Effects of BGA Rework Cycles on PCB Assembly Reliability

J. Liang*, G. Barr*, N. Dariavach*, and D. Shangguan**

Abstract
BGA component removal and replacement are required during product development and repair operations. In general, a single rework on specific location is permitted without causing excessive damage to solder joints, board materials, and adjacent components. However, situations exist where a multiple rework is required on the same location. Multiple reworks could induce a thick intermetallic layer between the BGA solder balls and Cu pads on the boards, leading to reliability concern [1, 2]. This paper examines the possible effects of rework cycles on bonding strength of solder balls, Cu pads and laminates. An effort was made to establish a sound scientific relationship among rework processes (cycle times), intermetallic thickness, and mechanical strength of BGA balls, as well as any possible intermetallic embrittlement. It is believed that these results can help shed some insight on the maximum permitted limits of BGA rework cycles.

Introduction

BGA removal and replacement are required during product development, and for manufacturing and field returns. In general, a single rework on specific location is permitted without causing excessive damage to solder joint reliability and board materials and adjacent components. BGA multiple revisions during a product development may force many engineering development boards to go through multiple removal and replacement cycles on the same BGA locations. Cross-section analysis of the multiple reworked sites could find that a thick intermetallic layer existing between the BGA solder balls and Cu pads on the boards. Due to concern that thick intermetallic could cause severe reliability issues, most of PC boards with BGA components are subjected to scrap after one or two repair cycles. This work summarizes the research we performed so far to assess the rework risk, and to try to establish a sound scientific relationship among rework processes, intermetallic thickness, and mechanical strength of BGA balls, as well as any possible intermetallic embrittlement; These results could give us some valuable information on the maximum permitted limits of such BGA rework.

Test Samples and Experimental Procedures

BGA Ball Shearing Testing

The ball shearing testing involves removing BGA, re-dressing pads, screen printing, place specific solder balls (with the same diameters as in the original BGAs), then reflow. This will give a very good indication on how much impact intermetallic grown in the rework processes will have on solder ball joint strength. The shearing tests are conducted on samples with 1, 2, 3 and 5 rework cycles on the same spots. Ball shear tests were conducted on an Instron 8854 micro-tester equipped with ball shear load cell and micro-mechanical stage. Tests were performed at the ram speed of 1.0 mm/min (0.0394 inch/min). The mechanical loading probe tip was kept at 0.005" from the surface of the component with a preload force of 0.5 lb (2.22 N) for all tests. Precise position of the load probe and maintaining preload force significantly improve repeatability of the test results due to the effect of the BGA geometry and probe/load cell non-linear behavior at small loads [3].

Four Point- Bending Tests

Test samples are cut off from the reworked boards with one rework, 2 reworks, 3 reworks and 5 reworks. Bending testing generates a tensile stress on the whole BGA solder joint system: PCB - pad - intermetallic- solder [4]. It will reveal the weakest link, and detect any pad-bonding strength degradation due to rework operations.

It is hoped that these tests and analysis will give us a clear picture on how badly the thick intermetallic after multiple rework operation will have on the strength and life of these BGA solder balls. It also will single out the general impacts of rework thermal on pad and lamination bonding strength. The results can clearly show us if the boards after multiple repair cycles would be able to work reliably in the field.

Test Sample Preparation and Experimental Setup

There are two sample sets prepared for ball shear test from a high density/high reliability board. Samples are produced under the following conditions: virgin, 1, 2, 3, 5 reworks. Each ball shear test sample had 10 attached balls after the last replacement stage, except sample which has virgin conditions. 22 BGA components, two PC boards, one bare board, and eutectic solder balls with diameter of 0.76mm were used. The virgin bare board went through a standard reflow (simulating the bottom site reflow process) before the paste was printed and BGA placed.

Four Point Bending Test

Sample preparation procedures for four point bending tests are similar to the preparation of ball shear samples except that the final component placement was used instead of solder balls. 32 BGA components, two PC boards, and one bare board were used. The virgin bare board also went through two thermals as for the ball shearing tests. The four point bending test samples orientations are shown in Figure 1. The four point bending test fixture and the system setup are shown in Figure 2.

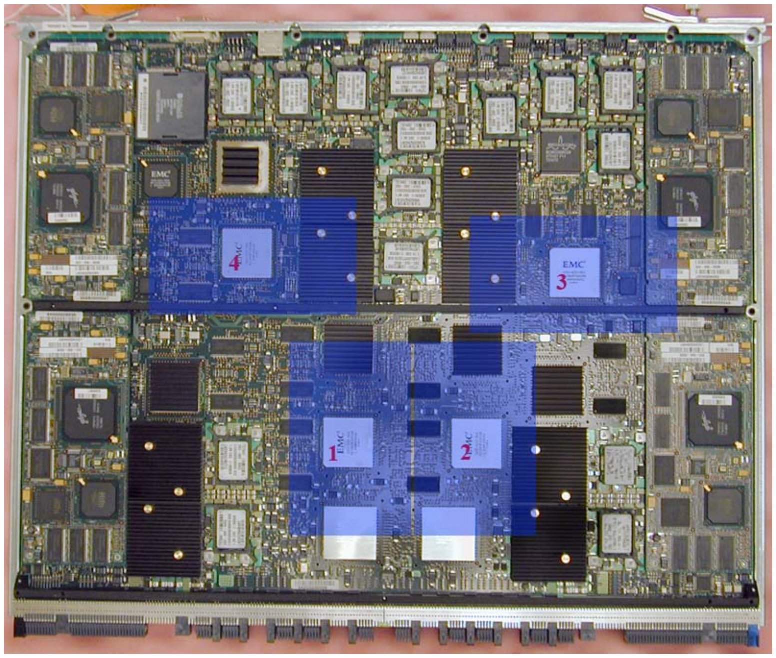
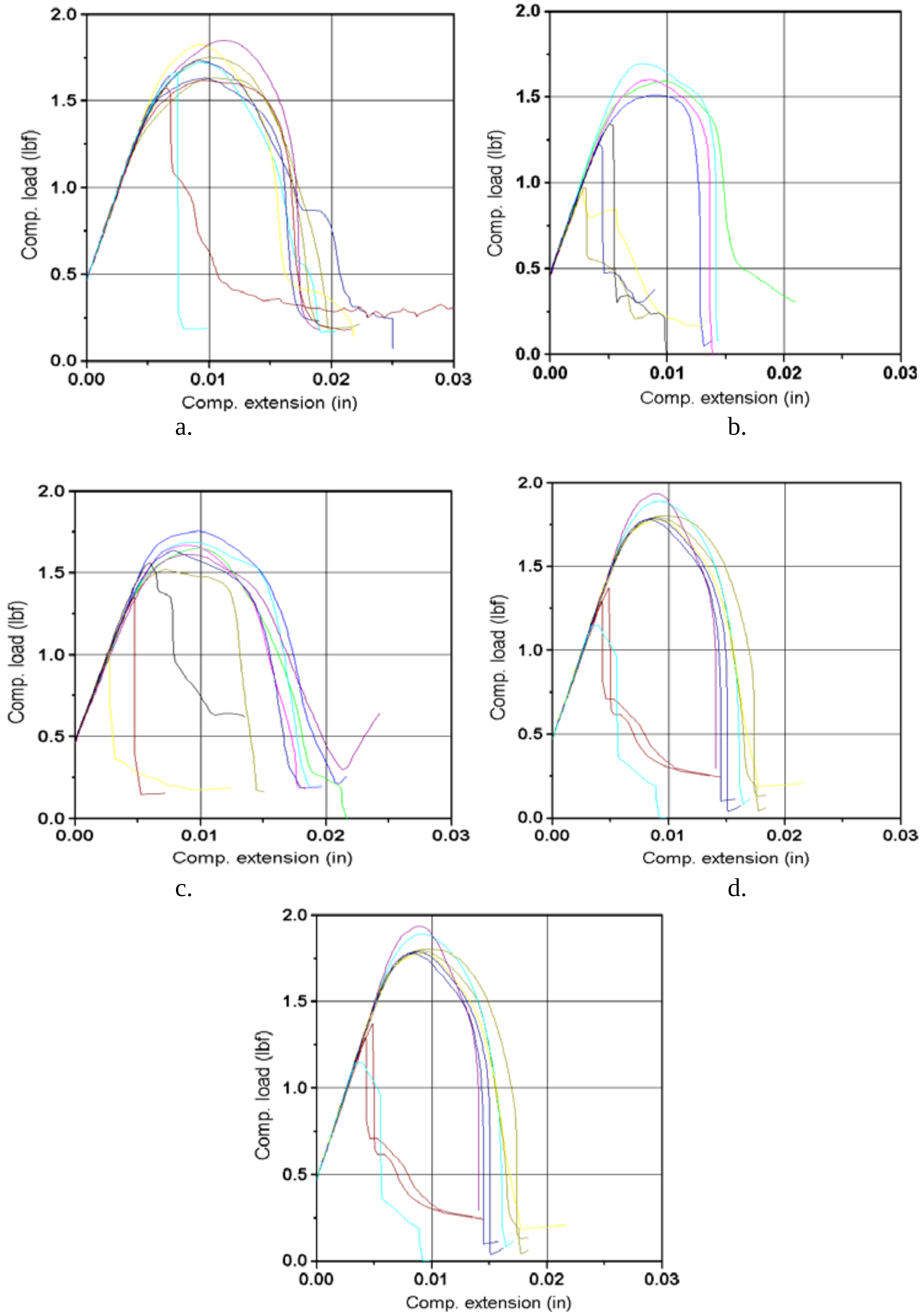


Figure 1 - Four point bending test mechanical sample orientation (blue areas).

