

# The Impact of Reflowing A Pbfree Solder Alloy Using A Tin/Lead Solder Alloy Reflow Profile On Solder Joint Integrity

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## ABSTRACT

The electronics industry is undergoing a materials evolution due to the pending Restriction of Hazardous Substances (RoHS) European Directive. Printed wiring board laminate suppliers, component fabricators, and printed wiring assembly operations are engaged in a multitude of investigations to determine what leadfree (Pbfree) material choices best fit their needs. The size and complexity of Pbfree implementation insures a transition period in which Pbfree and tin/lead solder finishes will be present on printed wiring assemblies. Ball grid array is one component style that has generated concern with respect to mixed finish scenarios. To better understand the reliability effect of mixed surface finish manufacturing, an investigation was conducted to evaluate the solder joint integrity impact of reflowing a Pbfree solder alloy using a tin/lead reflow profile. In this study, ball grid array components with tin/silver/copper (SAC) solder spheres were processed using a tin/lead reflow profile and then subjected to thermal cycle testing from -55°C to +125°C. Solder joint life measurements and failure analysis revealed premature solder joint failures due to non-uniform microstructure and poor wetting characteristics.

## BACKGROUND

Rockwell Collins has followed the European Union (EU) activities/efforts pertaining to the drafted Waste from Electrical and Electronic Equipment (WEEE) and Restriction of Hazardous Materials (RoHS) directives very closely since their inception. The RoHS directive requires the elimination of lead, mercury, hexavalent chromium, and two specific fire retardants from electronic assemblies by July of 2006. Avionics equipment and systems were neither specifically included or excluded from the directives. At present, Rockwell Collins is coordinating with EU representatives to define avionics' status as detailed by the RoHS directives. Rockwell Collins has adopted a proactive approach to the implementation of Pbfree processes by conducting internal investigative efforts, and participating in a number of industry Pbfree solder process focused efforts. The differences in process requirements for Pbfree and tin/lead solders raise both material and logistical concerns for electronic assembly. Pbfree solders require higher temperatures to reflow. Pbfree solders are alloyed with a wider number of metals which creates the potential for a far wider variety of intermetallics to be present in a solder joint. The more complicated compositions can result in solder joint microstructures that are not as thoroughly studied as current tin/lead solder microstructures. These material concerns are intensified by the possibility of Pbfree solders being unintentionally used in either processes designed solely for tin/lead solders or environments where material interactions are poorly understood, e.g. reworking a tin/lead solder joint with Pbfree solder. These mixed finish scenarios could negatively impact solder reliability. Rockwell Collins currently utilizes lead containing solder alloys in our soldering processes. The scope and complexity of Pbfree implementation ensures a transitional period in which both Pbfree and tin/lead solder finishes will be present on the same printed wiring assemblies. Understanding the potential impact of mixed finish scenarios on avionics product reliability is critical.

## OBJECTIVE

The objective of the study was to evaluate the solder joint integrity impact of reflowing a Pbfree solder alloy using a tin/lead reflow profile on BGA components.

## PROCEDURES

### Test Vehicle

The test vehicle used in the investigation was 0.082 inches thick, contained 18 layers of 0.5 ounce copper, and used an electroless nickel/immersion gold (ENIG) finish. The test vehicle laminate was FR4 per IPC-4101/26 with a minimum Tg of 170°C. The test vehicle contained 11 component test locations. Figure 1 illustrates the test vehicle design.

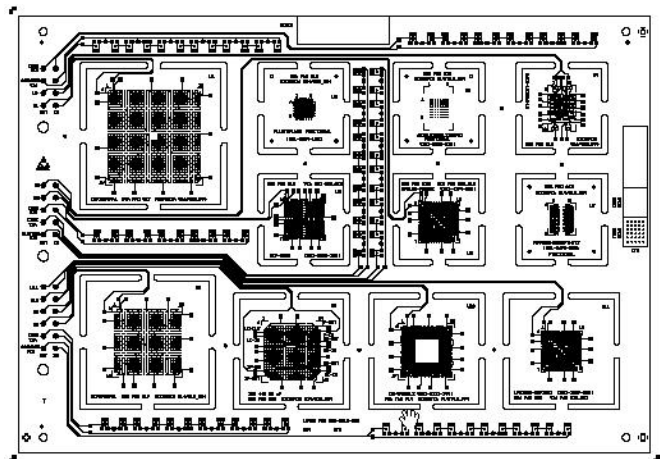


Figure 1: Test Vehicle Design

### Test Component

The test component was an 256 Daisy Chained, I/O 256, 17mm x 17mm square, 1.0 mm pitch Field Programmable Gate Array utilizing a Sn/4.0Ag/0.5Cu (SAC 405) soldersphere alloy. The BGA component was originally to

have tin/lead solderballs but was unintentionally supplied with Tin/Silver/Copper (SAC) solderballs. Process time constraints did not allow for the component supplier to replace the BGAs with Sn/Pb solderballs thus allowing the opportunity to investigate the interaction of a SAC solder alloy with a Sn/Pb soldering reflow process. Figure 2 illustrates the test component pwb pad pattern.

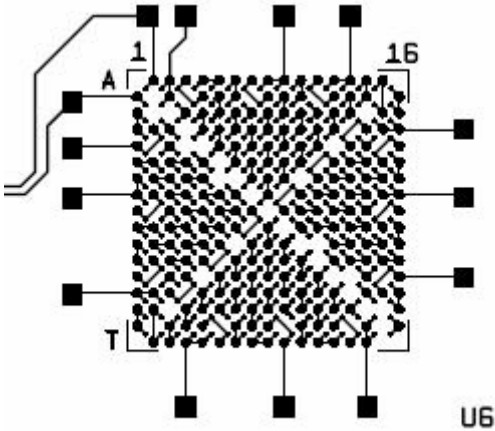


Figure 2: Test Component Pad Pattern

#### Assembly

##### Test Vehicle Assembly Flow

The test vehicles were processed as shown in the flow diagram in Figure 3.

