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Characterization, Reproduction, and Resolution of Solder Joint Microvoiding

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Abstract
Microvoids are tiny voids in solder joints and differ from the more well known solder joint voiding in their individual size and location. The microvoids discussed herein are described as an abundance of small voids at or near the interface of a PCBA solder joint. In the most severe cases of voiding, a solder joint my fail physically and electrically. Each void reduces the cross-sectional area of the solder joint; at some point the remaining solder is insufficient to meet functional demands. While information related to these tiny interfacial voids has existed in industry literature for several years, the use of recently available X-ray analytical equipment has raised the level of microvoid observation (See Figure 1). It is not known if microvoiding is responsible for previously failed assemblies to which no root cause failure mode had been assigned. Unlike "Black Pad" interfacial fractures related to Electroless Nickel Immersion Gold, microvoiding has not been directly related to a galvanic effect of PCB circuit design. This provides hope that the phenomenon may be more easily prevented, even on the most difficult designs.

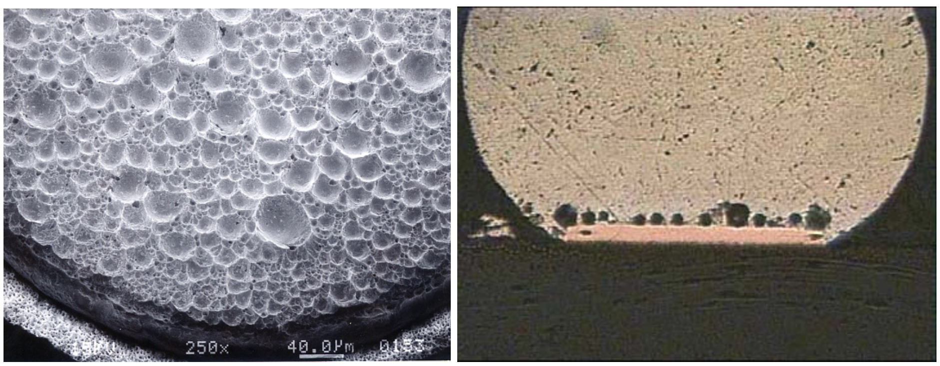


Figure 1 – Solder Joint Microvoiding by SEM (top-down) and Optical (cross-sectional)

This project summary is somewhat chronological. First, a description of solder joint microvoiding is presented. Next, the published literature discovered on the topic is reviewed. A set of experiments was conducted by project teams to screen the most influential variables. A major breakthrough arrived with the laboratory reproduction of microvoids. Once controlled, the primary factors affecting microvoid creation were quantified statistically. Finally, a set of process changes were studied and some recommendations offered. In particular, care should be taken to control copper surface preparation, silver thickness, and reflow temperature metrics. This paper focuses on the impact of immersion silver and how variations in its processing affect voiding. Caution should be taken throughout this summary: only select factors were studied in-depth. For example, the impact of non-silver surface finishes was not quantified. Other possible factors should be investigated to determine and quantify their contributions to microvoid creation.

Introduction

Solder joint voiding in assembled electronic equipment is a common phenomenon. The factors identified as causing solder joint voids include flux type, soldering temperature/dwell, surface cleanliness, and design factors such as microvia structure. Numerous technical articles continue to be published on this topic.[1, 2] Of note recently is IPC's 7095 specification describing the location, size, and specification of solder joint voids.[3] Microvoids, also known as champagne voids and champagne bubbles, are a subset of general solder joint voids. While solder joint voids vary in size and location, microvoids may be defined as voids less than about 40 micrometers in diameter. Microvoids, like all solder joint voids, become troublesome when they exist in sufficient number to reduce the overall cross-sectional area of the physical solder joint. In the most extreme case, the voids may exist in the thousands per soldered feature. Perhaps most importantly, microvoids may exist in a plane just above the interface with the PCB (Figure 2a and b). In this study, microvoiding was found just above the intermetallic layers formed between the copper from the circuit board and the tin from the solderpaste.

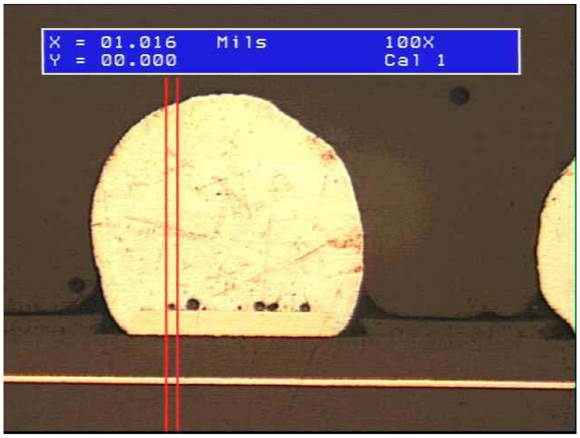


Figure 2a - Voiding Size in Solder Joints

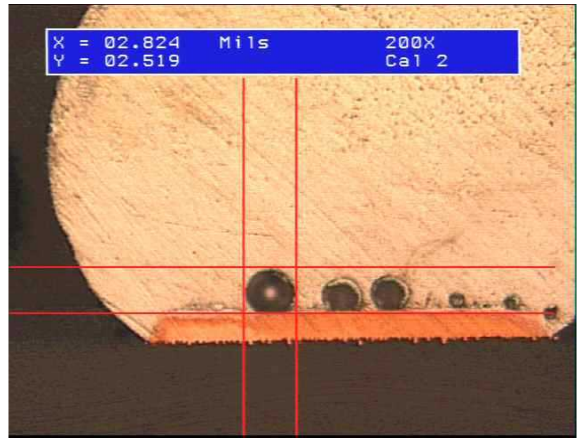


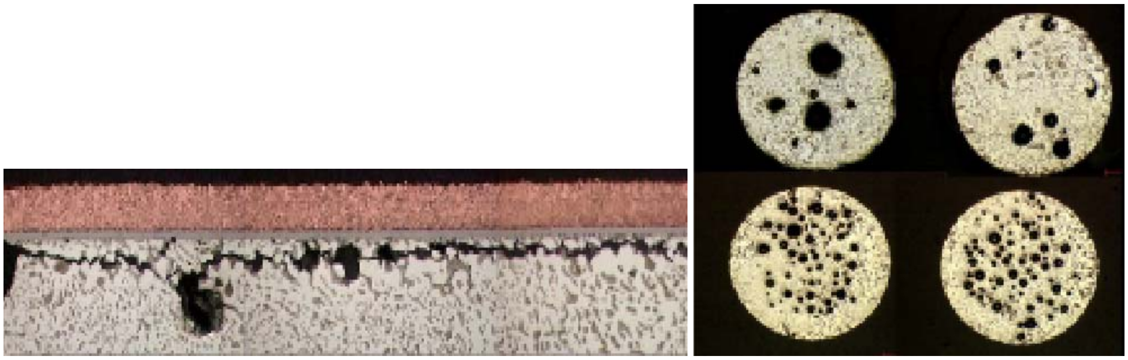
Figure 2b - Microvoiding and Macrovoiding

Higher quality inspection of solder joints, together with increased inspection frequency, allows for the detection of microvoiding. One might consider that microvoiding has always existed in solder joints, but in the past, solder joint analysis techniques were insufficient to detect microvoiding. In the past, very small voids might have been dismissed as artifacts of cross sectioning. Newer X-ray inspection equipment has allowed a major advance in inspectability of solder joint microvoids. In particular, higher energy equipment coupled with fine-resolution detectors permit the discovery of microvoids in a production setting. The use of such equipment allows for the detection of phenomena occurring in low frequency, such as microvoiding. Another factor affecting the increased detection of microvoiding recently is the assembly of higher density circuitry with challenging assembly temperature profiles. Very complex circuit boards are far more difficult to reflow due to temperature variation within the PCBA. Even with great care, temperature variation may exceed 20ºC. Results of NEMI investigations reveal that in order to decrease a 20+ºC temperature delta, engineers required an additional reflow module and decreased line speed. The optimized temperature delta was 16ºC.[4] To avoid excessive temperature exposure of sensitive components; low temperature PCB areas may experience insufficient soldering energy. In this scenario, fluxes volatilize, but do not leave the solder joint sufficiently before the solder hardens, entrapping voids.[5]

