LEAD-FREE AND TIN-LEAD ASSEMBLY AND RELIABILITY OF FINE PITCH WAFER LEVEL CSPs

Michael Meilunas[1], Muffadal Mukadam[2]
&
Peter Borgesen[1], Hari Srihari[2]

[1]Universal Instruments
Binghamton, New York, USA

[2]Binghamton University
Binghamton, New York, USA

ABSTRACT

The option of treating fine pitch wafer level CSP (WLCSP) devices as flip chips and assembling them using a flux dipping process appears to be an increasingly attractive alternative to traditional paste printing assembly. However, printing solder paste offers the advantages of increasing standoff and improving thermal cycle performance. This paper discusses solder paste printing and flux dipping assembly processes for 0.4 and 0.5mm pitch lead-free WLCSPs and the corresponding assembly results and thermal cyclic reliability obtained. Variables evaluated include reflow ambient, paste type, and stencil design. Reliability is also compared to results for the same components assembled under identical conditions using SnPb solder.

Key words: WLCSP, 0.4mm pitch, lead-free, assembly, reliability.

INTRODUCTION

Solder joint reliability is determined by many factors, most of which are fixed before the assembly process begins. Such factors include package design, printed circuit board design, and solder alloy. However, the reliability of a solder joint is also affected by the quality of the assembly process. Important assembly variables include stencil design, paste or flux material/volume, reflow ambient, and reflow profile.

Assembly yields and the long-term reliability of fine pitch WLCSPs are much more sensitive to assembly parameters than larger pitch devices. For example, it will be shown that 0.4mm pitch devices require relatively small stencil apertures with strict dimensional tolerances in order to avoid solder bridging during the assembly process. Furthermore, it is conceivable that 0.4mm pitch paste assembly cannot be successfully implemented with a stencil that is much more than .005” thick. Flux dipping eliminates stencil design requirements while significantly reducing the occurrence of solder bridging, but sacrifices the standoff and reliability enhancements obtained with paste assembly.

The experiment discussed evaluated the effects of stencil and process parameters on fine pitch WLCSP assembly yield and reliability. Stencil parameters (thickness and aperture dimensions) were varied for the 0.4mm pitch devices. Additionally, air and nitrogen reflow atmospheres and paste and flux assemblies were compared for the 0.4mm pitch devices. Paste variables investigated included type III and type IV particle sizes. The reliability of SnAgCu and SnPb devices was evaluated using 0/100^{o}C air-to-air thermal cyclic testing with in-situ event detection.

TEST VEHICLES

Two daisy-chained WLCSP designs were evaluated for this experiment. Design A is a 192 I/O 0.4mm pitch package containing a 16x16 solder joint matrix depopulated to a four row perimeter array. Solder ball diameter is approximately .010” and the balls are attached to the package body by .0078” diameter pads. Design B is a 98 I/O 0.5mm pitch package containing a 10x10 depopulated solder joint array. Solder ball diameter is approximately .012” and the balls are attached to the package body by .011” diameter pads. Both devices were acquired with 96.5Sn/3.0Ag/0.5Cu and 63Sn/37Pb solder balls. Ball side views of the devices may be found in Figure 1. Devices A and B have very similar body dimensions with each measuring approximately .275” on a side. However, the distance from the neutral point (DNP) to the center of the corner most solder bumps differs significantly. The maximum DNP for Device A is roughly .167” while the maximum DNP for Device B is approximately .125”. The DNP of these locations is important because the corner most joints are expected to fatigue earliest during thermal cycling.

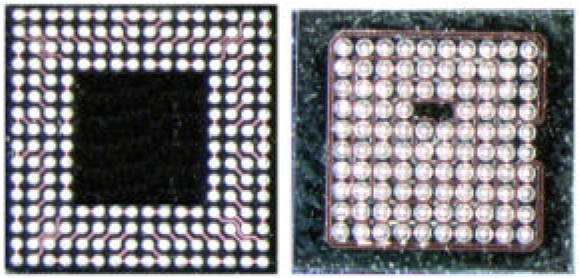

Figure 1. Ball Side View of Devices A (left) and B (right).

The printed circuit boards (PCB) utilized during the experiment were four-layer FR4 based substrates containing non-solder mask defined (NSMD) attachment pads. The nominal thickness of the boards was approximately .062". Six locations were available for 0.4mm pitch assembly and two locations were available for 0.5mm pitch assembly. The 0.4mm pitch locations contained .0062" diameter pads with .0105" mask openings. The 0.5mm pitch locations contained .008" diameter pads with .012" mask openings.

ASSEMBLY

0.4mm Pitch Paste Printing. Successfully implementing a 0.4mm pitch paste printing procedure may require an intensive development process. The process will likely be paste specific and depend highly on the rheology of the material. The processes developed for this experiment required several print parameter changes including squeegee angle. Ultimately, a 45^o squeegee angle was adopted for the experiment. Because print parameters vary from system to system, this paper will focus on stencil design and paste type.

