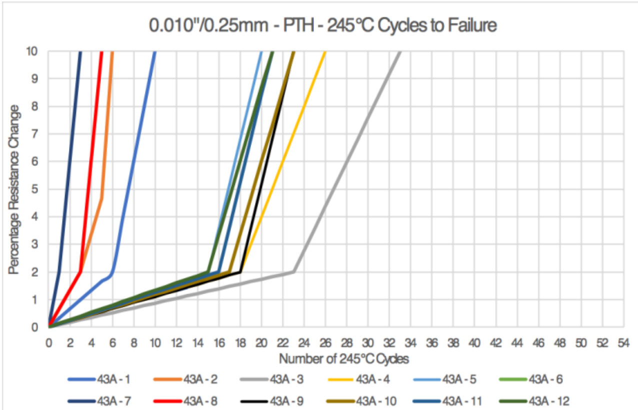
Three coupons for each type of wrap condition and via size were selected. Mean data from these thirty six coupons are shown in Table # 4. The data shows the plated copper thickness for wrap plating and minimum copper plating of through and buried vias. It should be noted that the average barrel copper thickness in through vias for Class 3 was slightly lower than Class 2 panels. Whereas for buried vias, the Class 3 had higher average copper thickness in the barrel of the vias than Class 2 panels. This could explain why through vias with Class 2 wrap performed slightly better than Class 3.

Table # 4

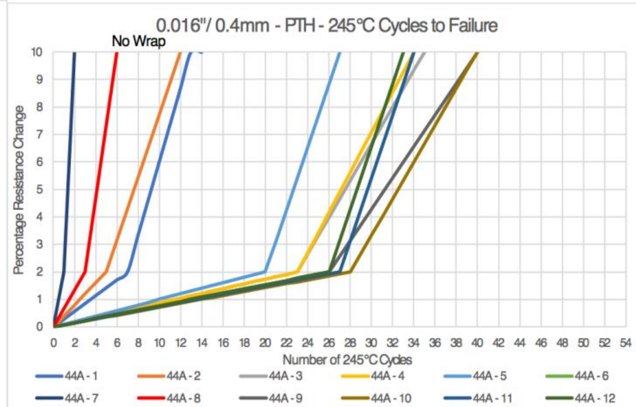
Type of via	Avg. Copper Wrap Thickness µm (inches)			Avg. Through via Barrel plating µm (inches)		
	Class 1	Class 2	Class 3	Class 1	Class 2	Class 3
Through Via	0	5.9 (0.00026")	10.6 (0.000417)	41.47 (0.00163)	35.05 (0.00138)	32.2 (0.001267)
Buried Via	0	10.6 (0.0004)	17.8 (0.0007)	35.99 (0.00142)	36.83 (0.00145)	40.0 (0.001575)

The IST tester performed continuous monitoring and recording of resistance measurements while the coupons were being tested. From this data it can be seen if the failure is a fatigue failure or a butt joint type of failure. Fatigue failure will show a gradual change in resistance to the point and then complete separation will occur. Data was extracted and plotted for all the coupons tested.

