SOLDER JOINT RELIABILITY ASSESMENT OF Sn-Ag-Cu BGA COMPONENTS ATTACHED WITH EUTECTIC Pb-Sn SOLDER

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ABSTRACT

This is the second report in a series of studies conducted at Intel addressing the solder joint reliability of Sn-Ag-Cu BGA-type components attached with eutectic Pb-Sn solder (Pb-free backward compatibility). The packages used in these studies were: a) 0.5 mm pitch vfBGA (very fine ball grid array), b) 0.8mm pitch SCSP (stack chip scale package), c) 1.0mm pitch and 1.27mm pitch wbPBGA (wire bond plastic ball grid array) packages. This paper focuses in the wbPBGA components and in comparison with the other two packages addresses the BGA Scaling effects on backward compatibility.

The packages were assembled under various board reflow profiles using standard Pb-Sn assembly conditions. Peak reflow temperatures varied from 208°C to 222°C with a soak profile or a direct ramp up profile. These reflow profiles result in either a homogenous microstructure of the solder joint because of the melting and collapse of the Sn-Ag-Cu BGA balls or a non-homogenous microstructure due to partial melting and collapse of the BGA balls. The solder joint reliability (SJR) was evaluated in terms of resistance to failure by subjecting assemblies to temperature cycles (-40 °C to 125°C, 30 minutes per cycle) and mechanical shock testing. Results from this SJR testing and detailed failure analysis are reported.

Key words: solder joints, reliability, BGAs, Pb-free, Pb-Sn and Sn-Ag-Cu solder compatibility.

INTRODUCTION

At Intel, *Backwards Compatibility* is defined as a lead free package (lead free terminals) or component that is capable of being solder attached to a Print Circuit Boards (PCB) using eutectic Sn/Pb paste under Intel recommended SnPb reflow profiles and process parameters while the final solder joints statistically meet or exceed current board level reliability goals.

The authors have previously reported solder joint reliability of eutectic Sn-Ag-Cu BGA balls attached to printed circuit boards (PCBs) with eutectic SnPb solder on fine pitch vfBGA (very fine ball grid array) and SCSP (stack chip scale packages). We concluded that the solder joints of these chip scale packages did not meet Intel's board reliability targets, if the solder joints were formed at peak temperatures below 217°C[1]. Continuing that work, larger BGA packages are evaluated and results are reported in this paper.

This work assesses the reliability of solder joints formed with Sn-Ag-Cu BGA ball terminals using the eutectic SnPb paste, under Intel recommended reflow conditions. These results are compared with eutectic SnPb solder joints. Reflow soldering profiles with peak temperature higher than 220°C (above the SnAgCu BGA ball melting temperature) as well as below 220°C (below the SnAgCu BGA ball melting temperature) are evaluated. Detailed failure analysis and microstructure characterization are also reported.

EXPERIMENTAL PROCEDURES

Package Description

Mechanical drawings of the wbPBGA packages evaluated in this study are shown as Figures 1 and 2.

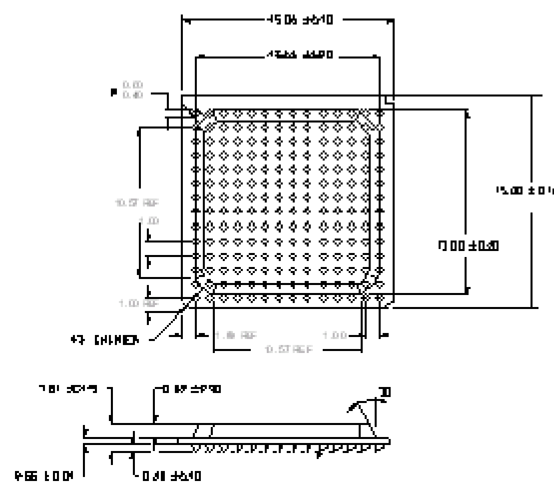

Figure 1: 196 I/O wbPBGA 15x15mm package dimensions. Ball Diameter is 0.40mm. Ball Pitch is 1mm.

These wbPBGA packages are comprised of a core substrate, which is wire-bonded to the silicon die. The 15x15mm and 35x35mm wbPBGA packages have a total package height of 1.81mm and 2.38mm, and ball pitch of 1.00mm and 1.27mm, respectively. The 15x15mm BGA has a 0.4mm solder sphere, whereas the 35x35mm BGA has a 0.6mm ball diameter, both measurements being before ball attach.

