Durability of Repaired and Aged Lead-free Electronic Assemblies

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Abstract
The reliability of aged and repaired lead-free and mixed lead-free/lead-based solder interconnects is an important issue for electronic equipment manufacturers. As a result of the global transition away from lead driven by government legislation and market pressure, maintained lead-based electronic equipment may need to be repaired with lead-free parts and materials due to improper labeling or inability to obtain proper replacement materials. An experimental study to examine the reliability of aged and repaired solder interconnects was conducted. Test specimens included thermally aged and non-aged lead-free and lead-based printed wiring assemblies with surface- mount components, including ball grid arrays (BGAs), leadless resistors, and quad flat packages (QFPs). Test specimens were subjected to aging and repair where lead-free and lead-based components and materials were intentionally mixed. Temperature cycle loading was used to examine the reliability of the solder interconnects. Test results show that thermal aging is more detrimental to lead-free solder interconnects than to lead-based interconnects for PBGAs. Further, the failure distribution of the lead-free assembled PBGAs was found to be wider than the distribution of the lead-based failures.

Introduction
The majority of electronics manufacturers have transitioned to lead-free materials and processes, both to comply with government legislation and to be compatible with the supply-chain infrastructure [1][2][3]. At the same time, electronic manufacturers, such as those for aerospace, military, and space applications, who are exempt from government-imposed restrictions, are attempting to maintain lead-based parts and assembly processes due to long-term reliability concerns with lead-free parts and assembly. In the current situation, lead-free parts may be intentionally or unintentionally used in a lead-based assembly process. Further, maintained lead-based electronic hardware may be repaired intentionally or unintentionally with lead-free parts or materials. At present, the long-term reliability of lead-free hardware and hardware repaired with mixed (Pb-free/Pb-based) solder is still in question. With regard to lead-free solder interconnect reliability, a significant amount of investigation has been reported in the literature [1,4-9]. These findings indicate that, under temperature cycle loading, in most cases solder-joint reliability of lead-free hardware will be as good or better than that of lead-based hardware. For lead-free BGA components assembled with lead-based solder, the reliability has been shown to be equivalent to pure lead-free assemblies, provided the lead is distributed evenly throughout the joint [9-11]. However, significantly early failures can occur if the lead is not distributed [10]. On the reliability of repaired hardware, very little information can be found. The most notable data comes from a recent study by a team of organizations working on a project sponsored by the Joint Council for Aging Aircraft (JCAA) and the Joint Group on Pollution Prevention (JGPP) [11]. In the JCAA/JGPP study, lead-free and lead-based versions of a standardized test design consisting of several types of conventional surface-mount components; a set of one type of insertion-mount package was produced and subjected to environmental tests. As a subset of the study, lead-free components were assembled with lead-based solder and lead-based assemblies were repaired by replacing lead-based components with lead-free components. As a control, some lead-based assemblies were repaired by replacing lead-based components with similar lead-based components. When the assemblies were subjected to a -55 to 125^{o}C temperature cycle, lead-free plastic ball grid array (PBGA) components assembled with lead-based solder and lead-free components that replaced lead-based PBGAs were found to have a higher characteristic life than their lead-based counterparts. However, the failure distributions of the lead-free PBGAs were found to be wider than observed for the lead-based PBGA parts. This wider distribution may be indicative of inconsistencies in the mixed and lead-free solder interconnect structures.

In addition to repair, the impact of aging on solder interconnect reliability and the repair of soldered assemblies should be considered. A recent study of lead-free and lead-based solder-joint interconnects has shown that thermal aging degrades solder pull strength [12]. However, it is unclear if the degradation due to thermal aging indicated in the pull strength test will show up in other environmental testing. In an effort to examine the impact of aging and repair on lead-free and lead-based soldered assemblies, the Center for Advanced Life Cycle Engineering (CALCE), in collaboration with the CALCE Electronic Products and Systems Consortium, conducted an experimental study. This study and the results are presented in this paper.

Experiment and test plan
To examine the impact of thermal aging and repair on solder-joint interconnect reliability of lead-free and lead-based hardware, a set of test boards were designed and manufactured. The test board design incorporated common surface-mount packages including PBGAs (plastic ball grid array), QFPs (quad flat packs) and leadless resistors. The parts were laid out on a single side of a board 62 mil thick and constructed with a low glass transition temperature (~130°C) FR4. The test components and the board formed low-resistance daisy-chained networks for monitoring interconnect reliability. To examine the impact of repair, select components on the manufactured test vehicles were removed and replaced. The test board, along with the components selected for replacement, is depicted in **Error! Reference source not found.**.

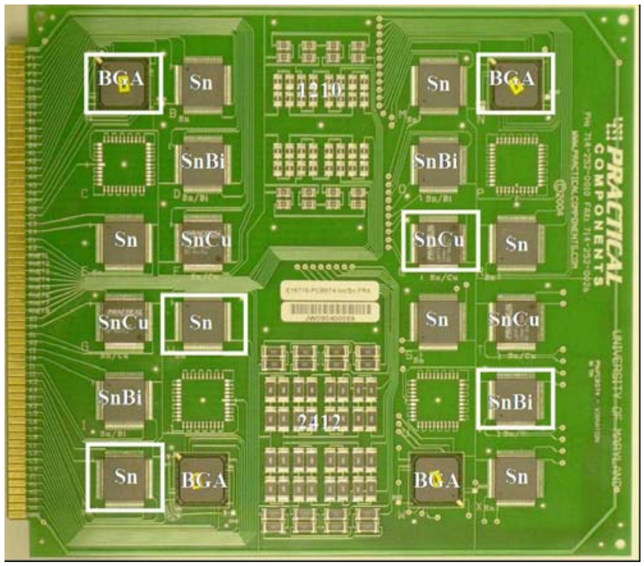

Figure 1 - Board layout and components to be repaired

For this study, lead-free and lead-based versions of the test designs were manufactured. For the lead-free version, the board finish was ImSn and the components were lead-free. Lead-free components included BGAs with Sn3.0Ag0.5Cu solder balls, QFPs with matte tin, Sn0.7Cu and Sn2.0Bi finished leadframes, and 2512 resistors with matte tin-finish terminals. The position of the lead-free finishes for the QFPs are identified in Figure 1. For the lead-based versions, the board finish was tin-lead-based hot air leveled solder (HASL) and the components had tin-lead finished terminals. For the lead-based boards, the BGAs had Sn37Pb solder balls and the QFP leadframes and 2512 resistors were finished with Sn10Pb. The metallurgy of all component finishes were verified using X-ray fluorescence (XRF). Six lead-free assemblies and six lead-based assemblies were used in this study. Table 1 provides a detailed description of the test assembles and repair materials when no lead-free and lead-based materials were mixed. Table 2 provides a detailed description of the test assemblies and repair when lead-free and lead-based materials were mixed. For tin-lead repair of the chip resistors and QFPs, Sn37Pb solder ribbon was used; for lead-free repair Sn3.0Ag0.5Cu solder ribbon was used. For the BGA repair, no solder paste was used. Cells involving mixing lead with leadfree solder have been highlighted.

Table 1 - Repair test plan without mixing of Pb in leadfree

Assembly	Details	Repair control				
		BGA solder ball	QFP lead finish			2512 lead finish
SnPb components - HASL (SnPb) board finish	Original component	SnPb	SnPb			SnPb
	Replaced component	SnPb	SnPb			SnPb
	Solder paste	None	SnPb			SnPb
Lead-free components – ImSn board finish	Original component	SnAgCu	Sn	SnCu	SnBi	Sn
	Replaced component	SnAgCu	Sn	SnCu	SnBi	Sn
	Solder paste	None	SnAgCu			SnAgCu

Table 2 - Repair test plan with mixing of Pb in leadfree

Assembly		Repair with mixing				
		BGA solder ball	QFP lead finish			2512 lead finish
SnPb components - HASL (SnPb) board finish	Original component	SnPb	SnPb			SnPb
	Replaced component	SnAgCu	SnPb			SnPb
	Solder paste	None	SnAgCu			SnAgCu
Lead-free components – ImSn board finish	Original component	SnAgCu	Sn	SnCu	SnBi	Sn
	Replaced component	SnPb	Sn	SnCu	SnBi	Sn
	Solder paste	None	SnPb			SnPb

Since situations arise when electronic assemblies are stored before being utilized in a system, the reliability impact of aging should be considered. Storage and age may also impact the reliability of repaired solder joints. To examine the impact of age, half of the lead-free and lead-based assemblies were aged at 125 °C for 350 hrs. before repair.

To assess solder-joint reliability, the repaired and non-repaired (control) assemblies were subjected to temperature cycling between -40 °C to 125 °C, with 15-minute dwells at temperature extremes. During the applied temperature cycle, the resistance networks formed with the individual components and the metal traces on the boards were continuously monitored. Failure was defined to occur when one or more resistance excursions greater than 300 ohms were recorded for a minimum of ten consecutive temperature cycles. The breakdown of the assemblies tested is shown in Table 3.

Table 3 - Board assemblies used for thermal cycling durability

Assembly	No Repair	Repair control	Repair with mixing (Pb in lead-free assembly)
SnPb component HASL-Board finish	1 non-aged 1 Aged	1 non-aged 1 Aged	1 non-aged 1 Aged
Pb-free component ImSn-Board finish	1 non-aged 1 Aged	1 non-aged 1 Aged	1 non-aged 1 Aged

Repair process for surface-mount packages

Repair was conducted in an IPC Class 3 OEM facility involved in repairing electronic assemblies. Board assemblies with components were repaired by replacing the original components with a new component of the same type. QFP and resistor components were repaired with hand soldering tools, while the BGA components were repaired using a hot air station. Details on the repair procedure have been listed in Table 4. Figure 2 shows the removal of resistors, and Figure 3 shows the reattachment of a BGA component.

Table 4 - Comparison of field and assembly repair methods

Repair step	Repair procedure
Component removal	BGA, QFP: Hot air at package top with heater set to 343 °C Resistor: Hot tweezers
Site redressing	Copper wick and soldering iron at 370 °C
Component replacement	QFP and resistor: Apply flux and manually solder using soldering iron and solder ribbon. BGA: Apply flux and reflow with hot air from heater at 370 °C, no solder paste applied, manual alignment

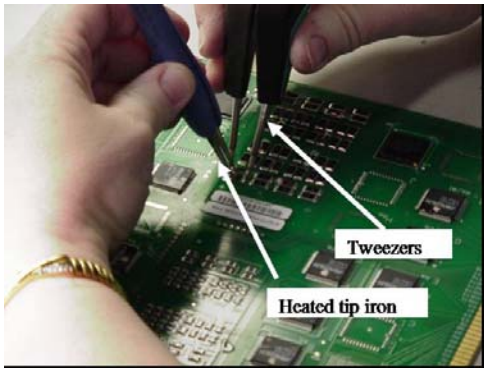

Figure 2 - Repair of resistors with tweezers

Figure 3 - Nozzle for QFP and BGA repair

Observations from repair
After repair all the components were inspected with X-ray. No defects were found in BGA components except for one open chain due to insufficient solder in the repaired BGA (Figure 4). Figure 5 shows a solder mask rip-off defect found on a repaired QFP package. Solder mask rip-off causes exposure of copper trace, which could result in failure due to copper migration and corrosion. No such defects were found in the non-repaired assemblies.

Figure 6 shows misaligned leads of a repaired QFP package, which causes reduction in the solder-joint area. According to the IPC-A-610D standard [13], a side overhang of < 50 percent is allowable for qualifying assemblies for class 1 and 2 applications, and < 25 percent is allowable for class 3 applications (classes as per the standard). Figures 7 and 8 show the optical image of solder balls at the edge and at the center, respectively, of a repaired BGA. A difference in solder joint height was clearly observed between the corner balls and balls in the middle of the outer rows. The observed effect indicates that the BGA components experience warpage during the assembly process. The difference in solder ball height was confirmed with X-ray images of the same BGA package (shown in Figure 9).

