Mechanical Shock Test Performance of SAC105 (Sn-1.0Ag-0.5Cu) and Sn-3.5Ag, BGA Components with SAC305 Solder Paste on NiAu and OSP Board Surface Finishes

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Abstract

Many BGA and CSP component suppliers have begun shipment of components with a variety of second generation lead-free solder ball alloys based on the improved mechanical shock resistance. Although in general mechanical performance has been improved, there have been questions raised on how much the mechanical performance of these lead-free solder ball alloys can vary with different board surface finishes such as NiAu and OSP.

Mechanical testing was performed on Sn3.5Ag and Sn1Ag0.5Cu 676 PBGA components with 1mm pitch and electrolytic Ni/Au finished component pads. These components were soldered with Sn3Ag0.5Cu paste on either electrolytic Ni/Au or high temperature rated OSP board surface finish. The mechanical shock data indicated that among the four board surface finish/BGA component sphere alloy combinations, the Sn1Ag0.5Cu (SAC105) BGA sphere with NiAu board surface finish had the lowest drop test resistance among the combinations evaluated, which was not expected.

Failure analysis of this and the other drop test combinations was carried out by dye-pry analysis and cross-sectioning to understand the failure locations on the soldered BGA joints. The results were assessed in terms of Weibull failure distributions, failure modes, failure locations, and microstructural analysis which included IMC thickness measurement and IMC compositional analysis and distribution. This analysis suggested a possible direct or indirect relationship between drop test results and unique IMC spalling of the Sn1Ag0.5Cu (SAC105) BGA sphere with NiAu board finish. The implications of these findings and areas for further study are discussed.

Introduction

There has been an increase in the shipment of lead-free BGA/CSP components with alloy compositions which are not Sn3Ag0.5Cu. Typically the alloy composition used for smaller CSP components have centered around Sn1Ag0.5Cu due to improved mechanical drop test performance for consumer electronics applications[1-9]. For larger BGA components, there have been studies and use of Sn3.5Ag BGA components.

Although there have been many studies looking at drop test performance of Sn1Ag0.5Cu CSP components, the authors are unaware of published studies looking at the affect of the interaction of different board surface finishes and the affect on mechanical shock test performance for Sn1Ag0.5Cu and Sn3.5Ag BGA components[10,11]. The aim of this work was to investigate the drop test reliability of Sn1Ag0.5Cu and Sn3.5Ag BGA components on OSP and NiAu board finishes which is presented in the following sections.

Experimental

Mechanical testing was performed on Sn3.5Ag and Sn1Ag0.5Cu 676 PBGA components with 1mm pitch and electrolytic Ni/Au finished component pads. These components were soldered with Type 3 Sn3Ag0.5Cu no-clean solder paste on either electrolytic Ni/Au or high temperature rated OSP board surface finish.

The test board and components used were the same as those used in previous evaluations of tin-lead and lead-free solder joint reliability [12,13] but the original 140 mm x 220 mm test board with 6 BGA package sites was modified as shown in Figure 1, yielding a 140 mm x 150 mm drop test board with 4 BGA package sites. This modification was done to obtain symmetry during mechanical shock testing.

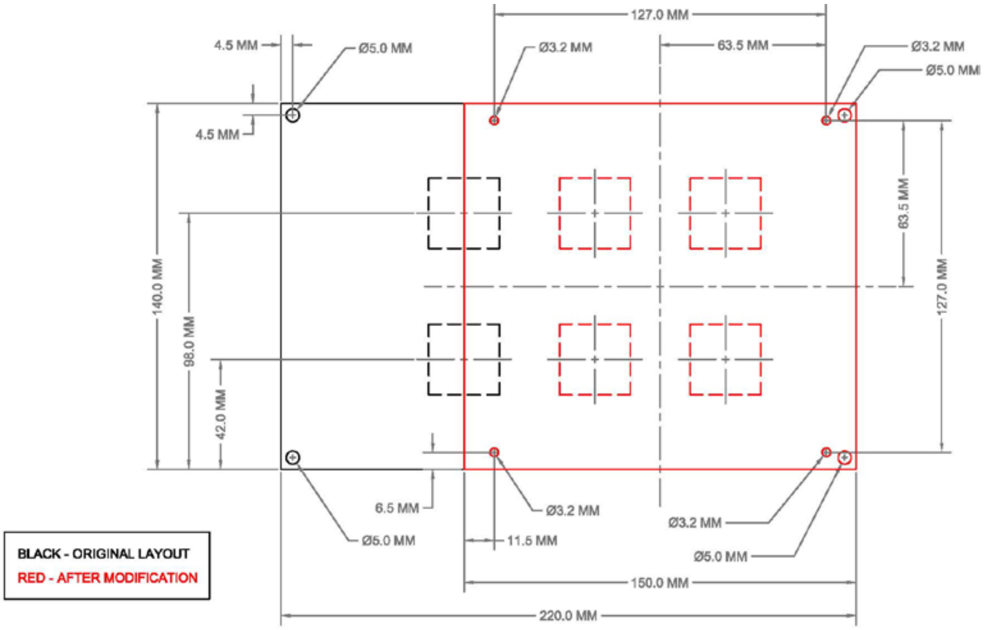


Figure 1: Test board modified for drop-testing

A total of 16 boards were built with Sn3Ag0.5Cu Type 3 no-clean solder paste and the PBGA676 components. There were 4 boards built with each board surface finish/ BGA component sphere alloy combination as shown in Table 1 and Figure 2.

Table 1: Board Surface Finish/ BGA Component Sphere Alloy Combinations assembled by board number. It should be noted that the component side surface finish was Electrolytic NiAu in all cases.

Board Number	Board Surface Finish	BGA Component Sphere Alloy
1	OSP	Sn1Ag0.5Cu
2		
3		
4		
5	OSP	Sn3.5Ag
6		
7		
8		
9	NiAu	Sn1Ag0.5Cu
10		
11		
12		
13	NiAu	Sn3.5Ag
14		
15		
16		

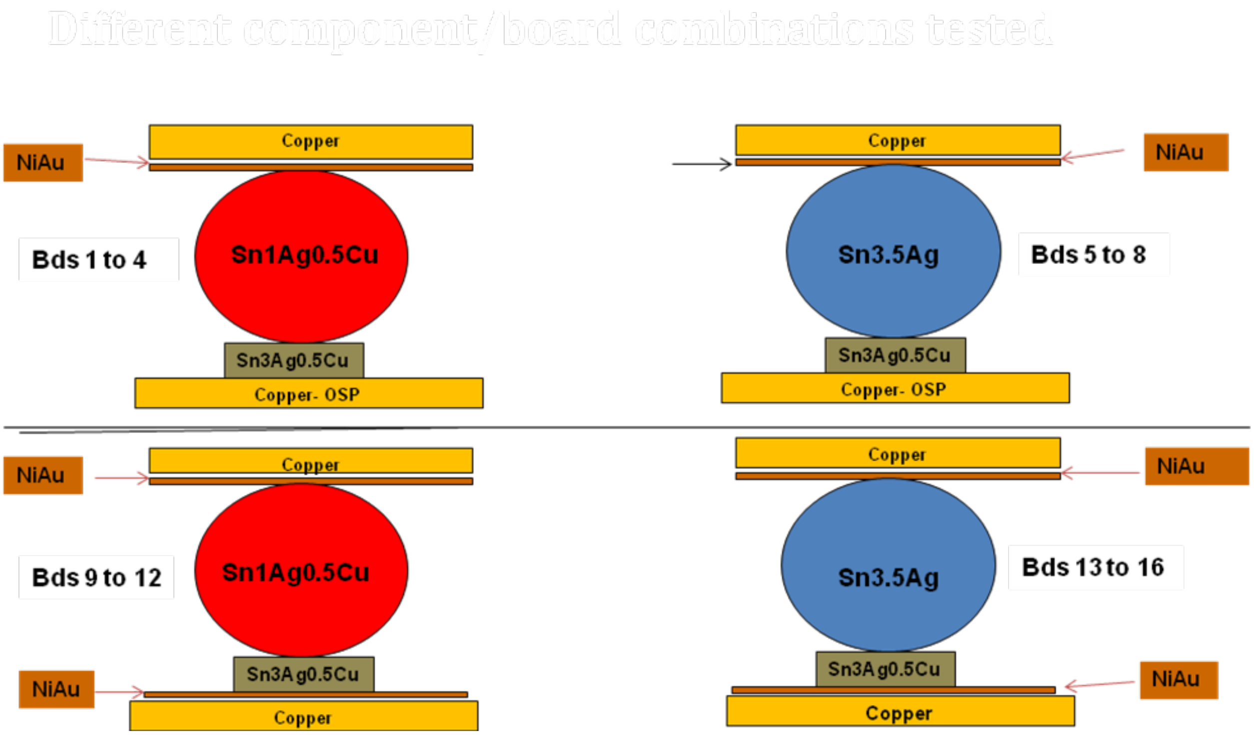


Figure 2: Different board surface finish/ BGA component sphere alloy combinations assembled by board number.

The boards were assembled with production printer, component placement and reflow equipment. The laser-cut stencil thickness was 125 µm (5mil) with 0.46 mm (18 mil) diameter openings. The reflow profile used is shown in Figure 3. The solder joint peak temperature at the BGA components ranged from 240°C to 242°C with the time over 217°C of 60 to 77 seconds. Reflow was conducted in air atmosphere. The assembled test board is shown in Figure 4.

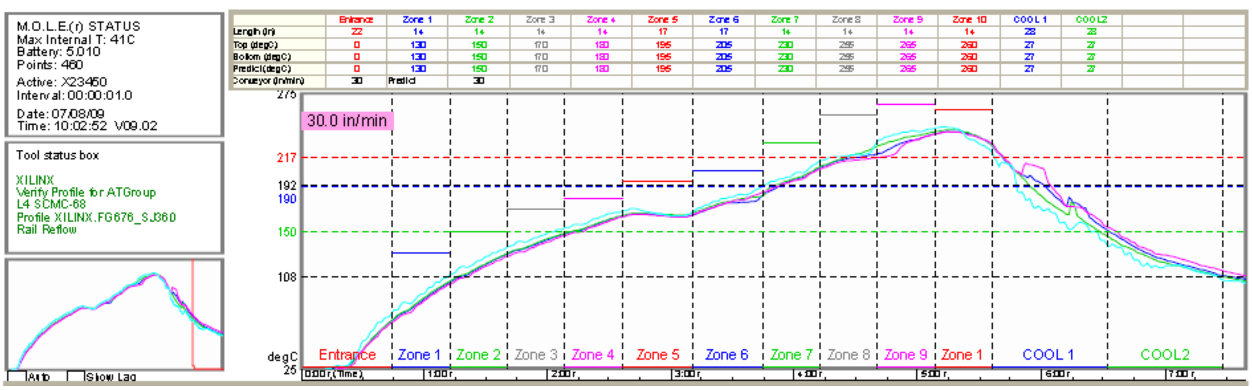


Figure 3: Reflow profile used for the mechanical drop test boards.

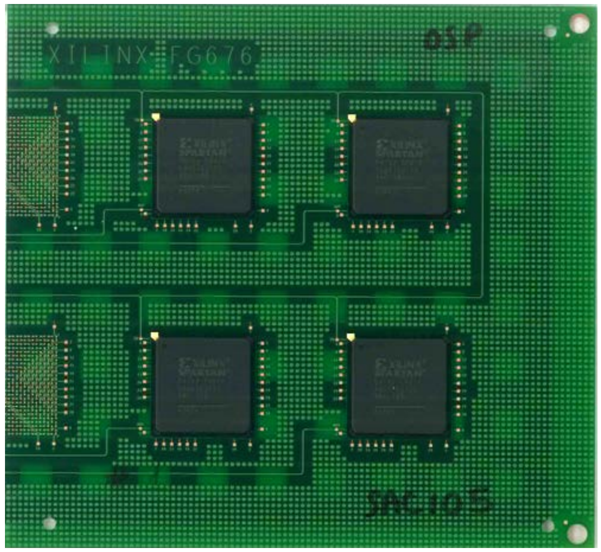


Figure 4: Assembled drop test board

The drop test board was secured to the test fixture at each corner of a 127 mm square region, centered about the 4 BGA package sites. Symmetrical loading at each of the test sites was verified using strain gages with measured strain during various drop conditions varying by less than 4 to 7% between the four BGA locations.

Figure 5 describes the mechanical shock test apparatus used at Hong Kong University of Science and Technology (HKUST) for this study. A JEDEC JESD22-B110A [14] drop condition "A" of 500g, 1.0 ms half-sine pulse, was initially evaluated on a set-up board, but a JEDEC JESD22-B110A [14] drop condition "F" of 900g, 0.7 ms half-sine pulse, was ultimately selected for this study to reduce the required drops-to-failure and overall test duration.

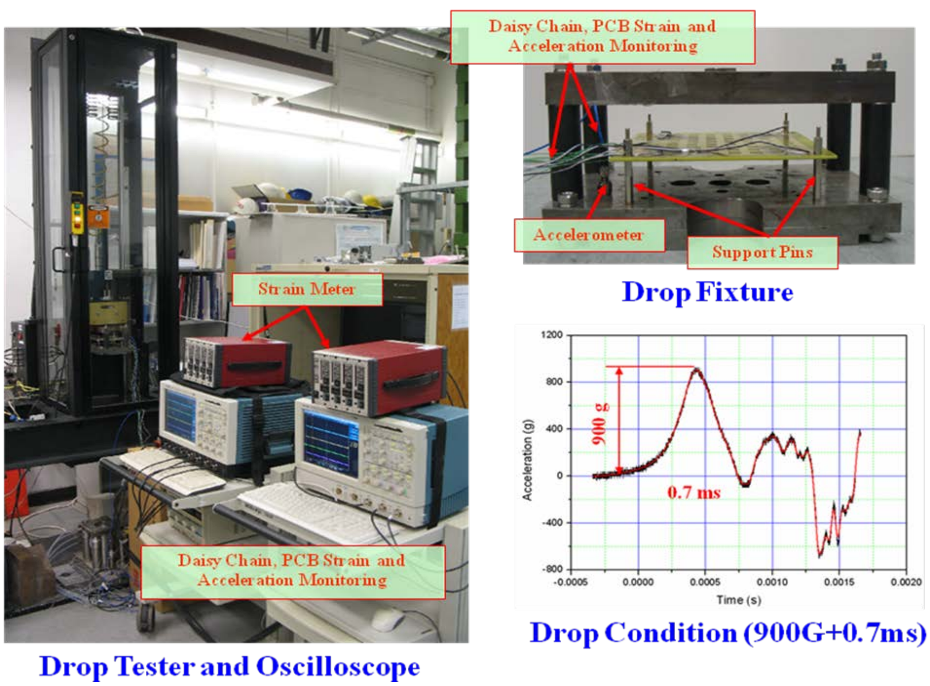


Figure 5: Mechanical shock test apparatus used

Each BGA test location included a separately monitored daisy-chain loop to determine first solder joint failure as shown in Figure 6. The daisy-chain net included all solder joints for a given package, but it was assumed that the solder joint furthest from the test board center failed first at each of the four BGA test locations as shown in Figure 7. For example, the maximum PWB strain measured at the outermost corner for each package was typically 55% higher than the innermost corner.

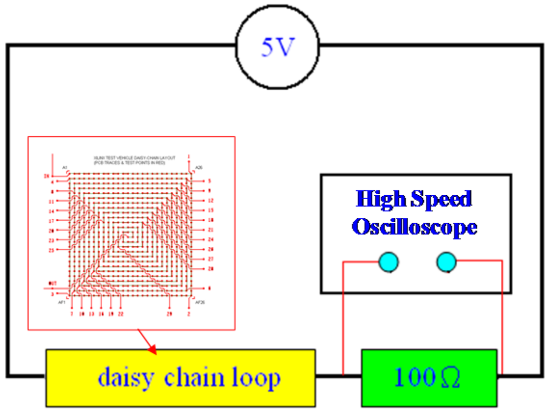


Figure 6: Daisy-chain loop monitored at each package location

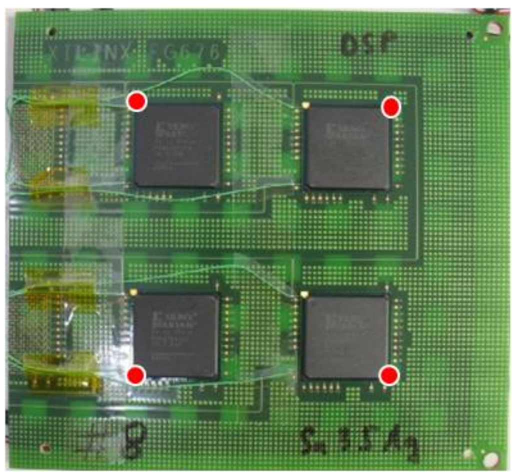


Figure 7: Highest solder joint strain locations (•) during mechanical shock

Drop testing of each board was repeated until a solder joint failure (daisy-chain net open) occurred at all of the four BGA locations. PWB strain monitoring at the highest solder joint strain locations indicated that the measured peak strain varied by less than 7% between the first and last failed device. Consequently, the peak mechanical shock at any solder joint was assumed to be approximately constant for each drop, independent of whether another device on the same test board had already failed. The BGA component package labeling for each drop test board is shown in Figure 8.

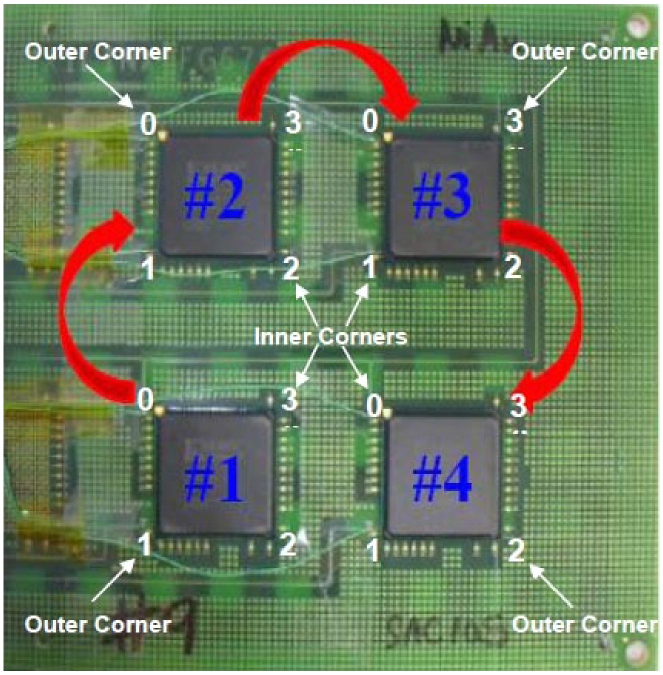


Figure 8: BGA Component Package Labeling for Mechanical Testing

Results and Discussion

Mechanical test results

The mechanical shock data indicated that among the four board surface finish/BGA component sphere alloy combinations evaluated, the Sn1Ag0.5Cu BGA sphere with NiAu board surface finish had the lowest drop test resistance, which was not expected. The mechanical test results were assessed in terms of Weibull plots and maximum strain distributions on the component locations on the board. A summary of the mechanical shock results is shown in Table 2.

Table 2: Mechanical shock test result summary for the four board surface finish/ BGA component sphere alloy compositions tested.

Board Number	Board Surface Finish	BGA Component Sphere Alloy	Component Package #1 Drops to Fail	Component Package #2 Drops to Fail	Component Package #3 Drops to Fail	Component Package #4 Drops to Fail
1	OSP	Sn1Ag0.5Cu	108	98	152	128
2			78	86	126	69
3			84	96	116	143
4			106	138	76	110
5	OSP	Sn3.5Ag	38	68	75	48
6			85	81	34	65
7			51	82	56	77
8			58	48	44	31
9	NiAu	Sn1Ag0.5Cu	26	32	23	42
10			35	46	53	47
11			25	17	44	68
12			71	29	39	31
13	NiAu	Sn3.5Ag	92	64	73	81
14			59	83	44	68
15			95	84	68	51
16			61	103	91	86

A Weibull failure distribution summary of the mechanical shock test results is shown in Figure 9. Consistent with expectations, the Sn1Ag0.5Cu BGA with OSP board surface finish was the best performing; however, the Sn1Ag0.5Cu BGA with NiAu board finish performed the worst, surprisingly, of all test combinations.

