Salt Atmosphere, Temperature Humidity, Mechanical Shock Environmental Stress Testing Results, and FMA of the JG-PP / JCAA Lead Free Soldering Program

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Abstract
The American Competitiveness Institute (ACI) performed a series of Environmental Stress Tests for the Joint Group of Pollution Prevention / Joint Council of Aging Aircraft (JG-PP / JCAA) Lead Free Soldering Program. The objective was to determine if Lead Free soldered hardware was equivalent to or better than its Tin Lead (SnPb) counterpart. The program's test vehicle was manufactured by BAE Systems in Irvine, Texas. The JG-PP / JCAA test vehicle was soldered with Tin Lead (SnPb) as a baseline, Tin Silver Copper (95.5Sn3.9Ag0.6Cu or SAC), Tin Silver Copper Bismuth ((92.3Sn3.4Ag1.0Cu3.3Bi or SACB), and stabilized Tin Copper (99.3Sn0.7Cu0.05Ni).

The Salt Atmosphere test was performed in accordance to ASTM B117 Test Method for 48 hours. The Temperature Humidity test followed the procedure MIL-STD 810F; Test Method 507.4. In both tests, no failures were found that could be attributed to the solder joints. Therefore, the Tin Lead and Lead Free soldered hardware can be considered equivalent.

Two types of Mechanical Shock tests were performed. The first Mechanical Shock test was performed using the test procedure MIL-STD 810F; Method 516.5; Procedure 1. The test was performed on all 3 axes. 2 components soldered with SACB failed the tests. The balance of the SnPb and Lead Free soldered components passed this mechanical shock test with no failures.

The second Mechanical Shock test was performed to a modified version of MIL-STD 810F; Method 516.5; Procedure 1, where the test vehicle was tested in the Z-Direction, at increasing levels to failure. The mechanical shock levels reached in this test were above those in the first mechanical shock test. Across all test levels and component types, the SnPb soldered hardware performed comparable or better than the SAC and the SACB soldered hardware.

Introduction
The Joint Group of Pollution Prevention (JG-PP), partnered with the Joint Council on Aging Aircraft (JG-PP / JCAA) initiated the JG-PP / JCAA Lead Free Soldering Program. This project's goal is to generate critical reliability data on circuit cards manufactured and reworked with Lead Free and Tin Lead (SnPb) solders for military and space applications. In 2004, the program manufactured hardware with various electronic packages with Lead Free solders. Environmental Stress Screening testing was performed. Members of the JG-PP / JCAA Lead Free Project Team include NASA, International Trade Bridge, American Competitiveness Institute, Rockwell Collins, Raytheon, Boeing, and BAE Systems.

The American Competitiveness Institute was assigned the task to perform Salt Atmosphere, Temperature Humidity Exposure, and Mechanical Shock environmental stress screening tests on the consortium's test vehicle, as illustrated in Figure 1. The objective was to determine if Lead Free solder joints reliability were equivalent to or better than Tin Lead (SnPb) solder joints.

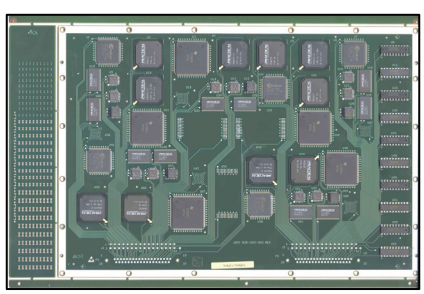

Figure 1 - JG-PP / JCAA Lead Free Soldering Program Demonstration Vehicle

Salt Atmosphere Test Procedure
The Printed Wiring Assemblies (PWA's) were exposed to a 48 hour Salt Atmosphere as per ASTM B117 and the agreement with the consortium. Given the number of samples it was necessary to do two sets of exposures with board types being

intermingled. The Printed Wiring Assemblies (PWA's) were tested for continuity prior to and after exposure as per instructions from the customer. Table 1 lists the boards which underwent Salt Atmosphere testing.