Plot # 9 – 0.25mm (0.010”)-PTH-245^0 C to Failure

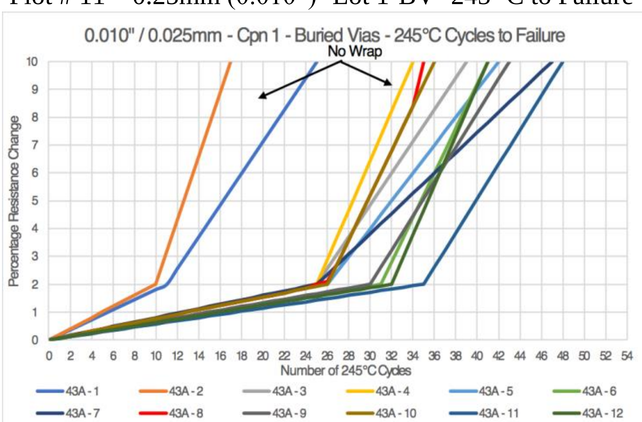


Plot # 10 - 0.4mm (0.016”) – PTH – 245^0 C to Failure

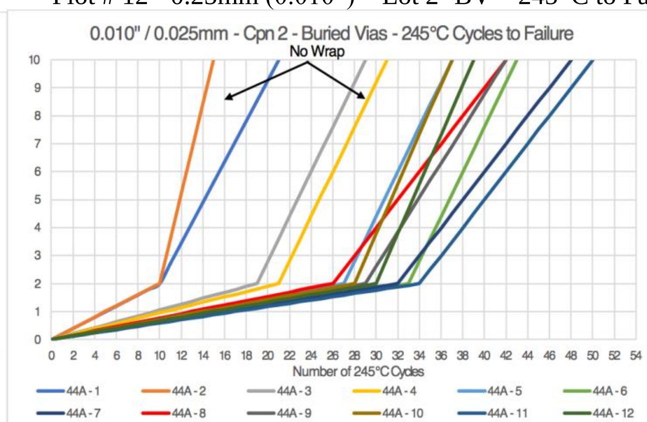


Wrap Guide - No Wrap – P1, P2, P7, P8 ---- Class 2 Wrap – P3, P4, P9, P10 ---- Class 3 Wrap – P5, P6, P11, P12

Plot # 11 – 0.25mm (0.010”)- Lot 1-BV -245^0 C to Failure



Plot # 12 - 0.25mm (0.010”) – Lot 2- BV – 245^0 C to Failure



Wrap Guide - No Wrap – P1, P2, P7, P8 ---- Class 2 Wrap – P3, P4, P9, P10 ---- Class 3 Wrap – P5, P6, P11, P12

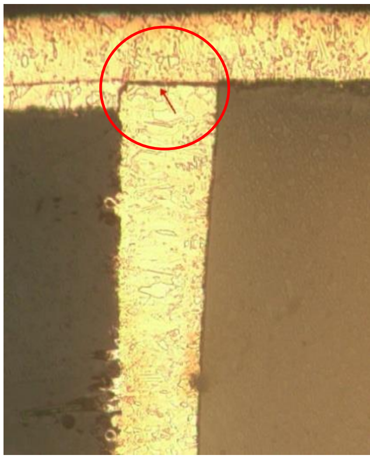
Plot # 9 and 10 are resistance plots for through vias for all three types of wrap conditions. Plots show that there is a gradual change in resistance to 2% and then the change in resistance accelerates at a much faster rate. For 0.25mm (0.010”) through vias coupons with no wrap, this change happens below 2 cycles and for 0.4mm (0.016”) through vias they went as high as 6 cycles. Whereas, for through via with Class 2 and Class 3 wrap the change in resistance to 2% started to happen beyond 14 cycles for 0.25mm (0.010”) via and 20 cycles for 0.4mm (0.016”) vias.

Buried vias (see Plot # 11 and #12) lasted longer than through vias. No wrap coupons went past 10 cycles before >2% change in resistance was observed. At the same time Class 2 and Class 3 coupons did not change by >2% after 25 cycles. Another observation was that buried vias without cap plating performed better than buried vias with cap plating. Typically a PWB will go through a maximum of 6 assembly / repair cycles. In both cases for buried vias these coupons went well beyond 6 cycles.

