Impact of Hole-Fill and Voiding on Pin Through-Hole Solder Joint Reliability

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Abstract
In this study, thermal cycling tests for samples of different hole-fill percentages and voiding were conducted, and cross sections of the PTH solder joints were performed to evaluate the solder microstructure, intermetallic formation, via hole-fill, and the condition of the PTH metallization and PCB dielectric prior to thermal cycling and at different times during thermal cycling. Different failure mechanisms were observed for solder joints with and without pin protrusion. PTH components with pin protrusion had better through hole-fill and less voids than PTH components without pin protrusion. The effect of hole-fill percentage and voiding on PTH solder joint reliability are discussed in detail.

Key Words: lead-free, SnAgCu, wave soldering, through-hole component, hole-fill, voiding, reliability,

Introduction
Hole-fill and voiding have raised many concerns on the solder joint reliability of the pin through-hole components using lead-free wave soldering processes. With the current lead-free process conditions, availability of flux materials, lead-free alloy surface tension and wettability, and copper dissolution, achieving a good hole-fill on a very thick board is a real process challenge using lead-free wave soldering, especially at component locations with heavy copper ground planes connected to those components. In addition, solder joints of lead-free PTH components tend to have more voids and larger voids than tin-lead solder joints.

In previous publications [2, 3] we reported the studies on the design and process optimization for large and thick boards for lead-free wave soldering. In this paper, we focus on the PTH solder joint reliability, particularly on the PTH solder joints with partial hole-fill and without pin protrusion. The impact of voiding on the solder joint reliability will also be discussed.

Test Vehicle and Components
A specially designed 406mm x 305mm test vehicle (Figure 1) was used for the lead-free wave soldering process development. Two board thicknesses (2.4mm and 5.0 mm) and two board surface finishes (immersion silver and immersion gold) were considered. The test vehicle had up to 14 layers with a maximum of 12 copper ground planes. It was designed into different areas for the study of the effects of pin-to-hole (P/H) ratio, pad/annular ring dimensions, spacing, orientation, thermal relief on hole-fill and for the reliability study of the PTH solder joints. The components in the reliability testing area were daisy chained.

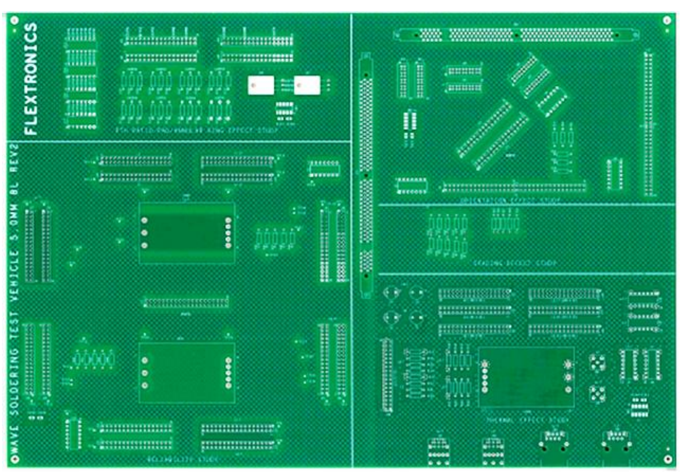


Figure 1 – Flextronics lead-free wave soldering test vehicle – Topside

A variety of through-hole components and selected surface mount components were included, such as headers, DIPs, aluminum capacitors, axial resistors, audio jack connector, BNC connectors, RJ45 connectors, DC-DC components, etc. A full list of the components is given in Table 1.

Table 1 - List of Components

Components	Qty/PCB	Component Type
Headers, 2x17pin, 100 mil pitch	40	PTH
Headers, 2x10pin, 50 mil pitch	6	PTH
DIP14,	14	PTH
Audio Jack	2	PTH
DIMM Connector	2	PTH
DC-DC Component	3	PTH
Axial Resistor	86	PTH
Radial Resistor	3	PTH
RJ45 Connector	2	PTH
BNC connector	2	PTH
Al Cap	4	PTH
Resistor 0402	20	SMT
Resistor 0603	40	SMT
Resistor 0805	40	SMT
Resistor 1206	20	SMT
SOT23	20	SMT
SO16	10	SMT

Hole-Fill Challenge

Typically, there is no hole-fill issue with board thickness below 2.4mm, when a lead-free wave soldering process is used, (Figure 2). As the board thickness increases, the hole-fill will decrease depending on the board design (number of connected copper ground planes and copper thickness) and the component type. Figure 3 shows the hole-fill percentage of many different components wave soldered in lead-free process using the 5.0mm thick boards. Many components had less than 50% hole-fill using fully optimized process conditions. In comparison, Figure 4 shows the hole-fill of the same components wave soldered in tin-lead wave soldering. As can be seen, there was slightly better hole-fill for components wave soldered in tin-lead process as compared with the same components in the lead-free process. The board thickness and the thermal mass of the connected copper ground planes make it more difficult to achieve good hole-fill for certain component types, regardless of the solder alloy (Figure 4).