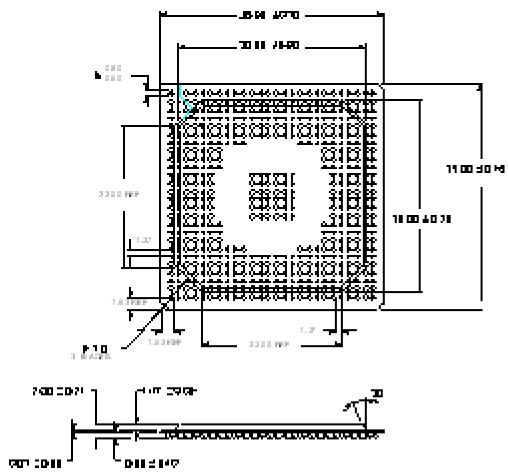

Figure 2. 544 I/O wbPBGA, 35x35mm package dimensions. Ball Diameter is 0.60mm. Ball Pitch is 1.27mm.

Test Vehicle Description

8 layer, standard FR4 boards were used in this study to simulate the projected product conditions. SnPb HASL and Entek® Plus OSP surface finishes were used on the PCBs. Each PCB had 6 wbPBGA land patterns, all of identical daisy chained design. The PCB size and component land pattern layout are shown in Figure 3.

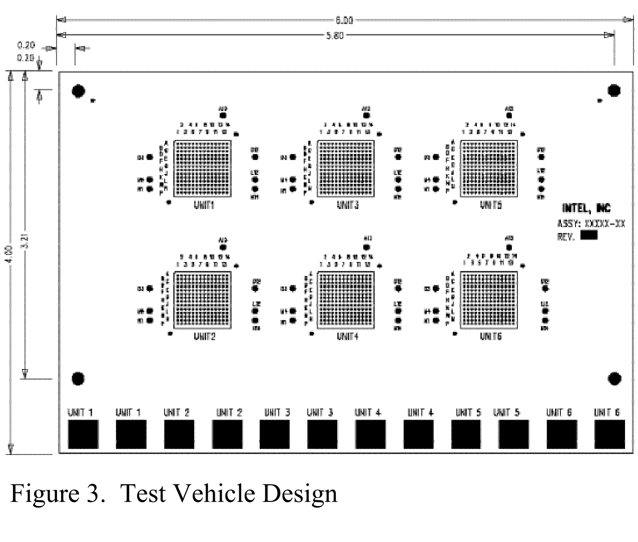

Figure 3. Test Vehicle Design

Board Level Temperature Cycling for Solder Joint Reliability (SJR) Assessment

Imposing assembled boards to temperature cycling did SJR assessment. The temperature cycle chosen to was between -40C and 125C temperature extremes, with a 30-minute per cycle period in an elevator dual chamber oven in which the transition time between the hot and cold zones was less than 2 minutes. An alternate temperature cycle, more popular for board assemblies, was between 0°C and 100°C. Discrete room and cold readouts were performed every 250 cycles. Failure data and Weibull plots were generated. Typically, the test vehicles were subjected to 1500-3000 cycles.

The reflow conditions and reliability goals for the wbPBGAs and previously reported vfBGA and SCSPs components are shown in Table 1. The goal was no failure after 1400 cycles at the -40°C to 125°C condition or 3500 cycles at the 0°C-100°C cycle condition, or statistically equivalent to SnPb POR control in a Weibull plot. All failures were analyzed to determine their root cause.

Table 1: Reliability Goals and Reflow Conditions for Various Packages Studied

Packages and Boards	Reliability Goal	Reflow Processes
0.5mm vfBGA, OSP/ENIG SF	<5% failure 2 800 cycles (-40C to 125C, 30 mins per cycle); no failure after 2 drops	208C+/-4 to 222C+/-4 peak temperature, 60 to 90 secs / 90 to 120 sec TAL, linear/soak profiles
0.8mm SCSP, OSP/ENIG SF		
1.00 mm pitch, 15x15 mm wbPBGA, HASL/OSP SF	No Failure after 1400 cycles (-40C to125C)/ 3500 cycles (0C to 100C) or statistically equivalent to SnPb control in Weibull Plot	
1.27 mm pitch, 35x35mm wbPBGA, HASL/OSP SF		

Mechanical Shock Testing

To assess SJR under mechanical shock conditions, each board was subjected to 6 shock cycles at 50G, for 11 msecs on each of 3 axis. Electrical Readouts on each package were obtained after the test to determine failures.

Assembly Process & Design of Experiment (DOE)

The packages were assembled on the test vehicle boards at Intel's Kulim, Malaysia board assembly plant. All assembled boards were inspected under X-ray for shorts. Electrical continuity tests were performed on each component for opens and the failing components were marked.

