A Novel Approach to Evaluate the Impact on Solder Joint Reliability due to Multiple BGA Rework

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Abstract
PCB assemblies with numerous BGAs often go through multiple BGA reworks but there is not much data to suggest its effect on the long term solder joint reliability of the BGAs. This study is focused in addressing this gap and to provide a recommendation for the number of BGA reworks that could be performed without any impact to solder reliability.

To prepare a test unit for evaluating BGA solder joint reliability after multiple reworks, many BGAs are required for the multiple detaching / attaching process. This traditional method is labor intensive and expensive. A novel method for test unit preparation of multiply reworked BGA is explored here. In this method, instead of detaching an old and replacing a new BGA, the same BGA unit was reflowed on the assembly multiple times to mimic the thermal excursion cycles. In the last rework cycle, a new BGA replaces the old one that has been reflowed multiple times. The validity of the novel method was explored by comparing the solder joint microstructures obtained by the traditional and novel methods. The interfacial intermetallic layers, resulting from both the traditional and novel methods using identical temperature profiles and after up to 5 rework cycles, had comparable intermetallic thickness and porous microstructure. In the unit prepared with the novel method, the intermetallic layer became thicker and denser as rework cycles progressed, but after the last rework cycle in which a new BGA was added, the intermetallic layer became thinner and porous.

Using the novel method, two different BGA packages were chosen, 9x15mm CSP and 45mm FCBGA, to study both small and large package designs. Solder joint reliability was evaluated by performing Accelerated Thermal Cycling (ATC) and mechanical shock testing on the as-assembled controls, 3 and 5 reworked samples. Test results showed that there was no impact to solder joint reliability due to multiple BGA reworks.

Introduction
Many of the high reliability products such as telecommunications, networking and high-end servers use large and complex PCB assemblies. These boards (or board assemblies) typically have numerous solder joints with several BGAs, ranging from small memory CSPs to large ASIC packages. Also, the complexity of the board increases the opportunity for test failure during the structural, diagnostic and system testing. A perfect surface mount assembly might still result in failing diagnostic or system testing due to electrical performance margins involved among the various packages that interact while the product is tested as a complete system. A few examples of such failures include those that are unable to be debugged, intermittent failures and package-related electrical performance issues. Most of these failures are diagnosed to BGA parts on the board. Consequently, the number of BGA reworks performed on a board continues to increase with the assembly complexity. Repeated BGA rework on a given board has many disadvantages, such as, increase in lead time to shipment, requirement of skilled technicians to debug, higher cost of the final product due to additional material and resource requirements. A review of the published literature for any data on reliability impact due to multiple BGA rework proved to be futile. This augmented our interest in evaluating the number of BGA reworks that may be performed at a given location or at multiple locations on the same board, without impacting the long term field reliability of the PCB as well as that of the BGA solder joints.

Typically, BGA rework involves a reflow cycle for removing the part, site dressing, paste printing or flux application, followed by another reflow cycle for soldering the fresh BGA package. This traditional rework process is very labor intensive, requires extensive resources and needs a new BGA package for every rework to be performed. Site dressing is one critical process that may cause physical damage to the PCB, depending upon the technique used and the operator skills. This site dressing operation during the BGA rework process could introduce more variables, which may cause lack of consistency in the board samples required for the reliability experiment and potentially damage the solder mask. Hence, we explored alternative or simpler BGA rework method, which would be equivalent to the typical or traditional one and also mitigate the labor and resource requirements required for this solder reliability study. However, the alternate rework method to be considered equivalent to the traditional method, must exhibit similar solder joint microstructure as a traditionally reworked BGA, for the number of reworks considered.

In order to mitigate the material requirements, the concept of performing the multiple rework without removing the BGA was considered. This is basically subjecting the same package through multiple rework reflow profiles. Various published studies [1] have discussed in detail the Intermetallic Compound (IMC) formed, scallop shaped η-phase (Cu_6Sn_5) with channels or deep groves for Cu-dissolution in to the solder, when a Sn37Pb ball is soldered to a Cu-pad. Nevertheless, with the increase in number of reflows without removing the part, one would expect for the □-phase scallops to grow in size and become more planar. Interestingly enough the idea of performing a traditional rework process for the last rework alone was considered. This concept not only reduces the number of BGAs required for this project but also minimizes any potential damage to boards due to site dressing operation. The expectation of this concept was that the introduction of a new BGA ball could provide sufficient Time Above Liquidus (TAL) to produce a microstructure similar to a traditionally reworked BGA.