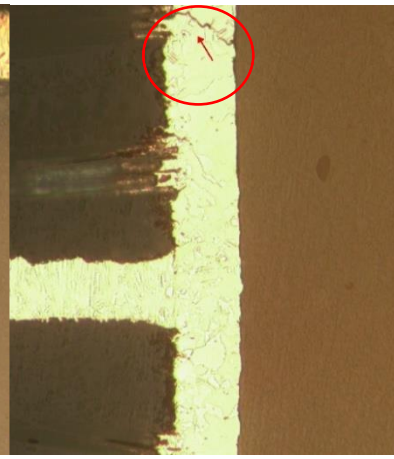
Micro-sections were performed for all three types of wrap conditions for both through and buried vias. For each type the coupon with the lowest, mean and highest cycles to failure were selected. Micro-sections data was analyzed to confirm the Copper wrap plating thickness, failure mode and barrel copper plating thickness. Average wrap thickness for Class 2 was 8.38µm (0.00033”) and for Class 3 was 14.22µm (0.00056”). The coupons classified as no wrap did not have any copper wrap plating. Figures 6 to11 are for the sections with no wrap, Class 2 wrap and Class 3 wrap. Predominately a butt joint type of failure was seen on coupons with no copper wrap plating with some having cracked barrel along with butt joint failure

Through Vias

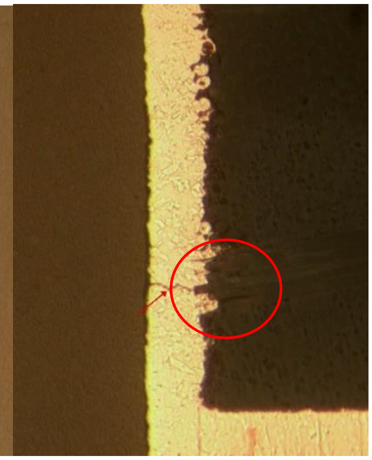
Figure6 – TV- No Wrap   Figure7 – TV – Class 2 Wrap   Figure8 – TV – Class 3 Wrap



Cycles to Failure – 6



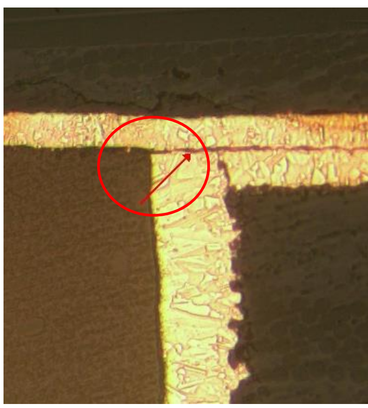
Cycles to Failure – 39



Cycles to Failure – 23

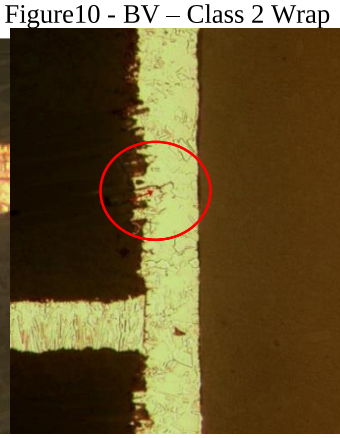
Buried Vias

Figure9 – BV – No Wrap



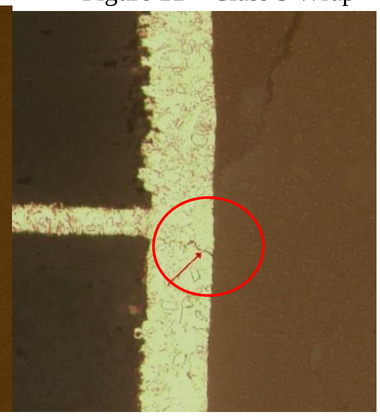
Cycles to Failure - 15

Figure10 - BV – Class 2 Wrap



Cycles to Failure – 57

Figure 11 – Class 3 Wrap



Cycles to Failure – 63

An initiation of a corner crack was seen on some of the Class 2 and Class 3 sections (see Figure 12). It needs to be noted that this section had gone through 29 lead-free assembly cycles and the section shows a complete barrel crack (see Figure 13).

