DOES COPPER DISSOLUTION IMPACT THROUGH-HOLE SOLDER JOINT RELIABILITY?

Craig Hamilton[1], Polina Snugovsky[1], Mario Moreno[2], Teng Hoon Ng[3], Juthathip Fangkangwanwong[3]
Celestica Toronto[1], Celestica Mexico[2], Celestica Thailand[3]

Matthew Kelly[4] and Marie Cole[5]
IBM Corporation Toronto, Canada[4], IBM Corporation Fishkill, NY, USA[5]
chamilto@celestica.com, polina@celestica.com, mattk@ca.ibm.com

ABSTRACT

The process issues relating to high copper dissolution rates have been well documented within the industry. The copper dissolution rates of SAC305/405 plus many of the leading alternative lead-free wave alloys have been characterized and pin-through-hole rework process windows assessed. One remaining gap within the industry is the understanding of how copper dissolution or thinning of the through-hole barrel wall/knee locations impacts the thermal and mechanical reliability of a pin-through-hole joint. This paper provides a summary of previous work performed to study and characterize the copper dissolution rates of various Pb-free wave alloys, as well as attempts to assess the impact of high levels of copper dissolution on the thermal reliability of a 14 I/O PDIP connector. A total of five PDIP connectors were designed onto a test vehicle, each individually daisy chained using bottomside traces, for in-situ monitoring. A design of experiment was defined as an attempt to vary the level of plated copper remaining after simulating the rework of the five PDIP connectors. Each board was subjected to 0-100°C ATC for 6,000 cycles with in-situ monitoring to detect failures throughout testing using data loggers. The results from this work indicate reliability concerns when a severe degree of copper dissolution occurs and shows signs of reduced reliability due to thinning of the copper plating thickness at the knee location. In addition, mechanical and thermo-mechanical loading are key elements necessary to confirm the reliability of a pin-through-hole joint, this paper however, focuses on thermal fatigue reliability assessment. Lastly, this paper will highlight limitations of the copper plating measurement methodology used and suggests alternative non-destructive options to inspect for copper dissolution within manufacturing environments.

Key words: copper dissolution, reliability

INTRODUCTION

Since the introduction of lead-free soldering into the electronics assembly industry, the issues surrounding copper dissolution have slowly begun to surface. Initially, the focus of lead-free implementation was on optimizing the SMT process - ensuring that quality, reliability and repeatability levels were acceptable. As knowledge was gained with the SMT process, attention shifted to back-end processes. A large part of that attention was (and still is) focused on the issue of copper dissolution. Over the past few years there have been a handful of studies from various companies and consortia on this topic. With the expiration of the RoHS 'lead in solder' exemption looming, many of the high reliability OEMs within the server/storage and aerospace & defense (A&D) segments, among others, are concerned about the reliability impact copper dissolution will have on the life of their products. This paper will summarize the collaborative work performed by the authors on this topic to date and some of the key outputs from various external bodies of work published on this subject. The main focus of this study however, was to document and understand the impact of moderate to severe levels of copper dissolution on the thermal fatigue solder joint reliability of a pin-through-hole solder joint.

The chevron chart below (Figure 1) illustrates the development process which was followed to study copper dissolution. The process flow essentially follows a standard "Six Sigma DMAIC[TM] process", of defining the problem, quantifying/measuring the process variables, analyzing the outputs, making improvements and implementing the solution/s with a process control system in place.

Figure 1. Copper Dissolution Development Process Flow

In summary, upon identifying the issues of copper dissolution during early lead-free solder fountain qualification trials; an initiative was established to first "define the problem". In this first study, the significance of each of the main factors within a typical solder fountain rework process has on impacting copper dissolution was analyzed [1]. The next two phases of work involved "quantifying the impact" of copper dissolution on the process of reworking a through-hole connector, and "identifying solutions" which help to mitigate the occurrence of copper dissolution [2]. Although there were numerous factors which could help to reduce copper dissolution, it was the use of alternative lead-free alloys which provided a solution that had a high degree of success, matched with minimal impact to the manufacturing process

itself. Prior to implementing a new alloy solution, the process performance and reliability of these alloys were studied. This alloy comparison was the primary focus of the "confirm reliability" phase of work [3,4].

The outcome of this body of work has provided many valuable lessons learned relating to copper dissolution. These results along with others published within the industry will be summarized in the section below.

BACKGROUND
As mentioned, there have been numerous industry studies over the past few years which have focused specifically on the topic of copper dissolution. This section will attempt to highlight and summarize some of the key outcomes from a group of studies and will identify the current industry gaps.

Copper Dissolution "Knowns"
The following questions typically asked relating to copper dissolution will be discussed, using references from previous studies:

- Is it "Dissolution" or "Erosion"?
- What is copper dissolution?
- Where does it occur?
- How can you detect it?
- Why is it a problem?
- What factors impact copper dissolution rates?
- What solutions can control or mitigate copper dissolution?
- What impact will the solution(s) have on manufacturing?

Dissolution vs. Erosion
The terms copper dissolution and copper erosion have both been used in many industry technical papers on this topic. This paper and all previous published papers from the authors on this topic refer to the phenomenon as copper "dissolution", as opposed to "erosion". The reason for this is as follows: Dissolution is a diffusion controlled process which results in a uniform attack of the copper layer over time (Figure 2a). The final outcome observed results in a smooth surface. Erosion, on the other hand, is more of a preferential etching of the grain boundaries, which results in the formation of a rough surface. In this case whole grains may be removed (Figure 2b).
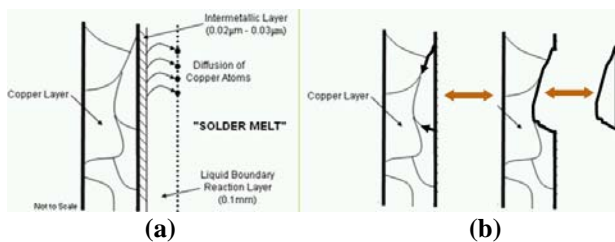

Figure 2. Illustration of (a) Dissolution and (b) Erosion

Copper Dissolution Defined
This section will summarize what copper dissolution is, where it occurs, how it can be detected and explain why it is

a problem. Copper dissolution is a natural phenomenon which occurs when molten solder comes into contact with copper plating. Over time portions of the copper plating will dissolve into the solder alloy. Dissolution is a process which is natural and necessary to form a solder joint. It is a process which forms intermetallic bonds, providing strength to the solder joint itself. Within the EMS process environment, it is often pin-through-hole (PTH) connectors where instances of copper dissolution will be found – but not always limited to this case.

