Assembly, Rework and Reliability of Lead-free FCBGA Soldered Component

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Abstract

Movements to lead-free assembly are being influenced by legislative and market requirements. Specifically Europe has passed legislation requiring the removal of lead from electronics assembly by 2006. Also, the perceived marketing advantage of a "green product" is beginning to be accepted. Though development work for lead-free components is increasing, work on lead-free components with higher I/0 has been fairly limited at this time.

The present work describes the evaluation of a 780 I/O lead-free Flip chip BGA component in terms of assembly below 260°C peak reflow temperature. FCBGA components were assembled at peak reflow temperatures of 225°C, 235°C, 245°C, reflow environments of air and nitrogen, and rework with peak reflow temperature 230 to 235°C with a novel rework nozzle. Solder joint formations from the different reflow processes were inspected using visual analysis, XRAY analysis, and physical cross sections. Each inspection showed good solder joints of all components mounted at the different peak reflow temperatures and environments.

Reliability of the mounted components was then tested by temperature cycling from 0-100°C. All components mounted in the different peak reflow temperatures and environments were stressed with the bulk of the stressed devices from reflow peak temperature of 235°C in nitrogen environment. All mounted components survived greater than 3500 cycles.

Introduction

The objective of the study was to assemble and rework lead-free FCBGA components on reliability test vehicles using a reflow profile with the lowest maximum temperature in either air or nitrogen atmosphere with standard production equipment to qualify them for lead-free assembly. Reliability results are reported after Accelerated Temperature Cycling for 1^{st} pass and reworked lead-free components.

Assembly and rework of the test vehicles was done at a standard manufacturing line using a Type 3 lead free no clean solder paste with alloy composition 95.8Sn3.5Ag0.7Cu. Solder paste printing was performed on standard paste printing equipment with metal squeegee blades with a print speed of 20mm/min. The metal stencil thickness was 6mils, stencil aperture diameter was 0.55mm (22mils), and board pad to stencil aperture ratio was 1:1. Rework of the components required a novel rework nozzle to minimize the temperature gradient from top of the package

The fully assembled test vehicle can be seen in Figure 1.

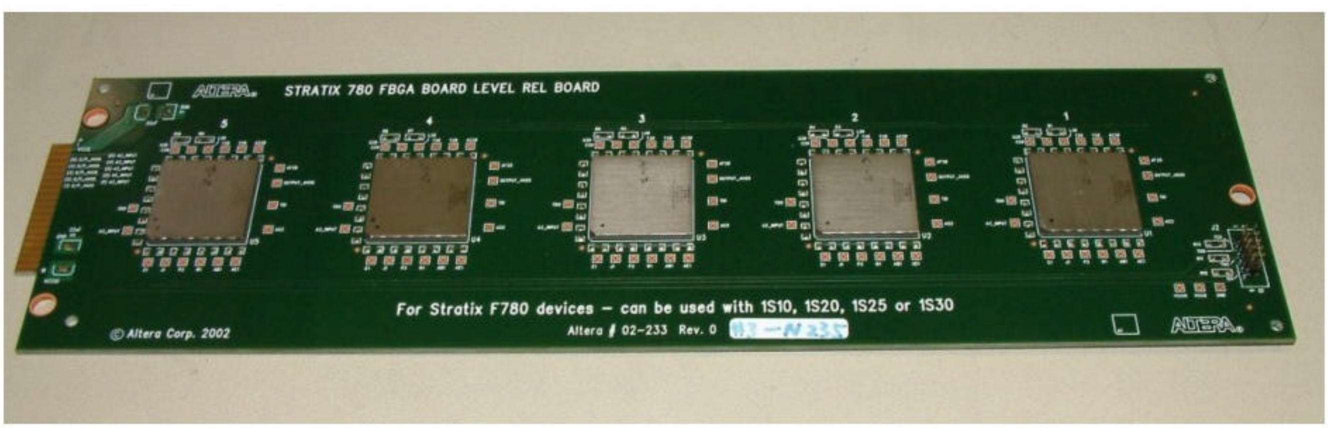


Figure 1 - Fully Populated FCBGA780 Test Vehicle Board

The physical characteristics and dimensions of the device and PCB are listed in Table 1 and 2 respectively.

Table1 - Component Specifications

Component dimensions	29X29 mm
Heat Sink	2 piece Copper
Substrate material	BT
Substrate thickness	1.3mm
Substrate plating finish	ENIG
Pad opening	SMD
Board pad size	0.55mm diameter
Solder ball diameter	0.6mm
Solder ball layout	Fully populated except corner pins
Solder ball composition	Sn3Ag0.5Cu

Table 2 - PCB specifications

Board thickness	93 mil
Board material	High Temperature FR4: Tg=170C
Number of layers	8
Board Dimensions	14 in x 4 in
Board Surface finish	OSP
Pad opening	NSMD
Board pad size	0.55mm diameter
Via coverage	Plugged and tented
Via aspect ratio	<6
a) Internal Cu layers-even (GND/VCC plane): 70% Cu coverage b) Internal Cu layers-odd (single traces): 40% Cu coverage	

Solder joint reliability was assessed by temperature cycling devices on printed circuit boards. This test is designed to identify failures caused by the Coefficient of Thermal Expansion (CTE) mismatch between the solder joint, component substrate and printed circuit board. Failures occur in the solder joint at points of maximum stress. For this evaluation, FCBGA device (EP1S25FC780) using flip chip interconnect with a large die size was studied. Board level reliability testing is performed using functional PLD devices programmed to simulate daisy chains, not daisy chains.

Experimental

First Pass Assembly of lead-free FCBGA

The FCBGA components were placed onto the paste printed boards using standard fine pitch component placement equipment.

The lead-free paste assembled component boards were reflowed in a 10 zone convection oven in either an air or a nitrogen atmosphere, using the reflow profiles developed. The lead-free reflow profiles used has 225°C , 235°C and 245°C solder joint peak temperatures with times over 217°C ranging from 50 to 70 seconds. A summary of the times over reflow and peak temperatures for the lead-free profiles are shown in Table 3.

Table 3 - Summary of Lead-free and Tin-lead Reflow Profiles

Max temperature (°C)	225	235	245
Time over reflow (Seconds)	50	70	70
Reflow atmosphere	N2/ AIR	N2/ AIR	N2/ AIR

An example profile (peak temperature = 235°C) can be seen in Figure 2. The delta T between the solder joint peak and the top surface peak of the FCBGA780 component for 1^{st} pass assembly was typically 2 to 3°C.

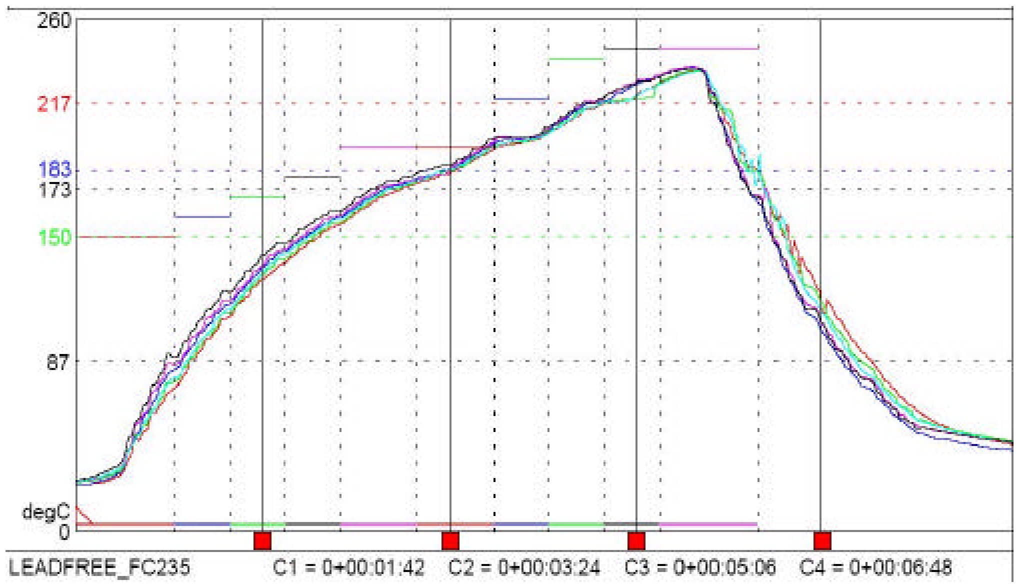


Figure 2 - Lead-free SMT Reflow Profile Developed for 235°C Solder Joint Peak Temperature

After reflow assembly, X-ray, visual, and electrical continuity testing was performed on all boards, then certain boards were selected for cross-sectional microstructure analysis of the soldered joints.