Taking into consideration the practical and economical intricacies involved, even on an experimental basis, in performing multiple BGA rework at any given board assembly house, it was determined that the solder reliability will be evaluated only for 3 and 5 BGA rework conditions. An experiment was designed to prove that the traditional and the proposed new or novel rework method resulted in similar solder joint microstructure. Finally, additional samples were built for solder joint reliability testing to evaluate the impact due to multiple rework.

PCB reliability was evaluated using test coupons by performing Deep Thermal Cycle (DTC) testing. Although CAF testing was also performed using another test coupon design, which was subjected to 0, 5 and 10 reflow preconditioning, the results will be presented separately in the near future.

BGA Rework – Traditional Vs. Novel Methodology

Rework Methodology – Test Plan

A 40mm FCBGA with Electrolytic Ni/Au finish was assembled on a PCB with Cu-OSP finish. An additional reflow was performed to simulate two SMT reflows as preconditioning. Six such samples were prepared as summarized in Table 1, which includes 3 and 5 BGA rework samples using the traditional and novel method respectively. Also, included were samples (Boards 5 and 6 in Table 1) without any component replacement to understand the effect of multiple reflow, without component replacement, on the intermetallic structures. To prepare the novel BGA rework samples, the samples were simply run through heat cycles without removing the component up to N-1 rework cycles. The N^{th} cycle was performed the traditional way. For example, the 3 BGA rework sample was prepared by subjecting it through 4 additional reflows to simulate 2 rework cycles. The 3^{rd} or the N^{th} rework was performed the traditional way. The traditional and novel BGA rework was performed using the same rework profile. The rework profile had a peak temperature of 205 to 210C with a Time Above Liquidus (TAL) of 60 to 75 seconds. Also, the time intervals between reflows were automated such that the samples would undergo identical thermal profiles, regardless of the rework method employed.

Table 1 - Summary of IMC Study to Compare Between the Traditional and Novel rework Methodology

Board#	Rework Detail	IMC Thickness (um)	IMC Comments
Board - 1	Traditional - 5 reworks	5 - 7	Porous structure
Board - 2	Novel – 5 reworks (New BGA for 5^{th} rework)	5 - 6	Porous structure
Board - 3	Traditional - 3 reworks	5 - 6	Porous structure
Board – 4	Novel - 3 reworks (New BGA for 3^{rd} rework)	5 – 6	Porous structure
Board - 5	2X rework heat cycles; no new part	2 - 3	Dense structure
Board - 6	4X rework heat cycles; no new part	3 - 4	Dense structure.

Rework Methodology – Results

Microstructures of BGA samples reworked using the traditional and novel rework methods were analyzed to determine if the novel method could replace the traditional one. The primary focus during this comparison was the microstructure of the bulk solder and the PCB side Inter Metallic Compound (IMC). Since the last BGA rework always had a new package independent of the BGA rework method, the package side IMC was not included for comparison purposes.

Figures 1 and 2 (a and b) & Table 1 shows the PCB side intermetallics of 3 and 5 BGA reworks in both traditional and novel method. The Cu_6Sn_5 (□-phase) exhibited the typical scallop shape in the 3 and 5 rework samples. The IMC thickness increased with the number of reworks performed. The IMC structure was similar in thickness range and porous in nature for both, 3 and 5 reworks, independent of the rework method employed.

The boards 5 and 6, which did not have the new BGA part after multiple rework simulation, was also studied at N-1 rework cycle, as shown in figures 3 (a and b). Multiple reflows during the novel method, without removing the package, resulted in dense/planar □-phase due to increase in the scallop size. Subsequent rework in the traditional manner, removing existing BGA and replacing with new BGA part, resulted in porous and scalloped □-phase microstructure. This phenomenon of dissolution of □-phase into an un-saturated solder (fresh BGA ball) due to subsequent reflow has been well demonstrated by Schaefer [1]. The microstructure study presented sufficient evidence that the degree of □-phase dissolution that occurred, for the rework profile conditions studied, during the N^{th} rework (traditional method) of a novel sample resulted in similar intermetallic structure as that of the traditionally reworked sample. Therefore, it was determined that the novel rework can be employed in place of the traditional rework method for this study.