Considering the PTH processes, the largest impact of copper dissolution will occur during the PTH rework process because of higher contact times. Typically it will take anywhere from 3-10 seconds to solder a board through the wave solder process. To rework a connector, it can take anywhere from 15-120 seconds, depending on the size and complexity of the connector and considering a 2X rework. In addition to contact time, the solder fountain process typically has flow rates which are more turbulent compared to the wave solder process. A paper released in 2008 did a good job in illustrating this fact [5]. The copper plating thickness of a PTH barrel was measured as received (baseline), after the wave solder process and then after a PTH rework operation (using both SAC305 and a SnCuNiGe alloy). The results showed that the majority of dissolution occurred during the PTH rework process. On average only 0.1mils (2.5μm) of copper plating was removed after the wave operation and an additional 0.7mils (17.8μm) removed after reworking with SAC305 alloy (Figure 3). This study also showed the benefits of using an alterative alloy in reducing the degree of copper dissolution which occurred – especially during the rework process.
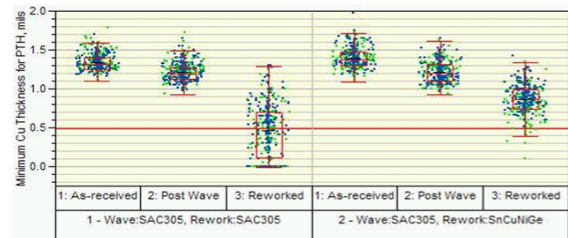

Figure 3. Copper Dissolution Results by PTH Process [5]

Factors that Impact Copper Dissolution Rates:
The following factors have been shown to have either a positive or negative impact on influencing or controlling the degree of copper dissolution during either a PTH wave solder primary attach and/or PTH rework process.

- Barrel geometry
- PCB surface finish
- Solder flow rate
- Process parameters
  - Contact (or exposure) time
  - Pot (or solder) temperature
  - Preheat temperature
- Alloy composition
- Copper plating Surface

Impact of Barrel Geometry:
Many studies have concluded that the bottomside "knee" location of the PTH barrel is the most susceptible to dissolution (Figure 4). A previous study [2] measuring the copper plating thickness at the barrel wall, knee and annular ring locations resulted in an established dissolution hierarchy which quantitatively confirmed that the knee location does in fact have the highest dissolution rate, followed next by the annular ring (or pad) and finally the inner barrel wall (Figure 5).
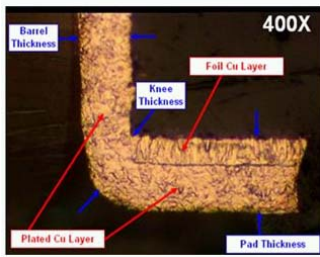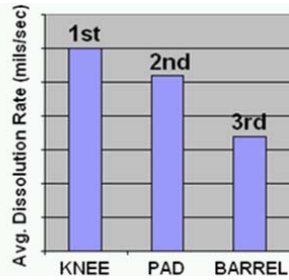

Figure 4. Barrel Nomenclature

Figure 5. Copper Dissolution by Geometry

This finding combined with the fact that the knee location has a thinner initial plating thickness than that of the pad, leads to the conclusion that the knee location will come to complete dissolution faster than the pad location (in the majority of cases). This finding has been well documented in many other studies [2,5,6]. This by itself creates a concern based on the fact that it is possible for a hidden defect to be present after reworking a PTH connector, which could result in future failures in the field (Figure 6a,b).
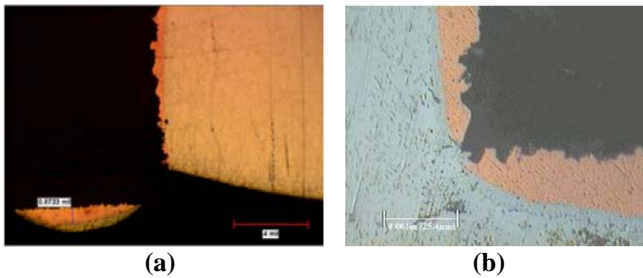

(a)   **(b)**
Figure 6. Evidence of Copper Dissolution at Knee Location, (a) Example Study 1 [2] ; (b) Example Study 2 [5]

Impact of PCB Surface Finish:
PCB surface finish selection can have an impact on the rate of copper dissolution. There is little difference in the rates between immersion finishes (ImmAg, ImmSn) and organic solder preservative (OSP) finish. The thin silver, tin or organic layer of these finishes provides very little defense against copper dissolution. The finishes themselves are typically thin enough to be removed during the primary attach process.

On the other hand, surface finishes which have a nickel barrier – e.g. electroless (ENIG) and electrolytic (NiAu) nickel gold finishes will dissolve more slowly compared to the copper based finishes. There are both chemical and physical properties which explain this fact. But in general, nickel is inherently less soluble in tin compared to copper, and in a way offers a protective barrier against dissolution. A study was performed to measure the differences in dissolution rates between an OSP finish and an ENIG surface finish while being exposed to SAC405 solder. After only 60 seconds over a solder fountain, the OSP sample experienced 100% copper dissolution of the knee (Figure 7). The ENIG sample after the same amount of time had very little dissolution of the nickel layer, and the copper layer was left untouched (Figure 8). Both the OSP and ENIG samples started with a 1.8mils (45.7μm) thickness at the knee location.
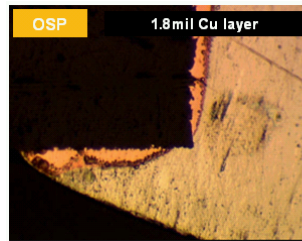

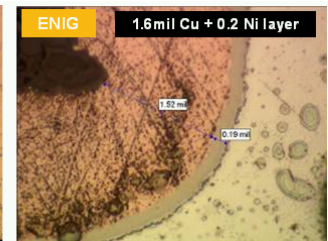**Figure 7.** OSP Sample   **Figure 8.** ENIG Sample

From these results, the nickel and copper dissolution rates were calculated. The copper layer dissolved at approximately 0.034mils/sec (0.86μm/sec) and the nickel layer dissolved at 0.0038mils/sec (0.10μm/sec) – a 9X slower dissolution rate (Figure 9). A separate study has also shown the benefits of the nickel layer in increasing the PTH rework process window. However, cases have been observed where ENIG plated samples have had knees completely dissolve after 60 seconds of exposure on a static SAC305 pot [7]. This indicates that surface finish alone is not a complete solution and other factors are involved in controlling the rate of copper dissolution.
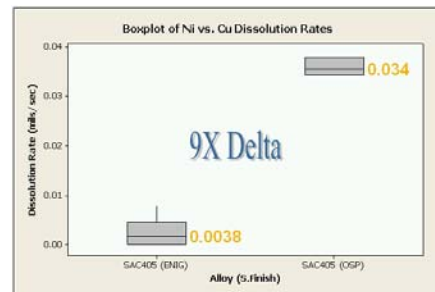