The two board surface finishes, OSP and NiAu, tested for Sn3.5Ag BGA yielded similar mechanical shock results, with lifetime results falling between the worst (NiAu/Sn1Ag0.5Cu) and best (OSP/Sn1Ag0.5Cu) combinations. Drop test results for Sn1Ag0.5Cu were highly sensitive to PWB surface finish, while Sn3.5Ag results were only moderately sensitive to board surface finish.

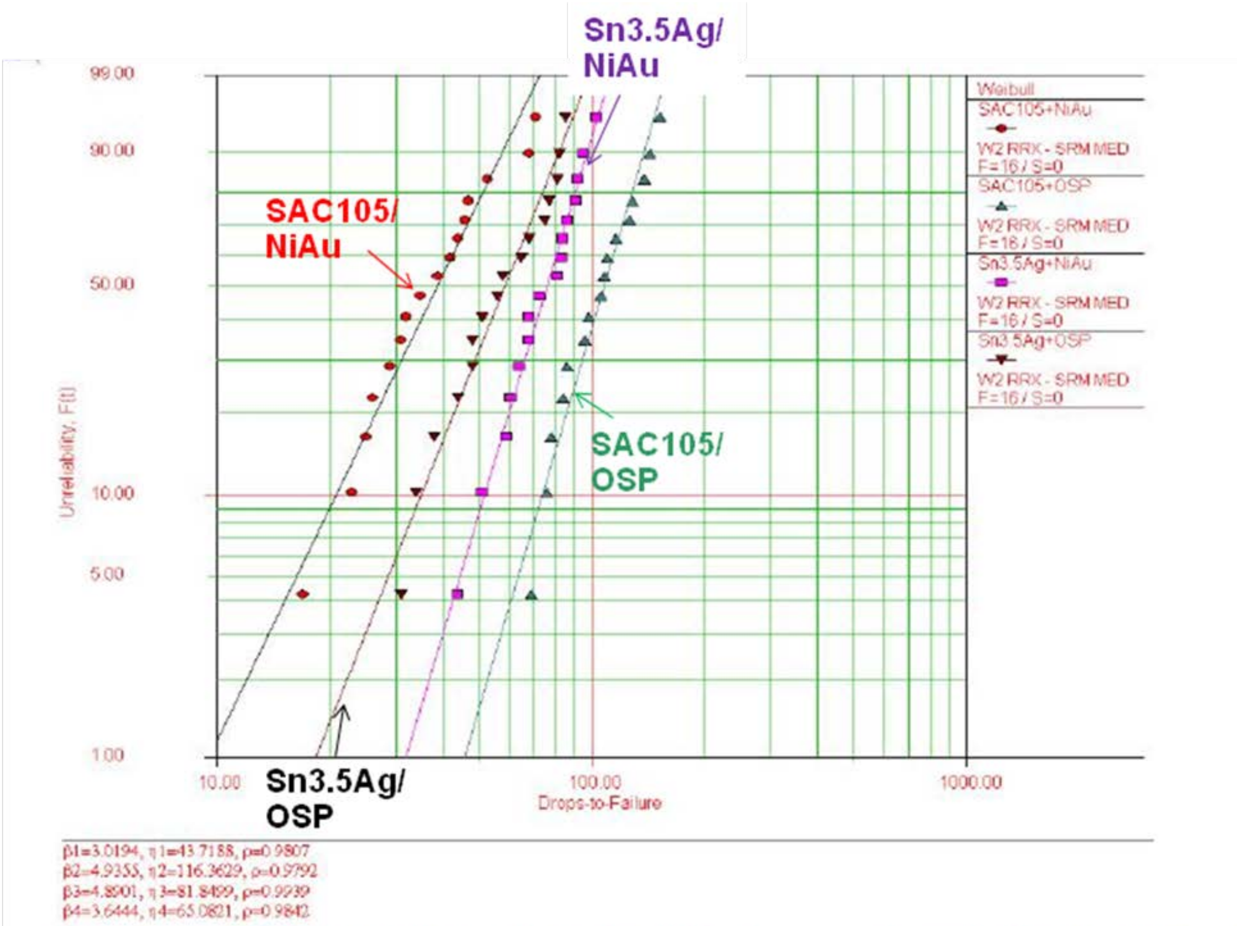


Figure 9: Mechanical shock test result summary (Weibull Failure Distribution)

Failure analysis results (including dye pry and cross-section results)

Failure analysis of the Sn1Ag0.5Cu BGA with NiAu board finish and the other board/component drop test combinations was carried out by dye-pry analysis and cross-sectioning to understand the failure locations on the soldered BGA joint. The failure analysis results were assessed in terms of visual inspection, dye and pry analysis, microstructural analysis as well as IMC thickness and composition/ morphology which are discussed in the following sections.

Visual Inspection

One board from each board surface finish/ BGA alloy composition combination was visually inspected on the outer row of the solder joints to identify any interconnect issues or other extraneous defects. No defects were found on boards with the OSP board finish, however on NiAu board surface finish test boards there were traces being pulled up along with the solder joints as shown in Figure 10. It was also noted that the NiAu board finish combination with the Sn3.5Ag BGA components exhibited greater amounts of lifted pad traces compared with the NiAu board finish with the Sn1Ag0.5Cu BGA component combination.

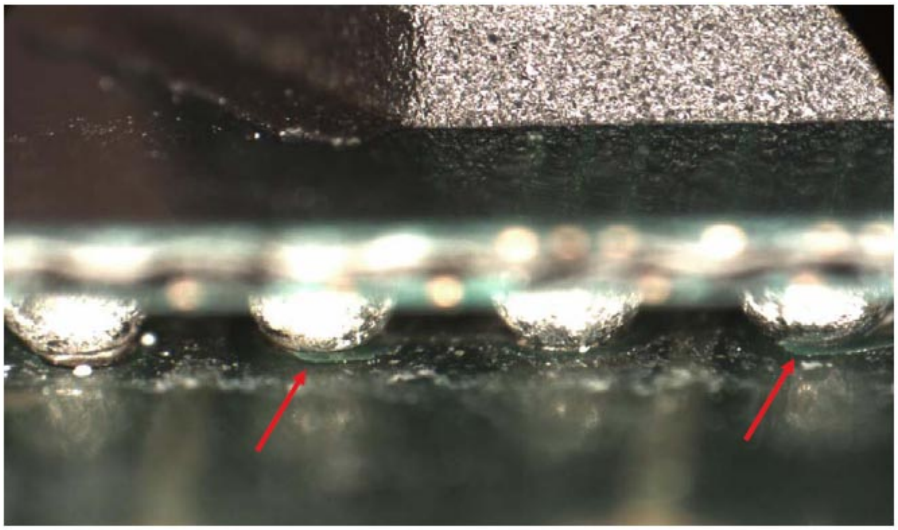


Figure 10: Lifted traces on soldered NiAu board surface finish after mechanical testing

<u>Dye and pry analysis</u>

Dye and pry analysis was performed on the number 1(#1) labeled BGA component for each of the 16 boards as shown in Figure 8. The analysis included inspection of each part's interconnection for dye penetration, taking images of each corner for each BGA on the PCB side and counting and categorizing the failed interconnects based on the corner of the BGA they occurred in. In addition images were taken of any solder joint failure occurring on the BGA side.

There were numerous failures noted with dye penetration through the PCB laminate, underneath the SMT pad. All these failures were seen in the corners or at the edges of the BGA with no failures seen in the central region of the component. The failure frequency appeared to be greatest near the inner and outer corners corner of each component as indicated in Figures 8 and 11.

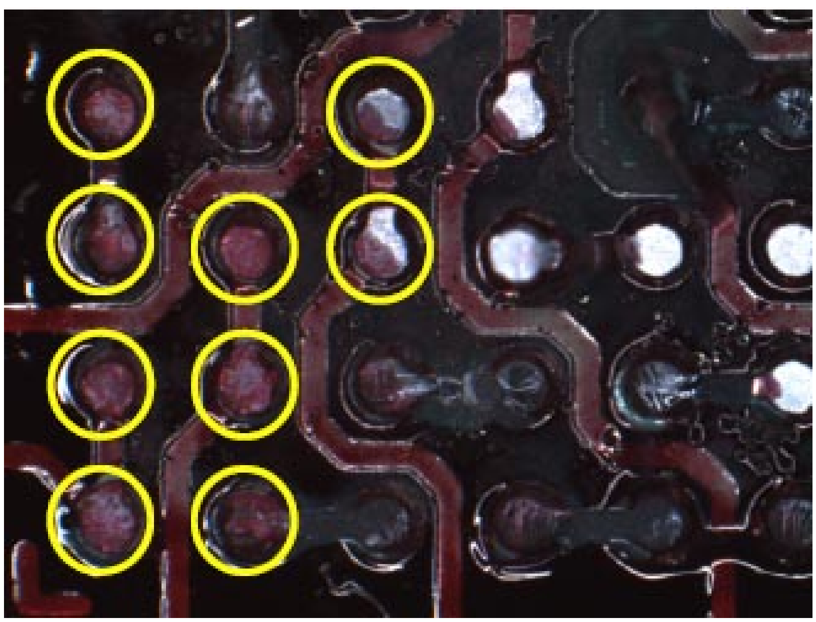


Figure 11: Sample image of dye and pry analysis with an outer corner of a BGA shown that was removed and inspected for dye penetration

The results of the dye and pry analysis on BGA component #1 from all the test boards are summarized in Table 3.

Table 3: Summary of dye and pry test results on #1 BGA component for all the mechanical test boards.

Board/ Component Part Number	Board Finish/ BGA Alloy Composition	No. of Cracks in BGA Corner 0	No. of Cracks in BGA Corner 1	No. of Cracks in BGA Corner 2	No. of Cracks in BGA Corner 3	Total Number of Cracks
01-1	OSP/ Sn1Ag0.5Cu	0	2	0	0	8
02-1		0	2	0	0	
03-1		1	0	0	0	
04-1		0	2	0	1	
05-1	OSP/ Sn3.5Ag	0	7	0	0	17
06-1		0	2	0	0	
07-1		0	5	0	1	
08-1		0	2	0	0	
09-1	NiAu/ Sn1Ag0.5Cu	0	5	0	4	45
10-1		1	6	0	2	
11-1		1	9	0	8	
12-1		0	5	0	4	
13-1	NiAu/ Sn3.5Ag	0	1	0	0	12
14-1		1	1	0	0	
15-1		2	2	0	2	
16-1		0	3	0	0	

It can be seen that interconnect failures were concentrated in the inner and outer corners of the BGA components tested, and that the NiAu board surface finish / Sn1Ag0.5Cu BGA test combination (Boards 9 through 12) was clearly the poorest performer in terms of the total number of red dye cracks observed.

<u>Microsectional analysis</u>

Cross-sections of failed BGA part #3 and BGA part #4 from Boards 1, 5, 9 and 13 (8 total cross-sections) were taken along the diagonal of the BGA as shown in Figure 12. The microsection was taken from the inner corner to the outer corner since it was known from the red dye analysis that the interconnects in these corners suffered the most severe damage.

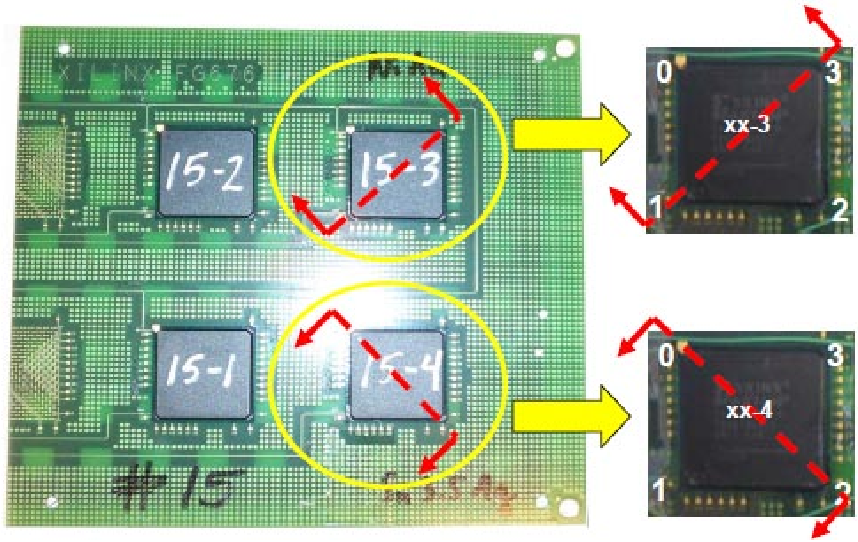


Figure 12: Cross-section instruction figures for test boards with BGA Part# 3 and Part #4

A sample cross-section shows solder joint cracking in the IMC at the board side for Board 1, BGA Part # 3 in Figure 13 for OSP board finish with Sn1Ag0.5Cu BGA. Board pad cratering is also shown for Board 1, BGA Part #3 in Figure 14.

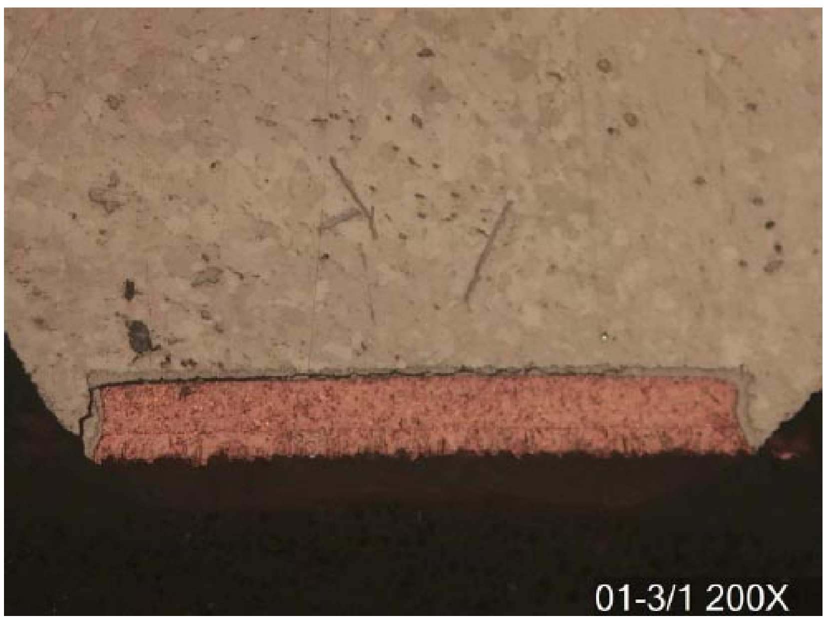


Figure 13: Sample image of a solder joint crack through the IMC at the board side for OSP board finish with Sn1Ag0.5Cu BGA (Board 1, BGA Part #3).

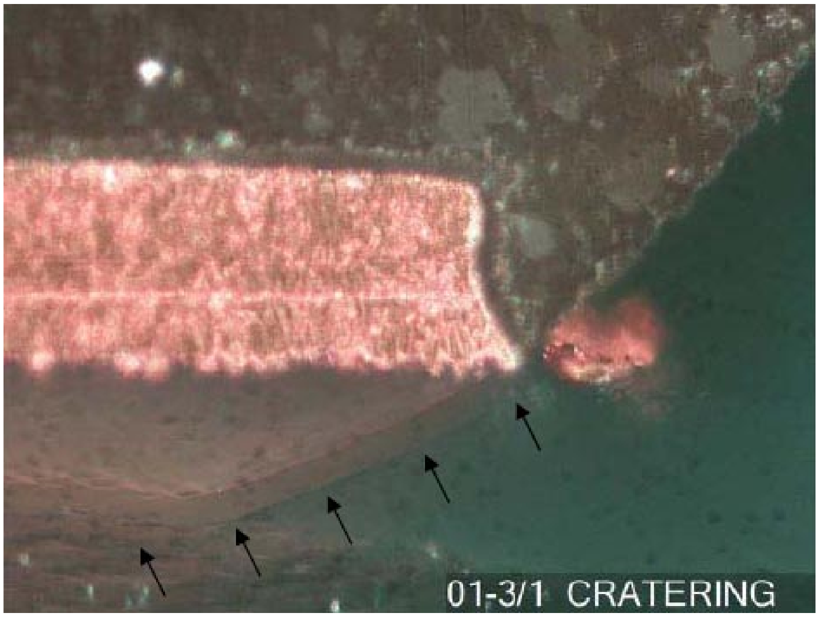


Figure 14: Sample image of laminate cratering at the edge of the interconnect. Every board had or had the initiation of pad cratering at the corners with OSP board finish and Sn1Ag0.5Cu BGA (Board 1, BGA Part #3).

The damage that was identified in the cross sections is summarized in Table 4.

Table 4: Summary of cross-section results for mechanical test boards.

Board #-BGA Part #	Board Finish/ BGA Alloy	PCB Side				Component Side			
		Solder Cracks		Laminate Cratering		Solder Cracks		Laminate Cratering	
		Inner	Outer	Inner	Outer	Inner	Outer	Inner	Outer
01-3	OSP/Sn1Ag0.5Cu	Y	N	Y	Y	N	Y	N	N
01-4	OSP/Sn1Ag0.5Cu	N	N	Y	Y	N	Y	N	N
05-3	OSP/Sn3.5Ag	Y	N	Y	Y	N	Y	N	N
05-4	OSP/Sn3.5Ag	N	N	Y	Y	N	N	N	N
09-3	NiAu/Sn1Ag0.5Cu	Y	Y	Y	Y	N	N	N	N
09-4	NiAu/Sn1Ag0.5Cu	Y	N	Y	Y	N	Y	N	N
13-3	NiAu/Sn3.5Ag	Y	N	Y	Y	N	Y	N	N
13-4	NiAu/Sn3.5Ag	N	N	Y	Y	N	Y	N	N

No laminate cratering was evident on the component side but was seen on nearly all test samples on the PCB side. Some solder joint cracking was also evident on the PCB side for the inner corners, but on the component side on the outer corners. The failure mechanisms observed were consistent with drop testing.

<u>IMC Thickness Measurement</u>

A SEM was used to capture images of the IMC on all four micro-sectioned test combinations to measure IMC thickness. The thickness was determined using the methodology illustrated in Figure 15[15].

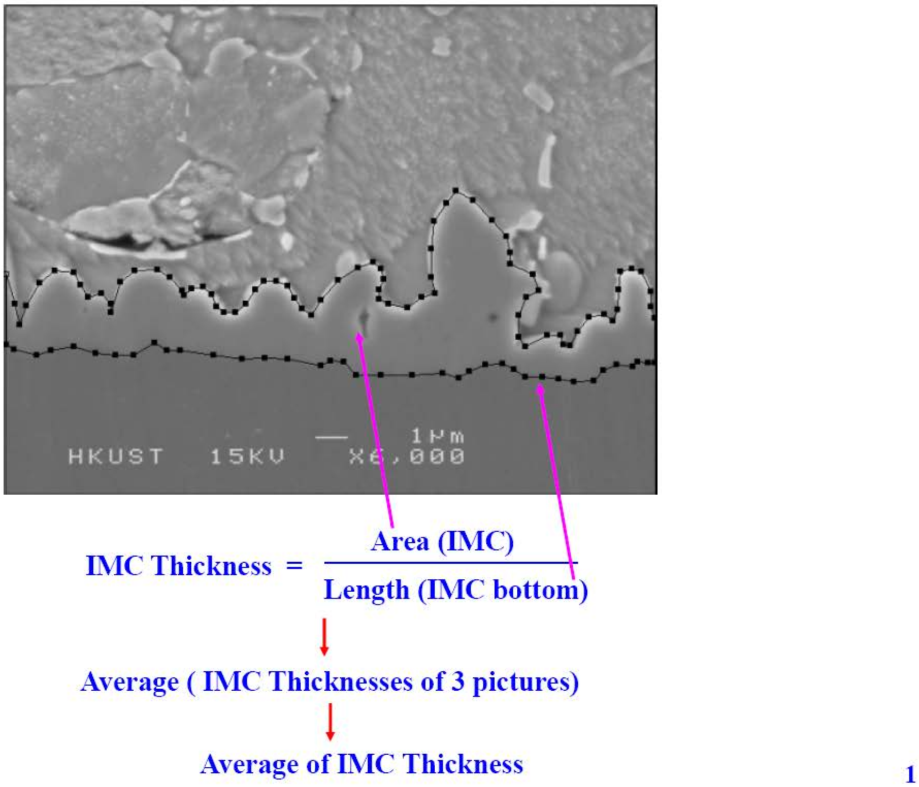


Figure 15: Method of IMC thickness measurement.