Based on the cross-sectional results which are described in the following sections and some limited ATC data, it was decided to select 235°C peak soldering temperature with nitrogen reflow atmosphere as the main test cell for 1^{st} pass assembly and reliability testing.

Electrical Continuity Testing

Prior to reliability testing of the assembled first pass boards, the FCBGA components are tested for electrical continuity. Since these devices are mounted to specifically designed PCBs that contain half of the daisy chain link, they can be configured to complete the daisy chain by using a string of inverters. A clock signal can then be sent and monitored by PC or logic analyzer.

This capability allows pre-stress electrical continuity testing, and also for continuous monitoring of all devices whiles the mounted board experiences reliability stress. Exact time to failure can be measured, and by proper design of the test PCB, the failure location can be easily and quickly identified.

Monitoring of the reliability experiments and qualifications is simplified by using an Altera Development environment like Quartus and MAXPLUS II for design and testing. The simplicity of layout that results from using a PLD allows all connections to be brought out to the bottom of the PCB to facilitate failure analysis.

Accelerated Temperature Cycling

Thermal cycling of the test vehicles was conducted between 0°C to 100°C with 10 minute dwells at each temperature extreme and approximately 12°C/min ramp and cool down rates. The cycle time was 2 cycles per hour in accordance with the IPC9701 reliability testing standard specification.

Rework of Lead-free and Tin-lead FCBGA

After 1^{st} pass assembly of the lead-free soldered boards at the 235°C peak soldering temperature in nitrogen reflow atmosphere, a selection of these boards were designated for lead-free FCBGA rework

An inherent problem with reworking lead free components is the high temperature gradient from the top surface of the component to the center solder joint during rework reflow. The higher melting point of the lead free alloy also added to the component removal and mounting difficulties; too high a maximum temperature would damage the device. The component had a package volume of > 350 Cumm, which is termed as a large package according to JEDEC 020B. Rework profiles were developed to minimize the temperature gradient while trying to maintain a reflow solder joint profile with max temperature of 235 C.

To develop this lead-free rework process within the given constraints, a typical convection BGA rework machine was used. It provided localized convection heat via nozzle directly to the top surface of the component, and bottom heating of the board. Both top and bottom heating allow for better thermal control. Even with this dual heating, the temperature delta between the solder joint and top of the component package was still > 20°C. Thus a rework profile developed with a peak solder joint temperature of 235°C would mean the component package temperature would be > 255°C

To overcome the high temperature gradient between the solder joint and component, a special custom made nozzle was designed. It differed from a standard rework nozzle by using a baffle to prevent direct heating of the top surface of the component. The heat flow using this baffle type of nozzle is pushed towards the outer edges and sides of the FCBGA as shown in Figure 3. Figure 4 shows the actual rework nozzle.

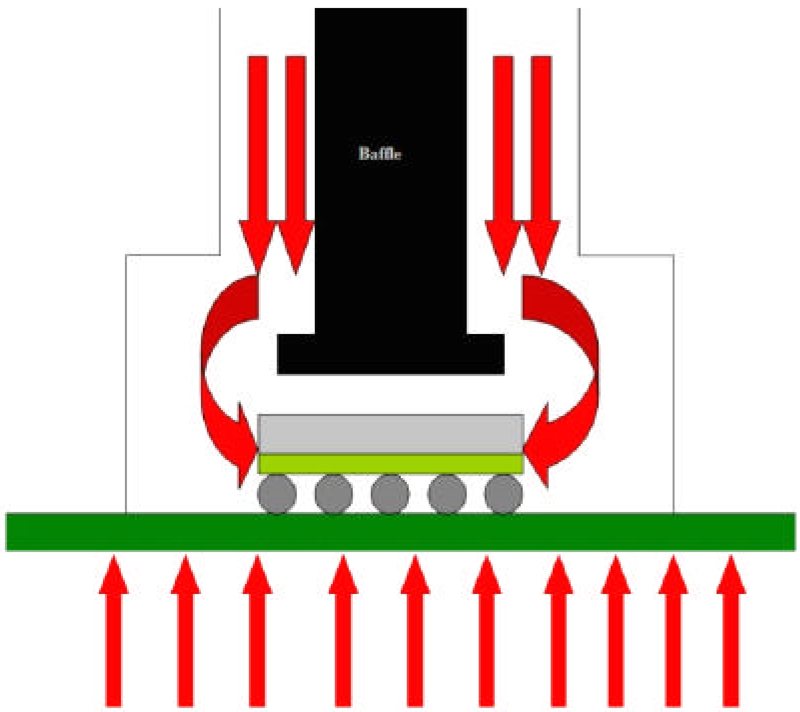


Figure 3 - Heat Flow around the Component using a Baffle-type Rework Nozzle Design

Figure 4 - Specially Designed Rework Nozzle (Side, Bottom and Top view)

As a result of this development work, a rework reflow profile was obtained with a max peak temperature of 244°C on the component surface while obtaining a max temperature of 229-233 C at the center solder joint as shown in Figure 5 and Table 4. The delta T between top surface of the component and solder joint ranged from 11-15C.

Table 4 - Lead-free SnAgCu FCBGA Rework Profile Summary using Baffle Style of Rework Nozzle

	Peak temperature (°C)	Time above Reflow (Seconds)	Total rework time (Minutes: Seconds)
Component top center device	244	129	8:09
Corner solder joint	229	84	7:48
Center solder joint	233	87	7:56

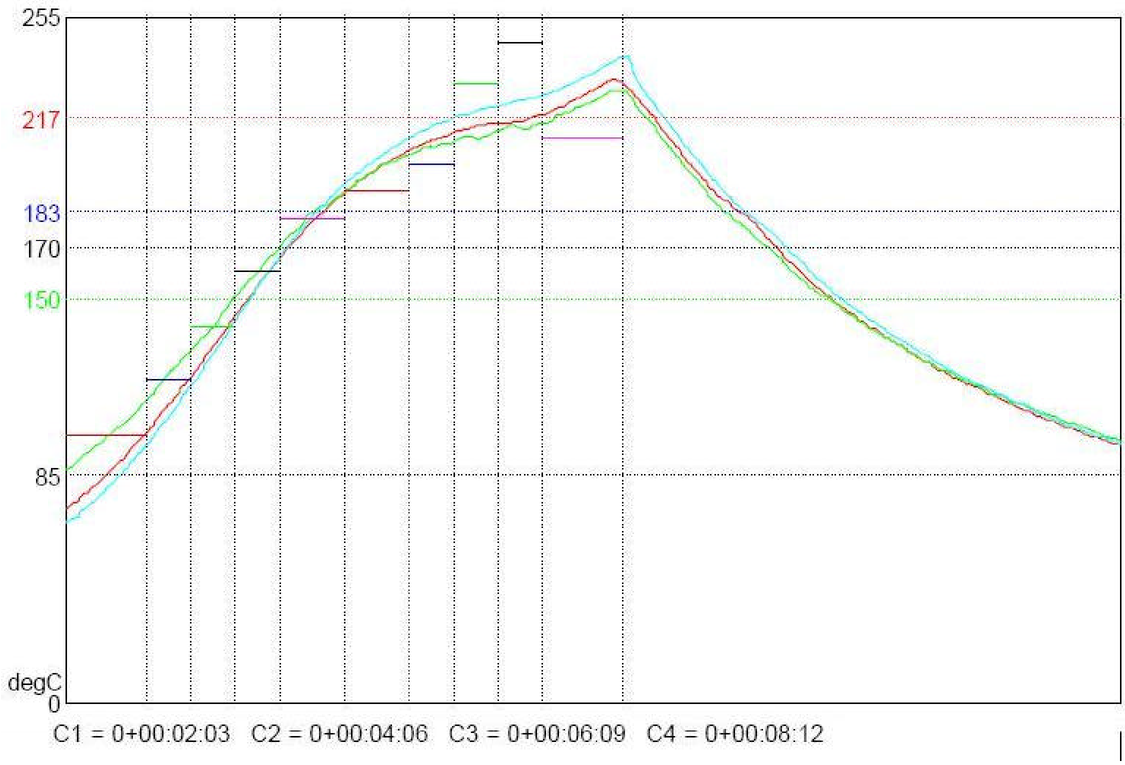


Figure 5 - Lead-free FCBGA780 Rework Profile with the Baffle Type Nozzle

After establishing a rework profile, selected 1st pass assembled FCBGA lead-free boards were reworked with new lead free FCBGA components in Nitrogen atmosphere using the same solder paste as the 1st pass assembly runs.