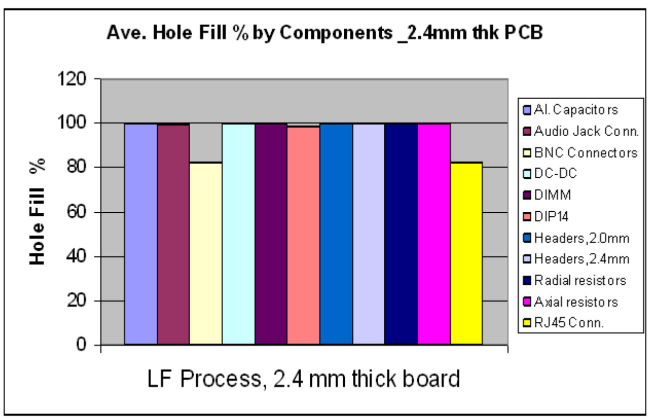


Figure 2 - Hole fill results for 2.4mm thick board. Good hole fill was achieved using 2.4 mm thick board

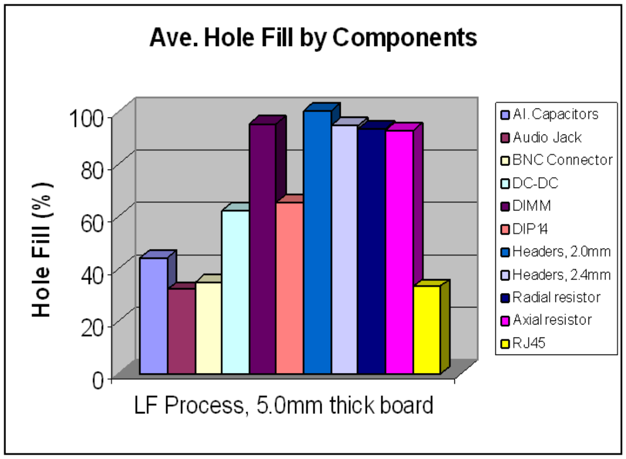


Figure 3 – Hole-fill results using 5.0mm thick board. Some components had less than desirable hole-fill.

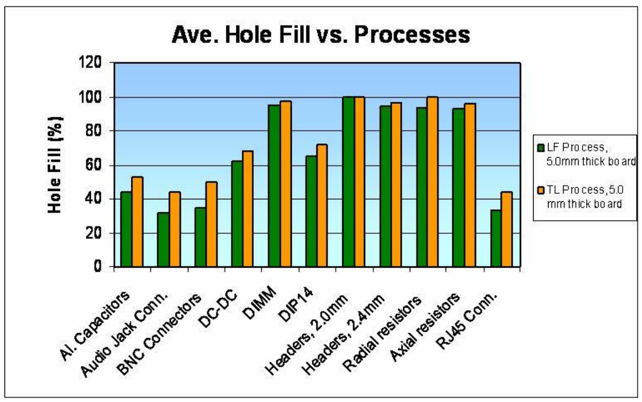


Figure 4 - Hole-fill vs. Component Type and Process. There was a slightly better hole-fill for components waved in tin-lead process as compared with the same components waved in lead-free process.

The internal copper plane had a significant impact on hole-fill. Copper thickness (copper weight) and the number of connected layers had an effect on hole-fill, with the influence of copper thickness on hole-fill being more noticeable. With the same amount of copper weight, the PTH component that is connected to multiple, but thinner copper layers resulted in better hole-fill than the PTH component connected to a heavy ground plane of the same amount of copper weight. For example, the PTH components that are connected to 2 layers of 0.5 oz copper resulted in better hole-fill than the components connected to 1 layer of 1.0 oz copper thickness. Similarly, the PTH components connected to 2 layers of 1.0 oz of copper thickness resulted in better hole-fill than the components connected to 1 layer of 2.0 oz of copper thickness (Figure 5). There was about 20-25% drop in hole-fill when the PTH solder joints were connected to 2 layers of 2 oz of copper thickness (Figure 5).