Table 1 - Salt Atmosphere Test Vehicles

Board #	Description Of Board (Component Finish / Solder used)
35	SnPb Hybrids and SnPb wire SnPb Manufactured
36	SnPb Hybrids and SnPb wire SnPb Manufactured
37	SnPb Hybrids and SnPb wire SnPb Manufactured
104	SnAgCu/SnAgCu
105	SnAgCu/SnAgCu
106	SnAgCu/SnAgCu
143	SnAgCuBi/SnCu
144	SnAgCuBi/SnCu
145	SnAgCuBi/SnCu

Salt Atmosphere Test Results

Of the 9 boards tested, 2 boards had 3 component failures, as depicted in Table 2.

Table 2 - Salt Atmosphere Test Results

Board #	Solder Alloy	Component Number
104	SnAgCu	U35
104	SnAgCu	U56*
105	SnAgCu	U3

ACI performed failure analysis on the 2 boards with component failures to determine the root cause of failure, and found the following:

Board 104: Component U35: Open circuits where the component leads were supposed to be in series (daisy chained) as shown in Figure 2.

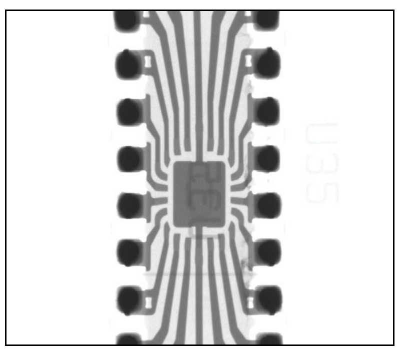

Figure 2 - Component with No Internal Wire Bonds

Board 104: Component U56: Continuity testing prior to and after the salt atmosphere exposure showed that there was an open circuit within the component, as illustrated in Figure 3.

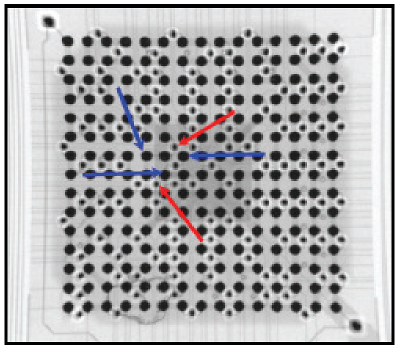

Figure 3 - BGA Package with Open Circuit (Red Arrows)

Board 105: Component U3: There was a resistance reading of 70.6 Ω across the terminals of the component indicating an improperly wired component, as depicted in Figure 4.

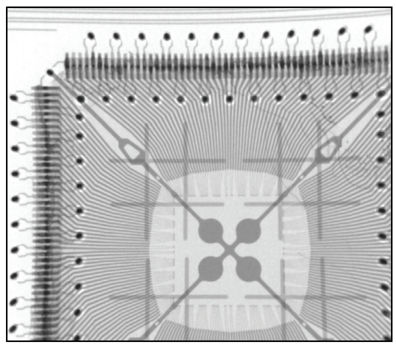

Figure 4 - X-Ray Image of Quad Flat Pack

Temperature Humidity Test Procedure
The Printed Wiring Assemblies (PWA's) specified were exposed to 30^{o}C and 95% RH for five 48-hour cycles per MIL-STD-810F Method 507.4. The PWA's were tested for continuity prior to and after exposure as per instructions from the consortium. Table 2 lists the boards that underwent Salt Atmosphere testing.

Table 2 - Temperature Humidity Test Vehicles

Board #	Description Of Board (Component Finish / Solder used)
38	SnPb Hybrids and SnPb wire SnPb Manufactured
39	SnPb Hybrids and SnPb wire SnPb Manufactured
40	SnPb Hybrids and SnPb wire SnPb Manufactured
107	SnAgCu/SnAgCu
108	SnAgCu/SnAgCu
109	SnAgCu/SnAgCu
146	SnAgCuBi/SnCu
147	SnAgCuBi/SnCu
148	SnAgCuBi/SnCu

Temperature Humidity Test Results

Of the 9 boards tested, 2 boards had 1 component failure, as depicted in Table 3.

Table 3 - Temperature Humidity Test Failures

Board #	Solder Alloy	Component Number
38	SnPb	U49
108	SnAgCu	U44

ACI performed failure analysis on the 2 boards with component failures to determine the root cause of failure, and found the following:

Board 38: Component U49: The open circuit was caused by a broken bond within the chip, as illustrated in Figure 4.

