As originally published in the SMTA Proceedings.

ASSESSING BACKWARD COMPATIBLE SOLDER JOINT RELIABILITY UNDER STANDARD AND MILDLY ACCELERATED TEST CONDITIONS

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ABSTRACT

Accelerated temperature cycling (ATC) was used to assess the thermal fatigue reliability of a Pb free, 37.5 mm fully populated, 1284 I/O ball grid array (BGA) package assembled with backward compatible, mixed alloy (Pb free BGA/SnPb paste) assembly processes. Two different temperature cycling profiles were used in the evaluation. The baseline profile was the standard accelerated temperature test cycle of 0 to 100 °C as prescribed by the IPC-9701 attachment reliability guideline (TC1). The second profile was a mildly accelerated cycle using a less aggressive temperature extremes and a smaller △T with a resultant range of 20 to 80 °C. The limited temperature extremes provided by the latter cycle result in lower strains more typical of service conditions. The surface mount assembly was done using custom SnPb eutectic soldering profiles designed to optimize the complete (full) mixing of the Pb and to create two additional test cells with levels of Pb mixing in the Pb-free BGA balls defined as low and medium. To complete the reliability comparisons and provide experimental controls, SAC405-SAC405 and SnPb-SnPb assemblies were included.

The results indicate that backward compatible, mixed alloy assemblies should have acceptable reliability under service conditions. Complete or full Pb mixing is preferred in order to achieve consistent and acceptable solder joint reliability.

Key words: Pb-free solder backward compatibility, mixed alloy assembly, thermal fatigue, and accelerated temperature cycling

INTRODUCTION

Although there has been widespread conversion to Pb-free manufacturing in the electronics industry, many high reliability equipment producers continue to manufacture and support tin-lead (SnPb) electronic products. Certain high reliability products from the telecommunication, military and medical sectors manufacture using SnPb solder assembly and remain in compliance with the RoHS Directive (restriction on certain hazardous substances) by invoking the European Union Pb-in-solder exemption [1]. Sustaining SnPb manufacturing has become more challenging because the global component supply chain is converting rapidly to Pb-free offerings and has a decreasing motivation to continue producing SnPb product for the low-volume, high reliability end users [2]. Availability of critical, larger SnPb BGA components is a growing concern. Because complete Pb-free conversion is not always a viable option, these BGA availability issues can force companies to use Pb-free BGAs with the SnPb solder assembly process. Assembling Pb-free BGAs with a SnPb surface mount assembly process often is referred to as backward compatible, mixed alloy, or mixed metals processing. Mixed alloy processing is an alternative manufacturing path when immediate, complete product conversion to Pb-free manufacturing is not possible.

The technical challenges associated with mixed alloy processing have been addressed in a significant number of studies [3-51] and those results have been reviewed and discussed in detail in previous publications [3, 48-53]. Many of those studies have focused on the optimization of process parameters that produce acceptable mixed alloy solder joint quality. This approach is understandable because mixed alloy assembly is not a drop-in replacement process. Mixed alloy studies using smaller BGA devices have shown that acceptable thermal fatigue reliability can be achieved with the backward compatible process [3, 6, 49, 53]. However, there are minimal mixed alloy thermal fatigue reliability data for BGA packages with a body size greater than 35 mm [49-53]. It is desirable to develop reliability data for larger packages because achieving acceptable mixed alloy assembly becomes more challenging as the package size and board complexity increase. The negative effects of large thermal mass and component warpage on Pb mixing was demonstrated in the work of Kinyanjui et al [48]. Therefore it is critical to understand the effect of imperfect mixing on reliability of large packages. In general, the literature indicates that there are fundamental inconsistencies and gaps that limit the understanding of mixed alloy reliability, particularly with larger body packages [4, 15, 16, 18, 32, and 35, 48-53].

Although recent studies, including some by the current authors, have demonstrated acceptable fatigue performance of large BGA mixed alloy assemblies [49, 51, 52-54], there have been studies that indicate additions of Pb degrade the reliability of Pb-free solder joints. The results of work by Borgesen and Meilunas suggest that the reliability of mixed assemblies could be a strong function of the thermal cycling parameters and the acceleration factor for those mixed assemblies [55]. They have hypothesized that mixed alloy assemblies may have a lower acceleration factor hence predictions based on standard accelerated test parameters could over estimate mixed alloy reliability. Specifically, they suggest that mixed joints may perform less well compared to pure Sn-Ag-Cu (SAC) or SnPb if testing is done using smaller temperature ranges (△T) or longer dwell times characteristic of most service conditions.