Figure 9. Copper vs. Nickel Dissolution Rates

With respect to lead-free HASL finishes, a previous study documented "excessive copper dissolution of the pads" resulting from a (horizontal) HASL process itself, using a Sn-0.7Cu alloy as the finish (up to 0.47mils (12μm) of copper was removed) [8]. To correct these issues, the subsequent surface finish processing of the lead-free HASL boards used a SnCuNi alloy as the finish – which reduced the degree of copper dissolution occurring during the HASL process to only 0.08mils (2μm) at the same pad location. The same study also documented issues of severe levels of copper dissolution occurring during the (2X) PTH rework

process using SAC305 alloy – "In many cases, there was complete copper erosion of the bottom side PTH land". Hence the lead-free HASL finished boards themselves did not provide any additional value in terms of mitigating the occurrence of copper dissolution during the PTH rework operation and offer higher levels of initial copper dissolution of the copper lands during the finishing process itself. A separate study documented that "with traditional lead-containing solder, the reduction in copper thickness was constant at a level of 0.06mils (1.5µm) for each soldering or HASL process, which was covered by the normal tolerances applicable to PCB fabrication and assembly processes. However, in lead-free soldering the reduction in copper thickness is typically 0.14mils (3.5µm) for each of the HASL or soldering process" [9].

Impact of Flow Rate
Early studies had indicated the significance of the location of the barrels relative to the opening of a typical solder fountain flow well on the level of copper dissolution which occurs [2]. Specifically, visual observations were made after multiple reworks that the center barrel locations, which were directly above the opening of the flow well, were dissolving at a much faster rate compared to those at the edges of the connector. The theory behind this observation is that the barrels located in the center are being subjected to higher flow rates compared to those at the end (Figure 10).
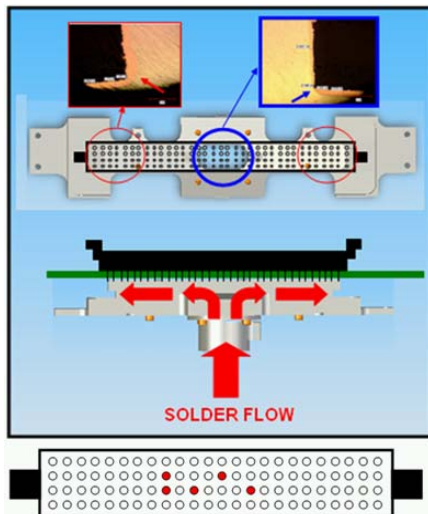

Figure 10. Impact of Flow Rate on Copper Dissolution

A more recent study published quantified this same observation by taking multiple copper plating measurements at various points along a PCI connector [10]. As can be seen from Figure 11, the results show a strong correlation between the edges vs. center of a PTH connector with regards to the degree of copper dissolution. Furthermore, studies in manipulating the solder turbulence within the center region of the flow well through various baffle designs have shown improvements in minimizing the occurrence of copper dissolution [5,11].
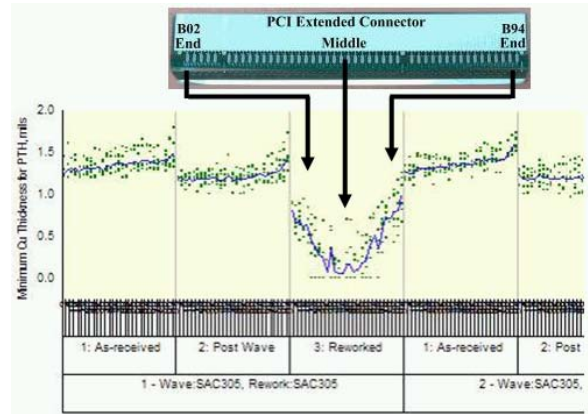

Figure 11. Minimum Copper Thickness Measurements taken across a PCI Connector after Wave and Rework [10]

Impact of Process Parameters:
Earlier studies [2] focusing on attempts to optimize a SAC405 solder fountain rework process in order to minimize copper dissolution determined that contact time was the most significant factor affecting copper dissolution. The higher the contact time, or exposure to molten solder, the higher degree of copper dissolution – a now well known and proven fact. The results from this particular study, however, showed that both preheat and pot temperature had little impact or significance on affecting dissolution within the ranges of temperature selected for that particular experiment (252°C to 278°C). However, the pot temperature results were trending in the direction expected: higher pot (or alloy) temperatures caused an increase in copper dissolution. A separate study, noted that a higher pot temperature proved to be "statistically and technically significant", with a much lower average copper thickness after a 30 second exposure of a PCI connector between 530°F (277°C) and 545°F (285°C) pot temperatures [5]. This result indicates that the higher the pot temperature the higher the rate of copper dissolution.

Impact of Alloy Composition:
The impact of alloy composition on the copper dissolution rate has been well documented [4,7,12,13]. Many studies have shown that tin (Sn) rich solders dissolve copper more readily when compared to eutectic Sn-Pb solders. As well, an increasing copper concentration within the solder causes a decrease in the amount of copper dissolved. Therefore, similar solders with higher percentage copper will dissolve less copper from the plating layer. Hence, SAC305 (0.5% Cu) will have a higher copper dissolution rate compared to SAC387 (0.7% Cu) [3,7]

In addition, it has been proven that additives such as nickel, bismuth and antimony act to reduce copper dissolution rates. Typically these elements improve solder grain structure, strength and/or ductility. However, they may be prone to defects such as fillet lifting, contamination issues and poor wetting [3]. Other additives, such as germanium, act as anti-oxidants and react with oxygen to reduce copper dissolution and help to improve wetting (i.e. effects barrel fill).