The changes described above occur at a time coincidental with other major changes in the electronics assembly industry. In particular, the trend towards "Lead-Free" assembly has introduced a new set of materials. Lead-free solder itself may have properties affecting microvoid formation due to surface tension and flux choice.[1] Higher temperature assembly, associated with Pb-free materials, exacerbates temperature variations during assembly. The Pb-free transition has also introduced new PCB surface finish materials. Immersion silver is experiencing a large increase in use due to its many benefits. With wide deployment of immersion silver, estimated at 5-15% of the PCB market in 2004, a certain number of observations of microvoiding on immersion silver coated PCB's might be expected. Since the use of immersion silver is coincident with better X-ray inspection capability, a hypothesis formed linking microvoids to immersion silver. As a leading supplier of immersion silver to the PCB manufacturing industry, MacDermid's R&D sought to investigate this hypothesis. This article focuses on the prevention of microvoids almost exclusively from the perspective of the silver PCB surface finish.

Literature Review

Several studies exist in published literature with reference to solder joint microvoids. A 2000 Lucent study of ENIG (Figures 3a and b.) was the cover story to IEEE's Transactions. The black-pad study produced unexpected failures from a crack propagating through a string of tiny voids located just above the intermetallic. *"The tendency for aggressive immersion Au plating baths to induce voiding is documented by Cordes and Huemoeller.*[6] *In their studies, they correlate severe voiding with a reduction in shear strength but they do not correlate this effect with thermal cycling data. There is evidence from other studies that arrays of small void can effectively shorten the crack path, resulting in a moderate reduction in solder joint fatigue life in a thermal cycling test. Voiding has a subtle effect on the quality of the solder joints and that is reflected in a lower Weibull slope for those affected packages."*[7]



(a) (b)

Figures 3 - Optical Views of ENIG Microvoiding in Cross-Sectional and Planar Views[7]

Voiding, and the effect on reliability at Motorola, was discussed by D.Banks et al. In this study, the presence of a small amount of voids was shown to be of a reliability benefit, as a method to allow relaxation of the solder joint when presented with physical stress. The propagation of cracks was interrupted when cracks encountered voiding.[8]

One theory attempting to explain solder joint microvoids employed the Kirkendall effect (Figures 4 and 5). At IEEE's 2004 ECTC, Texas Instruments reported solder joint fractures at the intermetallic/copper interface resulting from the formation of tiny voids. Kirkendall voids form when the rate of dissolution of one material (copper) into another (tin) is unbalanced, leading to displacement voids. This seems different from microvoiding in two respects, the voids occur at the copper side of the intermetallic, and the Kirkendall voids appear to grow with post-soldering temperature exposure.[9]

In a 2001 Solectron/ Smart Modular Technologies report "Impact of PCB Surface Pad Finish and Contamination on BGA," the authors determined that organic contamination of an electrolytic nickel/gold PCB finish produced solder joint voiding sufficient to cause package separation. The report recommended closer monitoring of the PCB fabrication processes to prevent such contamination.[10] (Figure 6.)

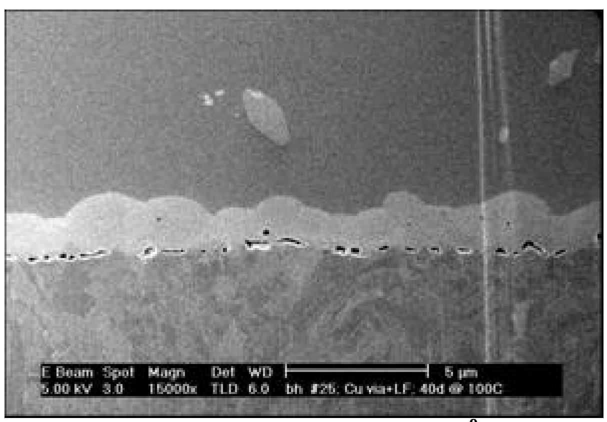


Figure 4 - Kirkendall Voiding[9]

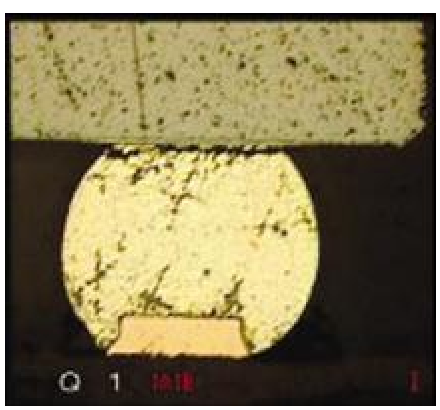


Figure 5 - Fracturing due to CTE Mismatch

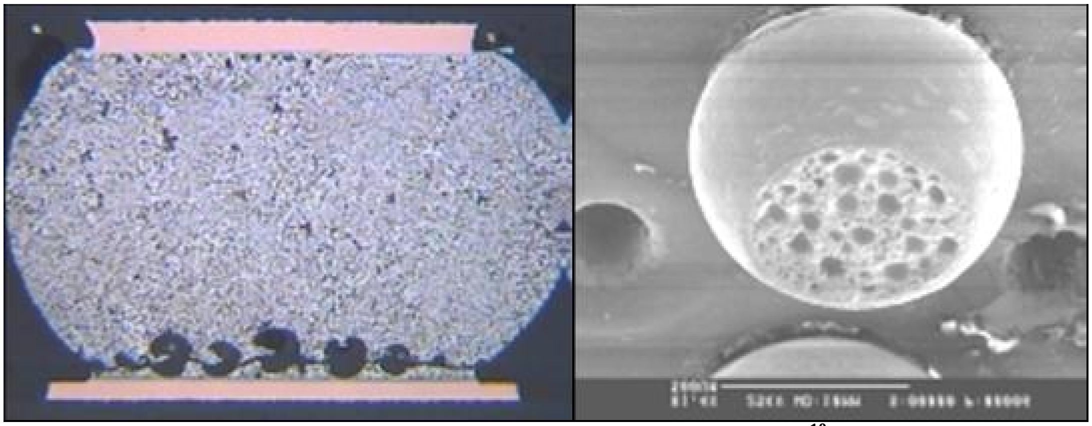


Figure 6 - Solder joint Fractures due to Voiding[10]

Rockwell Collins detected solder joint microfractures on tin-lead reflowed immersion tin. The microvoiding was investigated in response to a conspicuously reduced Weibull distribution of solder joint reliability. The 2000 paper, "An Investigation of the Effects of Printed Wiring Board Surface Finish and Conformal Coating for Ball Grid Array Assembly"[11] shows the improvement in solder joint reliability due solely to the better control of immersion tin deposition.

Most recently, Dage, a maker of high-powered X-ray inspection equipment, published summaries of void/microvoid inspection testing in June's edition of *Circuits Assembly* and at SMTA International 2004. Dage stated that the primary causes of void formation include insufficient reflow temperatures, trapped moisture, and the use of new solderpastes. The new pastes require higher temperatures, employ larger flux volumes, and may have higher surface tensions. OSP was determined to cause the highest number of void occurrences. On microvoids, the author stated; *"This voiding phenomenon has been found on PCBs with OSP, ENIG and immersion silver finishes. It is seen infrequently and does not exhibit a defined pattern, which points to a random failure mode, not simply a material mismatch."*[12, 13] (Figure 7).