All assembly work was performed using laser-cut stainless foil stencils and stainless squeegees. 15 stencil variations were evaluated including .004 and .005" stencil thickness containing both round and square apertures. Table 1 summarizes the stencil designs utilized. The stencil variables were evaluated for type III and/or type IV SnAgCu solder pastes. Each paste was screened over the PCB and the resulting deposits were visually inspected and photographed. WLCSPs were then placed on the acceptable prints and reflow soldered in a forced convection oven (discussed later). The assemblies were then examined electrically and through the use of an x-ray inspection system.

Stencil Thickness (mil)	Aperture Shape	Aperture Size (mil)	Area Ratio
4	Square	8	0.5
4	Round	9	0.5625
4	Round	10	0.625
4	Square	9	0.5625
4	Square	10	0.625
5	Round	8	0.4
5	Round	9	0.45
5	Round	10	0.5
5	Round	11	0.55
5	Round	12	0.6
5	Square	8	0.5
5	Square	9	0.45
5	Square	10	0.5
5	Square	11	0.55
5	Square	12	0.6

Table 1. Stencil Designs Evaluated for 0.4mm Pitch Assembly.

Printing at 0.4mm pitch offers limited options in terms of stencil aperture dimensions to counter solder bridging due to excessively large paste deposits at one extreme and electrical opens due to insufficient paste deposits at the other. Figures 2, 3, 4 and 5 demonstrate the differences between paste deposits obtained using the aperture design extremes evaluated for the .005" and .004" stencils. Additionally, the aperture sizes suitable for 0.4mm pitch are below the desired area ratio of .66[1]. This essentially means lower transfer efficiency, larger scatter, and increased sensitivity to issues such as board-to-stencil gasketing, board support, and stencil cleaning frequency.

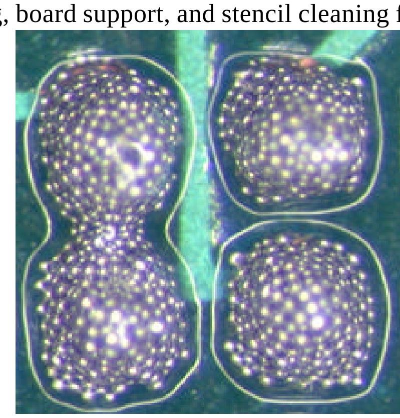

Figure 2. Type 3 Print Deposits at 0.4mm pitch, Created with .012" Square Apertures, .005" Stencil. Resulting Deposits were Often "Excessive".

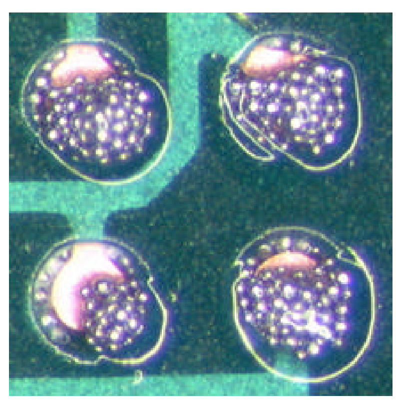

Figure 3. Type 3 Print Deposits at 0.4mm pitch, Created with .008" Square Apertures, .005" Stencil. Resulting Deposits were Often "Insufficent".

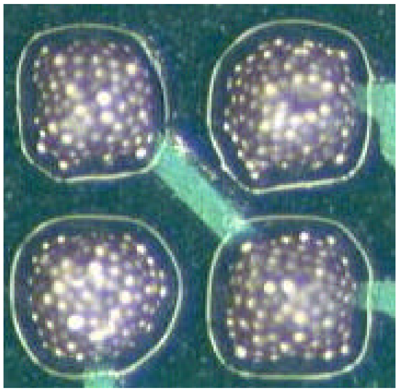

Figure 4. Type 3 Print Deposits at 0.4mm pitch, Created with .010" Square Apertures, .004" Stencil. Resulting Deposits were "Excessive".

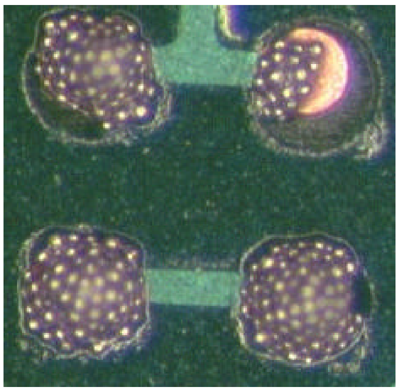

Figure 5. Type 3 Print Deposits at 0.4mm pitch, Created with .008" Square Apertures, .004" Stencil. Resulting Deposits were Often "Insufficient".