Figure 2 - Four point bending test fixture and setup.

Testing Results and Analyses
Ball Shearing

Figure 3a to Figure 3e present all the ball shearing testing with zero rework up to 5 reworks. There are two distinguished failure modes in these tests. When failure is with ball sheared-off the pads, there is no obvious degradation in the solder strength and no loss in ductility, and no intermetallic-caused embrittlement occurred. The other failure mode is the shearing-off of the pads from the board laminates. They all happened in the middle region of the BGA sites, where the pads design and orientation are different from other balls. All the curves in Figure 3 with a sharp load drop are all associated with this pad separation failure. The load for pad shear-off at these middle locations are running from about 1.0 lbs to 1.5 lbs. It is worth to note that the shearing strength dropped after the first rework, and then stay more or less the same up to 5 rework cycles.

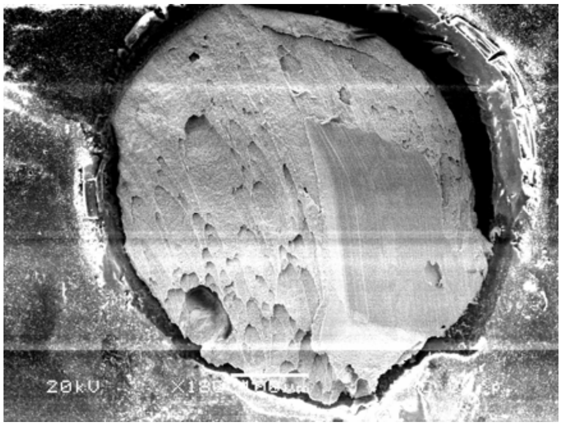


e.

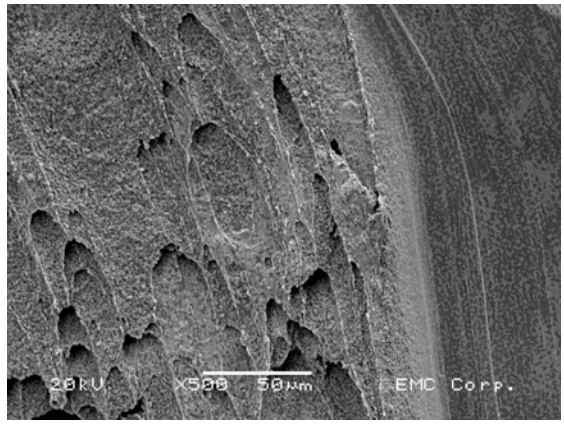
Figure 3 - Ball shearing test results for BGA balls with: zero (a), one (b), two (c), and three (c) and 5 (e) rework.

The fracture surfaces of the sheared balls are shown in Figure 4. All shearing failure mode is predominant ductile fracture. There is no obvious indication that there is any degradation in terms of solder ball strength and loss of any ductility. Figure 5a-d show the pad separation from the laminates, which is generally brittle.

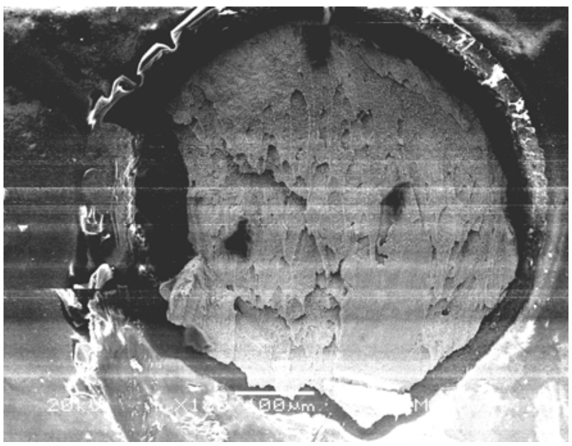
In summary, ball shear tests indicate that the solder strength is generally not degraded by multiple reworks up to 5 cycles. However, the pad separation strength is apparently affected by the rework operation, even after only one rework operation. It is clear that the intermetallic layer is not the necessary weakest link in the BGA/board interconnect systems



a.

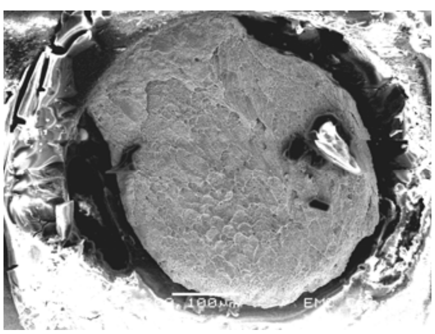


b

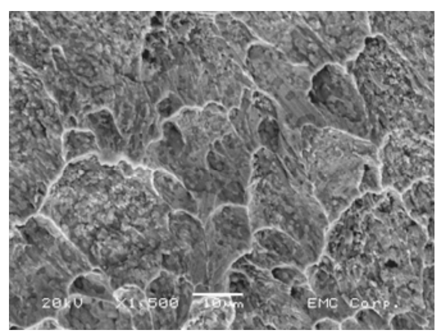


c

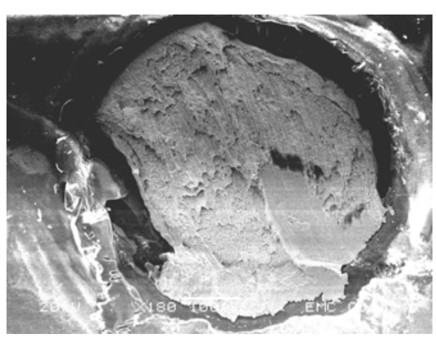
d



e

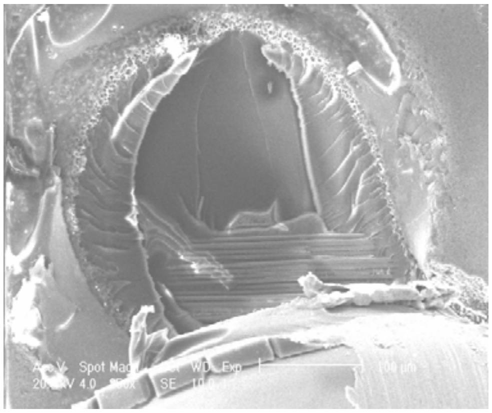


f

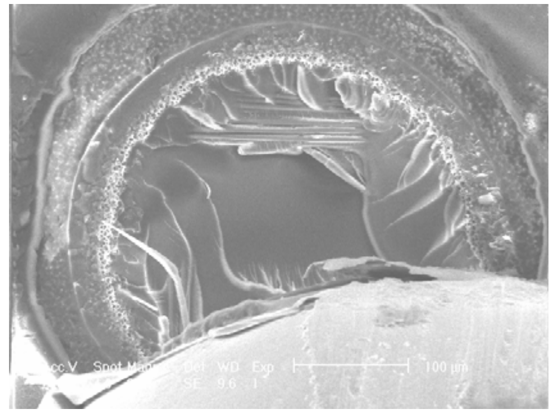


g.

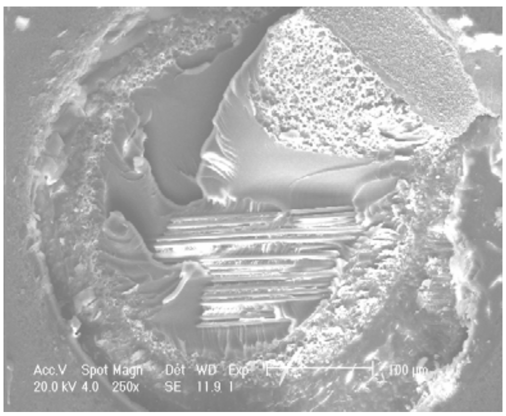
Figure 4 - SEM pictures of sheared ball on virgin board with zero (a, b), one (c), two (d), three (e, f) and five (g) rework.



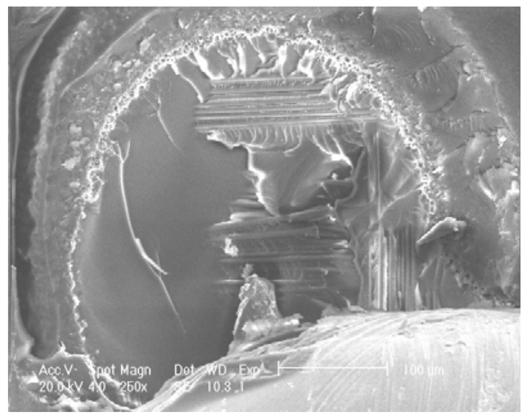
a.



b.



c



d.

Figure 5 - SEM pictures of pad separation after ball shear tests of boards with one (a), two (b), three (c) and five (j) rework.

Intermetallic Thickness vs. Rework Cycle:

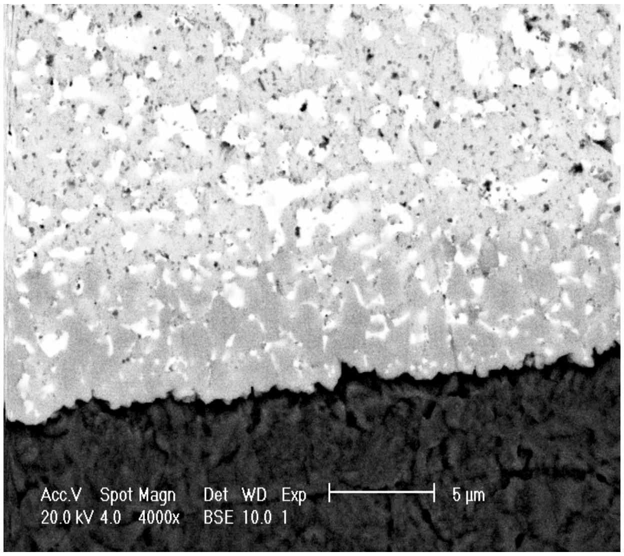
The intermetallic morphology and thickness are shown in Figure 6. The intermetallic, after a regular reflow and without any rework, is very thin and a continuous layer. After one rework cycle, the intermetallic layer increases significantly. With 5 rework cycles, that layer grew to more than 10 micro meters. It needs to point out that the intermetallic layer after rework is no longer pure/continuous Sn-Cu compounds; rather it is a mixture of intermetallic, Sn-rich, and Pb-rich phases. Intermetallic was loosely used here to describe this mixture layer; but strictly speaking, they are no longer the regular intermetallic composition and structures. The measured intermetallic thickness on one set of the ball sheering samples is also presented in Figure 7.