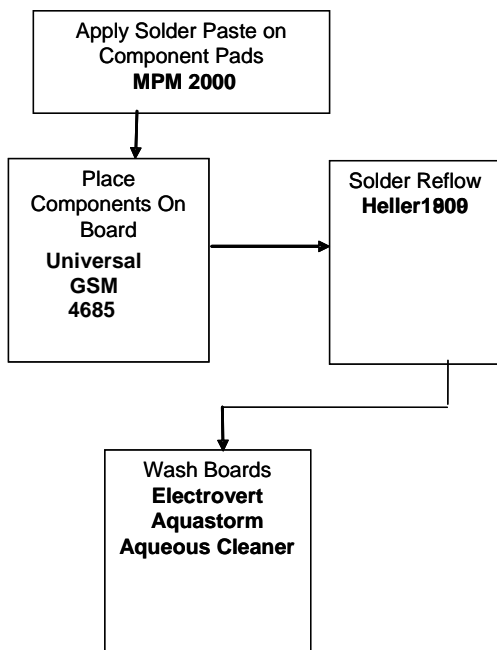


Figure 3: Flow chart of assembly process

##### Solder Paste Process

The first step of the test vehicle assembly process was the application of solder paste. An MPM Ultraprint 2000 using Indium's SMQ92J solder paste was utilized. Indium's recommend solder paste print parameters (e.g. print speed, print pressure) were followed. The solder paste stencil was

fabricated from 0.005 inches thick stainless steel material and utilized laser cut apertures.

##### Component Placement

The test vehicles were immediately transferred to the Universal GSM 4685 machine shown in Figure 4 upon completion of the application of solder paste. The test vehicles were fully populated.

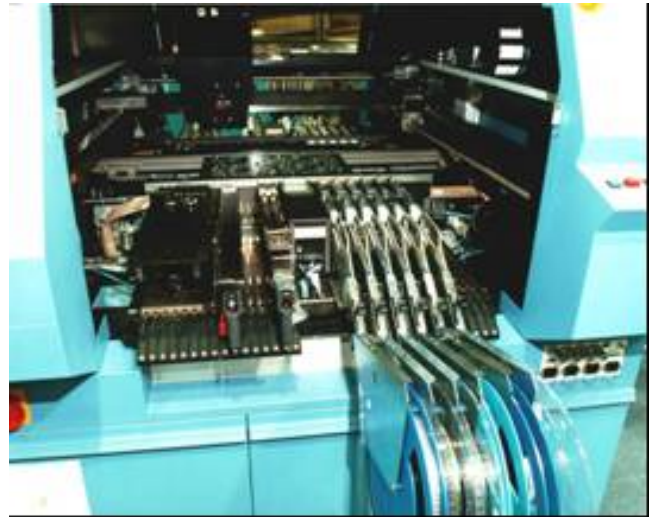


Figure 4: Universal GSM 4685 Machine

##### Reflow

The test vehicle was reflowed with a Heller 1809EXL Convection Reflow Oven. This oven had ten temperature zones for solder reflow. The conveyor speed was 34 inches per minute and the nitrogen flow was 1500 cubic feet per hour (approximately 150ppm O<sub>2</sub> concentration). The oven used the high convection setting, and the boards were placed on the rails. The reflow profile as measured on the test vehicle is shown in Figure 5.

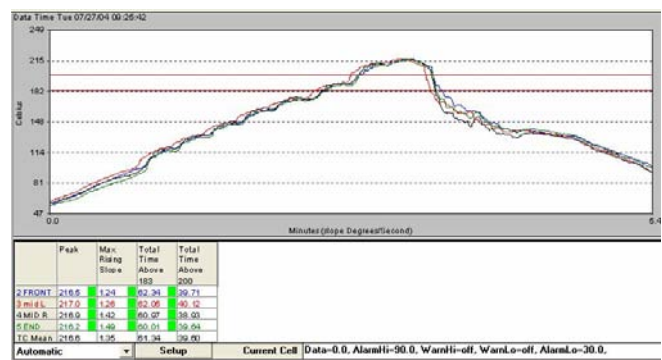
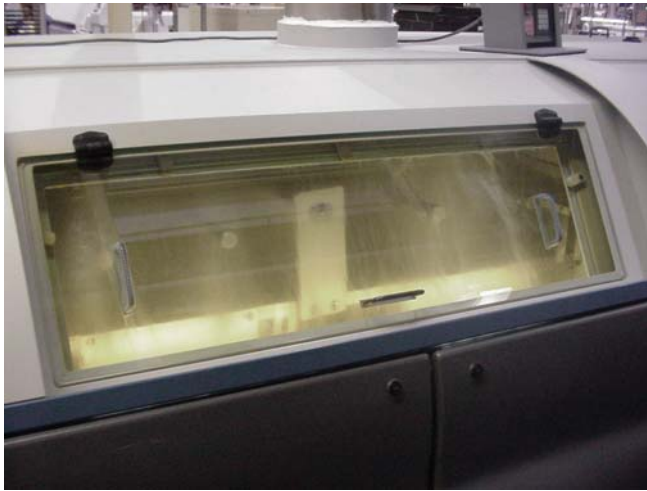


Figure 5: Thermal Profile

##### Cleaning

The boards were allowed to cool to room temperature after reflow and then placed an Electrovert Aquastorm in-line cleaning system for removal of solder flux residues. The in-line cleaner utilized Kyzen SSA saponifier/de-ionized water to remove the test vehicle flux residues. The in-line cleaner is shown in Figure 6.



**Figure 6: Inline Cleaning System**

#### Assembly Inspection

The solder joint quality and placement accuracy of all test vehicles were x-ray and visually inspected following the cleaning process. The inspection criteria were in accordance with Rockwell Collins Workmanship and the IPC-JSTD-001 specifications. No solder joint anomalies were observed during the x-ray inspection analysis.

#### Thermal Cycle Parameters/Methodology

The temperature cycle range used in the investigation was -55°C to +125°C with a minimum 11 minute dwell at each temperature extreme and a maximum temperature ramp of 10°C/min. Components for Rockwell Collins designs are evaluated against specific benchmarks. Components are expected to pass 2000 thermal cycles failure-free to be used in flight-critical, high performance applications. Other benchmarks are 1000 and 500 thermal cycles, which represent ground-based high performance and commercial avionics applications, respectively.