Solder Reliability Study

Test Vehicle and Reliability Test:

Accelerated Thermal Cycling (ATC) between 0 to 100C per IPC 9701 and shock testing per JESD-22-B110, service levels B, C and D were performed. These levels correspond to 100g, 240g and 340g. Shock testing was performed 6 times in the z-direction only.

A test vehicle of 5.5"x5.5" in size, 2.3mm in thickness with 12 layers of Cu and Cu-OSP as surface finish was designed. Two such test vehicles were designed, one had the footprint of a 1mm pitch FCBGA (full array) with a body size of 45mm and 1932 solder joints, while the other had a 0.8mm pitch CSP with a body size of 9.3x15.1mm and 92 solder joints, with only one component per board as shown in Figures 4 (a and b). The FCBGA and the CSP had Solder On Pad (SOP) and ENIG surface finishes respectively. 24 samples each for 0, 3 and 5 reworks were assembled for both the package types. 20 samples were tested through ATC and 4 underwent mechanical shock testing. Rework profiles for the FCBGA had a peak of 205C with TAL of 70secs. Similarly, the CSP had a peak of 215C and TAL of 80secs.

Results:

Shock testing of the FCBGA and CSP assemblies, reworked and non-reworked, did not exhibit any failures. Although the boards were not tested to failure, it is evident that there is no significant degradation of the solder joint mechanical reliability. The maximum principal strain observed during 340g testing was 1870 and 1050 micro strains for the FCBGA and CSP respectively.

As part of ATC testing, the FCBGA packages underwent 3500 cycles without any failures. Failure analysis included dye and pries and cross sectioning of 0, 3 and 5 rework assemblies, which showed typical solder fatigue cracks. The dye and pry results showed solder cracks as high as 50 to 75% of the package pad area (Figure 5a). The worst case joint was always under the die periphery for all the scenarios, reworked and non-reworked. A typical cross section of a FCBGA is shown in figure 7a, which has 50% crack on the package side.

The CSPs underwent 5000 cycles without any failures, except for one from the 3 rework samples, which failed at 3322cycles. This failure was confirmed to be a typical solder fatigue as shown in figure 6. The CSPs did not show any difference between the reworked and non-reworked samples with the exception of the one failed sample mentioned earlier. Dye and pry showed that the worst case crack propagation among 0, 3 and 5 rework CSP parts had a maximum of 50% dye penetration along the package pad interface (Figure 5b). A typical cross section of the CSP samples tested up to 5000 cycles is shown in figure 7b. Thus, we can conclude that there is no impact to solder joint fatigue life when reworked up to 5 times.

PCB Reliability Study

Testing Details:

Apart from solder joint reliability evaluation, the effect of multiple rework on PCB reliability was also studied using test coupons. However, instead of the intensive multiple rework profile preconditioning the PCB test coupons were actually subjected to mass reflow.

High Tg FR4 PCB coupons (figure 8) designed with a series of daisy chained plated through holes, manufactured by two different suppliers (A & B), was subjected to 5 and 10 times through a 225C peak temperature reflow with 85 seconds TAL. Samples without any reflow preconditioning were included as a control. The PCB coupon used was 0.114" thick with 26 copper layers and used OSP surface finish. 30 samples were used for each of the multiple reflow condition. The reflowed test coupons were inspected for delamination using CSAM. Subsequently, the coupons underwent 30 minute Deep Thermal Cycle (DTC) testing between -35 and 125C with 10mins dwell and 5mins ramps.

Results:

The FR4 test coupons reflowed 0, 5 and 10 times did not exhibit any signs of delamination. These coupons underwent 1000cycles of DTC testing with in-situ resistance monitoring. The PCB coupons provided by supplier A had comparable characteristic life ranging from 625 to 700 cycles with a time to first failure of 400 to 500 cycles. The coupons from supplier B did not have sufficient failures to create a Weibull plot. However the cycle to first failure was 720, 650 and 610 for the 0, 5 and 10 reflowed samples respectively. Based on these results, we can conclude that up to 4 BGA reworks can be performed without any degradation in PCB reliability.

