Copper Pad Dissolution and Microstructure Analysis of Reworked Plastic Grid Array Assemblies

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Abstract
An experimental study was conducted to examine the impact of rework processes on quality and reliability. In this study, 676 IO plastic ball grid array packages were assembled with Sn3.0Ag0.5Cu solder paste and eutectic SnPb solder paste. Selected parts on circuit boards were subjected to rework processes one time, three times and five times. X-ray inspection and environmental scanning electron microscope were used to investigate impact of part replacement on the ball grid array voids, the microstructure of intermetallic compound, and copper pads. Since the rework process includes multiple liquid solder state periods, it consumes more copper and makes the intermetallic compound growth trend an interesting topic. Copper pad dissolution was found in the samples after multiple rework processes. Lead-free assemblies consumed more copper than mixed assemblies because of higher concentration of Sn in lead-free solder. The thickness of intermetallic layer increased as the total rework time increased. Ultra thick intermetallic compound was found at the connection area between the copper pad and the copper trace after the rework processes were applied three times and five times, which may lead to reliability concerns.

1 Introduction

The Directive on the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment (RoHS), which became effective on July 1, 2006, mandates that electronics industries no longer use tin-lead solder. China, Japan, and other countries have also published environmental regulations to restrict tin-lead solder [1]-[3]. At the same time, there are exemptions for some products whose applications require high reliability. These exemptions have not impacted the conversion of piece part suppliers to being lead-free.

Rework is defined as the correction of a defect before the printed board assembly leaves the plant, and repair is defined as the correction of a defect found in the field [4]. Since the electronic industry is now using the lead-free solder predominately, it is important to understand the impact of rework process and reworked assemblies on reliability. Some literature addresses copper dissolution in plated through-hole (PTH) barrels in the rework process [5]-[8]. This creates a concern because it is possible for a hidden defect to be present after reworking PTH assemblies. Currently, no literature has focused on the copper dissolution of reworked ball grid array (BGA) assemblies, which is another possible hidden defect.

Assemblies formed by the mixing of SnPb and Pb-free material are termed "mixed assemblies". Many studies have focused on the microstructures of mixed and lead-free solder interfaces [9]-[11]. The microstructure of mixed assemblies formed by lead-free BGAs and tin lead solder paste is related to the volume of solder paste. The intermetallic compound (IMC) growth during the isothermal aging condition is well understood. A driving force of this phenomena is solid solder/solid pad interdiffusion. The rework process includes multiple liquid solder state periods, which makes the IMC growth trend an interesting topic.

2 Experiments

In this study, 676 IO BGAs with Sn3.0Ag0.5Cu (SAC305) solder balls were assembled with SAC305 and eutectic solder paste. Individual locations on the printed circuit boards (PCBs) were subjected to rework one time, three times and five times. X-ray inspection was used to investigate BGA solder voids. Parts were cross-sectioned to inspect the consumption of copper pads and the morphology of IMC. An environmental scanning electron microscope (ESEM) and an energy-dispersive x-ray spectroscopy (EDS) were used to investigate the growth of IMC, as well as the composition of IMC.A set of test boards was designed and manufactured to test the effect of multiple rework processes on the reworked assemblies. The components assembled on the board were 676 IO BGAs with SAC solder balls. There were two kinds of assemblies, those using pure lead-free solder (SAC BGA and SAC solder paste) and those using mix-solder (SAC BGA and tin-lead solder paste).

Six BGAs were assembled on each board as shown in Figure 1. Three locations were selected to be reworked (see Figure 1). These three locations were first reworked one time. Then two of the three locations were reworked another two more times, and the last location was reworked two more times. Thus, there were three treatments for these BGA assemblies locations: one replacement, which means remove the BGAs on the PCB and replace a new BGA; three replacements, which means remove the BGAs three times, and every time replace a new BGA on the PCB; and five replacements, which means remove the BGAs five times, and every time replace a new BGA on the PCB. Table 1 lists the test matrix of reworked assemblies. The PCB assemblies were subjected to preconditioning at 100°C for 24 hours before being reworked and between each rework.

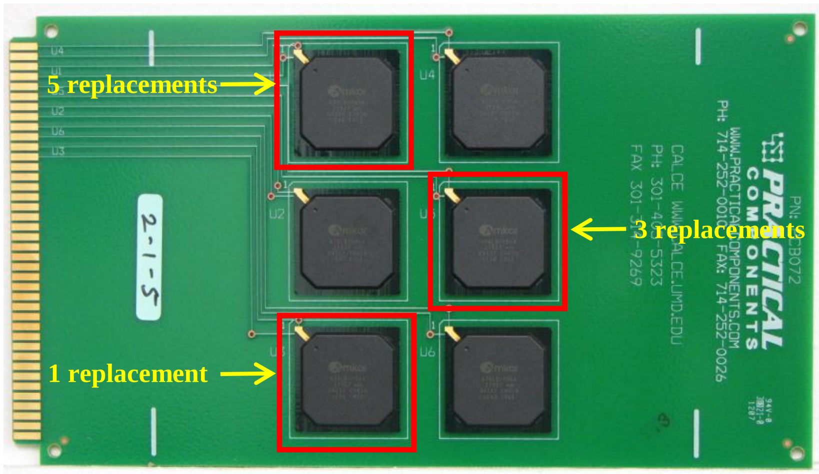


Figure 1: 676 IO BGA assemblies

Table 1: Rework test matrix of 676 IO BGAs

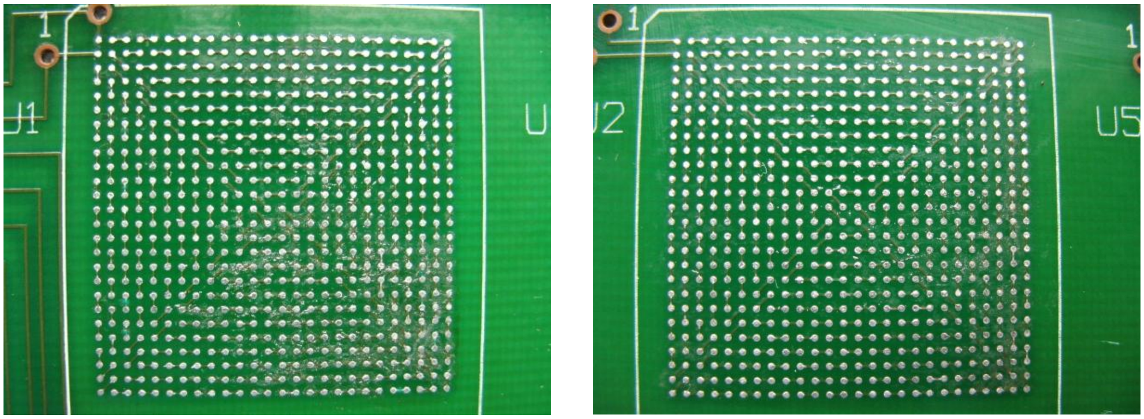
Assemblies Type	Part	Original	Repair Solder Ribbon/Paste	Reworked components
Lead-free assemblies	SAC 676 BGA	SnPb	SnPb	3
Mixed assemblies	SAC 676 BGA	SAC	SAC	3

The rework process of surface mount technology (SMT) components involves four steps: component removal, site redressing, component placement, and component reflow. To remove the components assembled on the PCB, a thermal profile needs to be set up to melt the solder. A thermal profile is established by various trial runs, as it depends on several factors such as board thickness, type of solder and component size.

A VJ Electronix SRT1800 rework station with a bottom heater and a hot nitrogen nozzle on top was used to replace the BGA components. The hot nitrogen nozzle was applied to each assembled BGA to heat up the solder, and at the peak temperature, when the solder melted, the component was removed by suction using a vacuum tool.

After the components were removed from the PCB, residue solder may be left on the pads. The pads must have a flat surface to insure the quality of replacement. In this study, the soldering iron and wick method was used to remove the residue solder from the pads. A fluxed copper braid was heated by the soldering iron and brushed over the pads. The heated braid melted the residue solder, and the solder was wicked up into the copper braid. Figure 2 shows the pads after site redressing. The pads showed a clean surfaces and solder mask were not damaged during the removal procedure.

Once the site was redressed, a mini-stencil was aligned and placed on the location, and the solder paste was printed on the pads. This mini-stencil was similar in size to the component and had openings that matched the pads. The lead-free rework used of Alpha OM-338 (SAC305), a type of lead-free, no-clean solder paste. The mixed solder rework used Indium SMQ-92J (6337), a no-clean, tin-lead solder paste. After solder paste was applied to pads, components were aligned and placed by semi-automated techniques to the locations. The hot nitrogen nozzle was placed above the components to melt the solder balls and solder paste. The new BGAs were assembled on the PCBs after cooling.



(a) (b)

Figure 2: Pads inspection after site redressing
(a) PCB pads of mixed assemblies; (b) PCB pads of lead-free assemblies

3 Results and Discussion

The non-reworked and reworked components were examined by X-ray inspection to assess the assembled and reworked quality. Then assembled BGAs were cut, molded, and cross-sectioned to investigate the copper pads and the intermetallic layer using environmental scanning electron microscope (Quanta FEG ESEM 200).

3.1 Void Calculation in Reworked and Non-Reworked Assemblies

IPC-7095 [12] offers information on BGA voids, including their sources, impact, detection, and elimination. Large voids can lead to reliability problems since a reduced cross-section of solder area has lower heat transfer, mechanical load burdening, and current carrying capability. X-ray inspection is the common detection equipment used to measure the void's percentage. Total voids larger than 30% of the solder ball diameter are considered unacceptable. The void's percentage can be the size of one void or the sum of the sizes of many voids.