After removal of the initially assembled component, the BGA pads on the board were redressed prior to placement of the new FCBGA component. The redressing technique used a soldering iron with the use of no-clean liquid flux from a flux pen together with a copper wick, to remove residual solder and provide a smooth level solder finish on all pads. The redressed pads were cleaned with IPA (isopropyl alcohol) to remove the excess flux. Lead-free solder paste was then printed onto the test vehicle boards using the same paste and the same aperture openings with the mini-stencils for 1st pass assembly. The new component was placed onto the solder paste printed pads and the developed rework profile used to reflow the new FCBGA component. After rework the lead-free components were inspected visually, X-ray, followed by electrical continuity testing.

Prior to reliability testing of the reworked boards, the FCBGA components were checked for electrical continuity like the first pass devices, by programming them to simulate a daisy chain through all I/O solder joints. All devices passed. The reworked boards were reliability tested in the same conditions as the first pass boards. Thermal cycling was targeted to 3500 failure free cycles.

Results and Discussion

First Pass Inspection

Visual

From visual inspection of the lead-free soldered FCBGA components using the three peak soldering temperatures (225°C, 235°C and 245°C) in air and nitrogen reflow atmospheres, all solder joints appeared very similar. The solder joints as shown in Figure 6 for the 1st pass lead-free soldered joint at 235°C peak soldering temperatures in nitrogen atmosphere has a mixture of dull and more uniformly shiny solder joint appearance in contrast to tin-lead soldered joints which are typically more shiny in appearance.

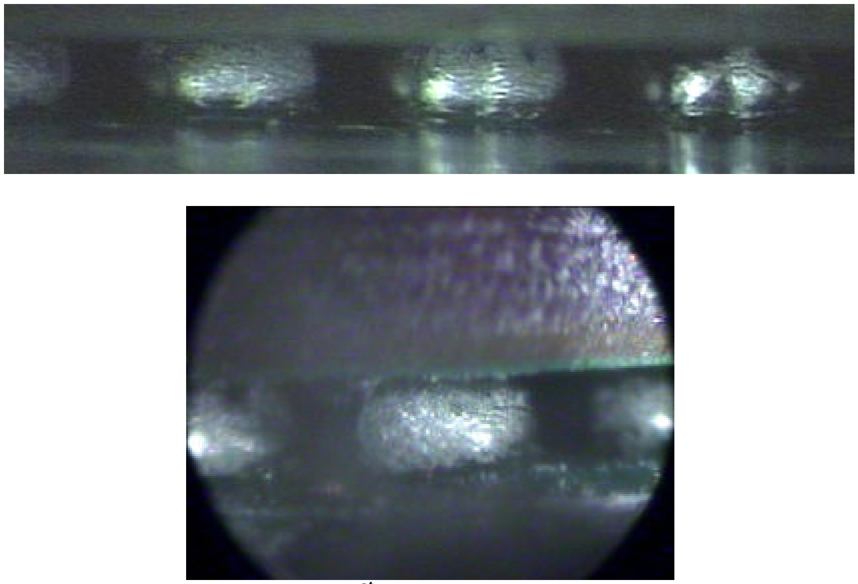


Figure 6 - Visual Solder Joint Appearance of 1st Pass Assembled Lead-free SnAgCu Soldered FCBGA780 Components with 235°C Peak Solder Joint Temperature in Nitrogen Reflow Atmosphere

X-RAY and Electrical Continuity:

From X-ray inspection of the lead-free soldered FCBGA components using the three peak soldering temperatures (225°C, 235°C and 245°C) in air and nitrogen reflow atmospheres, there did not appear to be an increased propensity for bridging or voiding. A typical example of the X-ray images observed is shown in Figure 7 for the 1st pass lead-free soldered joint at 235°C peak soldering temperatures in nitrogen atmosphere.

All first pass assembled lead-free assembled components passed electrical continuity.

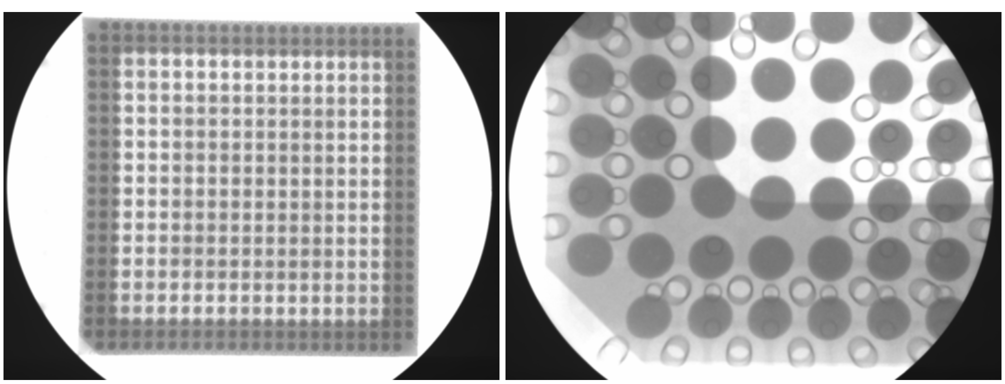


Figure 7 - X-ray Image of 1st Pass Assembled Lead-free SnAgCu Soldered FCBGA780 Components with 235°C Peak Solder Joint Temperature in Nitrogen Reflow Atmosphere

Mircrostructural Cross Section

Selected 1st pass assembled boards for lead-free and tin-lead components were cross-sectioned at time zero prior to reliability testing. Figure 8 compares the low magnification cross-sections of the lead-free FCBGA at 235°C peak temperature in Nitrogen atmosphere at three locations along a solder ball row (corner of component, silicon die edge, center point of component). There were small voids noticed at the board side of the solder joint.

Lead-free SnAgCu 235°C, N2, Corner | **Lead-free SnAgCu 235°C, N2, Die edge** | **Lead-free SnAgCu 235°C, N2, Middle**

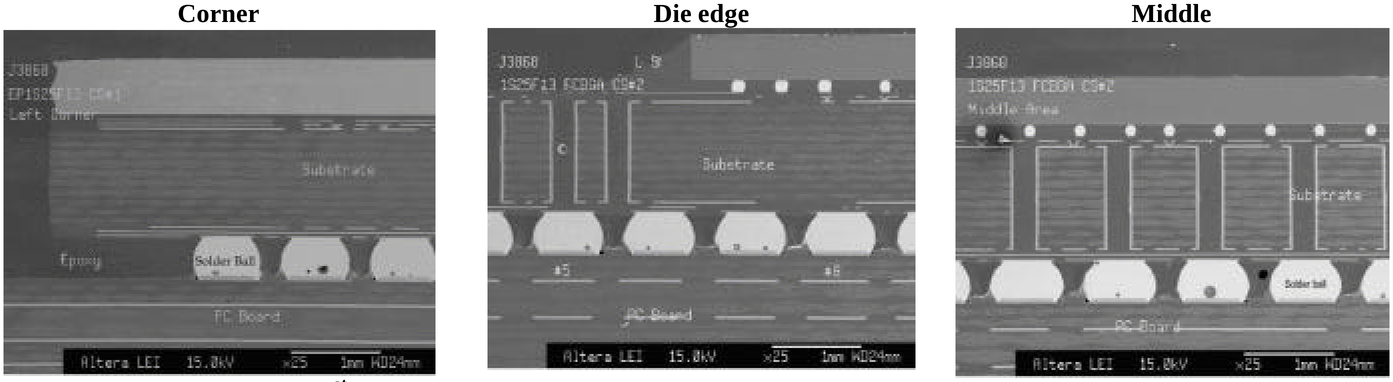


Figure 8 - Cross-sections of 1st Pass Assembled Lead-free SnAgCu Soldered FCBGA780 Components at 235°C Peak Solder Joint Temperature in Nitrogen Atmosphere Along a Solder Ball Row (Corner of Component, Silicon Die Edge, Center Point of Component)

Standoff height of the three different temperatures also showed very similar results. (See Table 5 and Figures 9-12.)