Summary and Conclusions

- Traditional and Novel method of BGA rework resulted in similar IMCs, thickness, shape and porous structure, for both 3 and 5 BGA reworks. Hence these methods are considered to be equivalent.

- In the novel rework method multiple reflows without removing the BGA resulted in thicker and planar IMC structure.

- Reworked and non-reworked samples did not have any failures during mechanical shock testing.

- ATC testing of FCBGA and CSPs did not exhibit any significant difference in solder reliability among the no-rework, 3 and 5 rework samples. The worst case joint was always under the die periphery for both the packages, while the largest crack was 75% and 50% of pad area on the package side of the FCBGAs and CSPs respectively.

- Solder joint reliability and mechanical shock testing indicates that up to 5 BGA rework, at any given location, can be performed without any risk to long term field reliability, in the absence of any visual defects due to mechanical and thermal damage.

- PCB reliability results suggest that up to 4 BGA rework can be performed without any risk to long term field reliability.

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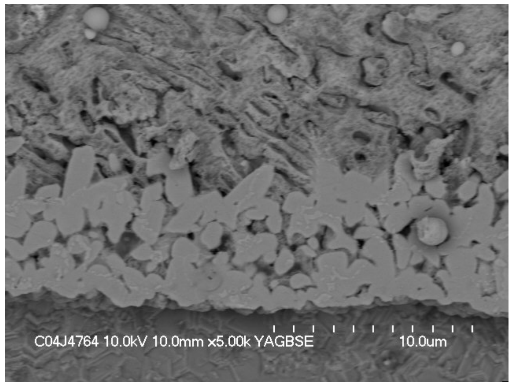

Figure 1a - IMC at the PCB side of a 3 times Reworked BGA Sample Using the Traditional Methodology

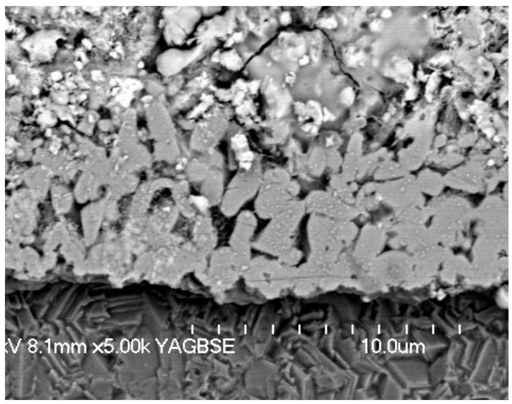

Figure 1b - IMC at the PCB Side of a 3 Times Reworked BGA Sample Using the Novel Methodology

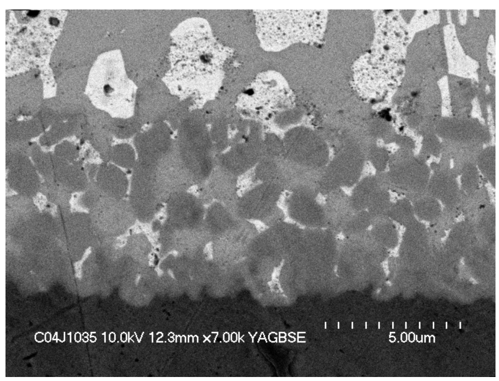

Figure 2a - IMC at the PCB side of a 5 Times Reworked BGA Sample using the Traditional Methodology

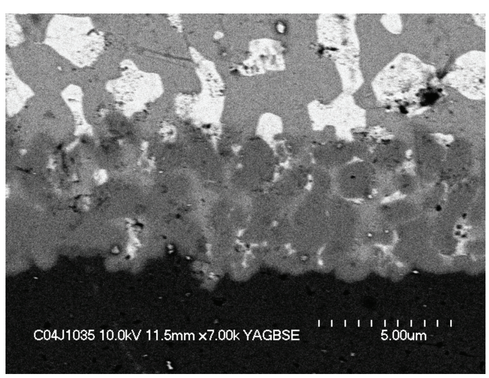

Figure 2b - IMC at the PCB side of a 5 Times Reworked BGA Sample Using the Novel Methodology