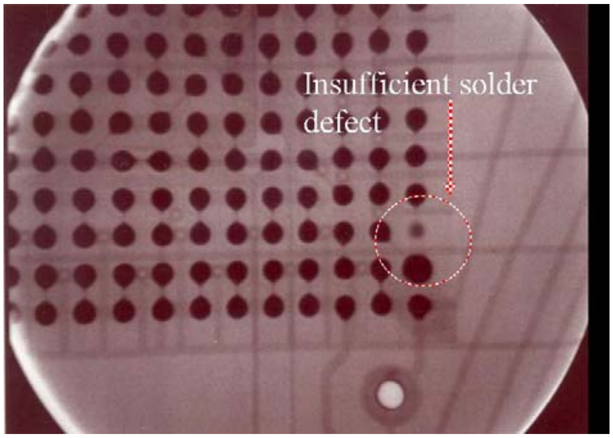

Figure 4 - X-ray image of BGA solder balls showing insufficient solder site

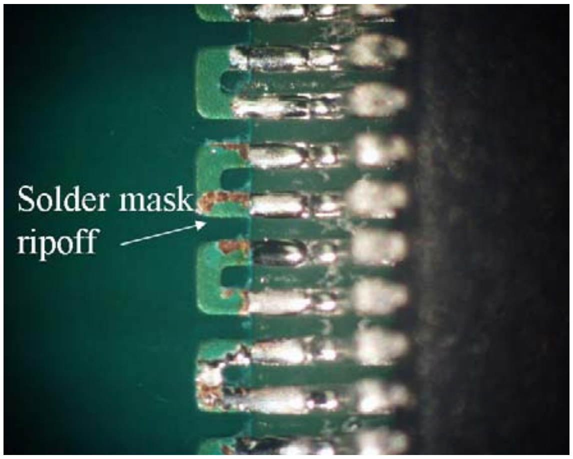

Figure 5: Solder mask rip off defect (QFP (Sn finish) repaired with Sn37Pb solder)

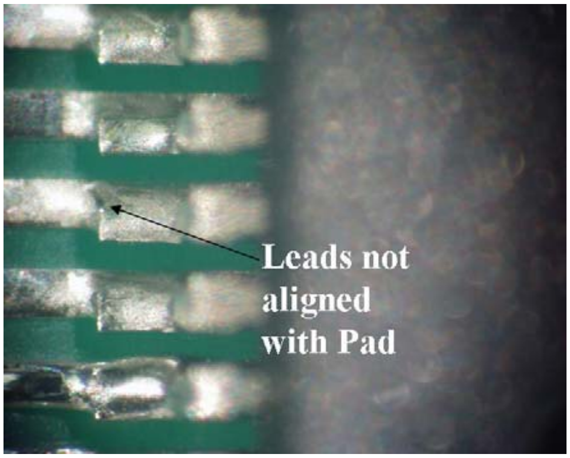

Figure 6: Lead not aligned with pad (QFP (tin-lead) repaired with Sn3.0Ag0.5Cu solder on HASL)

Figure 7 - BGA solder ball on the edges (corners) show less solder-joint height than midsection balls

Figure 8 - BGA solder balls on the midsection show higher solder-joint height than edge (corner) balls

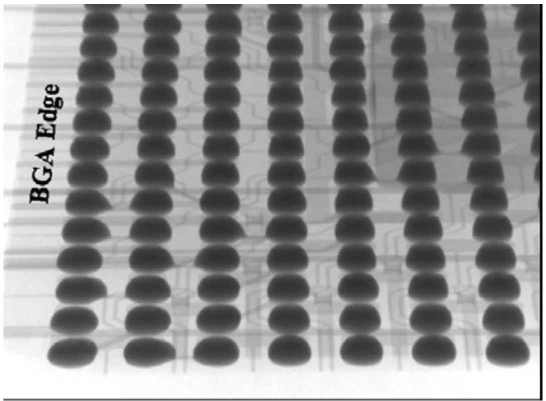

Figure 9 - X-ray image of BGA solder balls showing difference in ball diameter between corner and center

5 Reliability test results

After the majority of PBGA packages experienced failure due to temperature cycling, a comparison was made in the cycles to failure. Figure 10 provides a two-parameter Weibull plot of non-repaired lead-free BGA test data for aged and non-aged assemblies. Figure 11 provides a similar plot for the lead-based assemblies. Results indicate that thermal aging reduces the characteristic life of the PBGAs on the lead-free assemblies by approximately twenty-five percent, while the lead-based PBGAs showed only a five percent reduction in life due to thermal aging. In addition, a wider variation in cycles to failure is observed for the lead-free assembled PPGAs than for the lead-based assemblies.

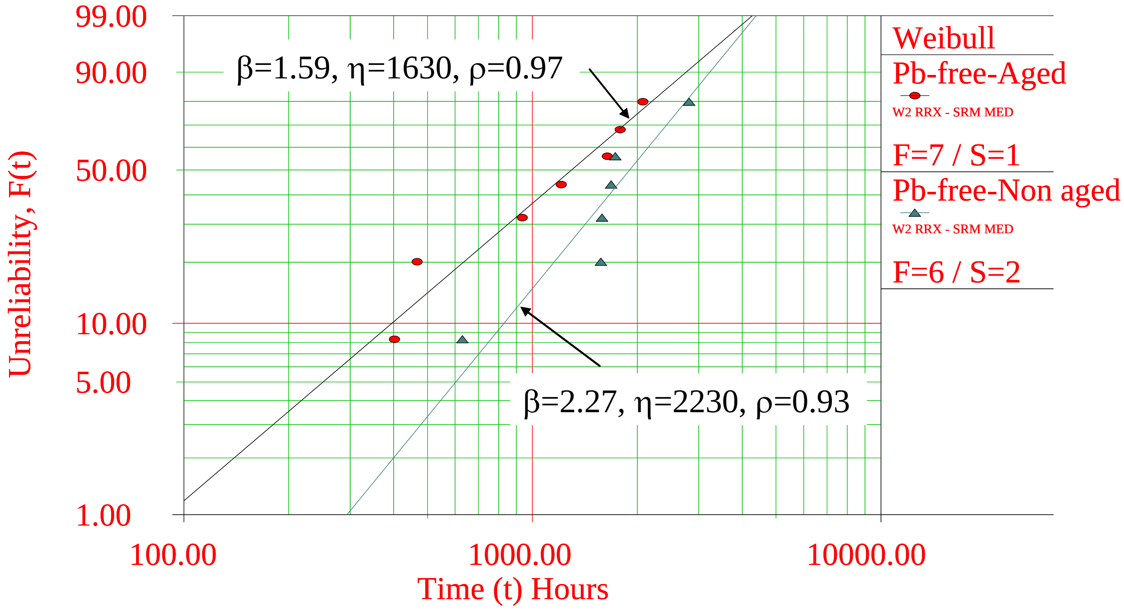

Figure 10 - Durability comparison of aged and non-aged lead-free solders joints

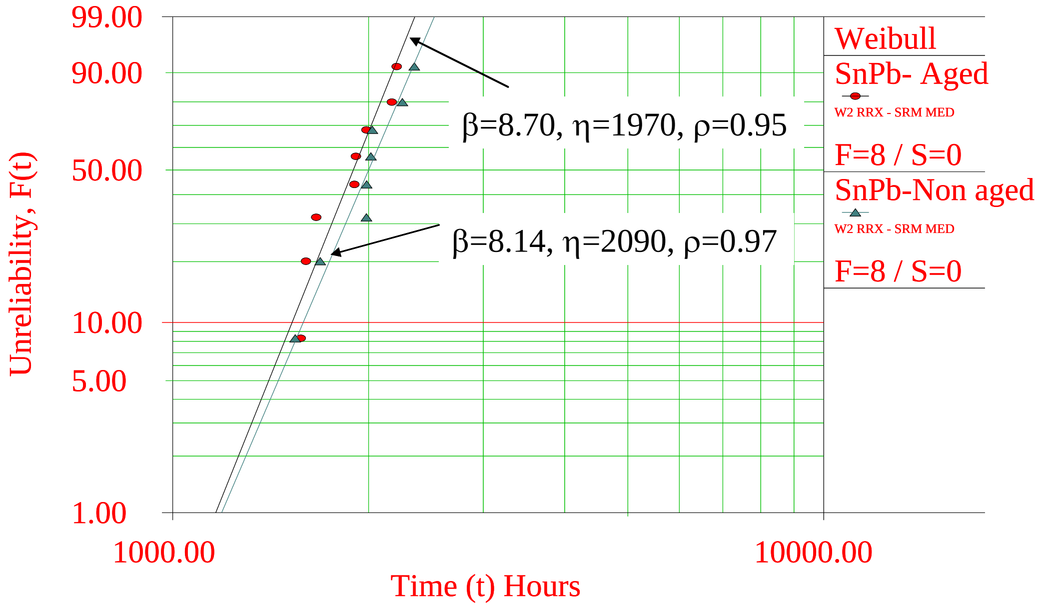

Figure 11 - Durability comparison of aged and non-aged SnPb solders joints

The recorded cycles to failure for the repaired PBGAs on the aged and non-aged lead-free assemblies are compared to the non-repaired PBGAs in Figure 12. In this figure, R (SnPb) indicates the original lead-free BGA was replaced by a lead-based PBGA. R (SnAgCu) indicates the lead-free PBGA was replaced by another lead-free BGA. The NA indicates a non-aged assembly and the A indicates a thermal aged assembly. Figure 13 shows a similar plot for lead-based assemblies. In this case, the R (SnPb) indicates that the original lead-based component was replaced by another lead-based component and the R (SnAgCu) indicates that the lead-based component was replaced by a lead-free component. Results show a large variation in failure times for repaired lead-free solder joints (see Figure 12) as compared with lead-based assemblies (see Figure 13).

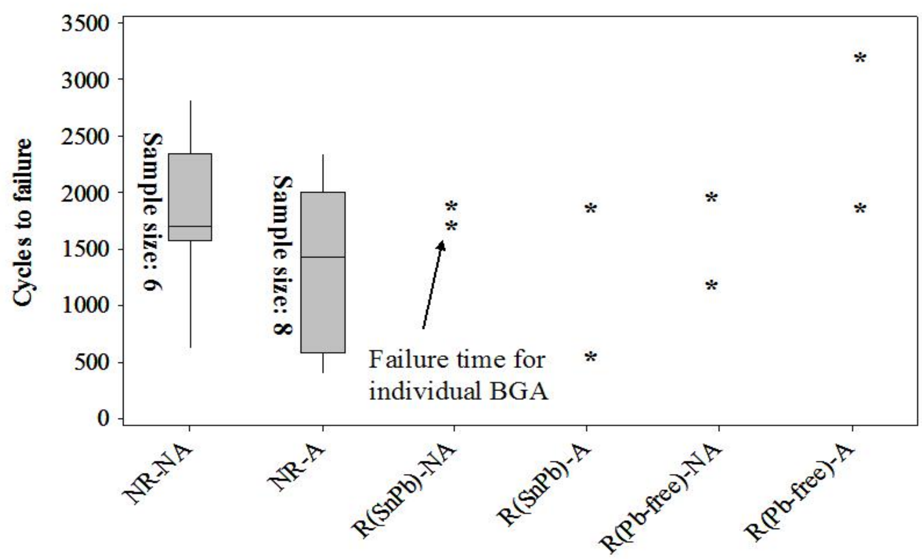

Figure 12 - Durability of repaired and non-repaired Pb-free solder joints

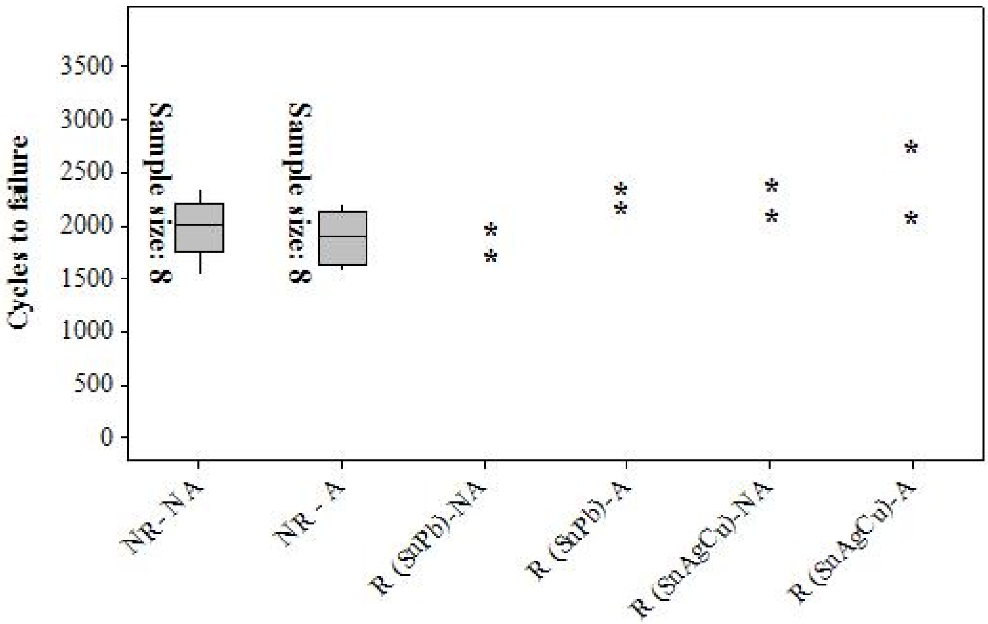

Figure 13 - Durability of repaired and non-repaired SnPb solder joints

Failure Analysis

Destructive physical analysis was conducted to determine the failure location in the resistance networks of the failed PBGAs. In all cases, the failure location was found to occur in the solder joint near the component side around the die shadow region for both lead-based and lead-free PBGAs. Material analysis of the copper pad on the component substrate for the BGA package confirmed that it was nickel-plated for both tin-lead and lead-free BGA components. Gold was not found in the solder region near the pad. The solder joint was solder-mask-defined at the component side and copper-pad-defined at the board pad side. Figure 14 shows the failure in a tin-lead solder joint at the component side in the bulk solder.