Table 5 - Typical Stand off Height Measurements for the First Pass Assembled Lead-free FCBGA Soldered Joints

	Stand-off Height (um)
Lead-free, 225°C peak, air	433.3
Lead-free, 235°C peak, Nitrogen	423.1
Lead-free, 245°C peak, air	420.5

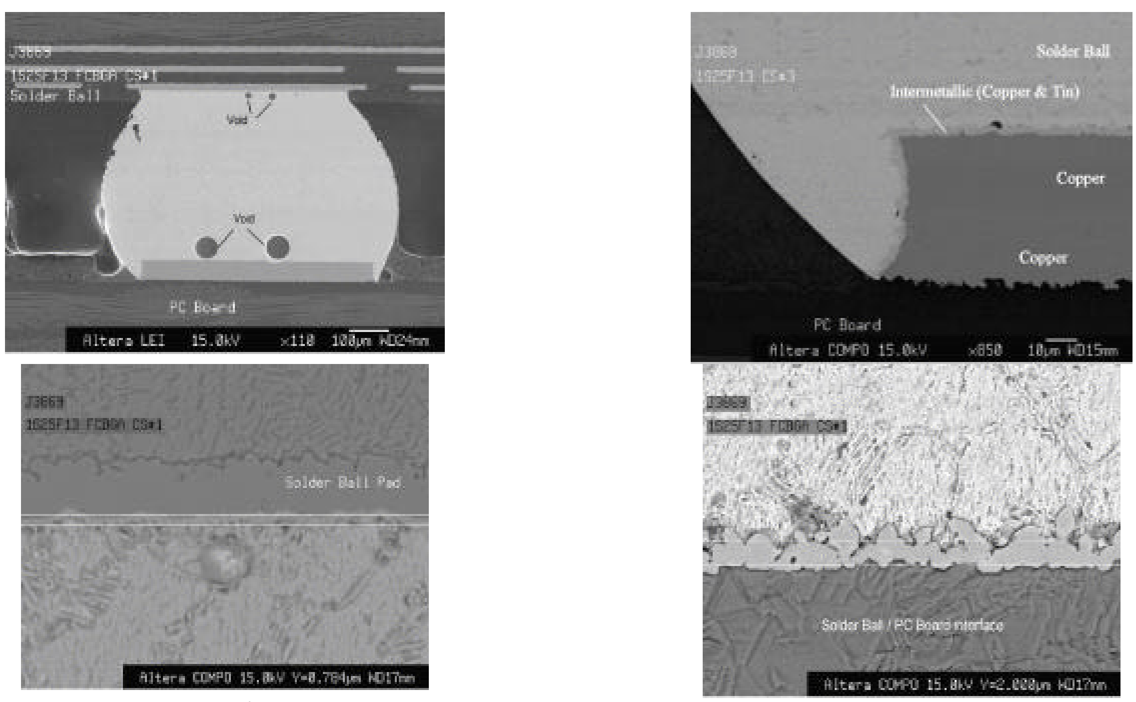


Figure 9 - Cross-sections of 1st Pass Assembled Lead-free SnAgCu Soldered FCBGA780 Components at 225°C Peak Solder Joint Temperature in Air Atmosphere

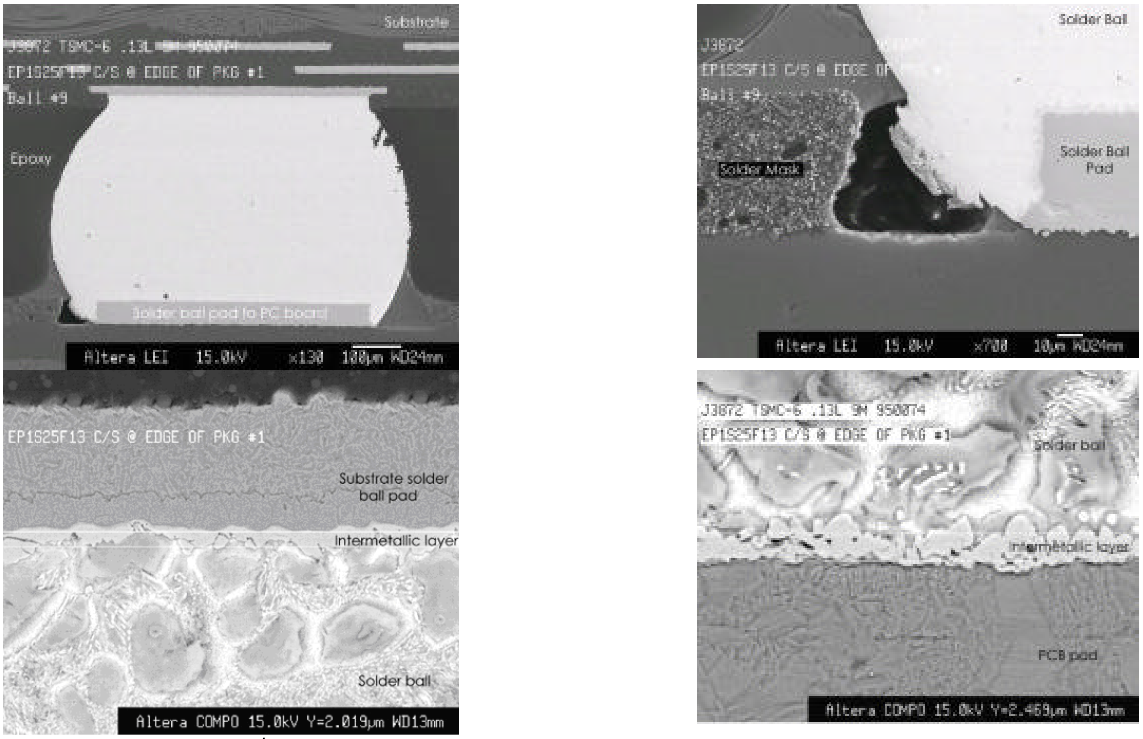


Figure 10 - Cross-sections of 1st Pass Assembled Lead-free SnAgCu Soldered FCBGA780 Components at 225°C Peak Solder Joint Temperature in Nitrogen Atmosphere