Table II is the board assembly build DOE matrix. The Leg #s in this table are not sequential since this DOE was a subset of a larger DOE entailing other legs not described here. The reasoning behind the choice of levels for each variable in the DOE matrix is given below.

<u>Board Surface Finish</u>: Two surface finishes were investigated, SnPb HASL and the Entek® Plus Organic Solderability Protectant (OSP). These two surface finishes are the most popular surface finishes in use today for the product segments in which the wbPBGAs were targeted for use.

<u>Solder joint metallurgy:</u> All package BGA balls were Sn-4.0Ag-0.5Cu (SAC405) Pb-free solders. The solder paste used for assembly was eutectic SnPb solders. Control Lot Assemblies were with Eutectic SnPb BGA ball attached with eutectic SnPb solder paste on OSP and HASL boards. The package side pad metallization was electrolytic plated Ni and flash Au.

Table 2: Design of Experiment (DOE) Matrix

Leg #	Pkg	Ball	Surface Finish	Paste	Reflow Profile	Peak Temp,C	TAL, secs
13	15x15	SAC	HASL	SnPb	Soak	208	30-40
15					Soak	222	60-90
16					Linear	208	60-90
19		SnPb			Control SnPb Reflow Profile		
23		SAC	OSP		Soak	208	30-40
25					Soak	222	60-90
26					Linear	208	60-90
29		SnPb			Control SnPb Reflow Profile		
14	35x35	SAC	HASL		Soak	208	30-40
17					Soak	208	60-90
18					Linear	208	60-90
21		SnPb			Control SnPb Reflow Profile		
24		SAC	OSP		Soak	208	30-40
27					Soak	222	60-90
28					Linear	208	60-90
31		SnPb			Control SnPb Reflow Profile		

Reflow Profile: Two types of reflow profiles were investigated. One was the soak profile, which is typically used for SnPb board assembly today. The temperature ramps up initially till it reaches a pre-determined soak temperature and then soaks at this temperature for a while to burn off the volatile ingredients in the solder paste. This soak profile design also equilibrates the temperature across the board. Subsequently, the temperature then ramps up to the molten range for the solder composition. The other profile is a ramp profile, which is devoid of the soak zone described above. Ramp profiles are adopted when higher board throughputs are required through the reflow soldering oven.

Peak Reflow Temperature: Two different peak reflow temperatures were investigated. The lower one, 208°C was picked so the SnAgCu balls of the components would not completely melt or collapse. The SnAgCu balls have a melting point of ~217°C. The other peak reflow temperature, 222°C was picked such that the SnAgCu balls would melt or collapse during the reflow soldering process. A tolerance of +/-4°C was set for the peak reflow temperature.

Time Above Liquidus (TAL): Two different TAL (above 183°C) ranges were investigated. The shorter range was 30-40 seconds and the longer range was 60-90 seconds. Both these two TAL ranges is typically used in most board assembly processes today. The shorter range is beneficial for board throughput through the reflow oven, but may preclude complete homogenization of the solder ball composition after the solder paste has melted. The longer range will allow ample time for the solder composition throughout the ball to homogenize and avoid any elemental segregation.

RESULTS

Assembly Yield

100% yield was observed for all the wbPBGA builds. The solder joint standoff height for 35x35mm packages was in the 23.1 to 25.0mil range. For 15x15mm packages, the solder joint standoff height was in the 12.6 to 13.1 mil range. While the deviation of solder joint standoff height is doesn't vary much between reflow profiles, longer time about liquidus and higher peak reflow temperature conditions were observed to result in solder joints with slightly shorter standoff heights.

Thermal Cycling Results

(1) *Assembly of Sn-4.0Ag-0.5Cu BGA packages attached with eutectic SnPb solder paste reflowed at the higher peak temperature (≥217 °C) on OSP and HASL boards.*

For 0.5mm pitch vfBGA and 0.8mm pitch SCSP packages, solder joints of Sn-4.0Ag-0.5Cu BGA ball attached with eutectic SnPb solder paste and processed at peak temperature of 222°C on OSP board surface finishes, met board level reliability goals [1]. As shown in Figure 6 and 7, there was less than 1% failure after 3000 thermal cycles of –40°C to 125°C for 35x35mm WBPBGA packages on OSP and HASL boards. While board assembly of 15x15mm packages passes 1400 cycles with no failure, the reliability of solder joints of Sn-4.0Ag-0.5Cu BGA with eutectic Sn-Pb solder paste is statistically worse than that of eutectic Pb-Sn control, as shown in Figure 4 and 5.