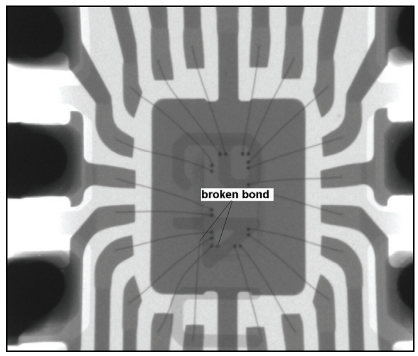

Figure 4 - Broken Bond within package

Board 108: Component U44: Continuity testing showed that there is an open within the component. The location of the open circuit was identified but the root cause could not be determined.

Mechanical Shock Tests Performed

ACI executed a pair of Mechanical Shock Tests for the program. The first test was based on the strict adherence to MIL-STD 810F; Method 516.5; Procedure 1, which is used for hardware certification. The second test was a modified version of MIL-STD 810F; Method 516.5; Procedure 1, where the boards were tested to failure. This test determined if the Lead Free Soldered assemblies performed similarly to Tin Lead (SnPb) soldered assemblies at high stress levels. The Mechanical Shock Tests utilized a Ling Electronics B335 Vibration Systems at BAE Systems in Lansdale, Pennsylvania.

Continuity testing was performed before and after each round of tests. A ny failure found was confirmed failures with the Anatech Event Detector. During the test, all hardware was continuously monitored. Per IPC SM 785 and IPC-9701 test standards, ACI detected electrical interruption lasting greater than 0.2 µsec and continuity interruption greater than 300 Ω up to 1000 Ω. Electrical events were recorded every 30 seconds using an event detector.

During testing, intermittent failures were found. ACI defined an intermittent failure as a component that fails test level but passes subsequent level. ACI considered this situation to be a failure at subsequent level. ACI captured the components with intermittent failures, noting when these failures occurred during the tests.

Mechanical Shock Test 1 Test Procedure

ACI performed the Mechanical Shock Tests in the X, Y, and Z axis. Table 5 illustrates the testing levels performed at each step. Figure 5 demonstrates how the test vehicles were mounted on the vibration table.

Table 5 -Mechanical Shock I Testing Levels

Step	Test	Initial G	Slope	Peak G	Ts (ms)	Cross-Over Freq.	Z-axis (thru-thickness)	X-axis	Y-axis	Total Shock
1.1	Functional test for flight equipment	4.5	6	20	15-23	45	3	3	3	9
1.2	Functional test for ground equipment	8.5	6	40	15-23	45	3	3	3	9
1.3	Crash Hazard test for flight equipment	9	6	75	8-13	80	3	3	3	9
1.4	Crash Hazard test for flight equipment	9	6	75	8-13	80	100	100	100	300

Figure 5 - JG-PP / JCAA Test Vehicle Mounted On Vibration Table

Mechanical Shock Test 1 Test Results

ACI found no failures from the Tin Lead (SnPb) and SnAgCu soldered hardware. However, three (3) TQFP-208 components and one (1) TSOP-50 component soldered with SACB failed the Mechanical Shock Test 1. Failures occurred during test step levels 1.1 and 1.2, as per Figure 6 intermittent failures found with the TQFP-208 at Level 1.4 in the Y-axis. .