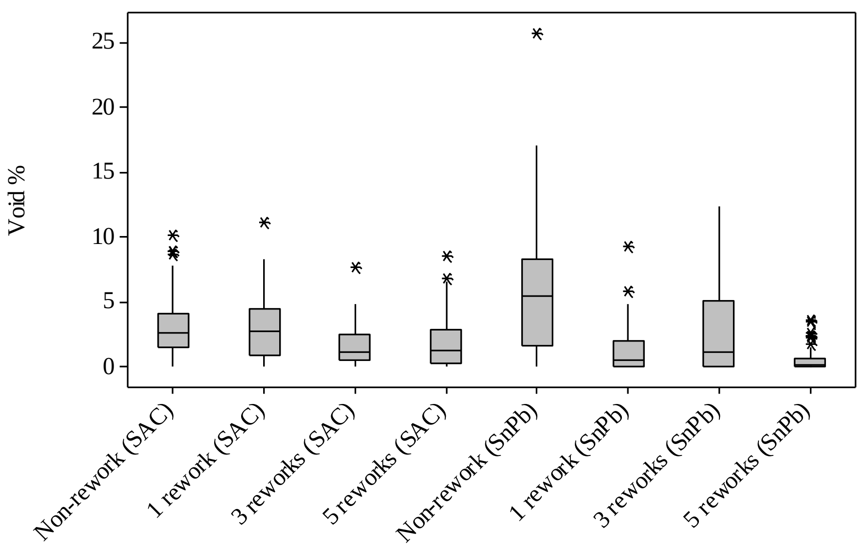


Figure 3: The calculation of void's percentage of non-reworked and reworked BGAs

X-ray inspection was used to detect the voids in non-reworked and reworked BGAs. For each BGA, 80 solder balls were examined from the four corners and the central part of the BGA to calculate the percentage of the voids. Figure 3 lists all of the voids' percentages in non-reworked and reworked BGAs. (The lines inside the rectangular box represent roughly the middle 50% of the data, and whiskers extend to either side indicating the general extent of the data. The stars refer to the outliers.) The lead-free assembled non-reworked BGA had a lower void percentage compared to the mixed assembled non-reworked BGA. But, after five replacements, the mixed assembled BGA had a lower void percentage than that of a pure lead-free assembled BGA. None of the BGAs failed the void's percentage calculation.

3.2 Copper Pad Dissolution

When a new component was attached to the pads during the rework process, reactions occurred between the solder balls and the PCB pads. Cu dissolved into liquid Sn and formed an intermetallic layer at the solder/pad interface. Hamilton and Snugovsky [8] addressed the Cu dissolution during the lead-free PTH rework process. They found that the copper pad dissolution rate of the lead-free (SAC) rework process was higher than that of the eutectic tin-lead rework process.

In this study, the copper pad thicknesses of lead-free and mixed assembly joints were measured using ESEM. For each sample, 27 measurements were documented. The results are plotted in Figure 4. The copper pad thicknesses of the non-reworked lead-free (SAC) assemblies and the non-reworked mixed assemblies were initially equal. However, after five replacements, the copper pad thickness of the lead-free (SAC) assemblies was only about 50% that of the mixed assemblies (see Figure 5 and Figure 6).

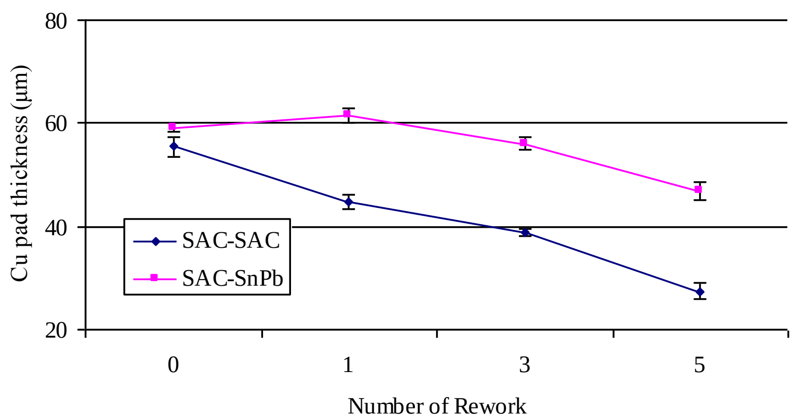


Figure 4: Copper thickness of lead-free and mixed assemblies

During the reflow process, liquid Sn and solid Cu reacted with each other to form intermetallic compounds at the solder/pad interface. Cu dissolves into liquid Sn very fast (in seconds), and there is a large driving force for the chemical reaction between Cu and Sn. The Cu-Sn IMC formation mechanism is controlled by the dissolution of Cu into liquid Sn followed by chemical reactions [13].

In SnAgCu solder, the concentration of Sn is higher than in SnPb solder. Higher concentration of Sn leads to higher Cu dissolution. Thus, the SnAgCu solder can dissolve more Cu than SnPb solder. In eutectic SnPb solder, Pb can be considered a solvent, which decreases the concentration of Sn. In mixed assemblies, when the Cu dissolves into bulk solder, the local Pb concentration will increase at the IMC/bulk solder interface, which blocks Cu dissolved into bulk solder. Thus, the loss of copper pad in lead-free assemblies is more than that in mixed assemblies.

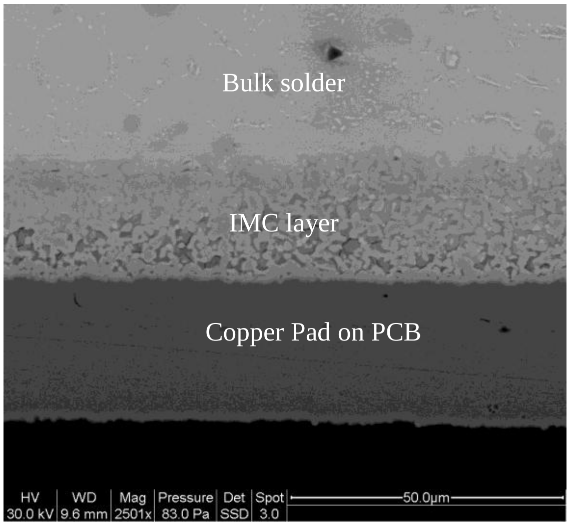


Figure 5: Solder/pad interface in lead-free assemblies after five replacements

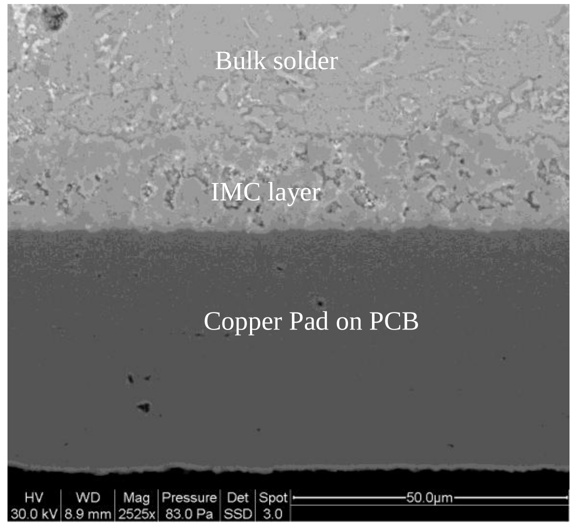


Figure 6: Solder/pad interface in mixed assemblies after five replacements

3.3 Over-Consumption of Copper Pad

The design of copper pads allows them to be electrically interconnected with different solder balls (see Figure 7). Figure 8 shows the schematic images of copper pad connections; the red circle indicates the site of over-consumption. During the rework process, the heat tends to conduct along the copper, since copper has very good thermal conductivity. Not much heat was conducted from the copper pad to the copper trace since the connection site between them was narrower compared to the area of copper pads. Thus, heat concentrated in the connection site led to thicker intermetallic compound formation and over-consumption of copper pad after multiple replacements. There is no copper pad over-consumption in the samples after one and three replacements, but the heat accumulation led to copper over-consumption after five replacements.

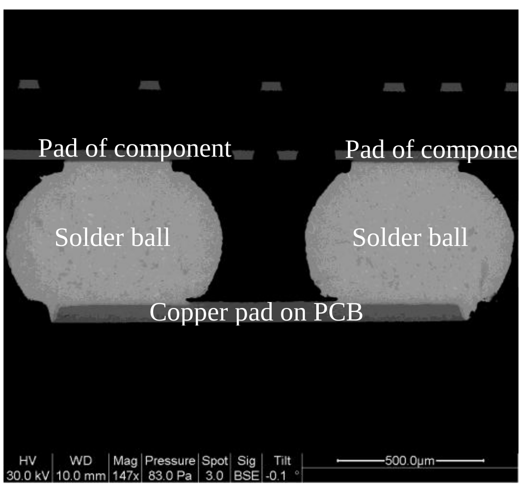


Figure 7: Backscattered electron images of two solder balls connection by the copper pads (mixed assemblies, 1 replacement)

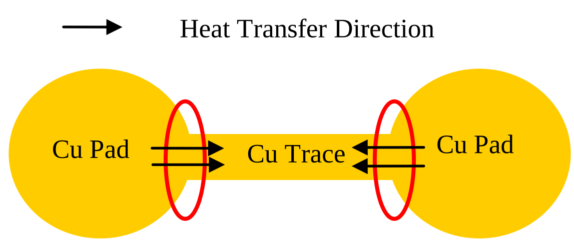
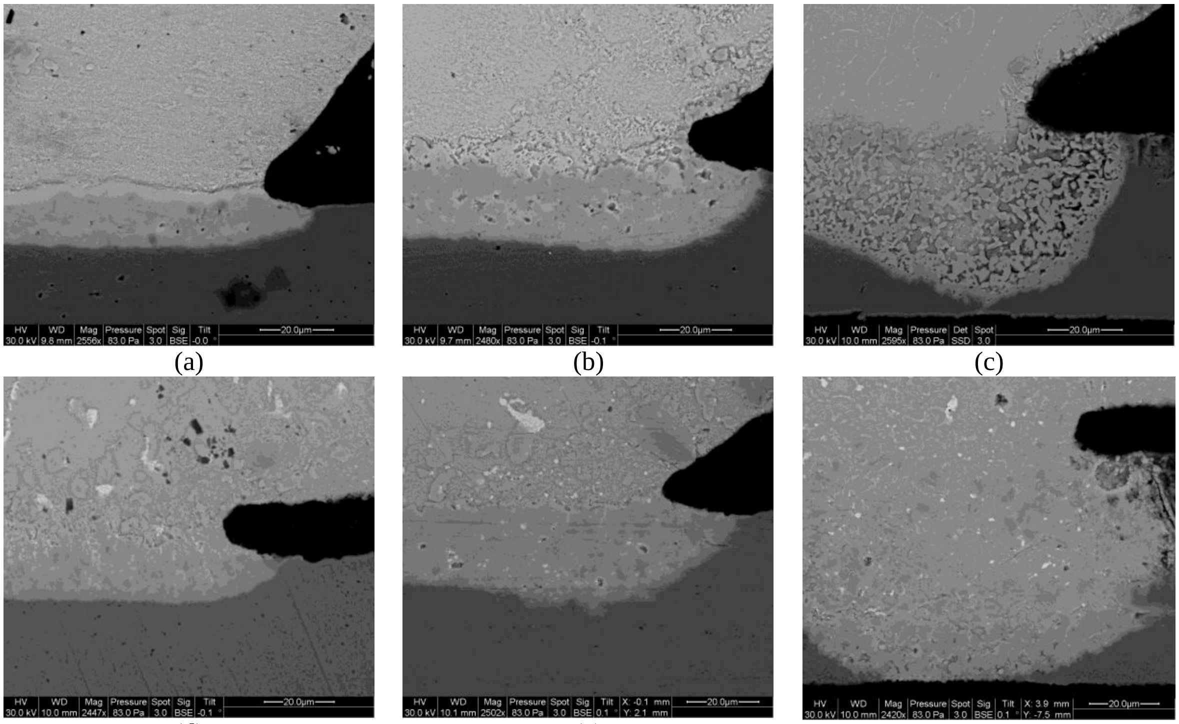