The IPC released a draft of the new BGA reference guide *IPC-7095A Design and Assembly Process Implementation for BGAs*[3] (Figure 8.) which recognizes the "type E" condition of small voids near the PCB interface. IPC-7095's proposed maximum for such voids by X-ray inspection is 20% of the solder joint diameter for Class III product, or 50% of the diameter for Class I equipment. Jisso's documentation adopts a similar recommendation.

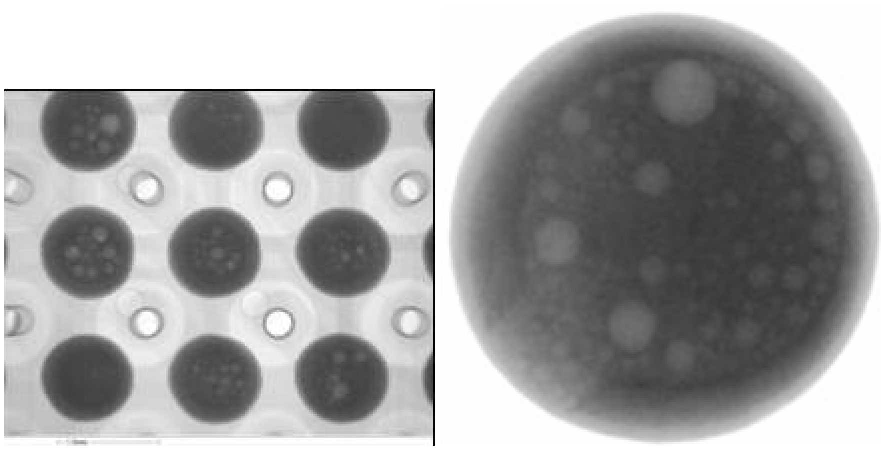


Figure 7 - Detection of Microvoids by 2D X-Ray Equipment[12]

Table 7-6 Void Size Limitations

Void Type	Void Description	Product Accept/Reject Criteria			Determined By
		Class 1	Class 2	Class 3	
A	Voids within the solder ball at incoming	36% of area = 60% of dia	20% of area = 45% of dia	9% of area = 30% of dia	Transmission or cross section X-ray (sampling)
B	Voids at Package Interface at incoming	25% of area = 50% of Dia.	12% of area = 35% of Dia.	4% of area = 20% of Dia.	Transmission * or Cross section X-ray (sampling)
C	Voids within the Ball after PCA reflow	36% of area = 60% of dia	20% of area = 45% of dia	9% of area = 30% of dia	Transmission * or cross section X-ray (sampling)
D	Voids at the package interface after PCA reflow	25% of area = 50% of Dia.	12% of area = 35% of Dia.	4% of area = 20% of Dia.	Transmission * or Cross section X-ray (sampling)
E	Voids at the mounting surface/ Printed Board after PCA reflow	25% of area = 50% of Dia.	12% of area = 35% of Dia.	4% of area = 20% of Dia.	Transmission * or Cross section X-ray (sampling)

Figure 8 - From IPC-7095A Design and Assembly Process Implementation for BGAs[3]

Initial Investigations

The initial investigation of a link between microvoiding and immersion silver was prompted by a high visibility failure of a PCB assembly at post-assembly power cycling. The investigation of the failure received immediate priority. Assigning priority to failure investigation may employ Failure Mode and Effect Analysis (FMEA) methodology.[14] The FMEA Risk Priority Number (RPN) is calculated from three key factors: severity, occurrence, and detectability. In this case, the severity of massive microvoiding was electrical failure (high.) The detectability of the microvoiding, on the existing assembly inspection stations, was poor due to the lack of X-ray units. The occurrence of the defect leading to electrical opens was low, resulting in just one or two PCBA's. The resulting RPN was sufficient to prioritize investigation of the microvoid occurrence on immersion silver boards.

A first step in the investigation process involved the formulation of theories surrounding microvoid expression. A list of factors thought to be possible contributors is presented in Table 1. At the beginning, the failure was thought to be entirely related to contamination and residue. Samples with actual functional failure did exhibit severe soldermask residue, which limited the available pad area for good soldering, and led directly to a weakened solder joint. However, microvoids did appear on X-ray images of other BGA solder joints that were not overly contaminated with soldermask. More theories relating soldermask to microvoiding emerged. Does soldermask contribute to microvoiding by providing a source of volatilized organics? Or will physical fractures occur only where the solder joint is already weakened by excessive soldermask residue? The issue of contamination remains as a leading contributor to microvoid vulnerability. Early samples demonstrating microvoids were traced to fabrication process areas with process control issues. Contamination on boards included oils, developer foam, tin resist and films of sublimated soldermask volatiles. Cross-contamination from shared rinses, conveyors for OSP, and nearby immersion tin provided additional residue. The silver process was improved to provide adequate pre-cleaning, silver bath analysis, use of a cleaner and microetch, dedicated rinsing, and improved rework procedures. After these steps were implemented, the X-ray occurrence of microvoiding was nearly eliminated. The next step was to determine if microvoiding existed on boards from multiple fabrication locations. Investigation demonstrated that some level of microvoids could be found on PCB's from all fabricators studied. Similarly, the site of PCB assembly was thought to be a leading factor, but microvoids were found by X-ray on assemblies made at several EMS locations. Increasingly, it seemed that microvoiding was far more widespread than initially believed.

Several hypotheses were proposed relating to the effects of copper surface structure on the production of solder joint microvoids. The copper may be altered in several different processing areas. The deposition of copper itself may produce rough deposits due to current density variations. Tin stripping and soldermask preparation processing may significantly affect the copper structure prior to surface finish. The final finish process employs a cleaner and microetch, but these relatively mild solutions are not adequate to overcome extremely rough or dirty copper. Another process capable of producing a poor copper structure is silver rework. For various reasons, operators may attempt silver rework by processing the PCB repeatedly through the plating bath. This method, along with other silver stripping methods, may easily compromise the integrity of the copper and silver deposits. Once altered by any of the above processes, copper deposits affect the quality of solder joints. Similar to the way in which a microvia leads to a solder joint macrovoid, small entrapped air pockets on a very rough copper surface may produce solder joint microvoiding. Studies at Universal, IBM, and Boeing detail the effects of copper structure on solder joint reliability.[15-18]

Table 1 - Initial Theories on Microvoid Causes

Insufficient temperature during solder reflows
Out-gassing of the organic within the silver deposit
Out-gassing of organic brighteners within the underlying copper deposit
Incorrect/impure flux chemistry in the solder paste
Volatilization of water on the PCB or within the solder paste
Excess oxides and/or tarnish on the silver deposit
Excess oxides and/or tarnish on the copper before surface finishing
Soldermask contamination on the copper
Tin contamination on the copper
Other contamination, such as machine oils, developer foam, etc…
Incomplete microetch alters surface finish grain structure
Surface tension differences between paste and silver
Silver catalyzes flux degradation, slows volatilization
Raw material and/or manufacturing variations in the silver chemistry
Excessive soldermask on the BGA copper pads
Kirkendall voiding – results from differential rates of metal dissolution
Incomplete rinsing of boards at PCB fabrication
Microscopic 'spheres' on the surface of the silver deposit
Cross-contamination of OSP with immersion silver at the fabricator
Immersion metal deposition rate affects underlying copper structure, leading to voids
Aggressive soldermask preparation affects copper structure, leading to voids
Rework of surface finish leads to poor copper/silver structure
Insufficient dissolution of silver into the solder joint (silver and/or organic embrittlement)
Silver bath decomposition creates tendency to microvoid with bath age
Re-deposition of organic-laden cleaners at the end of their bath-life
Handling-induced contamination before component assembly
Oxidation of solder spheres in the paste, flux viscosity

Recreating Microvoids: Testing with Fabrication Partners

In 2003, groups of companies representing the chemical supply, PCB fabrication, contract assembly, and OEM sectors began projects to recreate solder joint microvoids. Sets of test vehicles were fabricated; silver finished, and assembled using variables suspected of causing microvoids. One of the first DOE's investigated PCBA's constructed using three levels of silver thickness, two solderpastes, and baking after silver deposition. With no conclusive response, additional experiments were planned. One such experiment is summarized in Table 2. Boards were produced at three fabrication locations. From earlier observations, high thickness was suspected of impacting microvoiding in the production boards. Therefore, thickness was included in the DOE plan. Post-bake and pre-clean were included as a response to fabricator audits at the time of production defects.