The picture (Figure 6) for 2 rework cycles shows clearly the shearing deformation and fracture path is inside the solder not within the intermetallic mixture layer. It is clear that either thin (in the case of zero rework), or thick in the case of 5 rework cycles, has no obvious effects on the strength of ball shearing. This kind of mixture structure at the pad and solder balls may be a littler better to absorb small micro-cracking than the continuous more brittle intermetallic normally seen with high temperature aging or multiple high temperature exposures.

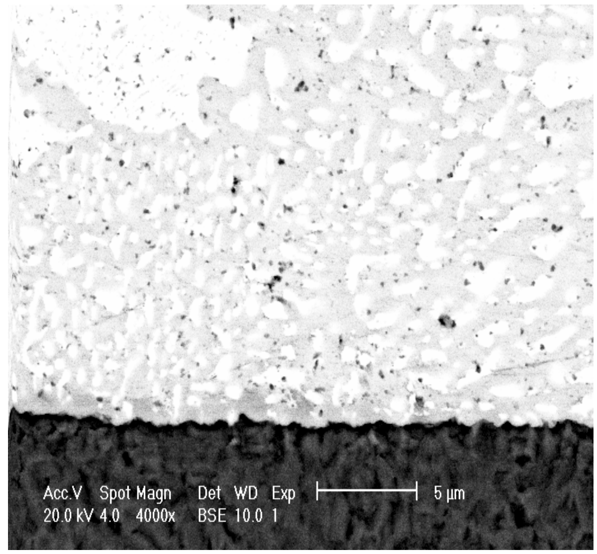
Four Point Bending Testing Results

Four point bending test samples were cut from the boards and then machined to final dimension of 5.5” long by 1.5” wide. The distance between upper loading bars is 3 inch, and distance between lower support bars is 5”. BGA components were located 0.1” from the lateral edge of the board. The Instron displacement rate used was 2 mm/min during the bending tests.

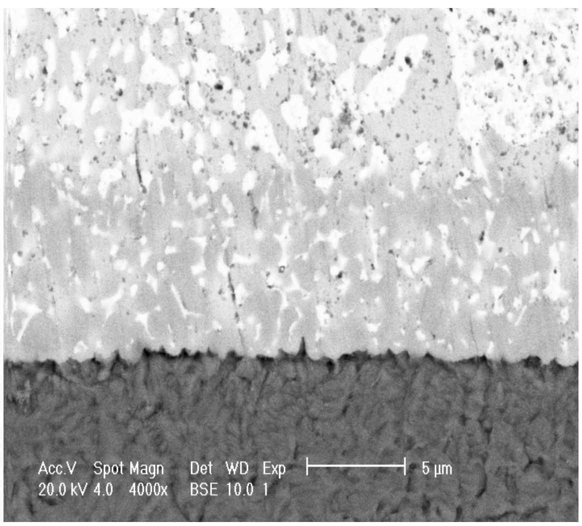
The four bending test results for boards with zero up to 5 reworks are shown in Figure 8. A drop in the load usually indicates a loss of stiffness of the samples, which usually corresponds to the separation of the BGA solder balls from the PC boards. It can be seen from the graph that there is a general drop of bending strength with increase in the number of reworks performed, with most significant drop after second rework. After 2 reworks, future rework cycles reduce the strength to a lesser degree. Even though the test results show the strength change with rework cycles, it does not point to where the failure is located and what kind of failure modes are active.



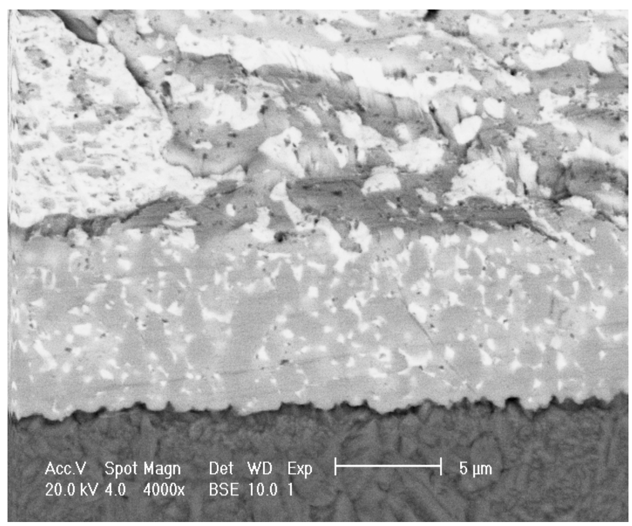
a.



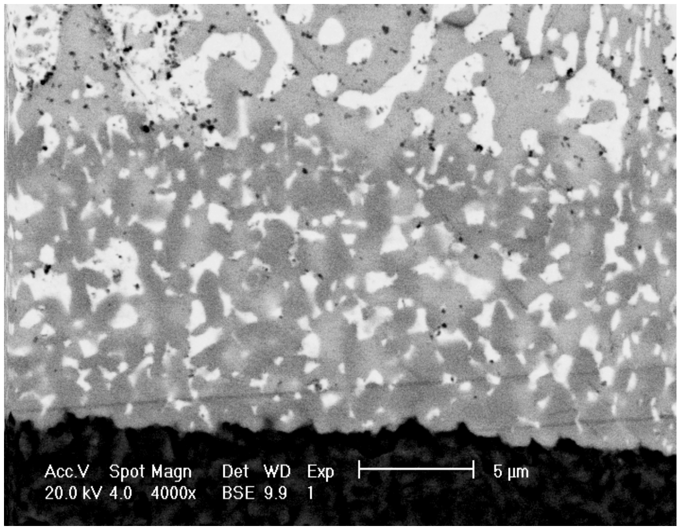
b.



c.



d.



e.

Figure 6 - Intermetallic morphology and thickness after zero (a), one (b), two (c), three (d) and five (e) rework cycles.

Director PCB SMT Pad Cu/Sn Intermetallic Thickness Measurements (Values are in Microinches)

Test Condition	SMT Pad	Area	Measured Value
Virgin	1	A	104
		B	75
		C	83
	2	A	60
		B	65
		C	74
	3	A	68
		B	75
		C	38
Mean:			71
Std. Dev.			18

Test Condition	SMT Pad	Area	Measured Value
Reflow 1x	1	A	279
		B	279
		C	324
	2	A	264
		B	249
		C	317
	3	A	241
		B	271
		C	287
Mean:			279
Std. Dev.			28

Test Condition	SMT Pad	Area	Measured Value
Reflow 2x	1	A	287
		B	219
		C	234
	2	A	264
		B	271
		C	279
	3	A	362
		B	257
		C	293
Mean:			274
Std. Dev.			41

Test Condition	SMT Pad	Area	Measured Value
Reflow 3x	1	A	354
		B	317
		C	324
	2	A	324
		B	347
		C	339
	3	A	332
		B	317
		C	324
Mean:			331
Std. Dev.			13

Test Condition	SMT Pad	Area	Measured Value
Reflow 5x	1	A	483
		B	422
		C	445
	2	A	490
		B	400
		C	385
	3	A	452
		B	407
		C	422
Mean:			434
Std. Dev.			36