Figure 8: Schematic images of heat transfer between the Cu pads and the Cu trace on a PCB

The consumption of the copper pad was relatively even for the parts after one and three replacements. However, the edge of the copper pad in the parts with five replacements was over-consumed. Figure 9 shows the backscattered electron images of the edge of the copper pads for the reworked lead-free and mixed assemblies. Both the lead-free and the mixed assemblies had similar copper over-consumption trends. After one replacement, the copper pads of the samples were relatively even; after three replacements, they had a small amount of over-consumption at the edge; after five replacements, they were almost consumed, and the intermetallic compound replaced the copper.



(a) (b) (c)

(d) (e) (f)

Figure 9: Backscattered electron images of the edge of the copper pad
(a) lead-free assemblies, one replacement; (b) lead-free assemblies, three replacements;
(c) lead-free assemblies, five replacements; (d) mixed assemblies, one replacement;
(e) mixed assemblies, three replacements; (f) mixed assemblies, five replacements.

3.4 Interfacial Intermetallic Compound Morphology

At the temperature of the reflow process, Cu_6Sn_5 is the first phase to form at the liquid Sn/Cu interface. The formation of Cu6Sn5 takes place within seconds. Cu dissolves into liquid Sn, and reacts with liquid Sn. An ultra-thin layer of Cu_3Sn forms between the Cu6Sn5 and the Cu pad, but it is too thin to be detected [13]. However, the Cu3Sn becomes thicker after long periods of isothermal aging [13]. The melting temperatures of Cu_6Sn_5 and Cu_3Sn are 415 °C and 638 °C respectively [14]. Thus, the interfacial intermetallic compounds (IMC) can remain in the residue solder, since the highest temperature is lower than 300°C during the solder removal process. When a new component attaches to the pad and reflows, a new IMC layer forms at the solder/pad interface. The interfacial IMC morphology of reworked parts is thus different from the as-assembled parts (see Figure 10).

The interfacial IMC of as-assembled joints was scallop shaped Cu_6Sn_5, and Cu_3Sn was not detected, perhaps due to the resolution of the ESEM. Unlike the continuous layer of IMC undergoing isothermal aging, a much thicker layer of IMC with a fragmentary shape was found at the interface of the sample after five replacements. The morphology of the IMC is related to the thermal process the parts experienced. The reworked parts went through reflow processes and isothermal aging (100°C, 24 hours) several times. The kinetic force of IMC growth during reflow was liquid Sn/solid Cu interdiffusion, while the kinetic force during isothermal aging was solid Sn/solid Cu interdiffusion. The difference in driving forces led to multiple layers of IMC formation at the interface of the solder/pad in the reworked samples. In the ESEM images, the morphology of the IMC appears fragmentary.

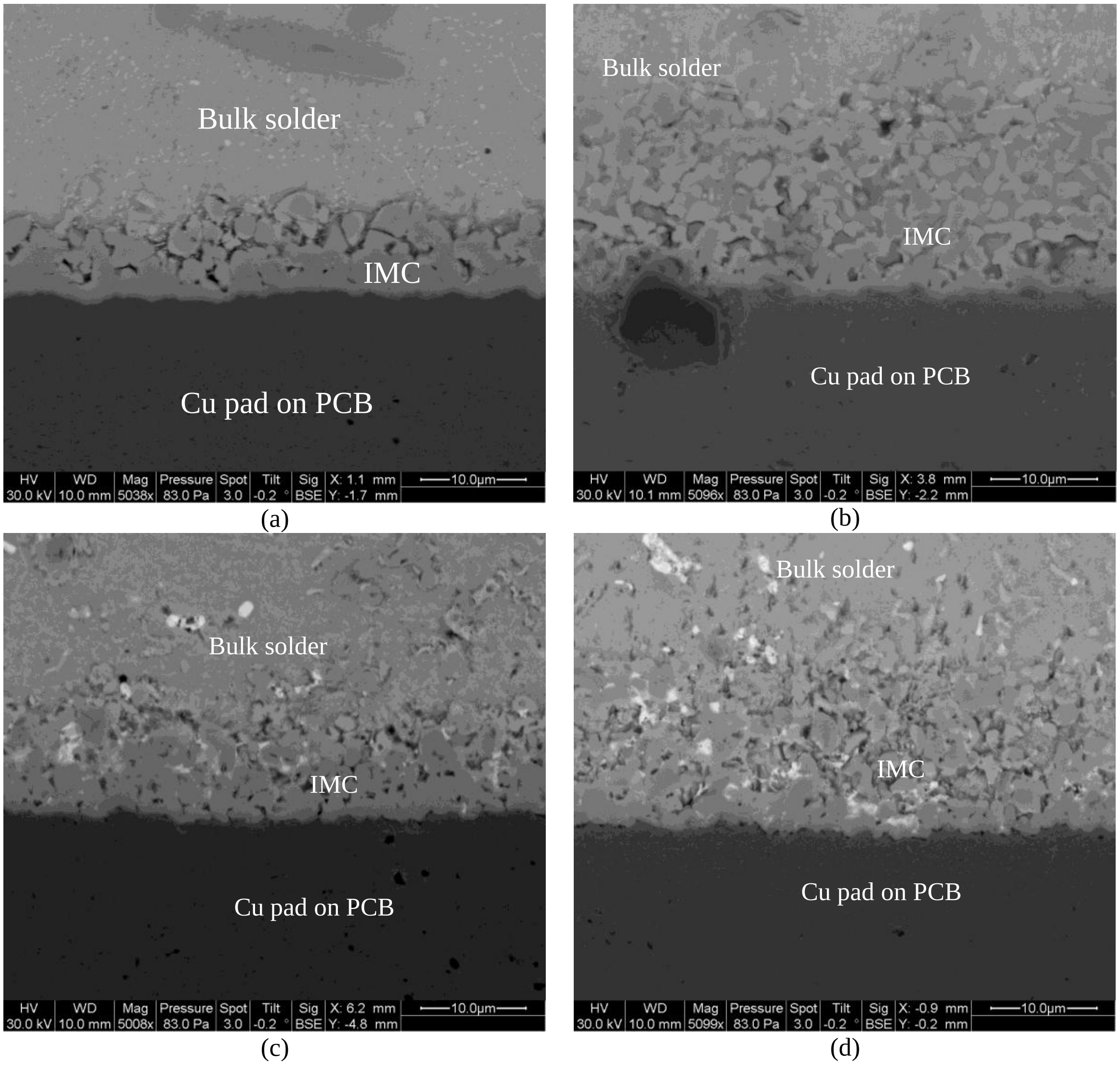


Figure 10: Backscattered electron images of IMCs at solder/pad interface
(a) Lead-free assemblies, as-assembled; (b) Lead-free assemblies, five replacements;
(c) Mixed assemblies, as-assembled; (d) Mixed assemblies, five replacements.

3.5 Interfacial Intermetallic Compound Thickness

Figure 10 shows that the interfacial IMC layer became thicker after the rework process for both lead-free and mixed assemblies. Figure 11 plots the interfacial IMC thickness of lead-free and mixed assembly joints for as-assembled and reworked samples. The interfacial IMCs growth of lead-free assemblies after rework process was much faster than the growth of the interfacial IMCs undergoing thermal aging conditions (normally below 150°C) [11]. A similar trend was found among mixed assembly samples; the interfacial IMC layer was much thicker than the interfacial IMC undergoing isothermal aging conditions. This was due to different thermal processes: isothermal aging and rework.

The driving force of interfacial IMC growth undergoing the isothermal aging condition is solid/solid interdiffusion, which is much slower than solid/liquid interdiffusion. In one rework process, there were three periods when the solder became liquid: component removal, site redressing, and component reflow. Prolonged liquid time enhances the interfacial IMC growth, which leads to much thicker interfacial IMC in comparison to the interfacial IMC undergoing thermal aging.

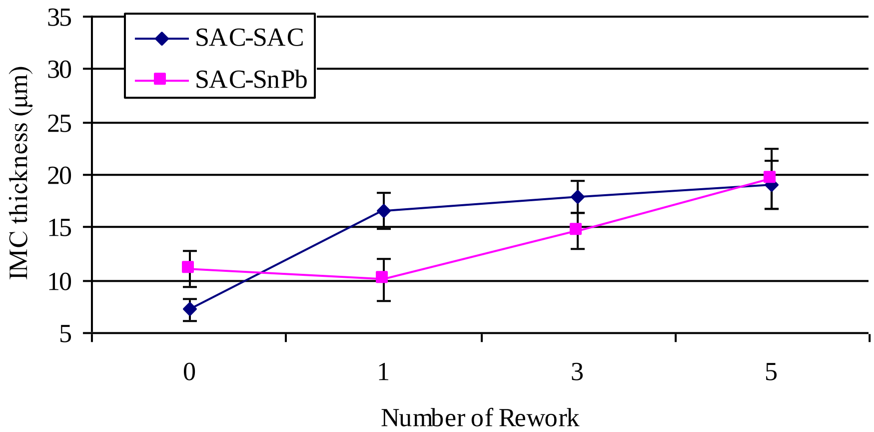


Figure 11: IMC thickness of lead-free and mixed assemblies after multiple rework processes

4 Conclusions

In this study, 676 IO PBGAs with Sn3.0Ag0.5Cu were assembled with Sn3.0Ag0.5Cu and eutectic Sn37Pb solder paste. Three selected parts of each assembly were subjected to rework one time, three times, and five times. X-ray inspection and ESEM were used to investigate the BGA voids, the IMC morphology, the IMC thickness, and the copper pad dissolution.