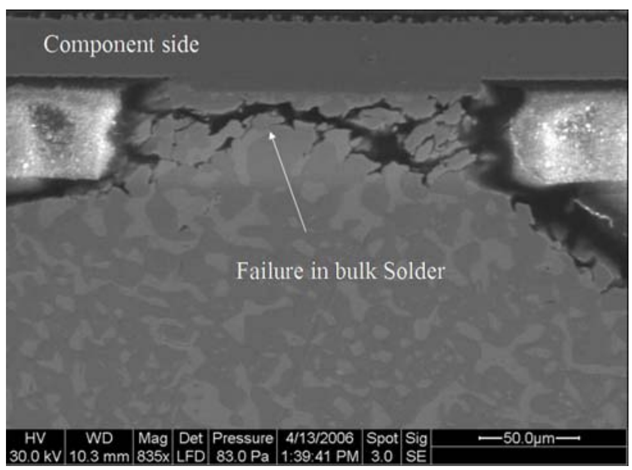

Figure 14 - Failure was found on the component side for BGA (SnPb) assembled with SnPb solder on HASL(SnPb) pad finish, not repaired, not aged

Figure 15 shows an electron image of the failure location for a non-aged lead-free solder joint. Like the lead-based PBGA, the crack was found to be in the bulk solder on the component side. Figure 16 shows an optical image of a failed solder ball for aged lead-free solder joint. For the thermal-aged solder joint, the intermetallic thickness at the board side is observed to be thicker than the intermetallic observed on the board side for the non-aged PBGA.

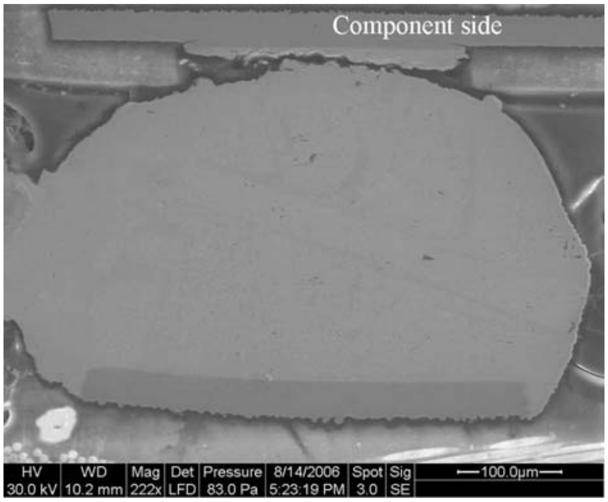

Figure 15 - BGA (SnAgCu)-SnAgCu solder-ImSn finish (non-aged)--failed ball shows failure on the component side.

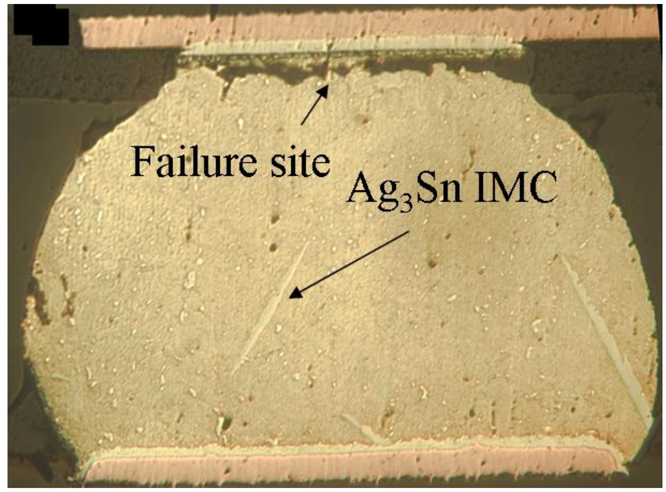

Figure 16 - BGA (SnAgCu)-SnAgCu solder-ImSn finish-aged--failed ball shows failure on the component side.

Elemental analysis was conducted using energy-dispersive X-ray spectroscopy (EDS) to investigate the presence of various elements above the fracture site. It was found that the area above the crack was rich in tin, which indicates the crack was present in the bulk solder below the intermetallic layer (see Figure 17).

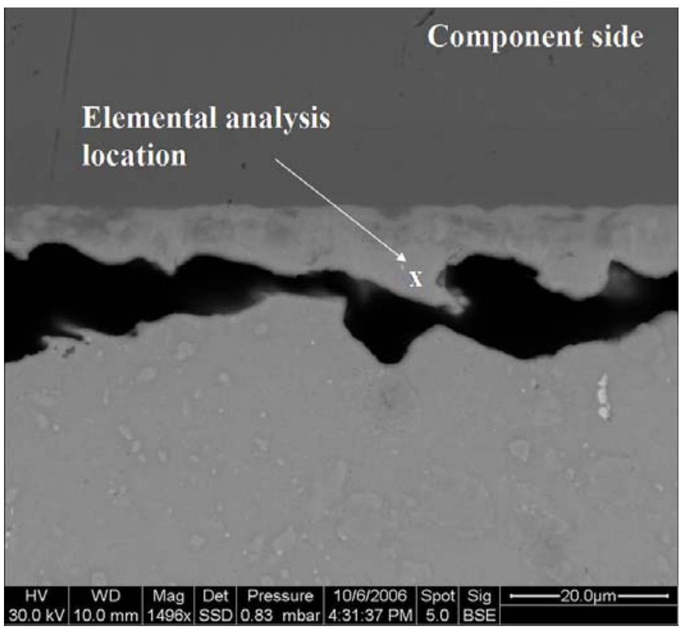

Figure 17 - BGA (SnAgCu) on HASL finish. Repaired by replacing BGA (tin-lead) with BGA (SnAgCu) on HASL (tin-lead) board. Failure location was seen in the bulk solder on component side

Further analysis was conducted to investigate whether lead was present in the solder joints formed when lead-free PBGAs were used to replace lead-based PBGAs on the HASL-finished boards. Energy-dispersive X-ray (EDX) analysis did not indicate the presence of lead in the repaired solder joint. Figures 18-22 show elemental mappings for various elements found in the microstructure of a replacement lead-free solder joint.

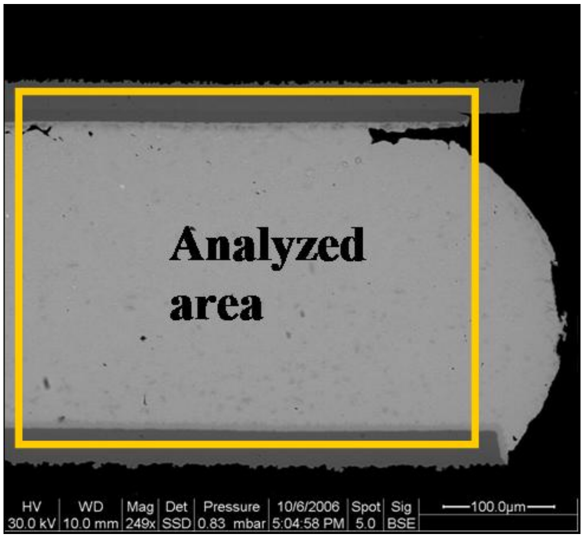

Figure 18 - Area analyzed for the presence of Pb

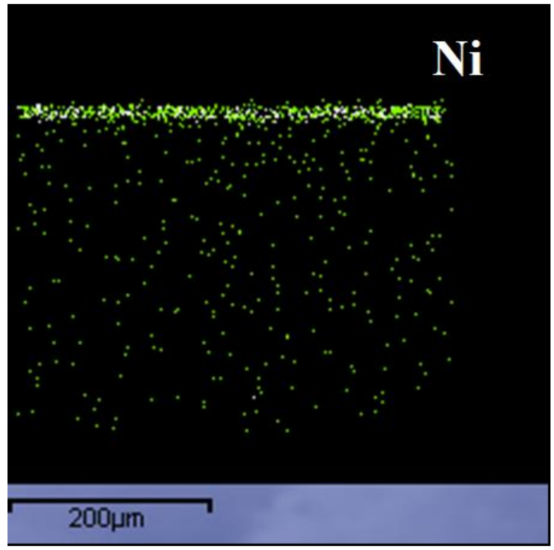

Figure 19 - Amount of nickel found in the area under analysis

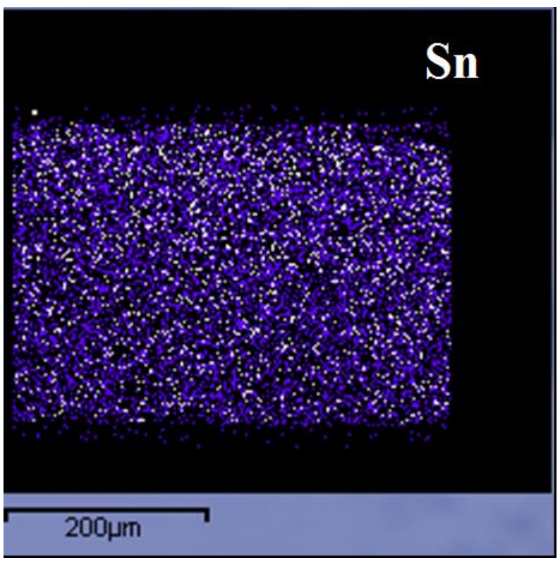

Figure 20 - Amount of tin found in the area under analysis

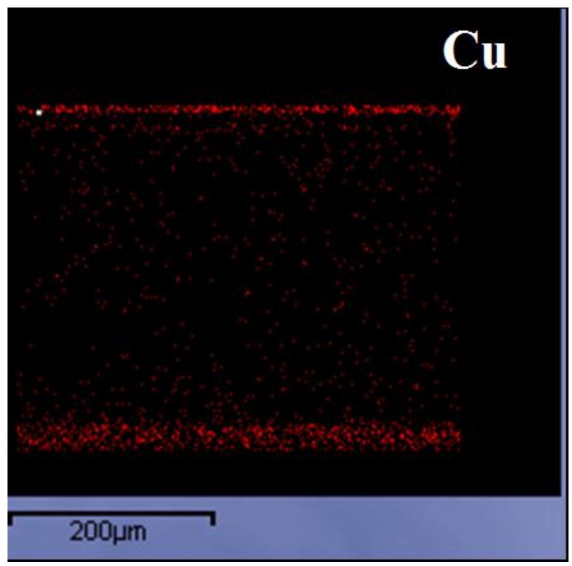

Figure 21 - Amount of copper found in the area under analysis

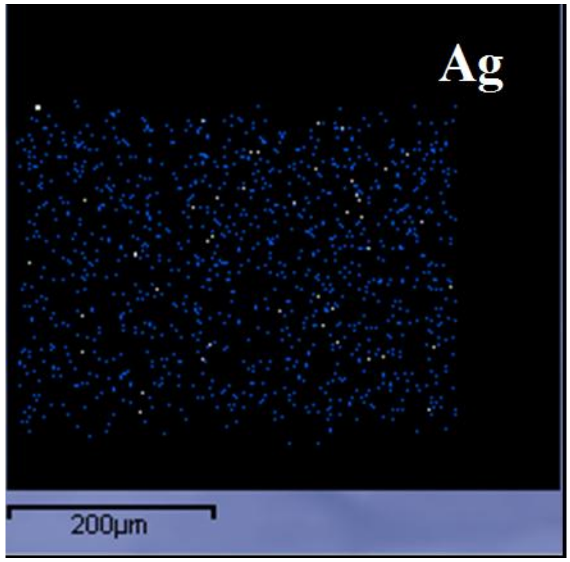

Figure 22 - Amount of silver found in the area under analysis

Conclusions

The impacts of thermal aging and repair of lead-free and lead-based assemblies were examined. Repair defects included lead misalignment, solder mask rip-off, and non-uniform solder-joint heights in PBGAs due to package warpage. Significant failure of the PBGA component population was induced by the application of a -40 to 125^{o}C temperature cycle. Physical analysis of the failed PBGAs found the failure site occurred in the solder near the component-side solder-mask-defined pad, regardless of solder type. The distribution of cycles to failure for lead-free PBGAs was found to be wider than the variation observed for the lead-based PBGAs. Further, thermal aging was found to have a more significant negative impact on lead-free PBGAs than on lead-based PBGAs. A wider variation in cycles to failure for repaired lead-free assemblies than for repaired lead-based assemblies was also observed. The variation may be due to the maturity of the lead-free assembly process, a characteristic of the lead-free solder under the imposed stress condition, or defects induced in the repair process.