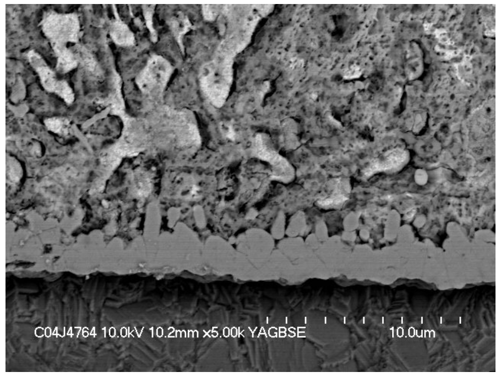

Figure 3a - IMC at the PCB Side of Board-5 (no fresh part)

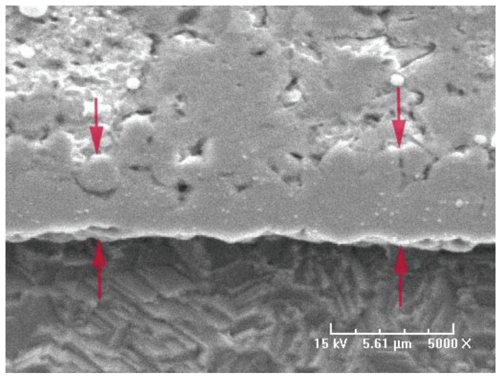

Figure 3b - IMC at the PCB Side of Board-6 (no fresh part)