This DOE demonstrated the challenge involved in recreating more than a background level of microvoids. This DOE offered no resolution to many of the hypotheses posed before the experiment. In particular, there was not enough response to verify or dispute the theories on contamination, oxides, cleaning, chemical concentration, and rinsing. The only clear response was an apparent connection between silver thickness and voiding. The next efforts were less ambitious. While the experiment in Table 2 attempted to study several aspects of microvoiding at once, the next experiments simply intended to reproduce microvoids.

Table 2 - DOE Summary

Hypothesis	Fabrication variation can cause microvoiding
Fab Location	4 (3 silver and 1 OSP)
Silver Thickness	0.25 and 0.75 microns
Post-Bake	Yes and No
Pre-Clean	Standard and ½ Cycle
Analytical	X-Ray, tensile pull and FM determination
Results	Only 2 samples resulted in microvoids High thickness result Possible post-bake interaction

Separate experimentation with a European fabrication partner tested theories relating the plating rate of immersion silver with plating quality and microvoid observation. Initial work seemed to support the idea of plating rate as controlled by pre-dip acidity and silver bath conditions (temperature and concentration.) This study did lead to more intensive investigation of the use of a neutral pre-dip system as a means for controlling initial rate of silver deposition, and therefore, augmented thickness control. The study was another confirmation that higher thickness increased the tendency for microvoid occurrence. (Table 3)

Table 3 - Plating Rate Investigation Summary

Hypothesis	Silver Plating Rate affects Microvoid Creation
Plating Time	Normal, High
Silver Bath Temperature	0.25, 0.75 microns
Post-Bake	Yes, No
Analytical	Ball shear, optical inspection
Results	Suspected microvoiding at high thickness and high activity silver plating

A follow-up test studied the intentional organic contamination of soldermask vapors on baked immersion silver deposits. The complicated PCB samples did not survive attempts to solder the samples in prototype laboratory reflow equipment. The difficult testing did not produce meaningful results.

Next, MacDermid partnered with a US fabricator to test a theory relating microvoids to silver bath age. The simple test vehicle (described below) was assembled on production assembly apparatus with real component connection, but did not recreate microvoids observable by X-ray. (Table 4)

As a part of this study, chemical samples were sampled from the production silver bath in order to link microvoids to the concentration of some material or contamination in the working solutions. The samples were analyzed using a battery of chromatographic, titrimetric, and spectrographic techniques. Daily bath samples from one fabricator in particular were collected and analyzed from November 2003 until April 2004. Even though an extensive database was collected, no relationship was ever discovered. Additionally, samples were collected from chemical manufacturing sites to discover if some unintentional manufacturing or raw material variation might explain the intermittent observation of microvoids. Once again, no such relationship was uncovered.

Table 4 - Bath Age Investigation Summary

Hypothesis	Silver bath age affects microvoid occurrence
Silver bath age	New, Aged, Old
Silver thickness	0.18, 0.38, 0.75 microns
Pre-dip type	Standard, neutral pH
Analytical	X-Ray, cross-section, ball shear
Results	Possible microvoids found by cross-sectioning No microvoids found by X-Ray

Recreating Microvoids: Laboratory Methods

At this point in time, the project team expressed frustration at the inability to controllably recreate microvoids observable by high-definition X-ray. The team stepped back to bring attempts to recreate microvoiding into the laboratory. When it became clear that a larger number of variables, and therefore a larger number of test boards, were required for microvoid recreation, the project team created alternative test vehicles (TV's) for quick testing. Sets of 4-layer and 6-layer TV's were built to allow for SMT soldering of dummy BGA packages (Figure 9.) Additionally, the TV's provided for reflow of paste and solder spheres. The part could be inspected for microvoids by optical cross-section or X-ray. Ball-shear testing was conducted on parts assembled with paste and spheres. One initial test yielded promising results. A set of simple solderability coupons with BGA pad footprints were plated with increasing levels of silver, screened with solderpaste, and reflowed. The thickest silver sample demonstrated a set of small voids just above the copper pad (Figure 10a,b and c.) This was the first time microvoids were observed by cross-section in simple experimentation. With the first successful recreation of microvoids in the lab, the next question arose; what characteristic of very thick silver contributes to microvoids?

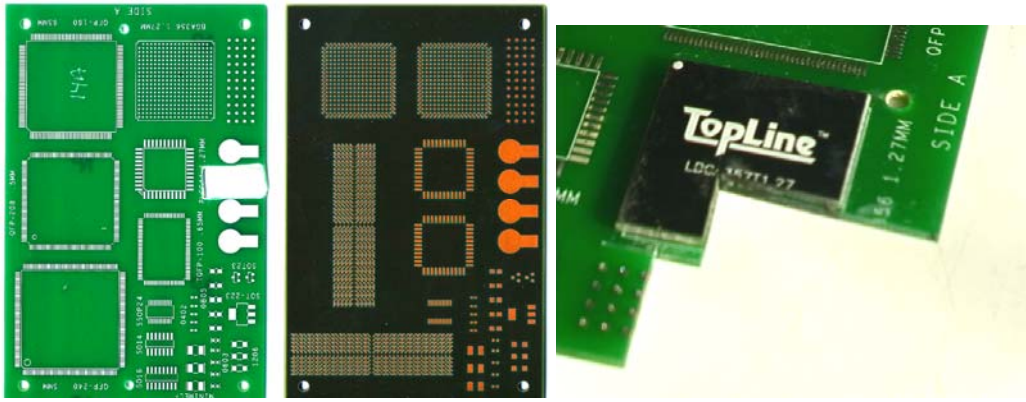
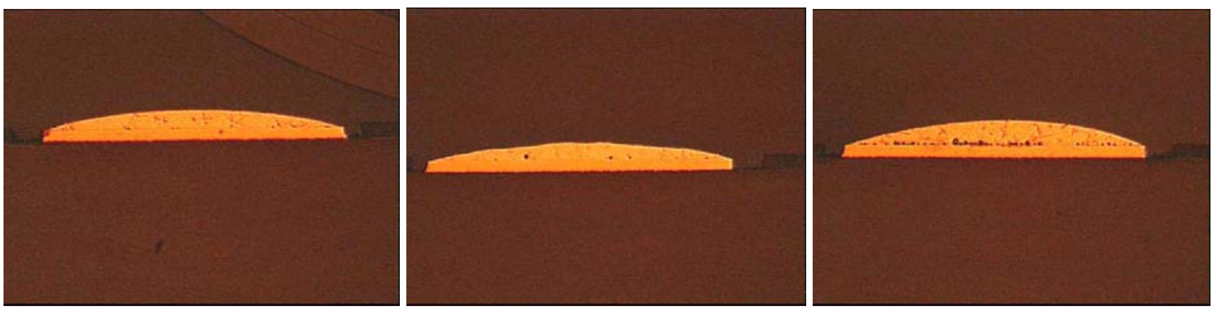


