The New Lead Free Assembly Rework Solution Using Low Melting Alloys

P. Snugovsky, S. Bagheri, Z. Bagheri, M. Romansky,
Celestica Inc.

Abstract
This paper describes a new lead-free SMT rework process which avoids component overheating, reduces board warpage and cratering, and prevents adjacent components from thermal damage. In the replacement of a BGA, on an organic substrate printed circuit board assembly, a solder alloy with the melting range lower than Sn-Ag-Cu solder is used. The lead-free solder pastes analyzed in this work include two Indium containing alloys, melting range 181-187°C and 138°C respectively, and a Bismuth containing alloy, melting range 195°-209°C. When the solder alloy melts, dissolution of the Sn-Ag-Cu balls occurs. The resultant composition and microstructure of the solder joints provide good mechanical and electrical properties with high fatigue life, while avoiding high temperature stresses on component bodies.

In this work CBGA937, PBGA196, and CSP46 components with SAC405 balls were assembled using SAC405 solder. Then rework was performed with three compositions of low melt solders using different profiles. The microstructures of mixed solder joints were analyzed using optical and scanning electron microscopy methods. Two solder pastes and rework profiles were chosen for thermal cycling. A limited ATC study was done in a temperature range of 0 -100°C. It was observed that fatigue life was component-dependant and when fully mixed, solder joints had better or equal reliability to that of the pure SAC405 assemblies.

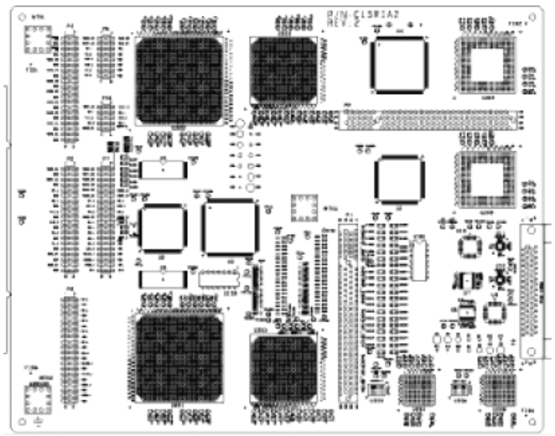
Introduction
A major challenge in the Pb-free assembly process is the rework of defective assemblies in a manufacturing environment [1-3]. Lead-free solders require processing at temperatures 30 to 40°C above those currently used for production with Sn-Pb solders. 232°C is the minimum recommended solder joint temperature for lead-free soldering using industry accepted Sn-Ag-Cu solder pastes. The component body temperature during rework is usually higher. For example, a CBGA might easily reach 260°C or even higher and this high temperature may damage the component. The adjacent and mirror solder joints might also be affected and reliability may be reduced. Board and substrate warpage is another problem with Sn-Ag-Cu alloys that could be difficult to avoid when reworking high I/O components on thick boards.

This paper describes a novel solution that allows a reduction of the rework temperature and improved solder joint reliability. The process may be used for rework during assembly manufacturing and after field failure.

Experimental
The influence of rework on solder joint structure and properties was investigated on the RIA2 test vehicle shown in Figure 1 [4]. Dimensions of the test vehicle were 203 mm x 253 mm x 2.36 mm, and it was fabricated with a lead free compatible laminate material capable of withstanding the higher temperature requirements of lead free processing. Surface finishes used on the RIA2 test vehicles were Organic Solderability Preservative (OSP), Immersion Silver (ImmAg) and Electroless Nickel Immersion Gold (ENIG). This test vehicle is daisy chained and allows for 4-wire in-situ monitoring of the components during accelerated thermal cycling (ATC).

To simulate representative component mixes on highly complex assemblies, different component types were placed on the test boards (Fig. 2). The assembly incorporates double sided SMT placements, PTH manual placements, bottom-side SMT glue placement and chip-cap wave solder attachment. Assembly was performed using no clean SAC 405 pastes in a nitrogen atmosphere using a standard 10 zone reflow oven.

The Hot Gas Rework was done on CBGA937, BGA196 and CSP46 components (Table 1). Site re-dressing was performed following component removal. Low melt solder paste was then applied to the re-dressed sites for all components.



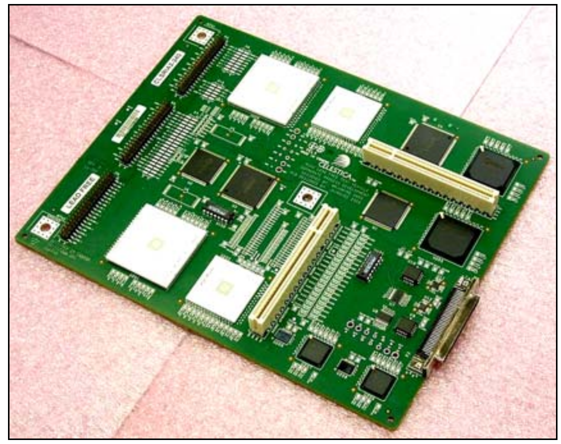


Figure1 - Test Vehicle RIA2 Design **Figure 2 - Assembled board RIA2**

Table 1 - Component description.

Component Type	I/O	Pitch, mm	Ball Composition (wt. %)
CBGA	937	1	Sn-3.8%Ag-0.5%Cu
PBGA	196	1	Sn-3.8%Ag-0.5%Cu
CSP	46	0.75	Sn-3.8%Ag-0.5%Cu

The rework investigation was performed in four steps. The first step was intended to investigate reworked microstructures using three different low melt alloys. Three commercially available alloys were chosen (Table 2). In first step, all assemblies were reworked on OSP finished boards in air. Hot gas rework profiles were created for each solder paste. The time above melting point was calculated from the solder paste melting points of 181°C, 138°C, and 118°C, respectively. Another important parameter that was analyzed was the time at the peak temperature. The criteria for rework parameter optimization were: proper shape of solder joint after rework, minimized voiding, uniform microstructure, and absence of or reduced low-melt **fractions** in the crystallized mixtures of solder paste and solder ball. Alloy C was excluded from the experimental matrix after the first step because of the high solder paste price precluding its use in most processes.

Table 2 - Solder alloys melting points

Solder alloy	Melting temperature, °C
Alloy A	181
Alloy B	138
Alloy C	118

In the second step, optimized rework profiles were used. This step was done on ENIG finished boards. Only alloy Pastes A and B were included for this part of the study.

The third step was performed to compare between 1X and 2X rework in air and nitrogen. In addition to OSP and ENIG, Immersion Ag assemblies were used. In this step, the influence of rework on adjacent components PBGA196 and CSP46 was investigated (Fig. 3). Two scenarios were analyzed. In the first scenario, both PBGA196 and CSP46 were removed at the same time. Then the CSP component was placed back using the low melt Paste A. After that, the PBGA was placed using the same low melt alloy. The second scenario was more thermally challenging. The CSP component was removed and a new component was attached with low melt alloy. Then the PBGA, which was assembled with SAC 405 solder, was removed using high heat for melting the Sn-Ag-Cu alloy. The last step was placement of the new PBGA device using low melt alloy Paste A.

In the fourth step, the influence on fatigue life of each of 1X and 2X reworks performed using optimized profiles was studied. One of the two identical ball grid array components of each of CBGA676, PBGA256, and PBGA196 on each board was reworked, and one remained untouched for comparison purposes. After the low melt rework, the boards were submitted to accelerated thermal cycling, concurrently with boards which were non-reworked as well as conventionally reworked boards.

Thermal cycling of the assembled test boards from 0°C to 100°C was performed in a Blue M Environmental stress chamber. The ATC profile is shown in Figure 4. It has a dwell time of about 15 minutes at both high and low temperatures, and 15 minutes ramp up and ramp down. The test duration was 6010 cycles. Cards were mounted in racks, which held the cards in position inside the chambers and allowed the air to circulate freely around them.

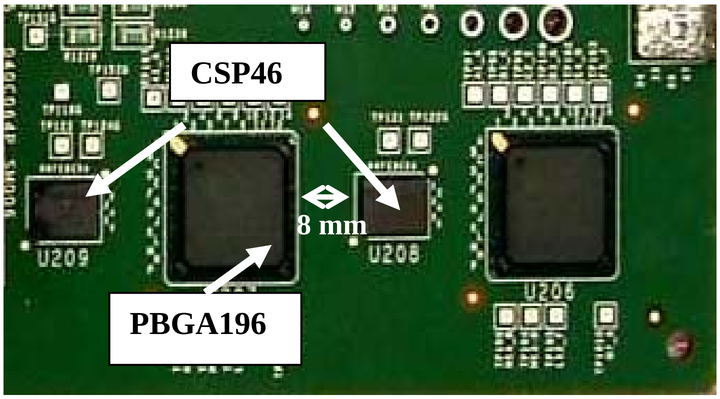


Figure 3 - Adjacent components

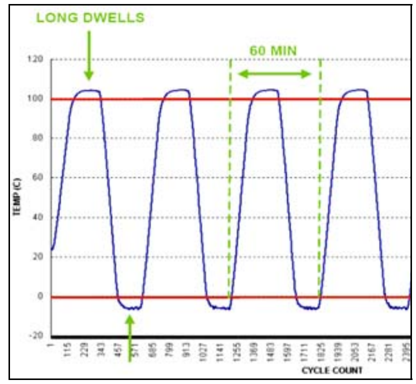


Figure 4 - Thermocouple reading of a test board

Reworked and thermally cycled solder joints were inspected using:

- Optical microscopy
- X-ray (Phoenix PCB analyzer)
- Scanning Electron Microscopy (SEM, Hitachi S-4500 and SEM Hitachi S-3000N)
- X-ray spectroscopy (Oxford EDX)

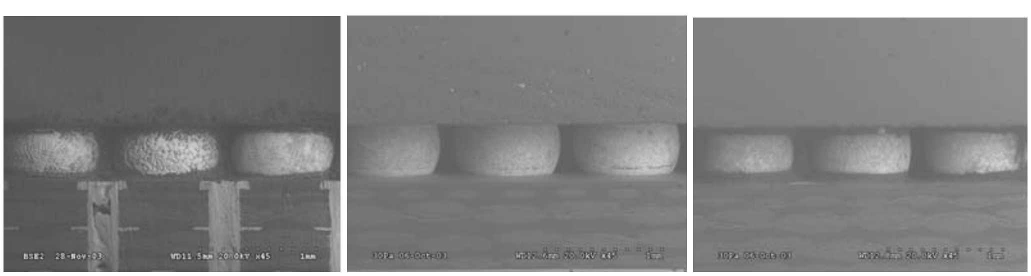
The Differential Scanning Calorimetry (DSC 2910) analyses were done to study solder joint solidification after mixing of the low melt solder with SAC 405 balls during rework. The DSC results showed that if full mixing was achieved, the low melt liquid was completely consumed, and the resulting composition crystallized at a reasonably high temperature range.

Results and Discussion

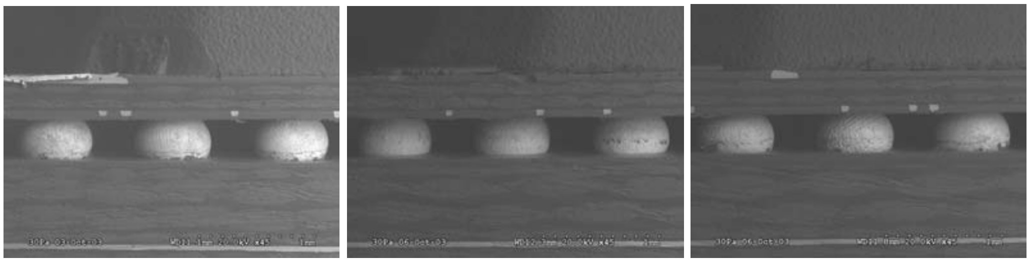
Microstructure of Reworked Solder Joints

In this study, the low melt solder paste was melted at temperatures below the SAC405 solder ball melting point. The solid solder balls were dissolved in the molten solder. The dissolution process depends on the rework parameters of temperature and time, and may cause full or partial mixing. Besides temperature and time, the ratio between the solder ball and solder paste volumes is especially important for complete mixing, and causes different microstructures for different components. The theory of solid solder ball dissolution in molten solder is described in a previously published paper [5].

No time-zero defects or open joints was found using a BGA scope, optical microscopy and SEM. Solder joints were properly formed, collapsed normally, and shaped well (Fig. 4).



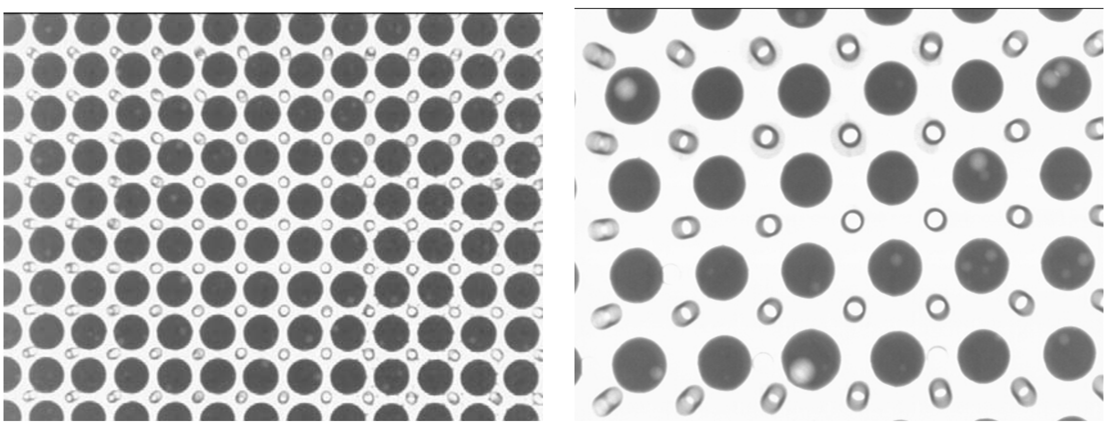
(a) **(b)** **(c)**



(d) (e) (f)

Figure 4 - Reworked SAC405 BGA using low melt solder paste, OSP, SEM, 45X: (a) CBGA937, Alloy A; (b) CBGA927, Alloy B; (c) CBGA937, Alloy C; (d) PBGA196, Alloy A; (e)) PBGA196, Alloy B; (f) PBGA196, Alloy C

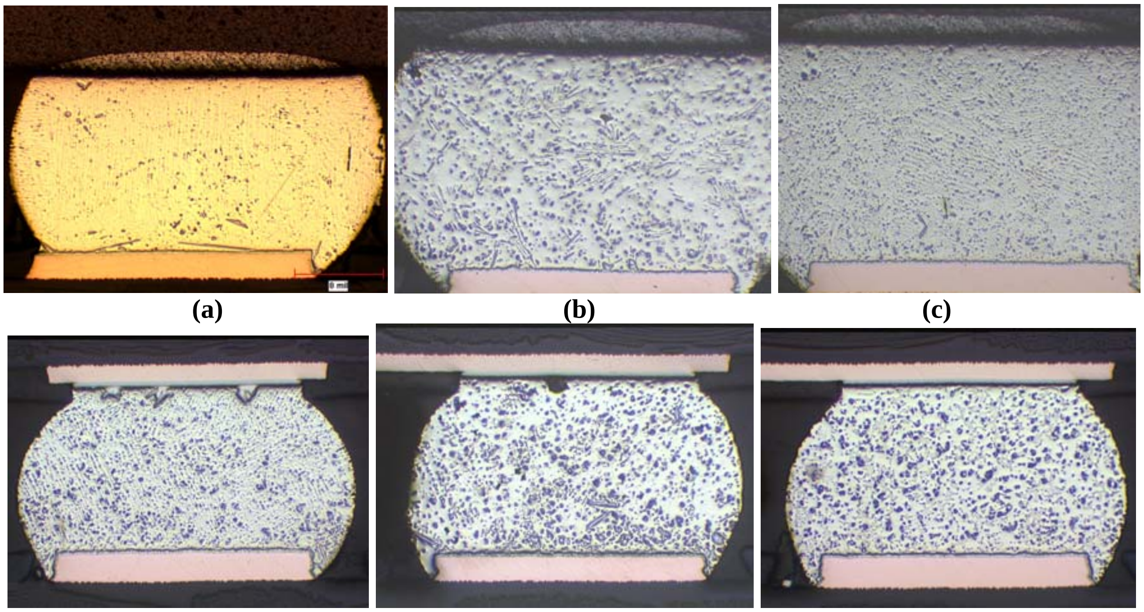
No defects were detected by X-ray after rework. There were no voids (Alloy A) or only small voids (Alloy B and alloy C) in CBGA937. In PBGA196, small voids were detected in Alloy B and C, and some larger voids were found in the central part of the Alloy A PBGA196. The ENIG finished boards exhibited lower voiding than OSP and ImmAg. The worst cases are shown in Figure 5.