Figure 12

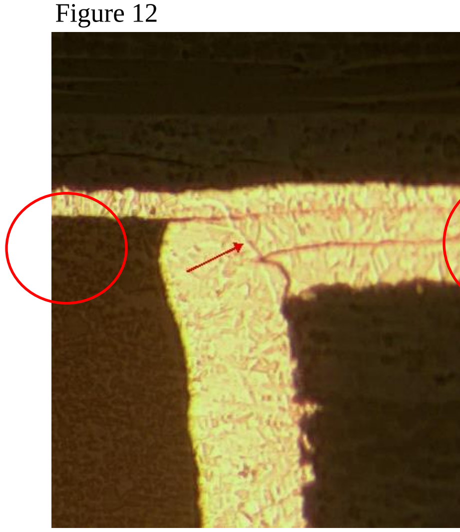
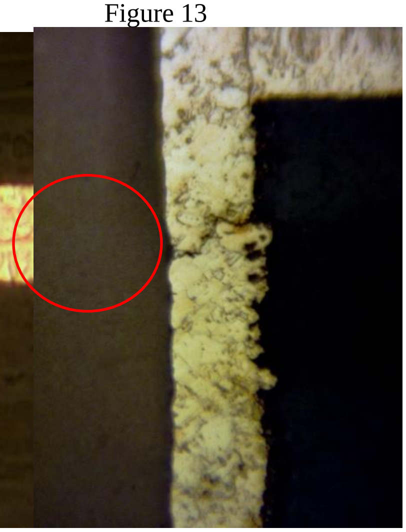


Figure 13



Conclusion:

Phase 1 data analysis showed that as long as there is some copper wrap plating, the main reason for failure was predominantly related to copper plating thickness in the barrel and not copper wrap plated thickness. Typically the failures were a fatigue type of failure. Since no coupon could be found which had no wrap plating at all it could not be categorically concluded that vias with no copper wrap plating would have followed the same failure mode. This led to the Phase 2 study.

The Phase 2 study showed that if coupons had IPC 6012 (C or D) Class 2 and Class 3 copper wrap plating thickness the failure mode would likely be barrel cracking, a fatigue type of failure. This was not true for Class 1 types with no wrap. Through vias with no wrap predominantly had unpredictable (butt joint) types of failure. Some sections also showed fatigue (barrel crack) failures.

This was not true for buried vias. All three types of copper wrap plating thickness coupons for buried vias had an average of 40.0 assembly cycles to failure. Even coupons with no wrap had an average of 31.3 assembly cycles to failure. Almost all failures for buried vias were fatigue related failures.

Weibull chart analysis, resistance plots, IST cycles and micro-sections analysis showed that barrel copper plating thickness has a major influence on cycles to failure rather than the copper wrap plating thickness, PTH via size and cap plating of buried vias.

It was also observed that plated through vias failed earlier compared to buried vias. There could be two factors which could cause the earlier failure. One being the length of barrel and the second being the greater volume of via fill material, which are both affected by z-axis expansion. Lead-free assembly (245^0 C) accelerated the time to failure compared to leaded assembly (230^0 C).

With a high degree of confidence, it can be stated that a board with Class 2 or greater wrap plating thickness is very reliable and any failure is not likely to be because of copper wrap plating thickness.

Future Work:

It was observed that some of the coupons with Class 2 and Class 3 wrap which had cracked barrels as a predominant failure also had shown an initiation of a corner crack. It must be kept in mind that these coupons have gone through an average of 37.5 assembly cycles and the failure mode is barrel cracking and not corner cracking.

High reliability customers do not accept any crack initiation in the area where the plating wrap is present. If a board is measured to have sufficient wrap but crack initiation is seen, the customer acceptance of this condition is required (MRB). For this reason, it is important to know when the cracks start. The next phase of testing will involve taking multiple coupons with Class 2 and Class 3 wrap and exposing them to a minimum of six assembly cycles. After that a coupon will be pulled out after every two additional cycles and micro-sectioned to look for any signs of copper crack initiation.

Acknowledgement:

The authors would like to thank PWB Interconnect and FTG Corp. management for committing multiple resources required to support manufacturing, testing, failure / statistical analysis and report writing for the Phase 1 and 2 work.

References:

1. Courtesy: IPC