The cross-sections of the four test combinations showing the IMC thickness at the board side are shown in Figures 16 to 19.

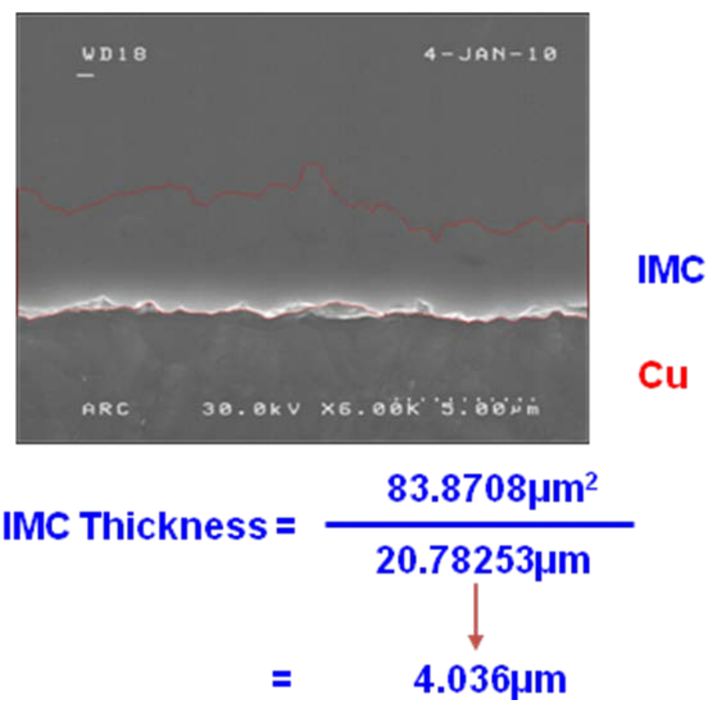
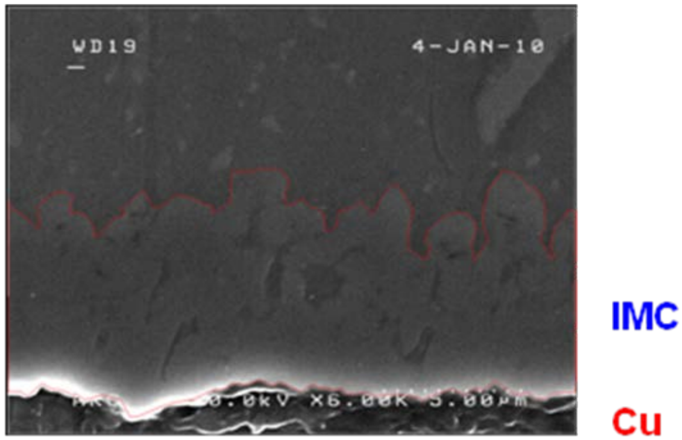


Figure 16: Cross-sectional image of OSP/ Sn1Ag0.5Cu BGA combination (Board 1-3) showing 4 microns of IMC at the board side.



$$\text{IMC Thickness} = \frac{141.9352\mu m^2}{20.828\mu m} = 6.815\mu m$$

Figure 17: Cross-sectional image of OSP/ Sn3.5Ag BGA combination (Board 5-3) showing 6.8 microns of IMC at the board side.

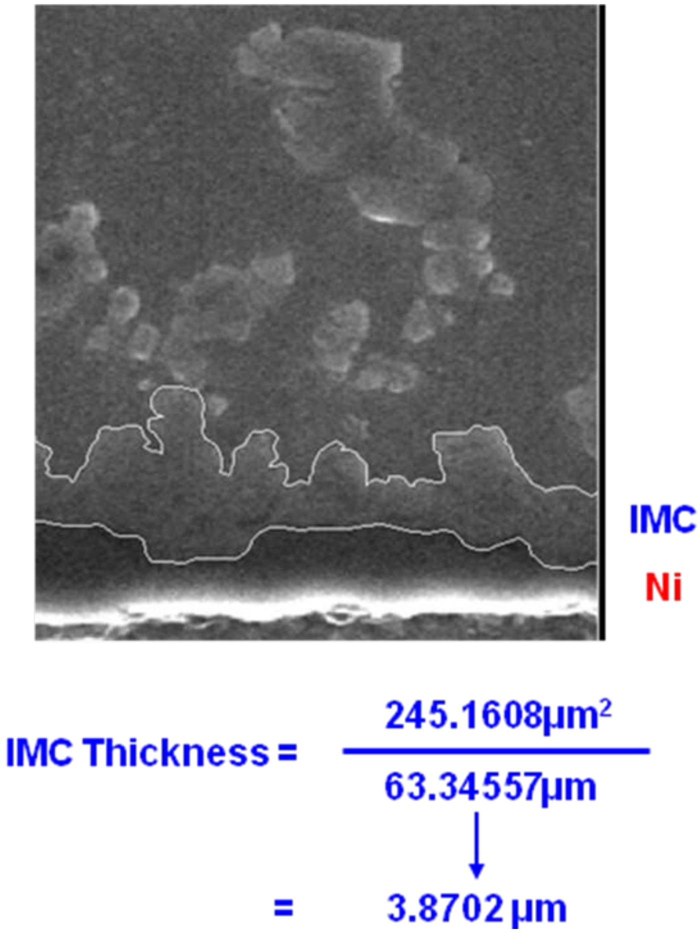


Figure 18: Cross-sectional image of NiAu/ Sn1Ag0.5Cu BGA combination (Board 9-4) showing 3.9 microns of IMC with islands of IMC formed in the bulk of the solder near to the board side.

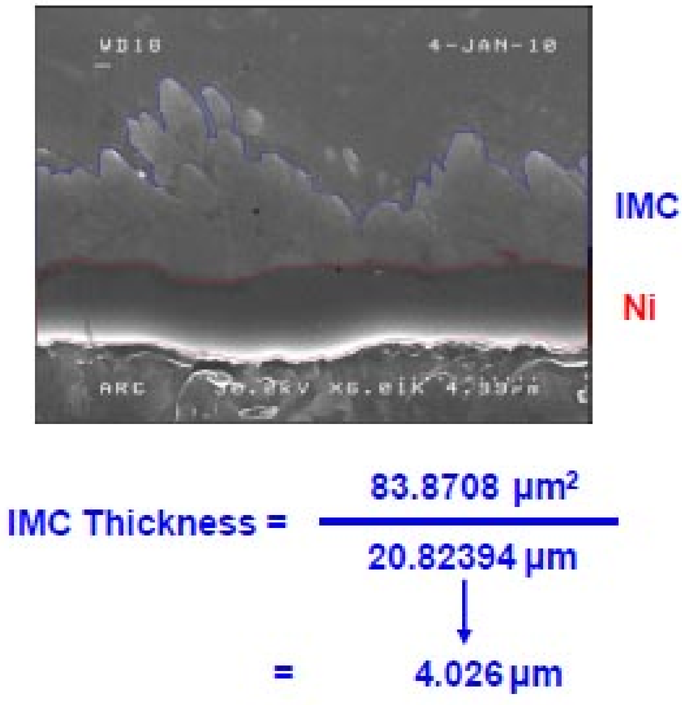


Figure 19: Cross-sectional image of NiAu/ Sn3.5Ag BGA combination (Board 13-4) showing 4 microns of IMC at the board side.

The IMC thicknesses for the two OSP board surface finish combinations varied from 4 to 6.8um with the IMC thicknesses for the two NiAu board surface finish combinations varying from 3.9 to 4 um at the board side.

IMC Morphological and Compositional analysis

The composition of the IMC at the board side was initially analyzed using an EDX in order to calculate IMC compositions for the four test combinations, however results were not sufficiently accurate. EPMA (Electron Probe Micro Analysis) was then used. Sample measurements were taken with EPMA followed by averages of the measurements which are summarized in Figure 20 with tin, copper, and nickel analyzed.

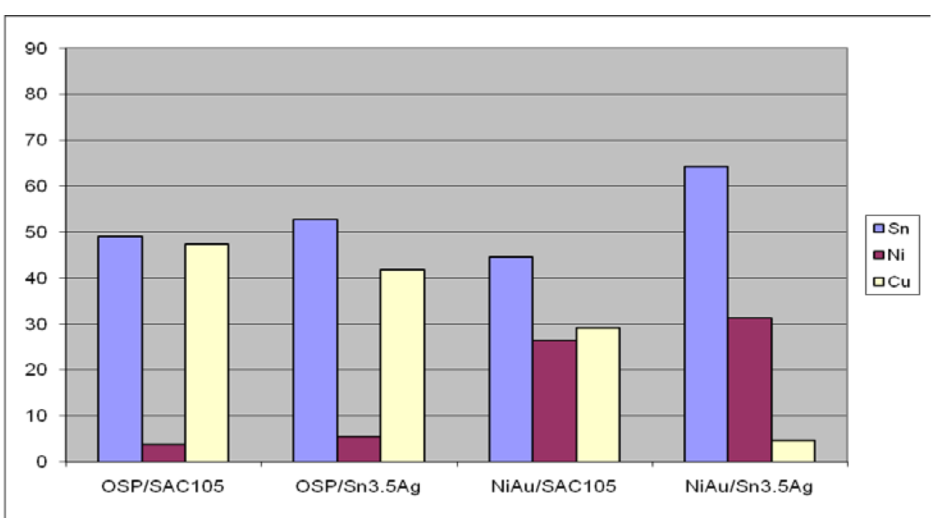


Figure 20: EPMA analysis of the IMC at the board side for the four board surface finish/ BGA alloy combinations evaluated showing tin, copper and nickel.

Based on the compositional information in Figure 20, the Cu_6Sn_5 IMC would be formed with the OSP/ Sn1Ag0.5Cu BGA and OSP/ Sn3.5Ag BGA test combinations. The NiAu/Sn3.5Ag BGA test combination would typically form Ni_3Sn_4 IMC[15,16]. For the NiAu/ Sn1Ag0.5Cu BGA combination Ni_3Sn_4 or $(Ni,Cu)_3Sn_4$ could be present in the bottom layer which was typically a thinner layer and $(Cu,Ni)_6Sn_5$ top layer could be present in the top layer of the IMC at the board side. Gold would also be present in the cross-sections from the NiAu board finish although it was not identified in the analysis.

The IMC formation for the NiAu finished test boards and SAC105 ball alloys had portions of the IMC that appeared to separate from the main IMC layer as "islands" in the bulk solder. Compositional analysis confirmed that these "islands" of IMC were identical to that in the main IMC layer next to the nickel base substrate at the board side.

The investigators of this study have not been able to identify the solder microstructural characteristics and fracture mechanisms that explain the uniquely weak mechanical shock response of the SAC105 solder on a NiAu circuit board finish; however, the IMC "islands" or "spalling" were only observed for this unique SAC105/NiAu combination. It is possible that the spalling itself is directly associated with the reduced mechanical shock strength, or perhaps it is merely an indicator that other more fundamental differences in the SAC105 BGA/NiAu board combination IMC exist, but have not been rigorously identified.

It is of interest to this study's researchers that in an unrelated investigation by the Universal Instruments AREA Consortium, involving among others SAC105 solder balls attached to a NiAu board surface finish substrate using a Sn3Ag0.5Cu(SAC305) solder paste, significant IMC spalling was observed after just a single reflow used for ball attach. The unique, independent observation of easier spalling for this material combination certainly indicates the possibility of a specific, unidentified IMC microstructural characteristic associated with the 62% reduction in SAC105/NiAu mechanical shock strength compared to SAC105/OSP in the current study.

For simple comparison, the Universal Instruments AREA Consortium provided selected micrographs of observed spalling for Sn1Ag0.5Cu ball spheres attached on NiAu board finish with Sn3Ag0.5Cu paste which are shown in Figures 21 and 22.

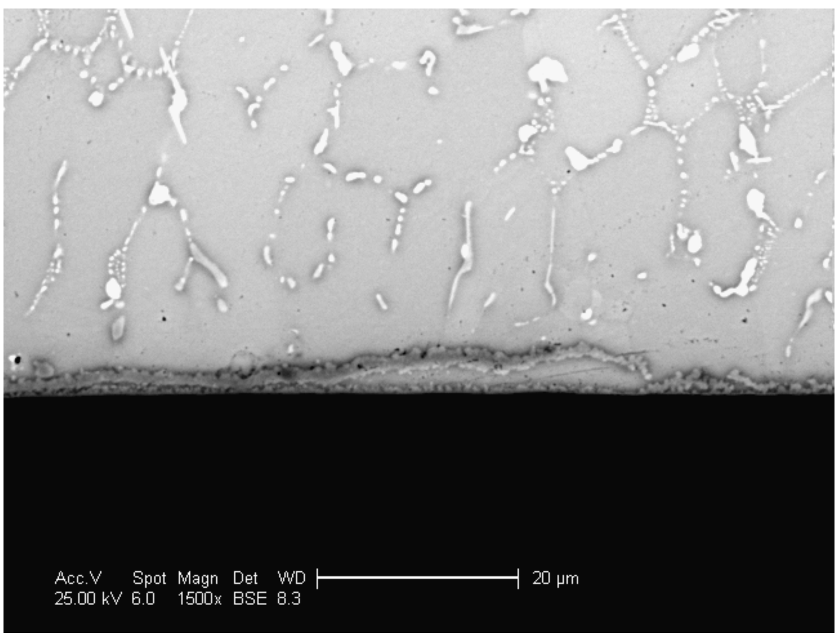


Figure 21: Sn1Ag0.5Cu ball sphere on Electrolytic NiAu attached with Sn3Ag0.5Cu paste showing spalling. Thin Bottom Layer of Ni_3Sn_4 at Ni interface with a top layer of $(Cu,Ni)_6Sn_5$: Ag_3Sn needles in the bulk solder. [Courtesy: Universal Instruments AREA Consortium]

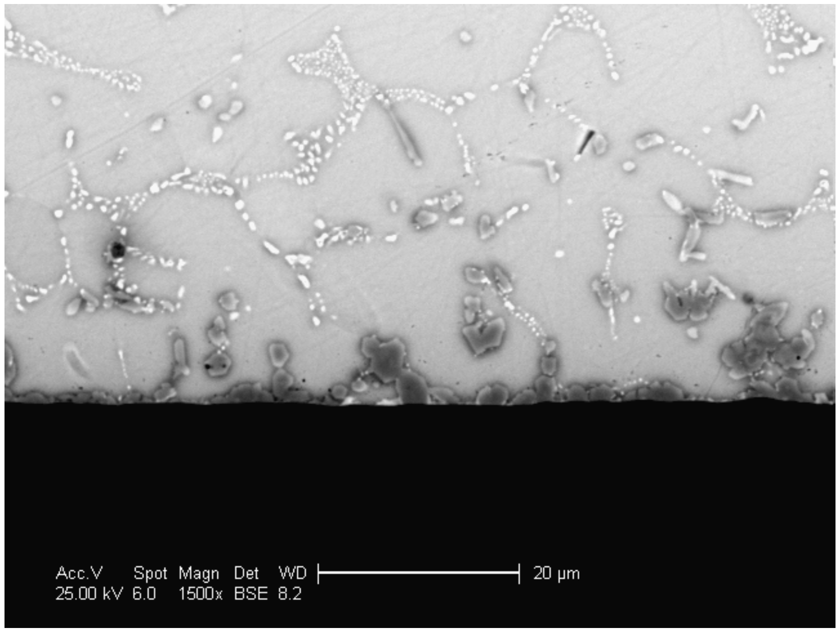


Figure 22: Sn1Ag0.5Cu ball sphere on Electroless Ni Immersion Au (ENIG) attached with Sn3Ag0.5Cu paste showing spalling. [Courtesy: Universal Instruments AREA Consortium]

As already mentioned the microstructure could have an effect on the drop test results with the SAC105 BGA sphere with NiAu board finish combination showing spalling of the IMC into the bulk solder joint compared with the Sn3.5Ag BGA sphere/ NiAu board finish combination and the other combinations tested.

Conclusions

Mechanical shock testing of four board surface finish/ BGA alloy type combinations showed that consistent with expectations, the Sn1Ag0.5Cu BGA with OSP board finish was the best performing; however, the Sn1Ag0.5Cu BGA with NiAu board finish performed the worst, surprisingly, of all test combinations. The two board surface finishes, OSP and NiAu, tested with the Sn3.5Ag BGA components yielded similar mechanical shock results, with lifetime results falling between the worst (NiAu/Sn1Ag0.5Cu) and best (OSP/Sn1Ag0.5Cu) combinations. Drop test results for Sn1Ag0.5Cu were highly sensitive to PWB surface finish, while Sn3.5Ag results were only moderately sensitive to board finish.

The drop test failure modes that were inspected with micro-sectioning, dye and pry analysis, and visual inspection were all consistent. The dye and pry analysis further brought to light that the greatest amount of damage of all the test combinations was the SAC105 BGA ball alloys with the NiAu board pad finish.

The BGA packages manufactured with SAC105 component spheres and attached to the NiAu board surface finish exhibited several unique behaviors:

1. 33-62% lower mechanical shock lifetime than the other sample configurations.
2. 260-560% greater incidence of corner interconnect fractures than the other sample configurations.
3. Only sample configuration that showed spalling at the board-side IMC.

The morphology of the IMC in the SAC105/NiAu test combination may have an effect on the poor performance of this test combination. The spalling effect forms large "islands" of IMC in the bulk solder region but close to the IMC layer on the board side. Test results from this study suggest a potential direct or indirect link between the observed IMC spalling in the SAC105/NiAu samples and reduced mechanical shock lifetime, but the specific failure mechanism has not yet been identified and requires additional investigation.

For applications in which mechanical shock lifetime is critical, such as handheld electronic devices, the limited test results suggest that SAC105 solder balls should not be used in conjunction with a NiAu plated circuit board due to the reduced mechanical drop performance.

Future Work

As already indicated additional work would need to be done on mechanical shock testing of NiAu board finish with Sn1Ag0.5Cu BGA components to understand the mechanical drop performance more as well as a more detailed investigation of the IMC morphology and related spalling effect and formation for the board surface finish/BGA component combination.

Acknowledgements
The authors would like to acknowledge Xilinx who provided components and boards for this work. The authors also gratefully acknowledge the input provided into the IMC spalling affect and mechanical drop test results by various persons and organizations.