Impact of Copper Plating:

It has been suspected that the plated copper surface itself may play a role in the copper dissolution process. A recent study [14] specifically focused on analyzing the differences in the grain structures, mechanical properties, and dissolution rates of ten electrodeposited copper samples. The theory was that loose, open grain structures associated with columnar grain morphology are perceived to dissolve more readily than tighter, fine, grain structures. Generally, finer grain structures exhibit higher bond strength between the grains, and thus require more energy to "break" loose or dissolve. The study found that two identical circuit boards from different suppliers can demonstrate vastly different dissolution properties in the same soldering process. Differences in the grain structures, mechanical properties, and dissolution rates of ten electrodeposited copper samples were observed. The results showed differences in dissolution rates among suppliers by a factor of 1.4X to 1.7X and the dissolution rates varied between plating baths within the same fabricator (Figure 12). However, no strong statistical correlations were found between grain structure and dissolution rates. Further work is on-going to confirm this finding.
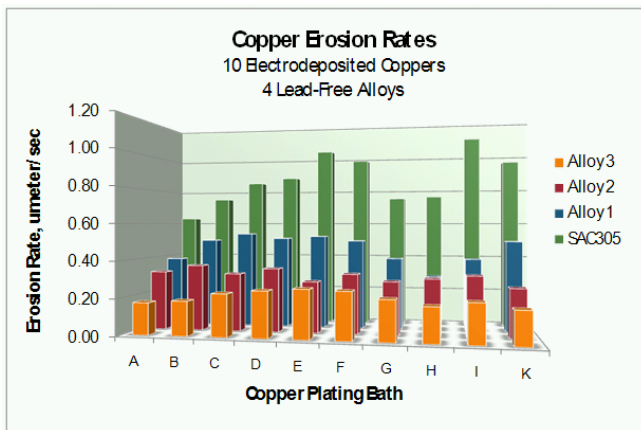

Figure 12. Copper Dissolution Rates of 10 Electrodeposited Coppers, using 4 Lead-Free Alloys [15]

Copper Dissolution "Unknowns"

One of the largest unknowns to date is the impact which copper dissolution has on the reliability of a PTH joint. Pin-through-hole joints themselves have historically known to be very robust. But what happens to the joint after portions of the copper plating have been removed? In addition to this concern, industry specifications do not exist which clearly define the final acceptable copper plating thickness after multiple rework operations. There is a current IPC specification addressing the recommended copper plating thickness for finished assemblies (IPC-6012B). However, this only addresses the PCB fabrication requirements and not post-process requirements. Currently, many companies are using a minimum specification limit of 0.5mils (12.7µm) of remaining copper plating after both a wave and/or rework operation [15].

THERMAL RELIABILITY STUDY

In order to understand the impact that various levels of copper dissolution have on the reliability of a through-hole joint, an experiment was defined and performed. The focus of this study was on measuring and correlating the final plating thickness of the PTH barrels to the life of the connector being subjected to ATC from 0-100°C for 6,000 cycles.

Design of Experiment

A total of five (5) PDIP components were designed onto a test vehicle, each individually daisy chained (Figure 13) with identical board design features. Each of the five PDIPs was subjected to various solder fountain contact times, with the end goal being to systematically reduce the copper plating thickness at the knee location by incremental values. For example, each of the five PDIP connectors on one board would have varying degrees of copper dissolution, from approximately 20% of the knee dissolved (Level 1) to 100% dissolution of the knee/pad (Level 5). Three alloys were included in the experiment (Table 1) and the response of the DoE was cycles to failure during ATC. The alloys selected for the study were SAC405 and two alternative lead-free alloys.
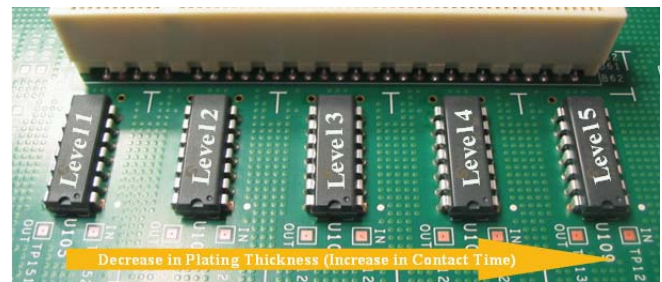

Figure 13. PDIPs Included in DoE, Individually Daisy Chained

Table 1. Copper Dissolution/Reliability DoE

Factors	Levels				
	1	2	3	4	5
Alloy	SAC405	Alloy A	Alloy B		
Plating Thickness at Knee	20% plating dissolved	50% plating dissolved	80% plating dissolved	100% knee + fillet to pad	100% knee & pad dissolved
(average mils)	(1.28 mils)	(0.80 mils)	(0.32 mils)	(0 mils)	(0 mils)

Baseline plating thickness at knee (mils): 1.2 (min) > 1.6 (mean) > 2.0 (max) ; 0.17 (StDev)

TEST VEHICLE

The test vehicle (Figure 14) used for the copper dissolution experiment, was designed as a mid-level complexity printed circuit board (PCB). The dimensions were 8.0" x 10.0" (203mm x 254mm), with a thickness of 0.093" (2.36mm). The PCB stack-up consisted of 12 layers, with 4 (2 ounce) ground layers. The surface finish was HTOSP with a high Tg FR-4 laminate, suitable for lead-free wave solder processing.
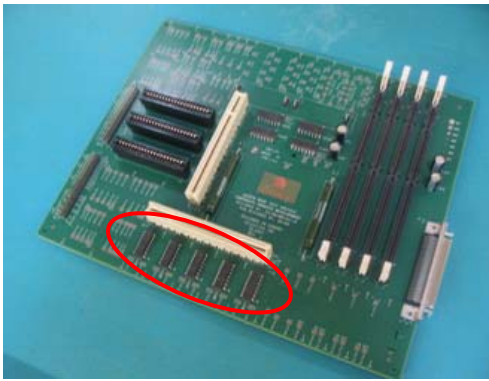
Figure 14. "Jasper" Test Vehicle

The PDIP connector daisy chain was intentionally routed on the bottomside layer to continuously monitor and measure any increase in resistance due to bottomside annular ring/knee copper dissolution (Figure 15).
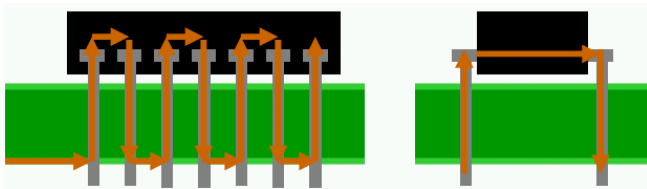

Figure 15. PDIP Daisy Chain Illustration

EXPERIMENTAL & FAILURE ANALYSIS METHODOLOGY

- Established design of experiment
  - **Factors:** (1) Copper plating thickness at knee ; (2) Alloy
  - **Response:** Cycles to failure
- Performed preliminary experiments to establish the correct level of contact time required to dissolve plating thickness to a desired level for each alloy.
  - Due to differing alloy dissolution rates, each alloy required different contact times to achieve the same approximate plating thickness.
- A standard solder fountain and flow well were used throughout the experiment.
- The PDIPs were not physically reworked (i.e. removed/replaced), in order to ensure consistency in contact time exposure for each alloy.
- Contact time measured was the time for which the PCB was exposed to molten solder and exposure was a continuous flow of solder (not cycled).
- Each PDIP was daisy chained, and boards placed into ATC chambers, 0-100°C for 6,000 cycles.
- First failures were immediately cut-out, cross-sectioned and copper plating thickness measured at the left and right knee.
- After 6,000 cycles, all remaining PDIPs were cross-sectioned (row 1, pins 1-7 only) and copper plating thickness measured at the knee (Figure 16).
  - Assumption: No significant difference in dissolution between rows 1 (pins 1-7) and 2 (pins 8-14)