The continuity of the BGA component was continuously monitored throughout thermal cycle testing by an event detector in accordance with the IPC-9701 specification. Each component was treated as a single resistance channel. An event was recorded if the resistance of a channel exceeded 300 Ω for longer than 0.2 μsec within a 30-second period. A failure was defined when a component either:

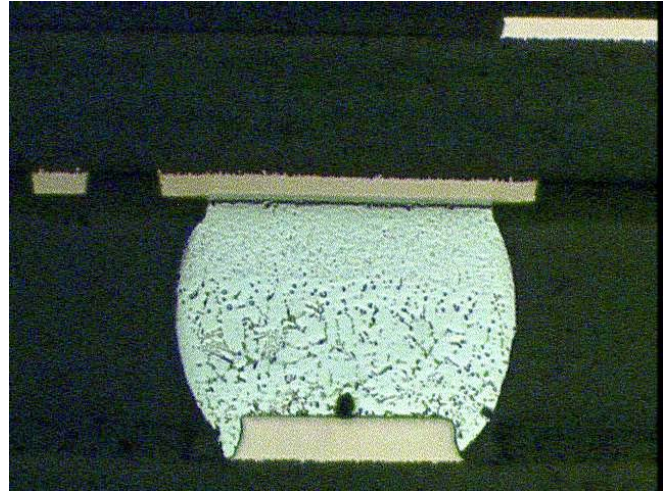
- Exceeded the maximum resistance for 15 consecutive events
- Had five consecutive detection events within 10% of current life of test or
- Became electrically open.

Once a solder joint was designated a failure, the event detection system software excluded it from the remainder of the test.

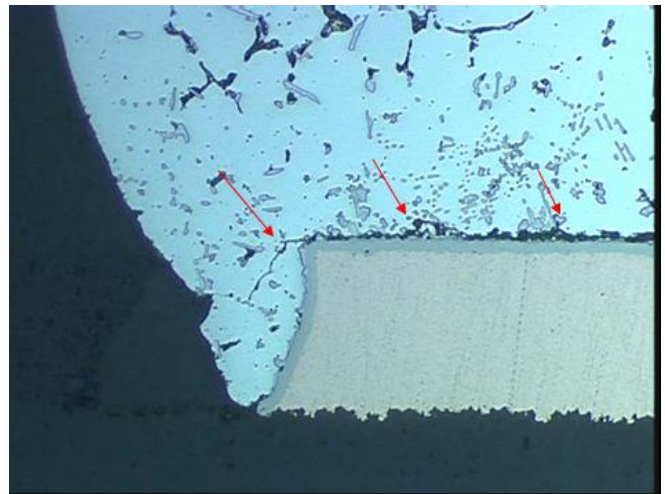
## TEST RESULTS

The test results indicated the first BGA solder joint failures occurred after 137 thermal cycles with a 276 thermal cycle

population average being recorded. Typical BGA solder joint failures measured during other area array component investigations [1] has been in the 1000-2000 thermal cycle range. Metallographic analysis was conducted to determine solder joint failure characteristics. Figures 7 and 8 illustrates the BGA solder joint failure observed during the metallographic analysis. The red arrows in Figure 8 point to the solder joint crack.



**Figure 7: Macro View of BGA Solder Joint Failure**



**Figure 8: Magnified View of BGA Solder Joint Crack**

The BGA solder joint failure is non-typical in a number of ways: (1) a solder joint failure at 137 thermal cycles would be considered premature and an indication of either a component fabrication or manufacturing error; (2) the solder joint crack was located at the solderball/pwb pad side of the solder joint – typical BGA solder joint cracks are located at the solderball/component pad side; (3) the solder joint crack was located at the solder matrix/solder joint intermetallic interface – typical solder joint crack location is in the solder matrix. Inspection of the solder joint revealed four distinct regions of differing microstructure. Each region has been designated as a Zone (A-D) for ease of discussion. Figure 9 illustrates the zones and Table 1 lists the microstructure observed in each zone.

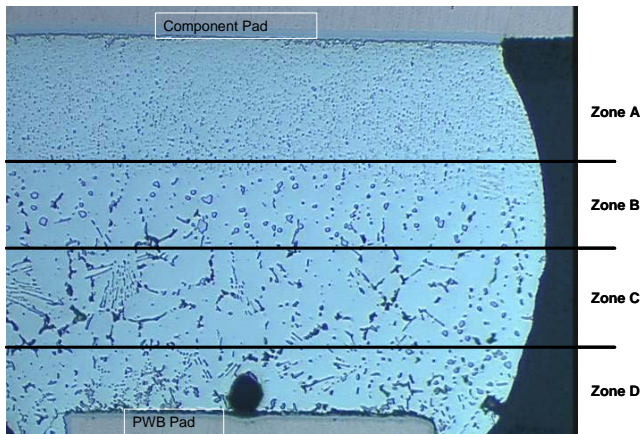


Figure 9: BGA Solder Joint Microstructure Zones

Zone	Microstructure Observed
A	Original SAC solderball - Tin Matrix, Fine Blocky & Platelet Intermetallic Phases
B	Tin Matrix, Large Blocky & Platelet Intermetallic Phases
C	Tin Dendrite Matrix, Interdendritic Phases, Fine Blocky & Platelet Intermetallic Phases
D	Tin Dendrite Matrix, Interdendritic Phases, Blocky & Platelet Intermetallic Phases, Solder Joint Crack

Table 1: BGA Solder Joint Zone Microstructure Observations

Scanning Electron Microscopy (SEM) analysis was conducted to determine the elemental identity of the observed microstructures in each of the designated zones. It should be noted that all metallographic cross section samples were overplated with gold to improve SEM analysis thus the presence of gold (Au) in the SEM Energy Dispersive Xray (EDX) and the SEM EDX line scan graphs is an analysis artifact unless specifically noted.