X-ray inspection results showed that none of the BGAs exceeded the criterion in the BGA voids calculation, according to the IPC-7095. Copper pad dissolution was observed for joints of both lead-free and mixed assemblies after multiple rework processes. The copper pad dissolution in joints of lead-free assemblies was found to be larger than that of mixed assemblies. This is due to the higher concentration of Sn in the lead-free solder, which means there is a faster reaction between liquid lead-free solder and Cu. Cu over-consumption was observed at the edge of pads after five replacements for both lead-free and mixed assemblies. During the reflow process, heat concentrated at the connection site between the copper pads and the copper traces, which led to the formation of ultra thick IMC and over-consumption of copper pad. Thick IMC and thin copper pad may lead to reliability concerns. Thus, more than three rework processes is not recommended.

IMC morphology of reworked samples was different from that of aged samples. The IMCs presented a fragmentary morphology due to multiple liquid solder periods, including component removal, site redressing, and component reflow. The growth of IMCs was much faster than the growth of IMCs undergoing the isothermal aging condition due to the prolonged liquid time in the rework process. Thus, reworked BGAs may have reliability concerns due to thicker IMC layer in real applications.

5 Acknowledgements

The authors would also like to thank the members of the CALCE Electronic Product and Systems Consortium for sponsoring work presented in this paper.

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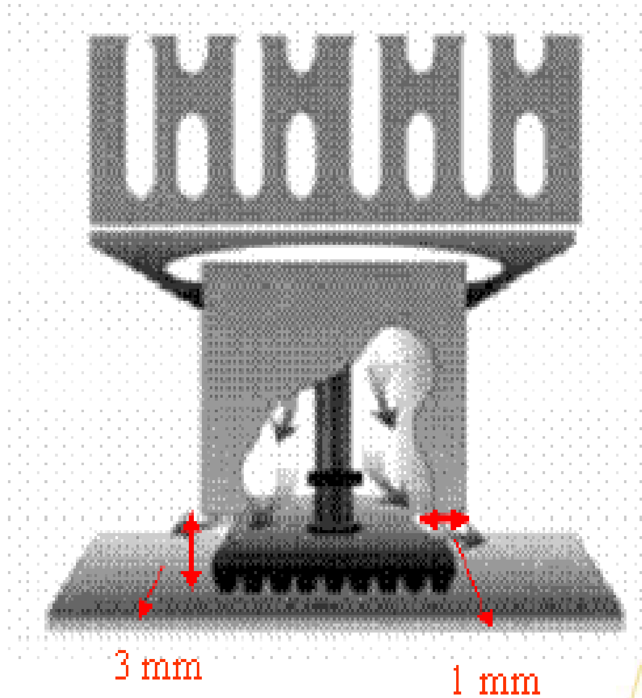
Background

- Equipment manufacturers use rework to increase yield.
- Rework is essential practices for high cost and limited volume electronics.
- Changes in processing temperatures and solder alloy can be expected to have a direct impact of the viability of rework practices.
- Reports and literature related to reliability of reworked electronic solder interconnections are limited.

Rework Process

Part replacement process flow

1. Preheating
2. Desoldering
3. Site redressing
4. Fluxing/solder paste
5. Part placement
6. Soldering
7. Inspection
8. Cleaning

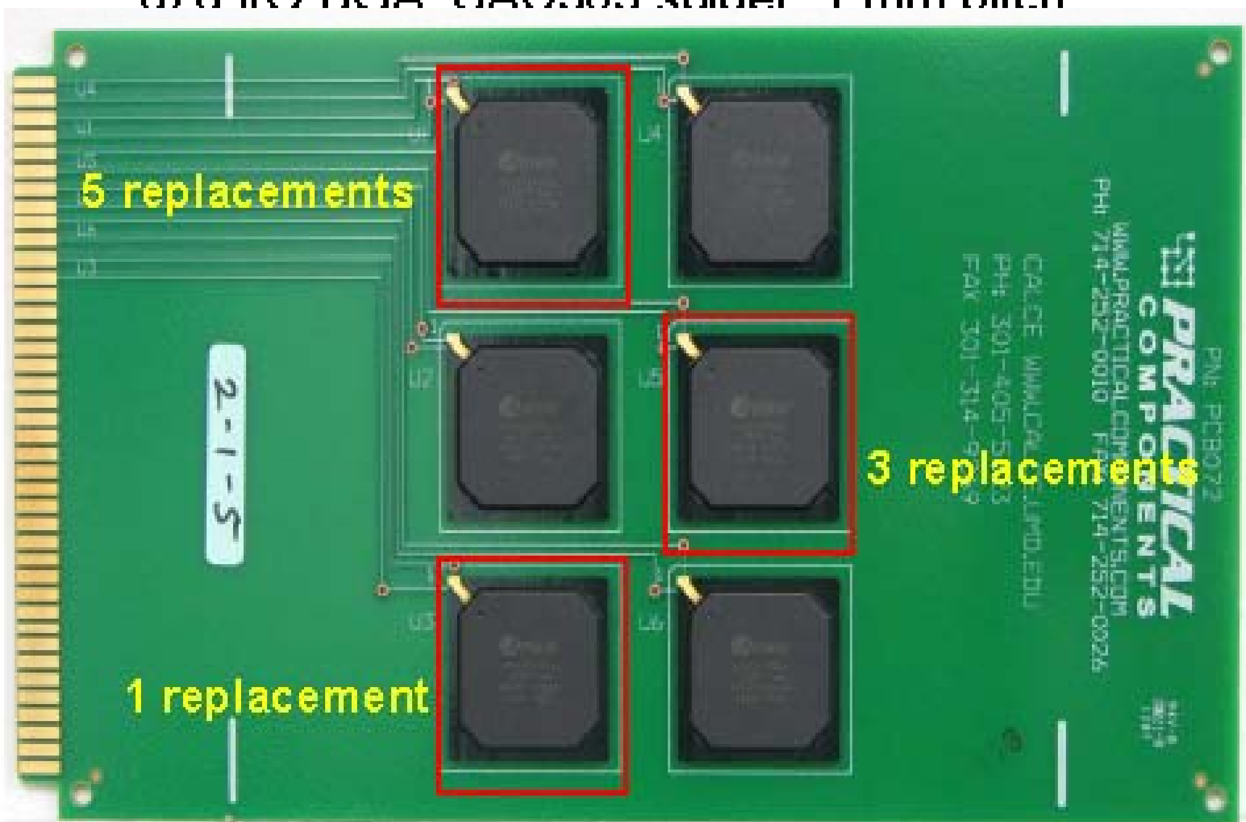


Component removal and attachment using hot air station

676 IO BGA Assembly

2.3 mm (90 mil) 370 HR FR4, OSP Finish, One resistance net per part

676 I/O BGA, SAC305 solder, 1 mm pitch



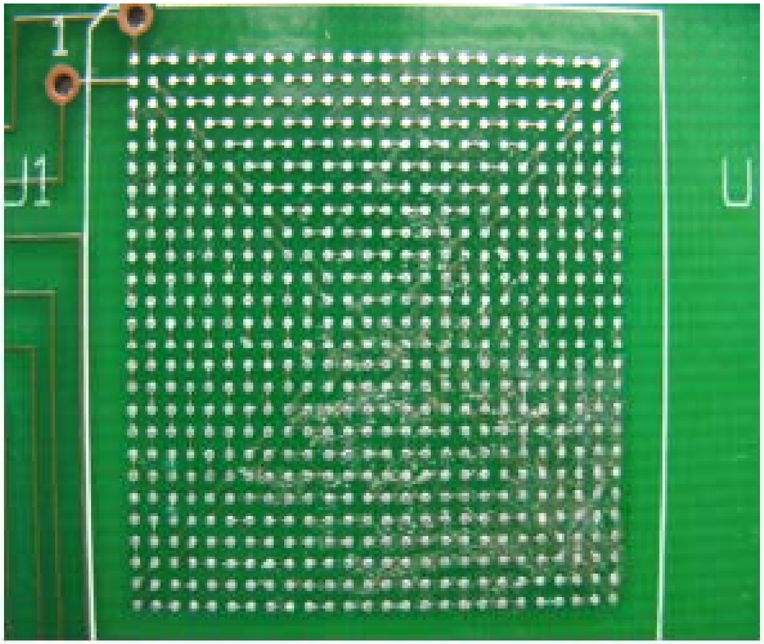
Two versions

- Lead-free assembly: SAC305 paste
- Mixed assembly: Sn37Pb paste

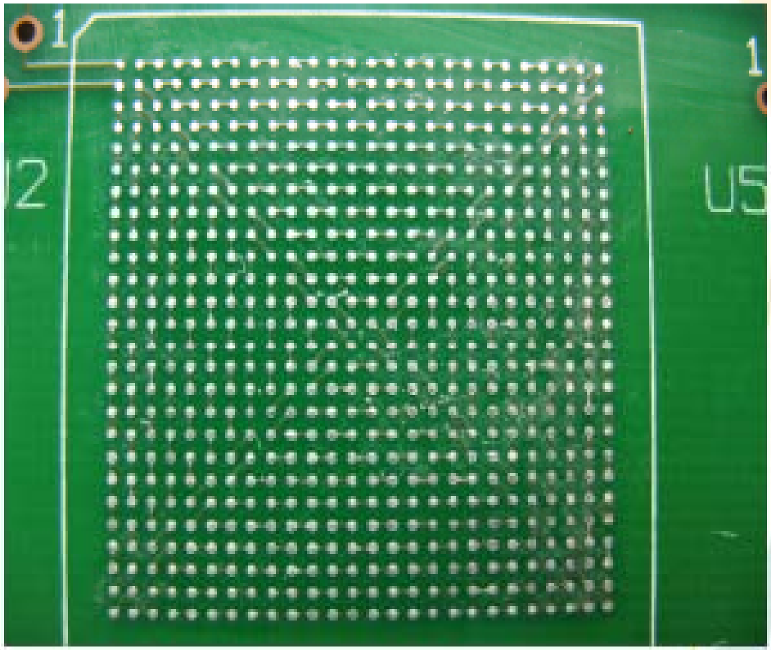
Rework Summaries

- Equipment
  - Micro stencil and VJ Electronix SRT 1800 rework station with bottom heater and N_2 heater on top
- Solder
  - Lead-free No-clean paste: Alpha OM-338 (SAC 305)
  - SnPb No-clean pate: Indium SMQ-92J (6337)
- Temperature
  - Lead-free assembly: Peak part temp. 282℃
  - Mixed assembly: Peak part temp. 282℃