(2) *Assembly of Sn-4.0Ag-0.5Cu BGA packages attached with eutectic SnPb solder paste reflowed at lower peak temperature (208 °C) on* OSP and HASL.

While all the solder joints of Sn-0.4Ag-0.5Cu BGA attached with eutectic SnPb paste meet the board level reliability goal in 0.5mm pitch vfBGA and 0.8mm SCSP packages on OSP surface finishes, the solder joints processed at 208°C peak temperature, 60s to 90s TAL linear reflow profile fail to meet temperature cycling goal (~7% cumulative failures @ 800 cycles). Failure analysis indicates the premature failures were due to joint skew caused by misplacement during picking and placement. This misplacement was not rectified during reflow soldering by the inherent self-aligning process driven by the surface tension of the molten solder when the solder ball becomes fully molten. In the present case, the lower surface tension of "mush" solder joints at temperature below 217°C are insufficient to drive this self aligning process. In order to overcome the issue, better alignment in the pick-replacement will be needed, especially for fine pitch BGA packages. However, current SMT technology capability in assembly house may not be able to overcome the issue. This has been documented in the previous published paper [1].

In wbPBGA package evaluations, most of the solder joints processed at 208°C peak temperature have statistically equivalent or better temperature cycles fatigue life comparing to SnPb control joints. Only legs with the 35x35mm package that were processed at 208°C and 30s to 40s TAL have the likelihood of missing the reliability goal (no failure after 1400 cycles) due to inconsistency of the solder joints. This inconsistency is indicated by a very low β, shape value, 2.76 (SnPb control β>10) in the Weibull plot shown in Figure 7. However, the cycles at statistical cumulative failure of 63% are high (> 4500 cycles). This issue can be eliminated with better process control, but it is unclear whether this level of process control is present at the assembly houses in the industry today.

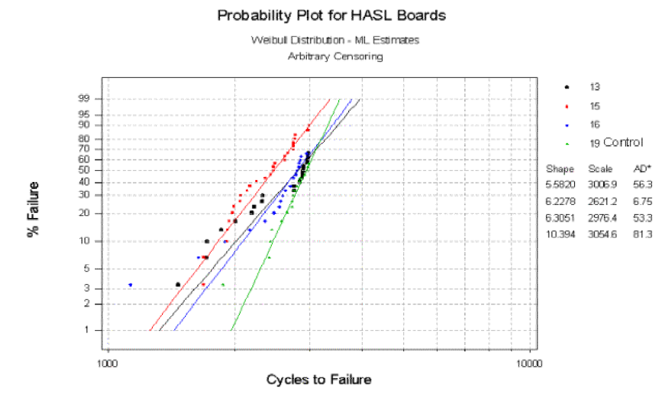

Figure 4. Weibull plot of failures of –40°C to 125°C thermal cycling testing for 15x15mm wbPBGA packages on HASL boards.

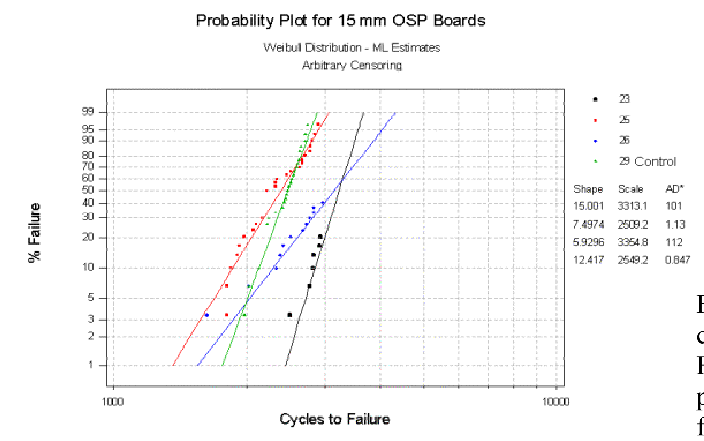

Figure 5. Weibull plot of failures of –40°C to 125°C thermal cycling testing for 15x15mm wbPBGA packages on OSP boards.

Mechanical Shock Results
4 boards per DOE leg were subjected to the Mechanical Shock Testing. No failures were observed for any of the legs.