Figure 9 - Test Vehicles Used To Screen Variables in the Laboratory



(a) (b) (c)

Figures 10 - Thickness Induced Microvoiding by Cross-Section of Reflowed Solderpaste
(From left, 1x, 1.5x, and 3x standard thickness)

Organic Content

Organic content within the circuit board assembly is a leading suspect when predicting solder joint microvoiding. Studies presented at the Universal webinar link solder joint reliability to the copper's brightener content.[15] the choice and content of organic materials within solderpaste flux is well known to influence solder joint voiding. In fact, solderpastes are specifically formulated for prevention of solder joint voids under various specific conditions.[19] Organic material is present not only in the copper plating of outerlayer conductors; it is also present in several of the PCB surface finish deposits. Several factors led to the suspicion that the immersion silver's organic content might lead to the microvoiding occurrence. Eckel described organic material in a gold metal deposit as a direct cause of microvoids; this organic content was the result of incorrect process control problems at the fabricator.[10] Also, the initial silver-coated production failure demonstrated soldermask residue as a contributor to solder joint weakness. Further, the effect of a flux /temperature interaction of BGA solder joint voids is well documented. The question remains; does the carbon present in the immersion silver deposit affect microvoid occurrence?

Immersion silver deposits may typically contain a small, almost undetectable content of organic material included for anti-tarnishing, grain-refining, or prevention of dendritic growth. While measurement of tiny amounts of material in ultra thin deposits is difficult, studies by Auger and XPS usually result in an approximation between 0.5% and 2.0% w/w of organic in the deposit. The difficulty in measuring the organic on this nanoscale deposit is due to the extreme thinness of the overall deposit. Investigation commenced in the effort to determine if the small amount of carbon material was sufficient to outgas and form microvoids.

In theory, one can estimate the amount of material required to form the gas voids in the solder joint. The ideal gas law $PV=nRT$ may be used to estimate the amount of volume that might arise from volatilization organics.[20] The derivation below calculates that the entire silver deposit would need to form a gaseous vapor in order to create an observable void volume. Clearly, another more massive source of volatilizing material, such as flux, soldermask residue, or PCB contamination must be involved.

Thickness of Silver 0.5 micron = 5e-5 cm
Area of 0.6mm BGA pad $\pi(0.03cm)^2$ = 2.83e-3 cm^2
Volume of Silver on 0.6mm BGA pad 1.423-7 cm^3
Grams of Silver on 0.6mm BGA pad 1.49e-6 grams (at 10.5 g/cc Ag)
Grams of Carbon on 0.6mm BGA pad 1.49e-7 grams (if C is 10% of ImmAg w/w%)
P = pressure in atmospheres 1 atm
n = number of moles of material = g/molecular weight 1.24e-8 moles as Carbon
R = ideal gas constant 0.0821 (L atm/mol °K)
T = temperature of solidification of solder = 183°C 456°K
V = nRT/P = (1.24e-8) (0.0821) (456°K) / 1atm 4.64e-7 Liters of solder joint gas volume = 462 μm3
Area of voids 1 micron in diameter on a BGA pad 462 μm2
Area of 0.6mm (600μm) BGA pad = π(300μm)2 282,743 μm2
Ratio of void area to pad area 462/282,743 = 0.16% (less than 1% of BGA area)
Even if the silver deposit is 10% carbon and all organic vaporizes without escaping the solder joint, microvoiding is < 1% of BGA area.

The assumptions in this model act to overestimate the predicted void volume. The typical thickness of silver is less than 0.5 micron. The organic content is less than 10%. 'Real' gasses typically occupy less volume than 'ideal' gasses. More direct investigation of the organic out-gassing theory was conducted through the use of Thermal Gravimetric Analysis and Gas Chromatography of heated samples. In both sets of experiments, any significant outgassing from the silver deposit would have been detected as a weight loss or a chromatographic peak. No outgassing was detected. As contrast, when a silver-plated sample was contaminated with undeveloped soldermask residue, large peaks were observed on GC/HS when heated to 215ºC.[21] To determine if the silver metal itself may have been causing an interaction, electrolytic silver samples were prepared. A pure deposit of electrolytic silver was deposited on laboratory test vehicles using a cyanide system. Microvoids were found in small quantity by cross-section but not by X-ray inspection, so the impact of silver purity on microvoiding remains unclear. Other tests were conducted in the attempt to determine if any particular ingredient of the immersion silver formulation affected microvoid occurrence. No significance was found as a dependence on any one, or group, of chemicals. Details of these experiments will be published separately.

Another characteristic of severe microvoiding was the location of small voids formed into a plane just above the junction of solder with the PCB's copper surface. If the silver or organic was responsible for embrittling this area of the solder joint, it was speculated that the silver should remain restricted to this area of microvoid observation. A sample of solder joint voiding was submitted for elemental mapping. (Figure 11.) In this experiment and in several other confirming experiments, the silver was found to be completely dispersed throughout the solder joint. With the completion of each test, more questions were raised. If the thick silver is completely dispersed, how does it interact to affect voiding?

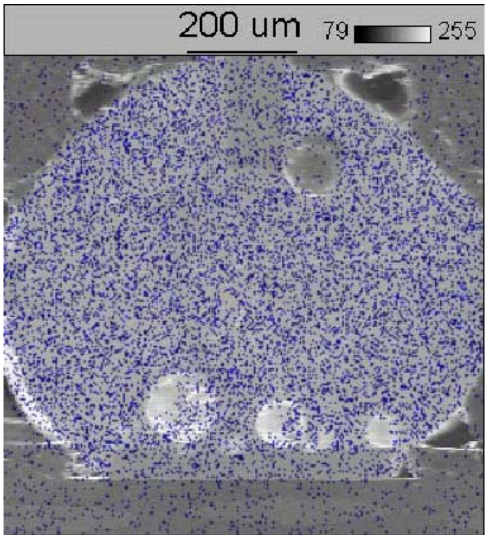


Figure 11 - Elemental Mapping Shows No Localization of Silver at the Voiding Boundary

Other theories were proposed to explain the observation of microvoiding at high silver thicknesses. One theory proposed that there may be an interaction between silver and flux causing the flux to more slowly exit the solder joint. Slowing the flux volatilization/evacuation from the solder joint should produce increased voiding. To study flux-silver interactions, the materials were heated to 200ºC, evolving gasses were trapped in "headspace" apparatus, and the gasses were quantified with Gas Chromatography. The solderpaste used was identical to the paste used in the initial assembly failures. A baseline measurement was created with volatiles evolved from paste alone. Additional measurements were acquired with paste screened on silver, OSP, and ENIG surfaces. ENIG and OSP measurements were very similar to the paste-only baseline. The volatiles were significantly lower for the paste-silver samples (see Figure 12). In this phase of the experiment, a clear interaction was found between the thick silver deposits and the flux/paste material. Somehow, the silver appeared to slow the formation of flux volatiles. One explanation proposed that a catalysis or decomposition of the flux by the silver was enough to slow volatilization. In practice, slowed flux evolution would result in voiding. If a flux interaction occurred at the surface, the voiding might be trapped at/near that surface, as seen in the microvoiding samples. Slower volatilization should exhibit itself in a manner similar to insufficient heat transfer during reflow – locked voids in the solder joint. Next solderpastes and flux media were studied. An interaction with silver was reproduced with other fluxes, but to a somewhat lesser degree. Microvoids were produced on a variety of solderpastes tested under stressing conditions; of note, Pb-free solderpastes did not produce microvoids in this test.