PCB Inspection After Component Removal



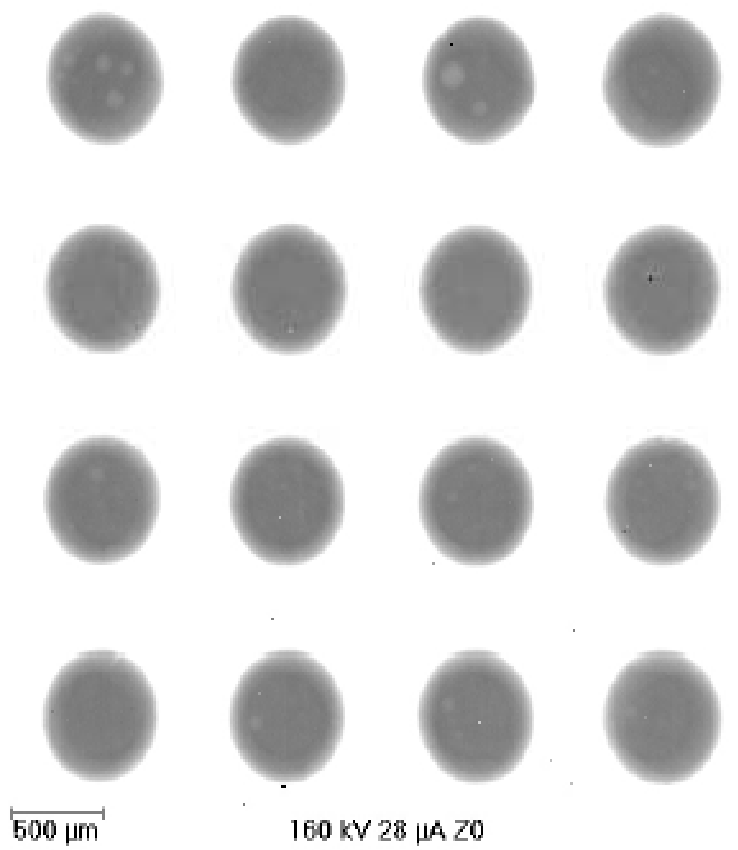
PCB pads of mixed assembly



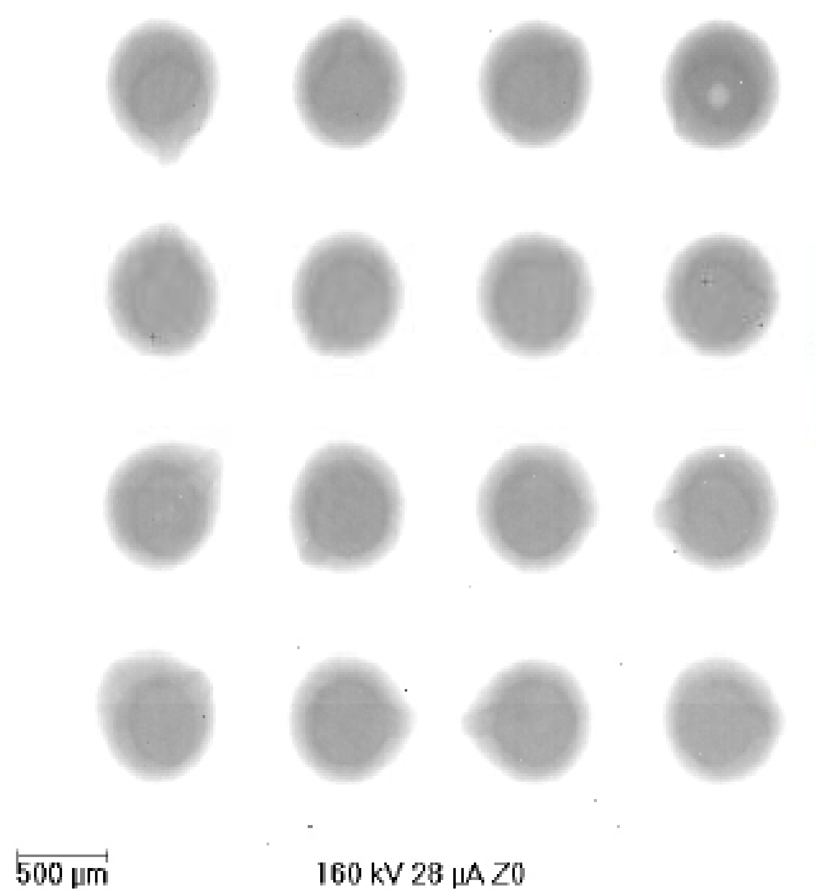
PCB pads of lead-free assembly

The pads showed a clean surfaces and solder mask were not damaged during the removal procedure.