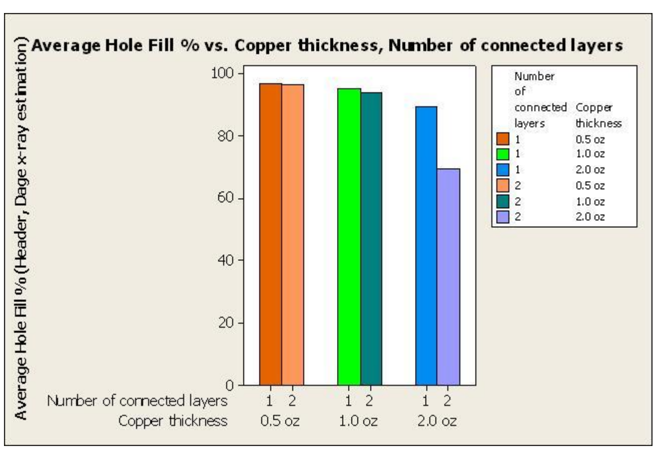


Figure 5 – Thermal effect on hole-fill

Voiding Concerns

Voids were seen on both tin-lead and lead-free solder joints (Figure 10). The study revealed that the P/H ratio significantly affected the amount and size of voids in the PTH solder joints (Figure 6). The smaller the PTH ratio (or the larger the hole diameter), the lower the extent of voiding. Figure 7 shows the images of PTH solder joints with different hole sizes. From the left to the right, the P/H ratios are 0.59, 0.53, 0.46, 0.36 and 0.30, respectively. As can be seen from the pictures, the P/H ratio of 0.59 had many voids, whereas almost no voiding was seen on the solder joints with P/H ratio of 0.3. Although more voids were seen on the components that had round pin shape as compared with square pins or rectangular pins (while the P/H ratio was the same), the effect of pin shape on voiding was not significant (Figure 7). More voids and larger voids were seen on the solder joints of 5.0 mm thick board than on the solder joints of 2.4 mm thick board. However, the pin-to-hole ratio was still the dominant factor that influences voiding. The ENIG boards had less voids than the immersion silver boards (Figure 8). More voids were seen on the solder joints without pin protrusion than on the solder joints with some pin protrusion (Figure 9). Figure 10 illustrates the voiding amounts of tin-lead and lead-free solder joints, and of lead-free solder joints with different board thicknesses and board surface finishes at the pin-to-hole ratio of 0.6 (the worst case).

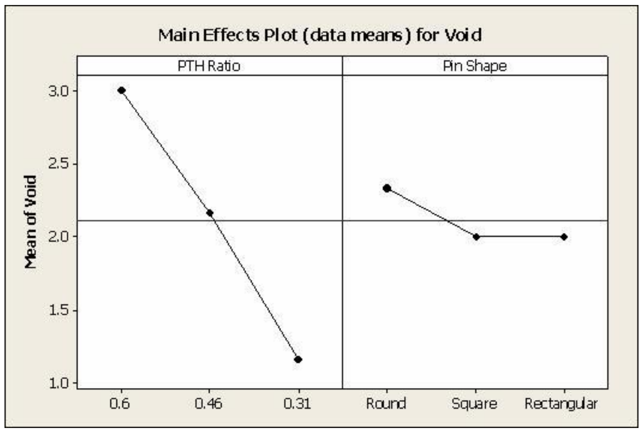


Figure 6 - The effect of PTH design on voiding. 1= little or no void; 2 = some voids; 3 = very large voids or champagne voids.

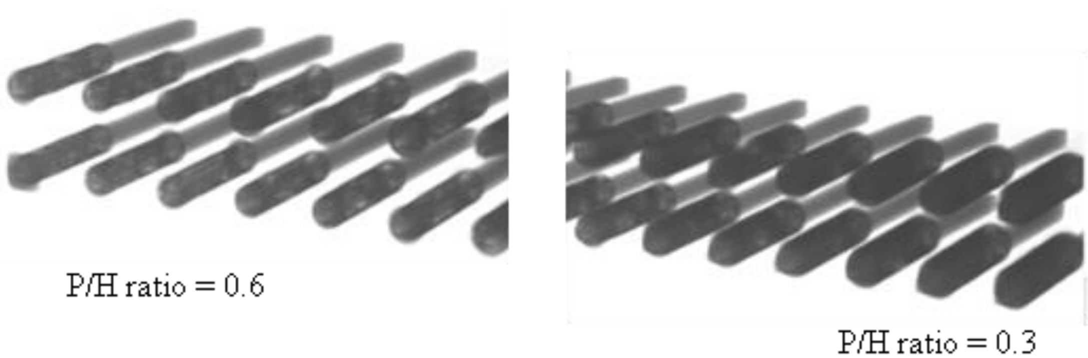
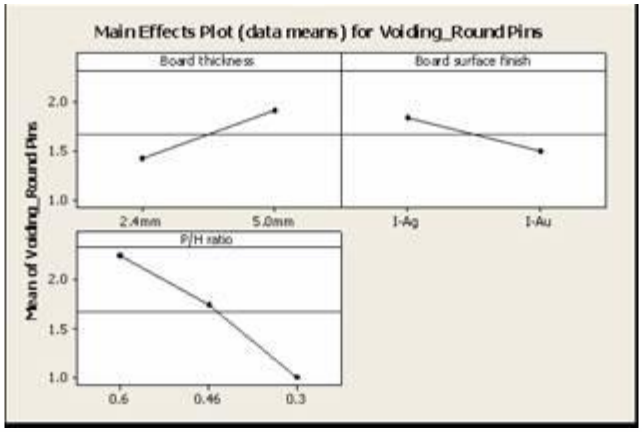


Figure 7 – X-Ray Images of PTH solder joints at different P/H ratios



Analysis of Variance for Voiding_Round Pins, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Board thickness	1	0.08333	0.08333	0.08333	4.00	0.184
Board surface finish	1	1.33333	1.33333	1.33333	64.00	0.015
P/H ratio	2	2.62500	2.62500	1.31250	63.00	0.016

S = 0.144338 R-Sq = 99.17% R-Sq(adj) = 95.42%

Figure 8 – Voiding vs. board thickness and board surface finish.