The results of the paste printing parameters for Device A are provided in Table 2. The conditions resulting in "Excessive" paste deposits lead to solder paste bridging prior to component placement and/or solder ball bridging after reflow and are unacceptable for an assembly process. The conditions leading to "Insufficient" paste deposits did not result in any electrical defects, nor did they affect reliability as shown later. However, the insufficient deposits are clearly not suitable for a six-sigma assembly process due to the increased risk of electrical opens.

Stencil / Aperture Design (mils)			Paste Type	Paste Print Inspection Results
Thickness	**Shape**	**Size**		
4	Circular	9	4	Insufficient
4	Circular	10	4	Excessive
4	Square	8	4	Insufficient
4	Square	9	4	Excessive
4	Square	10	4	Excessive
4	Square	9	3	Pass
4	Square	10	3	Excessive
5	Circular	8	3	Insufficient
5	Circular	9	3	Insufficient
5	Circular	10	3	Pass
5	Circular	11	3	Excessive
5	Circular	12	3	Excessive
5	Square	8	3	Insufficient
5	Square	9	3	Pass
5	Square	10	3	Pass
5	Square	11	3	Excessive
5	Square	12	3	Excessive

Table 2. Paste Deposit Inspection Results for 0.4mm Pitch Device A.

Table 2 indicates that just four stencil design variables evaluated were suitable for 0.4mm pitch assembly. Interestingly, the .004" stencil was not successfully utilized with type IV paste. This was a bit surprising given that the type IV paste is designed for improved flow through small aperture openings. However, the type IV paste was equally prone to clogging the smallest aperture sizes (.008" square and .009" circular) investigated as the type III paste –even after just three prints as shown in Figure 6. Additionally, the type IV paste actually resulted in excessively large deposits created by the .009 and .010" square apertures which resulted in flux bridging after printing (see Figure 7) and solder bridging during the reflow process.

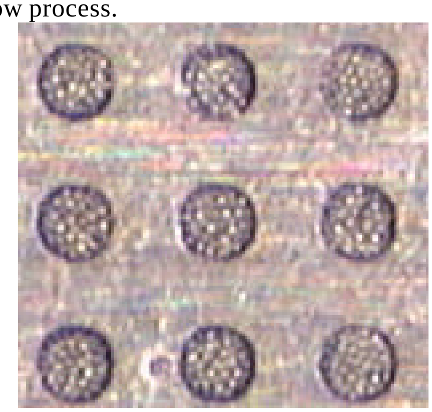

Figure 6. Clogged Stencil Apertures. Type 4 Paste Screened Over .009" Circular Apertures, .004" Stencil. Third Print between Cleanings.

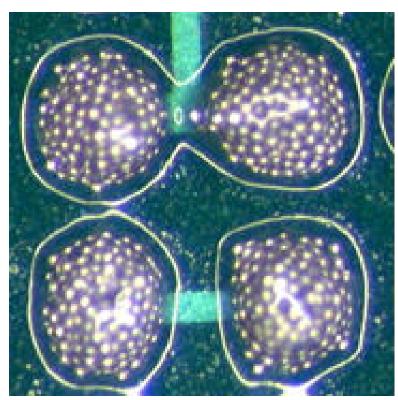

Figure 7. Type 4 Print Deposits at 0.4mm pitch Created with .010" Square Apertures, .004" Stencil. Deposits are "Excessive" –Resulting in Solder Bridging.

Ultimately, the authors chose the printing processes developed with the type III paste and the .004" thick stencil with .009" square apertures and the .005" thick stencil with .010" square apertures for future assembly work. These stencil designs produced zero defects, consistent deposit sizes and shapes, and did not require frequent stencil cleanings.

0.4mm Pitch Flux Dipping. The flux-only assembly process consisted of dipping Device A WLCSPs into a .003" thick layer of tacky flux prior to placement on the PCB. The devices were then reflow soldered in a force convection oven. The same no-clean tacky flux was used for SnPb and lead-free assembly. The tacky flux viscosity was 285 poise and the material had an activation temperature range of 130-185ºC. 100% of the flux assembled devices tested electrically good with no occurrences of solder bridging or solder balling observed during x-ray inspection.

0.5mm Pitch Paste Printing. Device B was successfully assembled using type III paste screened over .011" square apertures on .004, .005 and .006" stencils. These designs provided approximately 200% paste to PCB pad coverage while maintaining a deposit spacing in excess of .008" as shown in Figure 8. As of this writing, over 200 devices have been assembled with the .004" stencil without an electrical defect and over 100 devices have been assembled with the .005 and .006" stencils without an electrical defect.