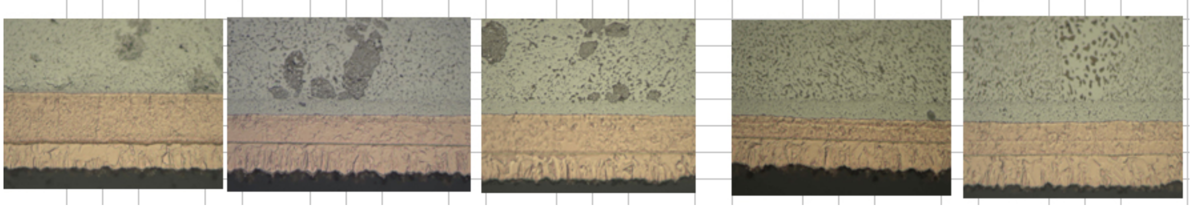


Figure 7 - Intermetallic Thickness versus. Rework Cycles

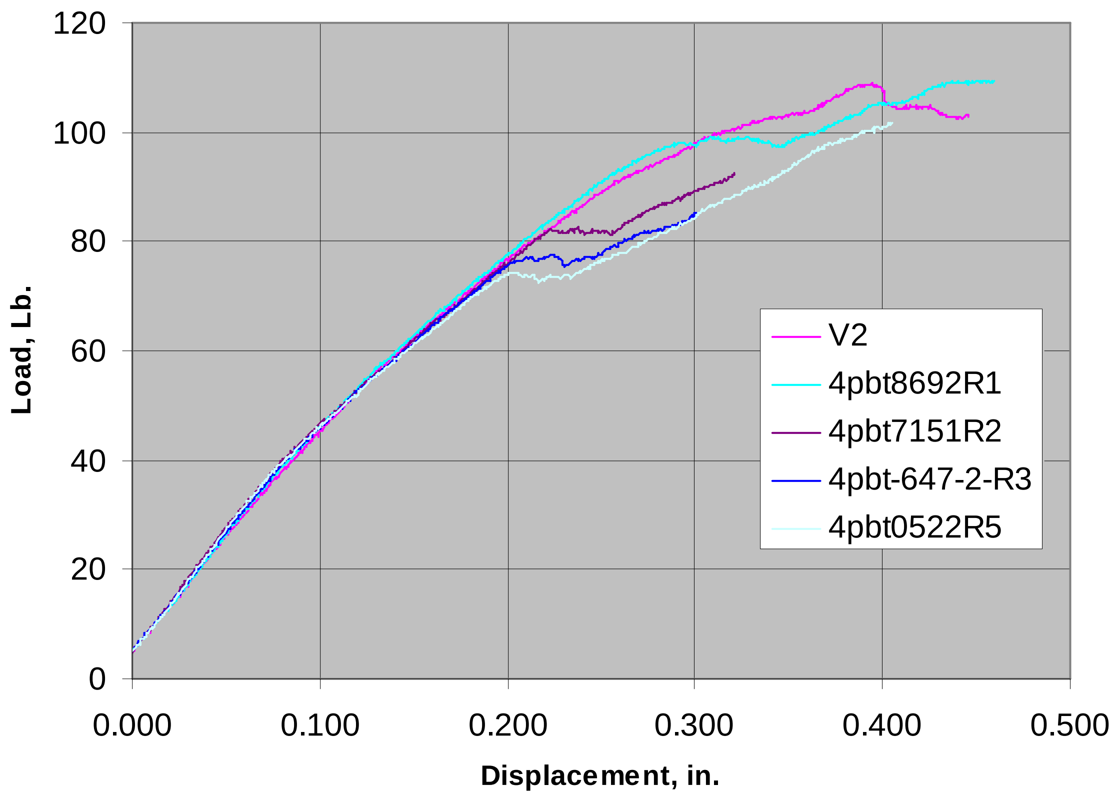


Figure 8 - Four point bending test results for reworked BGA/PC boards.

Cross-section and fracture surface analysis are shown in Figure 9-13, with variety of failure modes observed on the tested samples. The predominant failure in the bending testing is pad fracture from the board laminates. Partial intermetallic fracture from the pad was also seen on several locations. Complete fracture through the IMC, however, was rare and occurred at only three BGA interconnects and only on the sample with one rework cycle. Again, the IMC thickness did not increase the tendency to fracture through the IMC. It is clear from Figure 12 and 13, that the thick intermetallic layers are not embrittled, since the pad separated from the board during the testing, and the pad experienced macroscopic scale deformation. For ball 3 shown in Figure 13 with 5 reworks, it is among most stressed, but there is no obvious cracking during the whole bending test.

A complete cross section and SEM analysis of the first two rows of the post-bend test samples are shown in Figure 14. The fracture mode type for each ball was documented. The fracture mode categories were defined as follows:

0 - No cracking of within the solder, at the IMC interface, or within the PCB laminate.
1 – Ductile fracture within the bulk solder.
2 – Partial cracking at the IMC interface.
3 – Complete cracking through the IMC interface.
4 – Partial cracking of the PCB laminate.
5 – Complete separation of the Copper pad from the PCB laminate
6 – Mixed mode: Both partial cracking at the IMC and within the PCB laminate.

Again, these results indicate that while the intermetallic layer after multiple reworks can be very thick, it is not necessarily the weakest links. The pad bonding strength is generally reduced even after the first rework. The industry generally accepts two rework cycles. This study shows that both pad strength and solder ball strength are not reduced noticeably further after up to 5 reworks. There is still room to perform at least one more rework cycles beyond the current allowed rework cycle limit for BGA components.

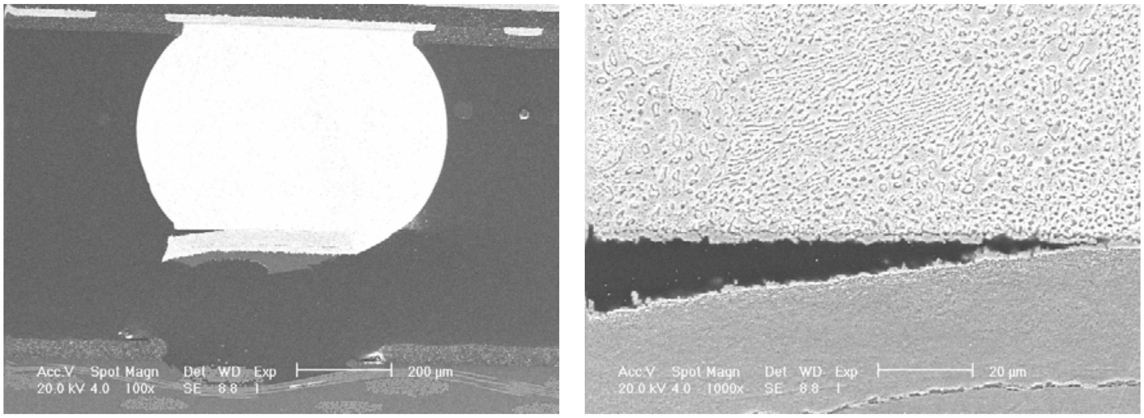


Figure 9 - Ball, Copper and laminate separation (zero rework).

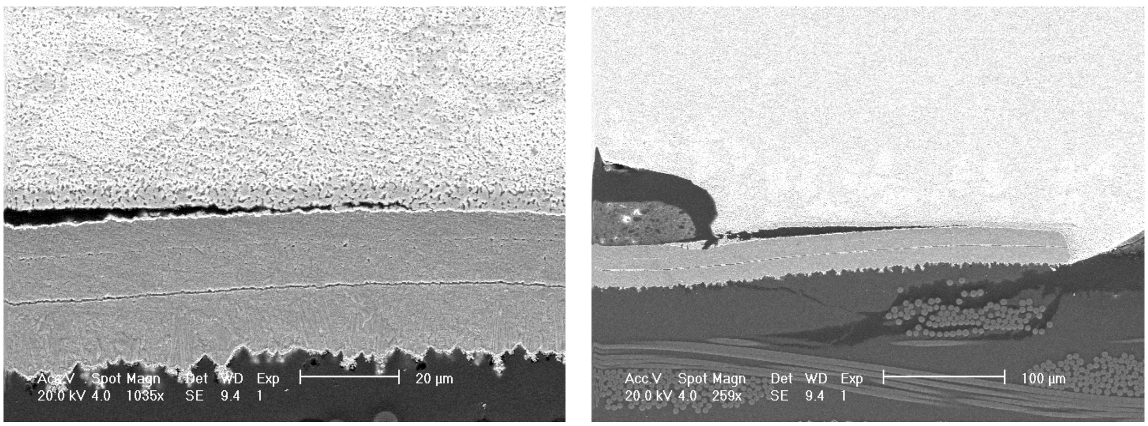


Figure10 - Failure modes of balls from first row of component after 1 rework cycle.

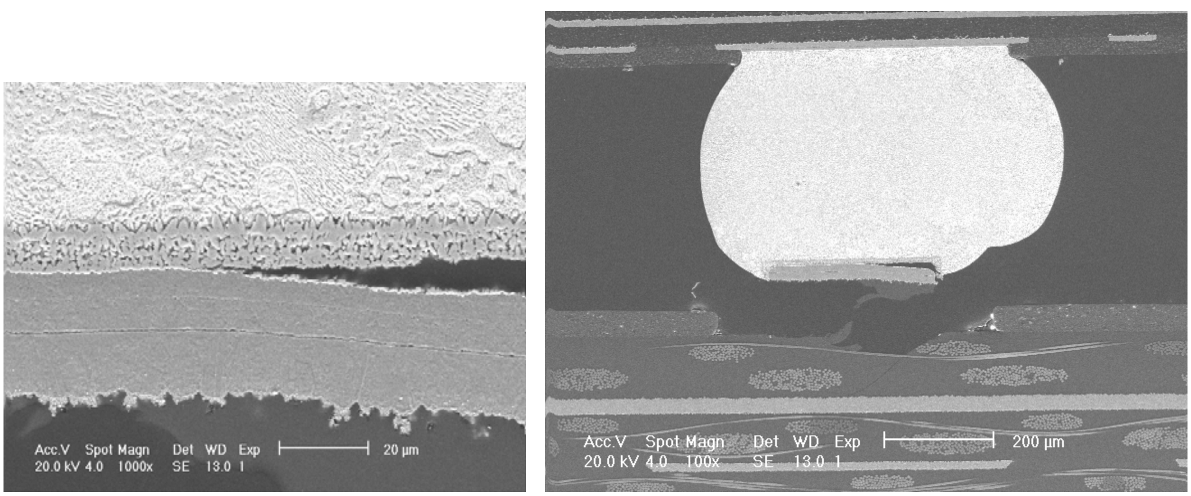


Figure 11 - Ball partial cracking and laminate separation after 3 rework cycles.