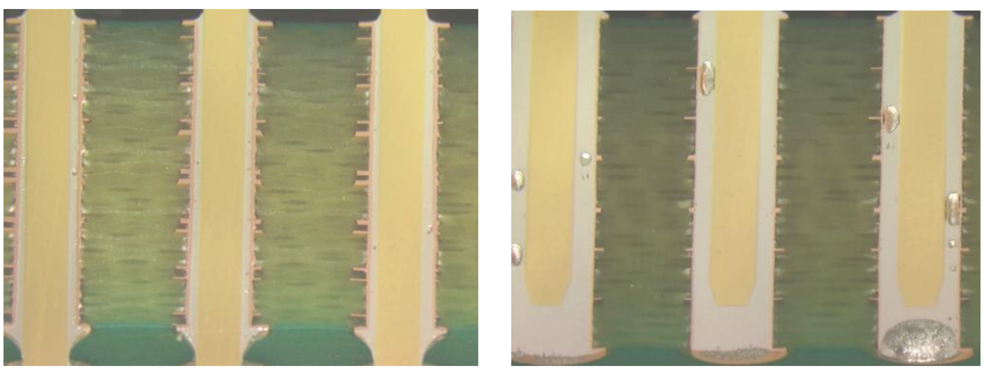
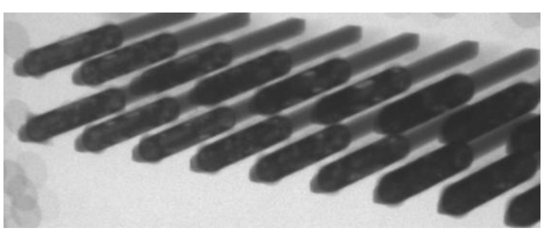
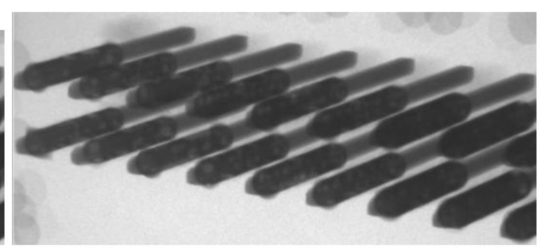


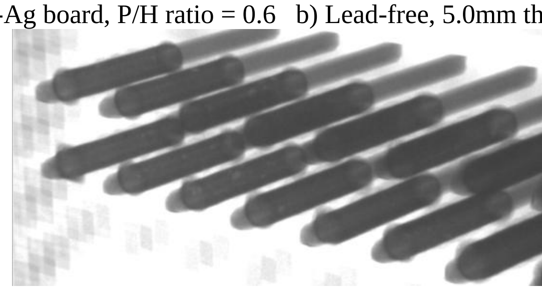
Figure 9 - Voiding vs. Pin length



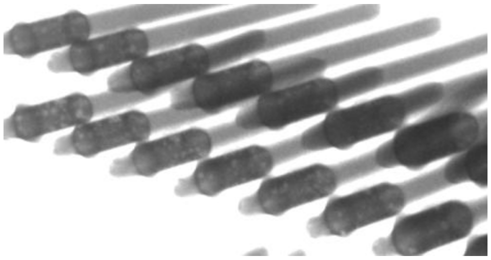
a) Tin-lead, 5.0mm thick, I-Ag board, P/H ratio = 0.6

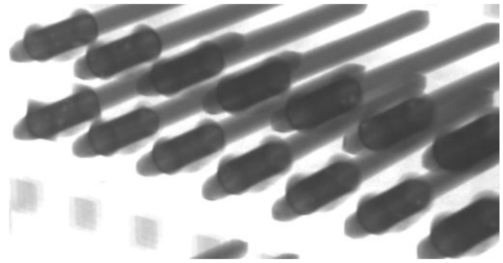


b) Lead-free, 5.0mm thk, I-Ag board, P/H ratio= 0.6



c) Lead-free, 5.0mm thick, ENIG board, P/H ratio of 0.6





d) Tin-lead, 5.0mm thick, I-Ag board, P/H ratio = 0.6 e) Lead-free, 5.0mm thk, I-Ag board, P/H ratio= 0.6

Figure 10 – X-ray images of PTH solder joint voids for different board thicknesses and board surface finishes.

Reliability Study

Sample Preparation

Samples of different hole-fill percentages, with immersion silver finish PCBs, were prepared for thermal cycle testing (Table 2). Two different board thicknesses (2.4mm and 5.0mm) and three different hole-fill percentages (30%, 50% and 100%) were investigated. The components were daisy chained for continuous monitoring during the testing. Solder joints with pin protrusion and without pin protrusion were considered. Samples with extensive voiding in the solder joints were also tested (Figure 11). Only the pin headers and axial resistors were included in the reliability test.

Table 2 – Samples for ATC testing

Board No.	PCB thickness	Board Descriptions (HF is % via hole fill from X-ray)
1	5.0 mm	100 % HF, with pin protrusion
2	5.0 mm	100 % HF, with no pin protrusion
3	5.0 mm	50 % HF, with pin protrusion
4	5.0 mm	50 % HF, with no pin protrusion
5	5.0 mm	30 %HF, with pin protrusion
6	2.4 mm	100 % HF, with pin protrusion
7	2.4 mm	100 % HF, with no pin protrusion
8	2.4 mm	50 % HF, with pin protrusion
9	2.4 mm	50 % HF, with no pin protrusion
10	2.4 mm	30 %HF, with pin protrusion

Figure 11 - X-Ray showing intentionally extensive voiding in PTH solder joints.