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Mechanical Shock Test Performance of SAC105 (Sn-1.0Ag-0.5Cu) and Sn-3.5Ag, BGA Components with SAC305 Solder Paste on NiAu and OSP Board Surface Finishes

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[1]Bath Technical Consultancy, [2]Motorola, [3]Oracle, [4]Hewlett-Packard Co., [5]Flextronics, [6]Altera, [7]Amkor, [8]Cisco Systems, [9]Hong Kong University of Science and Technology

Agenda

- Introduction
- Experimental
- Results and Discussion
- Conclusions
- Future Work
- Acknowledgements

Introduction

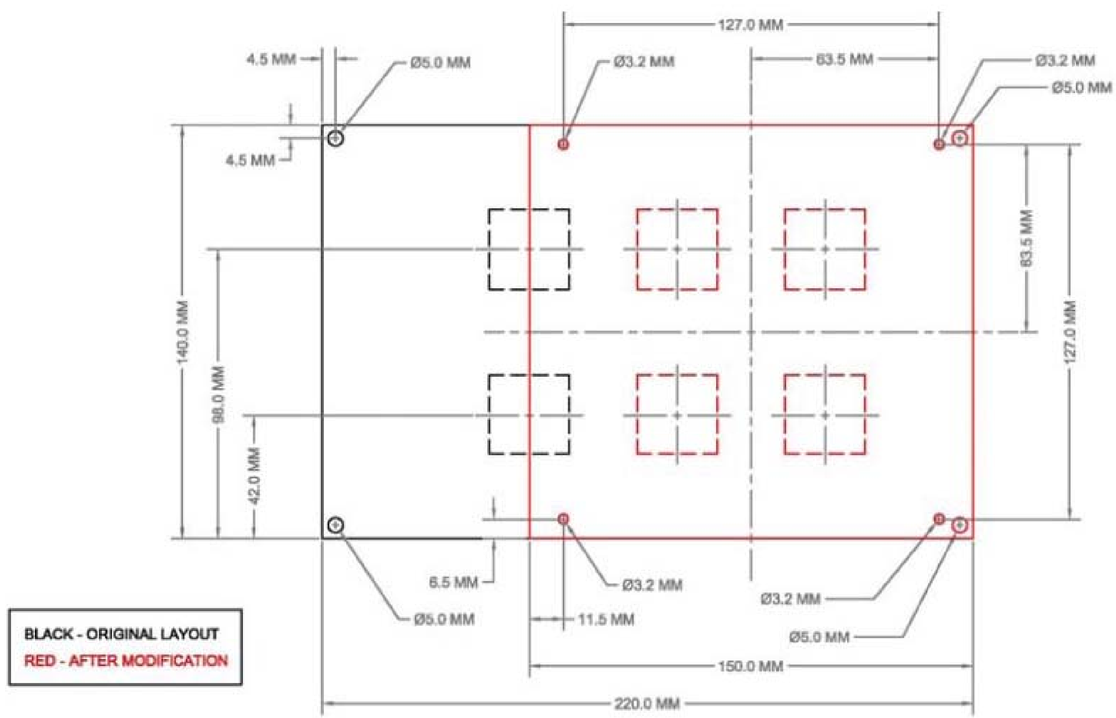
- There has been an increase in the shipment of lead-free BGA/CSP components with alloy compositions which are not Sn3Ag0.5Cu.
  - Smaller CSP components have centered around Sn1Ag0.5Cu due to improved mechanical drop test performance for consumer electronics.
  - Larger BGA components, there have been studies on use of Sn3.5Ag BGA components to reduce missing balls during test and shipment.
- Although many studies looking at drop test performance of Sn1Ag0.5Cu CSP components, limited published studies on interaction of different board surface finishes on mechanical shock test performance for Sn1Ag0.5Cu and Sn3.5Ag BGAs.
- This was the aim of this work.

Experimental

- Mechanical testing performed on Sn3.5Ag and Sn1Ag0.5Cu 676 PBGA components with 1mm pitch and electrolytic Ni/Au finished component pads.
- Components were soldered with Type 3 Sn3Ag0.5Cu no-clean solder paste
- Board finish was either electrolytic Ni/Au or high temperature rated OSP board surface finish.

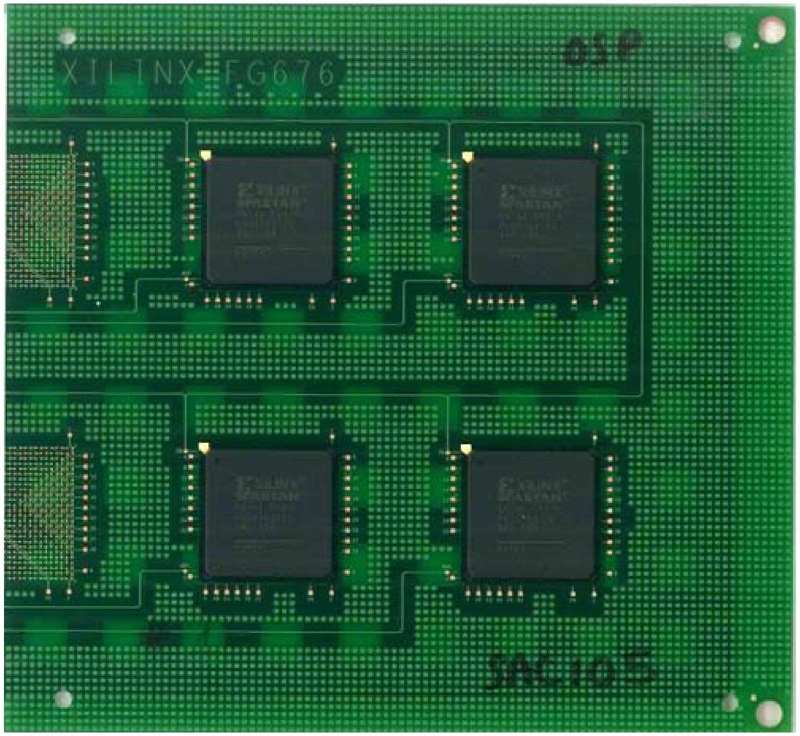
Experimental

- The test board and components used were the same as those used in previous evaluations but the original test board was modified yielding a drop test board with 4 BGA package sites.
  - This modification was done to obtain symmetry during mechanical shock testing.



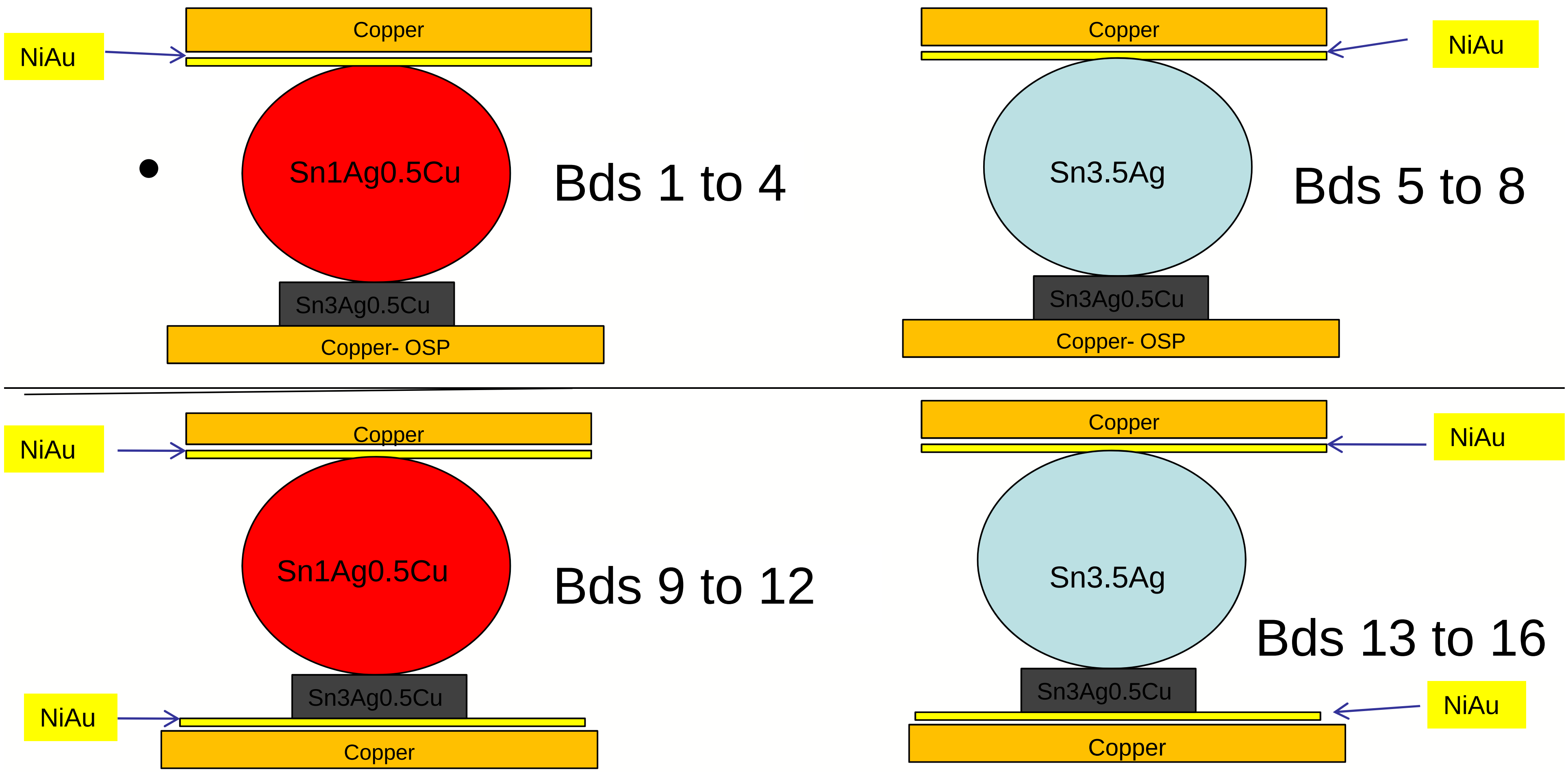
Build plan:16 boards were built with Sn3Ag0.5Cu solder paste for mechanical testing

Board No.	Board S.F	Component Type
1	OSP	SAC105
2	OSP	SAC105
3	OSP	SAC105
4	OSP	SAC105
5	OSP	Sn3.5Ag
6	OSP	Sn3.5Ag
7	OSP	Sn3.5Ag
8	OSP	Sn3.5Ag
9	NiAu	SAC105
10	NiAu	SAC105
11	NiAu	SAC105
12	NiAu	SAC105
13	NiAu	Sn3.5Ag
14	NiAu	Sn3.5Ag
15	NiAu	Sn3.5Ag
16	NiAu	Sn3.5Ag



Note: Component Side Surface Finish was NiAu in all cases

Different component/board combinations tested



Reflow Profile

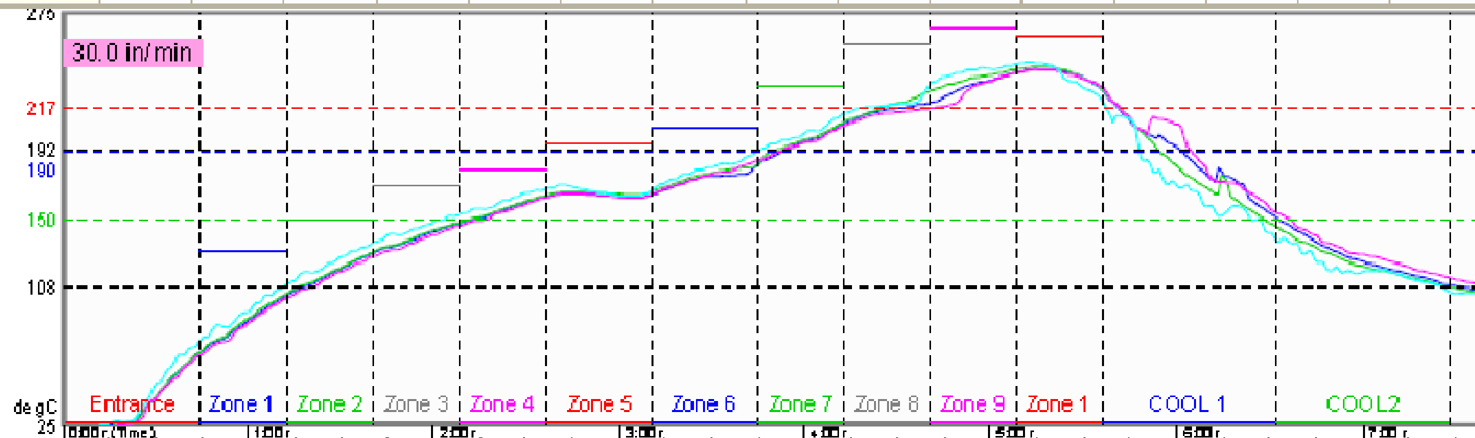
Solder Joint Peak Temp.= 240- 242ºC, Time over 217ºC = 60-77 sec.

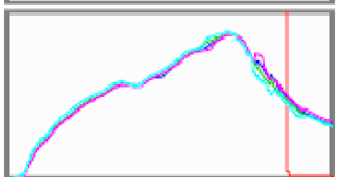
M.O.L.E.(r) STATUS
Max Internal T: 41C
Battery: 5.010
Points: 460
Active: X23460
Interval: 00:00:01.0
Date: 07/08/09
Time: 10:02:52 V09.02

Tool status box

XILINX
Verify Profile for ATGroup
L4 SCMC-68
Profile XILINX_FG676_SJ38D
Rail Reflow

	Entrance	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8	Zone 9	Zone 10	COOL 1	COOL2
Length (in)	22	14	14	14	14	17	17	14	14	14	14	28	28
Top (degC)	0	130	150	170	180	195	205	230	245	265	260	27	27
Bottom (degC)	0	130	150	170	180	195	205	230	245	265	260	27	27
Predict(degC)	0	130	150	170	180	195	205	230	245	265	260	27	27
Conveyor (in/min)	30	Predict	30										





Auto Show Lag

T Above Ref	Low = 150	Med = 190	Hi = 217	Cure Factor	Units
Sensor 1 BGA comp					
Sensor 2 BGA comp	00:04:20	00:02:10	00:01:09	0%	Time
Sensor 3 BGA comp	00:04:16	00:02:07	00:01:17	0%	Time
Sensor 4 BGA corner	00:04:19	00:02:15	00:01:00	0%	Time
Sensor 5 BGA pad	00:04:21	00:02:04	00:01:18	0%	Time

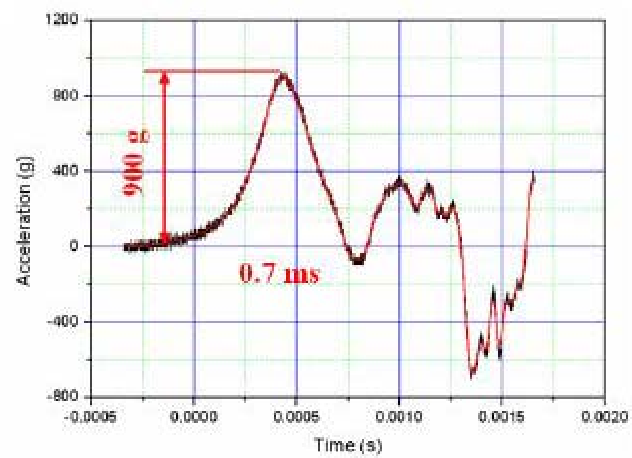
Zone Slopes	Entrance	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8	Zone 9	Zone 10	COOL 1	COOL2
Sensor 1 BGA comp													
Sensor 2 BGA comp	1.1	1.2	0.9	0.7	0.6	0.0	0.5	0.9	0.5	0.6	-0.4	-1.4	-0.7
Sensor 3 BGA comp	1.1	1.3	0.9	0.7	0.6	0.1	0.4	1.0	0.7	0.5	-0.5	-1.5	-0.7
Sensor 4 BGA corner	1.0	1.2	0.9	0.7	0.6	0.1	0.6	0.8	0.4	0.8	-0.3	-1.3	-0.7
Sensor 5 BGA pad	1.2	1.2	0.9	0.6	0.6	-0.0	0.7	0.8	0.6	0.4	-0.8	-1.5	-0.5

Summary Stats	Peak	Minimum	Max (+)Slope	Max (-)Slope	Time Above 217C	Time 150-190C	217C / Peak	Peak \ 217C
Sensor 1 BGA comp								
Sensor 2 BGA comp	240.6	22.2	2.16	-2.10	69.0	98.0	0.56	-0.90
Sensor 3 BGA comp	241.7	21.7	2.35	-2.28	77.0	96.0	0.51	-1.11
Sensor 4 BGA corner	240.0	21.7	2.35	-3.21	60.0	92.0	0.73	-1.08
Sensor 5 BGA pad	244.4	21.7	2.78	-3.70	78.0	100.0	0.52	-1.18
Range	4.4	0.5	0.62	1.60	18.0	8.0	0.00	0.00