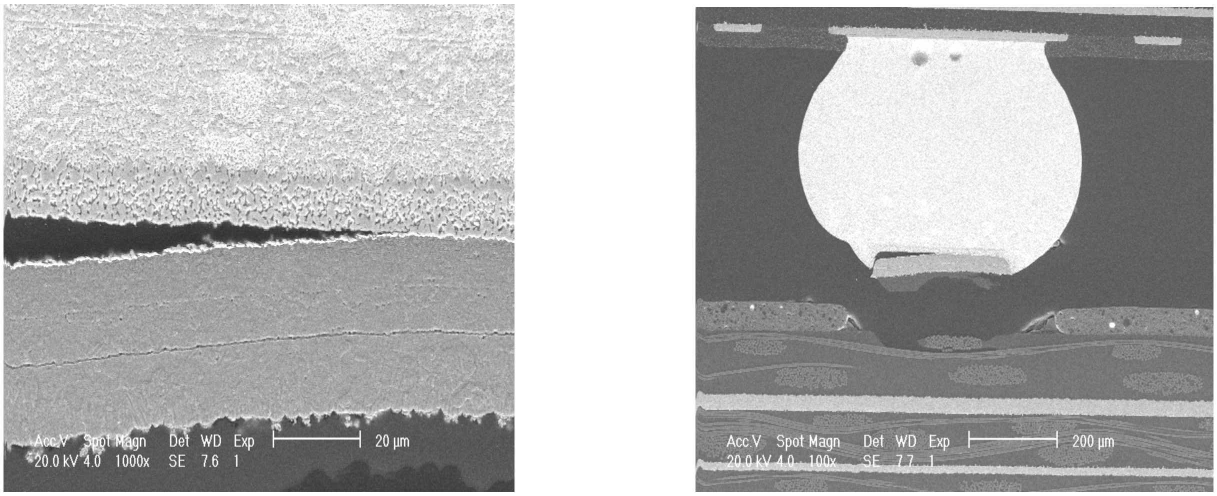


Figure 12 - Ball 8-partial cracking and laminate separation 5 rework.

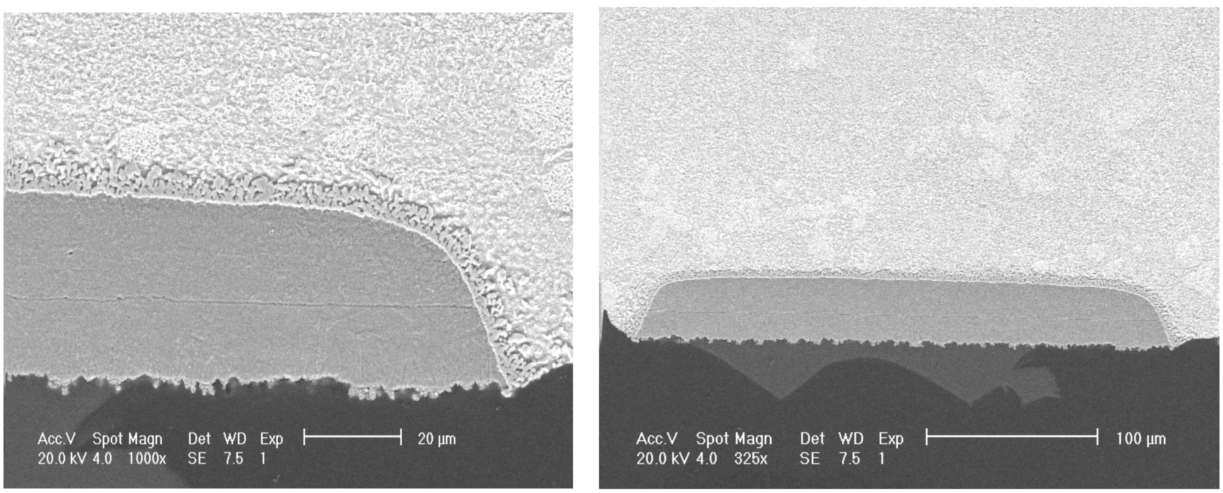


Figure 13 - Ball 3-no cracking from first row of component after 5 rework cycles.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
As-Received																																
Row AM	X	1	5	5	5	5	5	5	5	5	5	5	5	5	5	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	X
Row AL	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	6	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2
R1																																
Row A	X	5	3	5	3	5	5	5	3	5	5	5	5	5	5	5	6	6	6	6	0	0	0	0	0	0	0	0	0	6	6	X
Row B	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	6	6	0	0	0	0	0	0	0	0	4	6	6	6
R2																																
Row AM	X	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	6	0	0	0	0	0	0	0	0	6	6	6	6	X
Row AL	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	0	0	0	0	0	0	0	0	4	4	4	4	5
R3																																
Row AM	X	6	6	0	0	0	0	0	0	0	0	0	0	0	0	6	6	6	6	6	6	5	6	5	5	5	5	5	5	5	5	X
Row AL	6	6	6	6	6	0	0	0	0	0	0	0	0	6	6	6	6	6	6	6	6	6	5	5	5	5	5	5	5	5	5	5
R5																																
Row AM	X	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4	4	0	0	0	0	0	0	4	4	6	6	6	X
Row AL	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4	4	0	0	0	0	0	0	0	0	6	6	6	6

0 no cracking
1 solder crack
2 partial IM crack, no laminate separation or cracking
3 complete IM fracture
4 no cracking in IM, partial cracking of laminate
5 complete laminate fracture
6 partial IM crack, partial laminate cracking

"X" indicates no ball is present due to Bga component construction

Figure 14 Failure modes at each solder ball locations after 4 point bending testing.

Conclusions

Both ball shearing tests and four point bending tests show that strength of BGA solder ball itself was not reduced significantly after repair / rework operation from one up to five cycles. The intermetallic structure layer after rework is a mixture of IMC, Sn-rich and Pb-rich phases. While this mixture layer could reach more than 10 micro-meters in thickness, there is no indication from mechanical tests and cross-section optical / SEM analyses that this thick layer would reduce the strength of BGA solder balls, and cause premature embrittlement. However, the bonding strength of the copper pads to the laminates is reduced with rework/repair operation, with the great reduction coming from the first and second rework operation. In general, the industry recommends two rework cycles for BGA components on the same spot. This study indicates that further rework (up to 5) causes little further degradation; therefore there is room to increase the total rework cycle limit beyond recommended two for plastic BGA components.

Acknowledgement

Special thanks to Gordon Barr for preparing the rework sites and mechanical testing samples, also to Paul Callahan and his associates for the cross-section and SEM work.

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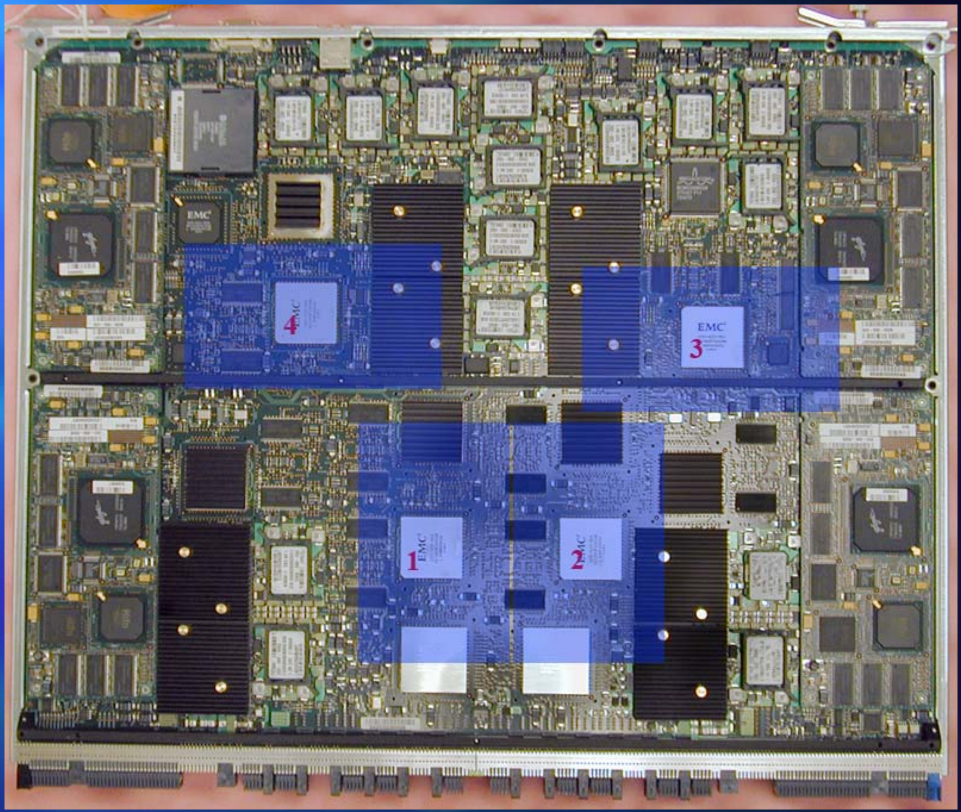
BGA Rework Issues

- BGA removal and replacement are required during product development, and for manufacturing and field returns.
- BGA multiple revisions during a product development may force development boards to go through multiple removal and replacement cycles on the same BGA locations.

Rework Risks:
Relationship among rework processes, intermetallic thickness, and mechanical strength of BGA balls, maximum permitted limits to BGA rework.