Voids in BGA Assemblies

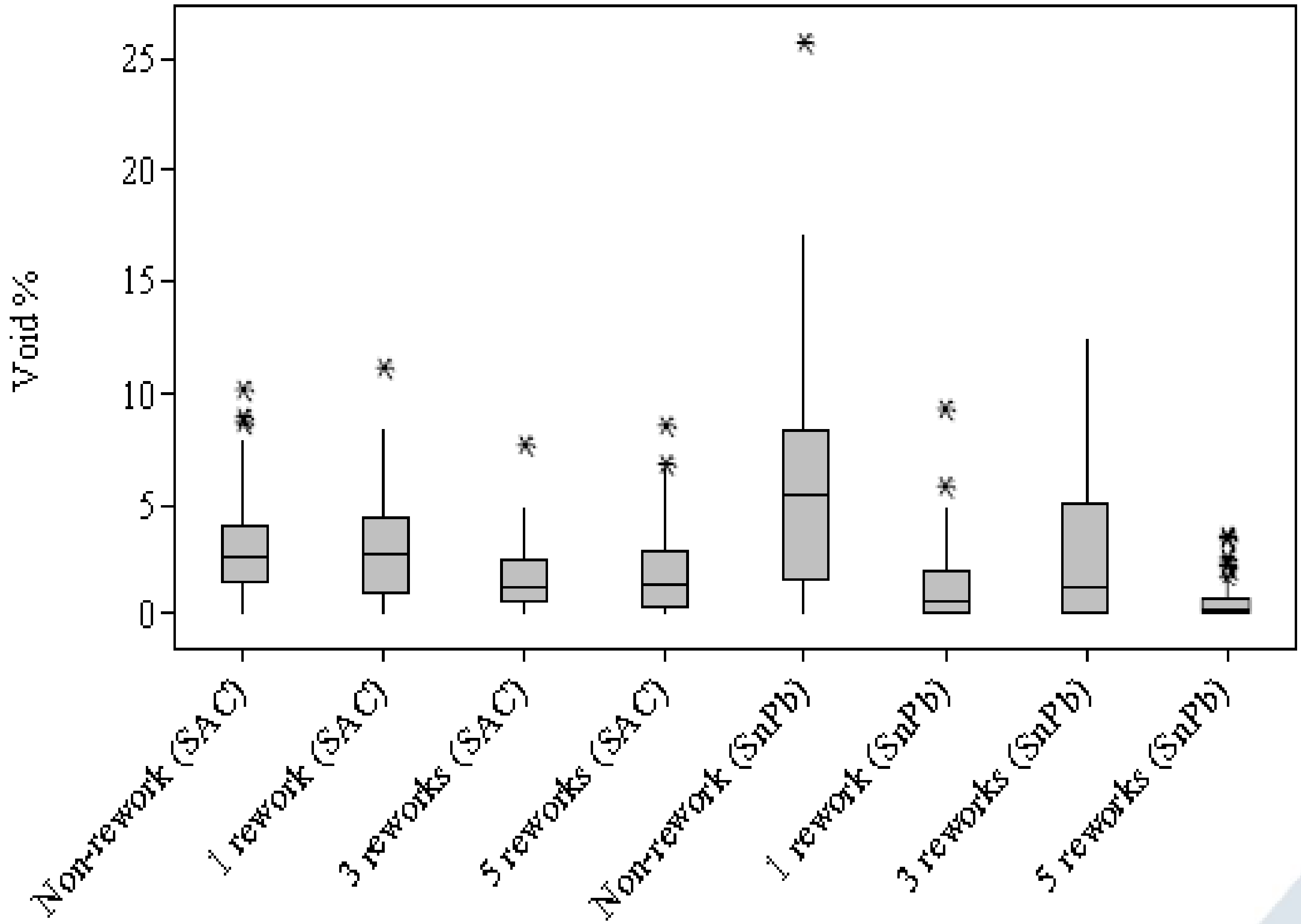


Voids in 5 times rework BGA with SAC solder

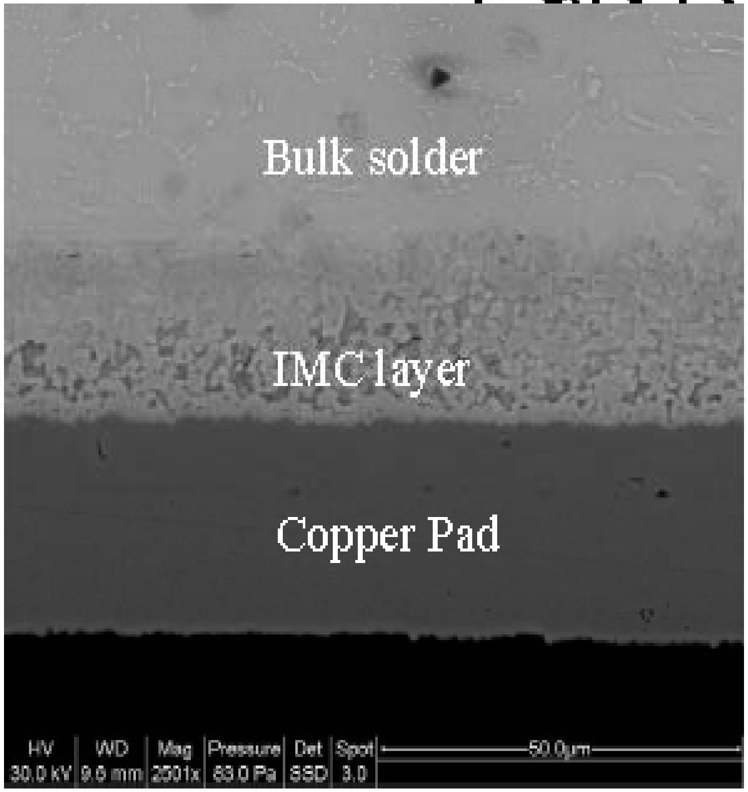


Voids in 5 times rework BGA with SnPb solder

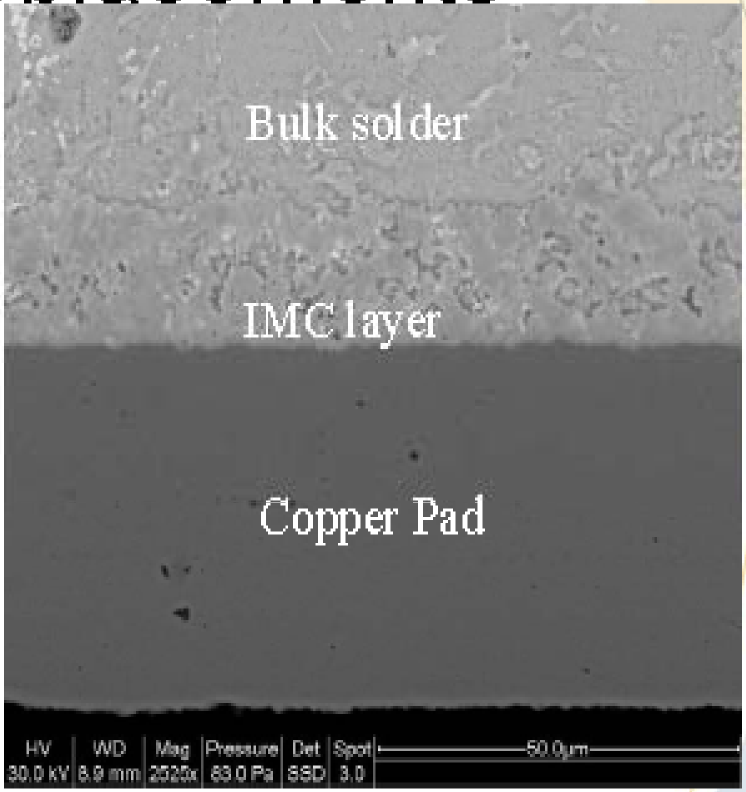
Voids Percentage of Reworked BGAs



Copper Pad Dissolution After 5 Part Replacements



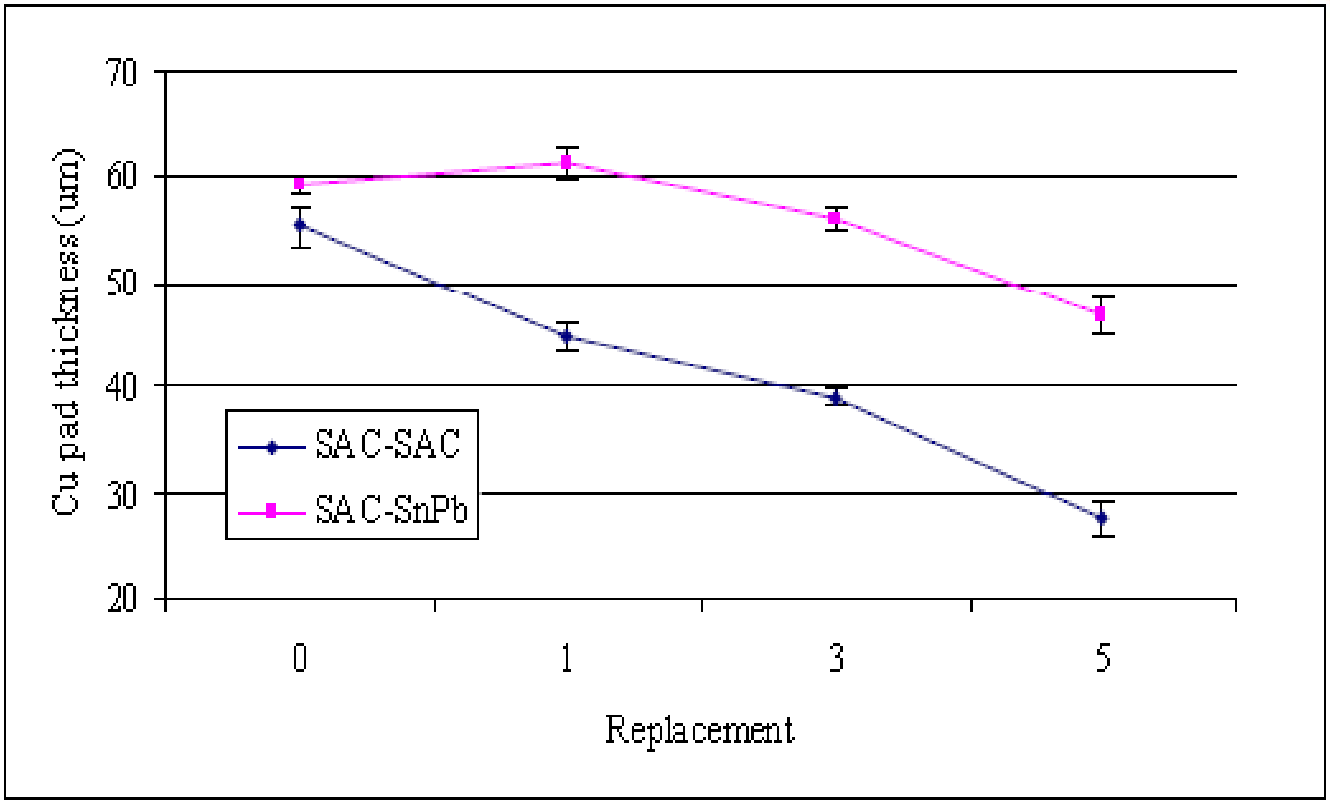
Solder/pad interface in reworked BGA with SAC solder



Solder/pad interface in reworked BGA with SnPb solder

The reworked BGAs with SAC solder lose more copper than those with SnPb solder.

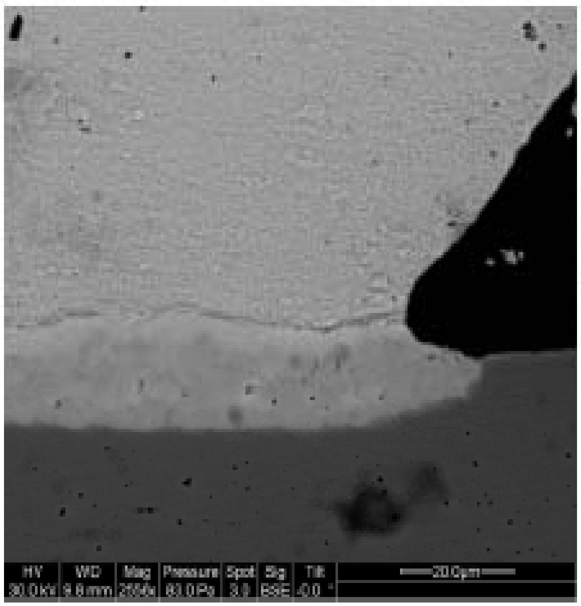
Copper Pad Thickness in Reworked BGAs



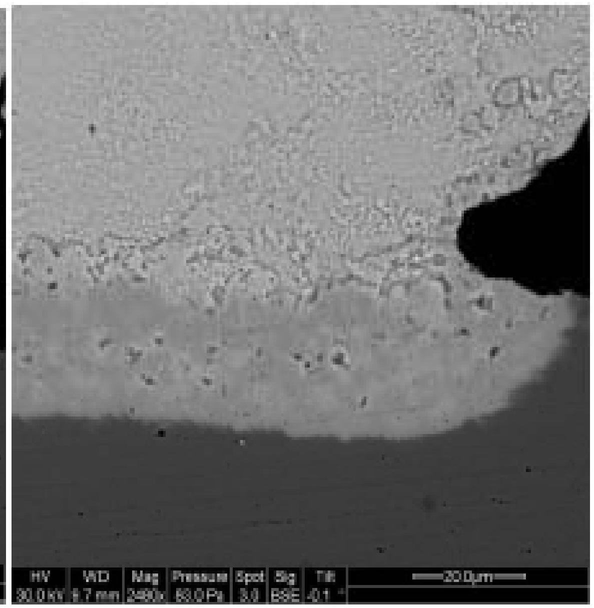
Preliminary evaluation of copper loss due to part replacements indicates a very dramatic loss of copper for the lead-free paste/lead-free BGA combination as compared to SnPb paste/lead-free BGA combinations.

*For each sample, 9 solder balls were selected, totally 27 measurements were calculated.