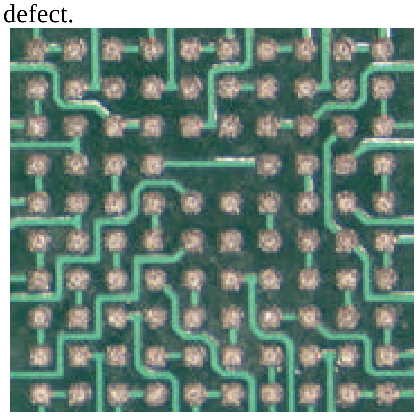

Figure 8. Type 3 Print Deposits at 0.5mm pitch, Created with .011" Square Apertures, .004" Stencil. No Assembly Defects Observed.

Reflow Soldering. Reflow atmosphere is critical to the solderability and wettability of solder to the PCB attachment pad surfaces.

Flux-only soldering of eutectic SnPb in air is possible only with a very limited set of fluxes, pad finishes, and reflow profiles[2]. This is particularly true for flip chip and near flip chip WLCSP assemblies. Paste printing offers wider process windows due to larger flux and solder deposits that minimize the impact of bump size variations. Lead-free alloys apparently require even more aggressive and/or greater quantities of flux or paste than Sn/Pb due to their lower wetting capabilities and higher required reflow temperatures.

Conversely, the use of nitrogen improves assembly yields, increases wetting, and improves self-centering over a wide range of reflow conditions while using non-aggressive no-clean fluxes. Unfortunately, nitrogen is expensive and extensive tombstoning of small components such as 0201s has been reported during nitrogen assembly[3]. Additionally, enhanced wetting and decreased surface tension obtained in nitrogen may increase solder bridging defects in fine pitch assemblies.

The flux dipping and paste printing assembly methods discussed previously were employed to evaluate the effects of lead-free soldering in air and nitrogen for the 0.4mm pitch Device A. Reflow was perfomed in a seven-zone forced convection oven. The flux dipped and paste printed assemblies were subjected to nearly identical reflow profiles utilizing a peak temperature in excess of 240ºC and a time above liquidus of approximately 45 seconds. Both air and nitrogen assembly was performed. The nitrogen atmosphere contained less than 50ppm oxygen.

Post-assembly inspection included electrical measurements, x-ray imaging and cross sectional analysis. The Pb-free devices assembled with paste or flux resulted in perfect yields for both air and nitrogen reflow environments. No electrical abnormalities or solder bridging was observed although the paste assemblies reflowed in air contained the occasional solder ball due to incomplete alloying between the solder bump and solder paste. The shape of the solder joints created in air was also noticeably rougher than those created in nitrogen and the average standoff height of an air reflowed joint was approximately 10% greater than the average standoff height of a nitrogen reflowed joint. Figure 9 contains representative images of paste assembled solder joints reflowed in air.

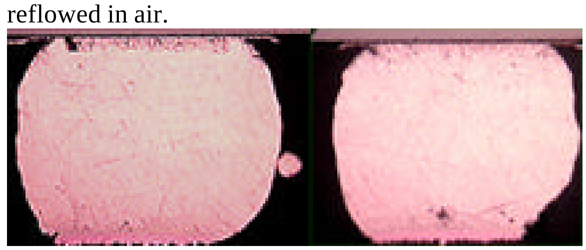

Figure 9. Cross-sections of Paste Assembled SnAgCu Solder Joints Reflowed in Air. Solder Balls and Irregular Surface Shapes Observed.

RELIABILITY AND FAILURE ANALYSIS

Selected test vehicles were subjected to 0/100^{o}C air-to-air thermal cycling. The thermal cycle consisted of 5 minute dwell times and 20^{o}C/min temperature transition rates. Continuous event detection was used to determine solder joint failure based on a modified IPC-9701 approach[4]. Each failure was defined as a single instance of the net resistance exceeding 300 ohms for a minimum duration of

200 nanoseconds (an “event”). The requirement that 9 additional events were necessary to confirm a failure was observed and it generally took less than 3 additional cycles to verify failure.

Failed components were removed from the thermal chamber following confirmation of electrical events on a regular basis. But, due to the short lifetimes encountered, the 0.4mm pitch devices were often subjected to a significant number of cycles beyond failure. Lifetime analysis was performed using two-parameter Weibull distributions with median rank regression. Characteristic lifetime, or N63.2, is the number of cycles at which 63.2% of the sample set has failed and is most often used to define reliability. First failure, or N01, is the projected time, in cycles, required for 1% of a sample set to fail and is an important consideration when defining the reliability of a product. Ultimately, the 11 test cells summarized in Table 3 were evaluated. Please note that the reliability experiment included testing of non-recommended parameters. The data found in Table 3 has many implications, most of which are discussed in the following sections.

Device B. The data acquired for Device B indicates that the type of paste (III or IV) used for assembly had a negligible effect on the reliability of the package. Instead, the solder alloy dominated the device performance with the SnAgCu alloy producing an N63.2 that was about 30% greater than the SnPb solder and an N01 that was nearly 25% greater than the SnPb device. A Weibull plot comparing the three test cells evaluated for Device B may be found in figure 10.