Test Sample Preparation

- Samples are produced under the following conditions: virgin, 1, 2, 3, 5 reworks.
- Each ball shear test sample had 10 attached balls after the last replacement stage, except sample which has virgin conditions



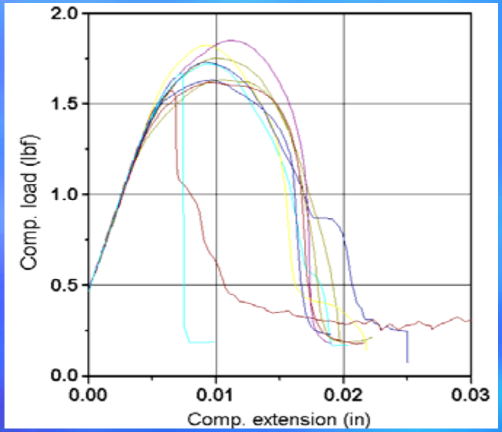
High density/high reliability board

Experimental Setup

BGA Ball Shearing Test

Four point bending test fixture and setup

BGA Shear Test Results and Analyses



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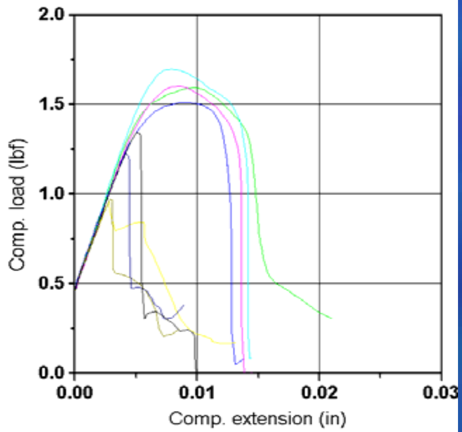


b)

Ball shearing test results for BGA balls with:

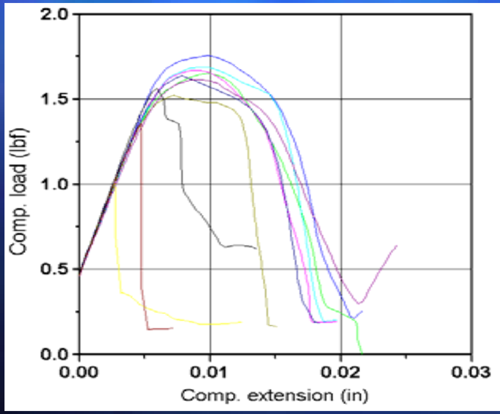
a) zero rework

b) one rework

c) two rework

d) three rework

e) 5 rework



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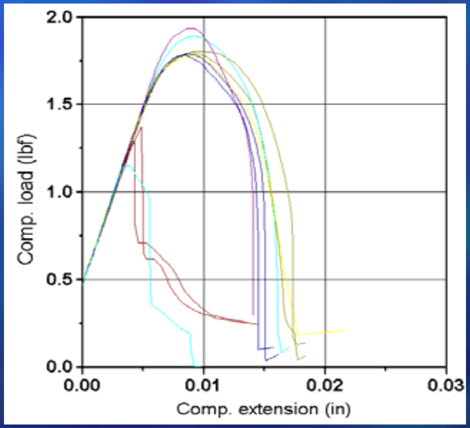

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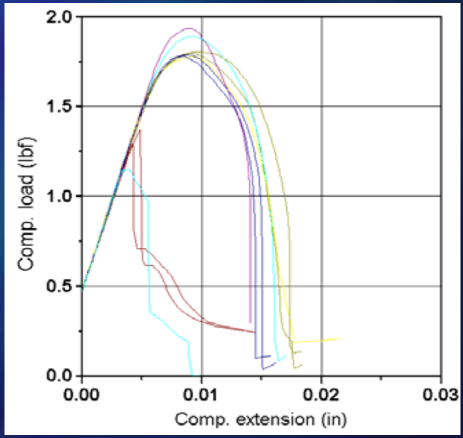
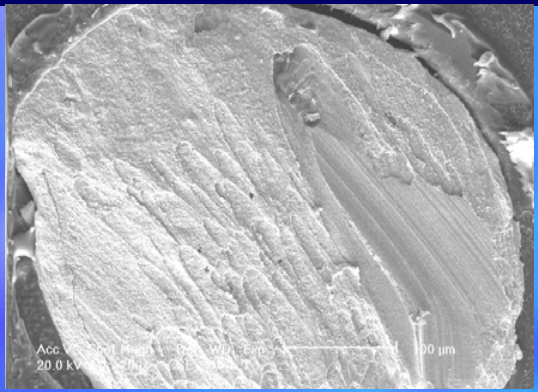
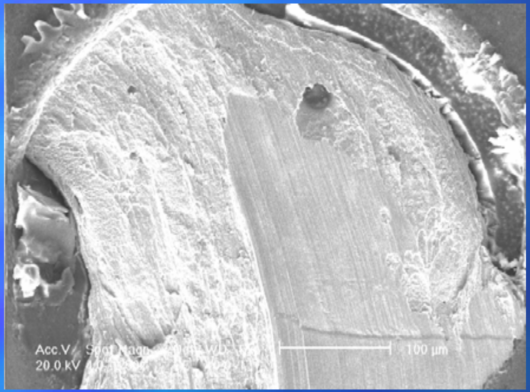


e)

SEM pictures of pad's surfaces after ball shear tests



a)



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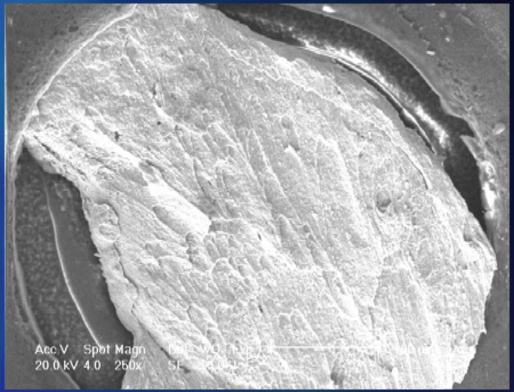

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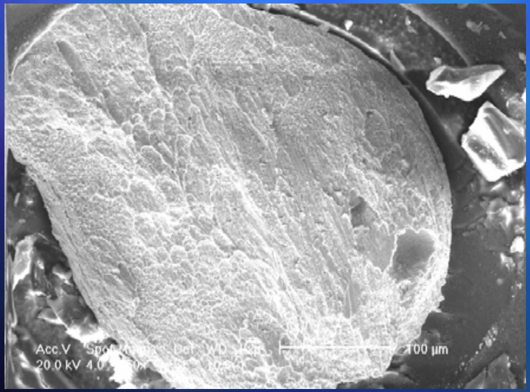

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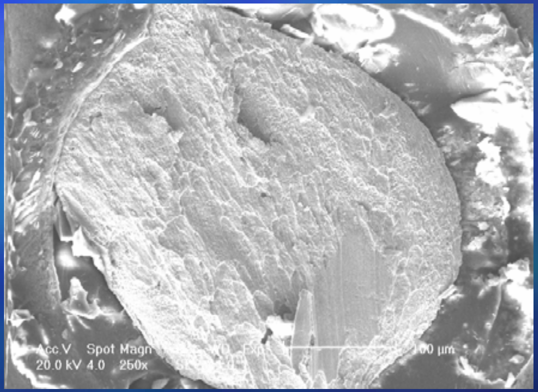
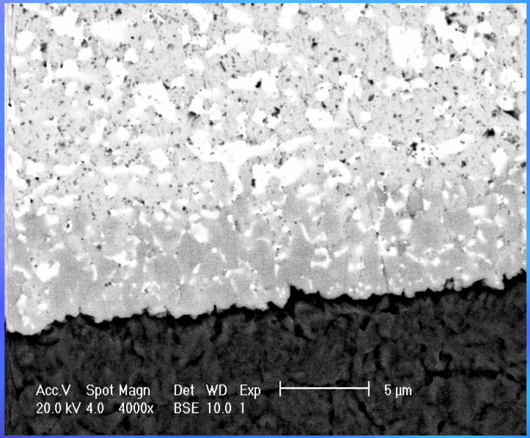


e)

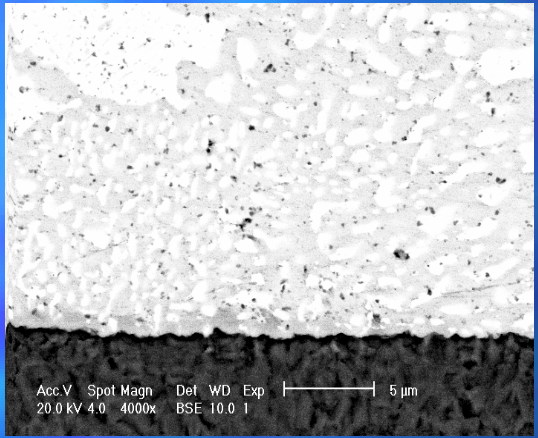
Ball shearing test results for BGA balls with:

a) zero rework
b) one rework
c) two rework
d) three rework
e) 5 rework

Intermetallic Thickness vs. Rework Cycle



a)



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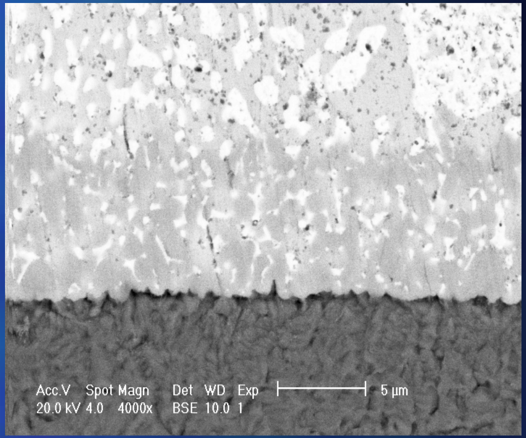

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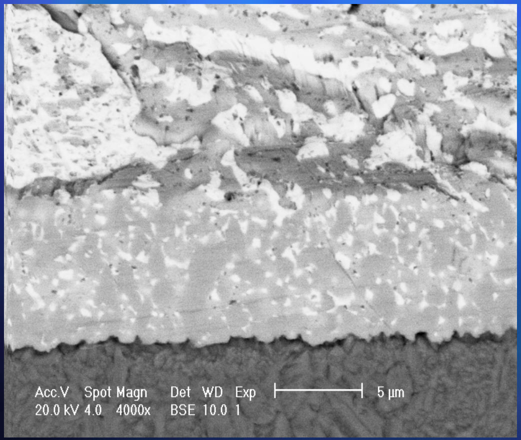