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Background and Objectives

Background

- Pb-free transition presents a compatibility concern with repairing electronic hardware.
  - Inability to obtain SnPb replacement parts.
  - Lack of clear assembly labeling
- Concerns with repair of electronic assemblies
  - Pb-free component will have to be utilized during repair of SnPb assembly.
  - SnPb solder may be utilized during repair of Pb-free assemblies in the absence of Pb-free solder.

Objectives

- Provide durability information on depot repaired Pb-free and Mixed (Pb-free/SnPb) solder interconnects
  - Effect of aging on durability of repaired assemblies
  - Effect of repairing Pb-free, SnPb and mixed solder joints

CALCE Rework Study

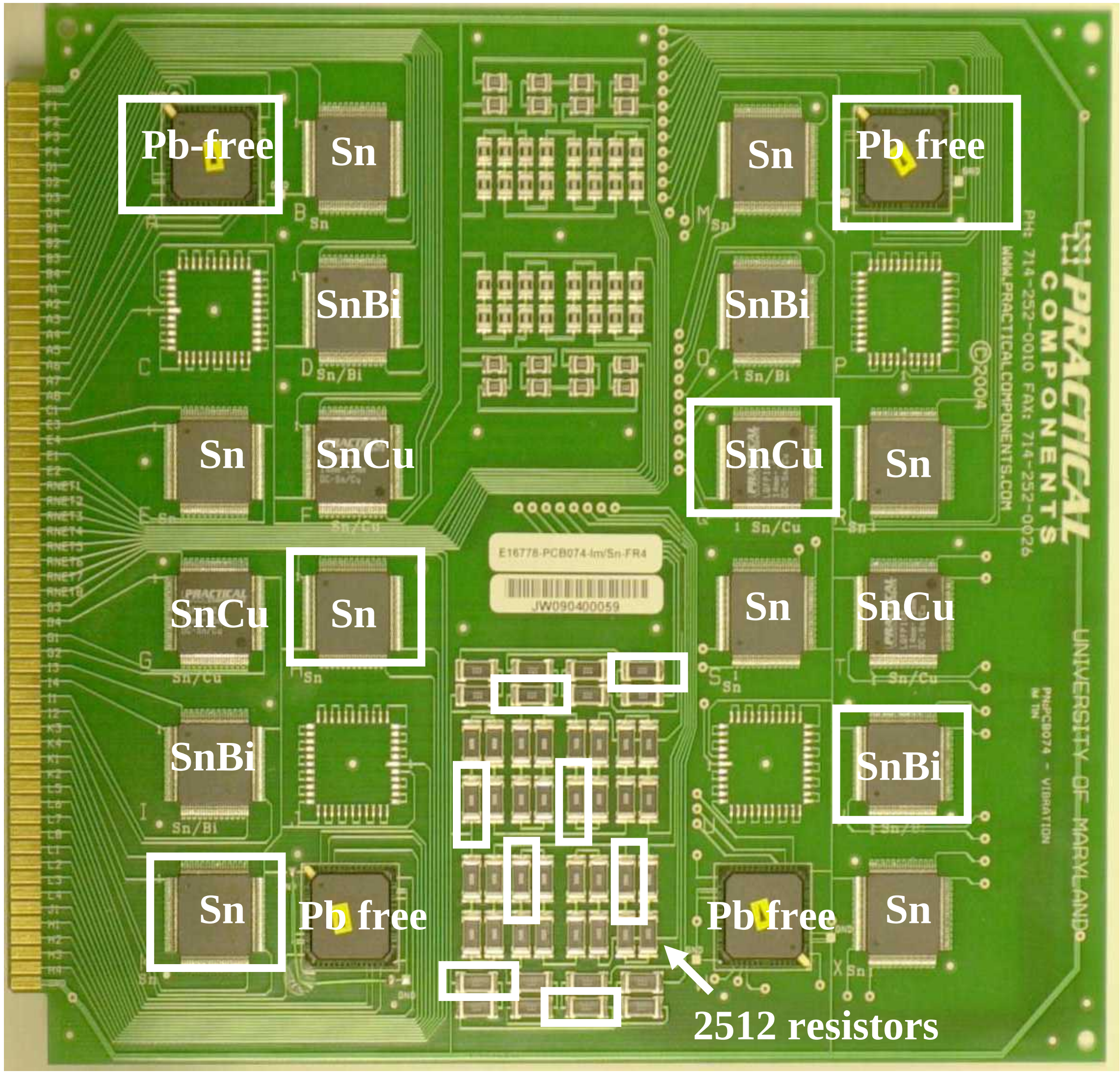
- Test Board -

Parts to be reworked

Board parameter

- 8”x7”, single layer, one sided (FR4) board
- Board thickness: 62 mils
- Parts to be reworked: 2 BGAs, 4 QFPs, 8 resistors (2512)
- Glass transition temperature (Tg): 130 ºC
- Pb-free Board – ImSn Finish
- SnPb Board – SnPb HASL

- **Pb-free parts**
  BGA (SAC305), QFP (Sn0.7Cu, Sn2Bi, Sn), 2512 Resistors - (Sn)
- **SnPb parts**
  BGA (SnPb), QFP (SnPb), Resistor (SnPb)



Test Plan

Assembly	No Repair	Repair control	Repair with mixing (Pb in Pb-free assembly)
SnPb part HASL-Board finish	1 Non aged 1 Aged	1 Non aged 1 Aged	1 Non aged 1 Aged
Pb-free part ImSn-Board finish	1 Non aged 1 Aged	1 Non aged 1 Aged	1 Non aged 1 Aged

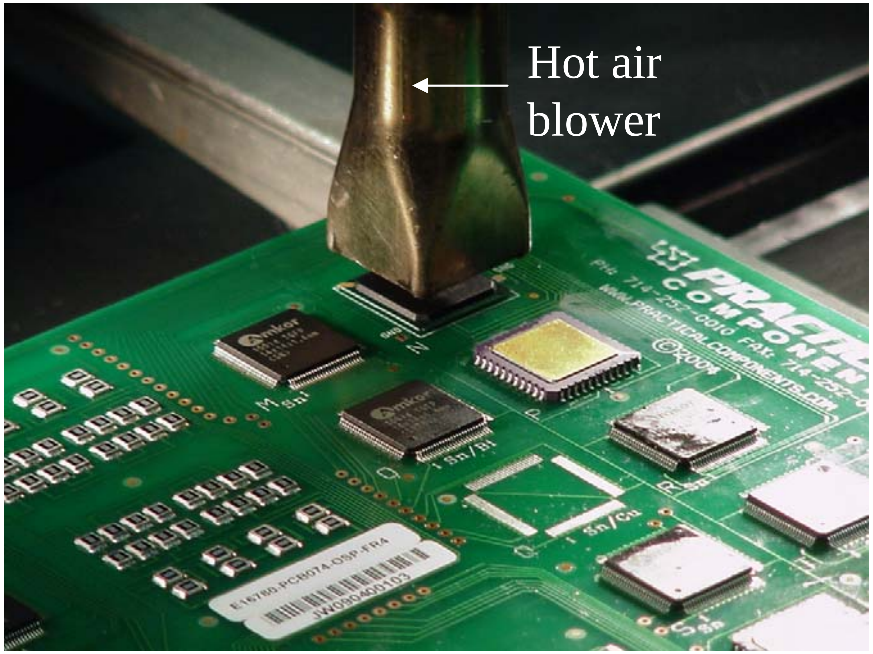
- Aging condition 125°C for 350 hrs. As reflowed assemblies were used as control for both assemblies.
- To test for durability, both aged and non aged assemblies were exposed to thermal cycling condition of -40 °C to 125 °C.
- In-situ resistance monitoring was conducted to detect solder joint failure. Failure criteria of resistance > 300 Ω for 10 consecutive thermal cycles within 10% of the cycles after the first failure was considered.

Repair Plan

Assembly	Repair	Repair (Control)	Repair with Mixing (Pb in Pb-free assembly)
		BGA	BGA
SnPb parts - HASL (SnPb) board finish	Original component	SnPb	SnPb
	Replaced component	SnPb	SnAgCu
	Solder paste	None	None
Pb-free parts – ImSn board finish	Original component	SnAgCu	SnAgCu
	Replaced component	SnAgCu	SnPb
	Solder paste	None	None

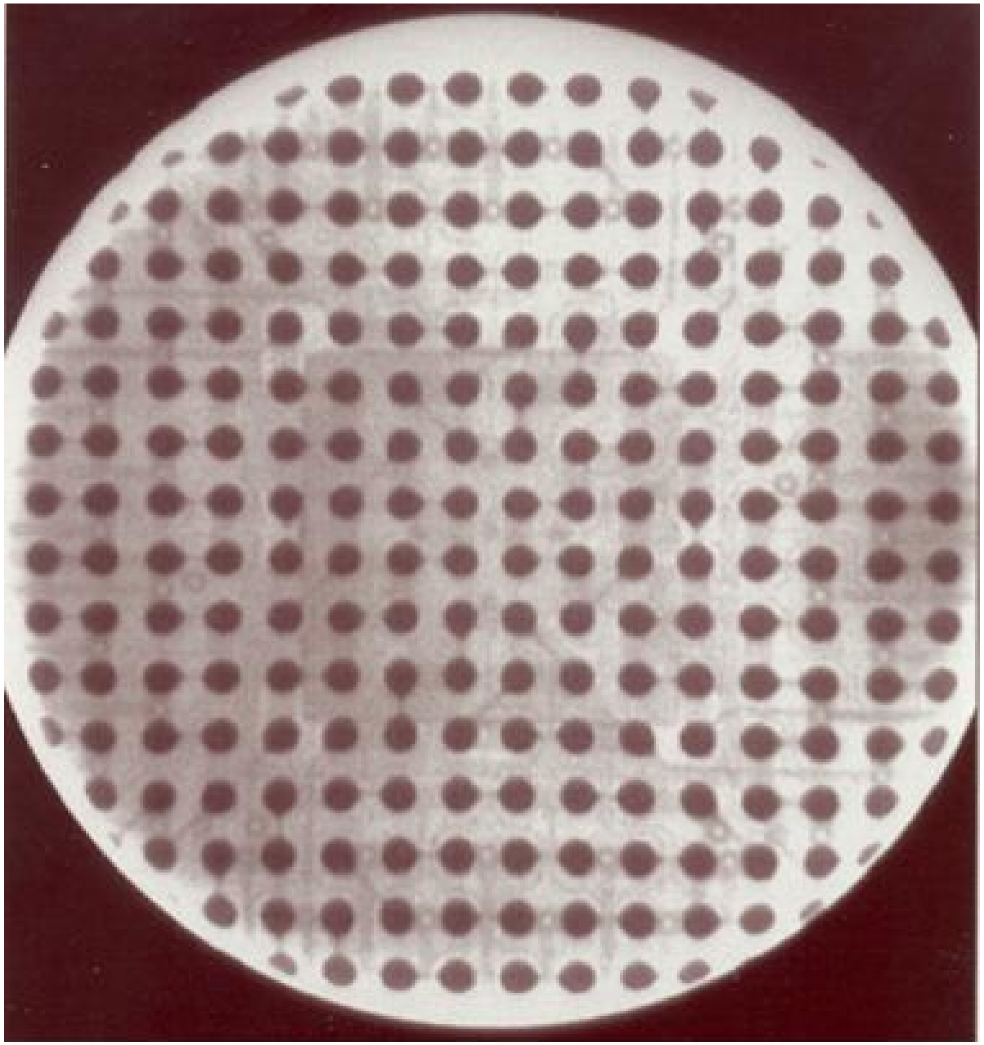
Repair Details

Repair step	Depot Repair Procedure
Component removal	BGA: Hot air at package top with heater set to 343 °C
Site redressing	Copper wick and soldering iron at 370 °C
Component replacement	BGA: Apply flux and reflow with hot air from heater at 370 °C, **no solder paste applied,** manual alignment