Thermal Cycle Test Conditions

The thermal cycle testing was performed in an air-to-air thermal cycle chamber, from 0 to 100°C with 15-minute dwell time at each peak temperature, and a temperature ramp rate of approximately 15°C per minute. The chamber profile of temperature versus elapsed time is shown in Figure 12.

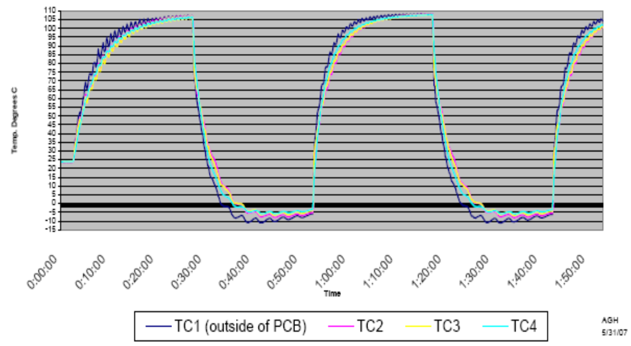


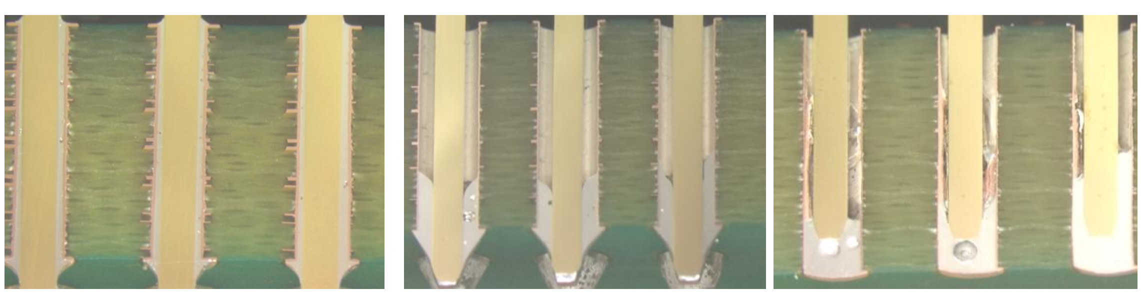
Figure 12 - Thermal Cycle Temperature Profile – 0 to 100 degrees C

Results and Discussions

<u>Solder Joint Microstructure – Time Zero Analysis</u>

Cross sections of the PTH solder joints (Figure 13) were performed to evaluate the solder microstructure, intermetallic formation, via hole-fill, and the condition of the PTH metallization and PCB dielectric, at time zero (prior to thermal cycle testing). The via hole fill values from the X-ray analysis were in reasonable agreement with the values from cross-sectioning for the samples with pin protrusion. The samples without pin protrusion exhibited less than expected hole-fill. The cross section revealed that only a small portion of the pins was covered in solder on samples without pin protrusion (Figure 13c).

No cracked solder joints were found on the time zero samples. There were no visual indications of a concern with copper dissolution at the knee of the PTH. No fillet lift-off solder cracks or cracked PCB solder eyelets were found at the ingress of the eyelet to the PTH barrel at time zero. The cross sections exhibited bending of the annular ring and copper eyelets, which was caused by the z–axis expansion of the PCB dielectric, during wave soldering (Figure 14). The Cu_6Sn_5 intermetallic compound (IMC) at the solder to copper interface on the immersion silver plated PCB vias exhibited a thicker and more uniform area coverage than the thin, ternary (Ni, Cu) Sn IMC layer on the pins (Figure 15). The area and thickness uniformity of the Cu_6Sn_5 IMC layer on the copper PTH metallization was normal, and the IMC thickness was 1 to 3 microns. The ternary (Ni, Cu) Sn IMC at the solder to nickel barrier plating interface on the pins is inherently very thin (less than approximately 0.5 microns), and barely visible at the magnifications used to collect the photos (Figure 15), where the nickel barrier layer on the pin base metal is the easily visible grey colored layer.



a) b) c)

Figure 13 - Cross sections of 5.0mm thick boards at time zero. a) Good HF (100%) with pin protrusion b) Poor HF (30%) with pin protrusion c) Poor HF without pin protrusion

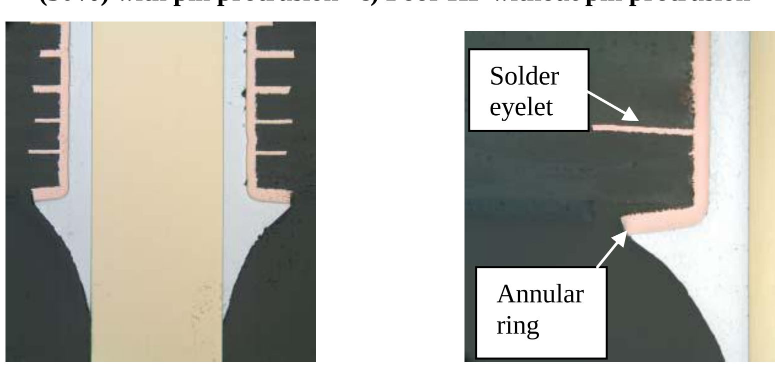


Figure 14 - X-ray of PTH construction and photos of cross sections of solder joints showing bending of copper metallization from Z-axis expansion of the PCB dielectric.