Failure analysis performed on selected Device B assemblies concluded that the corner solder joints located along the perimeter of the device were far more likely to fail than any other location. Fatigue cracks were located in the bulk solder material just below the intermetallic region at the device attachment pad. Figure 11 contains typical fatigue cracks observed within the SnPb and SnAgCu alloys. The SnPb samples generally failed due to a single crack that had propagated along the grain boundaries. The SnAgCu samples generally failed due to a primary crack that has propagated along the grain boundaries, but often contained secondary cracks in the same region.

Figure 11. SnPb (left) and SnAgCu (right) Solder Fatigue Failures Due to Thermal Cycling of Device B.

Device A. Several trends are apparent for the 0.4mm pitch Device A. Interestingly, the effects of the .004” thick stencil aperture dimensions are statistically insignificant at a 95% confidence level. The apertures evaluated, .010, .009, and .008” squares, all produced similar N63.2 values regardless of the paste type. Remember, only the .009” square apertures on the .004” stencil and type III paste are recommend to obtain good assembly yields.

A comparison between the SnAgCu and SnPb Device A assemblies indicates that the N63.2 of the SnAgCu alloy is nearly 80% greater than the SnPb and that there is a significant improvement in N01 when using SnAgCu. These results are strikingly more profound, but on the same order of magnitude, as the results obtained with Device B. Failure analysis of SnPb and SnAgCu solder joints through cross-section inspection determined that the corner solder joints located along the perimeter of the device were most likely to fail. The joints usually failed through the bulk solder material near the component attachment pad, as shown in figure 12. A few late SnAgCu fatigue failures (failed after 500 cycles) also contained solder joints that had cracked near the PCB pad.

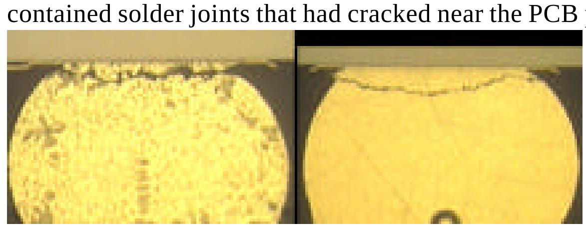

Figure 12. Typical SnPb (left) and SnAgCu (right) Solder Fatigue Failures Due to Thermal Cycling of Device A.

The 0.4mm pitch reliability data obtained for air and nitrogen reflow shows that there is no statistical difference between the sample sets assembled with paste (p value = .890). The same is true for the flux dipped assemblies reflowed in air and nitrogen (p value = .527), although Table 3 suggests otherwise. The information, as presented in Table 3 favors the fluxed nitrogen assemblies because the fluxed air assemblies produced very low N01 values while producing higher N63.2 values than the nitrogen samples as demonstrated in the Weibull plot of figure 13. Failure analysis would reveal that several of the flux-only assemblies reflowed in air were susceptible to a non-solder fatigue failure mechanism in which a solder bump physically separated from the device attachment pad at the intermetallic compound (IMC) as shown in figure 14. Such failures are not attributed to reflow atmosphere and can probably be categorized as “component defects”. This theory is supported by the fact that each assembly was performed separately utilizing devices from different manufacturer’s lots and it is possible that the lot selected for air reflow contained defective components. Devices in which this failure mechanism was positively identified included obvious early failures (31, 35, & 75 cycles) which were subsequently excluded from the Weibull analysis. These failures always contained a severely defective bump along the perimeter of the device. Similar defects were also observed in samples that survived more than the median number of cycles. However, the defects found in the late stage failures were not as severe nor did they occur in the most common failure locations.

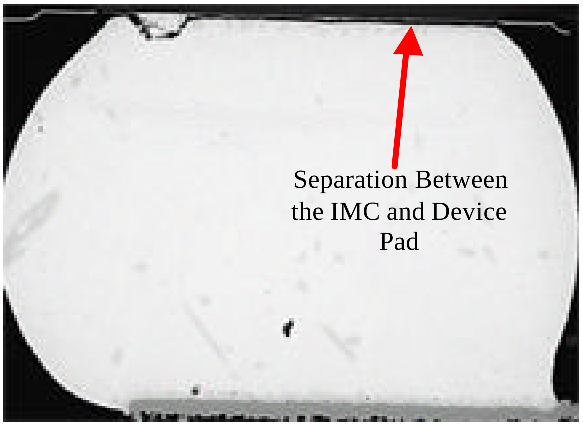

Figure 14. SnAgCu Failure Due to Separation Between the IMC and Device Attachment Pad. 35 Cycles to Failure.