(a) (b)

Figure 5 - Worst Case Voids in reworked joints: (a) CBGA937, Alloy B; (b) PBGA196, Alloy A

Uniform microstructures were formed during rework in both CBGA937 and PBGA196 using all three alloys (Fig.6). There was no portion of initial solder ball visible at the cross-sections of reworked solder joints. It shows that component solder balls were fully dissolved in liquid solder paste during reflow, and that the resulting liquid was solidified during cooling. The DSC analysis confirmed these metallographic observations..

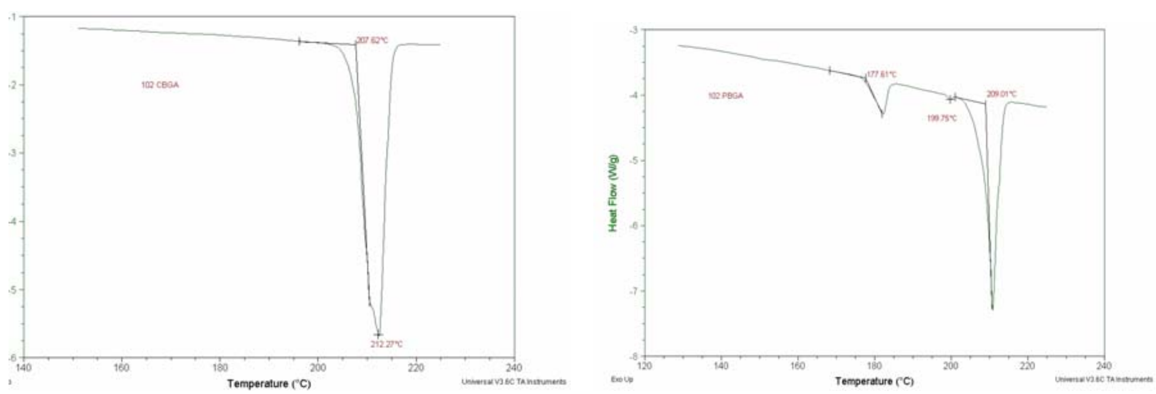


(a) (b) (c)

(d) (e) (f)

Figure6 - Microstructure of reworked solder joints, 100X: (a) CBGA937, Alloy A; (b) CBGA937, Alloy B; (c) CBGA937, Alloy C; (d) PBGA196, Alloy A; (e) PBGA196, Alloy B; (f) PBGA196, Alloy C

The DSC heating curve for reworked CBGA937 solder joints using Alloy B (181°C melting temperature) is shown in Figure 7a. The melting starts at 208°C, which is 17°C higher that the Indium-containing solder paste melting point. It melts in a relatively narrow temperature range, and stops melting at 212°C. This range is much below 217°C – the melting temperature of Sn-Ag-Cu solder balls. The reworked PBGA196 solder joints finish melting at an even lower temperature (209°C), confirming that SAC 405 solder balls are completely consumed (Fig. 7 b). The melting begins at 178°C.



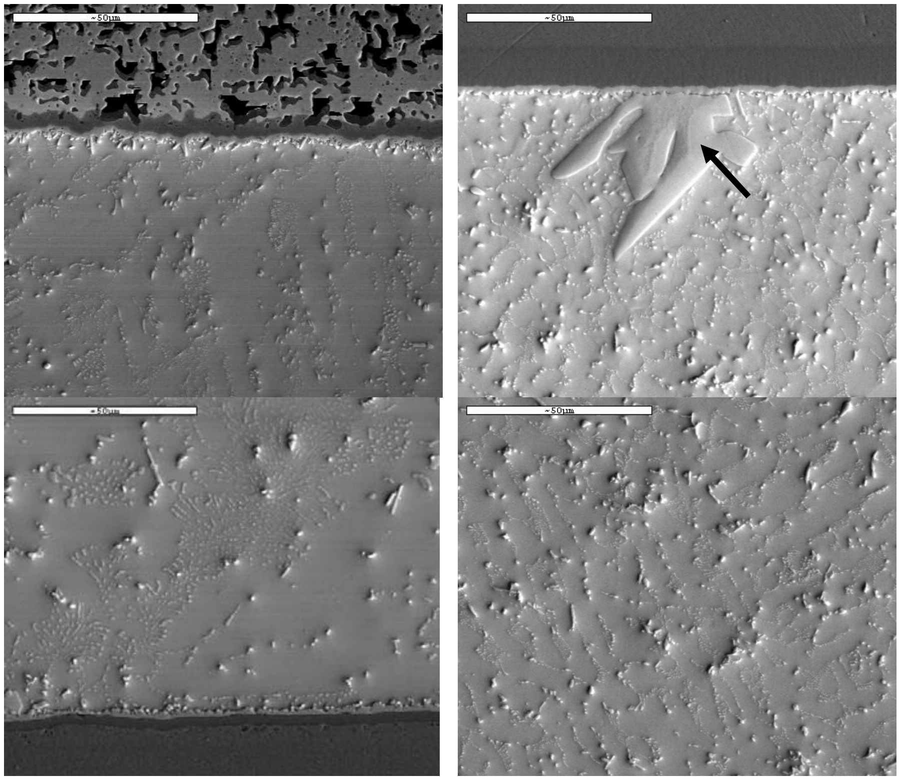
(a) (b)

Figure 7 - DSC heating curve for reworked CBGA937 (a) and PBGA196 (b) using Alloy A

The final composition of CBGA937 after rework is comprised of 3.7-3.8 % Ag, 3.8-4.0 % In, and 0.4-1.0 % Cu, depending on the board surface finish. The microstructures of these joints are very similar to pure Sn-Ag-Cu alloys. CBGA937 reworked solder joints have Ag_3Sn plates, Sn dendrites, and eutectic in interdendritic spaces. The number of Ag_3Sn plates is small, and they are not large in size. (Fig. 6a and 8a). The EDX analysis reveals some Indium both in the Ag_3Sn particles and in the Sn matrix. These data are consistent with the previously published paper on Sn-Ag-In alloy microstructure formation [6]. The ternary liquidus projection phase diagram [7] shown in Figure 9 may be used to interpret the microstructures. It shows that for low In content (0 to approximately 4 atom %), the compound phase is the Ag_3Sn type, with some In substituted for Sn. The matrix phase is the βSn type.

The PBGA196 after rework contains 3.6-3.7 %Ag, 6.0-6.2 % In, and 0.4-1.0 %Cu. Sn dendrites and eutectic are present in the CBGA937 microstructure. Large primary intermetallic particles that have a specific flower shape (Fig. 6d and 8b) are detected in the PBGA196 reworked solder joints. This compound contains a significant amount of In and is more likely the

$Ag_{2.7}$(In,Sn) type. It was found [6] that for intermediate In content in alloys (approximately 4 to 6 at %), the compound phase has the approximate composition $Ag_{2.7}$(In,Sn), where the In and Sn contents are approximately equal. It also may be the Ag_2In type that forms in alloys with a high In content (greater than approximately 6 at %). The occurrence and size of the particles depends on the rework parameters, and may be significantly reduced by parameter changes.



(a) **(b)**

Figure 8 - Microstructure of reworked solder joints, Alloy A, SEM, 1000X: (a) CBGA937; (b) PBGA196

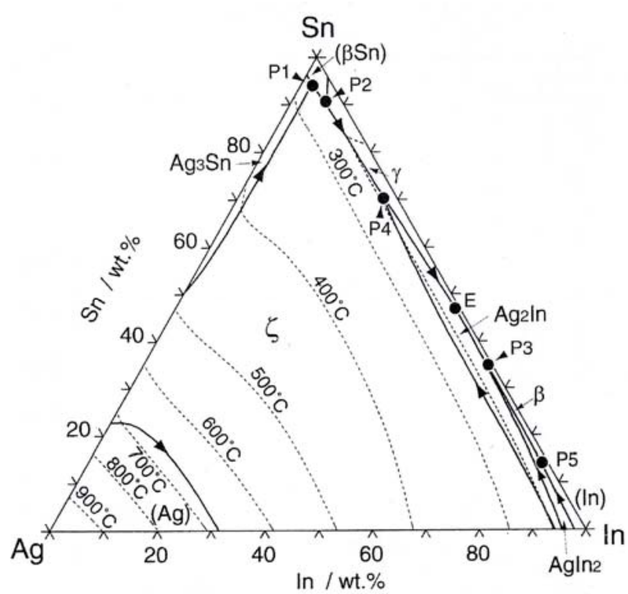
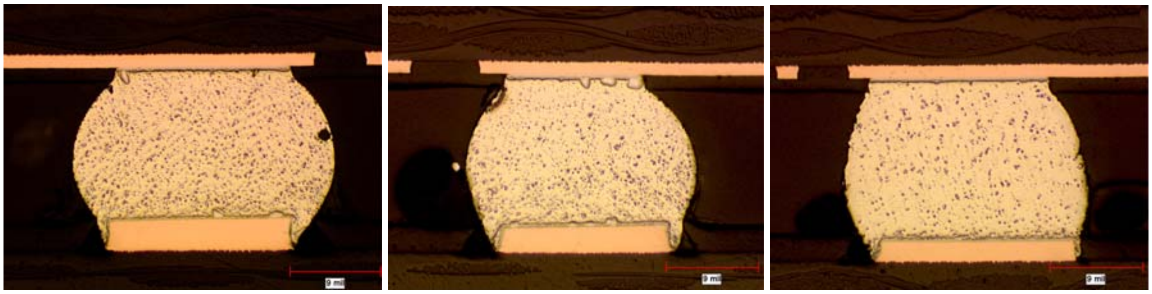


Figure 9 - Ternary liquidus projection related to the ternary Ag-In-Sn alloy system.

The reworked CSP 46 microstructure is similar to PBGA196 and is shown in figure 10. There are no significant differences between 1X and 2X reworks on both ImmAg and ENIG finishes. The influence of the rework of the adjacent PBGA196 is negligible.



(a) **(b)** **(c)**

Figure 10 - Microstructure of reworked CSP46, Alloy A, ImmAg, 100X: (a) 1X; (b) 2X; (c) 2X before PBGA196 rework

The reaction intermetallic layer at the board side is $(Cu,Ni)_6Sn_5$ with 3-5 % Ni. The intermetallic on the component side is a ternary compound, Sn-Cu-Ni, with the Ni content 10-15%. For the OSP and ImmAg finished boards, the thickness of the intermetallic layer on the board side is about 5µm in CBGA937 and 6µm in PBGA196, in both cases after 1X and 2X rework. The intermetallic layers on the board side of the ENIG finished boards is much thinner – about 1.8µm and 2.5µm in CBGA937 and PBGA196, respectively.

Both CBGA937 and PBGA196 solder joint compositions after rework with Alloy A provide an excellent balance of the desirable properties: strength, plasticity, and fatigue life, and superb fatigue resistance [8]. The described microstructures are also favorable for high reliability of the reworked solder joints.

The Sn-Ag-Cu balls (T_m – 217°C) and In-Sn solder paste Alloy C (T_m – 118°C) are fully mixed together, resulting in an alloy that melts at about 199°C (Fig. 11). The composition of the CBGA937 balls is about 3% Ag, 13% In, and 0.5% Cu. For an In content greater than approximately 8 at% (Fig.9) [7], the matrix phase is the γ phase of the In-Sn system.

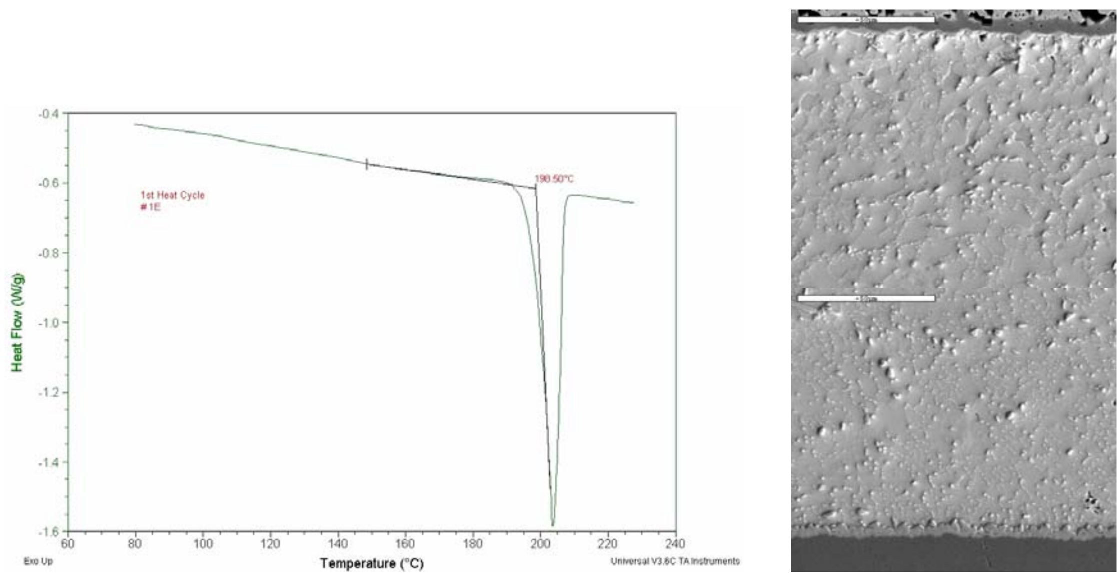


Figure 11 - Reworked CBGA937 using Alloy C; (a) DSC heating curve for reworked joint; (b) Microstructure, SEM, 1000X

The DSC results for reworked CBGA937 solder joints using Alloy B (138°C melting temperature) are shown in Figure 12. The first heating run shows a small melting peak at 137°C (Fig 12a). This indicates that a small amount of low melt Sn-Bi-Ag eutectic is present. The Sn-Ag-Bi phase diagram is shown in Figure 13. The ternary eutectic reaction L ↔ As_3Sn + (Sn) + (Bi) occurs at 137.1 °C (Fig. 13 [9]). The second heating run helps to mix the alloy completely and annihilate this peak (Fig. 12 b).The resulting alloy melts at 195°C. To properly mix the solder balls with Sn-Bi-Ag solder, the rework parameters were adjusted. The optimized rework profile with a longer dwell at peak temperature allowed for full mixing of the CBGA937 solder balls and solder paste. The reworked PBGA196 contained a low melt portion even after increasing the time at the reflow peak temperature of 217°C.