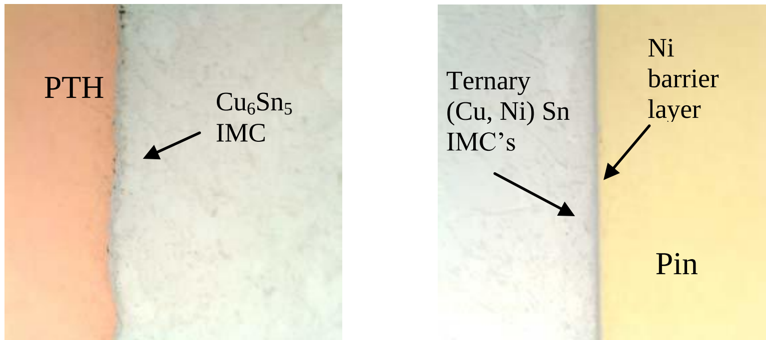


Figure 15 - Photo of cross sectioning showing intermetallics in solder joints

<u>Failure Analysis after 1000 thermal cycles</u>

All samples were continuously monitored during thermal cycling. One sample (board 9, J29) failed after 500 cycles (Table 3), and the sample was left in the chamber and was analyzed for failure mode only after 1000 cycles.

Table 3 - Electrical Resistance failures as of 1000 thermal cycles

Board No.	Board Thickness [mm]	Hole Fill %	Pin prot.	Conn. Location	R after zero cycles [Ohms]	R after 250 cycles [Ohms]	R after 500 cycles [Ohms]	R after 750 cycles [Ohms]	R after 1000 cycles [Ohms]
9	2.4	50	no	J29	0.248	1.218	open	open	open

X-ray inspection of the failure exhibited a hole-fill of approximately 25%; however, this particular sample did not have pin protrusion (e.g. Figure 17.c), so the actual solder coverage was effectively less than 25% (Figures 16.a – 16.b). Inspection of the pin following removal of the solder showed that the solder was not properly wetted to the pin and was likely mechanically contacting the pin rather than being metallurgically bonded. This resulted in the early failure, Figure 16.c.

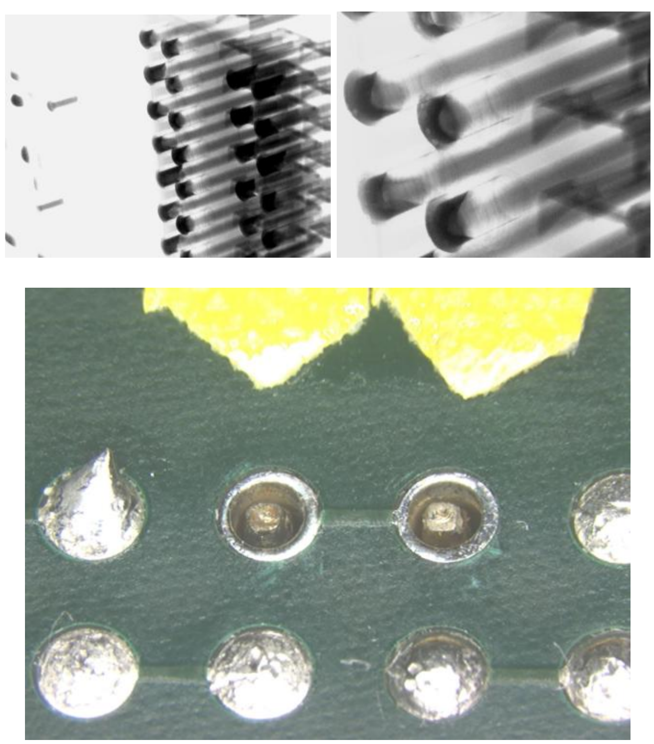


Figure 16.a – 16.c: X-Ray radiographs showing via hole-fill and light micrograph of sample failed 500 cycles.

Cross sectioning was performed for PTH components, and their solder joint microstructure was analyzed after 1000 cycles. Corner solder cracks and cracks along the sides of the PTH barrels were found following 1000 thermal cycles but these had not yet resulted in electrical opens. The presence of voids in the PTH solder joints facilitated the solder joint cracking under thermo-mechanical stress (Figure 17a), but the voids did not initiate cracks. Solder fillet lift-off cracks were not found. Samples with complete hole-fill and pin protrusion displayed cracks that originated at both the top and bottom fillets and propagated along the side of the PTH, e.g. Figures 17.a – 17.b. Samples without pin protrusion had cracks that propagated along the sides of the PTH barrel, and some originated in the middle of the solder joint (Figures 18.a – 18.b). Visual inspection suggested that the extent of the cracking on the 5.0mm thick PCBs was greater than on the 2.4mm thick PCBs. Cracked solder eyelets and cracked annular rings were found on some of the samples (Figures 19.a). The extent of cracked annular rings was greater in samples with complete hole-fill and pin protrusion because of the thermo-mechanical stress resulting from the CTE mismatch between the solder, pin base metal, and PCB materials. The analysis of time zero samples initially showed that the Z axis expansion from solder reflow had stressed the annular rings on the vias and solder eyelets, and then thermomechanical fatigue during thermal cycling likely cracked the copper metallization. Figure 19.b displays cracked copper in the via wall plating.