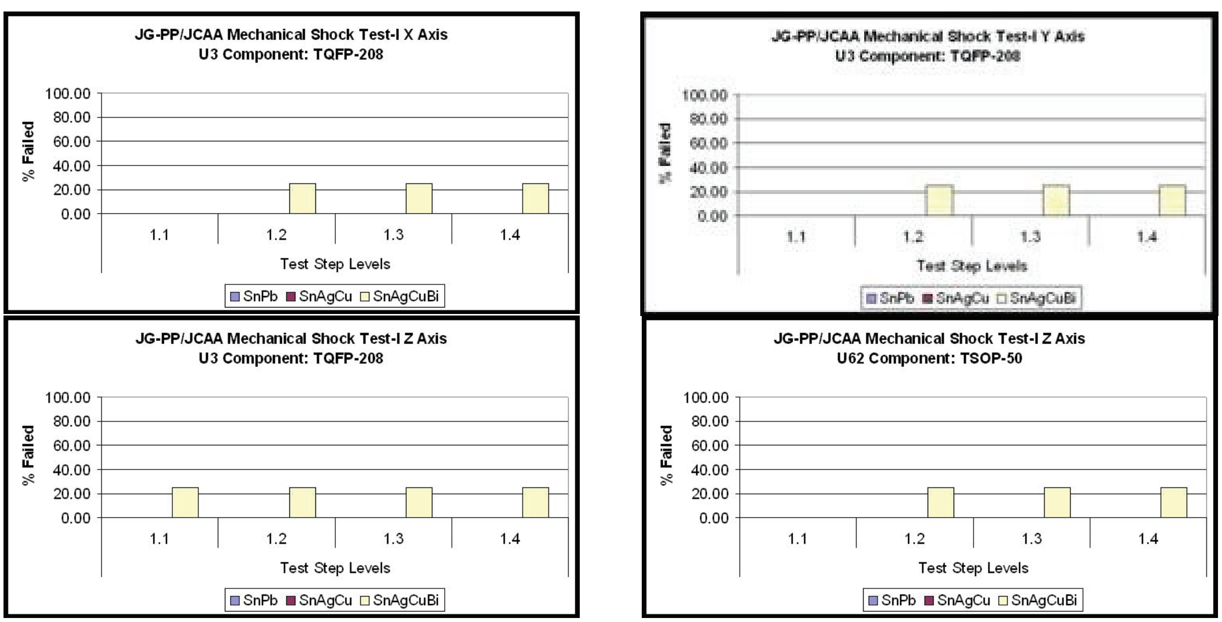

Figure 6 - Mechanical Shock Test 1 Test Results

Mechanical Shock Test 2 Test Procedure
ACI performed the Mechanical Shock Tests in the Z axis only. Table 6 illustrates the testing levels performed at each step.

Table 6 - Mechanical Shock II Testing Levels

Step	Test	Initial G	Slope	Peak G	Ts (ms)	Cross-Over Freq.	Total Shock
2.1	Functional test for flight equipment	4.5	6	20	15-23	45	100
2.2	Functional test for Ground equipment	8.5	6	40	15-23	45	100
2.3	Crash Hazard test for flight equipment	9	6	75	8-13	80	100
2.4	Level 1	12	6	100	15-23	80*	100
2.5	Level 2	25	6	200	15-23	80*	100
2.6	Level 3	35	6	300	15-23	80*	100
2.7	Level 4	52	6	500	15-23	80*	100
2.8	Level 5	72	6	700	15-23	80*	100
2.9	Level 6	90	6	1000	15-23	80*	100

Mechanical Shock Test 2 Test Results
Tin Lead (SnPb) soldered test vehicles performed better than the SAC and SACB soldered test vehicles. Lead Free Solder failures were most prominent after Level 2.3, as shown in Figure 7. The results are attributed to the higher mechanical shock levels experienced by the components, the quantity of shock pulses per test step level, and the tests being performed in the Z-axis only.

Tin Lead (SnPb) had high levels of intermittent failures. Approximately 50% of all Tin Lead (SnPb) soldered components tested had intermittent failures, at the Test Step Level 2.6. The SACB soldered test vehicles had intermittent failures at U17: CLCC-20 and at U57: TQFP-208. These failures were found at Test Step Level 2.3. SnAgCu had no intermittent failures.

At the higher shock levels, Level 2.4 (> 100 G Peak) and above, failure event data indicated simultaneous failures and intermittent failures of several devices. The intermittent failures confound the test data and do not allow clean interpretation of the test results. An intermittent contact/open may be result of several possibilities such as: shock failed solder/interconnect joints break and remake the contact or the failures are not at the device level but somewhere on the board interconnect chain at the board level or at the mechanical connector. For these reasons, we rigorously applied the IPC 9701 failure criteria. Failure was defined as an electrical interruption lasting greater than 0.2 μsec and continuity interruption greater than 300 Ω up to 1000 Ω.