Repair was conducted by a repair facility involved in conducting electronics repair under their qualified repair process

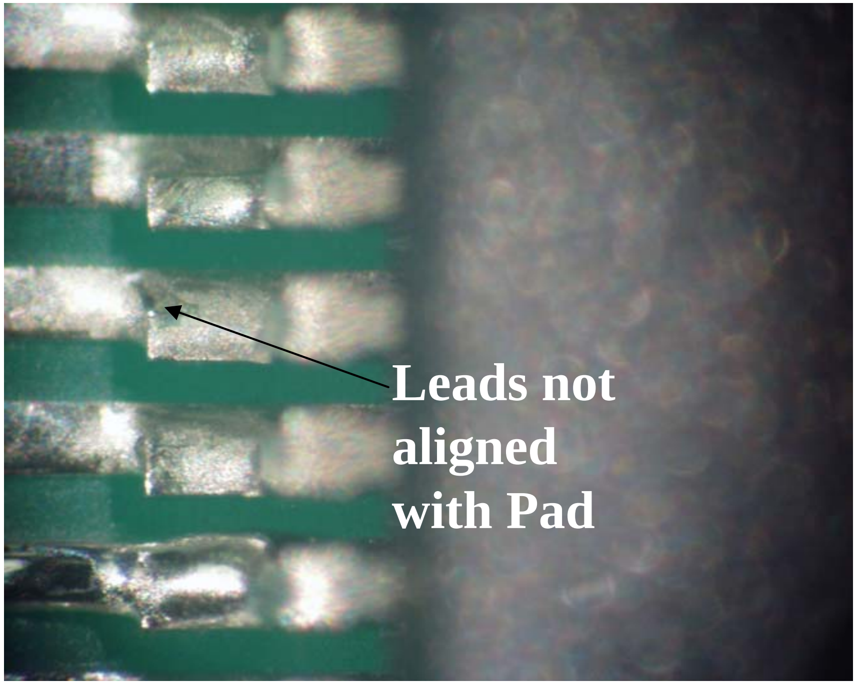
X-Ray Image of Reworked BGA



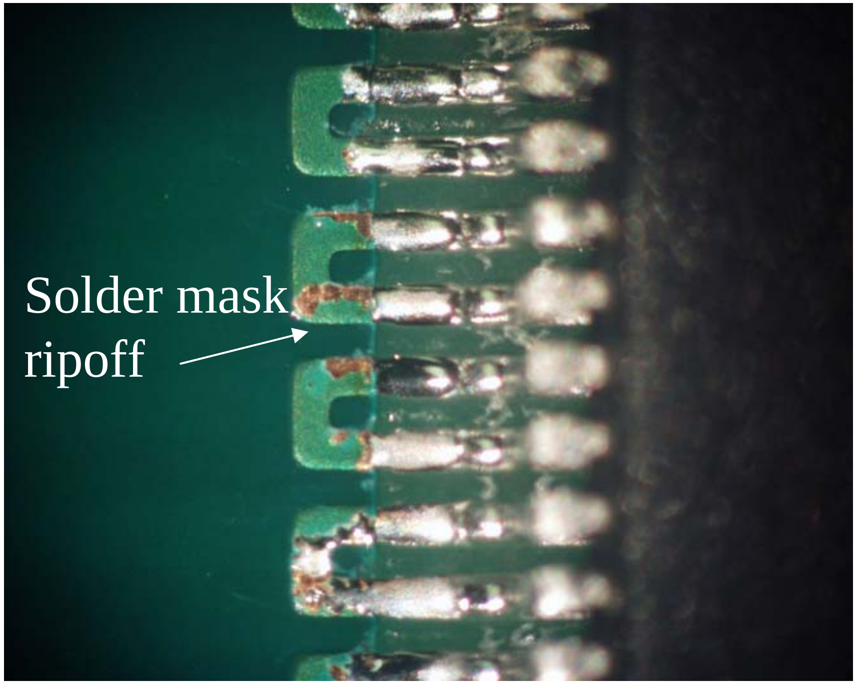
After BGA replacement, electrical continuity testing and X-ray imaging was used to verify solder ball attachment.

No defects were observed at the depot.

Detailed Inspection of Reworked QFPs



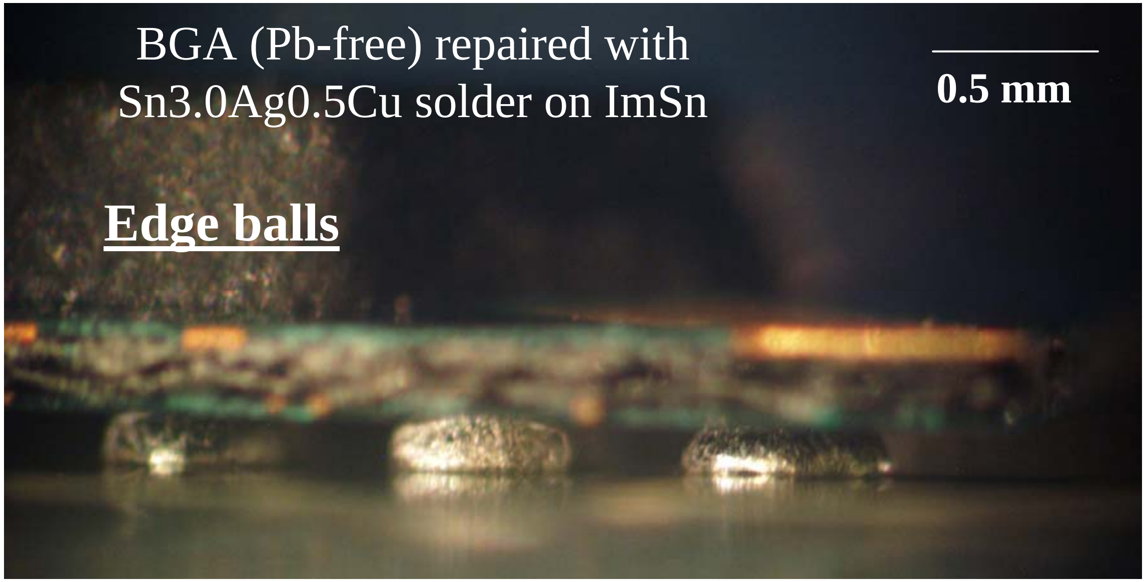
QFP (SnPb) reworked with Sn3.0Ag0.5Cu solder on HASL

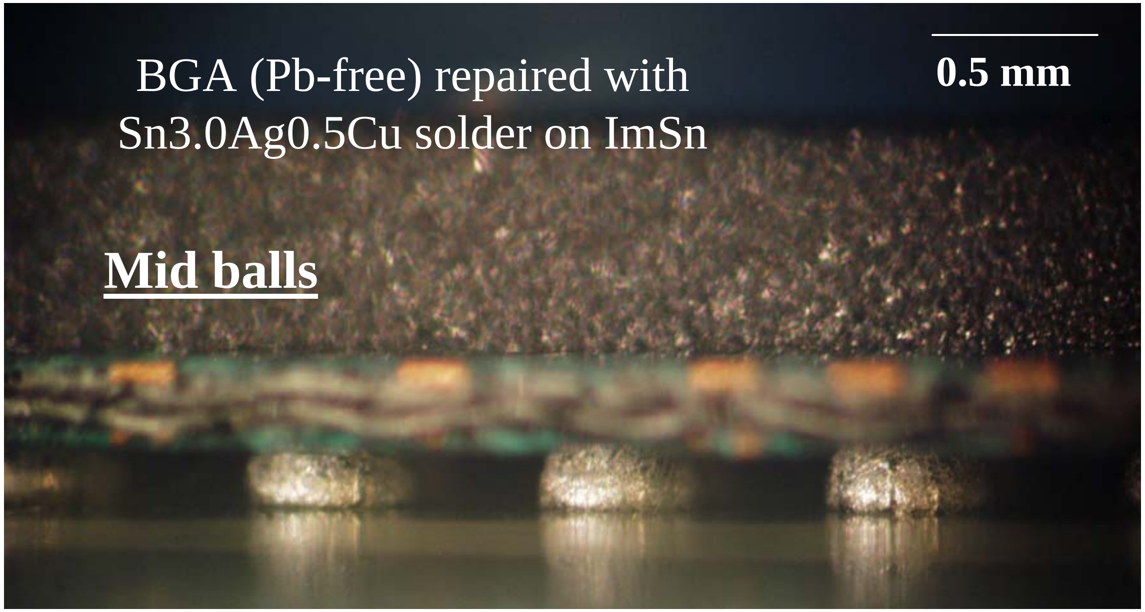


QFP (Sn finish) reworked with Sn37Pb solder

- IPC-610D: Side overhang < 50% acceptable for class 1 and 2 and < 25 % acceptable for class 3, Reworked assembly passes class 1 and 2 may not be acceptable for class 3
- Exposed copper may lead to other failure mechanisms

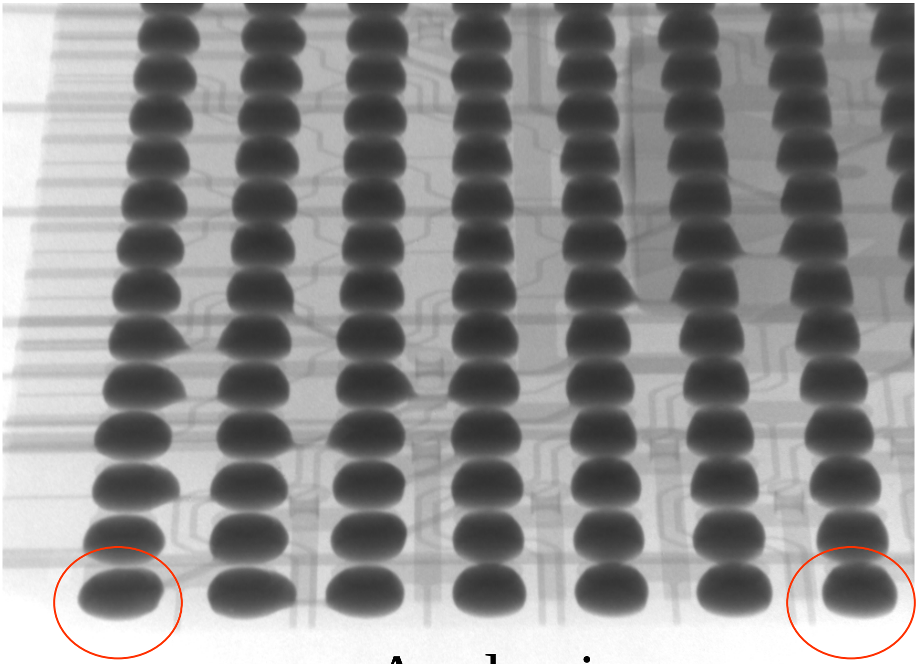
Detailed Inspection of Replaced BGAs



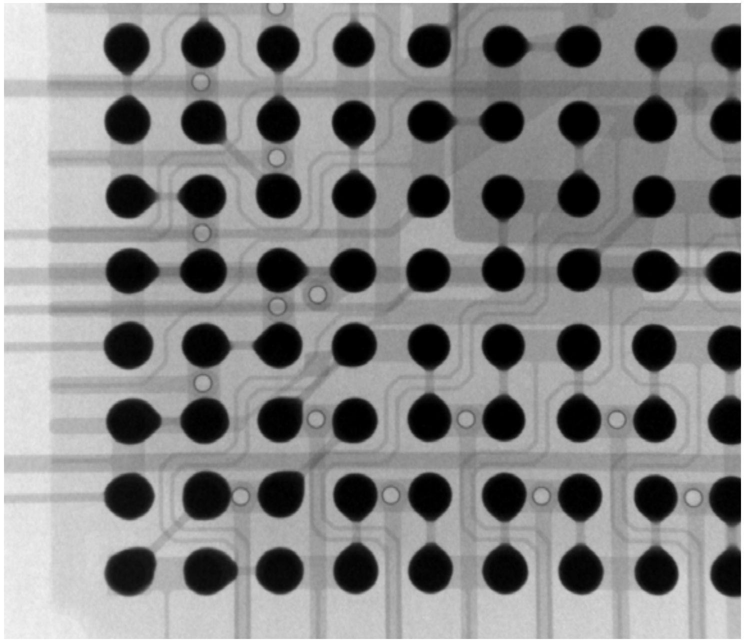


- Difference in solder joint height in the package was observed in repaired BGAs.
- Balls at the edge were squeezed more than those at the mid section of the package.
- Difference in solder height may be due to the warpage in the assembly of board.