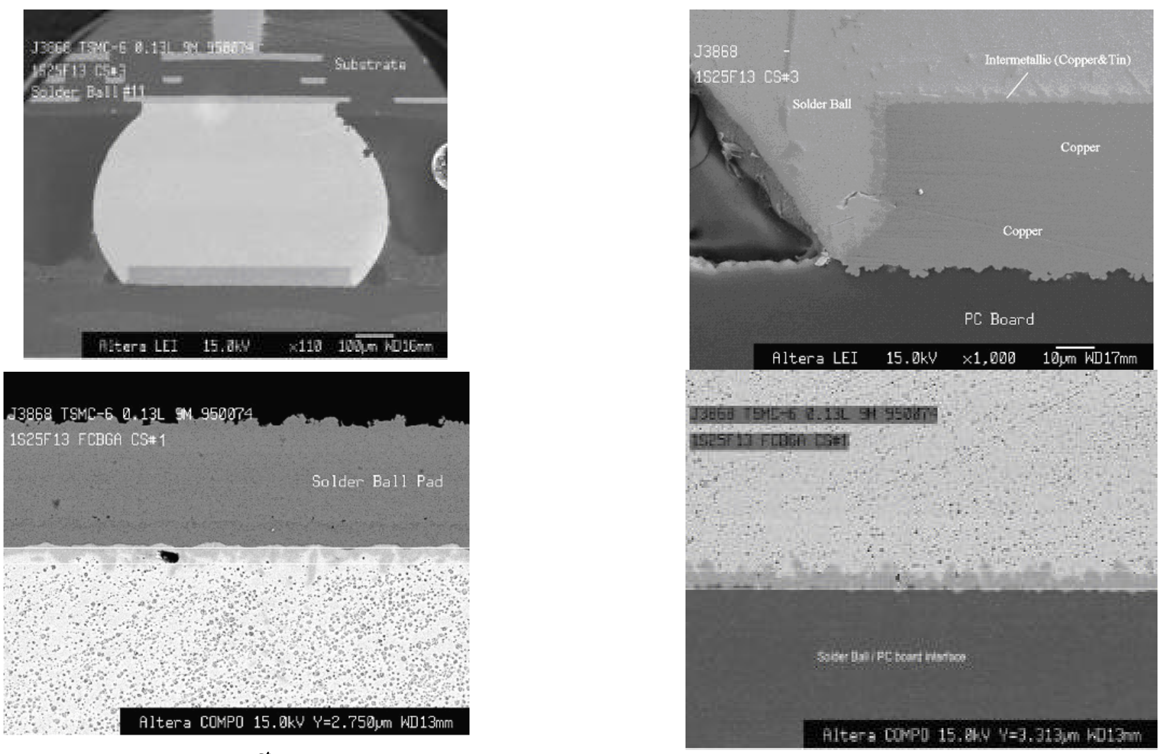


Figure 11 - Cross-sections of 1st Pass Assembled Lead-free SnAgCu Soldered FCBGA780 Components at 235°C Peak Solder Joint Temperature in Nitrogen Atmosphere

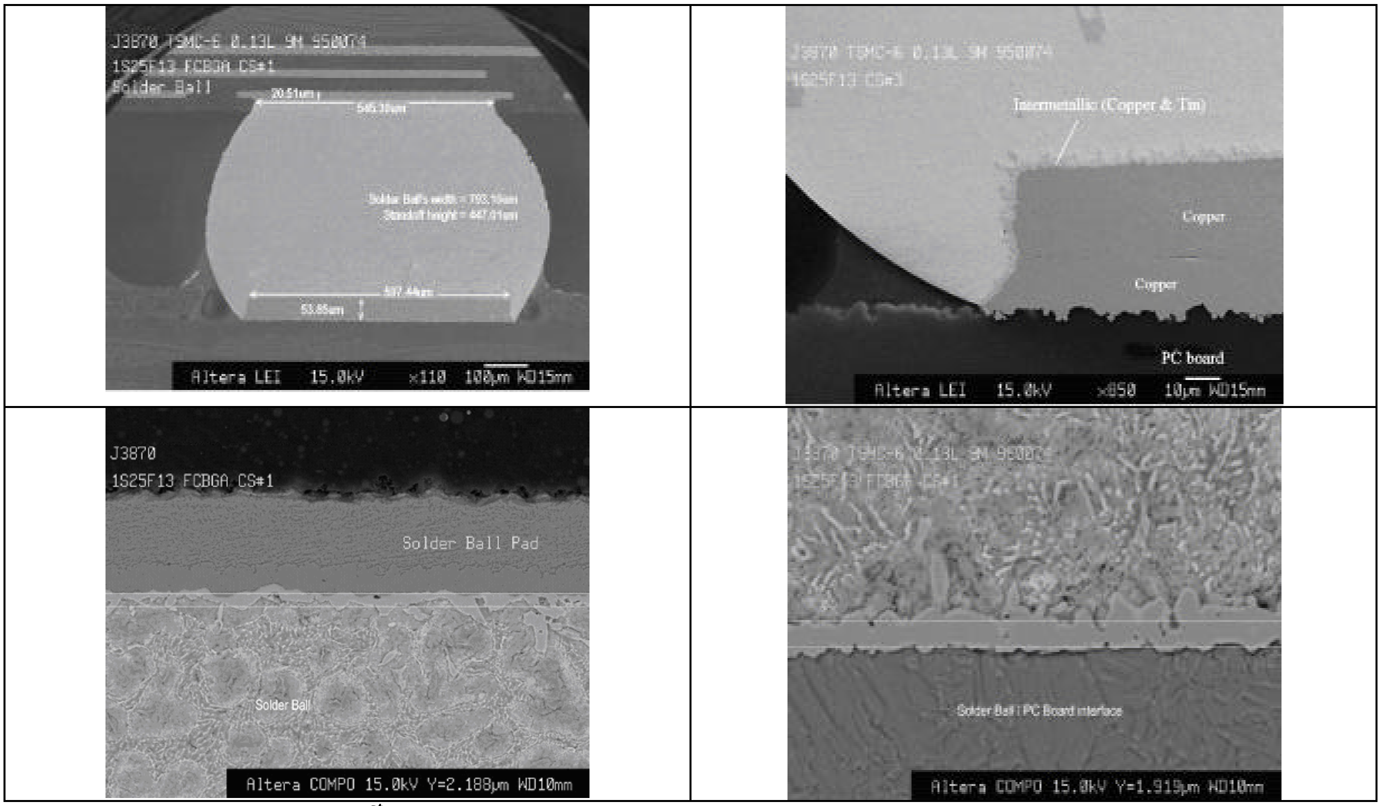


Figure 12 - Cross-sections of 1st Pass Assembled Lead-free SnAgCu Soldered FCBGA780 Components at 245°C Peak Solder Joint Temperature in Air Atmosphere

Selected individual cross-sections of 1st pass assembled devices at 225°C, 235°C, and 245°C peak solder joint temperature in air and nitrogen atmosphere are shown in Figures 13-17 respectively. Energy Dispersive X-Ray analysis (EDX) of the intermetallic compound (IMC) as seen in Figure 18 for Board side IMC and Figure 14 for component side IMC confirm Copper- Tin intermetallic on the board side and Tin-Copper-Nickel on the component side.

Figure 13 - Cross-sections of 1st Pass Assembled Lead-free SnAgCu Soldered FCBGA780 Components at 245°C Peak Solder Joint Temperature in Nitrogen Atmosphere