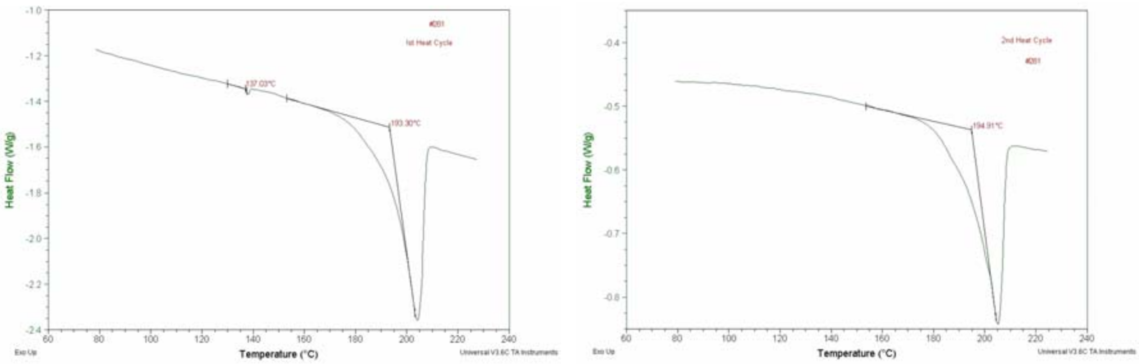
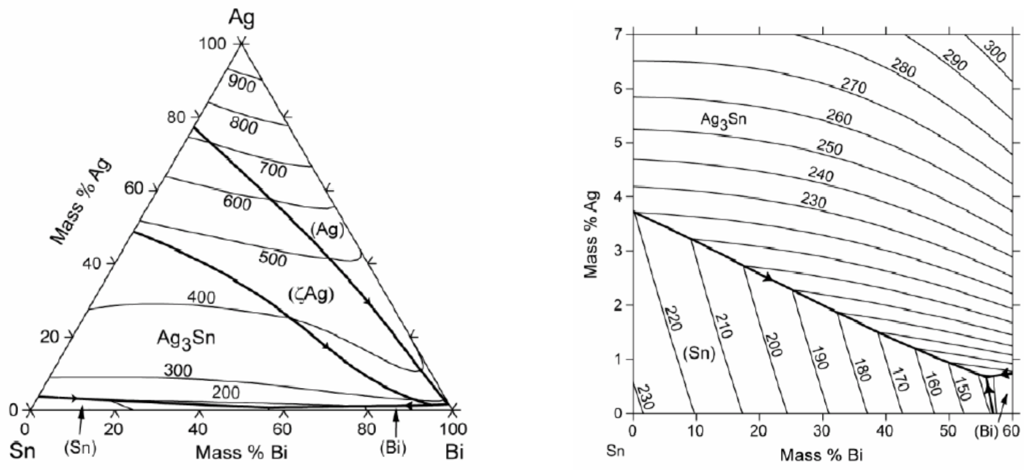


Figure 12 - DSC heating curve for reworked CBGA625 using alloy B: (a) first heating run; (b) second heating run



a **b**

Figure 13 - Liquidus projection of the Sn-Ag-Bi system (a) and Liquidus surface in the Sn-rich corner (b)

The CBGA937 joints reworked with Alloy B contain 3.2 - 3.3 % Ag, 12 - 14 % Bi, and 0.5 - 1.0 % Cu, depending on the board surface finish. The microstructure of these joints is really complex and is shown in Figure 14a. Small Ag_3Sn plates, Sn dendrites, and eutectic that contains Bi particles in addition to Sn, Ag_3Sn and Cu_6Sn_5 are present. The Bi particles are evenly distributed in the solder joints.

The composition of PBGA196 joints reworked with alloy B is slightly different from CBGA937 joints. They contain 3.0 - 3.1 % Ag, 16 – 17% Bi, and 0.4 – 1.0% Cu. The higher Bi content causes more eutectic Sn-Bi-Ag (Fig.14 b) in the microstructure and reduces the melting temperature.

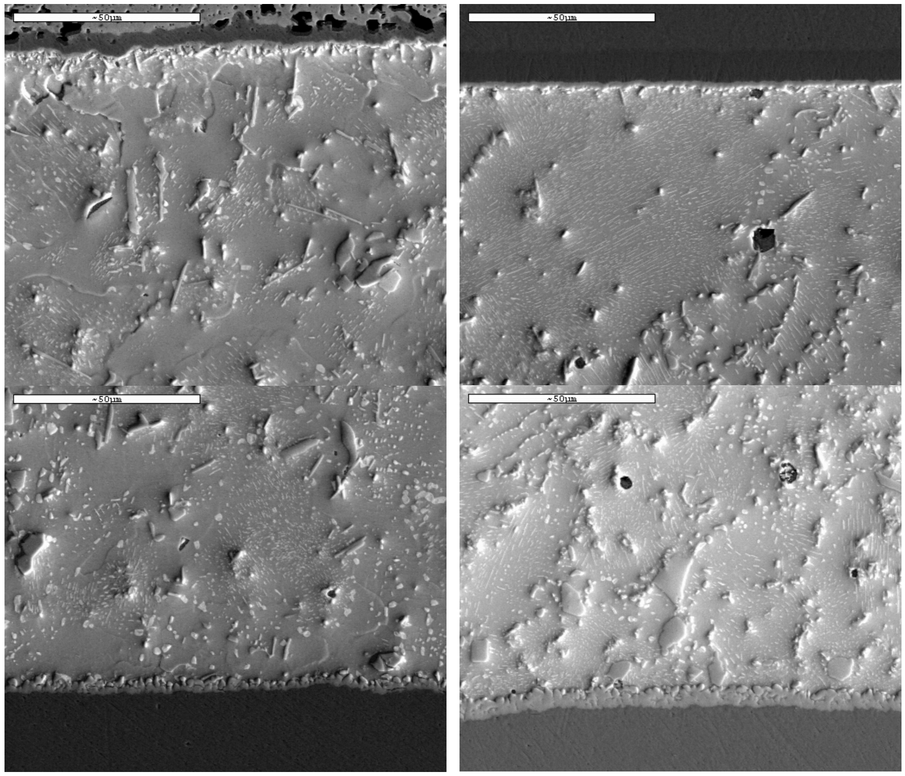
The intermetallic types on component and board sides in reworked solder joints using alloy B are the same as in joints reworked with Alloy A. The intermetallic layer in components reworked with the Bi-containing alloy is thinner compared to joints reworked with In-containing alloys. The thickness of the intermetallic layer on the board side of the OSP and ImmAg boards is 3µm and 5µm for CBGA937 and PBGA196, respectively.

There were no differences found between the microstructures of components reworked in air and nitrogen.

Thermal Cycling Reliability

A study of reworked solder joint behaviour under thermal cycling was done on a limited number of assemblies. The characteristics of reworked assembles are shown in Table 3. One of the two identical ball grid array components CBGA937, PBGA256, and PBGA196 on each board was reworked with either In- or Bi-containing alloys, and one was left untouched for comparison.

After 6000 cycles, the Weibull plots for CBGA937 reworked using Sn-Ag-In (Alloy A), Sn-Ag-Bi (Alloy B) solders, and for as-assembled pure SAC405 CBGA937 joints, were created (Fig. 15). The reworked SAC405 CBGA937 using In-containing alloy with final composition 3.7 - 3.8 % Ag, 3.8 - 4.0 % In, 0.4 -1.0 % Cu, remainder Sn, outperformed non-reworked pure SAC405 joints by a factor of two.



(a) **(b)**

Figure 14 - Microstructure of reworked solder joints, Alloy B, SEM, 1000X: (a) CBGA937; (b) PBGA196

Table 3 - Reworked Assembly Characteristics:

Board #	CBGA937		PBGA256		PBGA196		Process
	U202 no rework	U203 reworked	U205 no rework	U204 reworked	U206 no rework	U207 reworked	
1	SAC405	Paste A	SAC405	Paste A	SAC405	Paste A	1X
2	SAC405	Paste B	SAC405	Paste B	SAC405	Paste B	1X
3	SAC405	Paste A	SAC405	Paste A	SAC405	Paste A	1X
4	SAC405	Paste A	SAC405	Paste A	SAC405	Paste A	2X
5	SAC405	Paste B			SAC405	Paste B	1X
6	SAC405	Paste A	SAC405	Paste A	SAC405	Paste A	2X
7	SAC405	Paste B			SAC405	Paste B	1X
8	SAC405	Paste B			SAC405	Paste B	1X
9	SAC405	Paste B			SAC405	Paste B	2X
10	SAC405	Paste B			SAC405	Paste B	2X

The solder joints with a resulting composition of 3.2 - 3.3 % Ag, 12 - 14 % Bi, 0.5 - 1.0% Cu after rework of the CBGA937 with SAC 405 balls using Sn-Ag-Bi alloy did not perform as well as pure SAC 405 (Fig. 15). Nevertheless, comparison with the previous study [10] allows the authors to suggest that these joints are at least as reliable as pure Sn-Pb CBGA937.

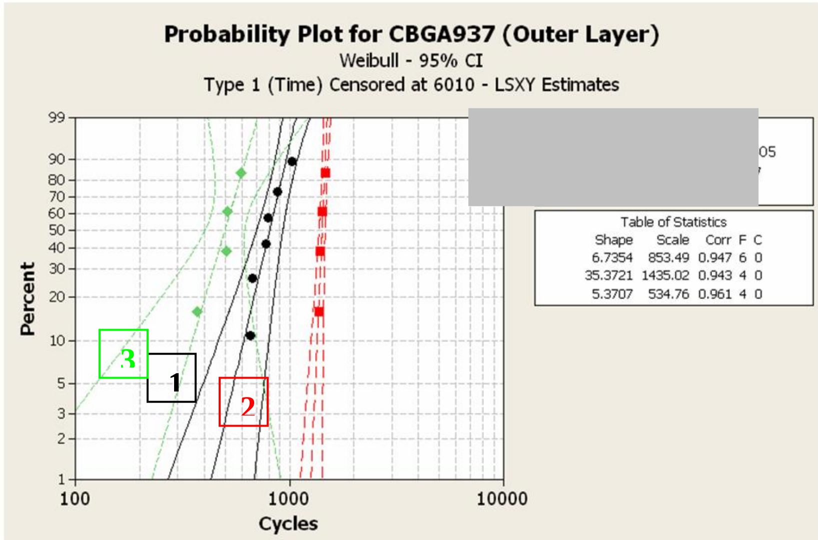


Figure 15 - Weibull plots showing the difference in fatigue lives at 0°C to 100°C for as-assembled pure SAC405 (1) and reworked CBGA937 using In-containing Alloy A (2) and Bi-containing Alloy B (3).

Failure analysis showed that there was no difference in failure mode between as-assembled and reworked CBGAs. Both alloys of Paste A and Paste B reworked CBGA937 joints have component-side failures as shown in Figure 16. Cracks propagate through the solder along the component pad intermetallic layer. They initiate from the solder joint surface and propagate inside the joint. Only peripheral joints were failed.

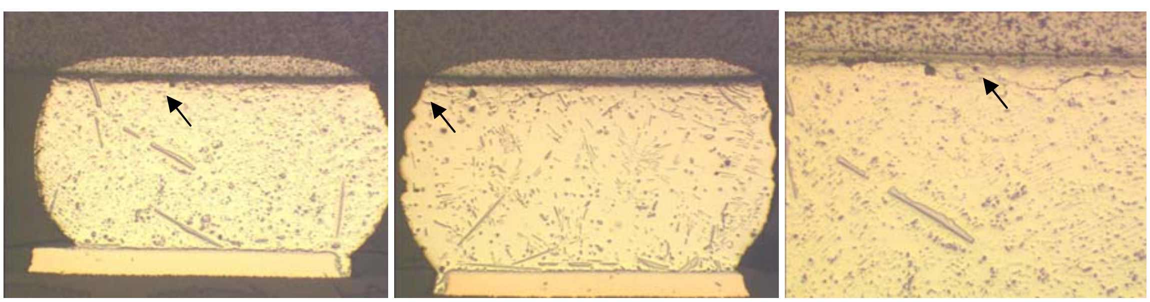
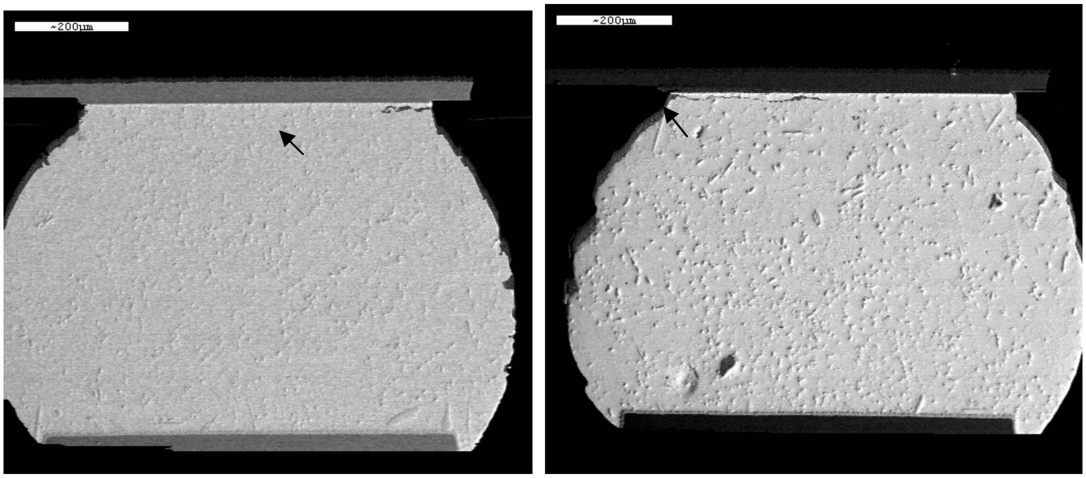


Figure 16 - Microstructure of reworked CBGA937 after ATC: (a) Paste A, 100X; (b) Paste B, 100X ;(c) Paste A, 200X

No failures were detected in PBGA256, either reworked with Sn-Ag-In and Sn-Ag-Bi alloys or not reworked, after 6010 cycles at 0°C to 100°C. Only partially cracked joints were found in PBGA196 after completion of thermal cycling. Figure 17 illustrates the microstructures of the reworked PBGA196 containing In and Bi, respectively. A typical fatigue crack propagates through a coarsening band at the component side.