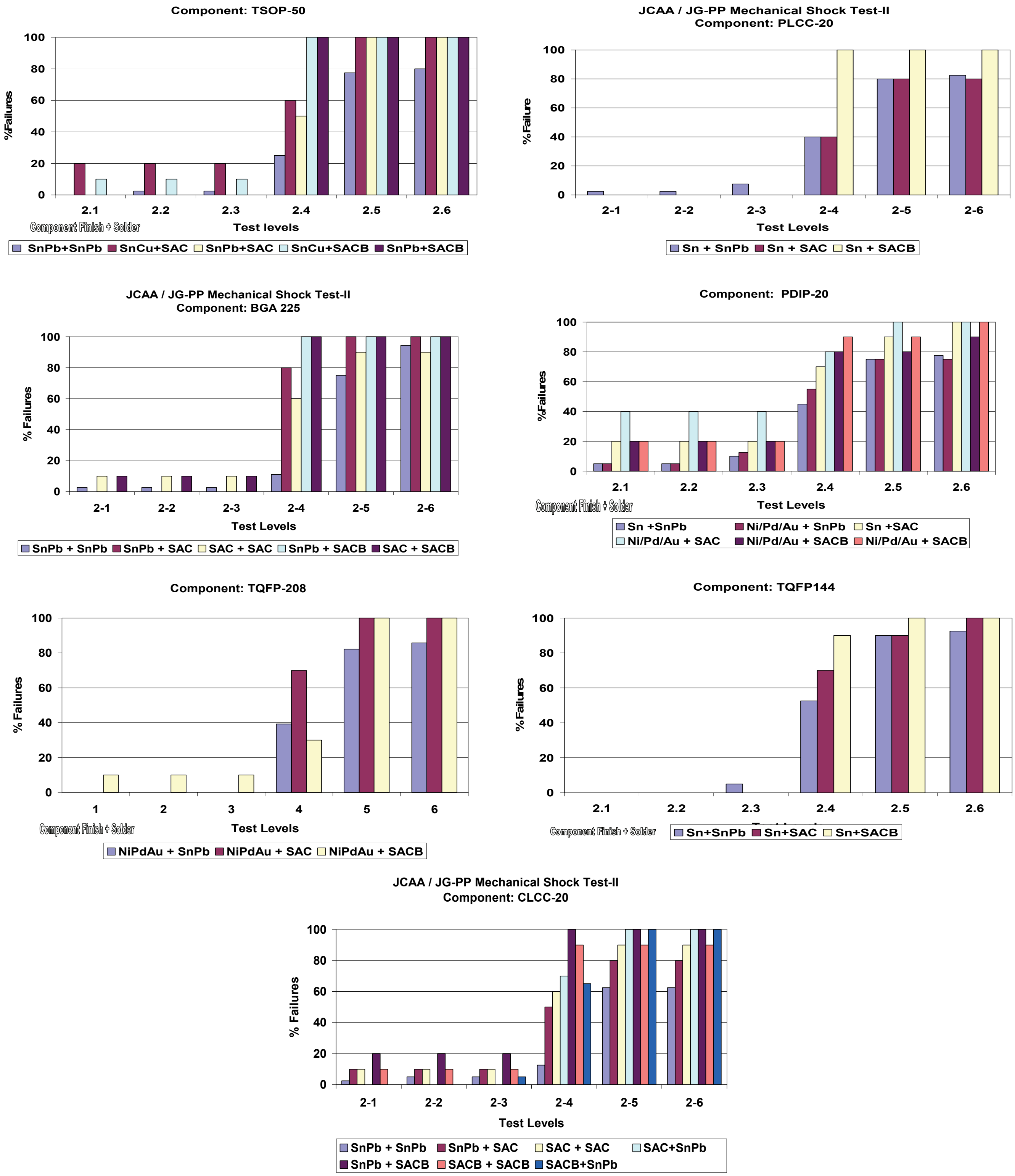

Figure 7 - Mechanical Shock Test 2 Test Results

Shock Test Failure Modes

Limited scale failure mode analysis of the failed solder joint was conducted using X-ray inspection, followed by micro-sectioning. Pinpointing a device level failure in the shock tested boards presents a challenge, since the device level electrical probe testing does not always lead to opens. In our failure analysis, we analyzed one board from each solder type and only BGA device failures were evaluated.