Mechanical Testing Equipment used at HKUST

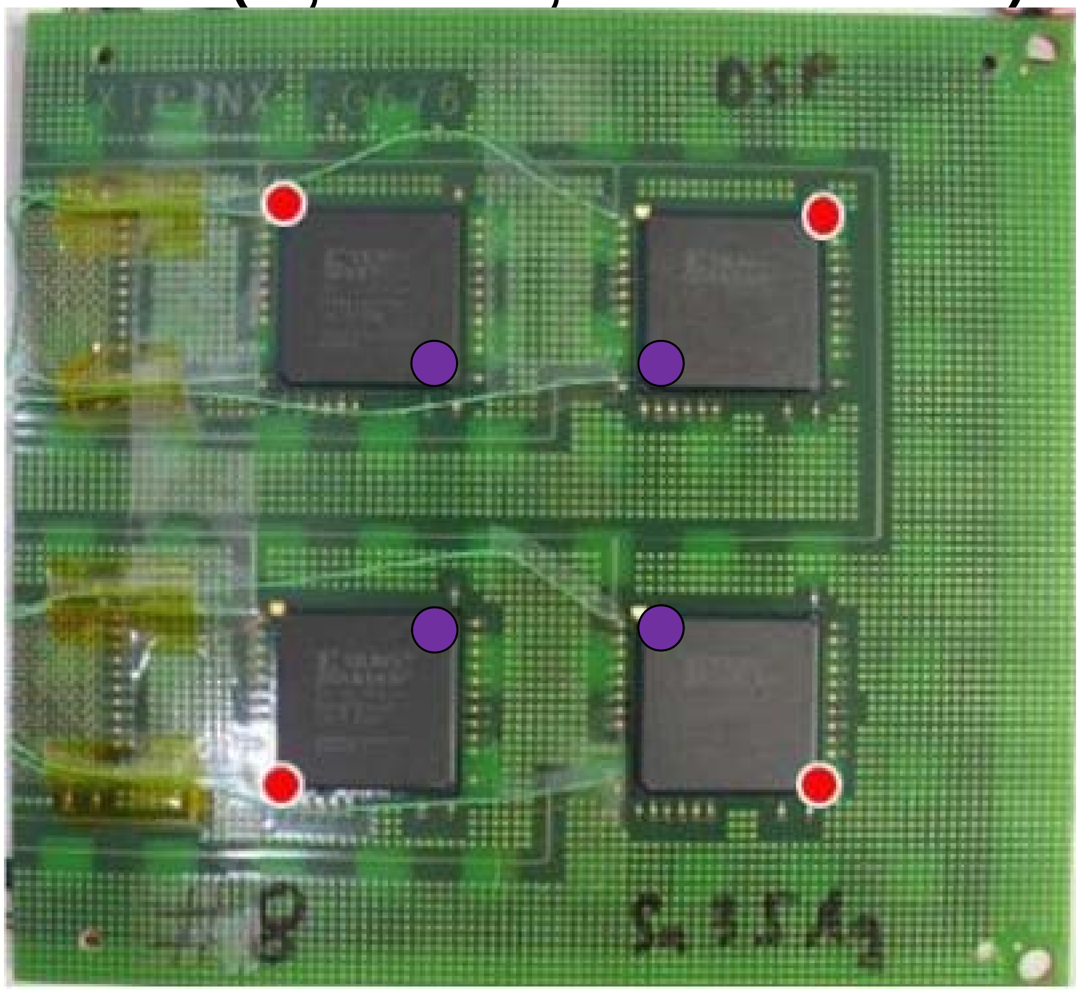
Drop Tester and Oscilloscope

Drop Fixture



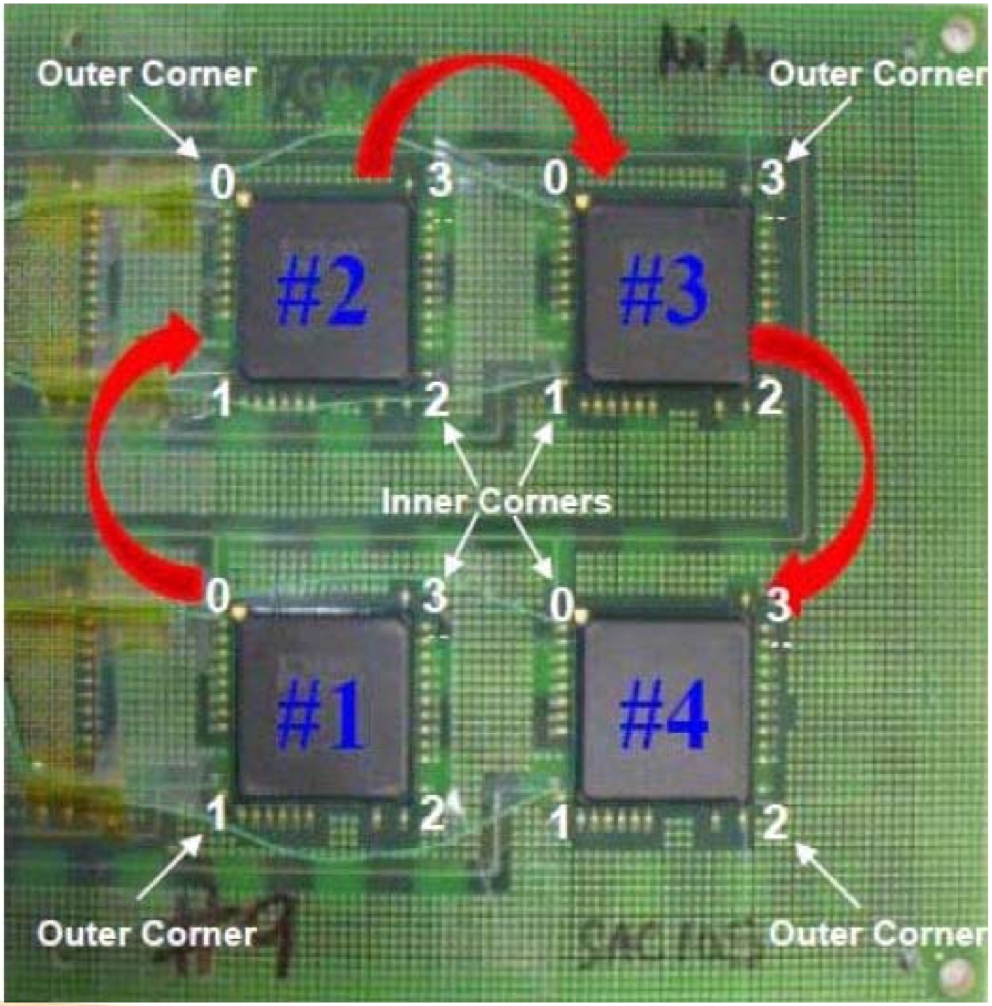
Drop Condition (900G+0.7ms)

Highest solder joint strain locations (•) during mechanical shock (1,800-2,000 uStrain)



● Inner corner strains = 1,130-1,280 uStrain

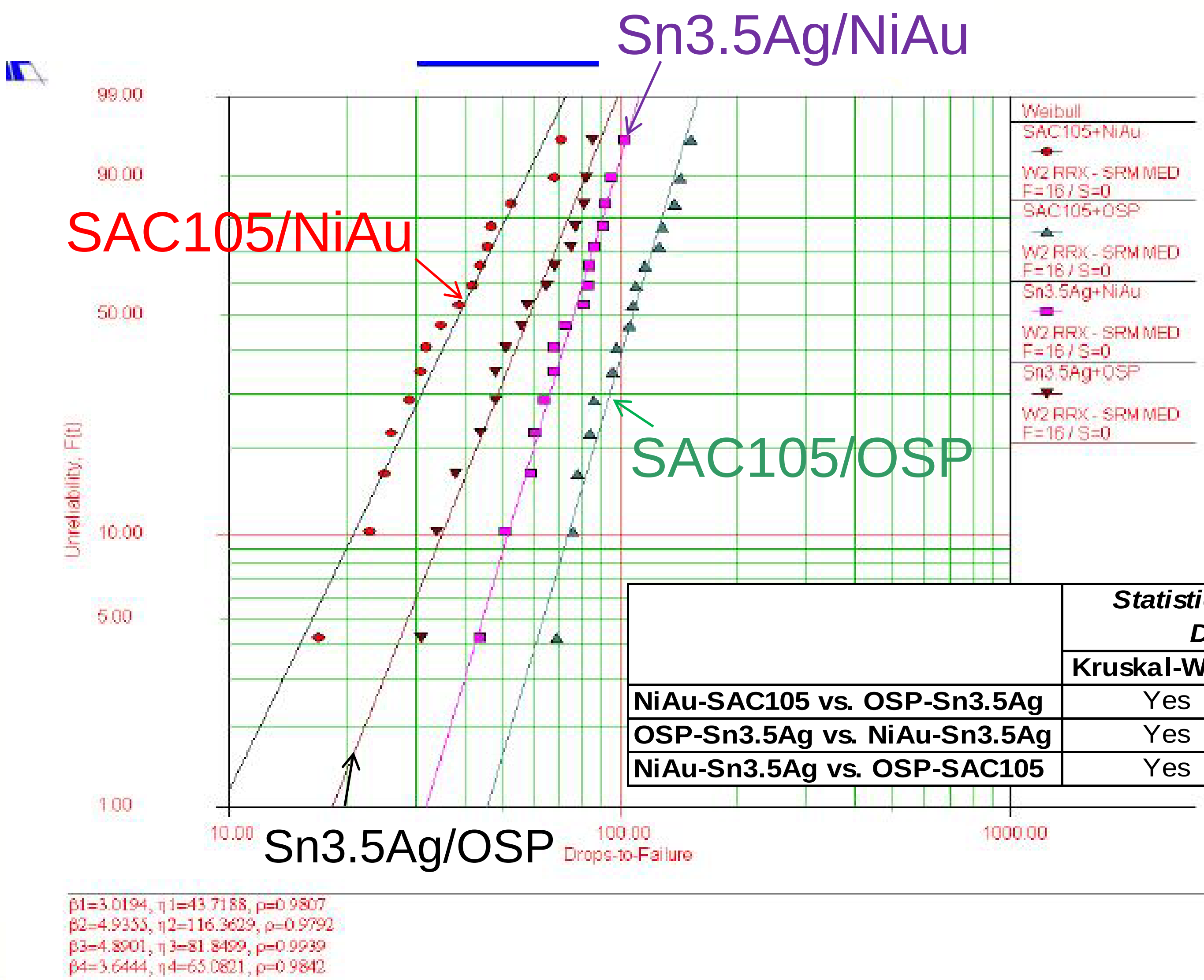
BGA Component Package Labeling for Mechanical Testing



Mechanical Testing Raw Data (Solder Paste: Sn3Ag0.5Cu, Component Side Surface Finish: NiAu in all cases)

Board Number	Board Surface Finish	BGA Component Sphere Alloy	Component Package #1 Drops to Fail	Component Package #2 Drops to Fail	Component Package #3 Drops to Fail	Component Package #4 Drops to Fail
1	OSP	Sn1Ag0.5Cu	108	98	152	128
2			78	86	126	69
3			84	96	116	143
4			106	138	76	110
5	OSP	Sn3.5Ag	38	68	75	48
6			85	81	34	65
7			51	82	56	77
8			58	48	44	31
9	NiAu	Sn1Ag0.5Cu	26	32	23	42
10			35	46	53	47
11			25	17	44	68
12			71	29	39	31
13	NiAu	Sn3.5Ag	92	64	73	81
14			59	83	44	68
15			95	84	68	51
16			61	103	91	86

Weibull Plot from Mechanical Testing

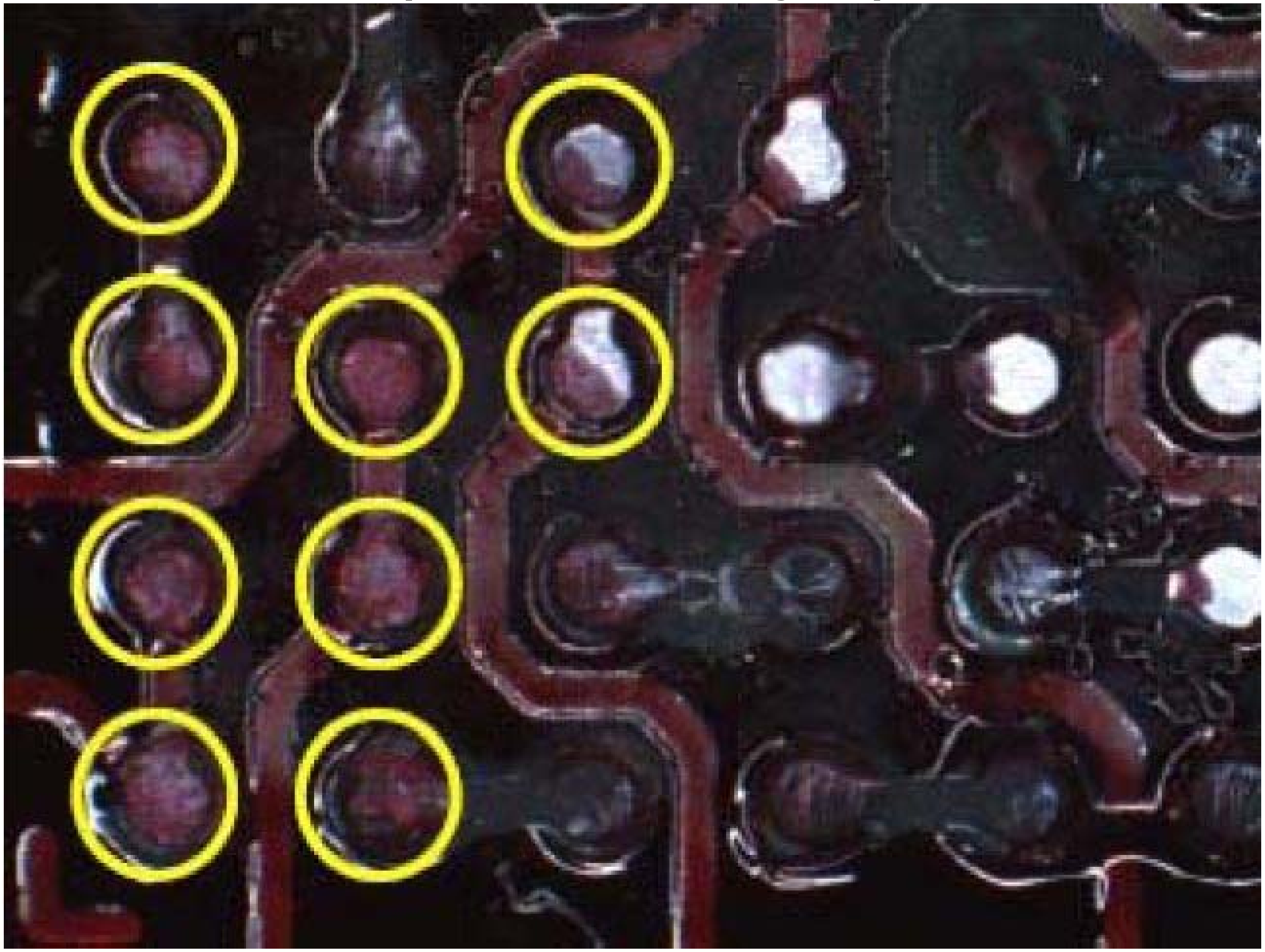


	Statistically Significant Difference?	
	Kruskal-Wallis	**Mood-Median**
NiAu-SAC105 vs. OSP-Sn3.5Ag	Yes	Yes
OSP-Sn3.5Ag vs. NiAu-Sn3.5Ag	Yes	No
NiAu-Sn3.5Ag vs. OSP-SAC105	Yes	Yes

Mechanical test results

- There is more sensitivity for the SAC105 BGA alloy composition to board surface finish relative to Sn3.5Ag BGA alloy composition based on the mechanical test results
- The NiAu/SAC105 test cell shows poor mechanical performance compared with NiAu/Sn3.5Ag which is not typically to be expected.
- SAC105/ NiAu reduced mechanical performance vs. SAC105/ OSP
- Visual inspection, dye-pry and cross-sections was performed on the failed samples.

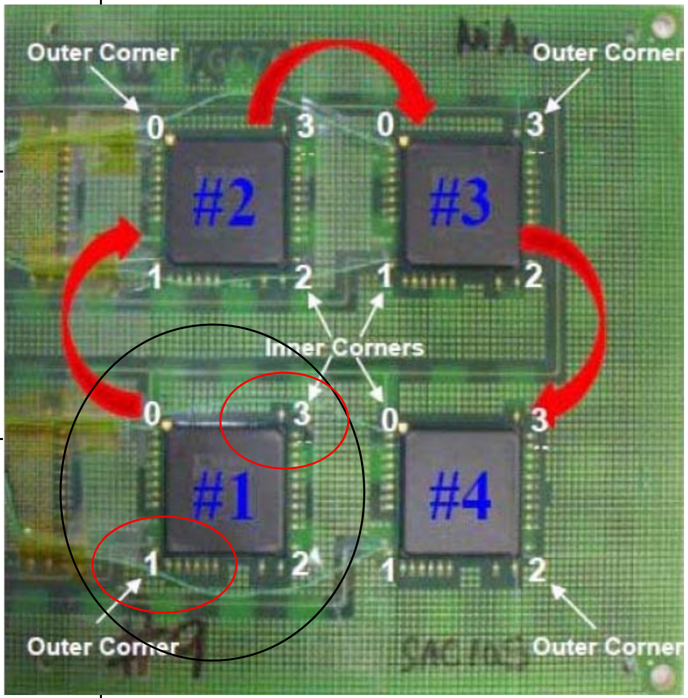
Sample image of dye and pry analysis with an outer corner of a BGA shown that was removed and inspected for dye penetration



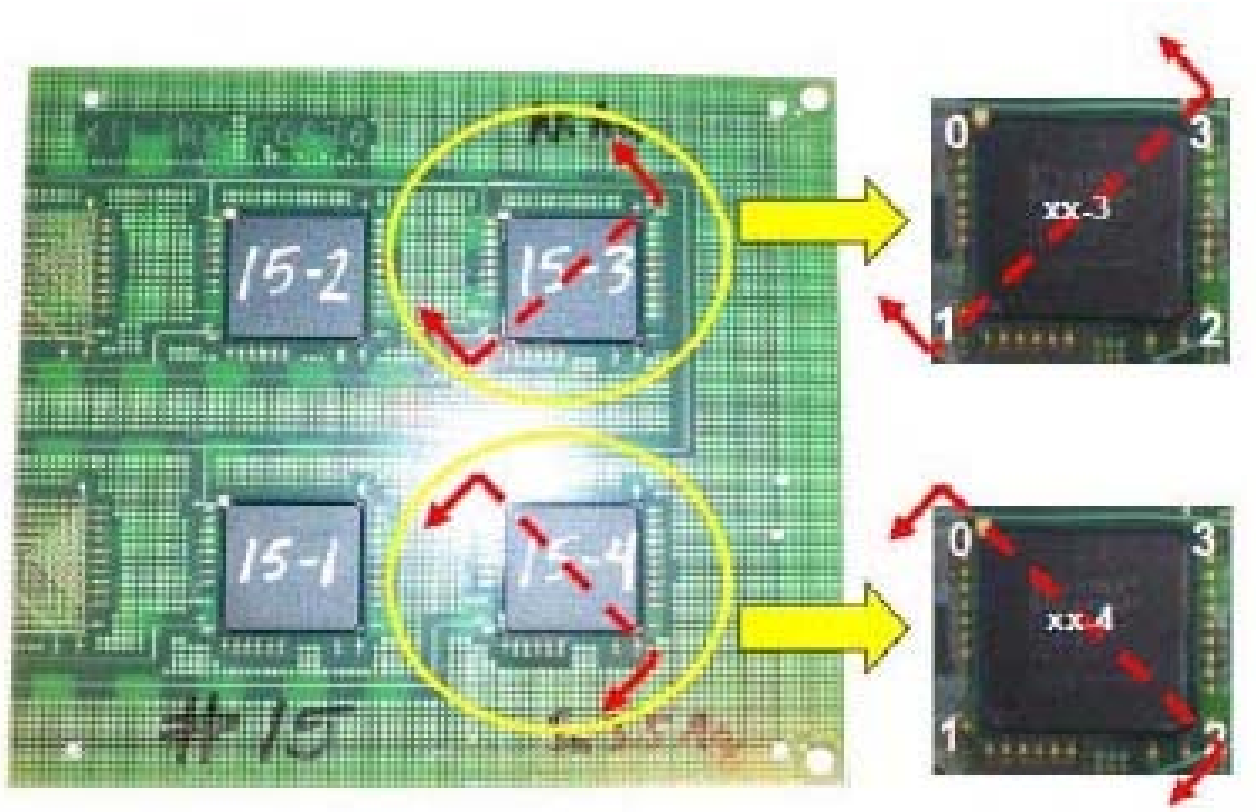
Example of board side solder joint cracks

Red Dye Solder Joint Crack Results after Mechanical Testing for Part # 1 on Boards 1-16

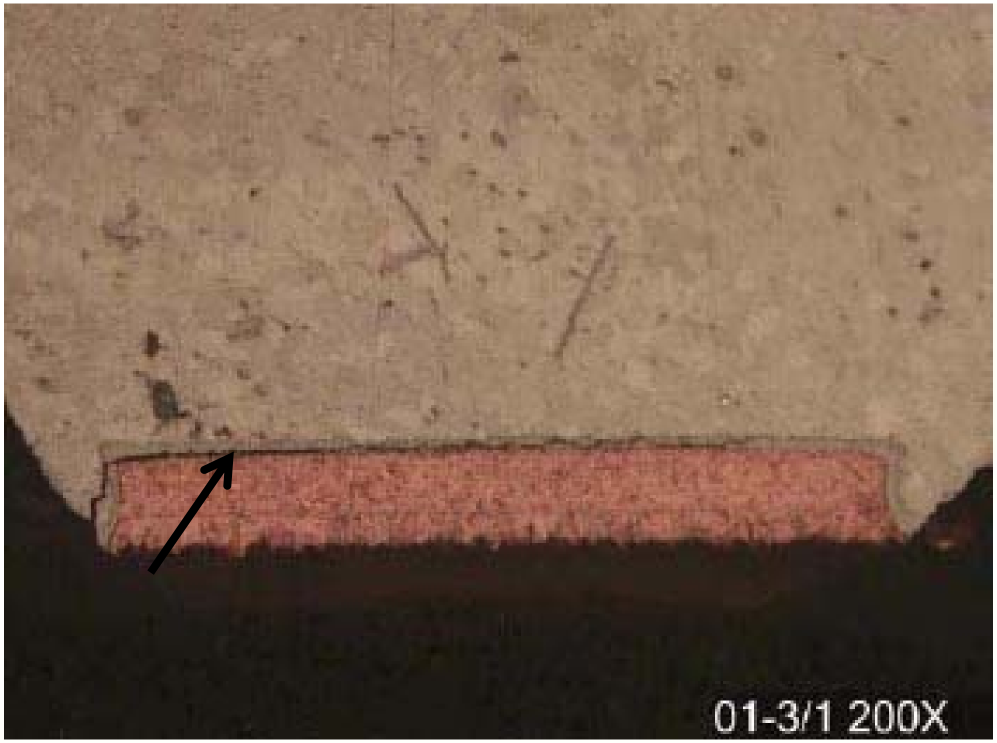
Board/ Component Part Number	Board Finish/ BGA Alloy Composition	No. of Cracks in BGA Corner 0	No. of Cracks in BGA Corner 1	No. of Cracks in BGA Corner 2	No. of Cracks in BGA Corner 3	Total Number of Cracks
01-1	OSP/ Sn1Ag0.5Cu	0	2	0	0	8
02-1		0	2	0	0	
03-1		1	0	0	0	
04-1		0	2	0	1	
05-1	OSP/ Sn3.5Ag	0	7	0	0	17
06-1		0	2	0	0	
07-1		0	5	0	1	
08-1		0	2	0	0	
09-1	NiAu/ Sn1Ag0.5Cu	0	5	0	4	45
10-1		1	6	0	2	
11-1		1	9	0	8	
12-1		0	5	0	4	
13-1	NiAu/ Sn3.5Ag	0	1	0	0	12
14-1		1	1	0	0	
15-1		2	2	0	2	
16-1		0	3	0	0	



Cross-section instruction figures for test boards with BGA Part# 3 and Part #4



Sample image of a solder joint crack through the IMC at the board side for OSP board finish with Sn1Ag0.5Cu BGA (Board 1, BGA Part #3).