(a) (b)

Figure 17 - Microstructure of reworked PBGA196 after ATC, SEM, 130X: (a) Alloy A; (b) Alloy B

CONCLUSIONS

- A new rework process with peak reflow temperature not higher than 217 + 2°C is demonstrated. The reduced process temperature avoids component overheating, reduces board warpage and cratering, and prevents neighboring components from thermal damage.
- The new rework solution includes:
  - Solder paste with a melting temperature close to the Sn-Pb eutectic alloy or even lower. When the solder paste melts, dissolution of the Sn-Ag-Cu balls occurs.
  - A unique reflow profile that allows the solder paste and solder ball to fully mix and form a uniform microstructure.
  - A solder paste alloy that, when mixed with the solder ball, forms solder joints with a resultant composition and microstructure with good thermomechanical and electrical properties.
- One of the three solder pastes (Alloy A) analyzed in this work provides an excellent combination of processability, resultant solder joint composition, microstructure, and reliability of reworked BGAs. These In-containing reworked solder joints outperform pure Sn-Ag-Cu joints, and have a great potential for harsh environment applications. The resulting composition is expected to have not only a long fatigue life, but good mechanical properties as well.
- More work should be done on solder paste composition and process parameters adjustment to reduce the Bi content in reworked solder joints. For some applications, Alloy B in its current formulation may be successfully used.
- Alloy A, in combination with modified process parameters such as solder paste volume and reflow profile, may be recommended for manufacturing rework as well as field failure rework. Use of Alloy A results in high reliability solder joints without damage to boards, packages, and adjacent components.

FUTURE WORK

A comprehensive reliability study is in progress on the In-containing alloy.

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Low Melting Alloys in Pb-Free Assembly Rework

Polina Snugovsky
Simin Bagheri
Zohreh Bagheri
Marianne Romansky

CELESTICA

Rework – A Major Challenge in the Pb-Free Assembly Process

- Higher soldering temperatures needed
  - soldering environment is 30 to 40°C above Sn-Pb
  - Sn-Ag-Cu solders required 232°C minimum
- Component bodies see more heat
  - May reach 260°C and higher
  - Possible component damage
- Potential issues for Adjacent Components
  - Extensive intermetallic growth
  - Melting
  - Open solder joints
  - Reliability reduction
- Potential issues for PWB and substrate
  - defects such as Warpage, Delamination, Barrel Cracks, Hardening, Cratering

The Solution: Low-Melt Alloys

By using alternative solder alloys you can:

- Reduce the rework temperature
- Improve solder joint reliability

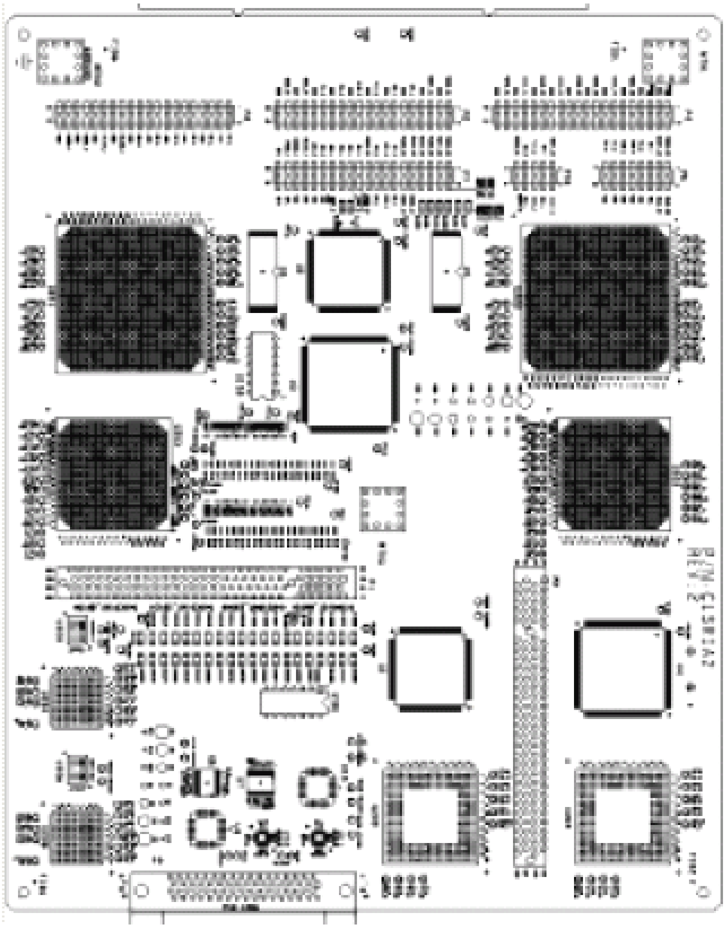
Useful for rework in both:

- Initial manufacturing
- Returns requiring rework

Key Areas of Investigation

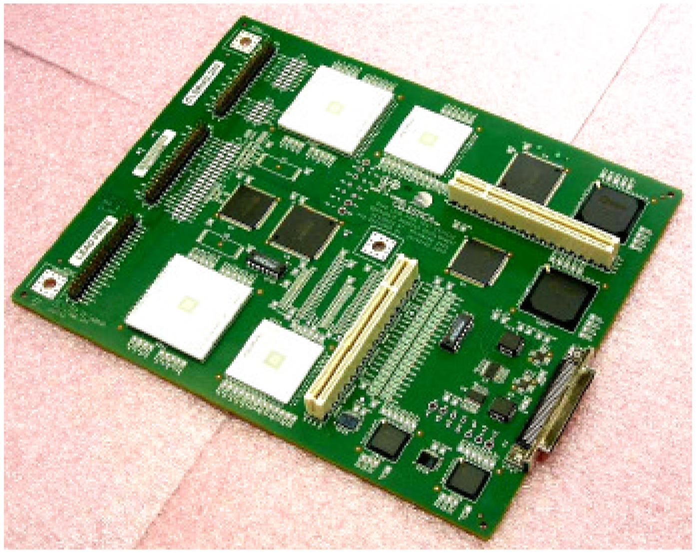
- Evaluate different Low Melt alloys
- Effects on multiple component types and sizes
- Comparison of Board Finishes
- Rework Parameter optimization
- Microstructure of reworked solder joints
- Reliability assessment through thermal cycling

Test Vehicle Design – ‘RIA2’



- 12 layer boards
- 203 mm x 253 mm x 2.36 mm
- Lead-free compatible laminate material
- Board finishes
  - OSP
  - Immersion Ag
  - ENIG

Assembly and Components



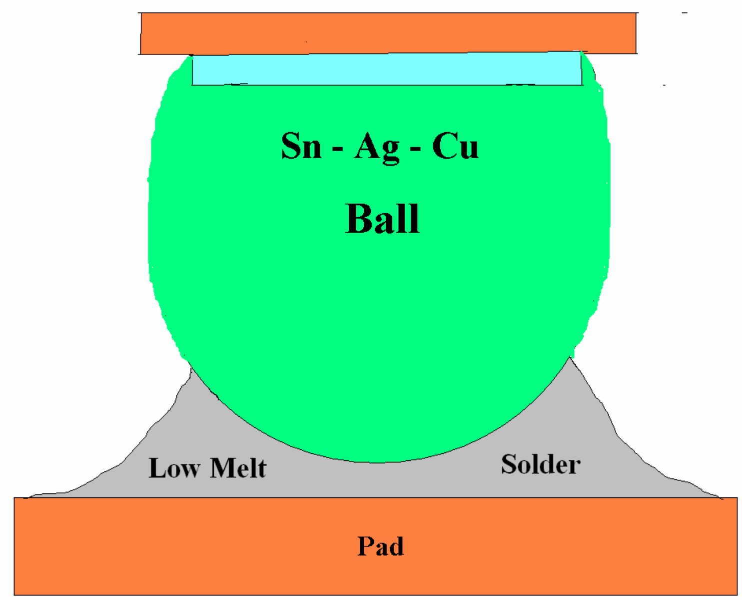
- Double sided SMT
- PTH
- No clean SAC 405 solder paste
- Nitrogen atmosphere
- 10 zone reflow oven

Component Type	I/O	Pitch, mm	Ball Composition (wt. %)
CBGA	937	1	Sn-3.8%Ag-0.5%Cu
PBGA	196	1	Sn-3.8%Ag-0.5%Cu
CSP	46	0.75	Sn-3.8%Ag-0.5%Cu

Hot Air Rework Process

- CBGA937, PBGA196, CSP46
- Component removal
- Site re-dressing
- Low melt solder paste applied

Solder alloy	Melting temperature, °C
Alloy A	**181**
Alloy B	**138**
Alloy C	**118**



Rework Parameter Optimization

- Criteria for rework parameter optimization
  - Proper shape of solder joint after rework
  - Minimized voiding
  - Uniform microstructure
  - Absence of or reduced low-melt fractions in the crystallized mixtures of solder paste and solder ball

Hot Air Rework DoE

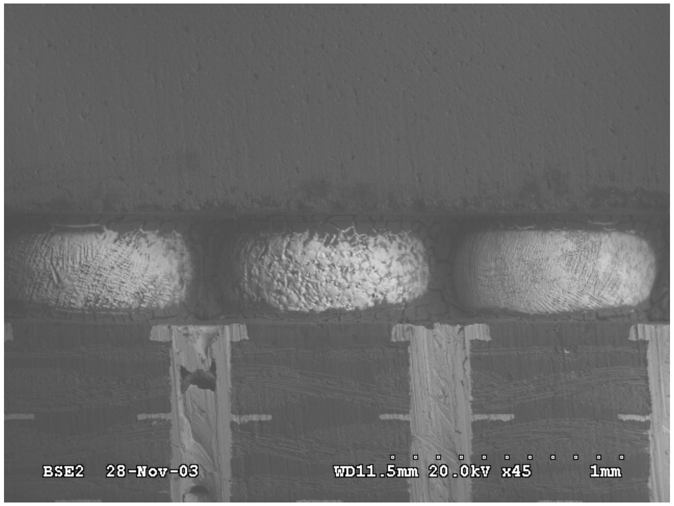
Rework investigation was performed in four steps

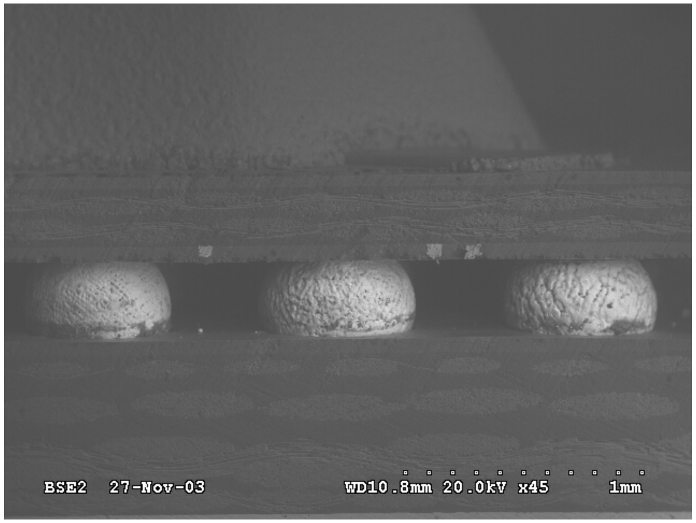
- Step one
  - Three different low melt alloys used for rework
  - OSP finished boards
  - Rework profiles created for each alloy solder paste
    - Time above melting point – 181°C, 138°C, and 118°C, respectively
    - Time at the peak temperature
  - Air

One alloy was excluded from the matrix after step one

Hot Air Rework DoE

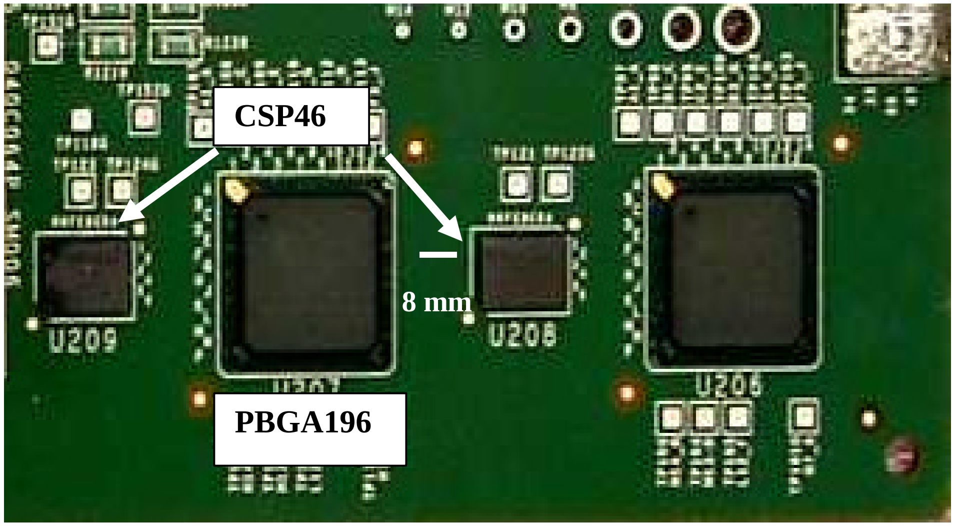
- Step two
  - Two low melt alloys used for rework
  - Optimized rework profiles
  - ENIG finished board
  - Air
- Step three
  - Two low melt alloys used for rework
  - 1X and 2X rework
  - Immersion Ag finished boards
  - Air and Nitrogen





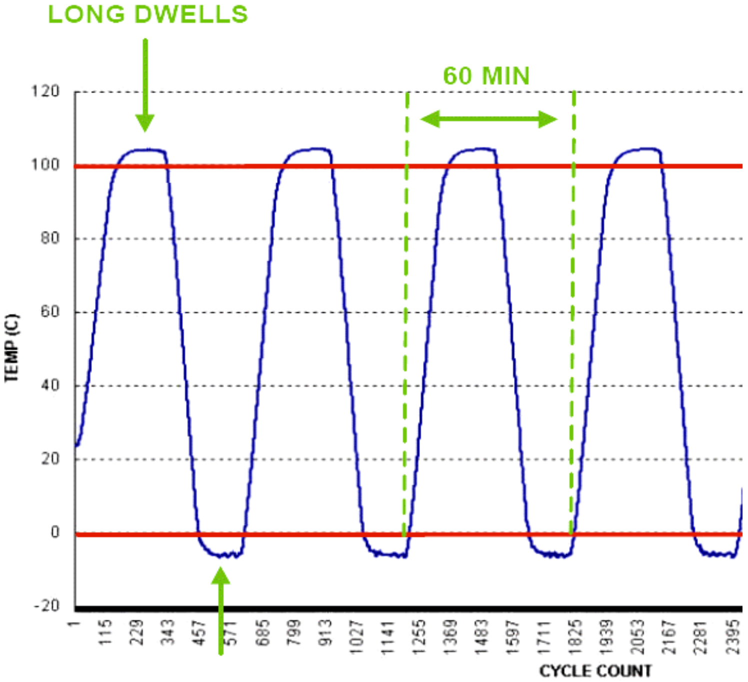
Hot Air Rework DoE

- Step three (cont.) – Influence on adjacent components
  - First scenario
    - PBGA196 and CSP46 were removed at the same time
    - New components placed using the low melt paste
  - Second scenario
    - The CSP46 was removed
    - The CSP was placed using the low melt paste
    - PBGA196 was removed, then replaced using low melt paste