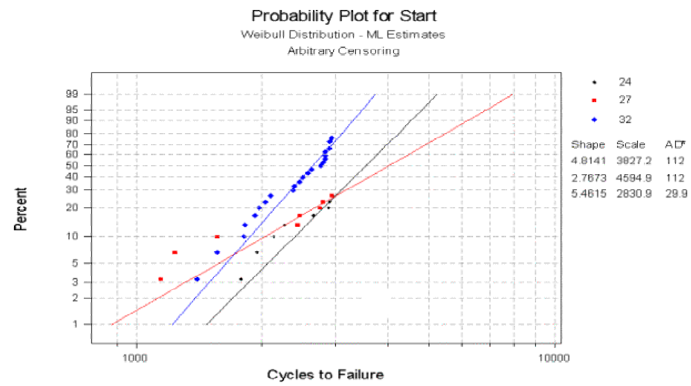

Figure 6. Weibull plot of failures of –40°C to 125°C thermal cycling testing for35mm x35mm WBPBGA packages on OSP boards**.** Note: solder joints processed at 216C peak and 60s to 90s TAL and POR Pb control have 0 failures after 3000 cycles.

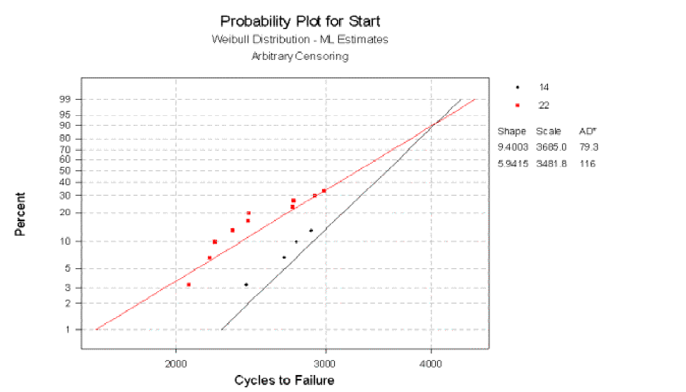

Figure 7. Weibull plot of failures of –40°C to 125°C thermal cycling testing for35mm x35mm WBPBGA packages on HASL boards**.** Note: solder joints processed at 216C / 208C peak and 60s to 90s TAL and POR Pb control have <1% failures after 3000 cycles.

Failure Analysis and Discussion
15x15mm Packages
Table 3 shows the details of the electrical readout failures on the 15x15mm wbPBGA packages under Temperature Cycling. The cycle# at which the failure occurred are listed in the extreme right column. All failures were on boards having HASL surface finish and those reflow soldered at the

lower peak temperature of 208C. All failures, but one, were for board assembled with the shorter TAL profiles.

Table 3. 15x15mm wbPBGA Electrical Readout Failures

Leg	Bd #	Unit #	Ball	SF	Paste	Profile	Cycle#
13	3	1	SAC	HASL	SnPb	Soak 30-40s TAL, peak 208C	2758
13	3	2					2756
13	3	4					2986
13	3	5					2913
13	3	6					2006
13	9	6					2323
16	6	2				Linear 60-90s TAL, peak 208C	1635

Figures 8 and 9 depict the cross-section of two solder joints on the units that had electrical failures. These photos indicate that:

(i) the solder joints had cracks all across the diameter at the package interface.
(ii) the package land diameter (or opening in the soldermask) is much smaller than the board land diameter, contrary to standard designs which have the package and board land approximately the same; failures typically occur at the smaller land diameters, as is the case here.
(iii) the Pb from the solder paste has mixed completely across the entire solder ball cross-section.

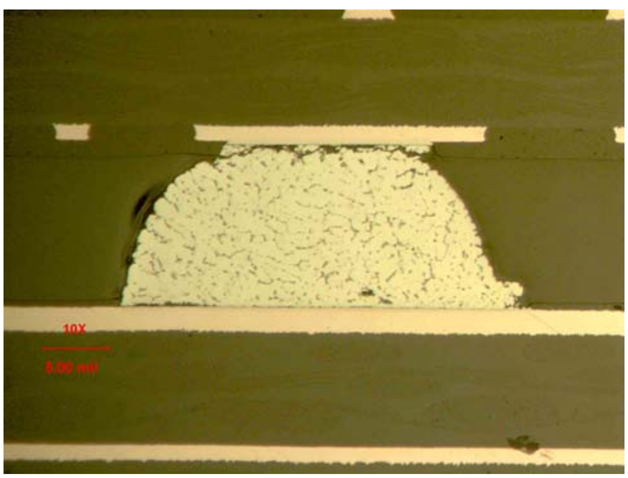

Figure 8: Cross-Section of a wbPBGA Solder Joint Failure for Unit 1 on Board 3, for Leg 13