Sample image of laminate cratering at the edge of the interconnect. (Board 1, BGA Part #3 Sn1Ag0.5Cu / OSP).

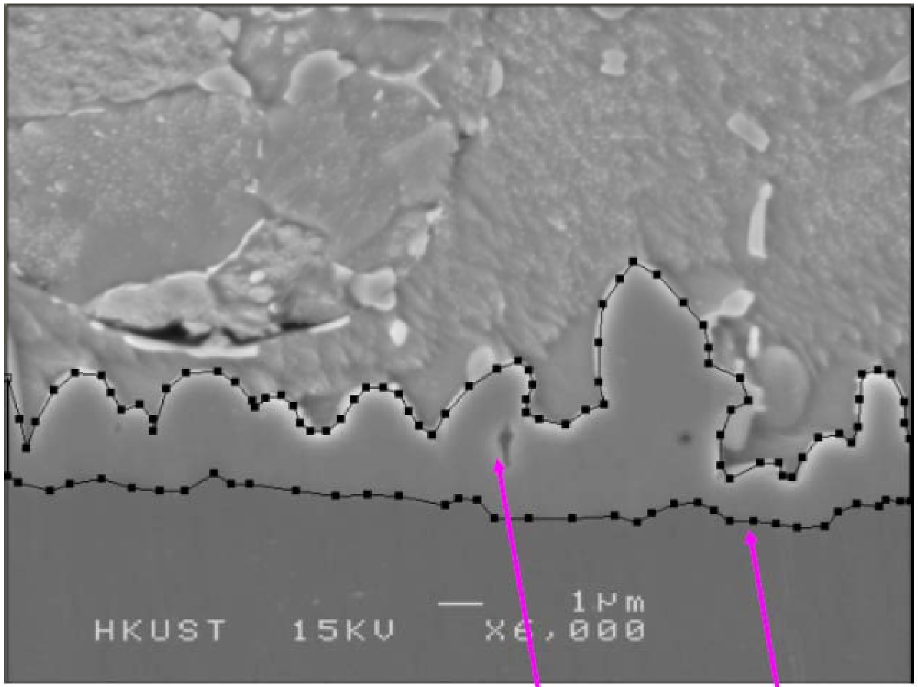
Note: Every board had pad cratering or the initiation of it

Cross-section Results for Mechanical Test Boards

Board #-BGA Part #	Board Finish/ BGA Alloy	PCB Side				Component Side			
		Solder Cracks		Laminate Cratering		Solder Cracks		Laminate Cratering	
		Inner	Outer	Inner	Outer	Inner	Outer	Inner	Outer
01-3	OSP/Sn1Ag0.5Cu	Y	N	Y	Y	N	Y	N	N
01-4	OSP/Sn1Ag0.5Cu	N	N	Y	Y	N	Y	N	N
05-3	OSP/Sn3.5Ag	Y	N	Y	Y	N	Y	N	N
05-4	OSP/Sn3.5Ag	N	N	Y	Y	N	N	N	N
09-3	NiAu/Sn1Ag0.5Cu	Y	Y	Y	Y	N	N	N	N
09-4	NiAu/Sn1Ag0.5Cu	Y	N	Y	Y	N	Y	N	N
13-3	NiAu/Sn3.5Ag	Y	N	Y	Y	N	Y	N	N
13-4	NiAu/Sn3.5Ag	N	N	Y	Y	N	Y	N	N

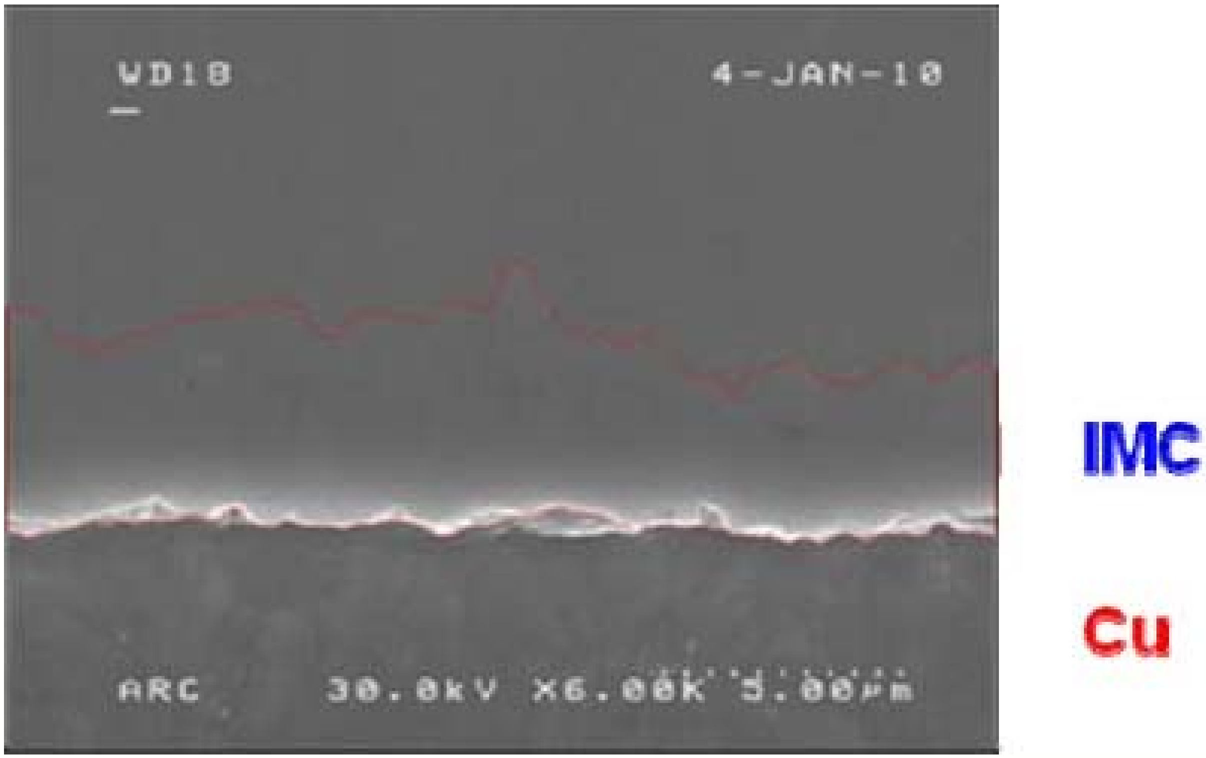
Pad Cratering was evident on all boards.
Solder Joint cracking, where it did occur, was more pronounced with the NiAu/Sn1Ag0.5Cu test cell at PCB side.

The Method of IMC Thickness Measurement

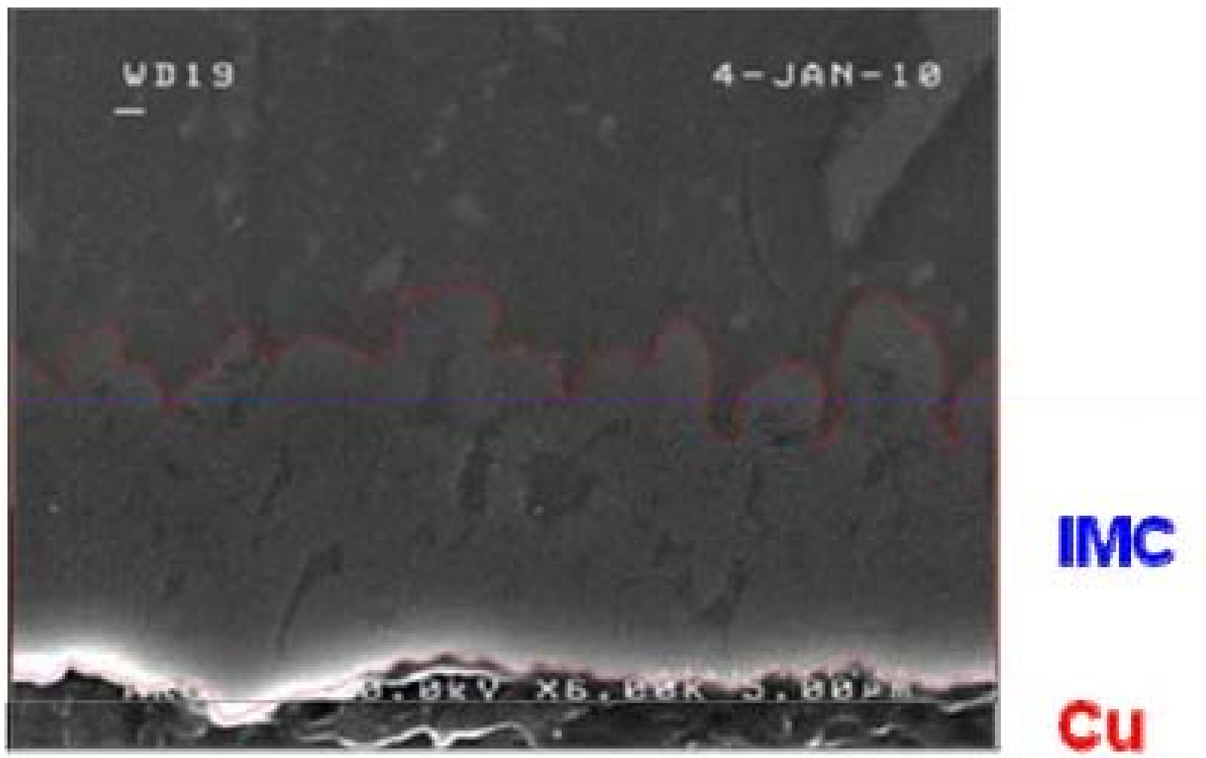


$$\text{IMC Thickness} = \frac{\text{Area (IMC)}}{\text{Length (IMC bottom)}}$$

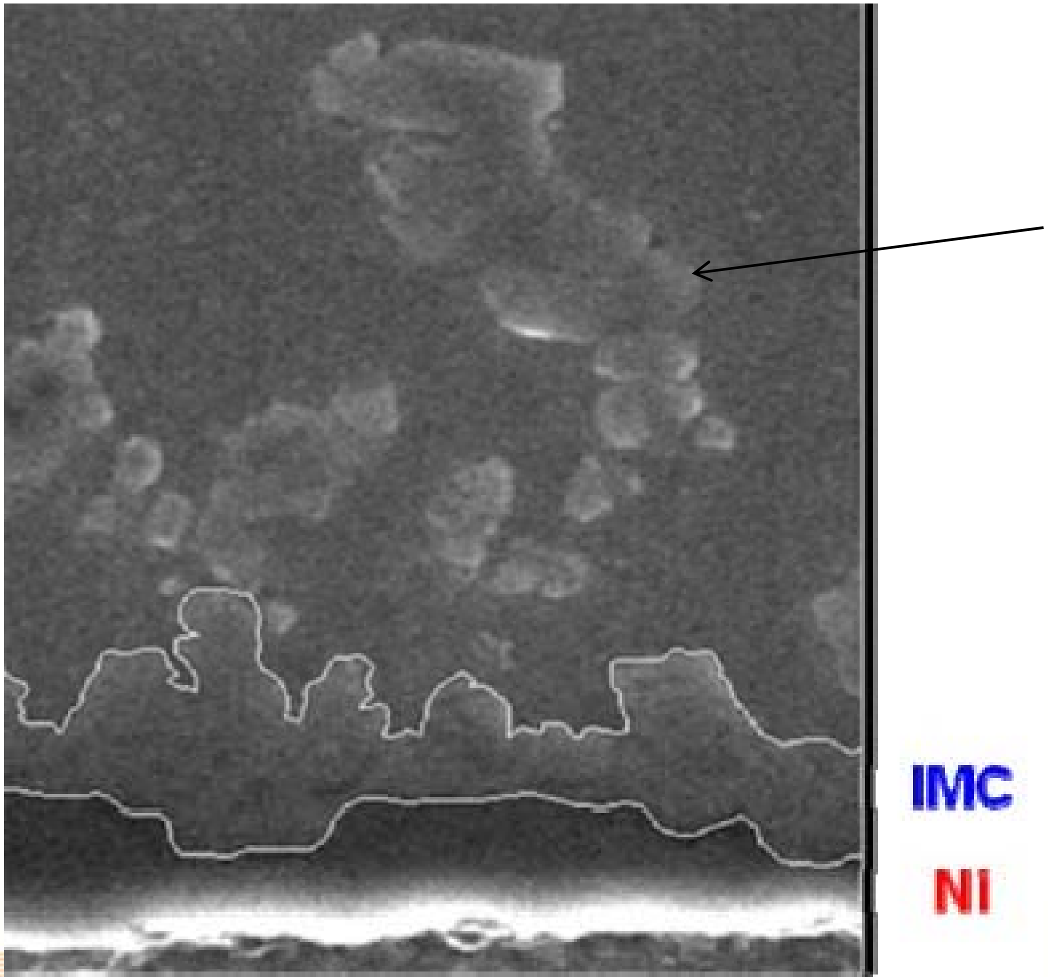
Cross section image of OSP/ Sn1Ag0.5Cu BGA combination (Board 1-3) with 4um IMC at board side



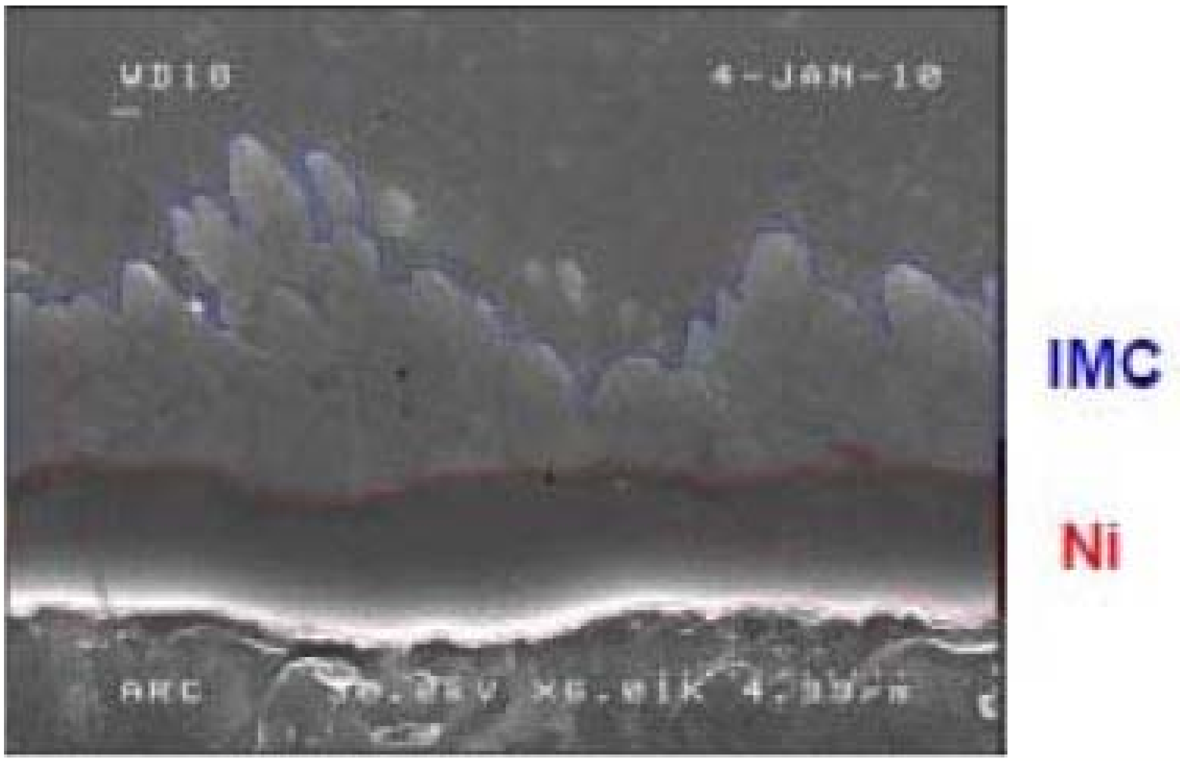
Cross section image of OSP/ Sn3.5Ag BGA combination (Board 5-3) with 6.8um IMC at board side



Cross section image of NiAu/ Sn1Ag0.5Cu BGA combination (Board 9-4) with 3.9um IMC at board side



Cross section image of NiAu/ Sn3.5Ag BGA combination (Board 13-4) with 4um IMC at board side

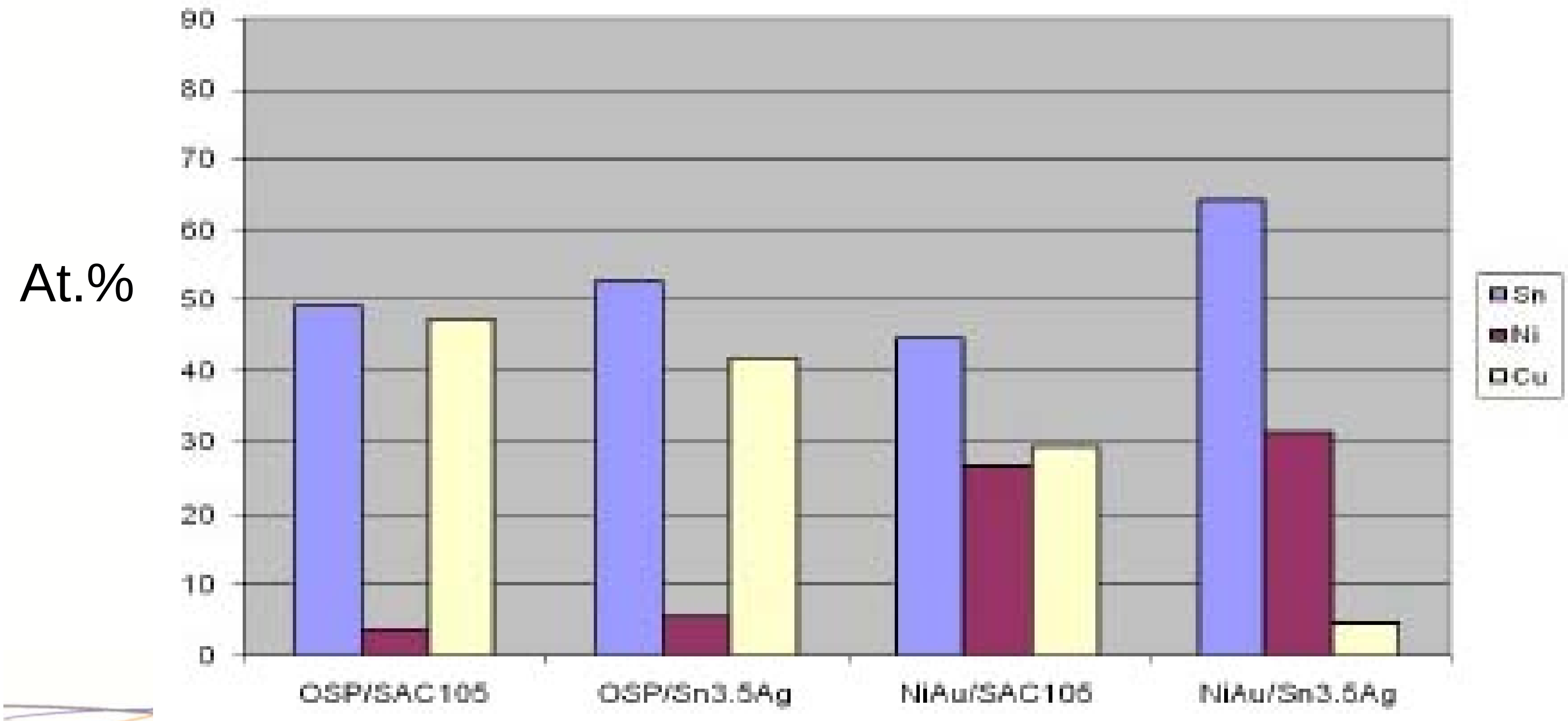


IMC thickness measurements for the 4 board surface finish/ BGA Alloy combinations

Board Number/ BGA Part Number	Board Finish/ BGA Alloy	IMC Thickness (um)
1-3	OSP/Sn1Ag0.5Cu	4
5-3	OSP/3.5Ag	6.8
9-4	NiAu/ Sn1Ag0.5Cu	3.9
13-4	NiAu/Sn3.5Ag	4

Differences in IMC thickness due to board surface finish (NiAu versus OSP) and different mixing temperatures of Sn3Ag0.5Cu paste (217ºC) with Sn1Ag0.5Cu (225ºC) or Sn3.5Ag (221ºC) BGA ball spheres.