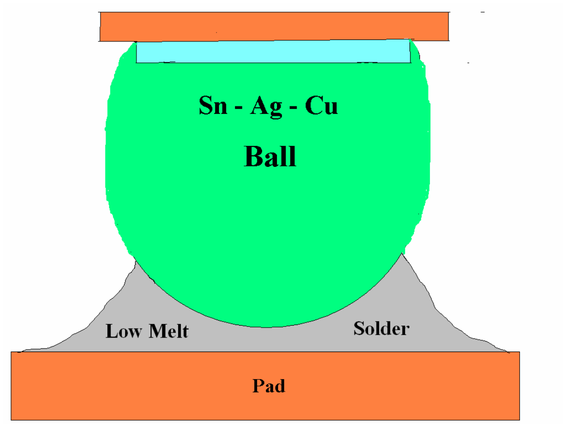
Hot Air Rework DoE

- Step four – Influence on fatigue life
  - Two low melt alloys
  - 1X and 2X rework
  - Optimized rework profiles
  - OSP and ImmAg finishes
  - One of two BGAs was reworked
  - 0 to 100°C cycling
    - 15 minutes dwell time
    - 15 minutes ramp up and ramp down
    - 6010 test cycles
    - 100% in-situ monitoring using dataloggers
    - Failure criteria - 5 consecutive measurements showing >20% overinitial reference value



Schematic on Low Melt Rework Metallurgy

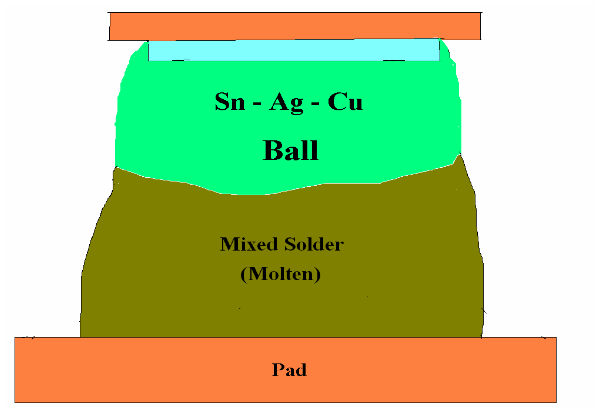
Before Reflow



$Tm_s < 217°C$

- Component is removed
- Pad is prepared
- Low Melt solder paste is placed
- Solder paste melting temperature is significantly below 217°C
- New component is placed
- Melting of Sn-Ag-Cu solder ball starts at 217°C

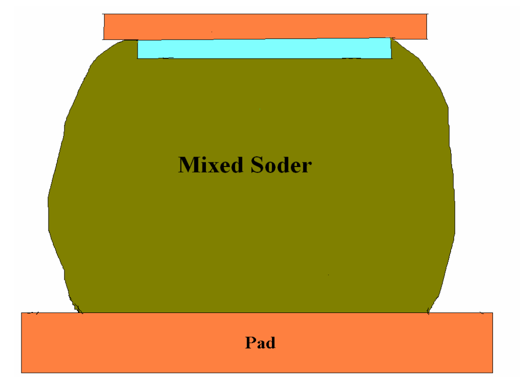
During Reflow



$Tm_b < Tr > Tm_s$

- The reflow peak temperature is below the SAC solder ball melting temperature and above solder paste melting
- Solder paste melts
- SAC solder ball is dissolving

After Reflow



Uniform microstructure

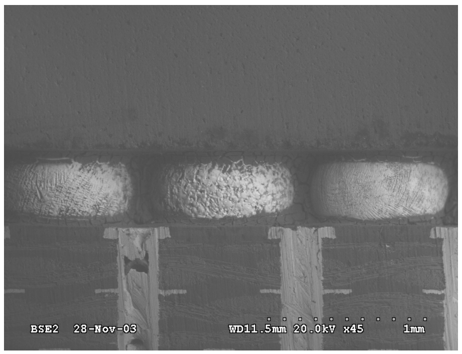
- Solder ball is fully dissolved in liquid solder
- The resulting liquid is solidified during cooling
- Solder ball and solder paste are fully mixed and uniform microstructure is formed

Tm_s - Solder paste melting temperature; Tm_b – SAC ball melting temperature; Tr – Reflow peak temperature

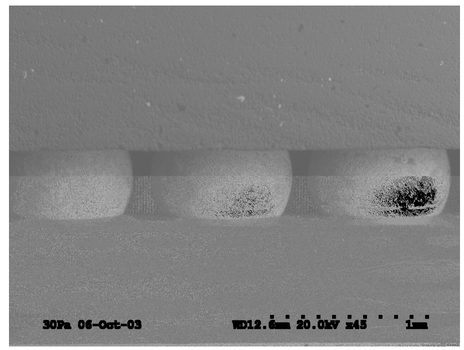
Reworked SAC 405 BGA

- No time-zero defects or open joints
- Joints properly formed, collapsed normally, shaped well

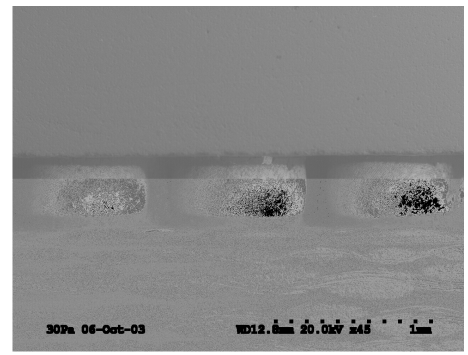
CBGA937



Alloy A

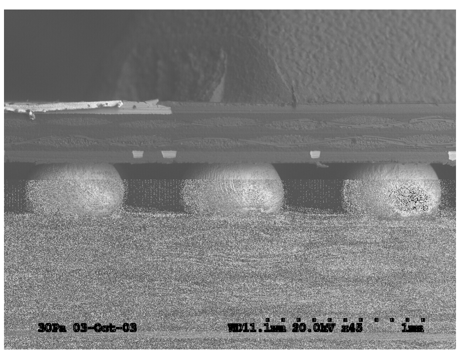


Alloy B

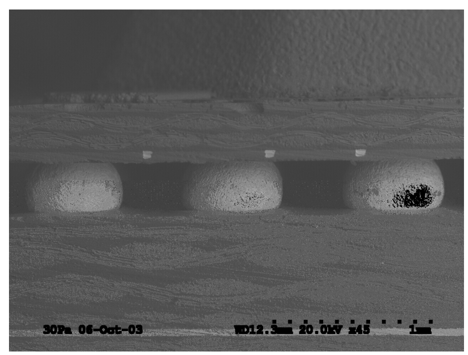


Alloy C

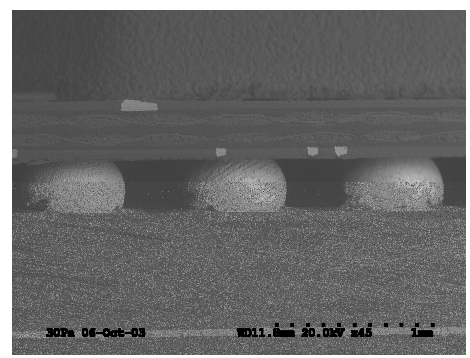
PBGA196



Alloy A



Alloy B



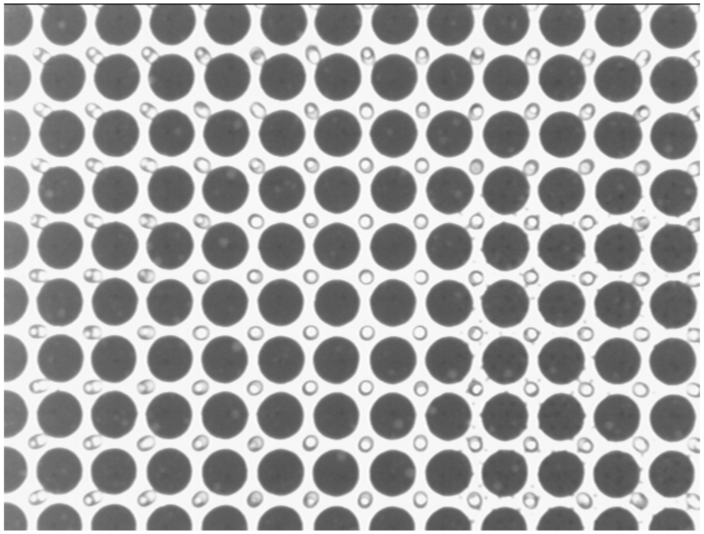
Alloy C

SEM, 45X

X-Ray Analysis of Reworked Joints

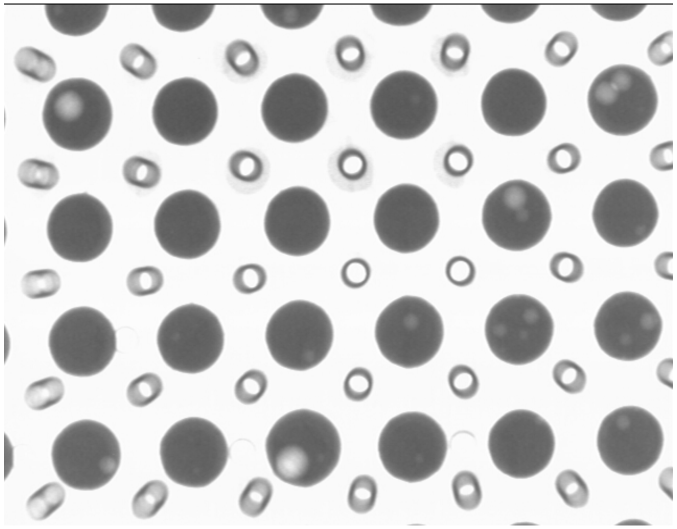
- CBGA937
  - Alloy A – no voids
  - Alloys B and C – small voids
- PBGA196
  - Alloys B and C – small voids
  - Alloy A - some larger voids
- ENIG – lower voiding than OSP and ImmAg