Assembling the 0.4mm pitch SnAgCu devices with paste results in significantly greater N63.2 and N01 than assembly with flux. The improvement in N63.2 is between 25 and 35% and is most likely due to the increased solder joint volume obtained with paste printing. A quick calculation determined that the approximate increase in solder joint volume by assembling with paste (.010" square apertures, .005" stencil, 60% transfer efficiency) instead of flux is about 28%. Cross-sectional analysis of the assemblies also indicates that the standoff height enhancement due to paste printing is 16% greater than flux-only assembly.

Scaling Reliability to Improve Design. Obviously, the reliability of the 0.5mm pitch Device B is significantly greater than that of the 0.4mm pitch Device A. This result was expected as the design of Device B included a lower corner joint DNP, larger solder balls (greater standoff height), and larger device side attachment pads (greater area for a crack to propagate through). The chart presented in Figure 15 utilizes the SnPb reliability data acquired from the current experiment and from other wafer level packaging research using 0/100°C thermal cycling[5, 6]. The chart contains the characteristic lifetime (N63.2) plotted against the approximated strain range on a log-log scale. Attachment pad diameter, which determines crack propagation length, is divided into the characteristic lifetime to normalize the N63.2. The strain range has been estimated by using equation 1:

Equation 1. $\text{Strain Range} = (\Delta\alpha \times \Delta T \times DNP) / h$

Where $\Delta\alpha$ is the CTE mismatch between the FR4 PCB and wafer level device (1.05×10^{-5}ppm/°C), ΔT is the cyclic temperature change (100°C), DNP is the distance from the neutral point to the center of the corner most solder joint (mm) and h is the average solder joint standoff height (mm).

Figure 15 indicates that the reliability of the wafer level packages fits a linear trendline on the log-log plot. Using this data we now argue that to achieve an N01 of 1000 cycles (an arbitrary, but frequently cited requirement) a 0.4mm pitch WLCSP device cannot contain a solder joint array larger than 8x8. We also argue that a .5mm pitch WLCSP cannot contain a solder joint array much larger than 9x9 to achieve the same N01. These numbers, of course, assume similar assembly practices, package construction, pad dimensions, and solder volumes as those used in devices A and B including a paste printing assembly process.

CONCLUSIONS

A reasonably robust paste printing process window for 0.4mm pitch area array devices exists. Paste printing is possible with .004" and .005" stencils. Recommendations include using type III solder paste and .010" square apertures in .005" stencil or .009" squares in .004" stencil. The process window for 0.5mm pitch printing is even larger and can easily accommodate .006" stencils without resulting in solder bridging. Flux dipping is an acceptable alternative to paste printing, but expect a 30% reduction in thermal cycle reliability due to decreased joint standoff.

Pb-free assembly in an air reflow environment is possible for flux dipping and paste printing WLCSP assembly. An air atmosphere will result in less collapse than a nitrogen environment thereby producing greater standoff heights. The reliability of an air assembly is statistically similar to that produced by a nitrogen assembly.

The present 0.4mm pitch SnPb component is too large to survive more than 300 0/100°C thermal cycles without underfilling while the SnAgCu device cannot survive much more than 500 thermal cycles without underfilling. The 0.5mm pitch component can produce a characteristic lifetime in excess of 1000 cycles with SnPb solder and 1500 cycles with SnAgCu solder.

WLCSPs are simple enough to allow scaling of the 0/100°C data for various designs/pitches, but the scaling developed is unlikely to extend to other cycling parameters. An N01 in excess of 1000 cycles is probable with an 8x8 array at 0.4mm pitch and with a 9x9 array at 0.5mm pitch.

REFERENCES

[1] IPC-7525, *Stencil Design Guidelines*, IPC, May 2000.

[2] Mun, J., "Flip Chip Assembly in Air from Manufacturing and Reliability Perspectives", Doctoral Dissertation, State University of New York at Binghamton, 2003.

[3] Adriance, J. & Schake, J., "Mass Reflow of 0201 Components", Proceedings - APEX, Long Beach, CA, March 2000, pp. 3-1 to 3-7.

[4] IPC-9701, *Performance Test Methods and Qualification Requirements for Surface Mount Solder Attachments*, IPC, January 2002.

[5] Meilunas, M., "Reliability of Wafer Level Packagages Assembled to TB6", Area Array Consortium, 2001.

[6] Meilunas, M., "Effect of Printed Circuit Board Surface Finish on the Air to Air Thermal Cycle Reliability of Chip Scale Packages", Area Array Consortium, 2003.