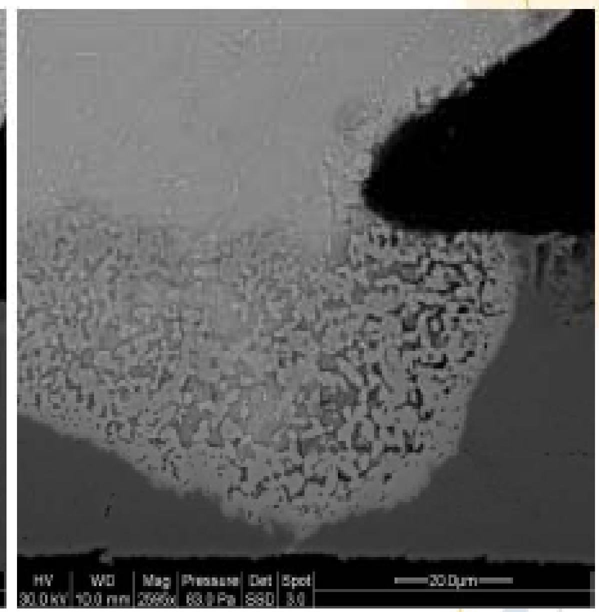
Copper Pad Over-Consumption (1/3)



Lead-free assembly
1 replacement



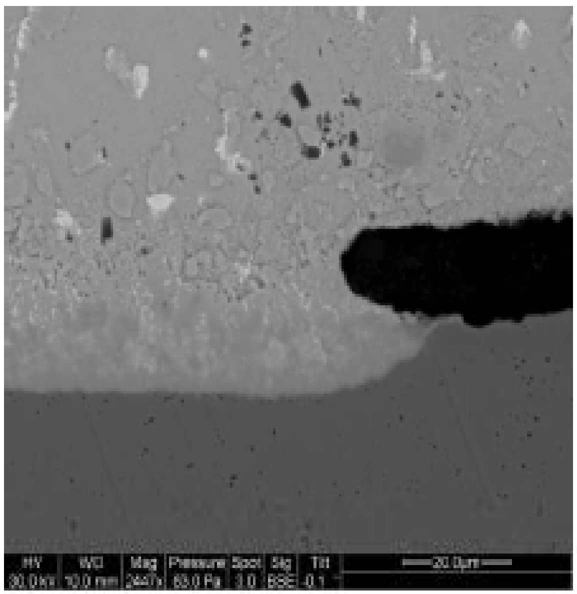
Lead-free assembly
3 replacements



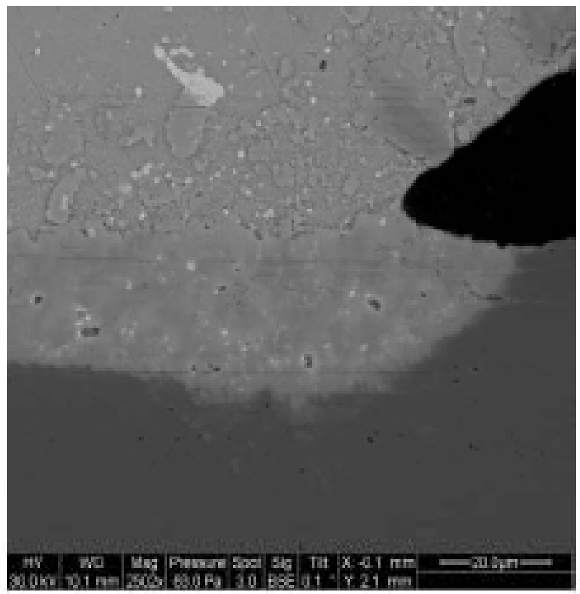
Lead-free assembly
5 replacements

After five replacements, the edge of copper pad was almost consumed, and the intermetallic compound replaced the copper.

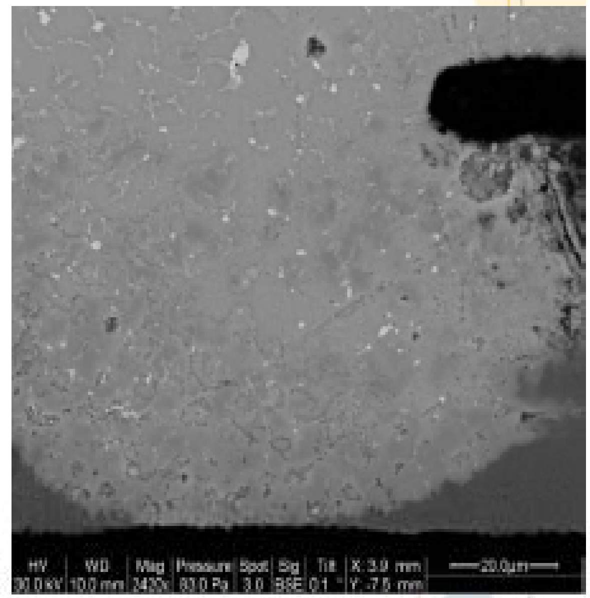
Copper Pad Over-Consumption (2/3)



Mixed assembly
1 replacement

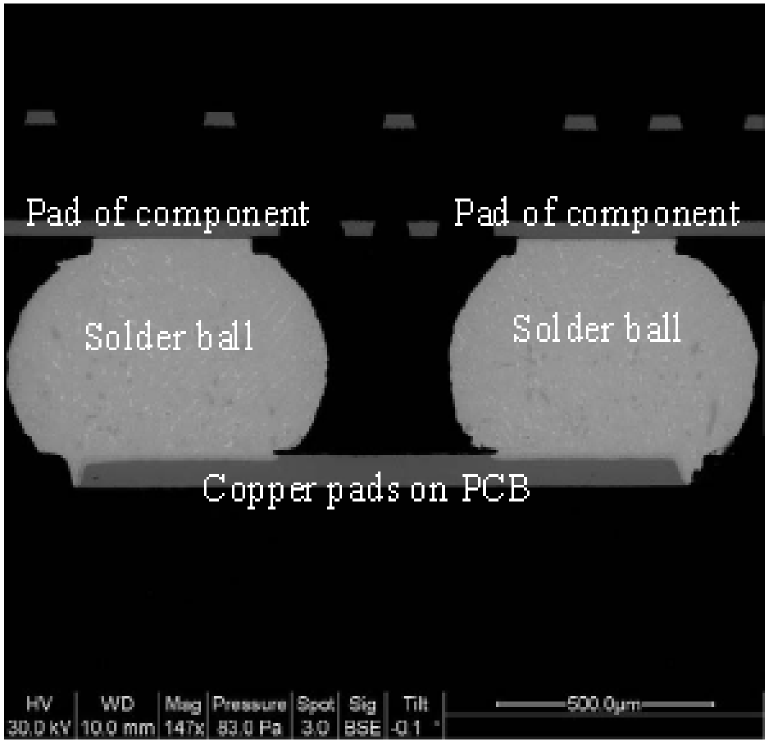


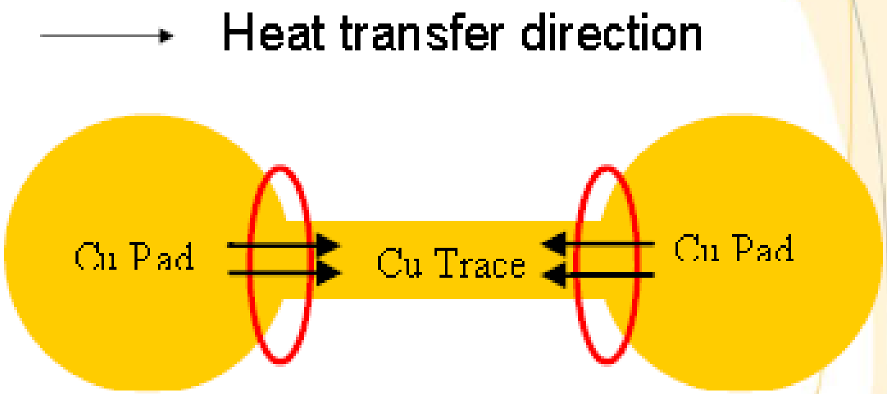
Mixed assembly
3 replacements



Mixed assembly
5 replacements

Copper Pad Over-Consumption (3/3)