CBGA937



Alloy B

PBGA196

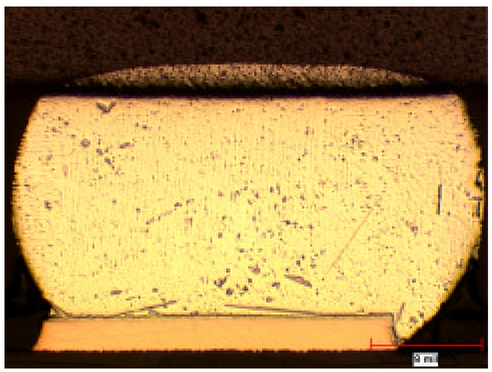


Alloy A

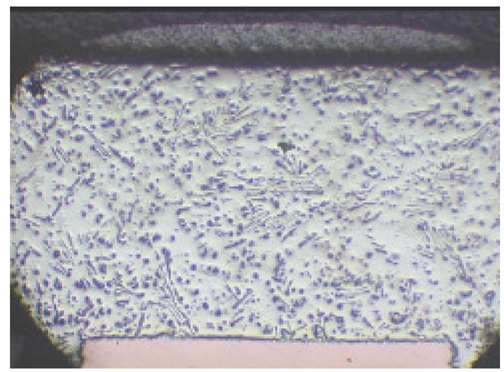
Reworked SAC 405 BGA Microstructure

- No portion of initial solder ball visible
- Uniform microstructure

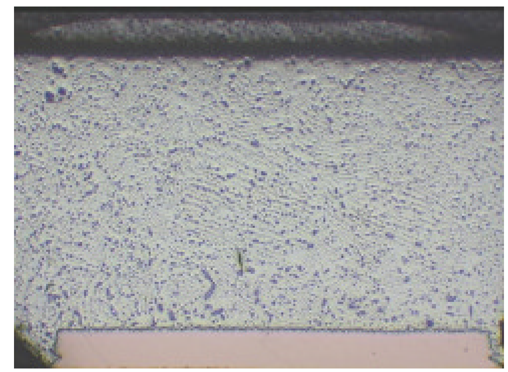
CBGA937



Alloy A

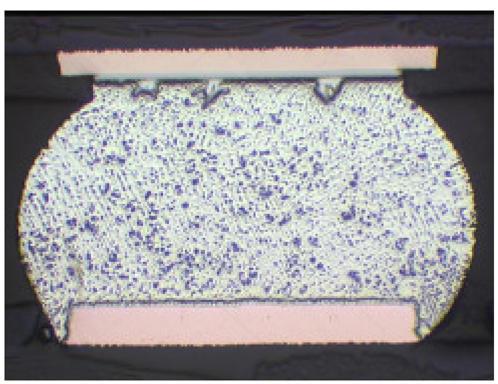


Alloy B

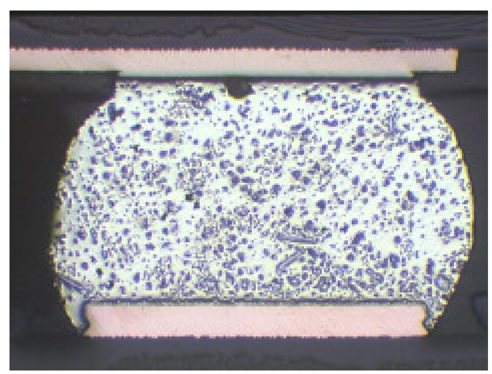


Alloy C

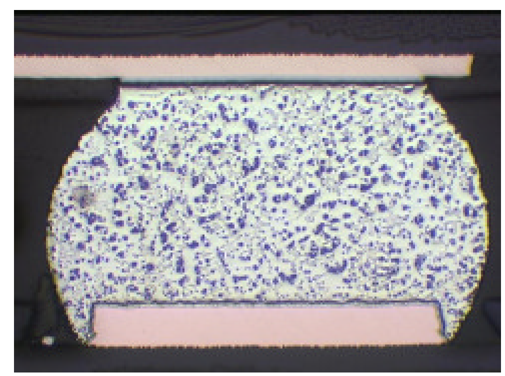
PBGA196



Alloy A



Alloy B



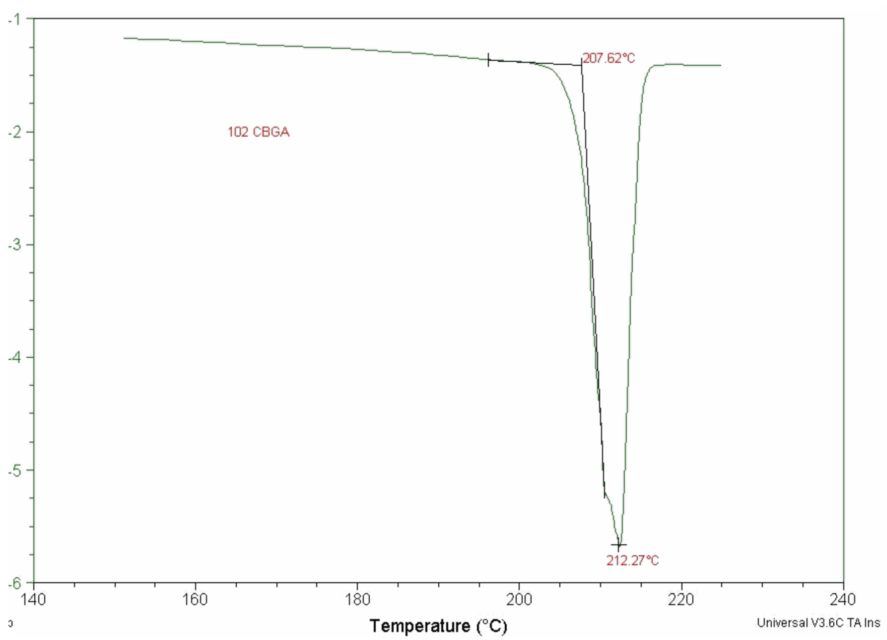
Alloy C

100X

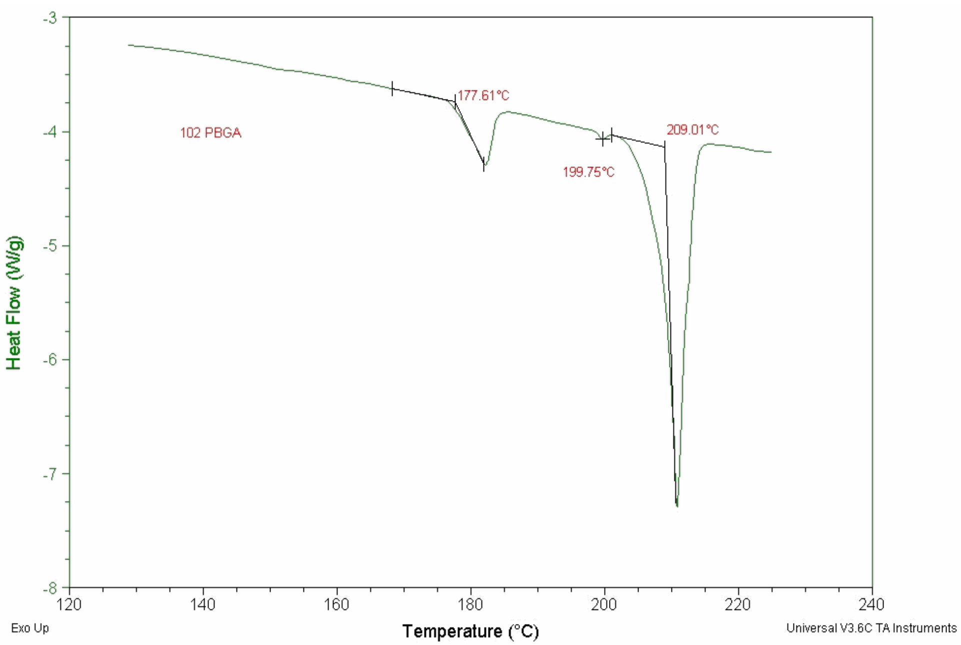
DSC Analysis

Rework with Alloy A (Tm – 181°C)

CBGA937

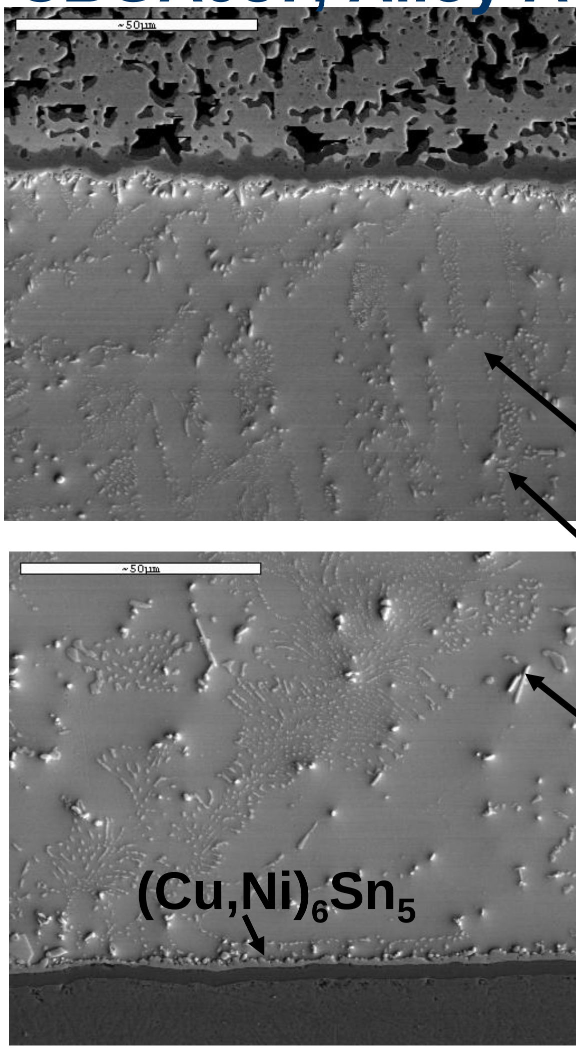


PBGA196



Microstructure of Reworked Solder Joints

CBGA937, Alloy A



ßSn

Eutectic

Ag$_3$Sn

SEM, 1000X

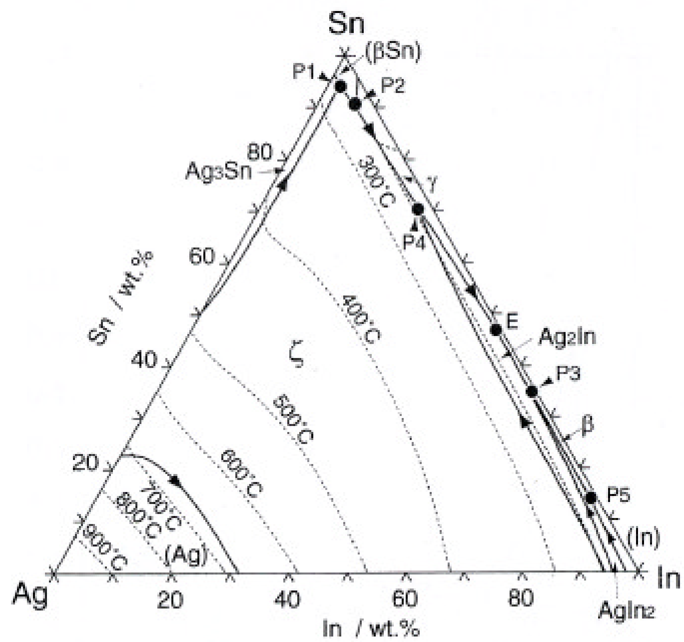
The final composition

- 3.7-3.8 % Ag, 3.8-4.0 % In, 0.4-1.0 % Cu
- Sn is the rest

Microstructure – similar to Sn-Ag-Cu

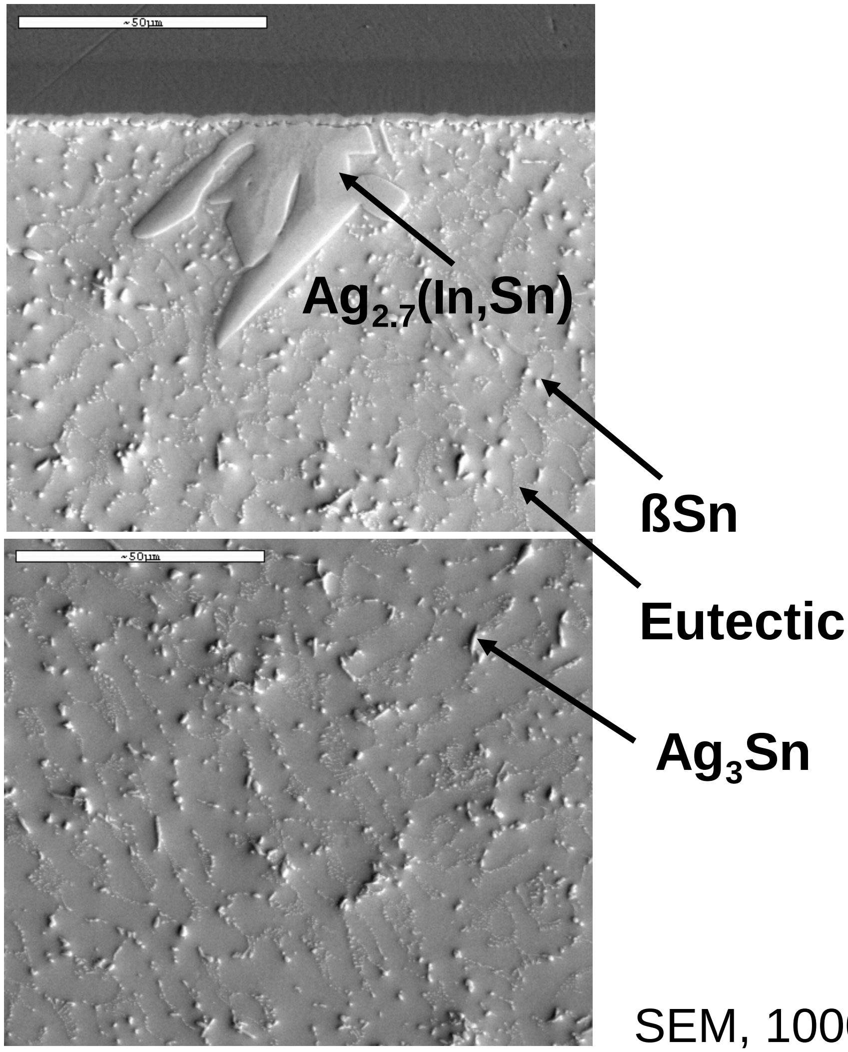
- Ag_3Sn – small number
- ßSn dendrites
- Eutectic in inter-dendritic spaces

In in both Ag_3Sn and ßSn



Microstructure of Reworked Solder Joints

PBGA196, Alloy A



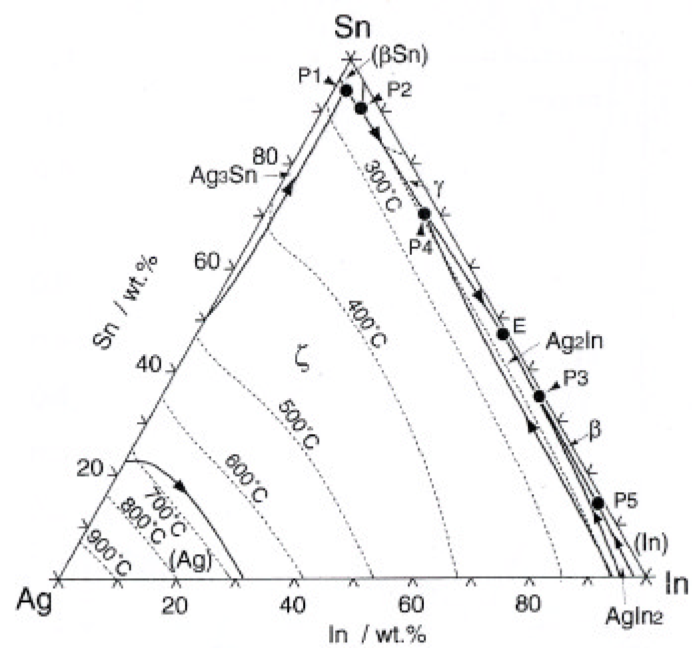
SEM, 1000X

The final composition

- 3.6-3.7 % Ag, 6.0-6.2 % In, 0.4-1.0 % Cu
- Sn is the rest

Microstructure

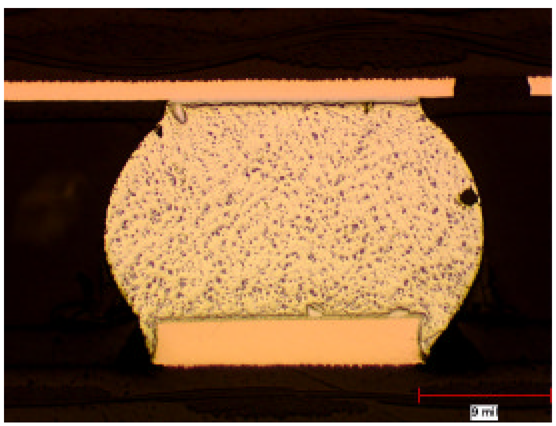
- $Ag_{2.7}(In,Sn)$- flower shape
- Ag_3Sn – small number
- ßSn dendrites
- Eutectic in inter-dendritic spaces



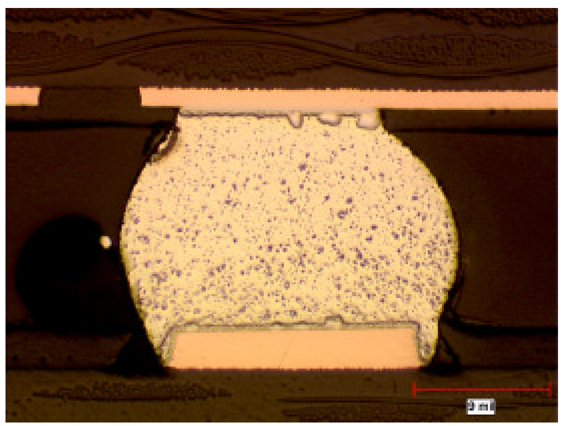
Microstructure of Reworked Solder Joints

CSP46, Alloy A

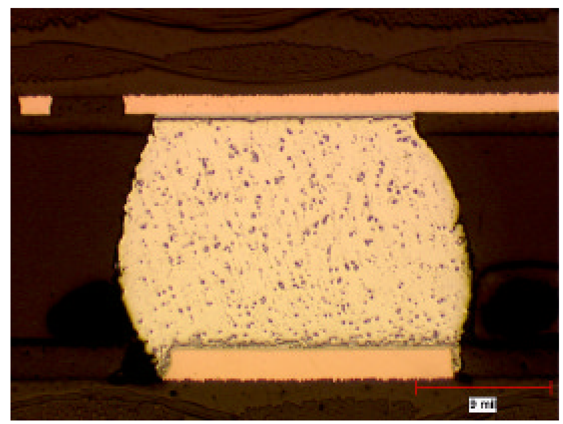
- Similar to PBGA196
- No significant difference between 1X and 2X reworks
- No significant difference between ImmAg and ENIG
- The influence of the rework of the adjacent PBGA196 is negligible