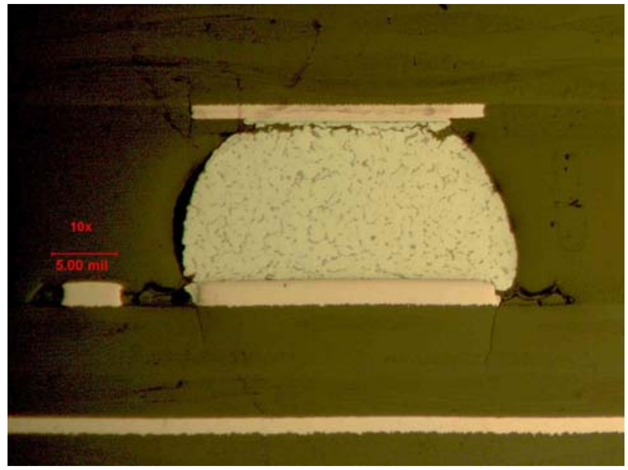

Figure 9: Cross-Section of a wbPBGA Solder Joint Failure for Unit 3 on Board 3, for Leg 13

Figures 10 and 11 show a close up view of the cracks in the solder joints of two other 15x15mm units on the same board as those shown in Figure 7 and 8. Though close to the intermetallic layer, the solder joint cracks appear to have propagated within the solder.

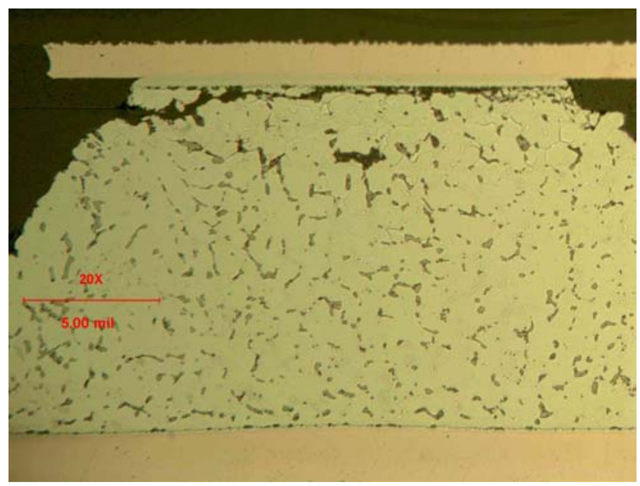

Figure 10: Cross-Section of a wbPBGA Solder Joint Failure for Unit 5 on Board 3, for Leg 13

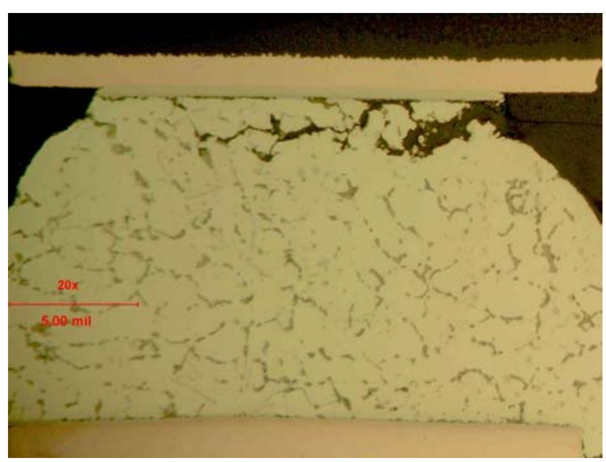

Figure 11: Cross-Section of a wbPBGA Solder Joint Failure for Unit 6 on Board 3, for Leg 13

Figure 12 illustrates a solder joint in a 15x15mm package, which had incomplete `mixing` of the Pb in the solder ball. This solder joint is from a board assembled with the same reflow profile settings as those solder joints illustrated in Figures 8-11. This indicates that the Soak, 30-40S TAL, 208C Peak Temperature profile cannot guarantee complete mixing of the Pb in the 15x15mm wbPBGA Backward Compatibility solder joints.

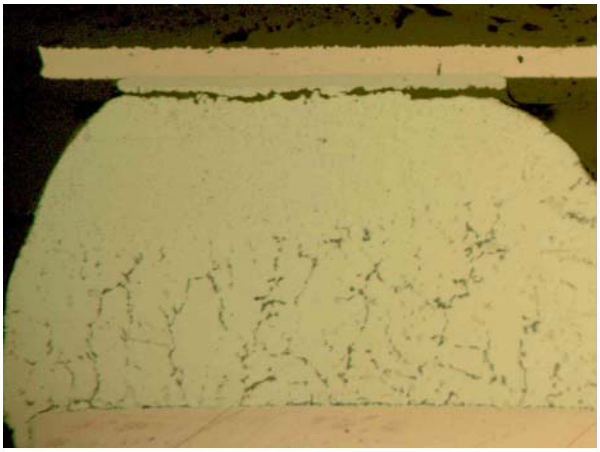

Figure 12: Cross-Section of a wbPBGA Solder Joint Failure for Unit 6 on Board 9, for Leg 13. This photo illustrates the incomplete mixing of Pb in the SAC solder ball.