- copper plating thickness at the knee was only measured and recorded
- A baseline "dummy" barrel was designed in line with each row of the PDIP connector. It was protected with solder mask, so that it would not be exposed to solder. Hence a baseline measurement was taken for each row cross-sectioned.
- Final plating thickness vs. cycles to failure was tabulated and statistically analyzed to determine whether any correlations exist.
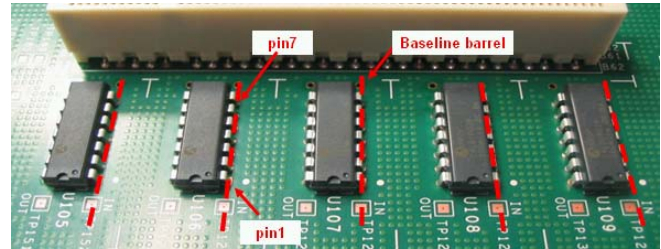

Figure 16. Cross-Section Location (Row 1-7)

RESULTS: BASELINE PLATING THICKNESS

A total of 290 baseline knee measurements were made per sample, from both left and right knees. The average measurement between left and right knee per barrel was calculated and results plotted in the below histogram (in mils) – Figure 17. The average baseline measurement was 1.6mils (40.6μm), with a standard deviation of 0.17mils (4.3μm).
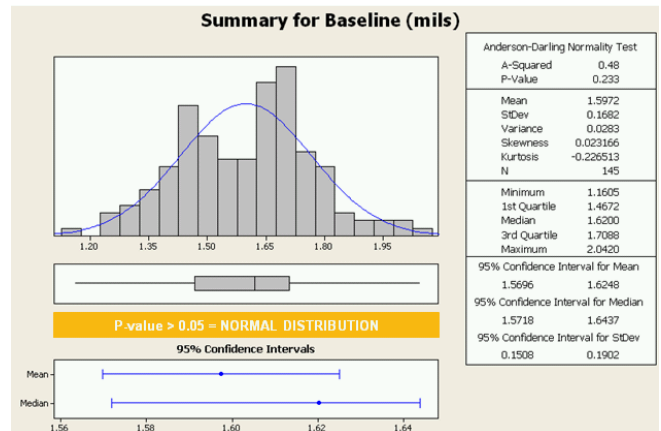

Figure 17. Histogram of Average Baseline Knee Thickness

RESULTS: COPPER THICKNESS BY DOE LEVEL

In addition to the baseline plating measurements taken per sample, the final results of the copper plating at each respective experimental level was measured and is shown below in Figure 18. On this plot, the actual vs. the desired plating thickness per level is shown. As can be seen, the final plating thickness obtained when using each alloy was well below the desired level. Although this was not as originally planned within the DoE, the variation in the final plating results still offer a range in copper plating thickness measurements to enable an analysis between plating thickness and reliability.
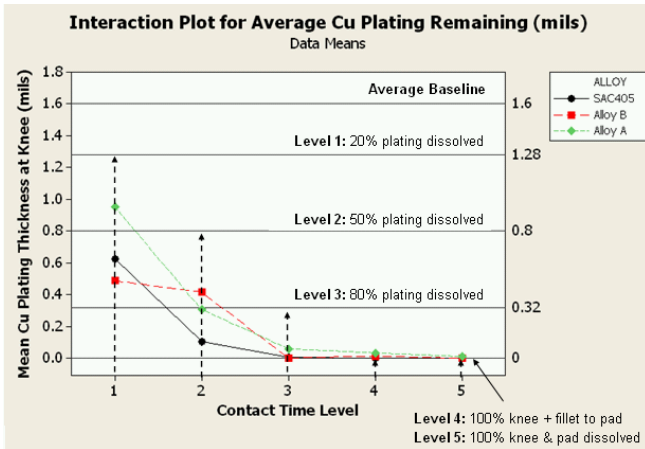
Figure 18. Final Copper Plating Thickness Results by Contact Time Level

RESULTS: COPPER DISSOLUTION TRENDS

Aside from analyzing the impact seen on thermal reliability, the final copper plating thickness measurement results were also analyzed to look for other trends relating to factors such as alloy type, barrel number and left vs. right knee. As can be seen from the interaction plot below (Figure 19), each of these factors had a significant impact on the copper dissolution results. In addition, a second order interaction existed between barrel location and knee (i.e. left vs. right).
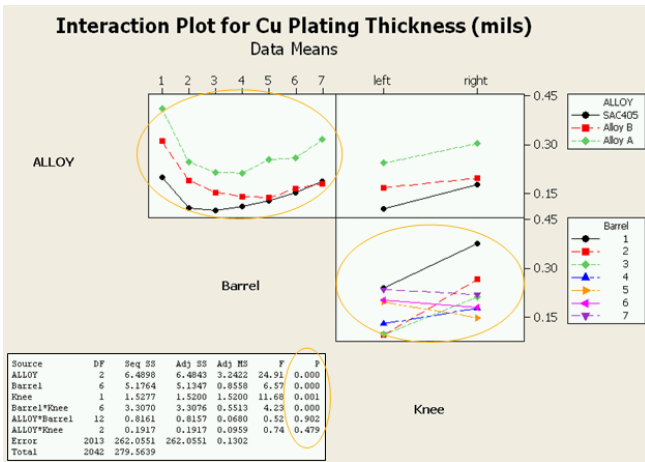

Figure 19. Interaction Plot for Copper Plating Thickness

Impact of Flow Rate

The results of the copper plating thickness by barrel location validate the earlier comments made relating to the higher degree of copper dissolution occurring at the center region of the PTH connector. It is interesting that these results still hold true even for a component as small as a PDIP, where the flow well opening was approximately the same size as the PDIP itself. This trend indicates that the solder flow direction to the outer edges produced a lower flow rate and higher turbulence was produced at the center region (Figure 20a,b).
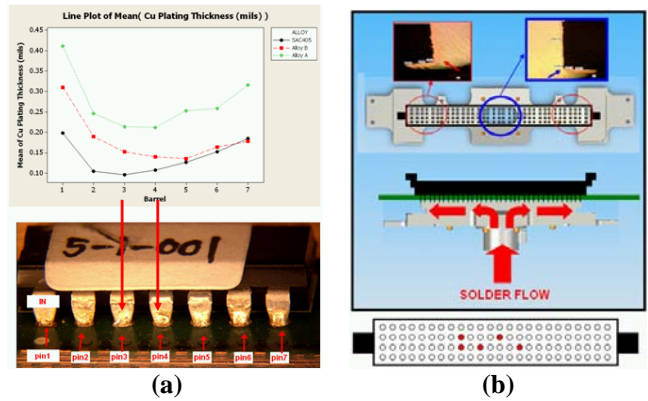