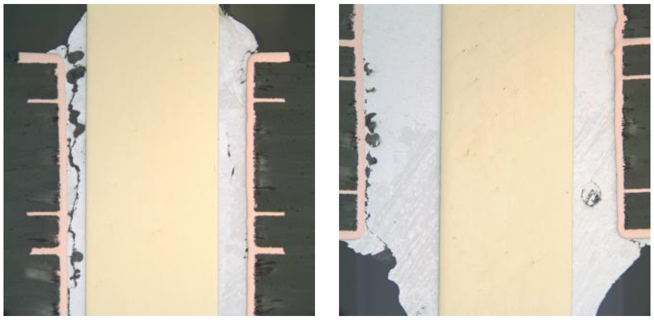


Figure 17.a-17.b - Showing worst case stress relaxation corner solder cracks initiating at the top and bottom fillets in samples with 5mm thick PCB, 100 percent hole-fill, and pin protrusion

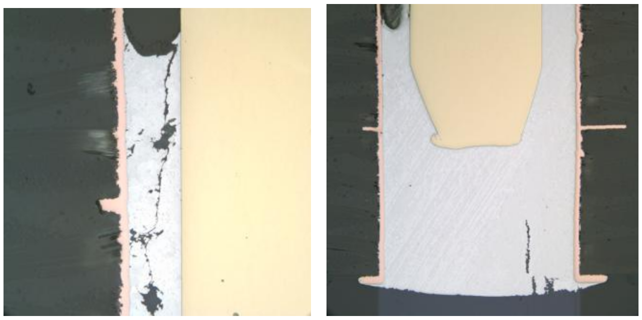


Figure 18.a and 18.b - Showing a worst case crack at the top of the solder fill (not 100% hole fill), and a crack initiating on the center of the bottom fillet in samples with 5mm thick PCB, 80 percent hole fill, and no pin protrusion

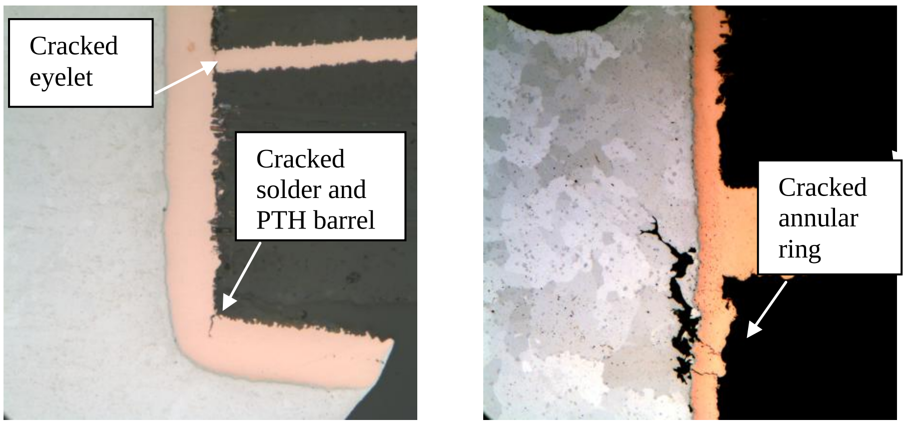


Figure 19 - PTH copper cracks

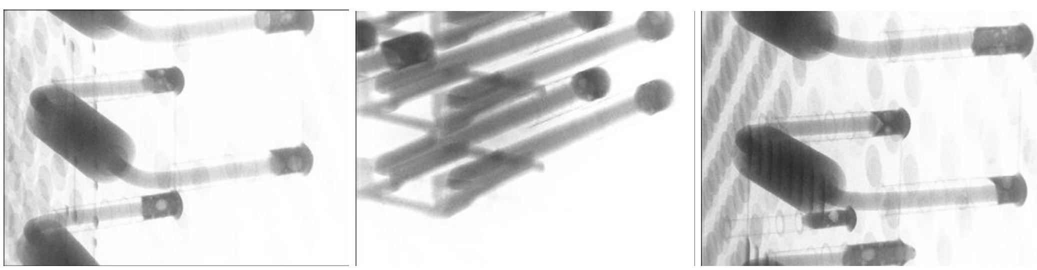
Failure Analysis after 2000 and 3000 thermal cycles

Five failures were observed for samples without pin protrusion between 1250 to 1300 cycles, and another open was seen at 2500 cycles (Table 4). The failures were electrically confirmed by manual probing. Failed electrical resistance samples were left inside the chamber, and were then cross-sectioned after 3000 cycles.