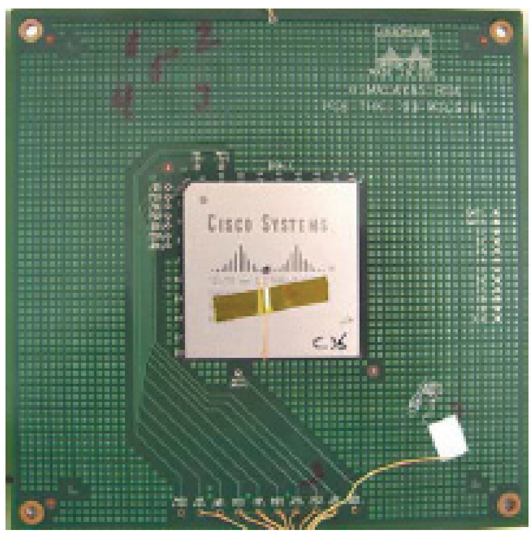

Figure 4 - Test board Assembled with 45mm FCBGA for Reliability Testing

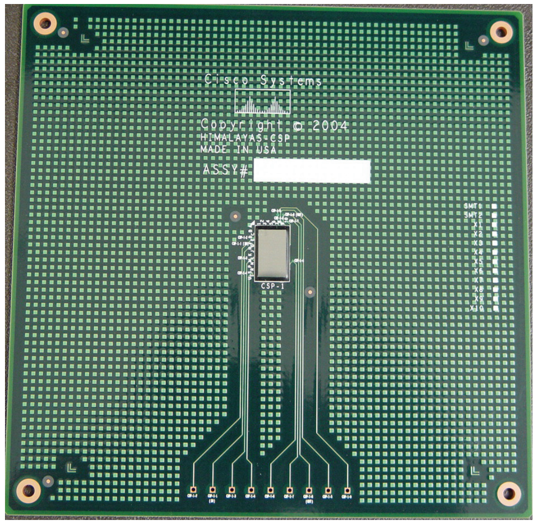

Figure 4b - Test Board Assembled with WBGA92 for Reliability Testing

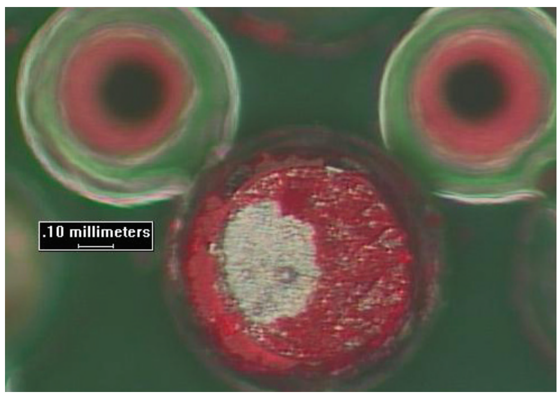

Figure 5a - 75% dye Penetration at the Package Interface for FCBGA

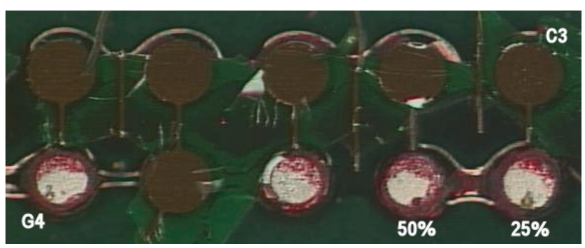

Figure 5b - 75% dye Penetration at the Package Interface for WBGA92

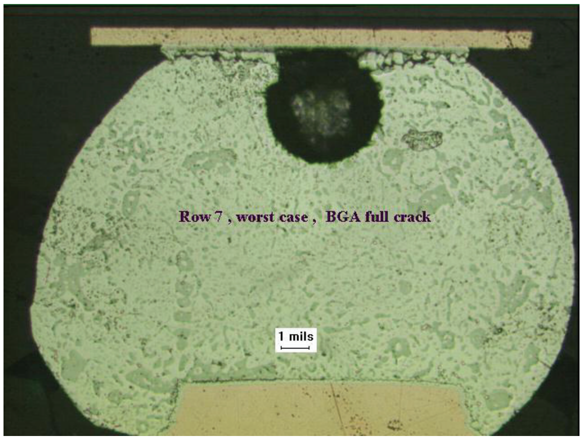

Figure 6 - Failure Mode of 3 Times Reworked WBGA Which Failed at 3322 Cycles

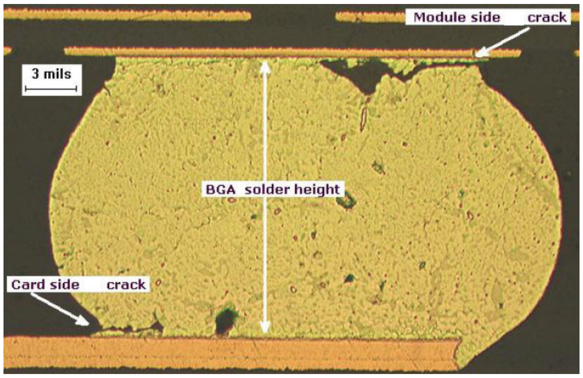

Figure 7b - Typical Cross section Image of an FCBGA after 3500 Cycles

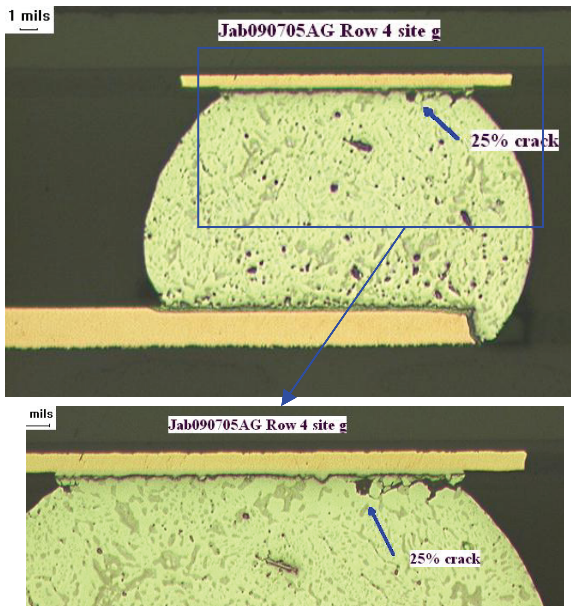

Figure 7b - Typical Cross Section image of an WBGA after 5000 Cycles

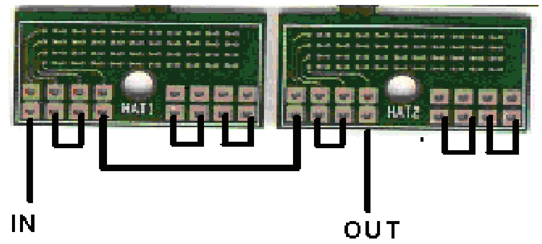

Figure 8 - PCB Coupon used for DTC Testing