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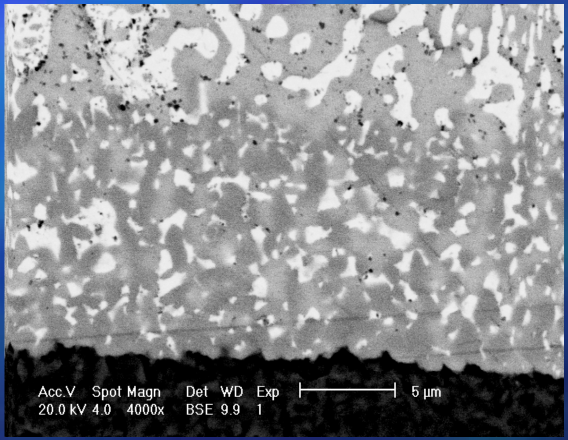


e)

Ball shearing test results for BGA balls with:

a) zero rework
b) one rework
c) two rework
d) three rework
e) 5 rework

Intermetallic Thickness vs. Rework Cycles

Director PCB SMT Pad Cu/Sn Intermetallic Thickness Measurements (Values are in Microinches)

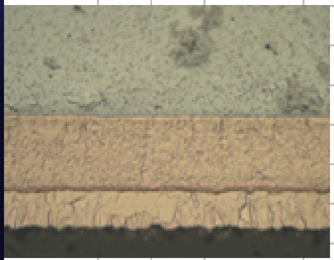
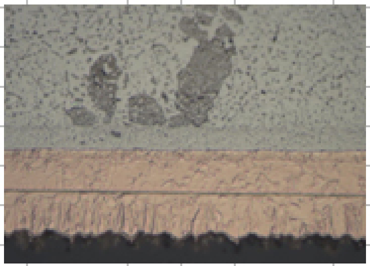
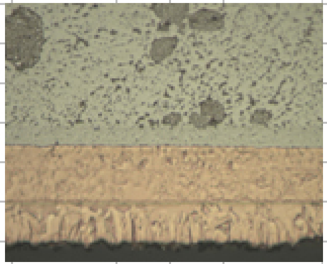
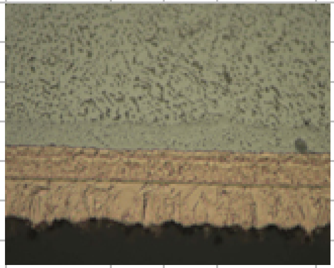
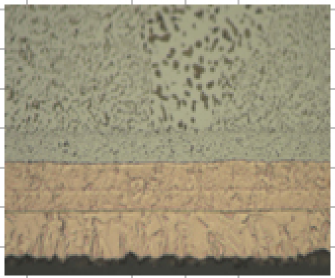
Test Condition	SMT Pad	Area	Measured Value
Virgin	1	A	104
		B	75
		C	83
	2	A	60
		B	65
		C	74
	3	A	68
		B	75
		C	38
Mean:			71
Std. Dev.			18

Test Condition	SMT Pad	Area	Measured Value
Reflow 1x	1	A	279
		B	279
		C	324
	2	A	264
		B	249
		C	317
	3	A	241
		B	271
		C	287
Mean:			279
Std. Dev.			28

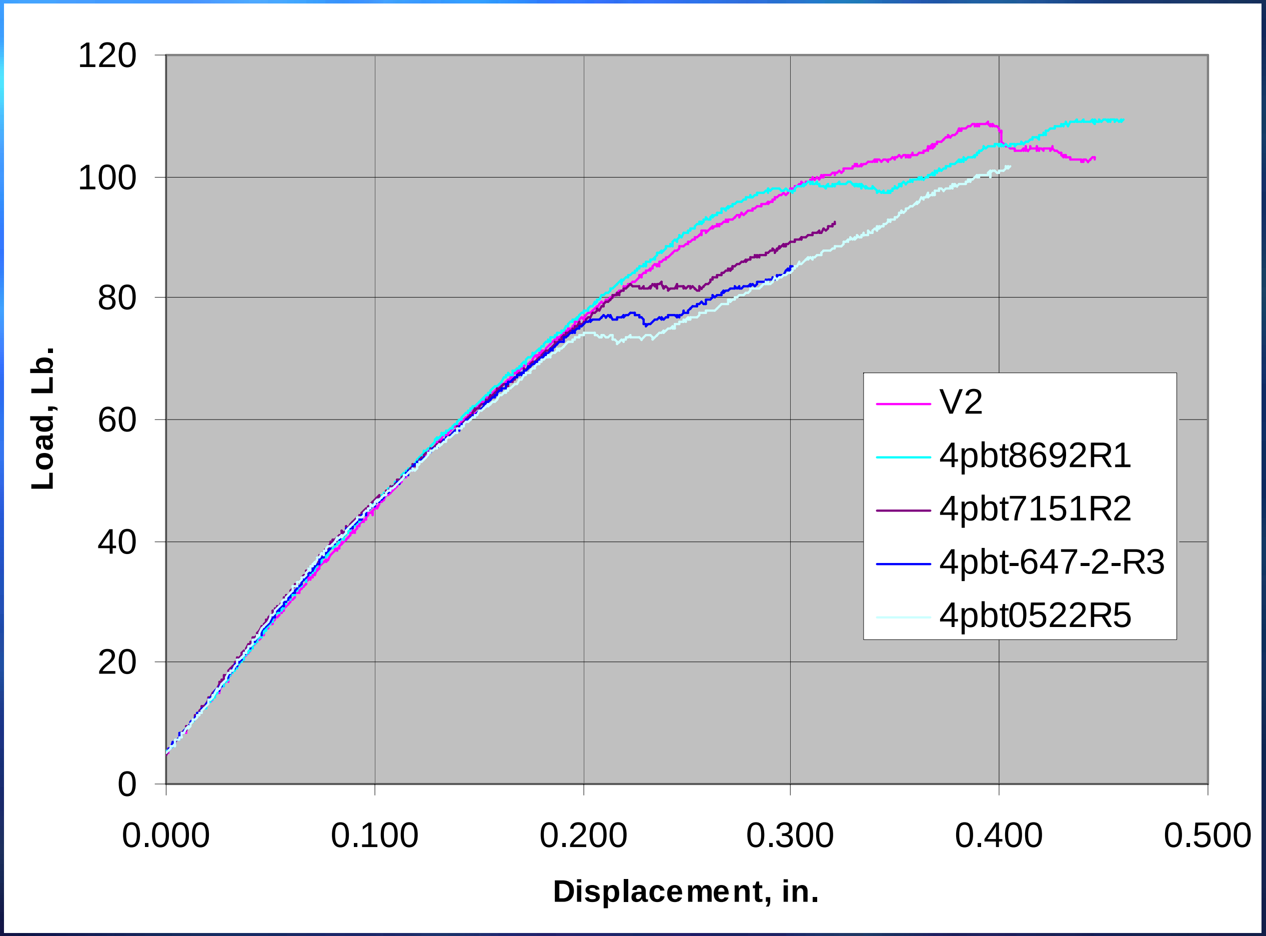
Test Condition	SMT Pad	Area	Measured Value
Reflow 2x	1	A	287
		B	219
		C	234
	2	A	264
		B	271
		C	279
	3	A	362
		B	257
		C	293
Mean:			274
Std. Dev.			41

Test Condition	SMT Pad	Area	Measured Value
Reflow 3x	1	A	354
		B	317
		C	324
	2	A	324
		B	347
		C	339
	3	A	332
		B	317
		C	324
Mean:			331
Std. Dev.			13

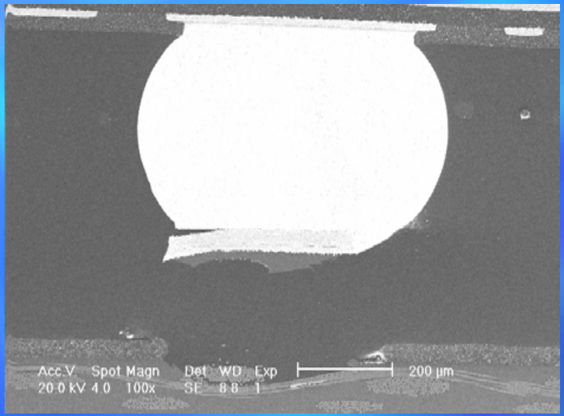
Test Condition	SMT Pad	Area	Measured Value
Reflow 5x	1	A	483
		B	422
		C	445
	2	A	490
		B	400
		C	385
	3	A	452
		B	407
		C	422
Mean:			434
Std. Dev.			36