(a)   (b)

Figure 20. Increased Copper Dissolution at Center of Connector, (a) Quantitative Results from Experiment, (b) Graphical Illustration of Historical Observations

Impact of Solder Flow Direction

With respect to the second order interaction between barrel and knee locations, it was observed that barrels 1-4 had a higher degree of dissolution at the "left" knee location and barrels 5-7 had a higher degree of dissolution at the "right" knee location (Figure 21). This indicates that solder flow direction had a significant impact on location of dissolution between left and right knee of a barrel itself.
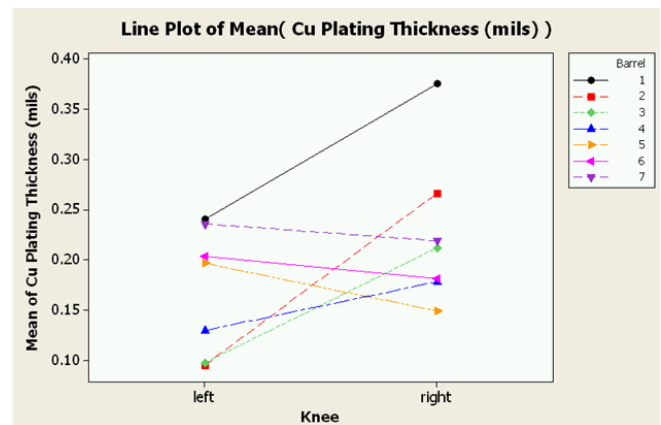

Figure 21. Final Copper Plating Thickness by Knee Location

A sample cross-section was taken to observe and further analyze this trend (Figure 22). As can be seen from the schematic, when the solder flow is pumped up through a single center opening it divides into two separate flows, moving in opposite directions towards the ends of the flow well. The solder flow which is moving to the 'right' in the illustration would come into a direct head-on contact with the 'right knee' of the barrels in its path. The pin itself would also act to alter the solder turbulence.
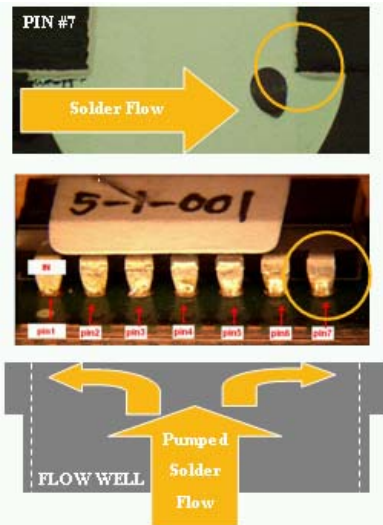
Figure 22. Impact of Solder Flow Direction on Copper Dissolution at Knee Location

RESULTS: THERMAL RELIABILITY STUDY

The results of the final cycles to failure data vs. the minimum copper plating thickness measurements taken after cross-sectioning are shown below in Figure 23. Unfortunately, the results from this experiment do not indicate any statistical correlation between final plating thickness measured (using cross-sections) and final thermal reliability of the connector. The authors of this paper are not suggesting that there is no correlation – rather, that there may be some experimental inaccuracies in the results based on the measurement methodology used (i.e. cross-sections) to capture the final copper plating thickness measurements. The results shown below suggest that it is possible to have 100% copper dissolution at the knee location and have the final cycles to failure range anywhere from an immediate time zero failure (i.e. 0 cycles) to surviving 6,000 cycles – which in itself is inconclusive.
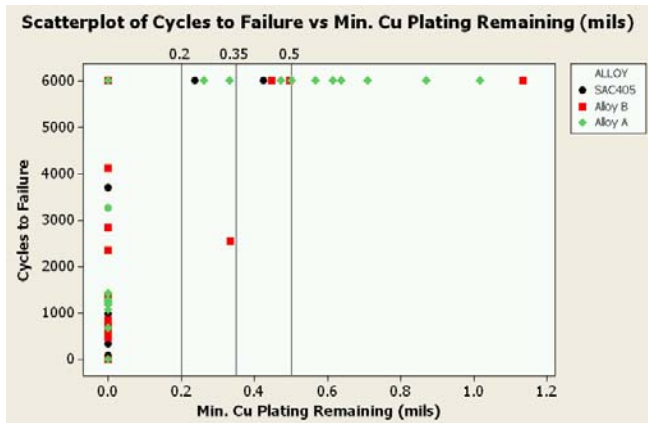

Figure 23. Cycles to Failure vs. Minimum Copper Plating Thickness

OBSERVATIONS

To better understand the above results, the cross-section samples were further inspected. Based on the inspection of these samples a few observations were made (Figure 24).
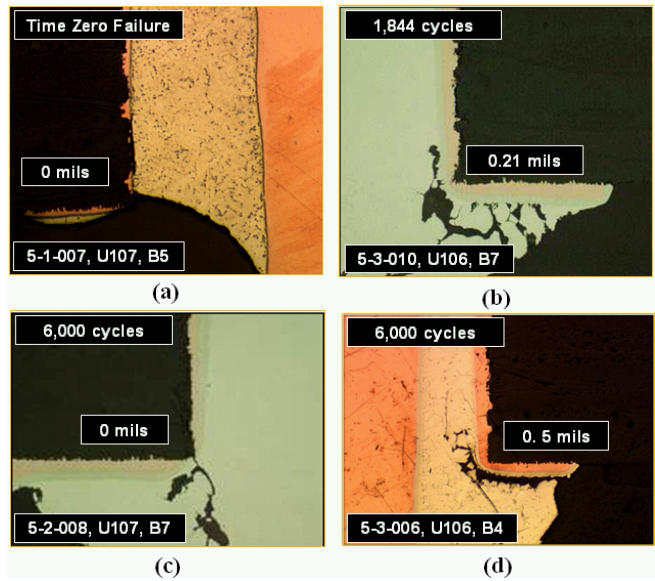

Figure 24. Example Cross-Section Images at (a) Time Zero cycles, 0mils plating; (b) 1,844 cycles, 0.21mils plating; (c) 6,000 cycles, 0mils plating; (d) 6,000 cycles, 0.5mils plating

The first observation was that all of the time zero failures, regardless of alloy, had a complete loss of the knee and a significant portion of the annular ring was dissolved (Figure 24a). In addition, there was no solder fillet attachment present from the pin to the annular ring. This would therefore cause a complete electrical disconnect of the bottomside daisy chain connection if this degree of dissolution occurred 360 degrees around the PTH joint. If the electrical trace was, however, located along an inner layer – then it is conceivable to have the same degree of dissolution and still have an electrical connection. It must be noted that these time zero failure results also correlate to earlier studies where the PDIP connector was physically 2X reworked, resulting in a similar copper dissolution outcome and time zero failures [4].