In the current study, accelerated temperature cycling (ATC) was used to assess the thermal fatigue reliability of a Pb free, 37.5 mm fully populated, 1284 I/O ball grid array (BGA) package assembled with mixed alloy (Pb free BGA/SnPb paste) processing. The surface mount assembly was done using a soldering profile designed to produce complete or full Pb mixing in the BGA solder balls [52]. In addition to the mixed alloy samples, the test program included SAC405-SAC405 and SnPb-SnPb assemblies for reliability comparisons.

Two different temperature cycling profiles were used in the evaluation. The baseline profile was the standard accelerated temperature test cycle of 0 to 100 °C as prescribed by the IPC-9701 attachment reliability guideline (TC1) [56]. The second profile was a mildly accelerated cycle using a smaller △T with a temperature range of 20 to 80 °C. The limited temperature extremes provided by the latter cycle result in lower strains more typical of service conditions [57]. The objectives were twofold: 1) develop reliability data for a large BGA with full and partial levels of mixing, and 2) test the Borgesen and Meilunas hypothesis by comparing the reliability of fully mixed assemblies under conditions of standard and mildly accelerated thermal cycles.

EXPERIMENTAL

Test Vehicle

The attributes of the Package Test Vehicle are listed in Table 1 and images of the top view of the package and populated printed circuit board test vehicle are shown in Figure 1.

The printed circuit board test vehicle is an 8 layer board with dimensions 12 inches x 8 inches x 0.093 inches. The board contains four identical component footprints. The component sites have metal defined (MD) land patterns that are 17 mils in diameter and the surface finish on the test vehicle is organic solderability preservative (OSP).

There is one daisy chain net for each land pattern. Daisy chain nets from each of the components patterns are brought out to a card edge connector and soldered connections are used to monitor the resistances of the daisy chain nets during temperature cycling.

Table 1: The package attributes for the 1284 I/0 BGA test vehicle used in the experimental study.

TV Description	Package TV attributes
Package Size	37.5 x 37.5 mm
Die size	10.15 x 20.98 mm
Substrate thickness	1.383 +/- 0.015 mm
Solder ball diameter	0.6 mm
Ball Pitch	1.0 mm
Solder ball metallurgy	SAC 405
Ball count	1284
Ball pattern	fully populated array w/ 7 corner sacrificial balls
Package surface finish	NiPdAu