Limited thermal cycling from -55°C to 125°C, using the consortium's extended thermal profile, was performed to confirm solder joint failures. This did not yield any additional failure locations. Subsequently, the Colored Dye Penetrant method was used to visually inspect the failed solder joints. This did not indicate any failures at the solder joints. However inspection of the PCB conductors entering the BGA balls appeared to have been cracked prior to application of colored dye. This was indicated by heavy oxidation in the break area as compared to breaks resulting from Pry process. To verify this, additional cross-sections of the failed samples were prepared.

BGA devices we evaluated from the SnPb, SAC and SACB boards had similar failure mode. In each case, the Cu trace connecting the daisy chain on the board broke, at the land-trace interface area. Most of the failures were located at the corner areas of BGAs. The cross-sections also revealed that some of the BGA solder balls had partially propagated cracks, indicating another emerging mode of failure. However, none of the solder joint exhibited complete solder joint failure. This signifies board level copper interconnect traces were the weak links in the case of the BGA devices. Figures 8 through 12 illustrate examples of the failures found from the Failure Mode Analysis.

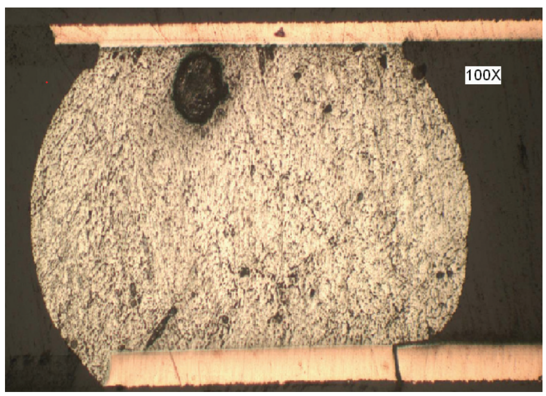

Figure 8 - Example of BGA Failure from Mechanical Shock Test 2

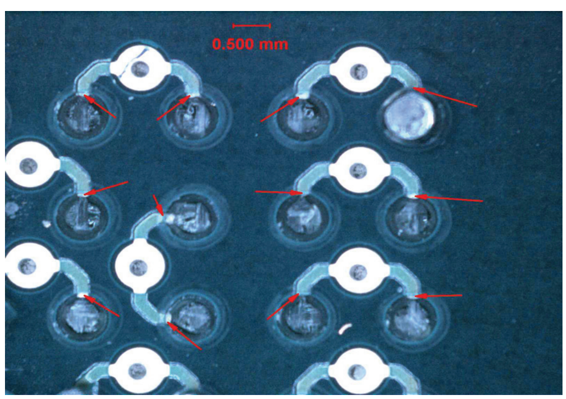

Figure 9 - Tin Silver Copper (SAC) Pry and Dye Failure Analysis, U6 PCB Trace Failures