35x35mm Packages

Table 4 shows the details of the electrical readout failures on the 35x35mm wbPBGA packages under Temperature Cycling. The cycle# at which the failure occurred are listed in the extreme right column. All failures were on boards having OSP surface finish and those reflow soldered at the lower peak temperature of 208C.

Table 4. 35x35mm wbPBGA Electrical Readout Failures

Leg	Bd #	Unit #	Ball	SF	Paste	Profile	Cycle#
24	8	1	SAC	OSP	SnPb	Soak 30-40s TAL, peak 208C	1780
24	12	3					1948
24	12	4					2900
27	4	4				Soak 60-90s TAL, peak 208C	2435
27	6	6					2800

Figures 13 and 14 show the cross-section of the wbPBGA solder joints that were indicated to have a failure during electrical read-outs. These photos indicate that:

(i) the solder joints had cracks (location indicated by the red circles in the photos) at both the Package and Board solder joint to land interfaces but these cracks had NOT propagated across the entire diameter of the lands;

(ii) there was incomplete mixing of the Pb in the SAC Solder ball. This incomplete mixing was more widespread in the 35x35mm wbPBGA solder joints than for the 15x15mm wbPBGA solder joints for the same reflow profile settings, which was expected due to the larger thermal mass of the 35x35mm wbPBGA components.

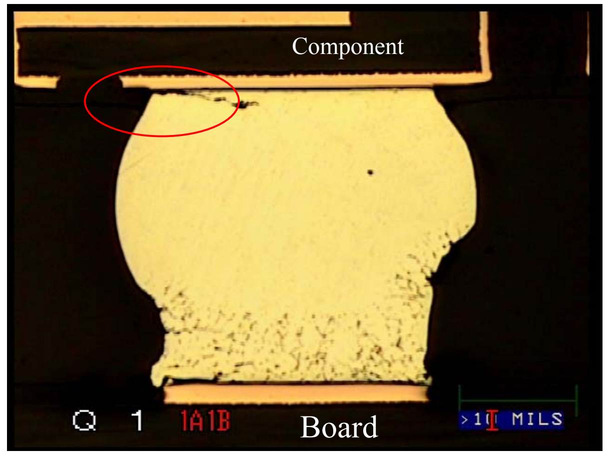

Figure 13: Cross-section of a wbPBGA Solder Joint for Unit 1, Board 8, for Leg 24.

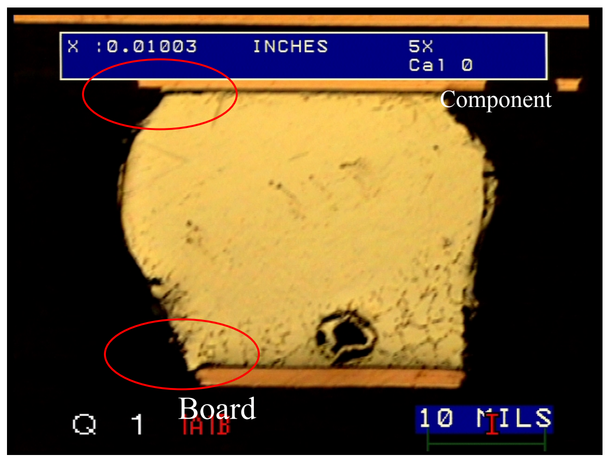

Figure 14: Cross-section of a wbPBGA Solder Joint for Unit 4, Board 4, for Leg 27.

Figure 15 depicts another similar Cross-section of a 35x35mm wbPBGA with a partial crack on the right side of the solder joint at the Solder to Board Land Interface.

A close-up view of this crack at a higher magnification is shown in Figure 16. This figure indicates that the crack propagates in the solder joint, and not in the intermetallic layer.

Figure 15 also illustrates that in ability of the BGA balls to self alignment during reflow due to the incomplete melting and collapse of the solder ball for peak reflow temperatures below the melting point of the solder joint.

Other salient points that can be surmised from the data obtained are:

- ➢ Package standoff height seems to make a difference in reliability, but ball shape could play a big role too.