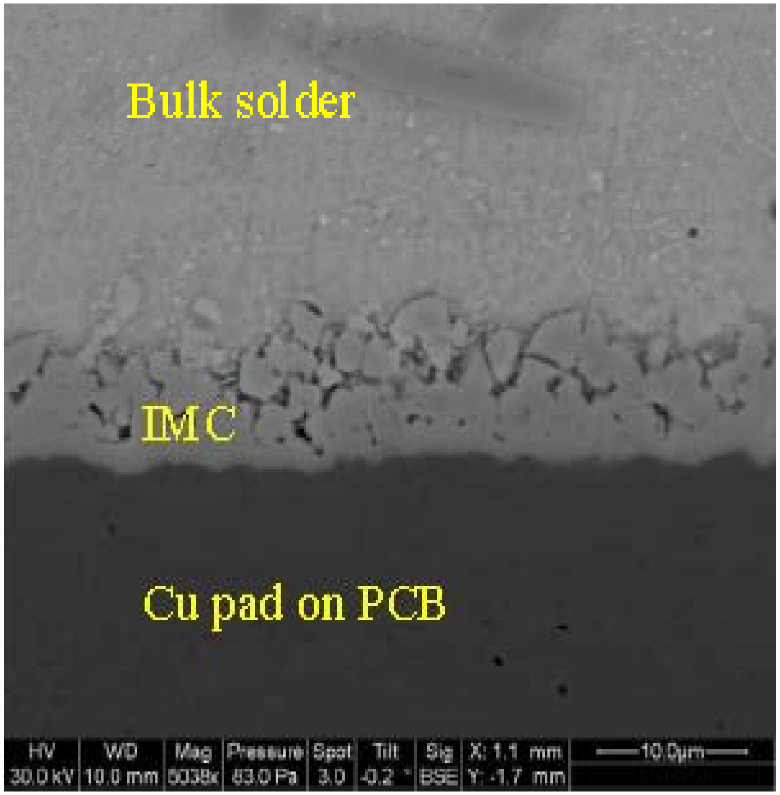




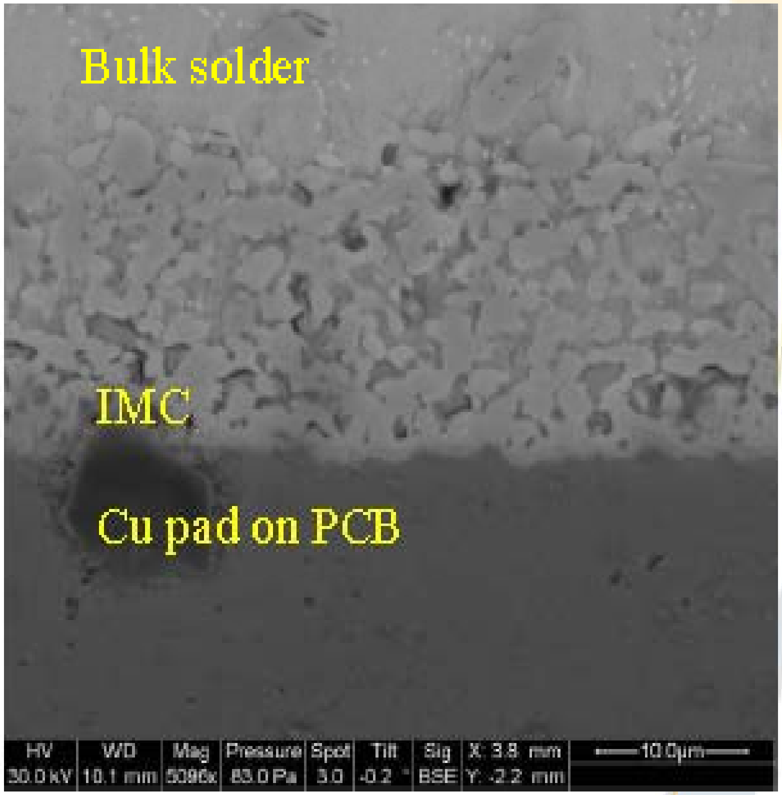
Schematic image of heat transfer between the Cu pads and the Cu trace on a PCB

During the rework process, the heat tends to conduct along the copper, since copper has very good thermal conductivity. Not much heat was conducted from the copper pad to the copper trace since the connection site between them was narrower compared to the area of copper pads.

Interfacial Intermetallic Compound Morphology (1/2)

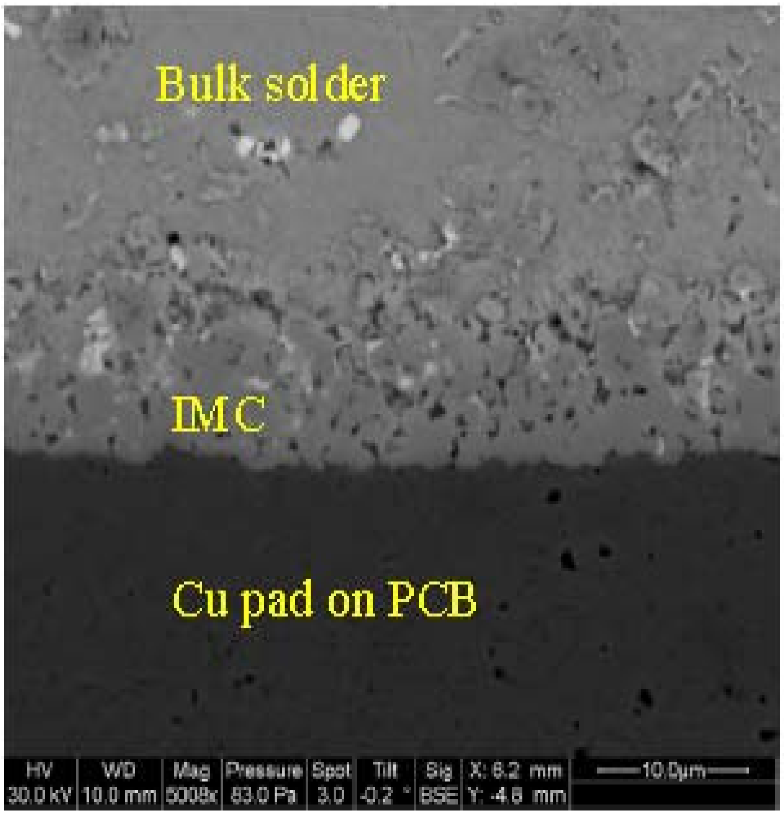


Lead-free assembly
as-assembled

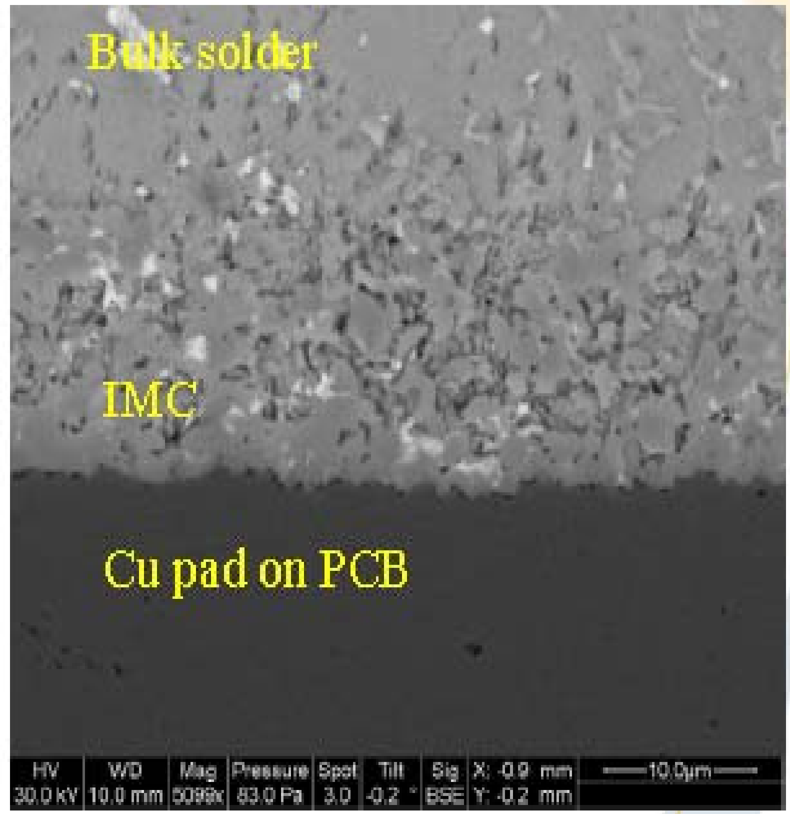


Lead-free assembly
after 5 replacement

Interfacial Intermetallic Compound Morphology (2/2)

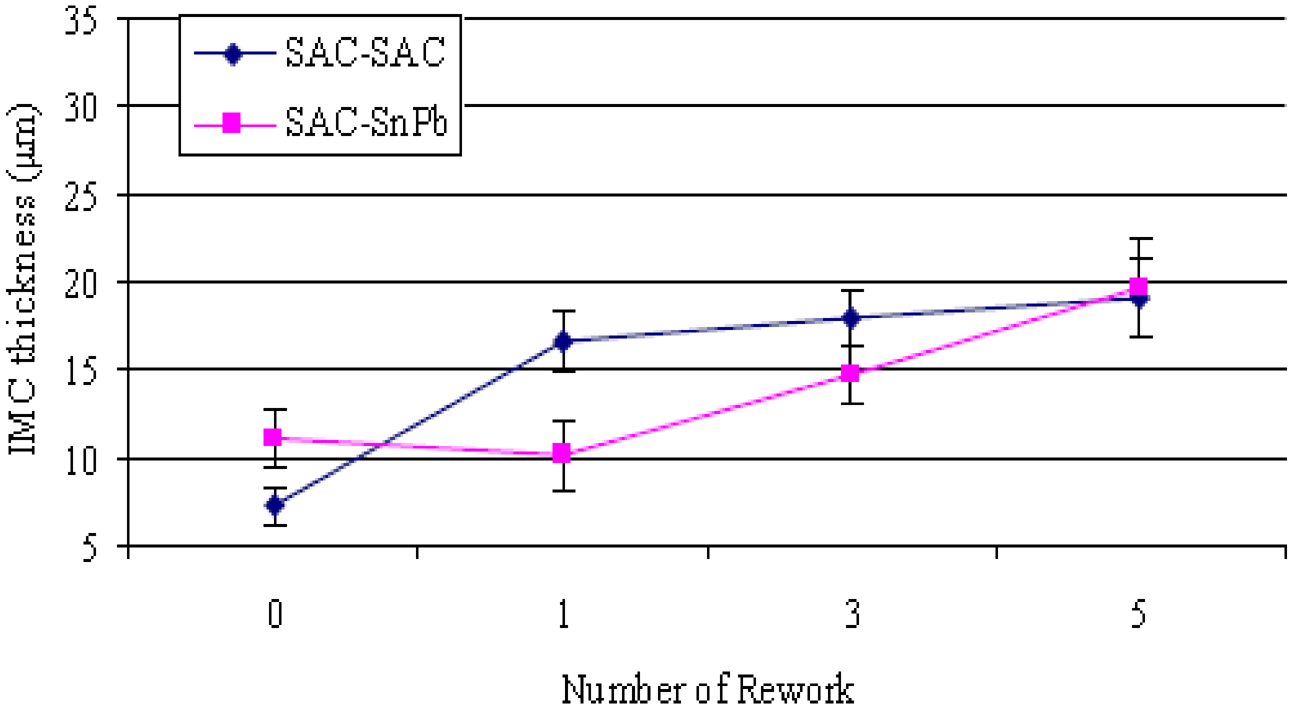


Mixed assembly as-assembled



Mixed assembly after 5 replacements

Interfacial Intermetallic Compound Thickness



Prolonged time of liquidus enhances the interfacial IMC growth, which leads to much thicker interfacial IMC.

Conclusions

- The copper pad dissolution in joints of lead-free assemblies was found to be larger than that of mixed assemblies.
- Cu over-consumption was observed at the edge of pads after five replacements for both lead-free and mixed assemblies.
- The IMCs presented a fragmentary morphology due to multiple liquid solder periods, including component removal, site redressing, and component reflow.
- The growth of IMCs was fast due to the prolonged l time of liquidus in the rework process.

Questions?