Detailed X-Ray Imaging of Replaced BGAs



Angle view



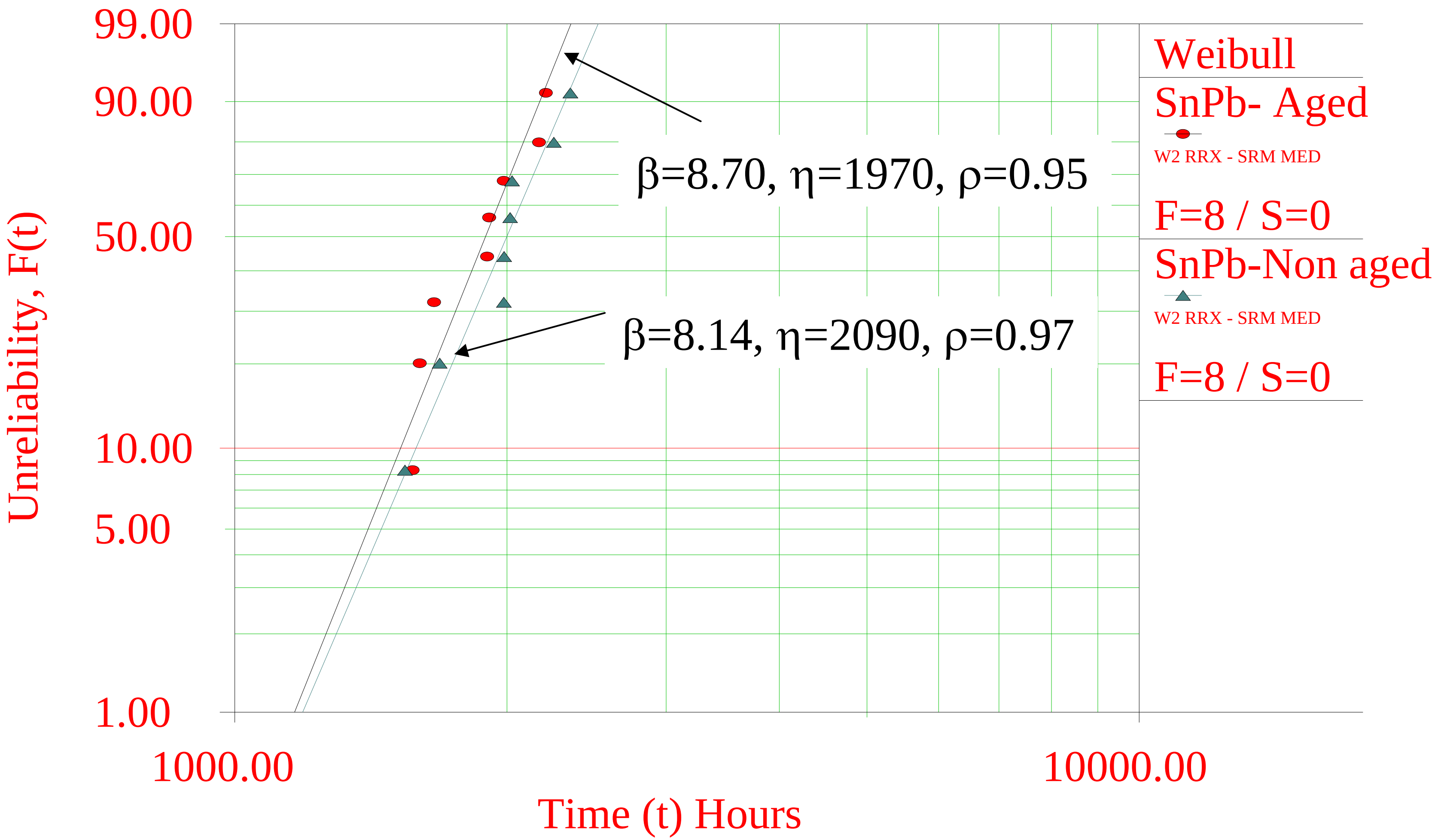
Top view

BGA (Pb-free) repaired with Sn3.0Ag0.5Cu solder on ImSn

Solder joint height in BGA was confirmed with X-Ray, balls at the edge were observed to have large diameter than those in the mid sections

SnPb Solder Joint Durability

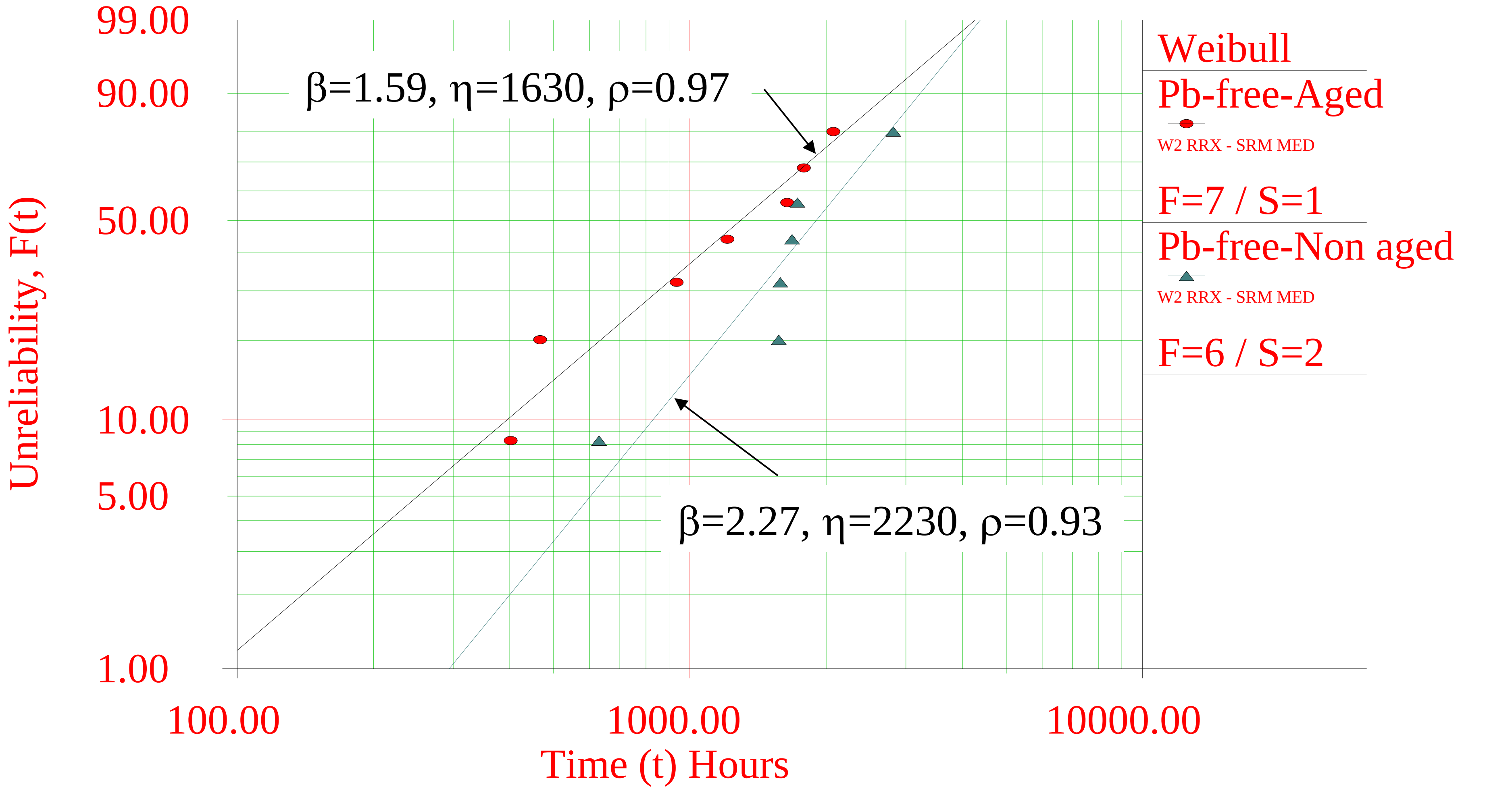
- BGA(Sn37Pb) – Sn37Pb Solder – HASL Pad Finish -



A decrease in life of 5% was observed between aged and non aged assemblies.