Device - Pitch	Paste / Flux	Alloy	Stencil Aperture	Atmosphere	N63.2 (cylcles)	N01 (cycles)
A - .4mm	Paste – Type 4	SnPb	10x10x4 mil	Nitrogen	267	168
A - .4mm	Paste – Type 4	SnPb	8x8x4 mil	Nitrogen	274	194
A - .4mm	Paste – Type 3	SnPb	10x10x4 mil	Nitrogen	265	168
A - .4mm	Paste – Type 3	SnPb	9x9x4 mil	Nitrogen	287	202
A - .4mm	Paste – Type 3	SnAgCu	9x9x4 mil	Nitrogen	516	295
A - .4mm	Paste – Type 3	SnAgCu	10x10x5 mil	Air	549	270
A - .4mm	Flux	SnAgCu	NA	Nitrogen	381	200
A - .4mm	Flux	SnAgCu	NA	Air	439	58
B - .5mm	Paste – Type 3	SnPb	11x11x4 mil	Nitrogen	1062	754
B - .5mm	Paste – Type 4	SnPb	11x11x4 mil	Nitrogen	1051	662
B - .5mm	Paste – Type 3	SnAgCu	11x11x4 mil	Nitrogen	1369	940

Table 3. N63.2 and N01 for the Variables Evaluated in Thermal Cycling

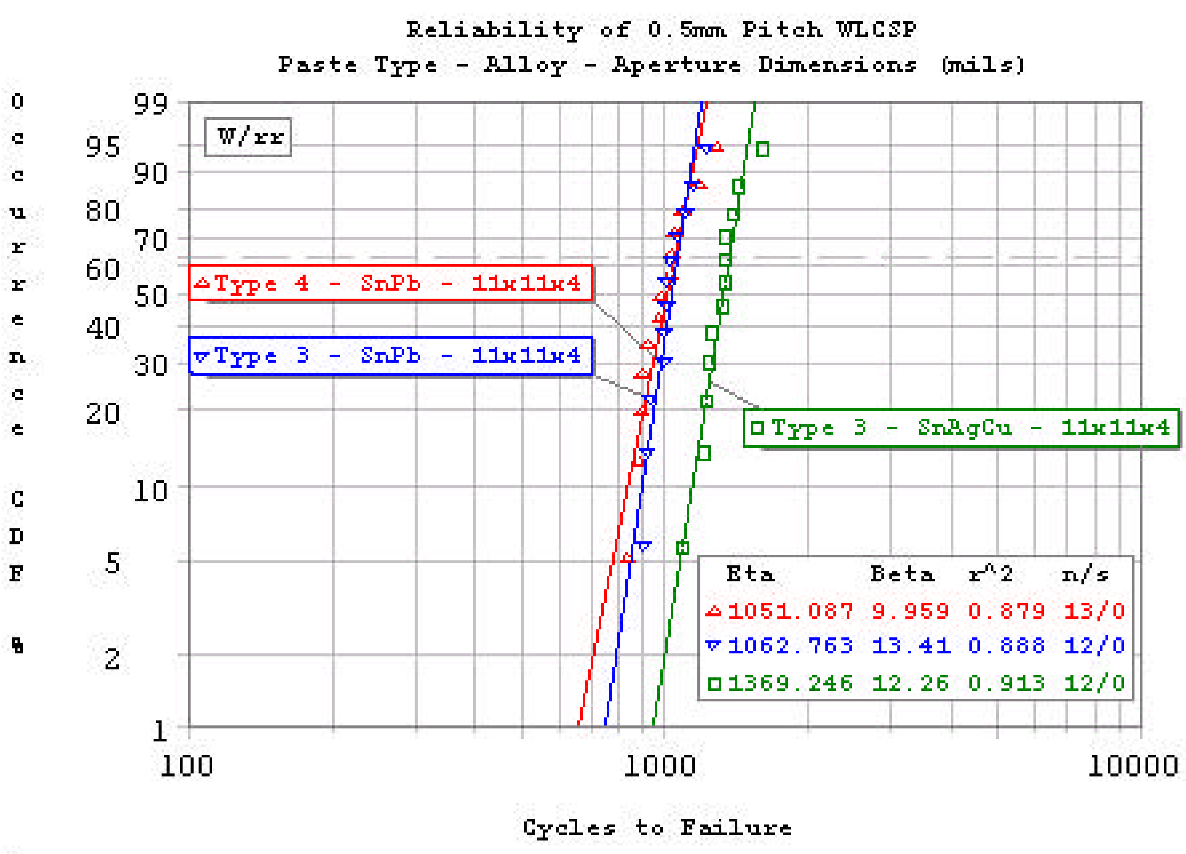

Figure 10. Weibull Plot of 0.5mm Pitch Device B Reliability Data

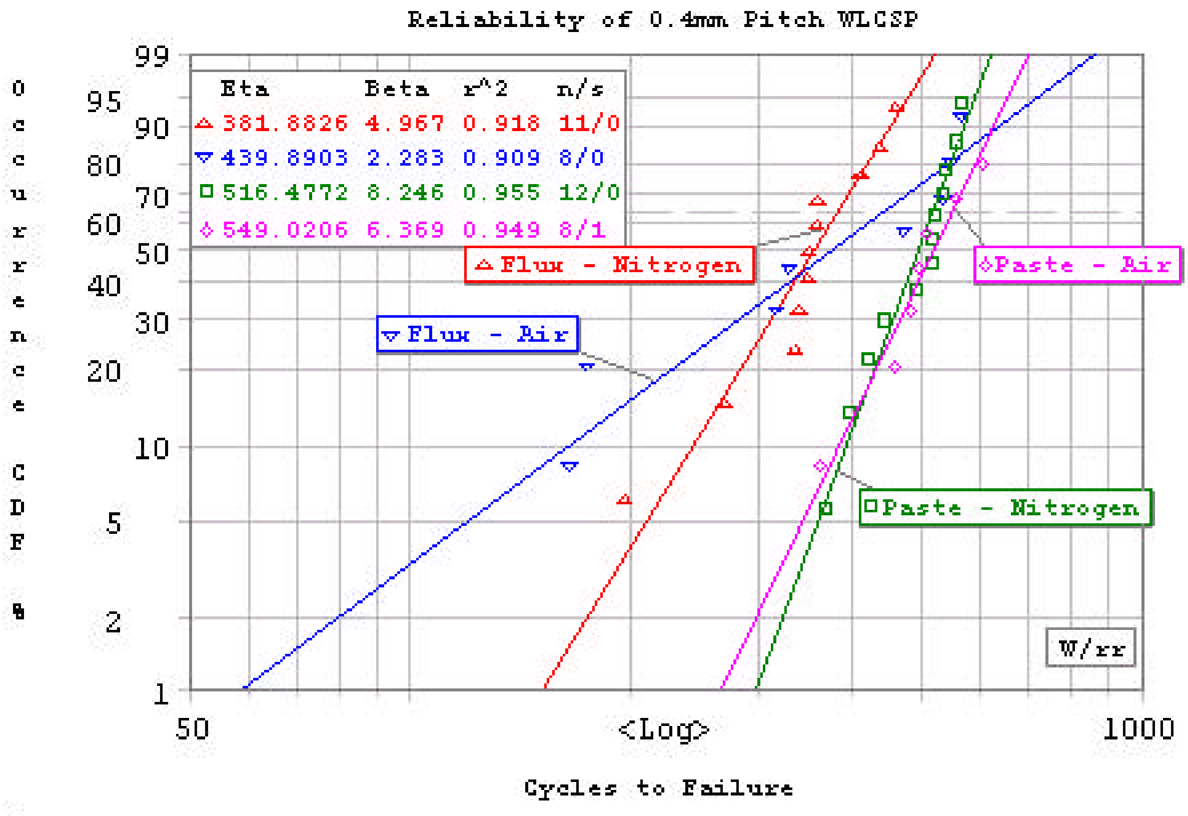

Figure 13. Weibull Plot of 0.4mm Pitch Device A Comparing Reflow Atmosphere

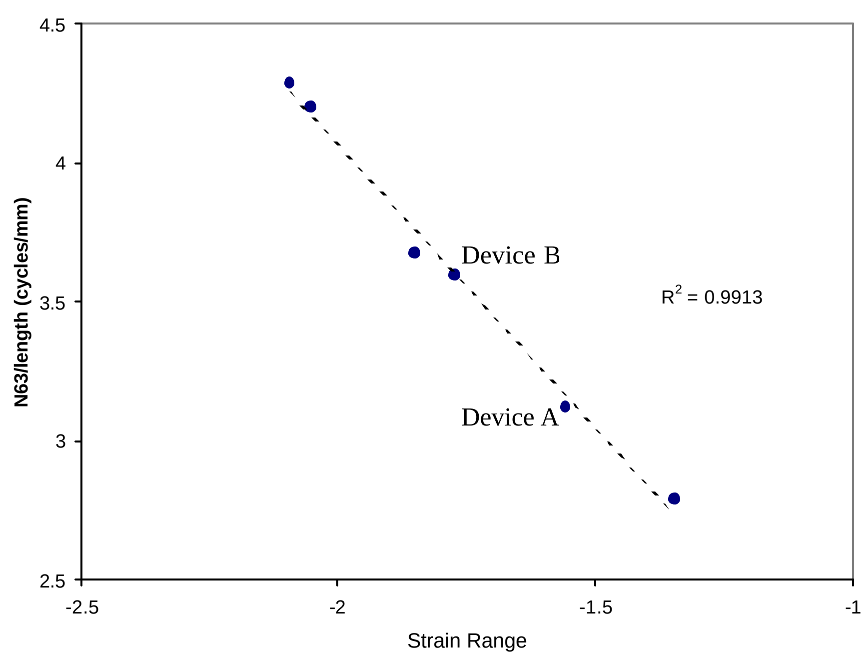

Figure 15. Normalized Characteristic Lifetime versus Strain Range[5,6]