With a better understanding of microvoids in the laboratory, other screening tests continued with fabrication partners. A study was commissioned to measure any impact of poor rinsing on microvoid formation. The hypothesis in this study proposed that residue on the PCB should interfere with good intermetallic formation and may cause outgassing when the residues were soldered. Once again, a thickness range of silver was investigated as well as a storage-time variable between soldermask and silver plating. The storage time may affect the lock-in of residues from incomplete soldermask developing. The residues from incomplete rinsing (short, low pressure, cold rinses) resulted in 6x the ionic contamination compared to TV's with good rinsing. X-Ray analysis did not show widespread voiding; some isolated pad areas on high-thickness samples and poor rinsing did exhibit microvoiding. (Table 5)

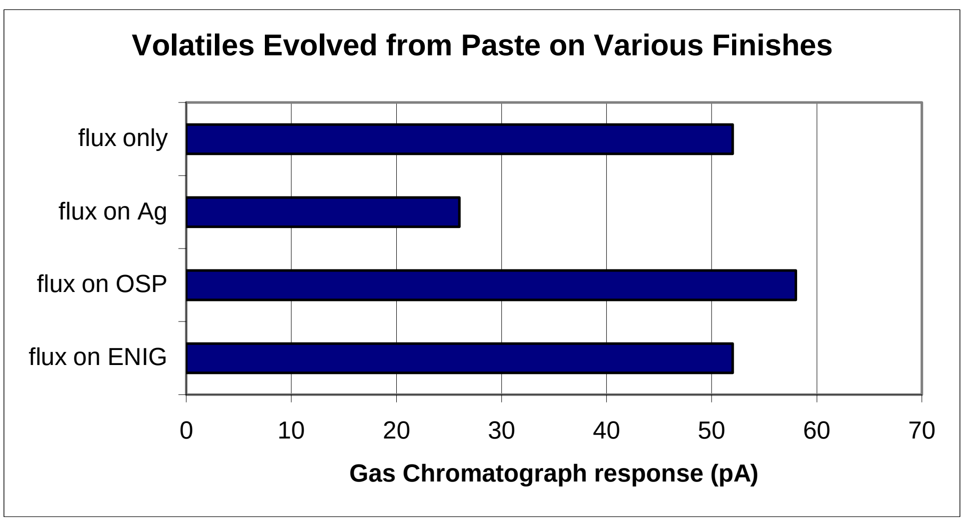


Figure 12 - Interactions between Solderpaste Flux and Surface Finish by Headspace GC

Table 5 - Ionic Contamination Summary

Hypothesis	Rinsing and soldermask residues cause microvoiding
Post-silver rinsing	Standard, ½x, 2x rinsing conditions 2-12 µg/in^2 (as NaCl)
Silver thickness	0.25, 0.50, 0.75 microns
Storage time between soldermask and silver	24 hours, 3 weeks
Analytical	Ionic contamination, solderability, X-Ray, cross-section
Results	Microvoids found by X-Ray on some BGA pads: Ag > 0.75 microns and poor rinsing

Another phase of the investigation soon yielded an additional factor in reproducing microvoids. In further experiments aimed at creating PCB contamination, tin stripping and soldermask preparation processes were investigated. Nitric and fluoboric strippers were used in attempts to incompletely strip tin plating before soldermask. In previous recreations of microvoiding, only very high thickness of silver (0.75 microns) reproduced the defect. In this experiment, a more moderate thickness of 0.4 microns showed microvoiding by cross-section and X-ray (Figure 13.) That sample was processed in the laboratory with nitric acid based tin stripping. Laser profilometry showed that the surface demonstrated far more roughness than control samples. One explanation proposed that a rougher surface of plated silver should contain the same volume of silver as a smoother surface at higher silver thickness. Another important observation from this experimental phase was that reproduction of microvoiding in the laboratory required decreased temperatures during solder reflow. In these and subsequent experiments, the peak temperature of the reflow profile was decreased by 10 or 20 degrees centigrade to result in microvoids. Several follow-up experiments gave supporting microvoid observations, but detections were still sporadic. Observations by cross-sectional techniques did not always match X-ray inspection results.

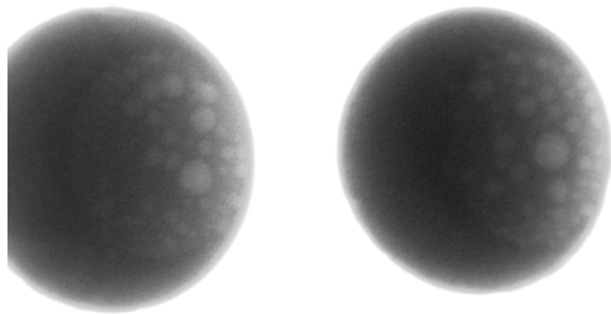


Figure 13 - X-Ray Microvoids on Rough Surfaces. Note the Ellipse of Voids at the PCB Surface

"Turning On, Turning Off" Microvoids

The data and conclusions from all the experimental phases pointed toward the interaction of several variables as being necessary to reproduce microvoids. Intuitively, this seemed correct, since a single variable factor would have been much easier to discover, and should have produced a higher frequency of microvoiding on the millions of production parts using immersion silver used in the world. The next experiment intended to combine the factors identified with causing microvoids. At the time of the experiment, the factors suspected were flux type, high silver thickness, rough underlying copper, and cool reflow soldering. The experiment was dubbed the "Perfect Storm" as it brought together the extremes of seemingly unrelated conditions. (Table 6)

The "Perfect Storm" experiment was a huge step forward in the on-demand recreation of microvoids. When a set of 15 test-vehicles was studied, the average microvoid score on a scale from 1-10 (10 denotes severe microvoiding) was 7.1. Comparatively, the control levels of the contributing factors produced an average score of 1.1. Some microvoiding was observed on the control group, particularly in one sample. This observation signified that not all contributing factors were entirely understood. In this experiment, however, the team achieved excellent correlation between the X-ray and cross-sectional methods for detecting microvoids. (Figures 14 and 15.)

Table 6 - Investigation Aimed at Aligning All Known Microvoid Factors

Hypothesis	Several factors set at extreme conditions will allow microvoids to be "turned on and turned off"
Reflow temperature	Standard, 20ºC below standard peak
Silver thickness	0.38, 1.50 microns
Copper preparation	Standard, roughened pre-treat and no microetch
Analytical	X-Ray, cross-section
Results (observed microvoids, scale from 1-10)	Average = 7.1, contributing factors Average = 1.1, non-contributing factors

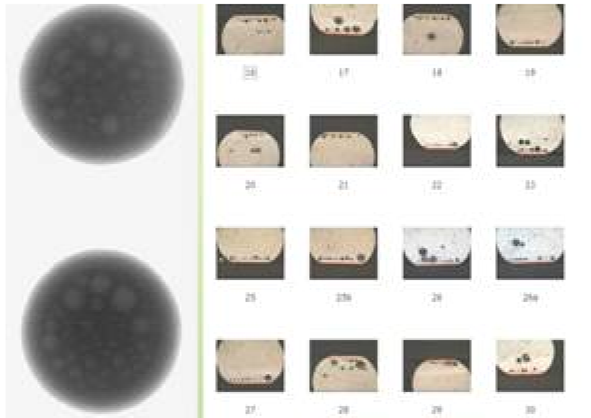


Figure 14 - Factors Promoting Microvoids

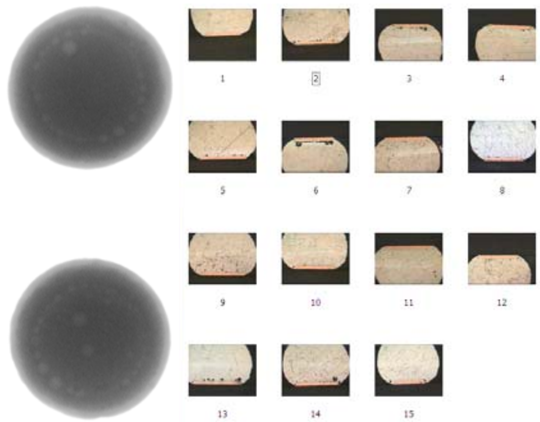


Figure 15 - Factors Preventing Microvoids

With the increased ability to reproduce microvoids, based on better control of void-inducing factors, the project team moved into a phase of statistical data evaluation. At this stage, there were three goals for performing statistical analysis.