#### SEM Zone A Analysis

The BGA solder joint zone A region was the farthest zone from the Sn63/Pb37 solder paste deposit and retained its original SAC solder microstructure. The component pad was a gold/nickel finish prior to SAC solderball attachment by the component fabricator. A tin matrix was present as expected for a SAC solder alloy. SEM EDX scanning found the fine blocky intermetallic phases to be composed of either tin/copper (Sn/Cu) or tin/silver (Sn/Ag). A nickel/tin (Ni/Sn) intermetallic phase was also identified at the solder/component pad interface as expected. The intermetallic phases were identified as  $Cu_6Sn_5$ ,  $Ag_3Sn$ , and  $Ni_3Sn_4$  in agreement with other industry studies [2, 3]. Some joints showed large platelets of  $Ag_3Sn$  intermetallic phase. Figures 10-13 illustrate the microstructure phases identified

in zone A and SEM EDX scans of those microstructure phases.

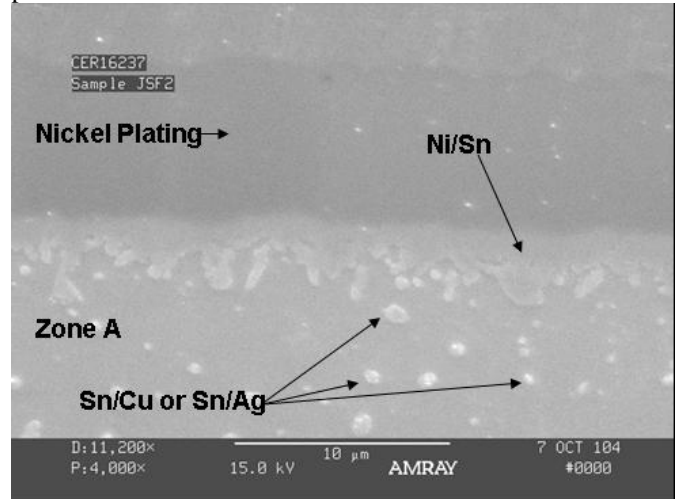


Figure 10: Zone A Microstructure Phases

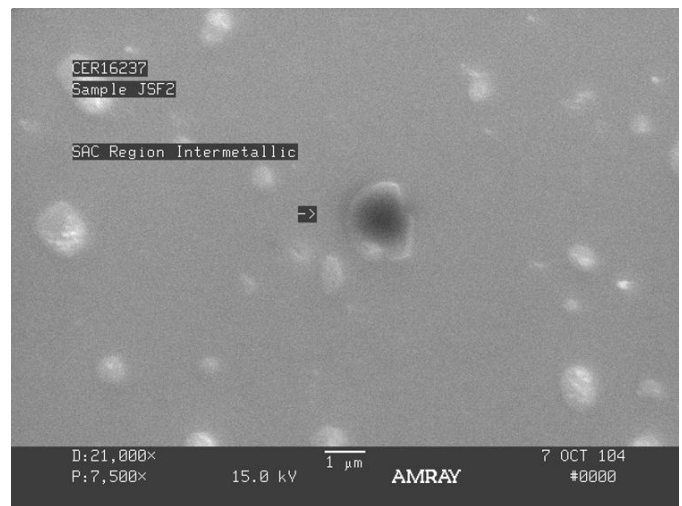


Figure 11: Zone A Fine Blocky Phases

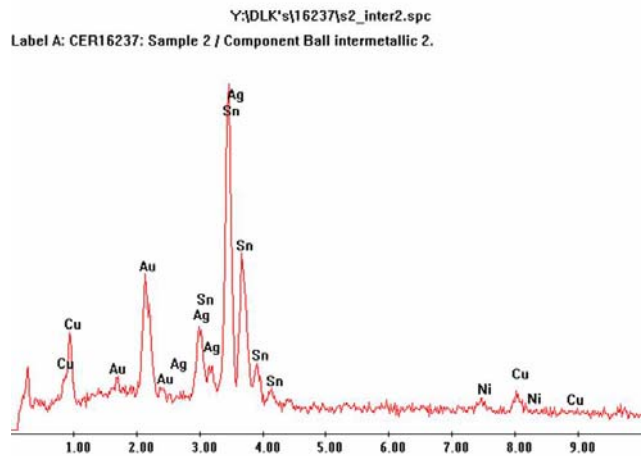
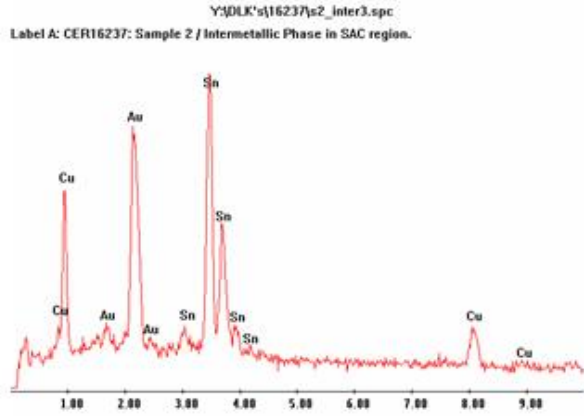