A total of 24 samples having a minimum of zero mils of copper remaining at a knee location along the row of barrels inspected resulted in early life failures (e.g. 1 cycle < *24 samples* < 6,000 cycles). This finding is significant, as it suggests that there can be an initial electrical connection even with high levels of dissolution on a few barrels of a PTH connector, but that the dissolution will induce a failure mode causing cracking of the fillet at the high stress knee location (Figure 24b). Despite some percentage of earlier failures, similar samples showing signs of copper dissolution and cracking at a 45 degree angle from the high stress knee location were able to survive 6,000 cycles (Figure 24c). Again, the resultant electrical failure of a PTH joint requires a complete crack formation around the perimeter of the pin. This fact may explain how the 19 samples with at least one location along the eight barrel cross-section having 100% copper dissolution at the knee location survived 6,000 cycles.

The final observation made was that excluding the samples which survived 6,000 cycles with 0mils remaining, all

samples which had a minimum of at least 0.35mils (8.9μm) of copper plating at the knee location survived 6,000 cycles.

DISCUSSION

A separate study published in 2007 came to a similar conclusion [16]. In this particular study, samples were subjected to contact times resulting in the thinning of the copper plating at the knee location. The study concluded through finite element modeling, that the knee location was indeed a high stress concentration point and subject to cracking under thermal loads. They found that the maximum stress concentration location is consistent with copper cracking at the barrel knee after rework and the shear mode along a 45 degree angle is dominant. This same study subjected samples to ATC thermal cycling (-40°C to +85°C), plus shock and vibration. It was found that the temperature cycling had the highest impact on crack formation on the PTH connecters. However, no electrical failures were associated with the knee cracking, due to "redundancy in the axial symmetric geometry". Their analysis, based on measuring solder crack length, indicated that samples which had a minimum of 0.5mils (12.7μm) of copper plating at the knee location resulted in no cracking through the solder fillet. Hence any final copper plating having a thickness greater than 0.5mils (12.7μm) of copper was classified as a "safe region". This finding corroborates the conclusions made from this paper, which suggest that the current specification of 0.5mils (12.7μm) of copper plating at the knee is a reasonable thickness to provide a reliable PTH solder joint post rework.

EXPERIMENTAL LIMITATIONS

One of the key outcomes of this work was the validation that the inspection methodology currently used to inspect for copper dissolution does not provide an adequate indication of the extent of the defect on a PTH joint. That is, a cross-section only provides the copper plating thickness measurements of a 360° barrel at two (2) specific locations along the vertical axis of a PTH barrel and fails to provide the copper plating thickness of the remaining plating surrounding the PTH barrel (Figure 25).
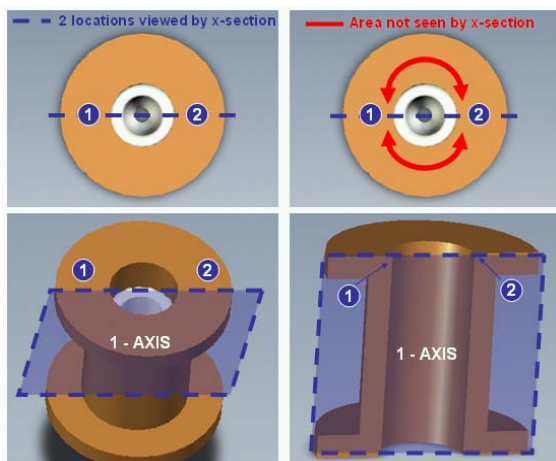
Another limitation of the experiment was the fact that not all of the barrels from the 14 I/O PDIP were cross-sectioned and measured. To minimize cost, it was decided to cross-section only one row from the two row PDIP – assuming that the degree of copper dissolution would be similar between rows. Based on the inconclusive results, this assumption may not be valid.

ALTERNATIVE COPPER DISSOLUTION INSPECTION METHODS

One of the challenges in an NPI or manufacturing environment is the luxury of being able to non-destructively inspect for the existence of copper dissolution on a product qualification, new product launch, or during volume production. Inspection techniques or visual indicators have been recommended to locate any signs of copper dissolution [2]; however, the visual signs appear often when the problem has already surfaced. That is, visual dimples on the PTH solder fillet are typically formed once 100% of the knee of a PTH barrel has been dissolved. In addition, signs of annular ring/pad dissolution, based on the hierarchy of dissolution discussed will also mean that the barrel knee has been completely dissolved by this point. The best method to date, to inspect for copper dissolution, is by taking a cross-section of the connector. However, this method may not be an option in some cases, due to limitations in product sample size, available time, and/or cost of the product itself.

3D X-Ray

A method of inspecting a PTH barrel non-destructively would prove very valuable for inspecting for early signs of copper dissolution. Until recently, the ability to visually inspect internal features, such as the copper wall of a PTH joint using x-ray technology was difficult. With the advent of a 3D x-ray system, an attempt to measure such internal features was made. Below is an example of a 3D x-ray image taken of the same 14 I/O PDIP connector (Figure 26). After scanning the sample, which took between 2-3 hrs, it was possible to view multiple axes of the PTH joints' internal features.
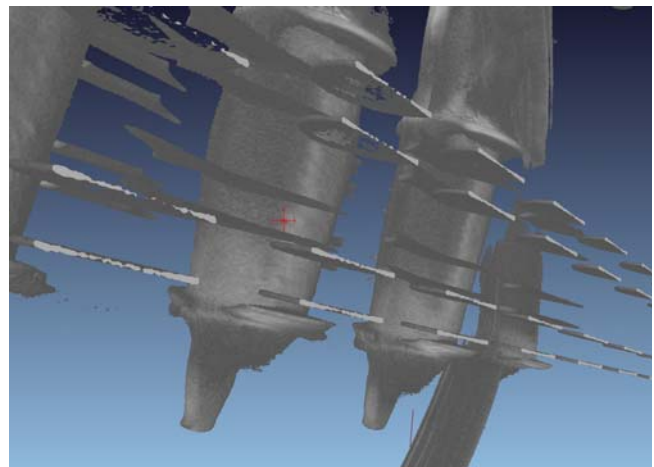