EPMA analysis of the IMC at the board side for the four board surface finish/ BGA alloy combinations evaluated showing tin, copper and nickel.



IMC Analysis (Board Side)

- Based on the compositional information, Cu_6Sn_5 IMC formed with the OSP/ Sn1Ag0.5Cu BGA and OSP/ Sn3.5Ag BGA test combinations.

- The NiAu/Sn3.5Ag BGA test combination would typically form Ni_3Sn_4 IMC.

- For the NiAu/ Sn1Ag0.5Cu BGA combination: Ni_3Sn_4 or $(Ni,Cu)_3Sn_4$ IMC could be present in bottom layer which was typically a thinner layer and

$(Cu,Ni)_6Sn_5$ IMC present in top layer.

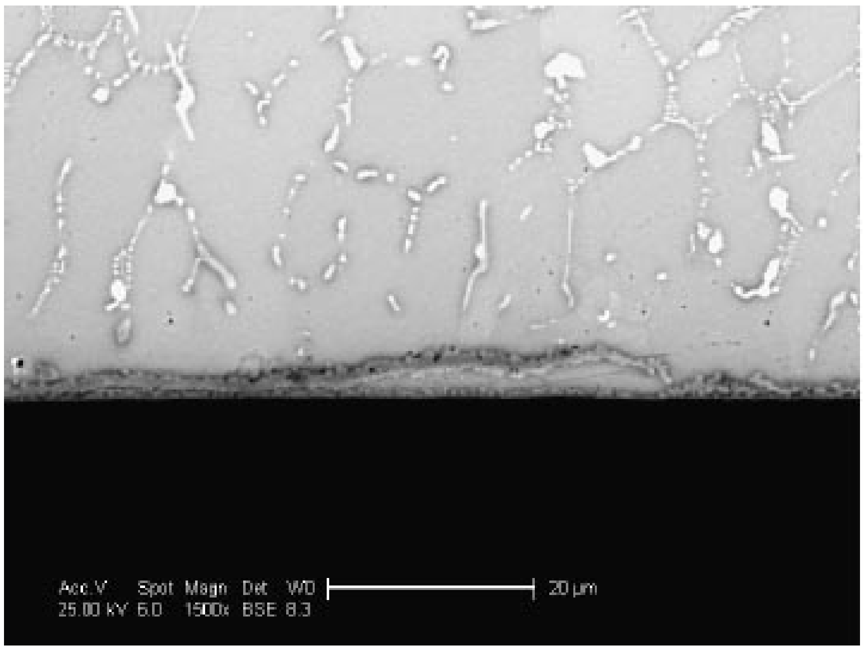
Cross-sectional analysis

- Board 9-4 (NiAu/ Sn1Ag0.5Cu) (with the low mechanical reliability result) had similar intermetallic thickness to Board 13-4 samples (NiAu/Sn3.5Ag).
- One area noticed in Board 9-4 (NiAu/Sn1Ag0.5Cu) microstructure which was different was an increased amount of ‘island’ IMC in the bulk of the solder close to main IMC layer.
  - This was much more noticeable than all other board surface finish/ BGA alloy combinations.
- This study not able to identify the solder microstructural characteristics and fracture mechanisms that explain the weak mechanical shock response of SAC105 solder on a NiAu circuit board finish; however, the IMC “islands” or “spalling” were the only main microstructural difference.

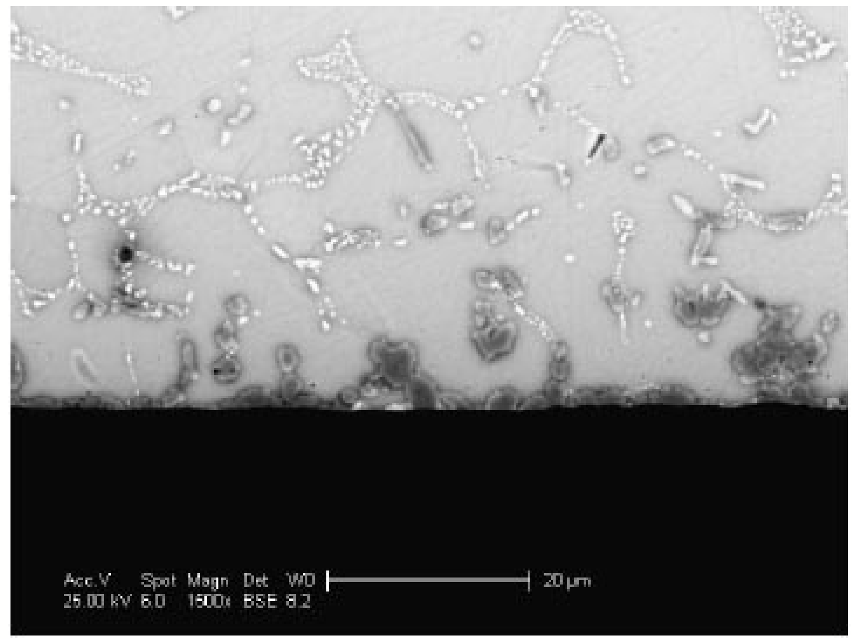
Cross-sectional Analysis (cont.)

- Spalling itself could be directly associated with the reduced mechanical shock strength, or perhaps it was an indicator that other more fundamental differences in SAC105 BGA/NiAu board combination IMC exist, but not rigorously identified.
- An unrelated investigation by the Universal Instruments AREA Consortium, involving SAC105 solder balls attached to NiAu board surface finish substrate using a Sn3Ag0.5Cu(SAC305) solder paste, showed significant IMC spalling observed after just a single reflow used for ball attach.
- This may indicate a specific, unidentified IMC microstructural characteristic associated with the reduction in SAC105/NiAu mechanical shock strength in the current study.

SAC105 ball sphere on different NiAu board finishes showing spalling
[Courtesy: Universal Instruments AREA Consortium]



Electrolytic NiAu
(spalling at main IMC layer)



Electrolytic Ni Immersion Au
(ENIG) [Spalling into bulk solder]

Conclusions

- Mechanical shock testing of four board surface finish/ BGA alloy type combinations showed that consistent with expectations:
  - Sn1Ag0.5Cu BGA with OSP board finish was the best performing;
  - however, Sn1Ag0.5Cu BGA with NiAu board finish performed the worst, which was surprising, of all test combinations tested.
- The two board surface finishes, OSP and NiAu, tested with the Sn3.5Ag BGA components yielded similar mechanical shock results, with lifetime results falling between the worst (NiAu/Sn1Ag0.5Cu) and best (OSP/Sn1Ag0.5Cu) combinations.
- Drop test results for Sn1Ag0.5Cu were highly sensitive to board surface finish, while Sn3.5Ag results were only moderately sensitive to board finish.

Conclusions (cont.)

- The BGA packages manufactured with SAC105 component spheres and attached to the NiAu board surface finish showed:
  - 33-62% lower mechanical shock lifetime than the other sample configurations.
  - Only combination with “spalling” at the board-side IMC.
  - Greatest amount of damage from dry and pry and cross-sectional analysis

Conclusions (cont.)

- Morphology of the IMC in the SAC105/NiAu test combination may have an effect on the poor performance of this test combination.
- The spalling effect forms large "islands" of IMC in the bulk solder region but close to the IMC layer on the board side.
- Results suggest a potential direct or indirect link between the observed IMC spalling in the SAC105/NiAu samples and reduced mechanical shock lifetime, but specific failure mechanism has not yet been identified.
- For applications where mechanical shock lifetime is critical, such as handheld electronic devices, limited test results suggest that SAC105 solder balls should be used with an OSP board surface finish.

Future Work

Additional work needs to be done on:

- mechanical shock testing of NiAu board finish with Sn1Ag0.5Cu BGA components to further understand mechanical drop performance
- more detailed investigations of IMC morphology associated with Sn1Ag0.5Cu soldered BGA components on NiAu board finish and the spalling effect/formation.

Acknowledgements

- The authors would like to acknowledge Xilinx who provided components and boards for this work.
- They also gratefully acknowledge input provided into the IMC spalling affect and mechanical drop test result interpretation by various persons and organizations in the industry.

Appendix

Board No.	Board Pad Finish	Solder Joint	Drops-to Failure			
			#1	#2	#3	#4
1	OSP	SAC105	108	98	152	128
2	OSP	SAC105	78	86	126	69
3	OSP	SAC105	84	96	116	143
4	OSP	SAC105	106	138	76	110
5	OSP	Sn3.5Ag	38	68	75	48
6	OSP	Sn3.5Ag	85	81	34	65
7	OSP	Sn3.5Ag	51	82	56	77
8	OSP	Sn3.5Ag	58	48	44	31
9	NiAu	SAC105	26	32	23	42
10	NiAu	SAC105	35	46	53	47
11	NiAu	SAC105	25	17	44	68
12	NiAu	SAC105	71	29	39	31
13	NiAu	Sn3.5Ag	92	64	73	81
14	NiAu	Sn3.5Ag	59	83	44	68
15	NiAu	Sn3.5Ag	95	84	68	51
16	NiAu	Sn3.5Ag	61	103	91	86

Samples with green circles were the last to fail on board which would give more meaningful FA results as other samples on board were continually dropped after the first failure.

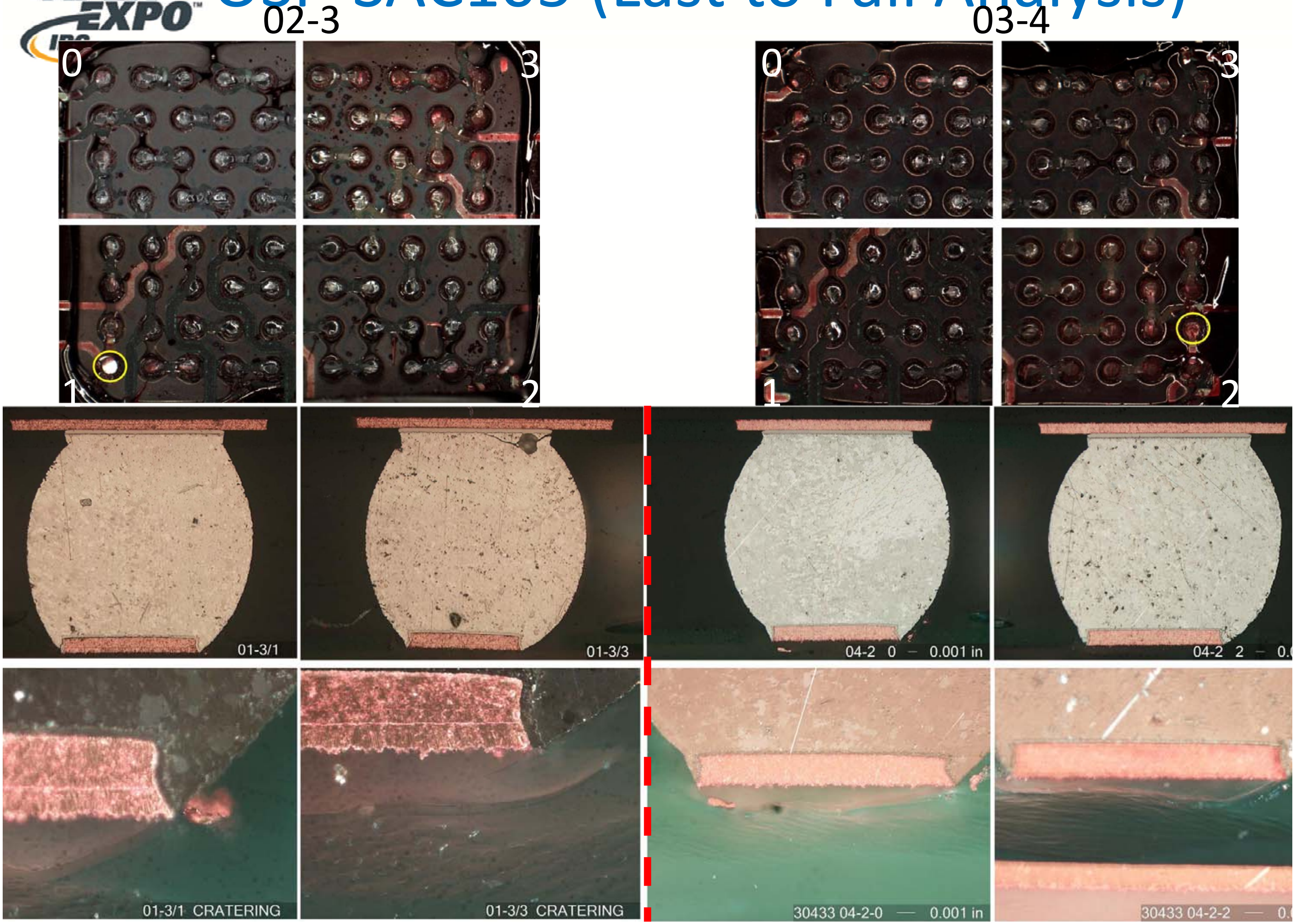
Dye Solder Joint Crack Results for Part # 1 on Boards 1-16 (Boards 6-1, 8-1, 12-1, 13-1, 15-1 were last to fail)

Board/ Component Part Number	Board Finish/ BGA Alloy Composition	No. of Cracks in BGA Corner 0	No. of Cracks in BGA Corner 1	No. of Cracks in BGA Corner 2	No. of Cracks in BGA Corner 3	Total Number of Cracks
01-1	OSP/ Sn1Ag0.5Cu	0	2	0	0	8
02-1		0	2	0	0	
03-1		1	0	0	0	
04-1		0	2	0	1	
05-1	OSP/ Sn3.5Ag	0	7	0	0	17
06-1		0	2	0	0	
07-1		0	5	0	1	
08-1		0	2	0	0	
09-1	NiAu/ Sn1Ag0.5Cu	0	5	0	4	45
10-1		1	6	0	2	
11-1		1	9	0	8	
12-1		0	5	0	4	
13-1	NiAu/ Sn3.5Ag	0	1	0	0	12
14-1		1	1	0	0	
15-1		2	2	0	2	
16-1		0	3	0	0	

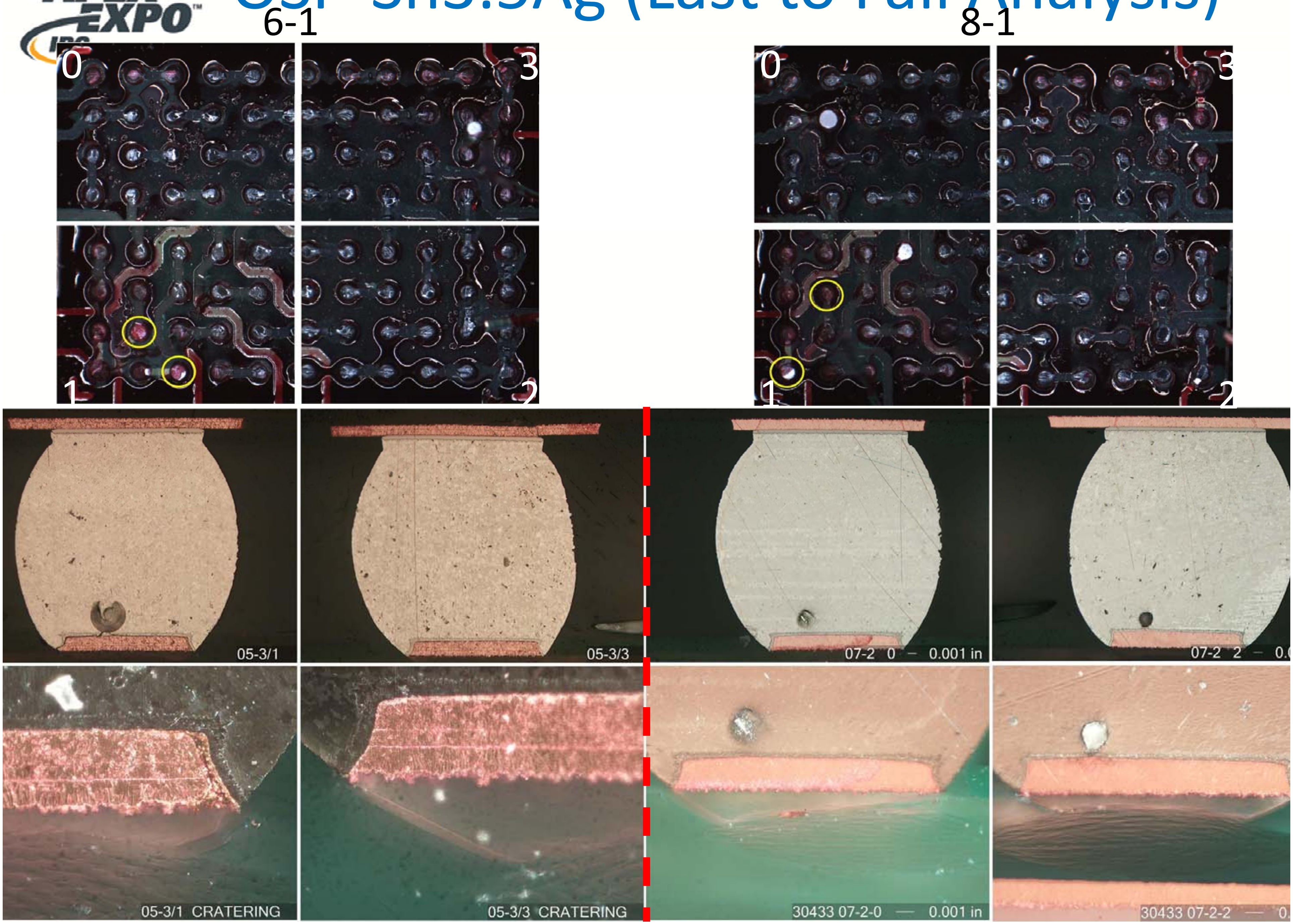
Cross-section Results for Mechanical Test Boards (Boards 1-3, 5-3, 9-4 were last to fail)