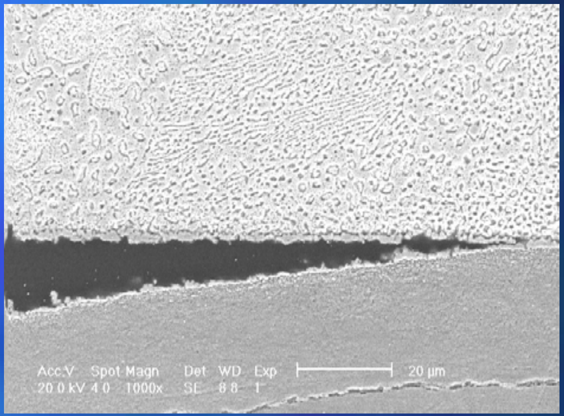






Four point bending test results for reworked BGA/PC boards

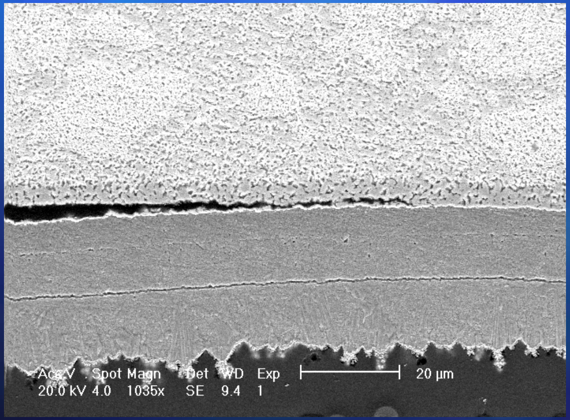


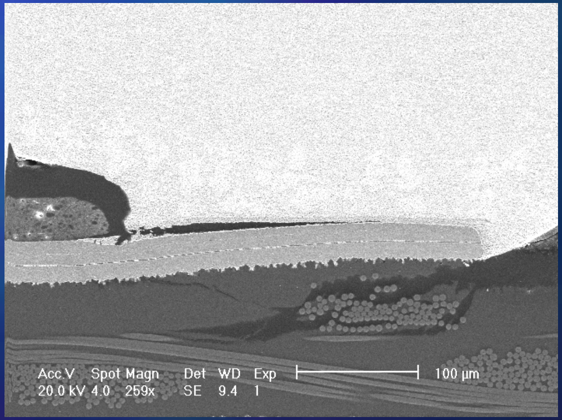
Failure Modes





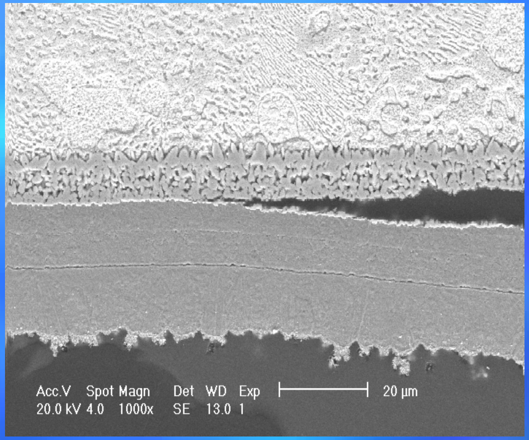
Ball , Copper and laminate separation (zero rework).

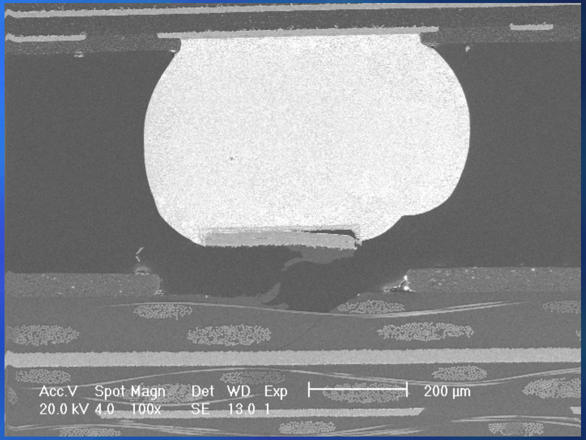




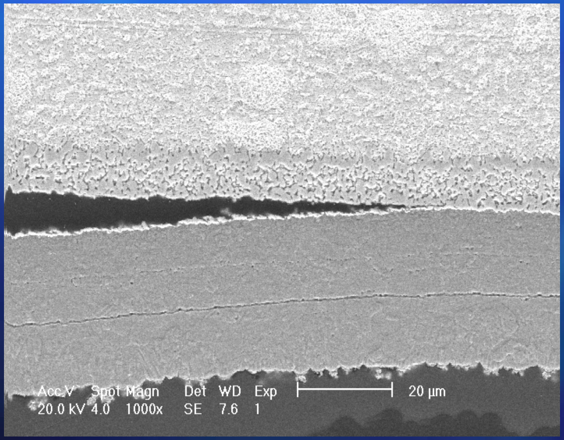
Failure modes of balls from first row of component after 1 rework cycle.

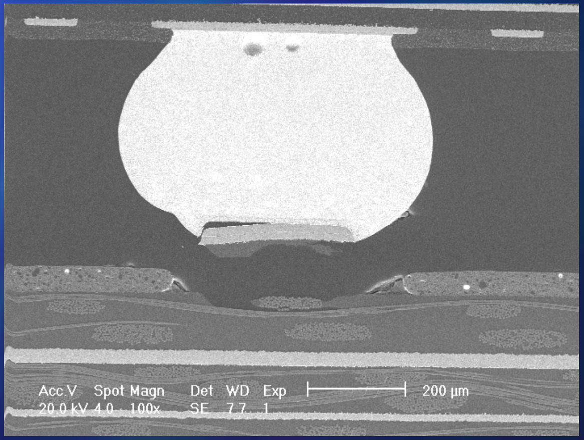
Failure Modes





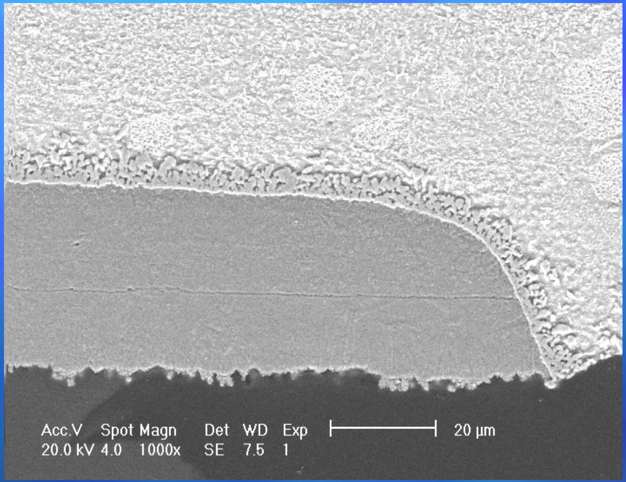
Ball partial cracking and laminate separation after 3 rework cycles.

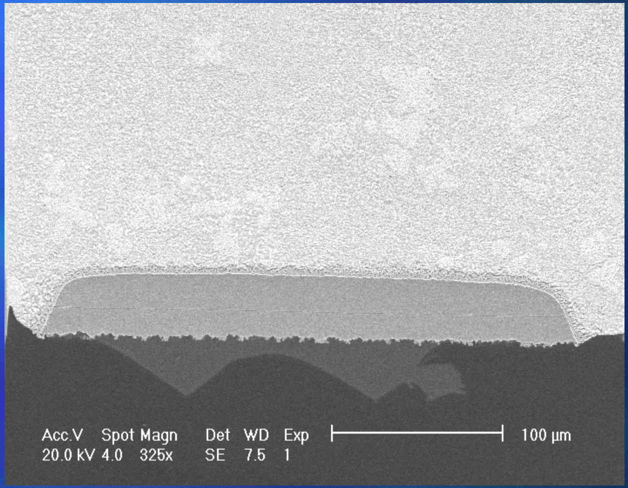




Ball 8-partial cracking and laminate separation 5 rework. cycles

Ball 3-no cracking from first row of component after 5 rework cycles.





The fracture mode categories were defined as follows:

0 - No cracking of within the solder, at the IMC interface, or within the PCB laminate.
1 – Ductile fracture within the bulk solder.
2 – Partial cracking at the IMC interface.
3 – Complete cracking through the IMC interface.
4 – Partial cracking of the PCB laminate.
5 – Complete separation of the Copper pad from the PCB laminate
6 – Mixed mode: Both partial cracking at the IMC and within the PCB laminate.

Failure modes at each solder ball locations after 4 point bending testing

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
As-Received																																
Row AM	X	1	5	5	5	5	5	5	5	5	5	5	5	5	5	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	X
Row AL	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	6	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2
R1																																
Row A	X	5	3	5	3	5	5	5	3	5	5	5	5	5	5	5	6	6	6	6	0	0	0	0	0	0	0	0	0	6	6	X
Row B	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	6	6	0	0	0	0	0	0	0	0	4	6	6	6
R2																																
Row AM	X	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	6	0	0	0	0	0	0	0	0	6	6	6	6	X
Row AL	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	0	0	0	0	0	0	0	0	4	4	4	4	5
R3																																
Row AM	X	6	6	0	0	0	0	0	0	0	0	0	0	0	0	6	6	6	6	6	6	5	6	5	5	5	5	5	5	5	5	X
Row AL	6	6	6	6	6	0	0	0	0	0	0	0	0	6	6	6	6	6	6	6	6	6	5	5	5	5	5	5	5	5	5	5
R5																																
Row AM	X	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4	4	0	0	0	0	0	0	4	4	6	6	6	X
Row AL	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4	4	0	0	0	0	0	0	0	0	6	6	6	6

0 no cracking
1 solder crack
2 partial IM crack, no laminate separation or cracking
3 complete IM fracture
4 no cracking in IM, partial cracking of laminate
5 complete laminate fracture
6 partial IM crack, partial laminate cracking

"X" indicates no ball is present due to Bga component construction

Conclusions

- BGA solder ball strength was not reduced significantly after repair / rework operation from one up to five cycles.
- There is no indication from mechanical tests and cross-section optical / SEM analyses that this thick intermetallic layer would reduce the strength of BGA solder balls
- The bonding strength of the copper pads to the laminates is reduced with rework/repair operation.

This study indicates that further rework (up to 5) causes little further degradation, therefore there is room to increase the total rework cycle limit beyond recommended two for plastic BGA components.