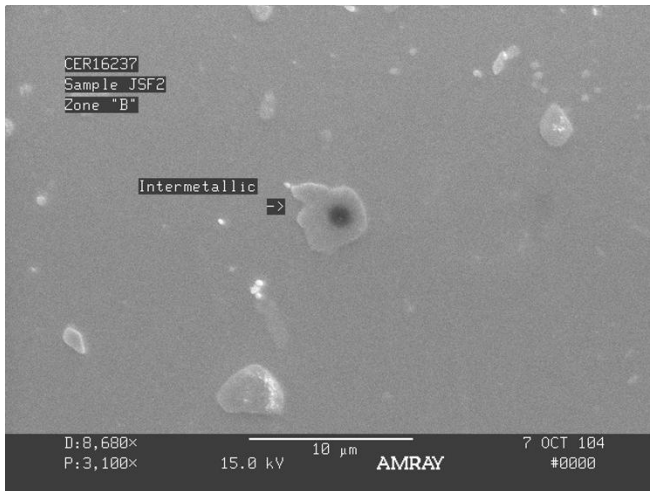
Figure 12: SEM EDX Scan of Sn/Ag Phase



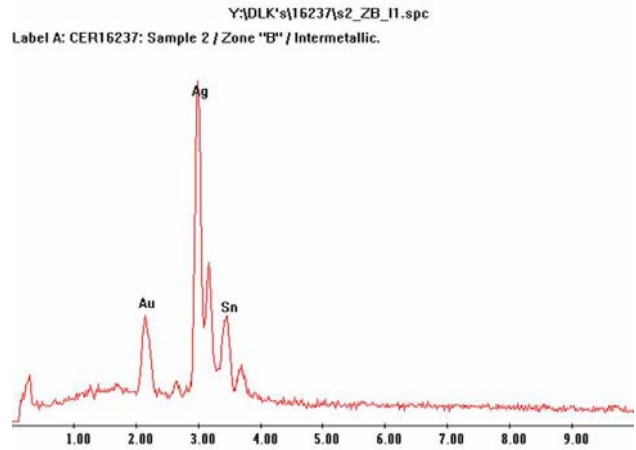
**Figure 13: SEM EDX Scan of Sn/Cu Phase**

#### SEM Zone B Analysis

A tin matrix is still present in Zone B of the BGA solder joint. Zone B shows the following changes: the fine blocky intermetallic phases were replaced with large blocky intermetallic phases; the intermetallic phases were identified as  $\text{Cu}_6\text{Sn}_5$ ,  $\text{Ag}_3\text{Sn}$ , - no  $\text{Ni}_3\text{Sn}_4$  was identified. Figures 14-15 illustrates the  $\text{Ag}/\text{Sn}$  microstructure phase identified in zone B and SEM EDX scans of that microstructure phase.



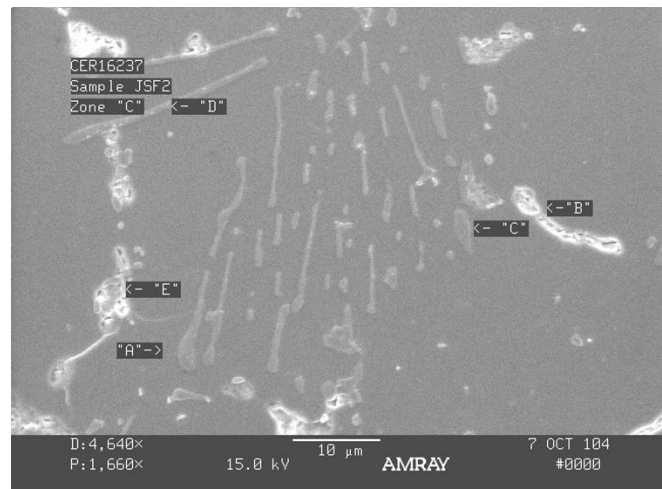
**Figure 14: Zone B Large Blocky Phases**



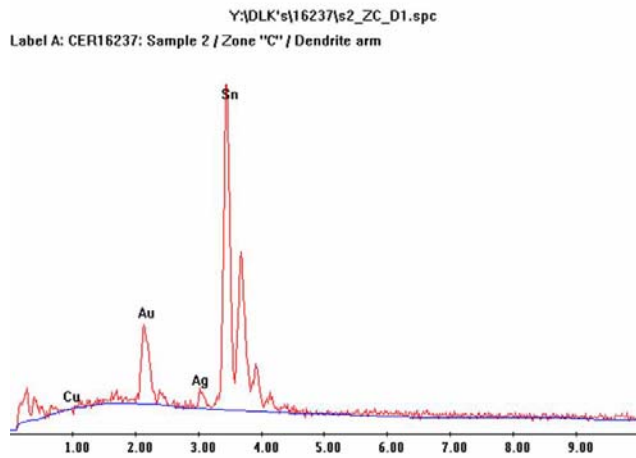
**Figure 15: SEM EDX Scan of Sn/Ag Phase**

#### SEM Zone C Analysis

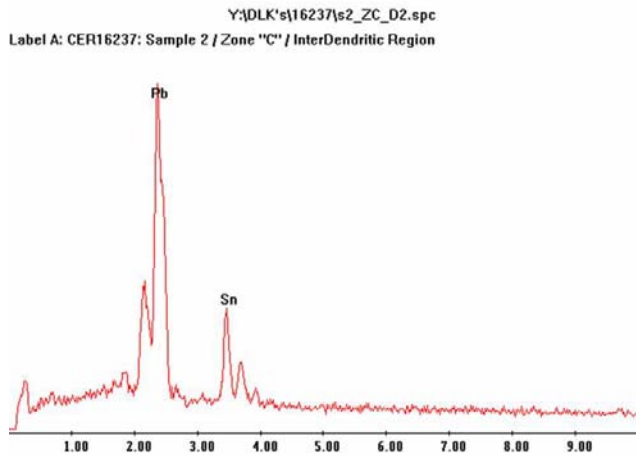
The BGA solder joint zone C region had undergone significant microstructural change. The tin matrix observed in Zones A and B changed to dendritic solidification in Zone C. The large blocky intermetallic phases were identified as  $\text{Cu}_6\text{Sn}_5$  and  $\text{Ag}_3\text{Sn}$ . A fine platelet intermetallic phase ( $\text{Ag}_3\text{Sn}$ ) was observed and a 96.5Sn/3.5Ag eutectic phase was found in the interdendritic regions. Additionally, the first indication of the Pb from the 63Sn/37Pb solder paste deposit was identified in the interdendritic regions. Figures 16-18 illustrate the microstructure phases identified and SEM EDX scans of the zone C microstructure phases.