Board #-BGA Part #	Board Finish/ BGA Alloy	PCB Side				Component Side			
		Solder Cracks		Laminate Cratering		Solder Cracks		Laminate Cratering	
		Inner	Outer	Inner	Outer	Inner	Outer	Inner	Outer
01-3	OSP/Sn1Ag0.5Cu	Y	N	Y	Y	N	Y	N	N
01-4	OSP/Sn1Ag0.5Cu	N	N	Y	Y	N	Y	N	N
05-3	OSP/Sn3.5Ag	Y	N	Y	Y	N	Y	N	N
05-4	OSP/Sn3.5Ag	N	N	Y	Y	N	N	N	N
09-3	NiAu/Sn1Ag0.5Cu	Y	Y	Y	Y	N	N	N	N
09-4	NiAu/Sn1Ag0.5Cu	Y	N	Y	Y	N	Y	N	N
13-3	NiAu/Sn3.5Ag	Y	N	Y	Y	N	Y	N	N
13-4	NiAu/Sn3.5Ag	N	N	Y	Y	N	Y	N	N

OSP-SAC105 (Last to Fail Analysis)

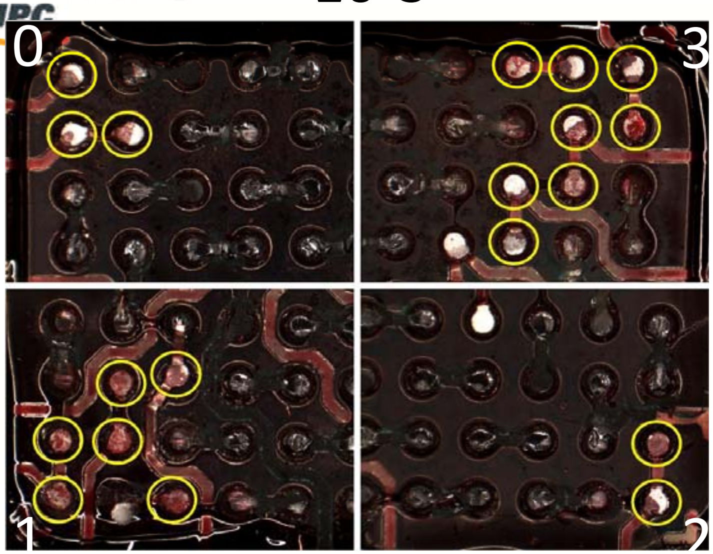


OSP-Sn3.5Ag (Last to Fail Analysis)

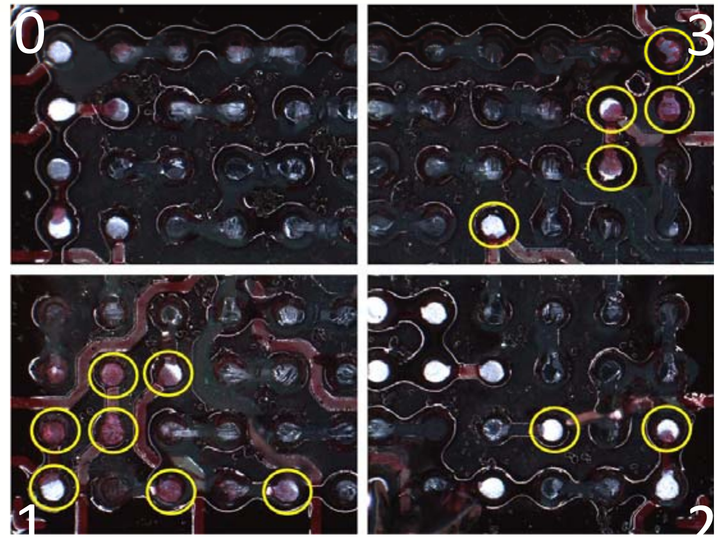


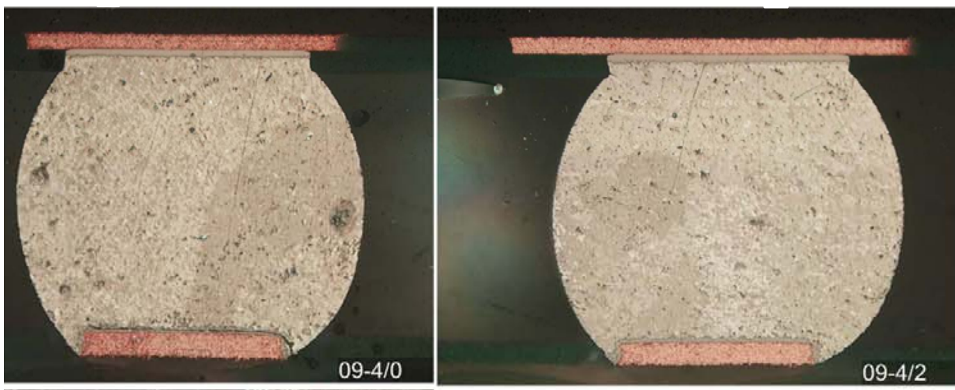
NiAu-SAC105 (Last to Fail Analysis)

10-3

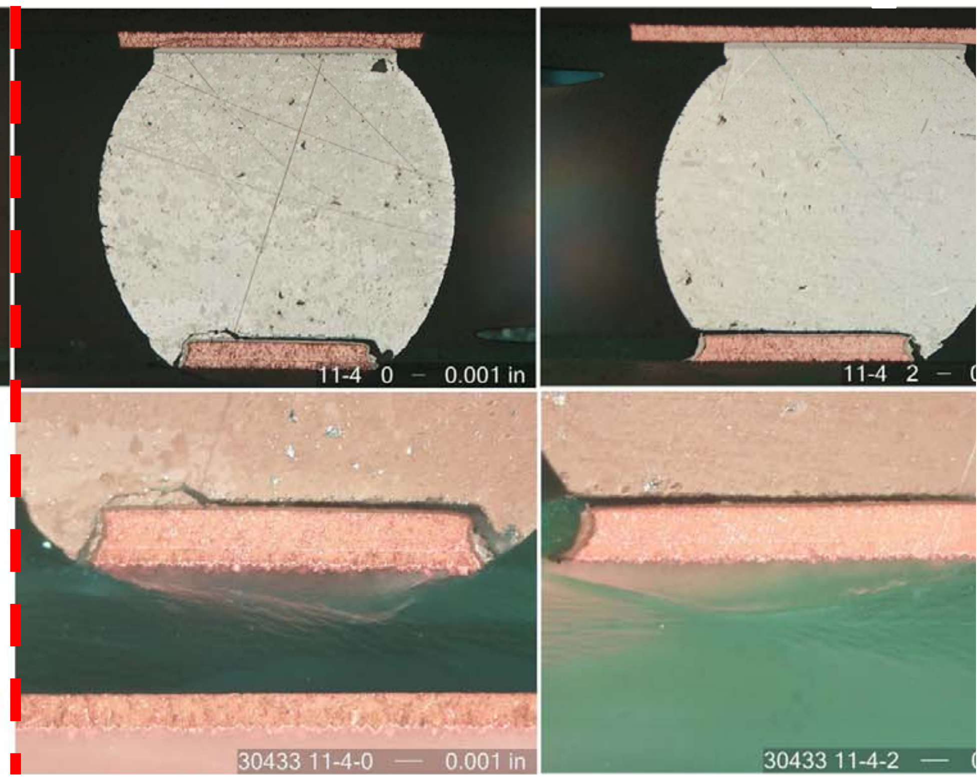


12-1



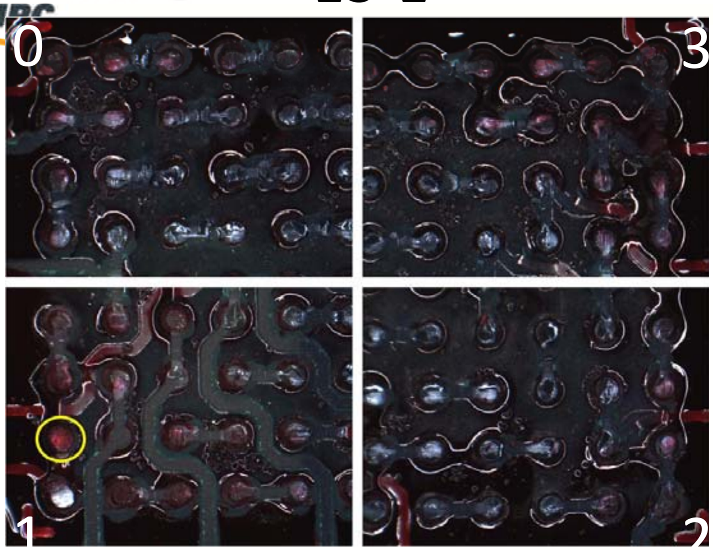


Board pad cratering and board side solder joint cracking.

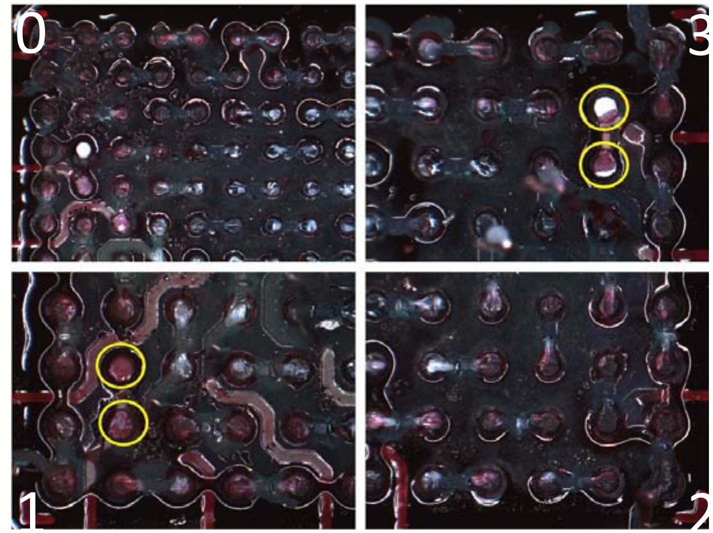


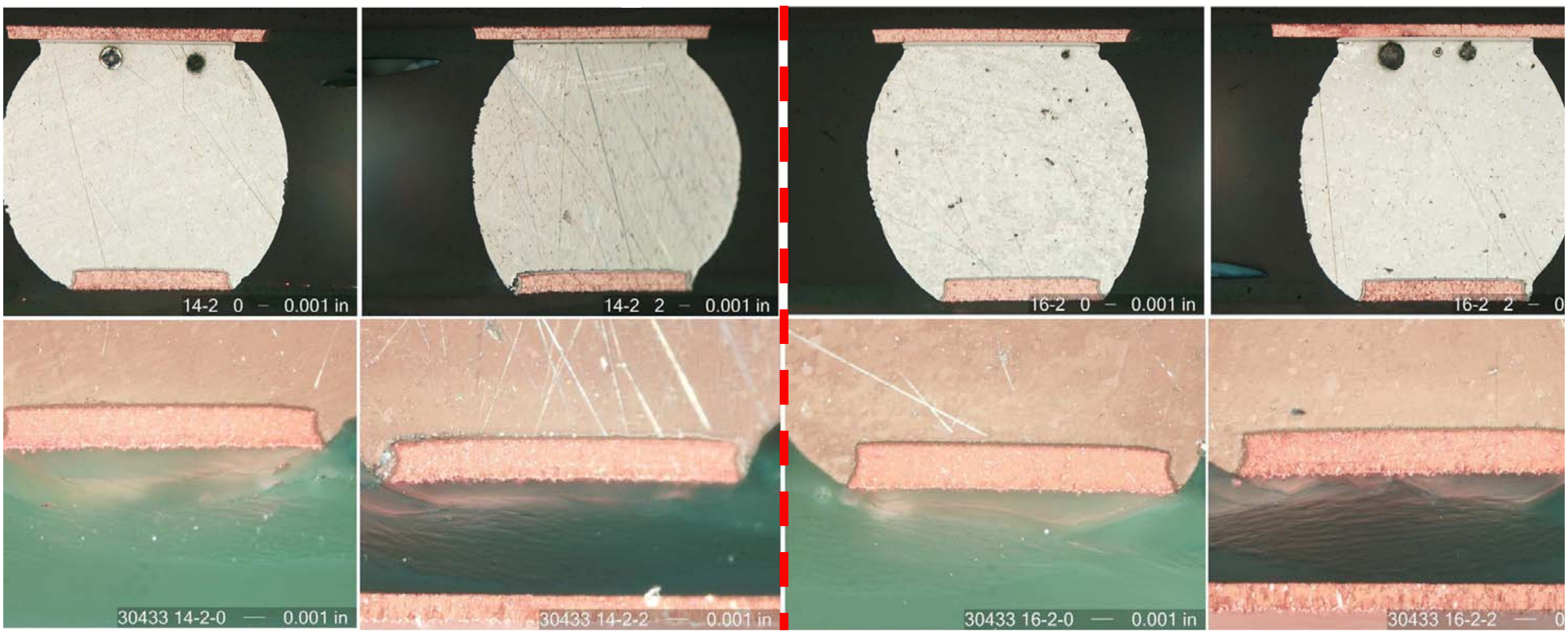
NiAu-Sn3.5Ag (Last to fail analysis)

13-1

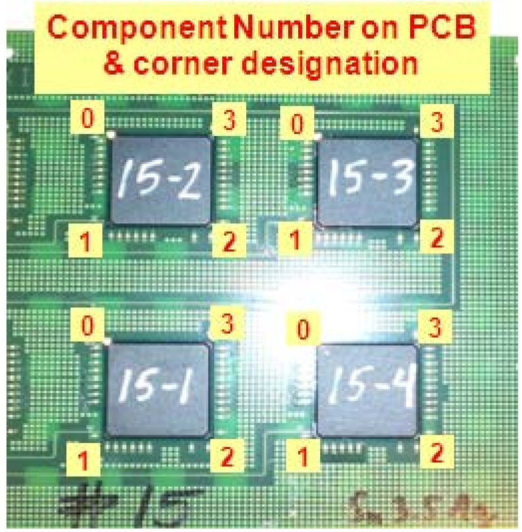


15-1



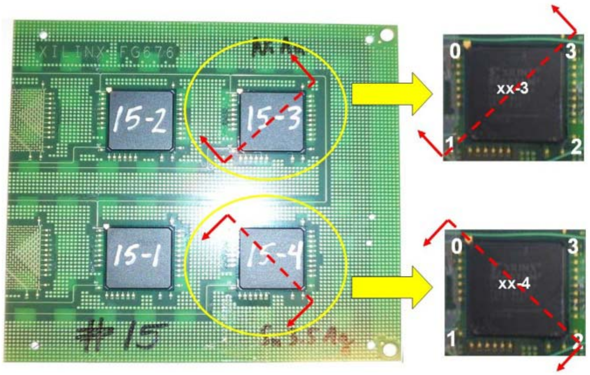


Red Dye Data
(Last to Fail Analysis)

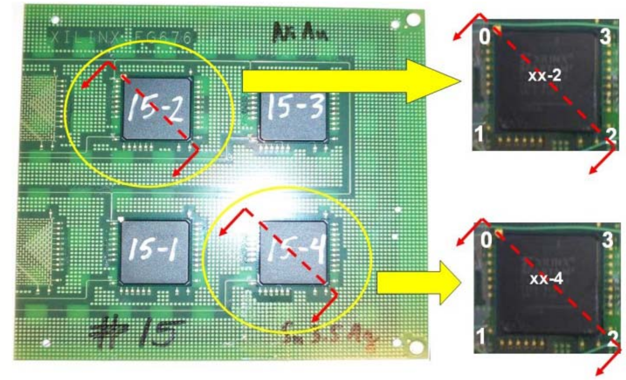


					PCB SIDE Cracks Red Dye: >90% Stain Data				PCB SIDE Cracks Red Dye: 1%-90% Stain Data				COMPONENT SIDE Cracks Red Dye: >90% Stain Data				COMPONENT SIDE Cracks Red Dye: 1%-90% Crack Data				PCB SIDE PAD Cratering Red Dye: >90% Stain Data				PCB SIDE PAD Cratering Red Dye: 1%-90% Stain Data			
Board No.	Board Pad Finish	Solder Joint	Component No.	Drops-to Failure	CNR 0	CNR 1	CNR 2	CNR 3	CNR 0	CNR 1	CNR 2	CNR 3	CNR 0	CNR 1	CNR 2	CNR 3	CNR 0	CNR 1	CNR 2	CNR 3	CNR 0	CNR 1	CNR 2	CNR 3	CNR 0	CNR 1	CNR 2	CNR 3
1	OSP	SAC105	3	152																								
2	OSP	SAC105	3	126	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	3	1	8	2	2	2	3
3	OSP	SAC105	4	143	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	9	2	3	3	4	2
4	OSP	SAC105	2	138																								
5	OSP	Sn3.5Ag	3	75																								
6	OSP	Sn3.5Ag	1	85	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	8	0	9	2	2	2	3
7	OSP	Sn3.5Ag	2	82																								
8	OSP	Sn3.5Ag	1	58	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	8	0	7	2	5	2	5
9	NiAu	SAC105	4	42																								
10	NiAu	SAC105	3	53	0	6	1	3	3	0	1	5	0	0	0	0	0	0	0	0	0	5	1	3	2	2	1	1
11	NiAu	SAC105	4	68																								
12	NiAu	SAC105	1	71	0	5	0	3	4	2	2	2	0	0	0	0	0	0	0	0	0	2	0	4	3	2	1	2
13	NiAu	Sn3.5Ag	1	92	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	8	5	10	4	3	4	3
14	NiAu	Sn3.5Ag	2	83																								
15	NiAu	Sn3.5Ag	1	95	0	2	0	0	0	0	0	2	0	0	0	0	0	0	0	0	15	9	14	8	0	3	2	3
16	NiAu	Sn3.5Ag	2	103																								

Cross-section Data
(Last to Fail Analysis)



- Cross section parts 01-3, 05-3, 09-3 & 13-3 diagonally between corners 1 and 3 (see pic on following page).
- Cross Section parts 01-4, 04-2, 05-4, 07-2, 09-4, 11-4, 13-4, 14-2, 16-1 diagonally between corners 0 and 2 (see pic on following page).
- Take photo's of corner solder joints from each cross section to add to report.
- Label samples to match the board/part & corner identifier (ex. 01-3 /1 & 3, 01-4/0 & 2, etc…)



Micro-section Legend:
X - Microsection crack on PCB side
X - Microsection crack on COMPONENT side
X - PCB pad cratering seen in microsections

					Microsection Results 75%-100% Crack				Microsection Results 50%-74% Crack				Microsection Results 25%-49% Crack				Microsection Results 1%-24% Crack				Microsection Results Pad Cratering			
Board No.	Board Pad Finish	Solder Joint	Component No.	Drops-to Failure	CNR 0	CNR 1	CNR 2	CNR 3	CNR 0	CNR 1	CNR 2	CNR 3	CNR 0	CNR 1	CNR 2	CNR 3	CNR 0	CNR 1	CNR 2	CNR 3	CNR 0	CNR 1	CNR 2	CNR 3
1	OSP	SAC105	3	152		X										X						X		X
2	OSP	SAC105	3	126																				
3	OSP	SAC105	4	143																				
4	OSP	SAC105	2	138													X				X		X	
5	OSP	Sn3.5Ag	3	75		X														X		X		X
6	OSP	Sn3.5Ag	1	85																				
7	OSP	Sn3.5Ag	2	82													X		X		X		X	
8	OSP	Sn3.5Ag	1	58																				
9	NiAu	SAC105	4	42	X														X		X		X	
10	NiAu	SAC105	3	53																				
11	NiAu	SAC105	4	68	X		X										X		X		X		X	
12	NiAu	SAC105	1	71																				
13	NiAu	Sn3.5Ag	1	92																				
14	NiAu	Sn3.5Ag	2	83															X		X		X	
15	NiAu	Sn3.5Ag	1	95																				
16	NiAu	Sn3.5Ag	2	103													X		X		X		X	