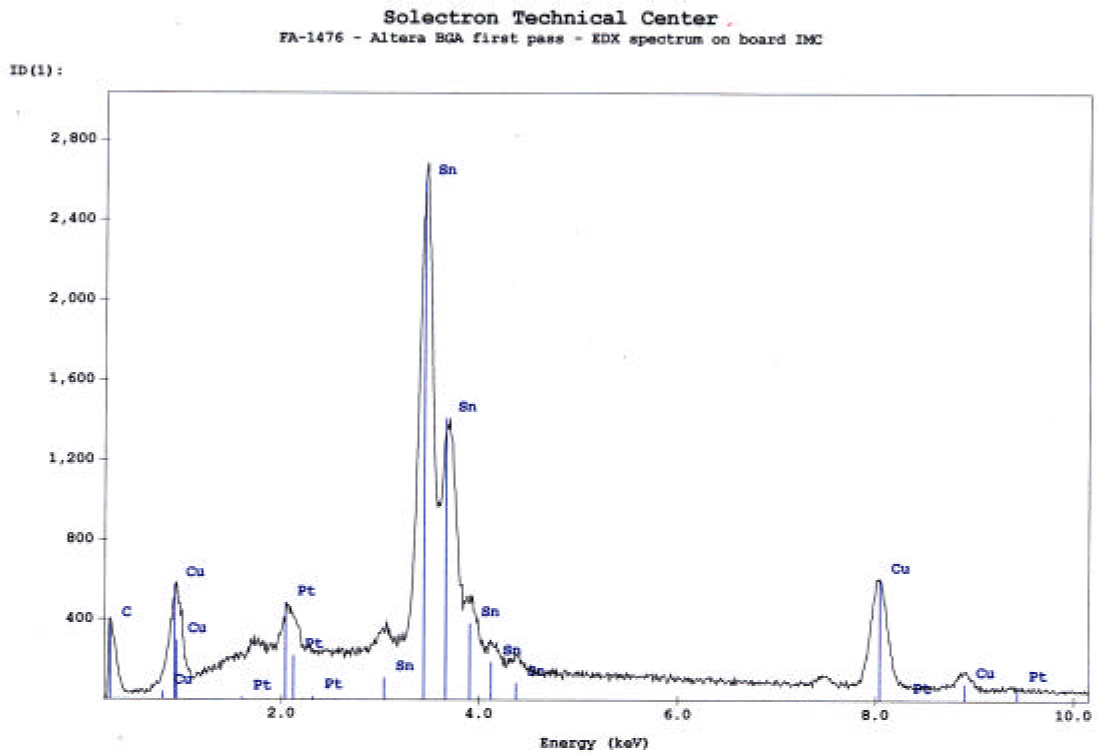


Figure 14 - EDX Trace for Board Side Intermetallic Compound for Lead-free 1st Pass Assembled FCBGA780 at 235°C Peak Solder Joint Temperature in Nitrogen. Copper-tin Intermetallic is Present

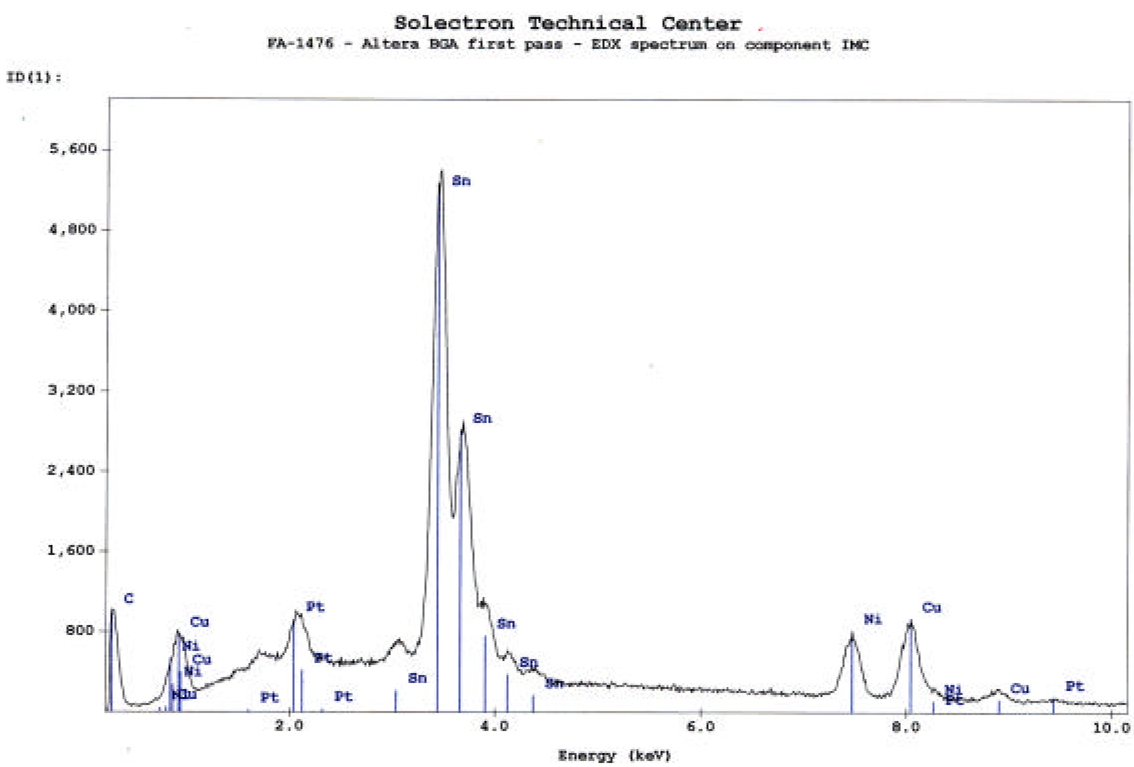


Figure 15 - EDX Trace for Component Side Intermetallic Compound for Lead-free 1st Pass Assembled FCBGA780 at 235°C Peak Solder Joint Temperature in Nitrogen which Indicates the Presence of both Nickel Tin and Copper-tin Intermetallic Creating a Ternary SnCuNi Intermetallic Phase

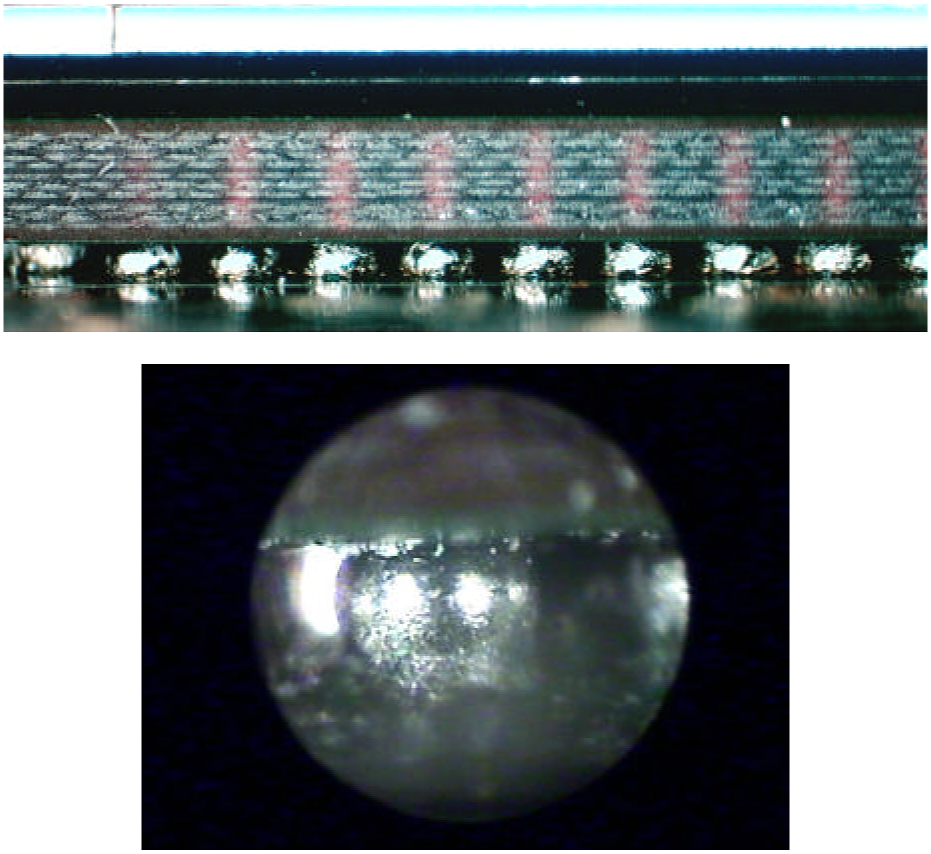


Figure 16 - Visual Solder Joint Appearance of Reworked Lead-free SnAgCu FCBGA780 Components with 230 to 235°C Peak Solder Joint Temperature in Nitrogen Atmosphere