**Figure 16: Zone C Microstructure: "A"- Sn/Ag Platelet, "B" – Pb Interdendritic Region, "C" – Sn/Ag Blocky Phase, "D" - Sn/Ag Platelet, "E" - Pb Interdendritic Region**



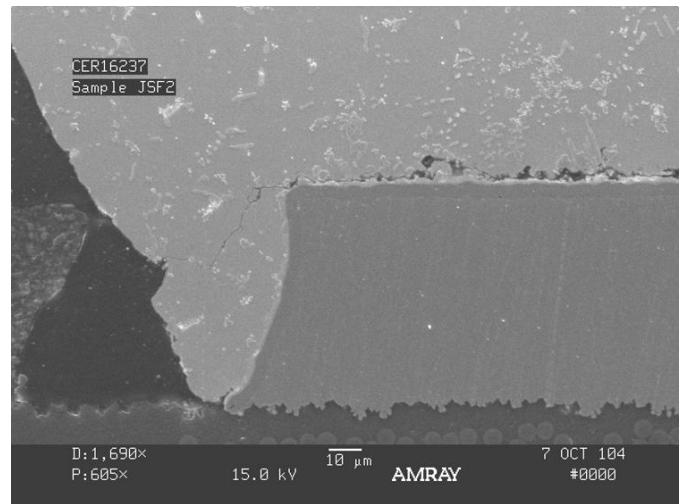
**Figure 17: SEM EDX of Dendrite Phase**



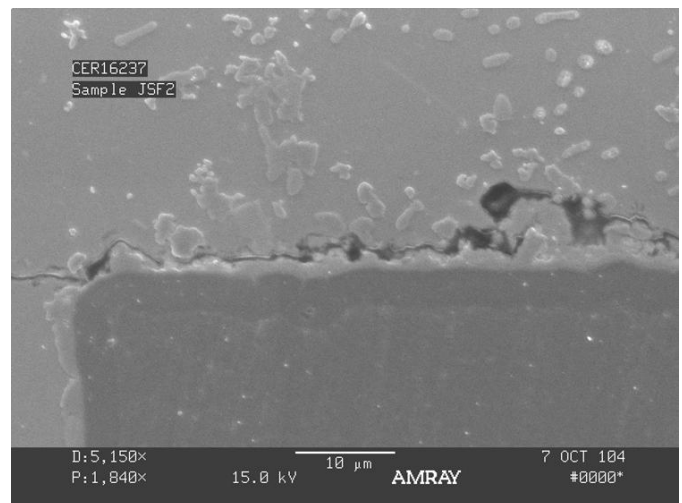
**Figure 18: SEM EDX of Interdendritic Region**

#### SEM Zone D Analysis

The BGA solder joint zone D region was the zone directly in contact with the 63Sn/37Pb solder paste deposit. Zone D is a region composed of tin matrix, sporadic tin dendrite occurrence, platelet and blocky intermetallics, regions of Pb, and the solder\pwb pad interface. A Ni/Sn intermetallic phase was present due to the use of the ENIG pwb finish. Figures 19 and 20 illustrate the solder joint crack and the microstructure phases in zone D.



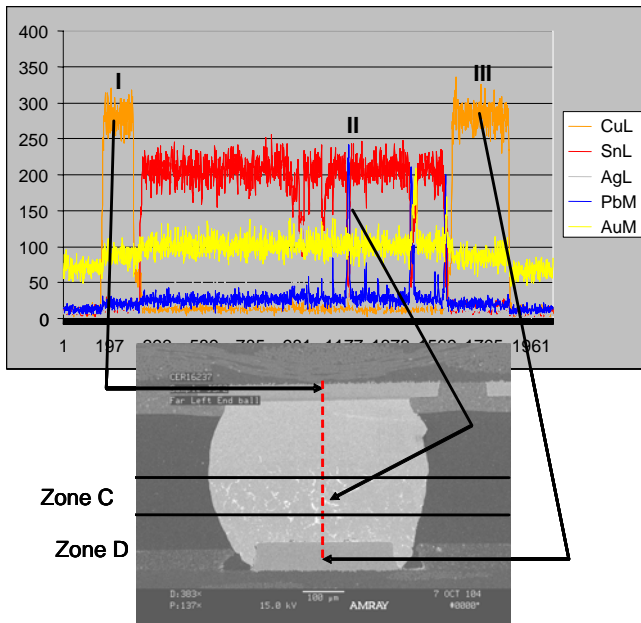
**Figure 19: Zone D Solder Joint Crack and Phases**



**Figure 20: Magnified View of Solder Joint Crack**

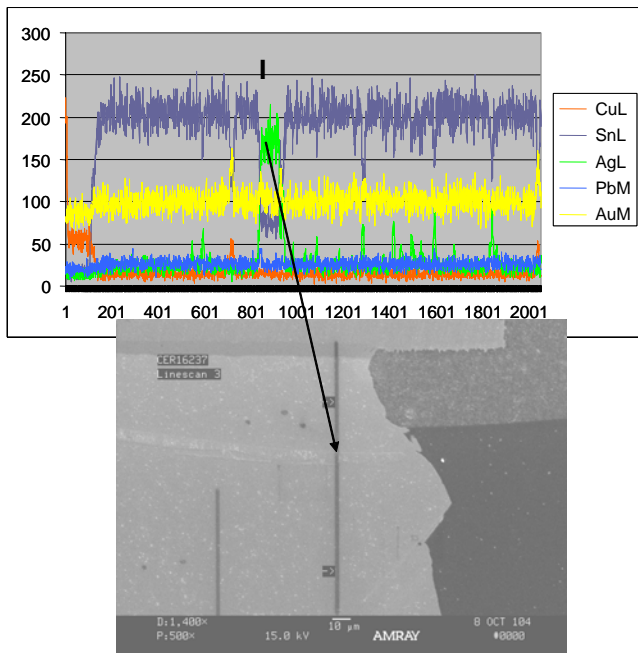
#### SEM EDX Line Scans

Several SEM EDX line scans were completed to determine the elemental constituent change across a region in contrast to the SEM EDX measurements taken of specific microstructure phases. Figure 21 illustrates a line scan across a BGA solder joint. The component and pwb copper pads are very evident at the beginning and end of the line scan. A large Pb peak was also recorded as the line scan traversed across an interdendritic region in zone C.