Shape and height were however, not control parameters in the DOE.

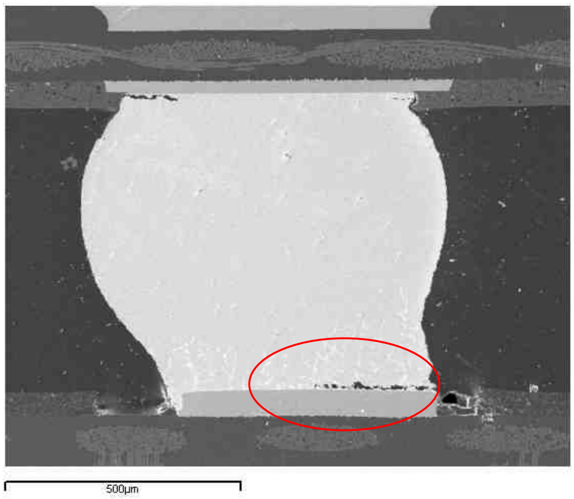

Figure 15: Cross-section of a wbPBGA Solder Joint for Unit 3, Board 12, for Leg 24. The red circle indicates a Solder Joint Crack location

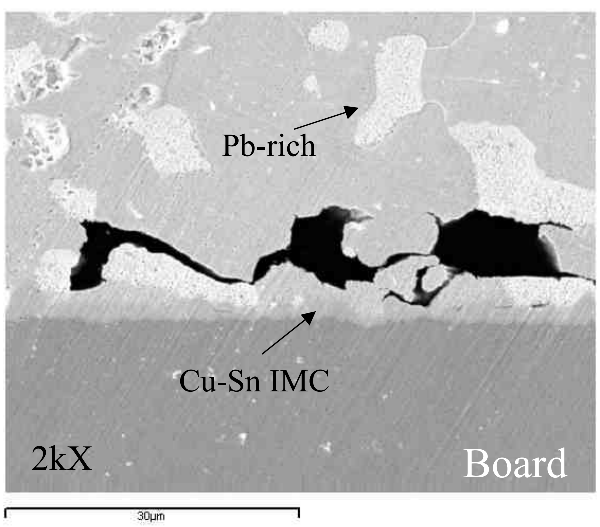

Figure 16: A closer view (at higher magnification) of the Solder Joint Crack in Figure 15.

- The level of Pb diffusion into the partially collapsed SAC solder ball differs with package thermal mass, and reflow profile setting, but also varies within the same reflow profile setting. But, this does not seem to be a big contributor to the fatigue life.
- Reliability of **total Pb-free** solder joints was different depending on strain level imposed on the solder joints. While solder joints of 0.5mm pitch vfBGA, 0.8mm SCSP and 1.0mm pitch 15mmx15mm WBPBGA have better or equivalent thermal cycle (–40°C to 125°C, 30min. per cycle) fatigue life, 1.27mm pitch 35x35mm WBPBGA was worse than POR Pb-Sn solder joints (see figure 6 and 7). It is consistent with IBM's recent assessment [2]. However, this IBM data [2] indicated that total Pb-free solder joints are more reliable if the same solder joints are thermal cycled in 0°C to 100°C temperature range
- Further, in the reliability data reported by IBM [2] total Pb-free solder joints in 32x32mm CBGA (Ceramic BGA, Sn-Ag-Cu BGA ball attached with Sn-Ag-Cu solder paste) were shown to be more reliable than eutectic SnPb solder joints when thermal cycled in 0°C to 100°C temperature range, but, less reliable when the same solder joints thermal cycling in –40°C to 125°C temperature range. Hence, reliability prediction with Pb-free solder by copying eutectic SnPb will results in a big error without considering thermal strain effects.

CONCLUSION

In summary, assembling Sn-4.0Ag-0.5Cu BGA packages on boards is not a "drop in" solution for current eutectic Sn-Pb solder assembly manufacturing due to industry board level assembly capability. Reliability and process risk is low when process peak temperature is higher than 217C because the ball would have collapsed completely and would have a homogeneous microstructure. However, reliability and process risk is high for the solder joints formed with a reflow profile having a peak temperature less than 217C, because the solder joints will have an inhomogeneous microstructure resulting from only a partial collapse of the SnAgCu ball. Much more process development is needed to over come the issue

ACKNOWLEDGEMENT

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[2, "The effect of temperature range during thermal cycling on thermomechanical fatigue behavior of selected Pb-free solders", James C. Bartelo, ECTC proceeding 2002.