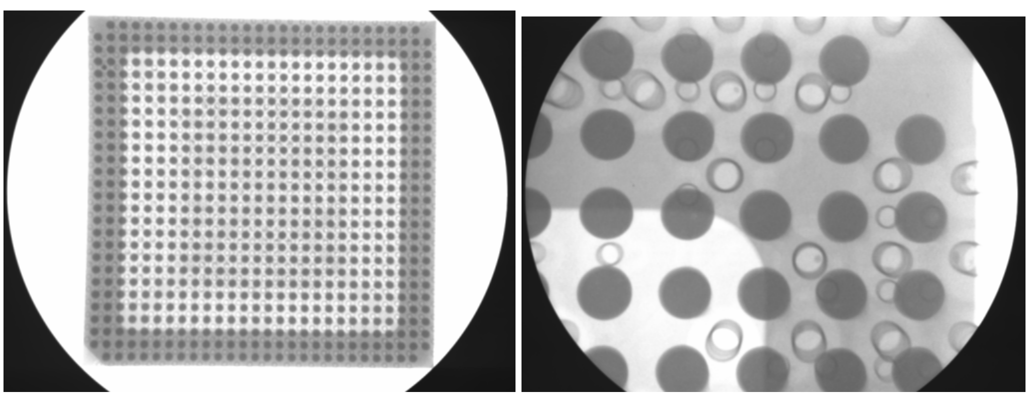
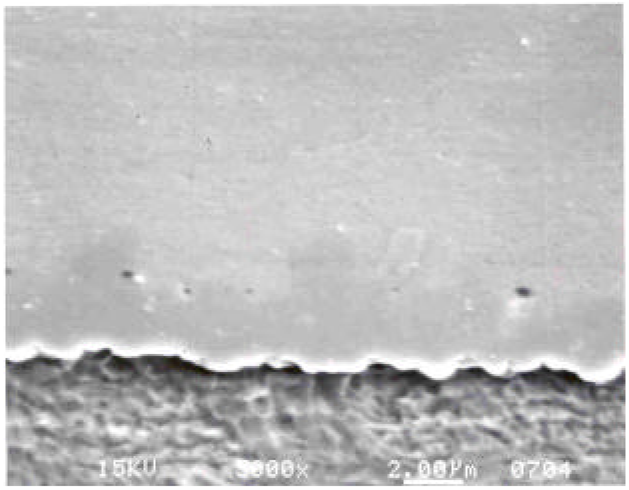
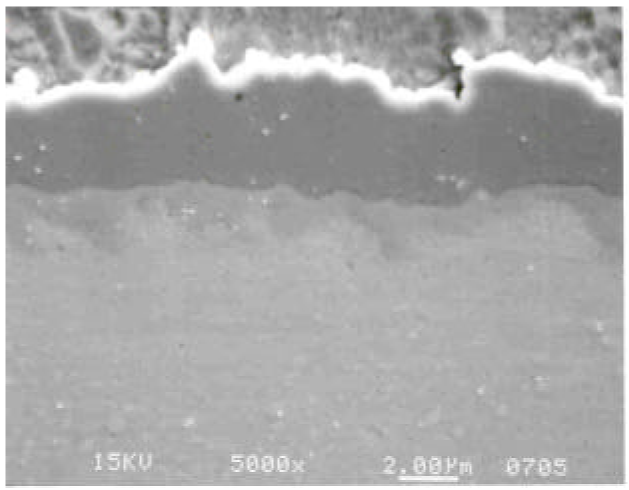


Figure 17 - X-ray Image of Lead-free Reworked FCBGA780 Components with 230 to 235°C Peak Solder Joint Temperature in Nitrogen Atmosphere



a. Board Side IMC, Lead-free Rework (230-235°C, Nitrogen)



b. Component Side IMC, Lead-free Rework (230-235°C, Nitrogen)

Figure 18 - Cross-sections of Lead-free Reworked FCBGA780 Component at 230 to 235°C Peak Solder Joint Temperature in Nitrogen Atmosphere

Board side intermetallic thicknesses are in the similar range for all cross-sections (~1.9 to 2.5 um) as shown in Table 6. Component side intermetallic thicknesses are in a range of 0.90 µm – 2.53 µm.

Table 6 - Typical Board Side Intermetallic Thickness Measurements Lead-free Soldered FCBGA Components

	Board Side Intermetallic thickness (um)	**Substrate Side Intermetallic thickness (um)**
Lead-free 1st pass (Air, 225°C peak, 50s over 217°C)	2.2	1.5
Lead-free 1st pass (Nitrogen, 225°C peak, 50s over 217°C)	2.5	2.0
Lead-free 1st pass (Nitrogen, 235°C peak, 68sec over 217°C)	2	2.53
Lead-free 1st pass (Air, 245°C peak, 66s over 217°C)	1.9	2.19
Lead-free 1st pass (Nitrogen, 245°C peak, 66s over 217°C)	2.3	0.90

Selection of Reflow Profile

Review of visual and XRAY analysis did not show an advantage of using one reflow profile over another. Macro cross section images of the mounted cross sections also did not show any significant distinction. Reliability data (temperature cycling 0-100C) did not show any difference between the three temperatures. All were failure free up to 3500 cycles. (See reliability portion of paper)

Because of SMT manufacturability considerations, it was decided to use 235°C peak temperature profile in nitrogen reflow atmosphere for the main reliability test cell of 1st pass assembly. This temperature takes advantage of the potential benefits of improved process capability of reflowing in a nitrogen atmosphere and is the lowest reflow profile tested that is far enough away from the melting point of the SnAgCu solder paste and ball (217°C) to not cause process parameter concerns.

Rework Inspection

After choosing a 1st pass peak reflow temperature to mount the devices to be tested for ATC, a low temperature rework reflow profile was developed to remount devices for ATC. The development of the profile is described in section 3.2. An important emphasis that needs to be made is the temperature gradient that exists in the traditional method for rework. The use of the baffle to prevent direct convection heating on the component is critical to preventing thermally stressing the component beyond its thermal threshold. The new baffle nozzle minimizes this gradient.

Rework Visual Inspection

From visual inspection of the lead-free reworked FCBGA components at 230 to 235°C peak soldering temperature in nitrogen atmosphere as shown in Figure 16, there did not appear to be a measurable difference in lead-free solder ball appearance between the 1st pass and rework. The lead-free reworked solder joints may have a more cratered surface appearance than first pass lead-free soldered FCBGA.

X-RAY and Electrical Continuity

From X-ray inspection of the lead-free reworked FCBGA components nitrogen reflow atmosphere, there did not appear to be an increased propensity for bridging or voiding between the reworked and 1st pass components. There were no anomalies detected after X-ray inspection. A typical example of the X-ray images observed is shown in Figure 17 for the lead-free reworked joint at 230 to 235°C peak soldering temperatures in nitrogen atmosphere.

All the lead-free reworked components showed electrical continuity pass

Microstructural Cross Section

A lead-free rework board was cross-sectioned at time zero prior to reliability testing. Cross-sections of lead-free reworked FCBGA780 component at 230 to 235°C peak solder joint temperature in nitrogen atmosphere are shown in Figure 18.

Reworked board side intermetallic thickness was found to be in a similar range for both lead-free 1st pass assembled and reworked cross-sections. Intermetallic layer thicknesses for 1st pass lead-free soldered components ranged from 1.9 to 2.5 micron. The intermetallic layer thickness for the lead-free rework FCBGA component was around 3 micron.

SEM/ EDX analysis was performed on the reworked lead-free components to identify the types of intermetallic phases present at the board and component sides of the solder joint.

Figure 19 shows the EDX trace for the board side intermetallic of the lead-free reworked FCBGA at 230 to 235°C peak in nitrogen atmosphere which indicates the presence of copper-tin intermetallic.

Figure 20 shows the EDX trace for the component side intermetallic of the lead-free reworked FCBGA at 230 to 235°C peak in nitrogen atmosphere which indicates the presence of both nickel-tin and copper-tin intermetallic creating a ternary SnCuNi intermetallic phase.