- Ranking the leading factors affecting microvoids
- Identifying significance of secondary factors (copper roughness, ionics,…)
- Proving reliability of preventing microvoids with process control

In a series of experiments, large numbers of replicates and test conditions were studied using the SMT test vehicle. The results were interpreted using Design Expert software (see Figure 17.) In each test, the results indicated the leading factors to be:

- Cool Reflow Temperature
- High Silver Thickness
- An interaction between reflow temperature and silver thickness

Other factors did prove some statistical significance in data analysis, but were less reproducible. These factors included the type of copper pre-treatment, ionic cleanliness, and pH of the process chemistry. The effect of copper pre-treatment remained unclear. Some results indicated that insufficient removal of tin and/or soldermask was a leading effect. Other data showed that very rough surfaces, above a Surface Area Ratio (SAR) of 0.05, promoted microvoiding. (Figure 16.)

In most testing, it should be noted that extreme conditions were needed to recreate microvoiding on demand. For example, soldering samples with a reflow profile at 20ºC below recommended peak was the most effective way to reproduce voiding. Similarly, silver thicknesses of 1.5 microns (60 microinches) were needed to achieve microvoiding in the laboratory, while silver deposits on actual production product would not normally exceed 0.60 microns (24 microinches.) It is unclear what might occur when other surface finishes were processed at such extremes. As stated earlier, these studies focused on interactions with immersion silver (Figure 17).

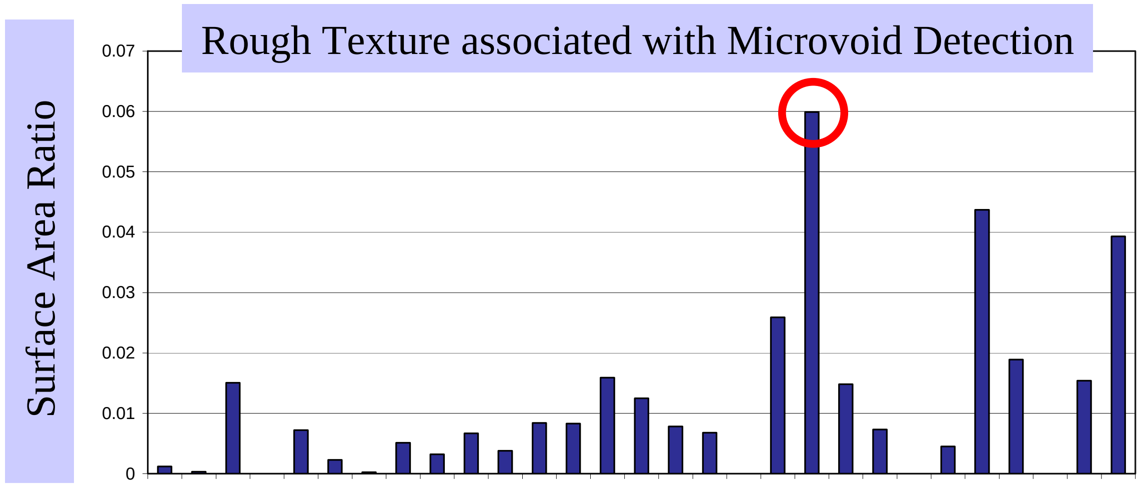


Figure 16 - Profilometry Measurement of a Microvoiding Sample Shows Extreme Surface Roughness

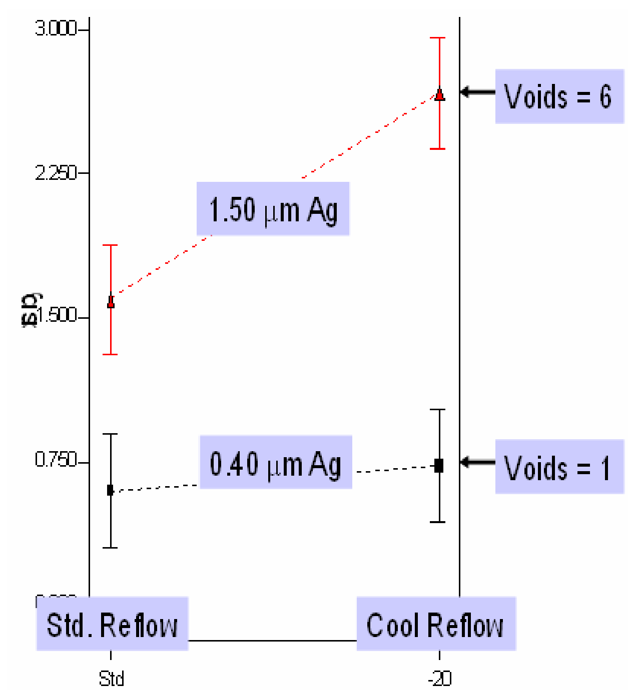
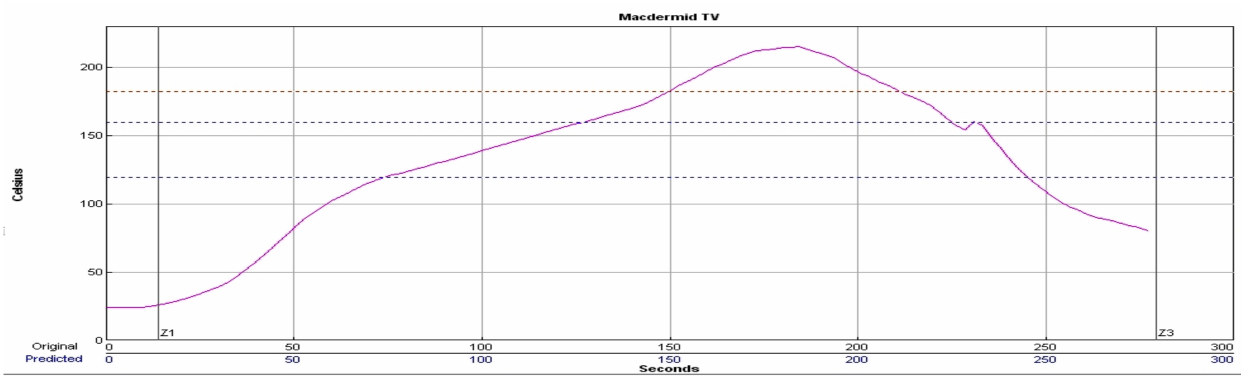


Figure 17 - The Effects of Ag Thickness and Reflow Temp (x-axis) on Microvoiding (square root, y-axis)

Assembly Reflow Temperature

The assembly interactions related to microvoid creation are strong. Cool reflow profiles showed microvoiding when other factors were outside normal operating conditions. The cool reflow profile used in these studies was achieved by lowering the peak temperature by 10ºC or 20ºC. See Figure 18 for details. While a drastic change such as this was needed to produce microvoiding on simple test vehicles, much more complicated PCB-component assemblies are more sensitive to smaller temperature deltas. In actual assembly, a 20ºC difference in peak temperature may have solderability and non-wetting consequences, but real assemblies are exposed to these temperature deltas.[4,22] A study of PCB's similar to the initial failure discussed above showed that the leading method to create microvoids (on the complex actual production assemblies) was through cooler reflow profiles. Another indication of the importance of temperature is the distribution of microvoiding on BGA footprints. The microvoiding is typically revealed on the periphery of solderballs where cooling occurs fastest (see Figure 14.) Additionally, where surface copper traces provide solder joints a heatsink, the voids occur in highest density.