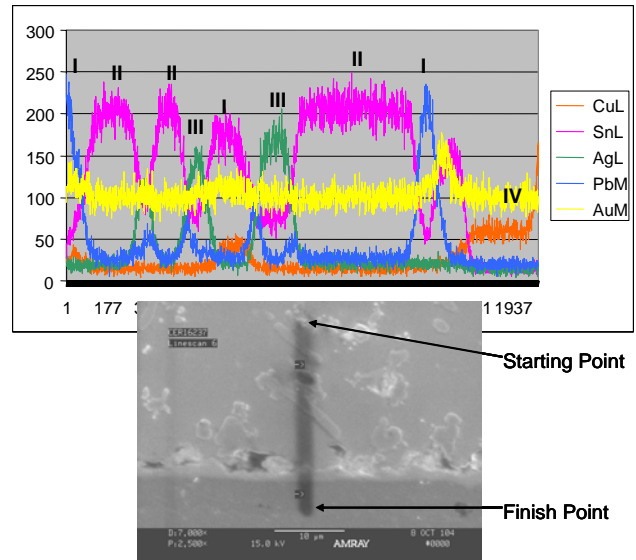
**Figure 21: SEM EDX Line scan of BGA Solder Joint; (I) Copper of Component Pad; (II) Lead in Interdendritic Region; (III) Copper of PWB Pad. X axis is the scan distance and the Y axis is the elemental count scale.**

A line scan traversing a large platelet phase produced a large silver peak complementing the SEM EDX specific phase measurements defining the structure as  $Ag_3Sn$  intermetallic (see Figure 22).



**Figure 22:  $Ag_3Sn$  Intermetallic Indication By SEM EDX Line scan; (I) Silver Peak Upon Traversing Large Platelet Microstructure Phase. X axis is the scan distance and the Y axis is the elemental count scale.**

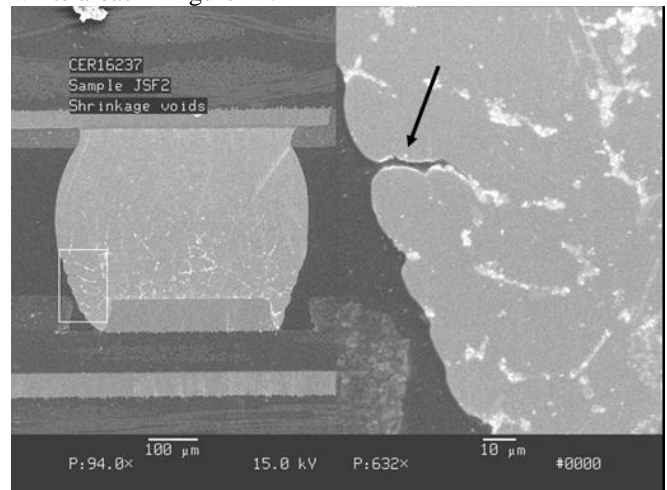
A SEM EDX line scan was completed traversing the solder joint crack in Zone D. The measurements indicated Pb in the interdendritic regions and the solder joint/pwb pad interface,  $Ag_3Sn$  intermetallic phase, and the tin microstructure matrix. Figure 23 illustrates these line scan results.



**Figure 23: SEM EDX Line scan; (I) Lead Peak; (II) Tin Peak; (III) Silver Peak; (IV) Copper Peak. X axis is the scan distance and the Y axis is the elemental count scale.**

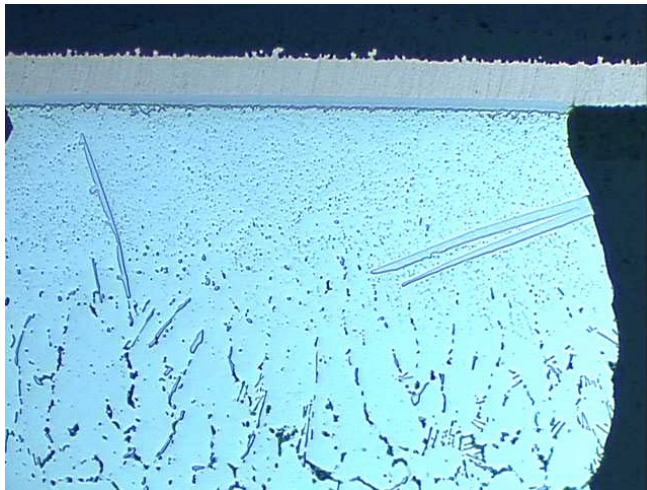
#### Other Microstructure Observations

Two other microstructure observations were made during the SEM analysis: the presence of shrinkage voids and large intermetallic platelet phases. The shrinkage voids observed were associated with the formation of the tin dendritic matrix and are the result of solder solidification. The voids are not associated with Kirkendal voiding phenomena. Thermal cycling did not induce or propagate the shrinkage voids into cracks. Other industry investigations [2, 4] have documented similar results for the shrinkage voids. Figure 24 illustrates a typical shrinkage void found in the BGA solder joints. The segregation of Pb from the 63Sn/37Pb solderpaste is clearly visible in the interdendritic regions as white areas in Figure 24.



**Figure 24: Shrinkage Void (arrow)**

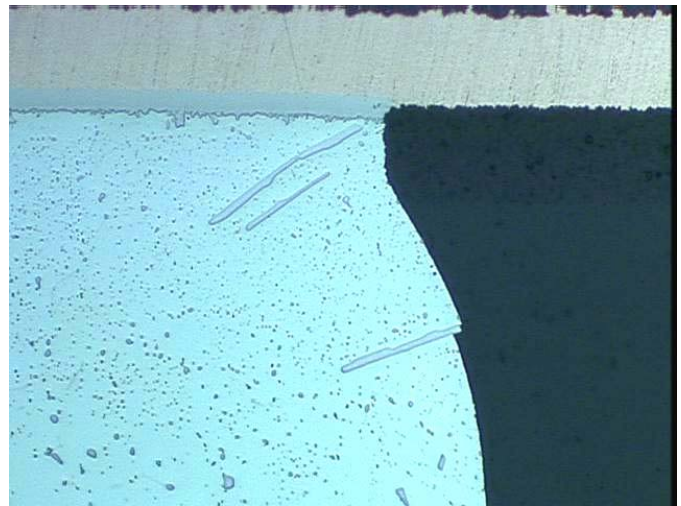
The presence of a large platelet intermetallic phase was observed during the metallographic analysis. Their solder joint location was predominately in zones A and B. SEM EDX analysis revealed these large platelets to be the  $Ag_3Sn$  intermetallic phase. A number of occurrences were documented where these platelets intercepted the BGA solder joint surface disrupting the solderball shape. Thermal cycling did not induce or propagate any cracking at/along the length of the large platelets. Other studies have observed similar large platelet intermetallic phases [2, 5, 6]. One industry investigation [7] purposed that the large platelet intermetallic phase could potentially be beneficial by imparting additional structure and strength to the solder joint. Figures 25-28 illustrate the large platelet intermetallic phase observed.