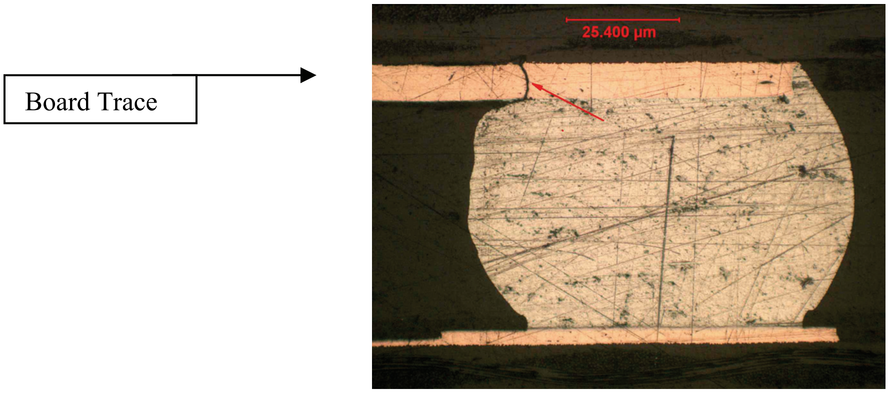

Figure 10 - Tin Lead (SnPb) U44 PCB Trace 1R Failure

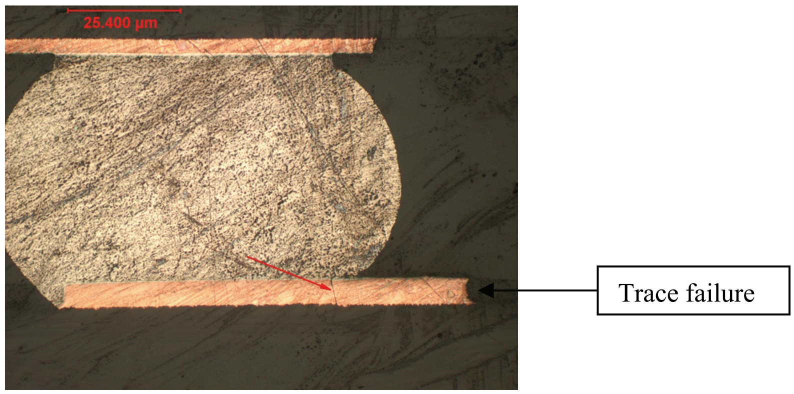

Figure 11 - Tin Silver Copper (SAC) U44 BGA Trace 2R Failure

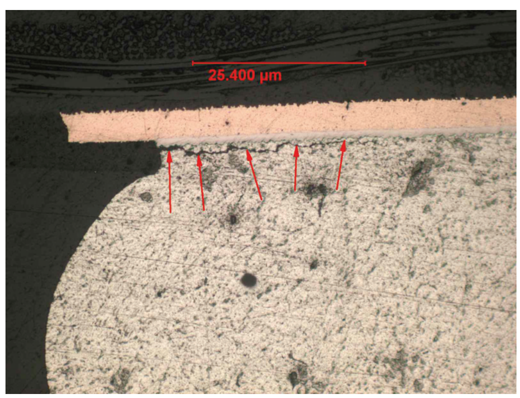

Figure 12 - Tin Lead (SnPb) U44 BGA Solder Crack

Conclusions

Based on the components and boards which have undergone Salt Atmosphere and Temperature Humidity testing, the Tin Lead (SnPb) solder joints, the Tin Silver Copper (SnAgCuBi - SAC) solder joints, and the Tin Silver Copper Bismuth (SnAgCuBi - SACB) solder joints were not the root cause of failure. It was determined that the failures were cause by packaging or wiring defects. Based on the Salt Atmosphere and Temperature Humidity Exposure tests performed, the Tin Silver Copper (SnAgCu) Lead Free solder joints and the Tin Silver Copper Bismuth (SnAgCuBi - SACB) solder joints reliability were equivalent to Tin Lead (SnPb) solder joints.

In the first Mechanical Shock Test, the Tin Lead (SnPb) and Tin Silver Copper (SnAgCu - SAC) soldered assemblies passed the environmental stress screening testing described in MIL-STD 810F; Method 516.5; Procedure 1. The Tin Silver Copper Bismuth (SnAgCuBi - SACB) soldered assemblies had three (3) TQFP-208 components and one (1) TSOP-50 component that failed.

In the second Mechanical Shock Test, at the lower levels of shock (< 100 G Peak) the Tin Lead (SnPb) performed slightly better than the Lead Free Tin Silver Copper (SnAgCu - SAC) and the Tin Silver Copper Bismuth (SnAgCuBi - SACB) soldered assemblies. At the higher mechanical shock test levels (> 100 G Peak), Tin Lead (SnPb) performed better than the Lead Free Tin Silver Copper (SnAgCu - SAC) and the Tin Silver Copper Bismuth (SnAgCuBi - SACB) soldered assemblies. This difference is dependent upon the type of electronic package used. However the test data at these levels of shock is confounded by the intermittent failures.

It is speculated that more solder joints survived the second Mechanical Shock Test than originally thought. Performing Failure Mode Analysis determined that the several copper traces failed at the land-trace interface area. Failures within the electronic package and hardware instrumentation can also yield failures that were attributed to the solder joint in the prior discussions. BGA solder joint cross sections revealed that several BGA solder balls had partially traversed cracks, but no complete failure.

All analysis and data will be included in the final JG-PP / JCAA Lead Free Soldering Program Report, scheduled for release at the end of February 2006.

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