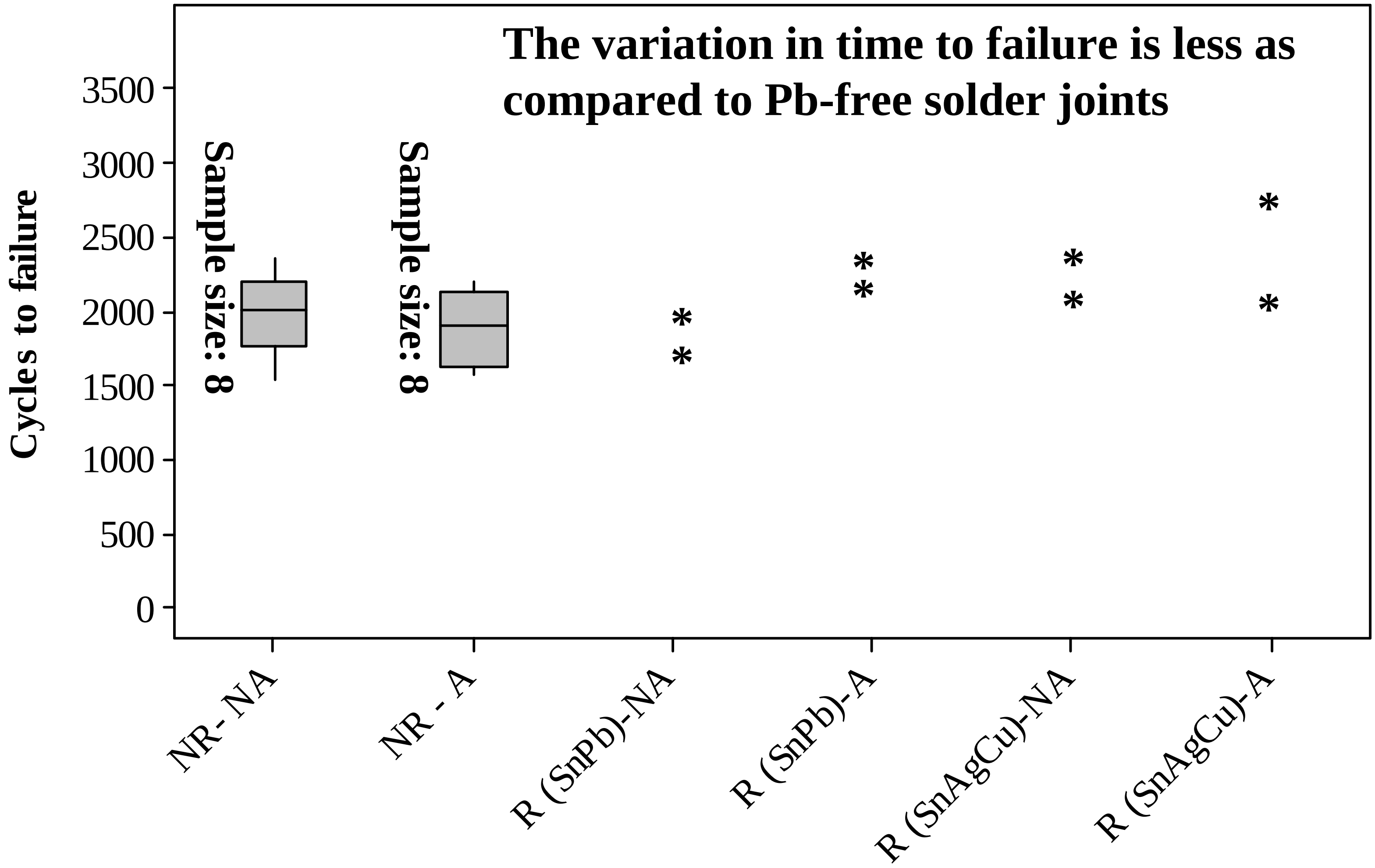
Pb-free Solder Joint Durability

- BGA (Sn3.0Ag0.5Cu) – Sn3.0Ag0.5Cu Solder – ImSn Pad Finish



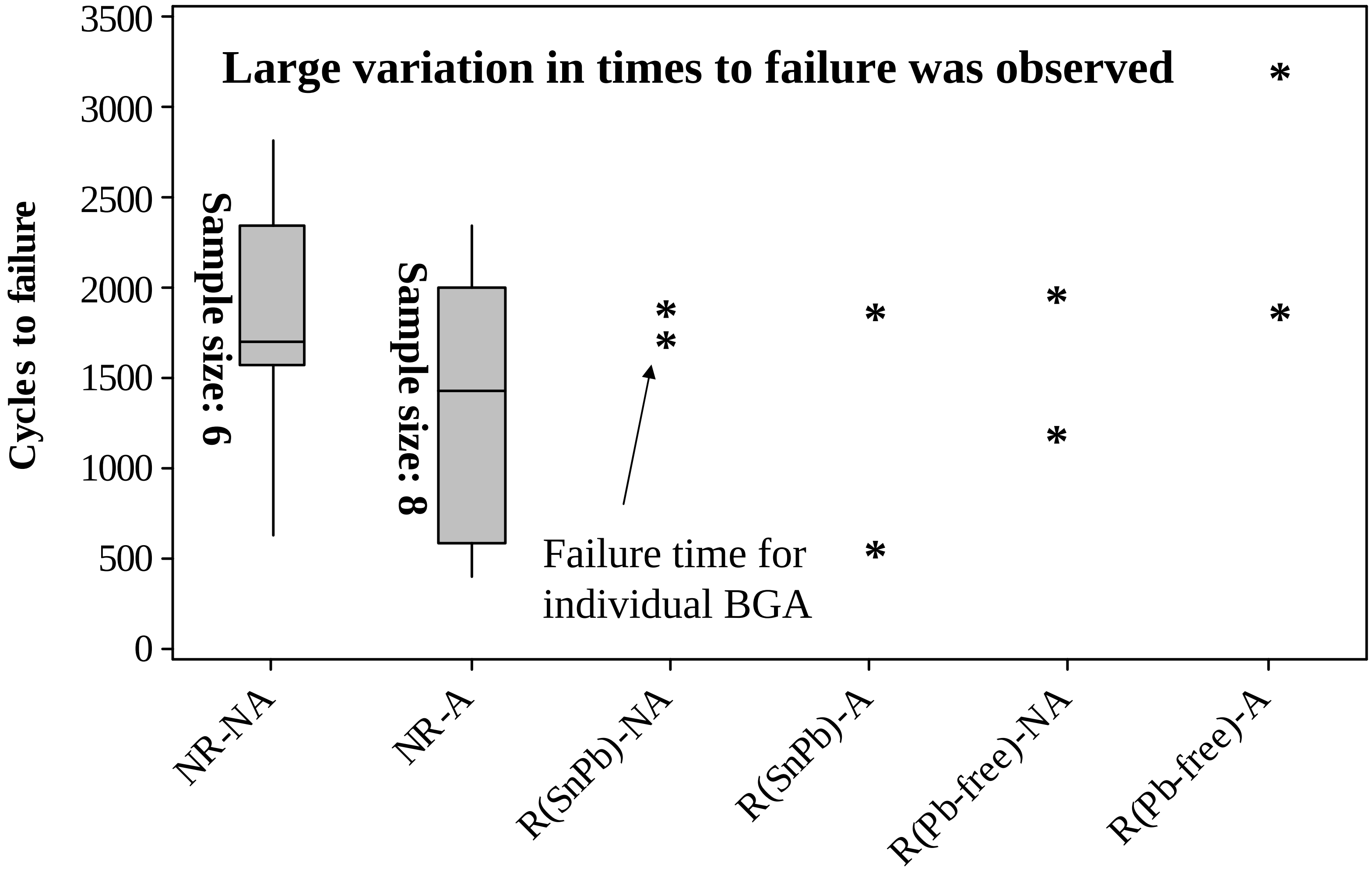
A decrease in life of 25% was observed between aged and non aged assemblies.

Effect of Aging and Repair on Durability - BGA (SnPb) Component -



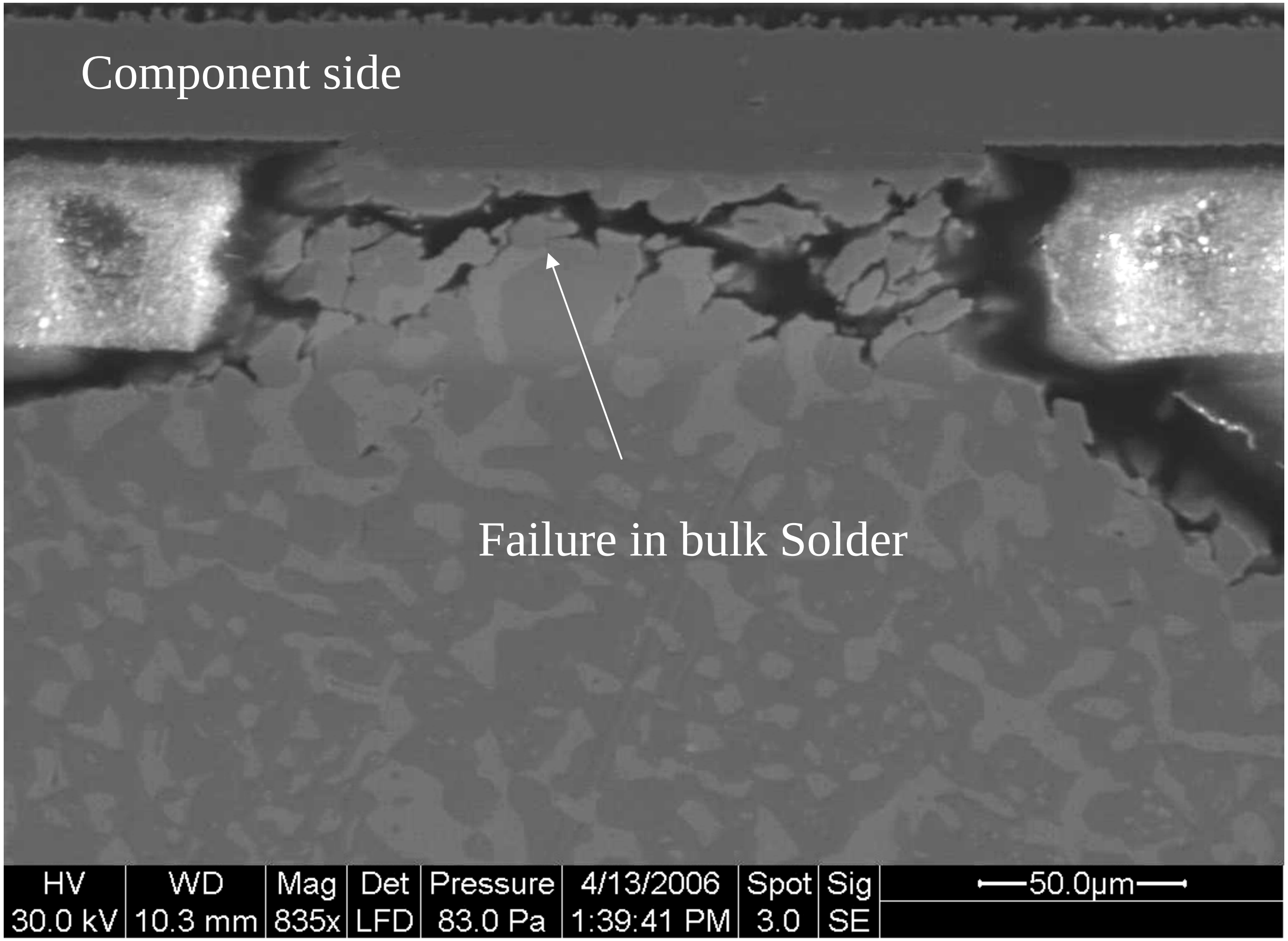
NR – No repair, NA – Non aged, A – Aged, R (SnPb) – Repaired with BGA with SnPb balls, R (SnAgCu) – Repaired with BGA with SnAgCu balls

Effect of Aging and Repair on Durability
- BGA (SnAgCu) Component -

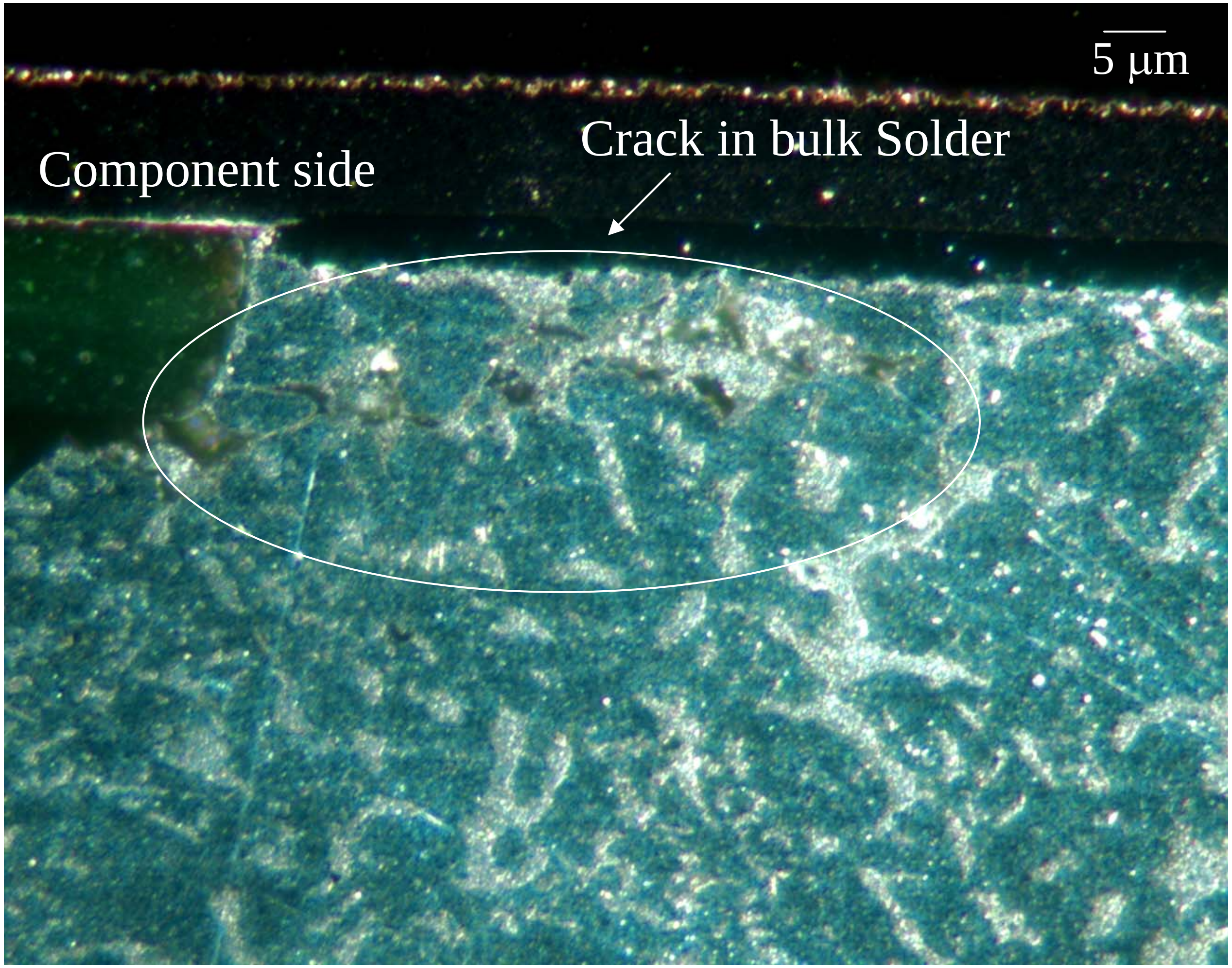


*NR – No repair, NA – Non aged, A – Aged, R (SnPb) – Repaired with BGA with SnPb balls,
R (SnAgCu) – Repaired with BGA with SnAgCu balls