Figure 25. Limitations of Cross-Section to Measure Copper Dissolution

Figure 26. 3D X-Ray Image of 14 I/O PDIP Connector

There was also the ability of viewing specific barrels in a cross-section view, as seen in Figure 27. From this view, it was possible to distinguish the copper plating material from the solder alloy. Although the image is not perfectly focused, it can be seen that a continuous copper plating layer still remains on this particular sample. In discussions with the equipment vendor, it is possible to further enhance the image through software modifications. Assuming that the image can be processed further, this indicates that there is a capable non-destructive method of inspecting for internal copper dissolution, at the knee location in particular. That being said, this solution does have limitations, with respect to cost and cycle time. Accounting for the capital depreciation of a new machine and operator time, the cost to use this method of inspecting for copper dissolution can potentially be greater than the cost to cross-section the same sample. In addition, it takes approximately 2.5 – 3hrs to create a 3D image of a sample. In comparison, it takes approximately 1.5hrs to complete a cross-section.
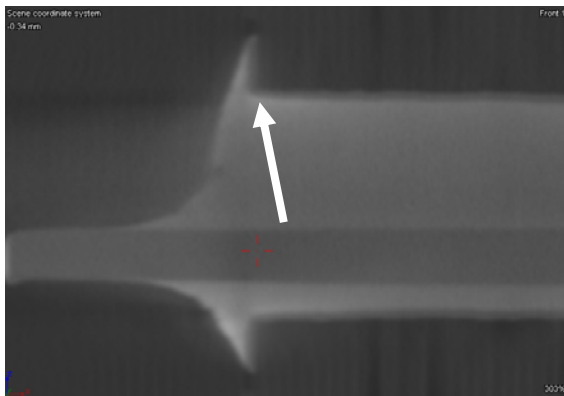

Figure 27. X-Ray Image of Cross-Section of PTH

Horizontal Cross-Section
Another alternative inspection method investigated was a horizontal cross-section, as opposed to a vertical section (Figure 28). This is a destructive method of inspecting for copper dissolution, but may be a method which provides the complete 360 degree picture regarding the amount of copper dissolution which has occurred on a PTH barrel.
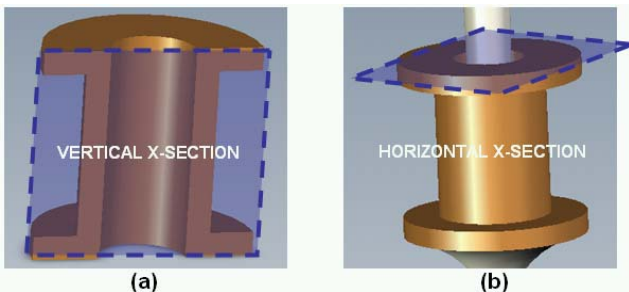

(a)   (b)
Figure 28. (a) Vertical Cross-Section ; **(b)** Horizontal Cross-Section

To evaluate this method of cross-sectioning, three horizontal cross-sections were performed on the same 14 I/O PDIP connectors. One cross-section was performed on a primary attach sample (Figure 29) and two others performed on

samples which were further exposed to 30 seconds (Figure 30) and 60 seconds (Figure 31) on the solder fountain. An attempt was made to grind each sample down to one half the thickness of the annular ring. From these three samples a 360 degree view of the copper annular ring is evident and the progression of copper dissolution which has occurred is clearly visible when comparing each sample. It is also very clear to see from Figure 30, that depending on the axis chosen to perform a 'vertical' cross section, one can yield entirely different result, due to the uneven dissolution which occurs around the circumference of the barrel. There are however, limitations associated with this method of cross section. For instance, it is difficult to accurately and repeatedly control the depth and angle to which the sample is grinded. It is also impossible to determine the exact remaining copper plating thickness. A vertical cross section, although with its own limitations, does allow for a measurement of critical dimensions such as the knee location. A horizontal cross section may not be considered as the primary method to inspect for copper dissolution, but may be used in addition to vertical cross sections to obtain the complete picture.

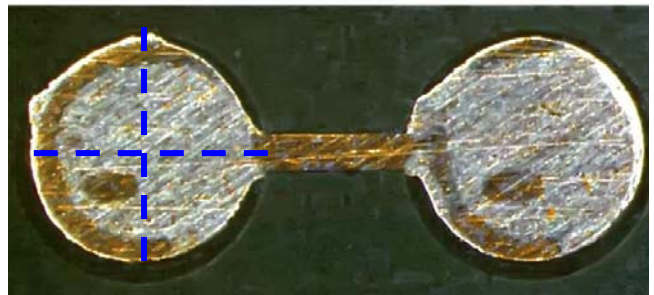**Figure 29.** Horizontal Cross-Section, Primary Attach Sample

Figure 30. Horizontal Cross-Section, Primary Attach + 30 Seconds Solder Fountain Exposure
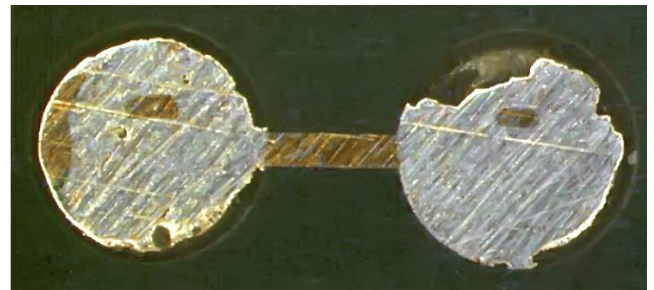

Figure 31. Horizontal Cross-Section, Primary Attach + 60 Seconds Solder Fountain Exposure

CONCLUSION

Based on this and other studies on this topic, copper dissolution is indeed a natural phenomenon which occurs during formation of a solder joint to a copper plated surface and there are a number of factors which jointly interact to influence the rate at which the copper surface is dissolved. It is clear from this study, that severe degrees of copper dissolution can have a quality and/or reliability impact. Even though the inspection methodology had limitations in accurately portraying the exact copper dissolution of the PTH barrels, there were samples which: (1) electrically failed immediately, (2) had early fatigue failure or (3) survived up to 6,000 cycles – each with varying degrees of copper dissolution. These experiments, and the results of other industry work, have shown that having a remaining copper plating thickness of at least 0.5mils (12.7μm) provides a reasonable level of plating to resist barrel cracking, under thermal fatigue loads. This result, however, would need to be verified under mechanical and thermo-mechanical reliability testing to further validate this specification under all conditions. In addition, this work has shown that there are currently non-destructive 3D x-ray and horizontal cross section techniques which can be used to measure copper dissolution on a product, however, additional work is required here.

FUTURE WORK

Understanding the importance of locating a non-destructive method of inspecting for copper dissolution, further efforts in optimizing the 3D x-ray process and researching other non-destructive methods will be pursued.

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