1X rework



2X rework



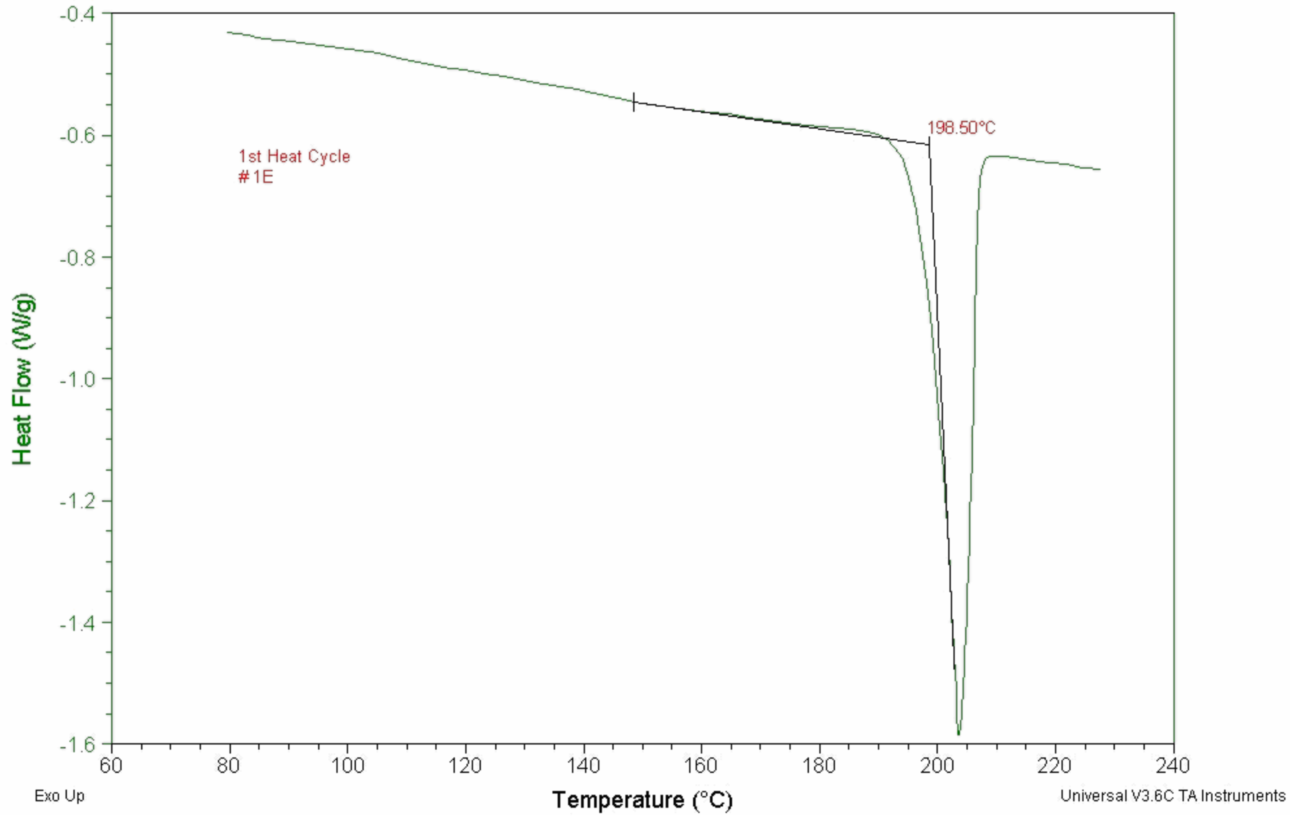
2X rework before PBGA rework

100X

DSC Analysis

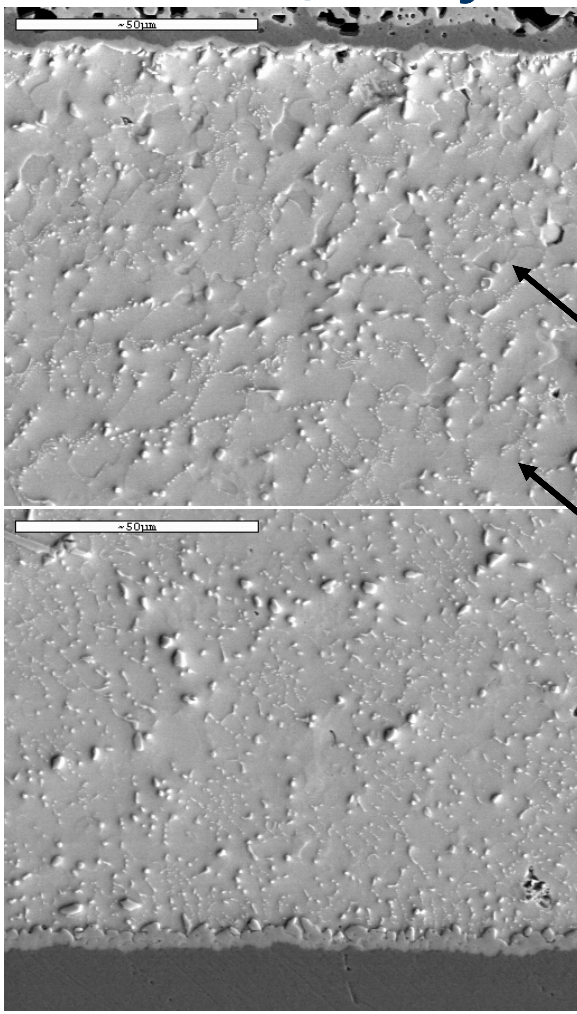
Rework with Alloy C (Tm – 118°C)

CBGA937



Microstructure of Reworked Solder Joints

CBGA937, Alloy C



? phase

Eutectic

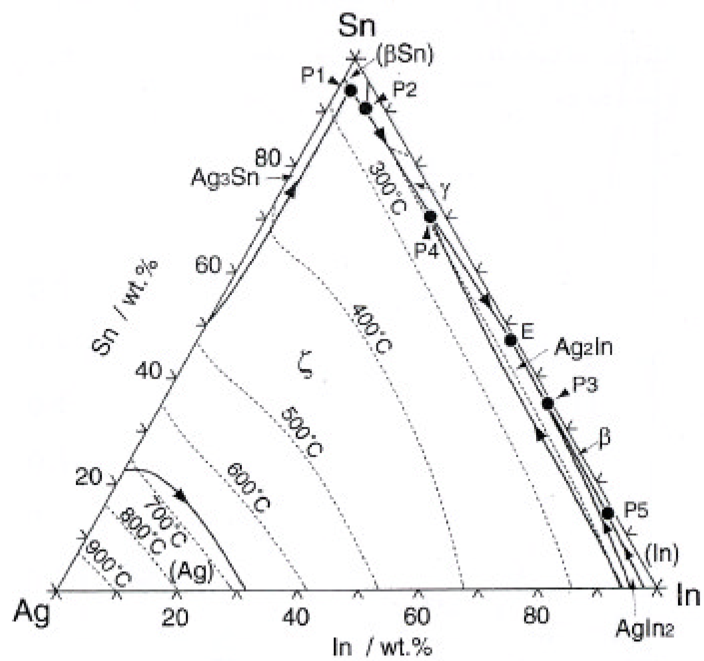
SEM, 1000X

The final composition

- ~ 3 % Ag, 13 % In, 0.5 % Cu
- Sn is the rest

Microstructure

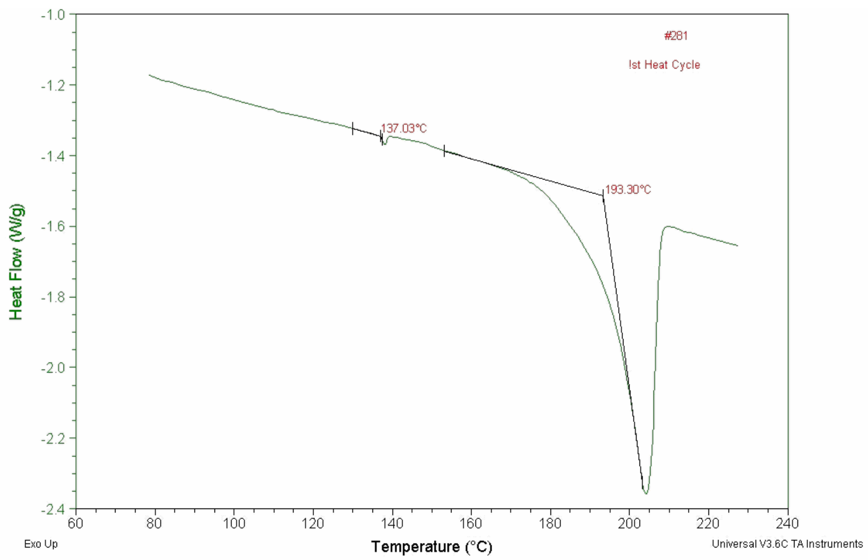
- ? phase dendrites
- Eutectic in inter-dendritic spaces

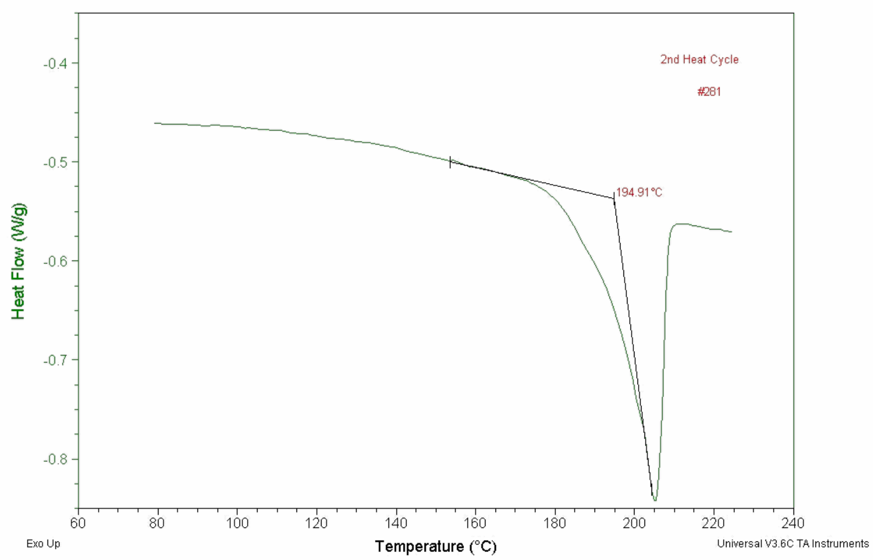


DSC Analysis

Rework with Alloy B (Tm – 138°C)

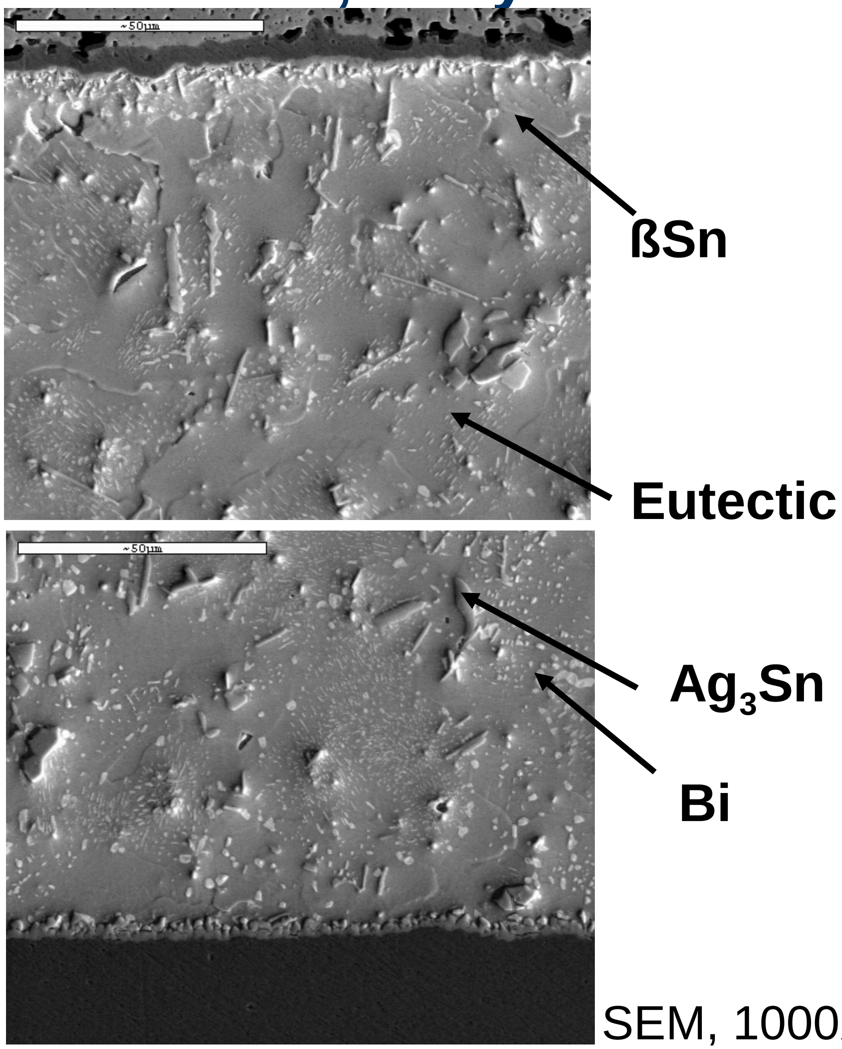
CBGA937





Microstructure of Reworked Solder Joints

CBGA937, Alloy B



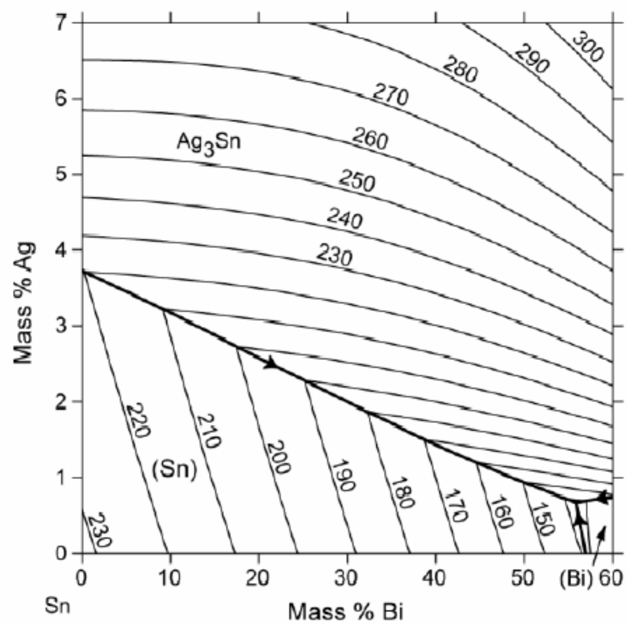
SEM, 1000X

The final composition

- 3.2-3.3 % Ag, 12-14 % Bi, 0.5-1.0 % Cu
- Sn is the rest

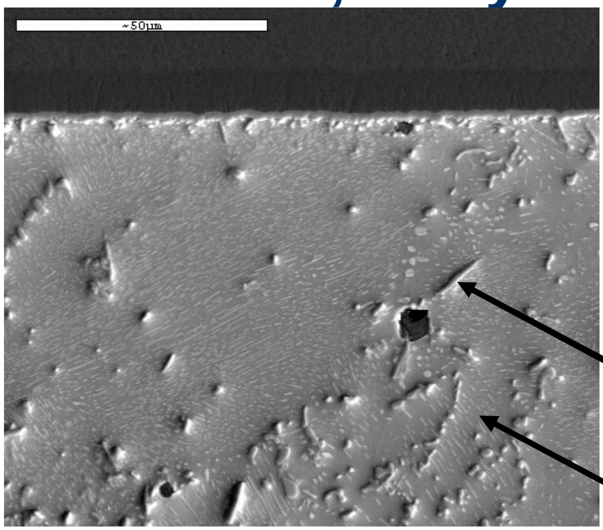
Complex microstructure

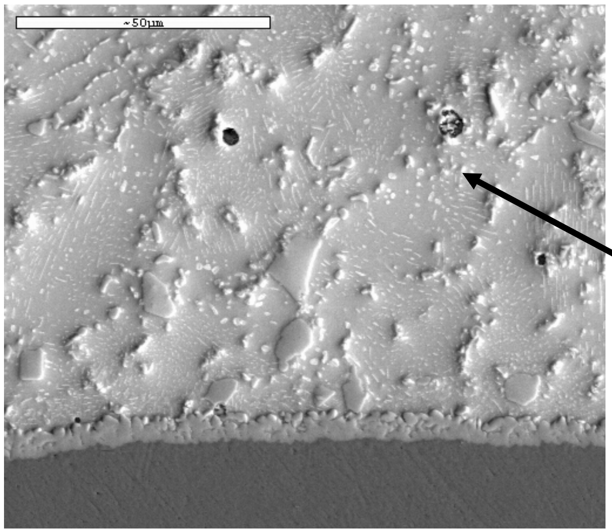
- Ag_3Sn – small number
- ßSn
- Eutectic in inter-dendritic spaces
- Bi particles in eutectic: $Ag_3Sn + Cu_6Sn_5 + Sn + Bi$