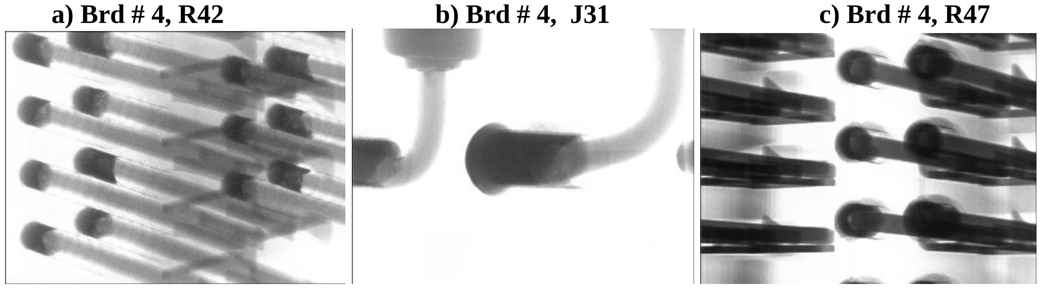
Table 4 – Electrical Resistance Failure after 3000 cycles

Board No.	Board Thickness	Board Descriptions	Resistance failure	Cycles to Failure	Failed Locations
1	5.0 mm	100 % HF, with pin protrusion	0		
2	5.0 mm	100 % HF, with no pin protrusion	0		
3	5.0 mm	50 % HF, with pin protrusion	0		
4	5.0 mm	50 % HF, with no pin protrusion	1	1250	R42
4	5.0 mm	50 % HF, with no pin protrusion	1	1251	J31
4	5.0 mm	50 % HF, with no pin protrusion	1	1265	J23
4	5.0 mm	50 % HF, with no pin protrusion	1	1300	R47
5	5.0 mm	30 %HF, with pin protrusion	0		
6	2.4 mm	100 % HF, with pin protrusion	0		
7	2.4 mm	100 % HF, with no pin protrusion	0		
8	2.4 mm	50 % HF, with pin protrusion	0		
9	2.4 mm	50 % HF, with no pin protrusion	1	500	J29
9	2.4 mm	50 % HF, with no pin protrusion	1	1250	R46
9	2.4 mm	50 % HF, with no pin protrusion	1	2500	J28
10	2.4 mm	30 %HF, with pin protrusion	0		

All of the failures were samples with no pin protrusion. The x-ray radiographs (Figure 20) showed poor hole fill (<25% for most samples, except for board #9, R46). Cross sections revealed that only a small portion of the failed pin length was wave-soldered. Figures 21.a and 21.b showed the pin's solder length of board 4, location J23. Figure 21.c showed the typical solder length of board # 9, location J28 that had an electrical open after 2500 cycles. Approximately less than 20-25 mil of PTH pin length was soldered on all samples that were electrically open up to 3000 cycles.

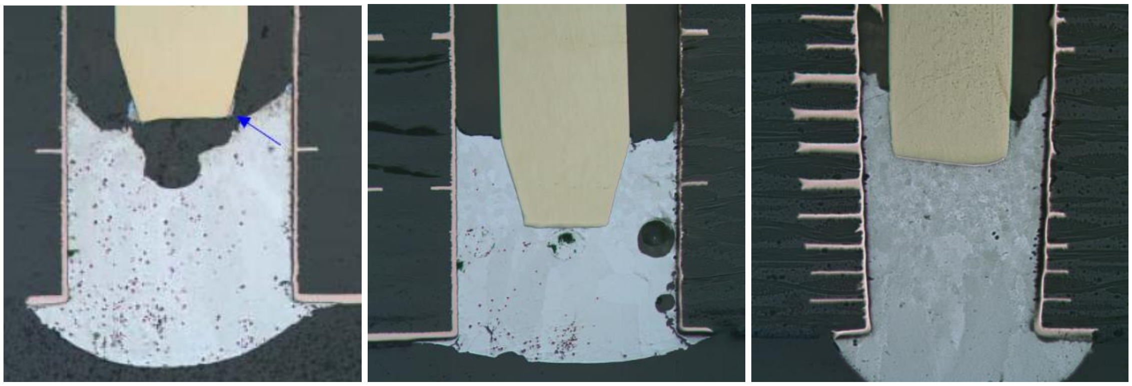


a) Brd # 4, R42 **b) Brd # 4, J31** **c) Brd # 4, R47**



d) Brd # 4, J23 **e) Brd # 9, R46** **f) Brd # 9, J28**

Figure 20 - X-ray images of samples with electrical resistance failure. Figure 20.a-d from board #4. Figure 20.e-20.f was from board # 9. All samples had no pin protrusion and poor hole-fill.



a) brd #4, J23, pin 32　　b) brd #4, J23, pin 33　　c) brd # 9, J28, pin 14

Figure 21- Cross-sections of the failed electrical samples after 3000 thermal cycles.

Conclusions

Pin protrusion is necessary for achieving good hole-fill for lead-free wave soldering of thick boards, as PTH components with pin protrusion have better PTH hole- fill and fewer voids than those without pin protrusion. Cracks were visible in the solder joints, but they did not result in open solder joints as of 1000 thermal cycles. Open solder joints were observed after 1200 cycles for PTH components with very poor hole-fill and without pin protrusion. None of the samples with pin protrusion had open solder joints up to 3000 thermal cycles. Voids facilitated the solder joint cracks, but no failure was initiated at the voids. The thermal cycle test is still on-going.

Acknowledgements

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