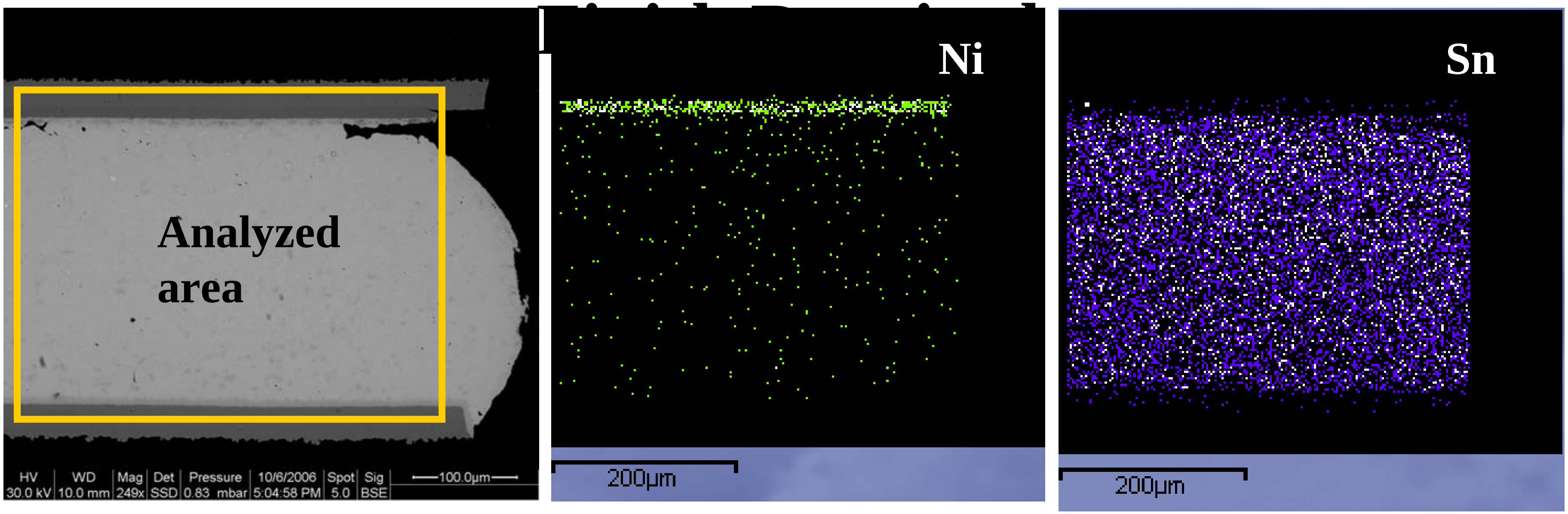
BGA (Sn37Pb) – Sn37Pb Solder – HASL Pad Finish Thermal Cycle Failure Site – Non Aged –

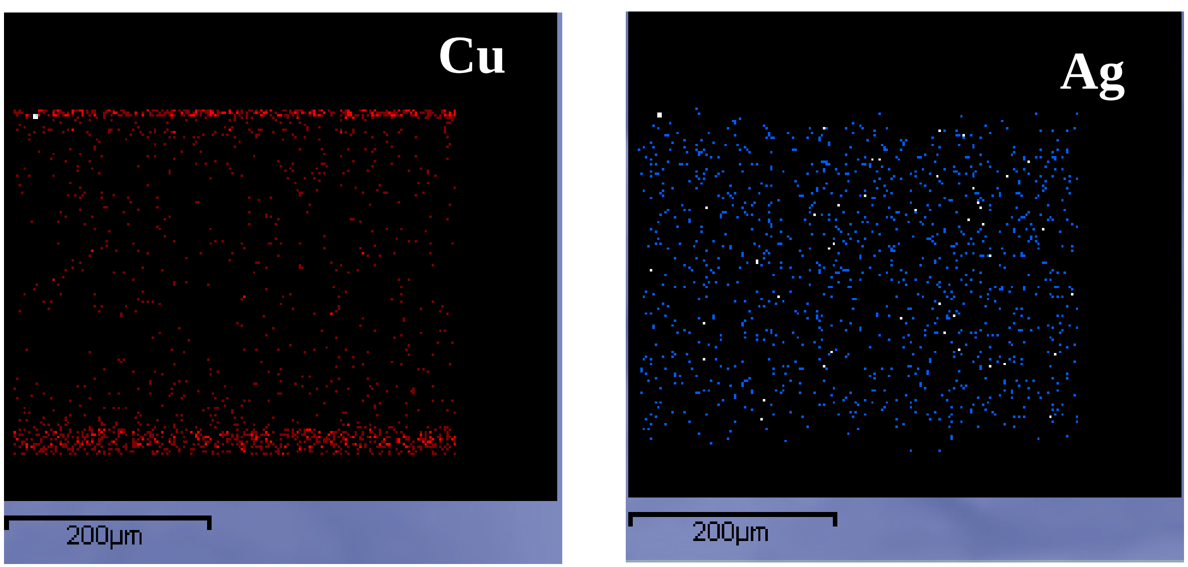


BGA (Sn37Pb) – Sn37Pb Solder – HASL Pad Finish – Crack Propagation Location – Aged –



BGA (SnAgCu) on HASL (SnPb) Pad

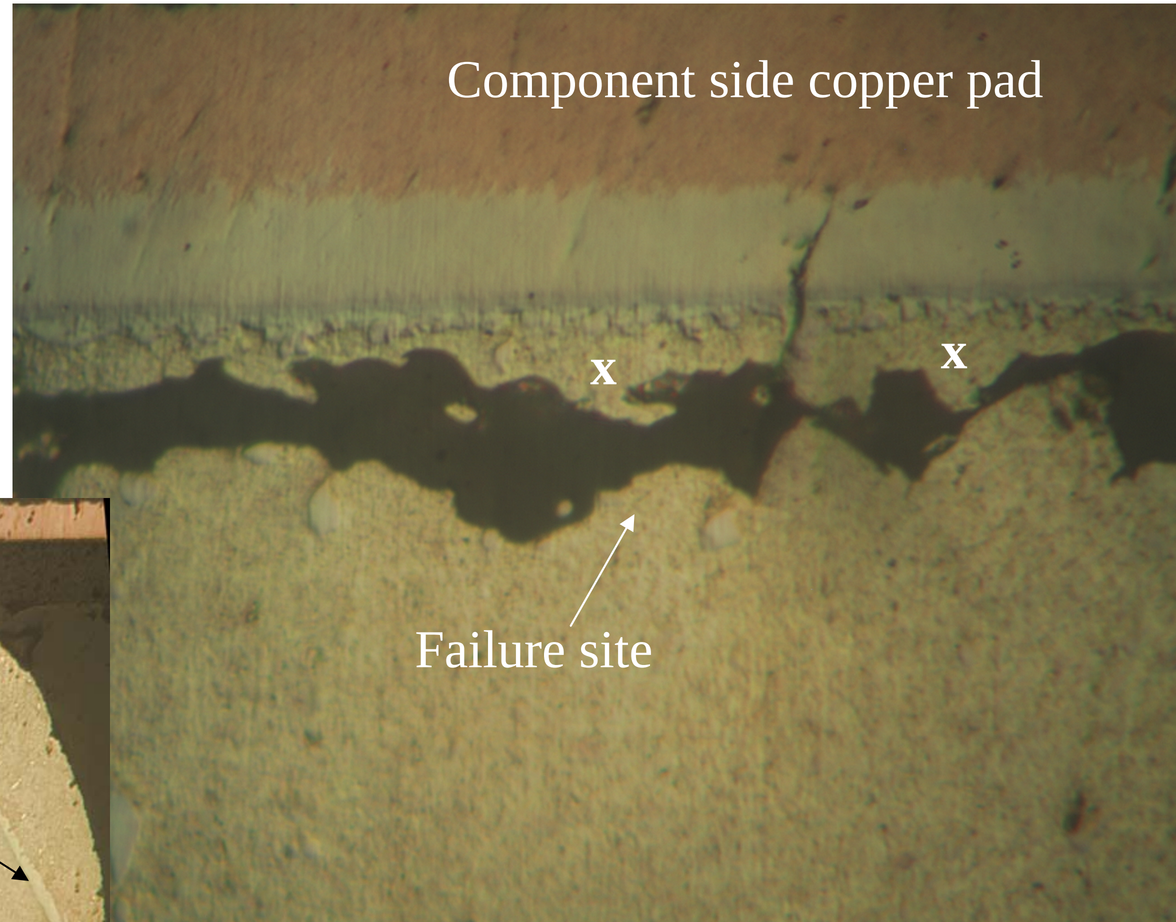


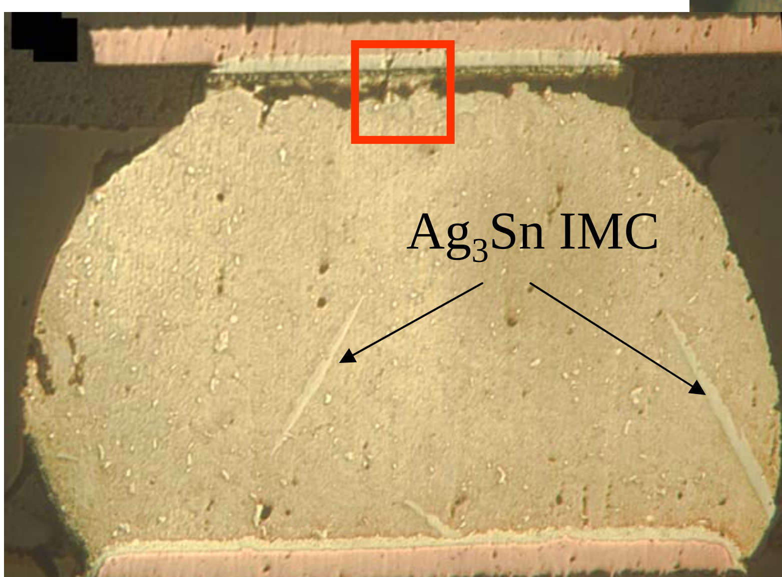


- BGA (SnPb) replaced with BGA (SnAgCu) on HASL(SnPb) assembly
- No Pb was found in the solder joint

BGA (SnAgCu) – SnAgCu Solder – ImSn Pad Finish – Aged –

Observation: 100% Sn was found in the marked locations above the crack which indicated the location of crack to be in bulk solder





Observations and Conclusions

- Failure of BGAs occurred a the component side in the bulk solder.
- Aging found to have a larger negative impact on Pb-free assemblies (25% reduction) than on SnPb assemblies (5% reduction).
- SAC BGAs on Pb-free assemblies showed a larger variation in time to failure as compared to SnPb BGAs on SnPb assemblies.
- SAC BGAs used to replace SnPb BGAs on SnPb assemblies showed similar reliability to as assemblied SnPb PBGAs
- Replace BGAs on Pb-free assemblies showed a wider variation in reliability.