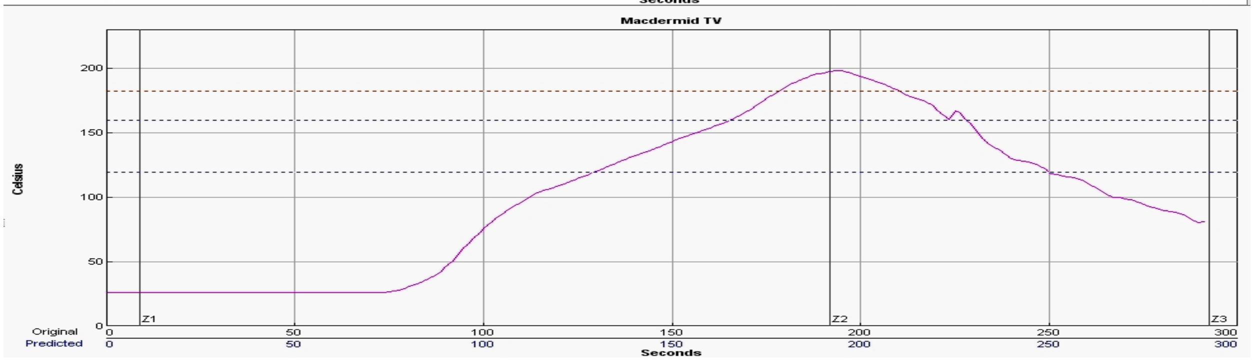


Figure 18 - Assembly Profiles used in Laboratory Testing

Strength of Microvoid Samples

Much focus of the above experiments has been on the detection of microvoids by optical microscopic inspection and certain high-resolution X-ray equipment. Not as much investigation in this project team was focused on the reliability of solder joints exhibiting severe microvoiding. To compare inspection techniques with physical testing methods, a severely microvoided sample was tested for ball shear strength as compared to controls exhibiting no microvoids. Solder spheres were soldered onto a 400 I/O BGA footprint using the factors identified to produce microvoiding. The resulting parts measured 9 on the 1-10 microvoid scale by X-ray. A control part had a 0 measurement. All spheres were sheared using a Dage 4000. The "9" sample showed a significant (30%) reduction in ball shear strength compared to the "0" control, with an even more significant drop (54%) in the mean minus 3 standard deviations (see Figure 19). Perhaps surprisingly, the severely microvoided sample did not easily fall off the BGA pads.

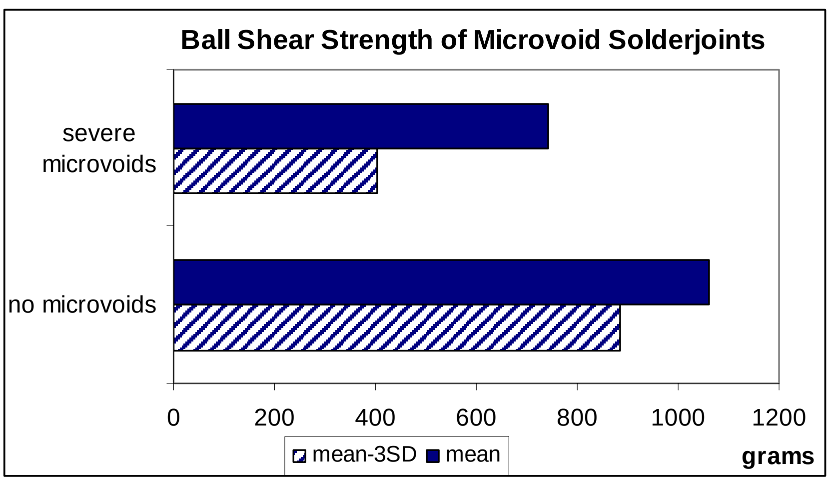


Figure 19 - Strength of Microvoided Solder joints

Preventing Microvoids

While some factors have shown statistical validity as influencing microvoid formation, other factors remain as suspected contributors. Still other factors have not been studied in depth, such as the relative impact of non-silver surface finishes when processed under extreme conditions. For the factors uncovered in this project, there exist ways to prevent microvoid occurrence.

Silver Thickness Control

In most experiments, very high thicknesses of silver were required to cause problematic levels of microvoiding. Drastic reduction of immersion silver thickness is not a real option since thicknesses below 0.13 microns may lead to increased tarnishing, migration of copper through pores, and possible loss in contact functions. However, thickness may be reduced as much as practical while maintaining this lower limit. Lower thickness is accomplished in several ways. Primary importance is given to correct measurement of the silver thickness; see IPC-4553 for measurement suggestions.[23] Thickness variation may be lowered by ensuring a uniformly microetched surface. Finally, the chemical suppliers will provide ways to control the chemical bath through pH, temperature, and pre-dip to allow optimum rate control. Of course, dwell time in the silver bath provides most direct control, as long as sufficient time is maintained in the cleaner, microetch, and rinses.

Deposit Quality

The quality of the immersion silver bath itself has no meaning if other nearby processes are not well engineered and maintained. The copper must be free of organic and tin residues. The roughness of the incoming copper must not be highly variable. The microetch immediately before silver deposition needs to render the copper into a clean, uniform surface. Rework should be prevented, as improper rework may lead to excessive roughness and thickness. If unavoidable, rework must be conducted in strict accordance with supplier recommendations. Silver surfaces with excessive surface area roughness will mimic extremely thick silver deposits. After silver, parts need to be well rinsed, handled and packaged with care, as data shows a link between ionic residue and microvoids. For quality acceptance, tarnish should be prevented, even though no link between tarnish and voiding was discovered.

Assembly Control

Action at the assembly house will lead to less vulnerability to voiding, even within maximum temperature restraints. Studies show that adjusting various aspects of the profile, such as pre-heat, ramp rate and peak temperature all affect microvoiding. Bruno, etal minimizes voiding with medium pre-heat and low ramp rate.[5] Use of low-voiding fluxes and better control of paste storage, etc. may impact voiding as well.[1,19] However, it is not clear that reducing macrovoids will also reduce microvoiding. With the relatively recent interest in microvoiding, there is limited information linking microvoid prevention to solder joint voiding in general. More direct study of all assembly-related factors is needed.

Conclusions and Recommendations

Time has shown that solder joint fracture due to microvoiding is not a commonly observed failure mode in the industry. The observation of microvoiding by close X-ray inspection reveals microvoiding as a somewhat common phenomenon, but since the use of high-resolution X-ray is relatively new for this exact type of examination, it seems clear that some level of microvoiding has always been present. Microvoid creation is not due to a sole processing factor. Had it been, the problem would have been much more easily detected and resolved. Microvoiding is the result of several interacting conditions. Fixing just one of the interacting factors allows for the control of microvoiding. More investigation is needed into the connection between voiding observation and functional performance by industry-accepted reliability testing.

Microvoiding does seem to be associated with the use of immersion silver, and to some unknown extent, the use of ENIG, OSP, immersion tin, HASL and other finishes. Studies show that operating the silver process under recommended process and thickness controls will help prevent the occurrence of functional failures by solder joint microvoids. Numerous studies, measuring X-ray microvoiding, cross-sections and ball-shear strength, show that high-thickness silver soldered at low-temperature conditions produces microvoids. Thickness control is a very important factor, so methods for better controlling thickness are recommended. Better measurement techniques and sufficient measurement frequency are important.

New process changes, intended to provide a more consistent surface texture and silver thickness/volume should be implemented. A quality inspection program, employing thickness measurement and cross-sectional investigations should be installed. In addition to process changes made within immersion silver and other final finish processes, assembly and design factors should be optimized towards the minimization of microvoids.

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