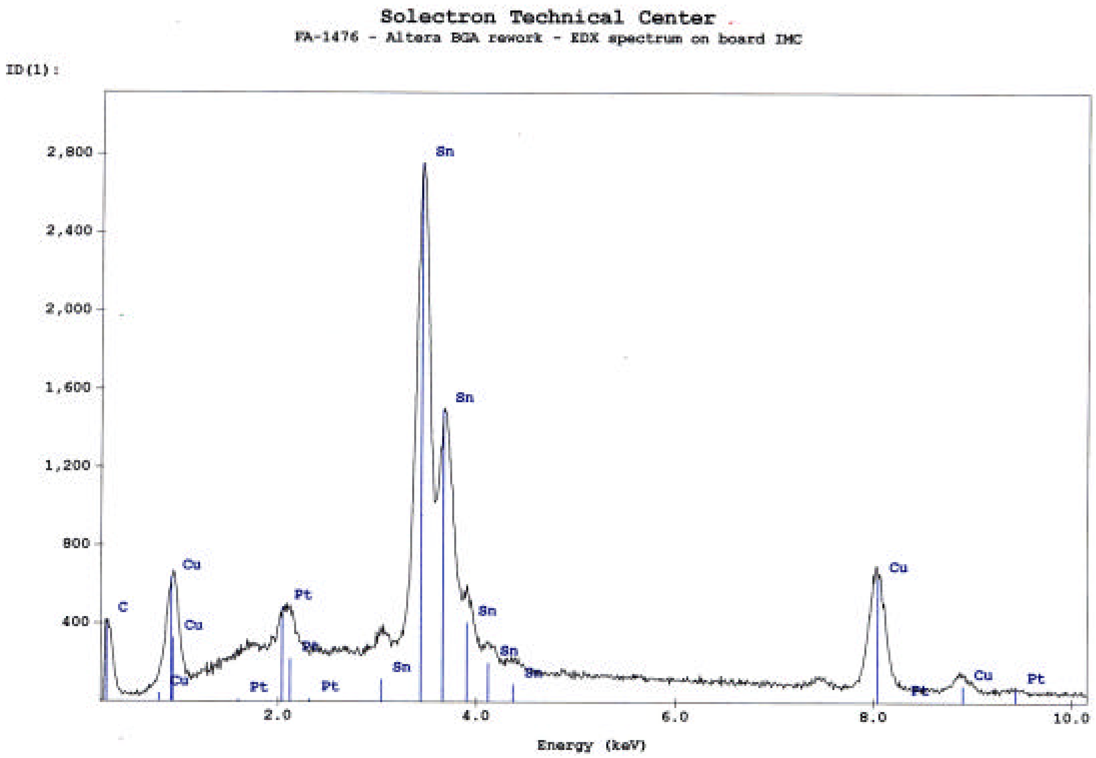


Figure 19 - EDX Trace for Board Side Intermetallic Compound for Lead-free Reworked FCBGA780 at 230 to 235°C Peak Solder Joint Temperature in Nitrogen. Copper-tin Intermetallic is Present

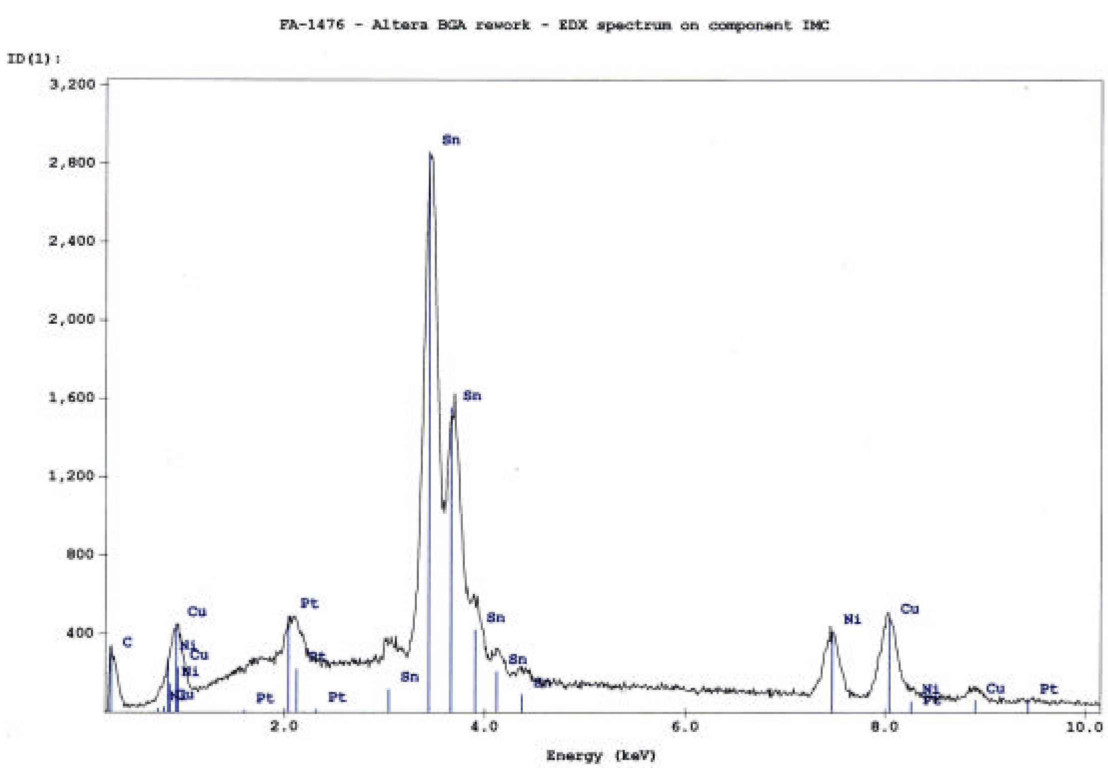


Figure 20 - EDX Trace for Component Side Intermetallic Compound for Lead-free Reworked FCBGA780 at 230 to 235°C Peak Solder Joint Temperature in Nitrogen which Indicates the Presence of both Nickel tin and Copper-tin Intermetallic Creating a Ternary SnCuNi Intermetallic Phase

Reliability Testing

Selected lead-free 1st pass and reworked boards for the FCBGA component were thermally cycled. Thermal cycling was targeted to 6,000 cycles or 50% failures of each individual test cell. Table 7 summarized the ATC results.

Table 7 - Board Level Reliability Results

	Temperature cycles (0C-100C)	Component fails
1st pass assembly 225°C peak in air	> 3500 cycles	0/10 component fails
1st pass assembly 225°C peak in N2	> 3500 cycles	0/5 component fails
1st pass assembly 245°C peak in N2:	> 3500 cycles	0/5 component fails
1st pass assembly 235°C peak in air:	> 3500 cycles	0/5 component fails
1st pass assembly 235°C peak in N2:	**> 3500 cycles**	**0/34 component fails**
Rework assembly 230 to 235°C peak in N2:	**> 3500 cycles**	**0/10 component fails**

All lead-free components cycling will be continued to 6,000 cycles or 50% sample size failure.

Conclusions:

- Lead-free soldered FCBGA components were successfully assembled using standard surface mount equipment at 3 different peak soldering temperatures (225°C, 235°C, 245°C) in air or nitrogen reflow atmosphere on 93mil thick OSP surface finish boards.
- In addition, lead-free rework of these components was successful using a 230 to 235°C peak soldering temperature in nitrogen atmosphere using a novel rework nozzle designed to minimize the temperature gradient between the top of the component and the BGA solder joints during reflow.
- Cross-sectional and X-ray analysis of the lead-free assembled and reworked components gave no major anomalies. Visual inspection of lead-free soldered joints indicated a duller solder joint appearance compared to tin-lead soldered components but this had no influence on reliability.
- Reliability testing was performed for the lead-free 1st pass assembled and reworked FCBGA components using thermal cycling from 0 to 100°C. There were no component solder joint failures after 3,500 thermal cycles for both 1st pass and reworked components which passed the requirements of the components under test.

Future Work

A lead-free SnAgCu FCBGA 1508I/O component with a larger package body size is currently under consideration to assemble, rework and reliability test. These larger sized components may pose more thermal challenges in terms of the component peak temperature reached during assembly and rework operations.

Acknowledgements

The authors would like to acknowledge the various persons within the two companies who helped to conduct cross-sectional analysis, assembly, rework and reliability testing of the lead-free FCBGA component test boards.