Microstructure of Reworked Solder Joints

PBGA196, Alloy B





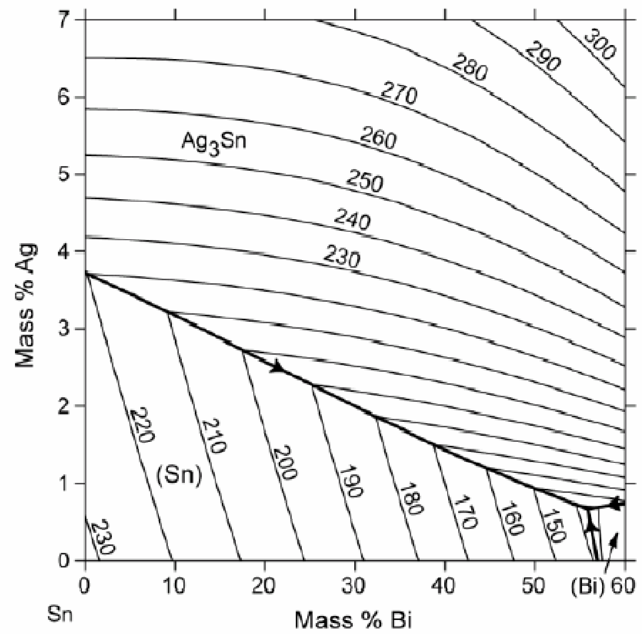
SEM, 1000X

The final composition

- 3.0-3.1 % Ag, 16-17 % Bi, 0.4-1.0 % Cu
- Sn is the rest

Complex microstructure

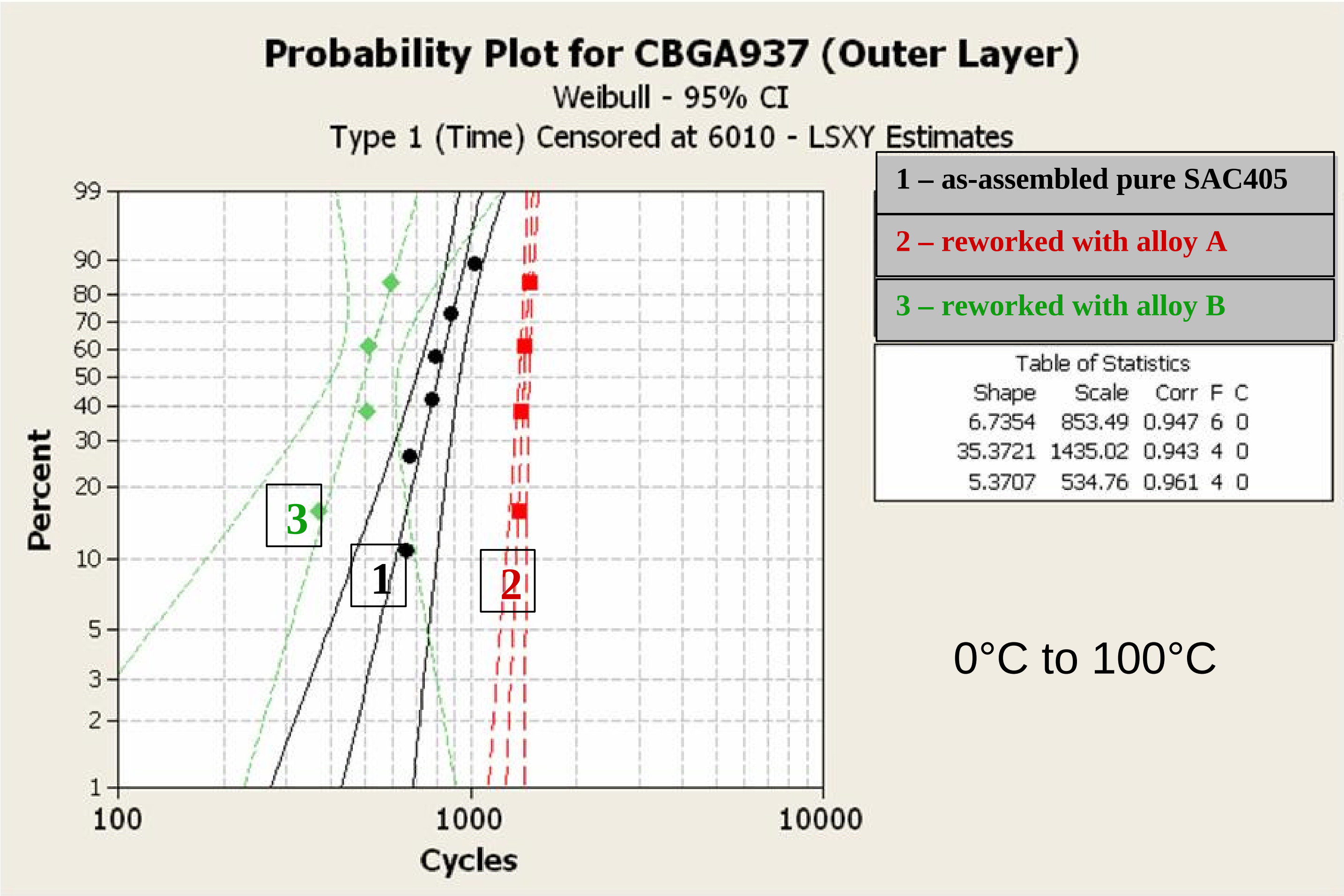
- Ag_3Sn
- Eutectic mainly
- Bi particles in eutectic: $Ag_3Sn + Cu_6Sn_5 + Sn + Bi$



Thermal Cycling Results

Board #	CBGA937		PBGA256		PBGA196		Process
	U202 no rework	U203 reworked	U205 no rework	U204 reworked	U206 no rework	U207 reworked	
1	SAC405	Paste A	SAC405	Paste A	SAC405	Paste A	1X
2	SAC405	Paste B	SAC405	Paste B	SAC405	Paste B	1X
3	SAC405	Paste A	SAC405	Paste A	SAC405	Paste A	1X
4	SAC405	Paste A	SAC405	Paste A	SAC405	Paste A	2X
5	SAC405	Paste B			SAC405	Paste B	1X
6	SAC405	Paste A	SAC405	Paste A	SAC405	Paste A	2X
7	SAC405	Paste B			SAC405	Paste B	1X
8	SAC405	Paste B			SAC405	Paste B	1X
9	SAC405	Paste B			SAC405	Paste B	2X
10	SAC405	Paste B			SAC405	Paste B	2X

Thermal Cycling Results



0°C to 100°C

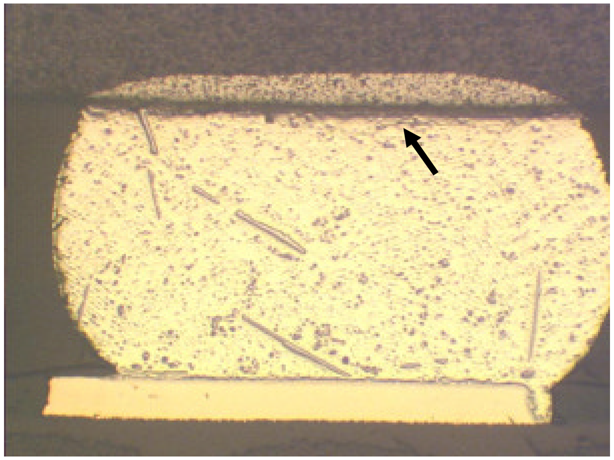
- The reworked SAC405 CBGA937 using In-containing alloy outperformed non-reworked joints by factor of two
- The reworked SAC405 CBGA937 using Bi-containing alloy did not perform as well as pure SAC405

Thermal Cycling Results

CBGA937

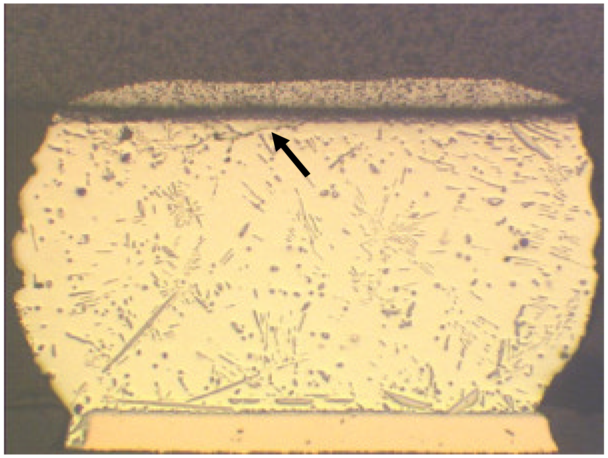
- Same failure mode for as-assembled and reworked joints
- Both alloys of Paste A and Paste B reworked joints have component-side failures
- Cracks propagate through the solder along the intermetallic layer
- Only peripheral joints were failed

Paste A



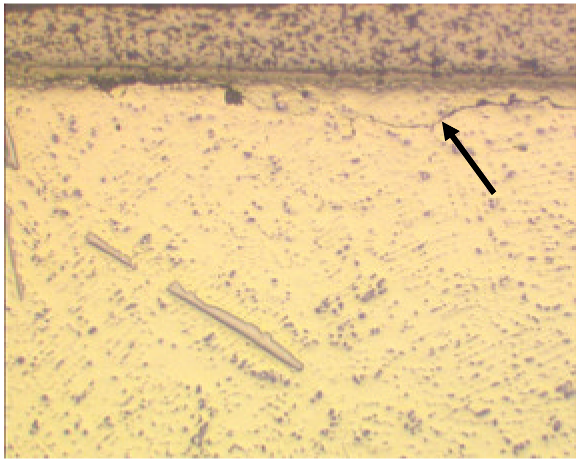
100X

Paste B



100X

Paste A



200X

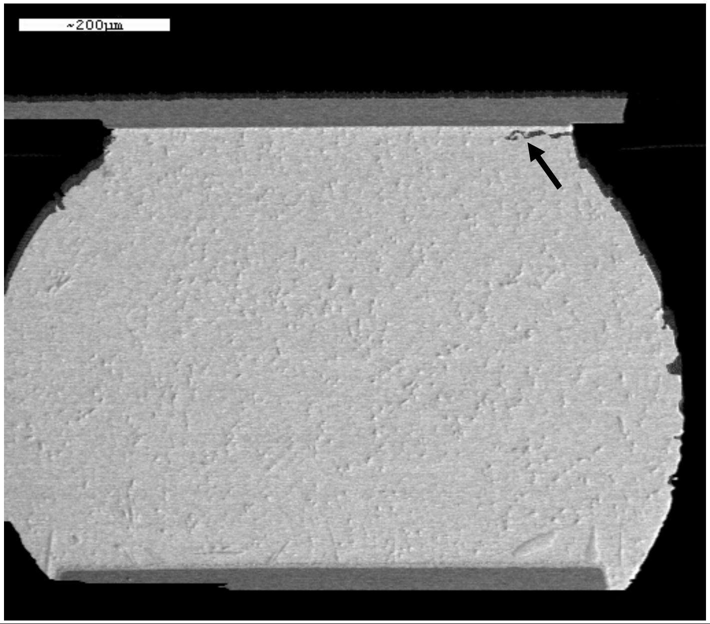
Thermal Cycling Results

PBGA256 and PBGA196

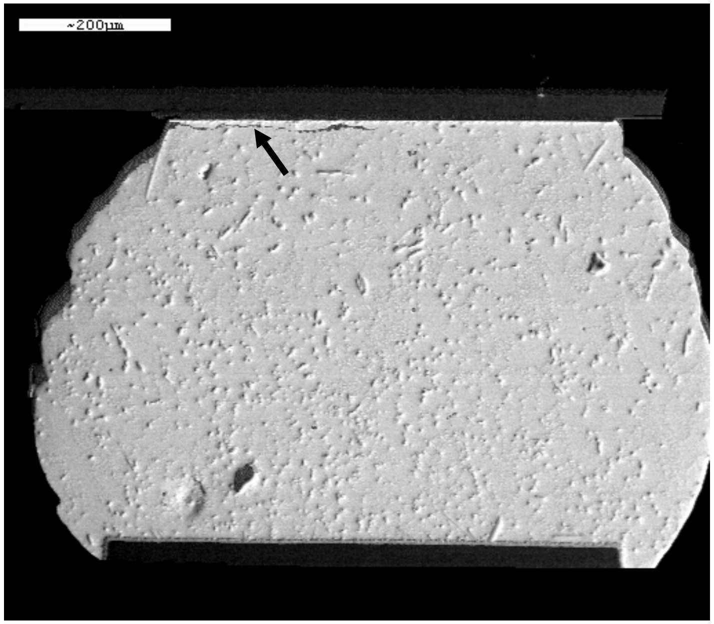
- No failures after 6010 cycles at 0°C to 100°C
- Partially cracked joints
- Typical fatigue cracks through coarsening bands at the component sides

PBGA196

Paste A



Paste B



Conclusions

- A new rework process with peak reflow temperature less than 219°C for Lead-free soldering
  - Avoids components overheating
  - Reduces board warpage and cratering
  - Prevents neighboring components from thermal damage
- New rework solution includes:
  - Solder paste with a melting temperature close to the Sn-Pb eutectic alloy
  - When the solder paste melts, dissolution of the Sn-Ag-Cu balls occurs.
  - A unique reflow profile that allows the solder paste and solder ball to fully mix and form a uniform microstructure.
  - A solder paste alloy that forms solder joints with good thermo-mechanical and electrical properties when used with Sn-Ag-Cu solder balls

Conclusions

- Alloy A containing In provides an excellent combination of
  - processability (ease of use)
  - solder joint composition
  - microstructure
  - reliability
    - Outperform pure Sn-Ag-Cu joints
    - The resulting composition is expected to have good mechanical properties as well
    - Has a great potential for harsh environment applications.

- Alloy B containing Bi in its current formulation may be successfully used for some applications
  - More work should be done on solder paste composition and process parameters adjustment to reduce the Bi content in reworked solder joints

Conclusions

- Alloy A containing In, in combination with modified process parameters such as solder paste volume and reflow profile, may be recommended for manufacturing rework as well as field failure rework.
- Use of Alloy A results in high reliability solder joints without damage to boards, packages, and adjacent components.

Future Work

A comprehensive reliability study is in progress on the In-containing alloy

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