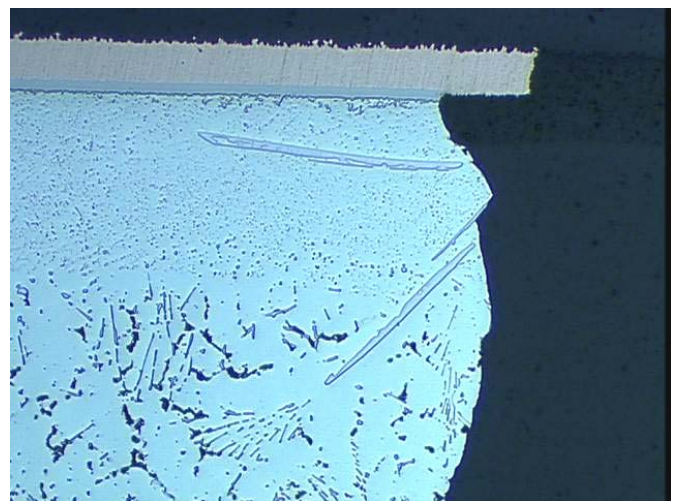
**Figure 25: Large Sn/Ag Platelet**



**Figure 26: Magnified View of Figure 25 Platelet**



**Figure 27: Large Sn/Ag Platelets in Zone A/B**



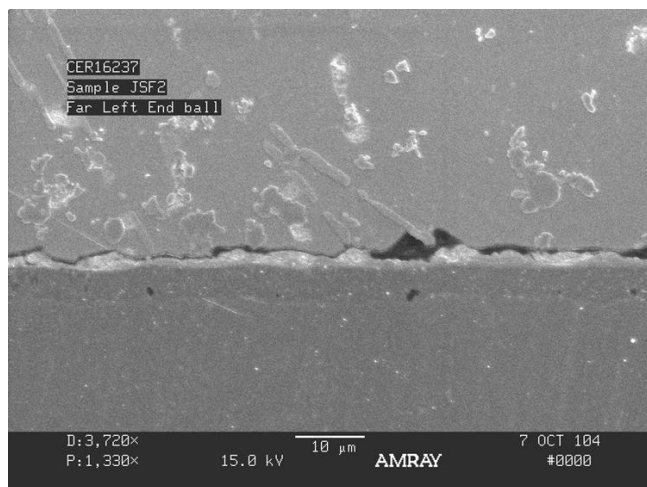
**Figure 28: Solderball Disruption Due to Large Sn/Ag Platelets in Zone A/B**

## DISCUSSION

A review of the SEM EDX analysis reveals an interaction of the non-uniform microstructure and the solder joint crack. Figures 29-30 illustrate further evidence of degradation of the BGA solder joint integrity. Figure 30 shows a Sn/Ag intermetallic platelet intercepting a void region along the crack/pwb pad interface. The presence of the Sn/Ag intermetallic platelet intruding into the void space demonstrates the presence of the void during platelet growth or formation of the void upon solder joint solidification – physical evidence of nonwetting/dewetting behavior of the nickel surface during solder joint formation. Soldering nickel surfaces is more complex than soldering copper surfaces due to nickel oxide/flux reactions and the slow diffusion rates of nickel into solder [8]. Secondly, the SEM EDX measurements show that the solder joint microstructure was not uniform. Several industry studies [2, 9, 10, 11] have documented that the formation of a 177°C ternary eutectic alloy (62.5Sn/36.1Pb/1.4Ag) is possible in a mixed surface finish manufacturing scenario. This investigation results show the 177°C ternary eutectic alloy formed in Zones C/D in the interdendritic regions. The

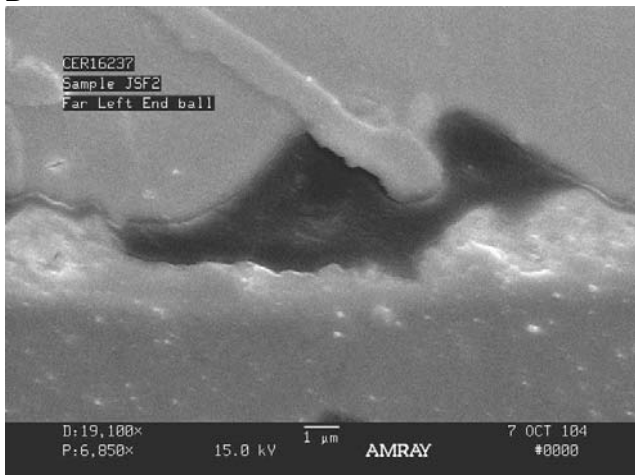


combination of a nickel surface and the non-uniform solder joint microstructure resulted in solder joint degradation leading to solder joint failure. Other industry studies [2, 5, 6, 7, 12] have reported that allowing the formation of a uniform solder joint microstructure with mixed surface finish manufacturing assemblies results in a Pbfree solder joint integrity equal to or better than Sn/Pb solder joint integrity. The non-homogeneous microstructure seen in this study is the result of a Pbfree solderball subjected to a eutectic solder reflow temperatures and lead to solder joint failure.



**Figure 29: Solder Joint Crack In Zone**

D



**Figure 30: Magnified View of Figure 29**

## CONCLUSIONS

Area array components (ball grid arrays, chip scale packages, flip chip packages) with Pbfree solder sphere alloys should not be reflowed using a tin/lead reflow profile due to the resulting non-uniform solder joint microstructure and potential poor board surface finish wetting interactions.

## ACKNOWLEDGEMENTS

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SEM efforts, and Peter Van Zante for his scathing critique of the manuscript.

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