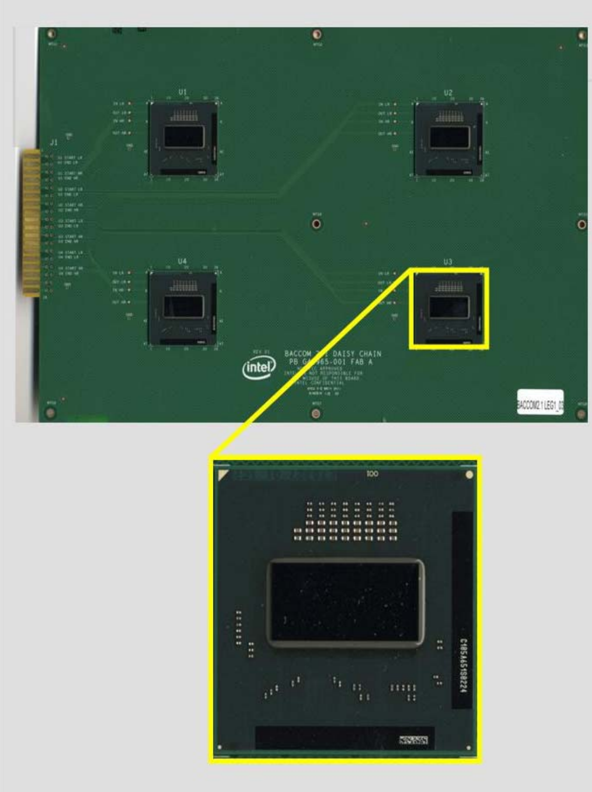


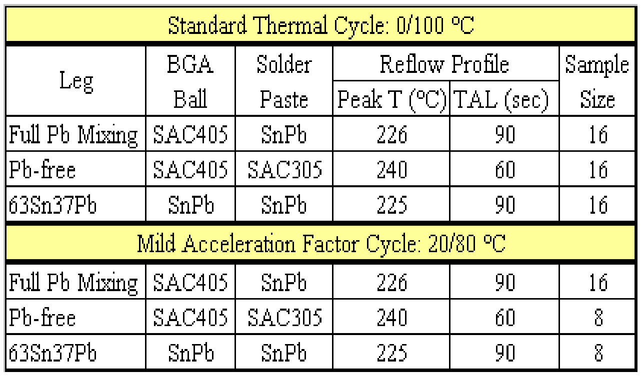
Figure 1: Top views of the populated printed circuit board and the BGA Package Test Vehicle.

Surface Mount Assembly

This work is part of a larger experimental study to evaluate the effect of various Pb mixing levels on solder joint thermal fatigue reliability in a large, high density BGA component [53]. In the current study, the thermal cycling profile is the main experimental variable and only the effect of full Pb mixing is explored.

A sample size of either 16 or 8 was used for the various lead free, full mixed, or SnPb legs. Table 2 lists the details for each of the 3 basic experimental legs in this study. The surface mount profile development and detailed supporting metallography are described in a previous publication [53].

Table 2: Assembly details and sample sizes for all the experimental legs.



<table>
<tr><th colspan="6">Standard Thermal Cycle: 0/100 °C</th></tr>
<tr><th rowspan="2">Leg</th><th>BGA</th><th>Solder</th><th colspan="2">Reflow Profile</th><th>Sample</th></tr>
<tr><th>Ball</th><th>Paste</th><th>Peak T (°C)</th><th>TAL (sec)</th><th>Size</th></tr>
<tr><td>Full Pb Mixing</td><td>SAC405</td><td>SnPb</td><td>226</td><td>90</td><td>16</td></tr>
<tr><td>Pb-free</td><td>SAC405</td><td>SAC305</td><td>240</td><td>60</td><td>16</td></tr>
<tr><td>63Sn37Pb</td><td>SnPb</td><td>SnPb</td><td>225</td><td>90</td><td>16</td></tr>
<tr><th colspan="6">Mild Acceleration Factor Cycle: 20/80 °C</th></tr>
<tr><td>Full Pb Mixing</td><td>SAC405</td><td>SnPb</td><td>226</td><td>90</td><td>16</td></tr>
<tr><td>Pb-free</td><td>SAC405</td><td>SAC305</td><td>240</td><td>60</td><td>8</td></tr>
<tr><td>63Sn37Pb</td><td>SnPb</td><td>SnPb</td><td>225</td><td>90</td><td>8</td></tr>
</table>

Microstructural Characterization and Failure Analysis

A baseline characterization was performed on representative board level assemblies from each of the experimental legs. These baselines document the basic microstructures before temperature cycling for comparison to samples removed from the temperature cycling chambers for failure analysis. Microstructural characterization and failure analysis was done using optical metallography (destructive cross-sectional analysis), polarized light microscopy (PLM), and scanning electron microscopy (SEM). The SEM operating in the backscattered electron imaging (BEI) mode was used to differentiate phases and characterize the extent of Pb mixing in the SAC microstructure. The effectiveness of the BEI techniques was reported in previous studies on mixed assembly [3, 49, 53].The SEM was used to confirm the thermal fatigue failure mode.

Low magnification backscattered electron images of the three experimental Legs, designated as Pb-free, Full Pb Mixing, and eutectic SnPb, are shown in Figure 2. This combination of backscattered imaging and low magnification is useful for comparing the distribution of Pb within the Full Pb Mixed and eutectic SnPb solder balls.

A Full Pb Mixed sample is shown in Figure 2a. In the backscattered imaging mode, the Pb-rich phase appears as bright white regions in the gray Sn matrix. The Pb-rich precipitates are dispersed from the bottom to the top of the solder ball. The eutectic SnPb solder paste has mixed throughout the solder ball during reflow assembly, which is the basic criterion for Full Mixing.

A eutectic SnPb sample is shown in Figure 2b. As expected, the 37 wt. % Pb content of this alloy results in a much higher volume fraction of the Pb-rich phase.

A Pb-free baseline sample shown in Figure 2c contains a significant volume fraction of small Ag_3Sn intermetallic precipitates along with Cu_6Sn_5 intermetallic precipitates in a matrix of Sn (gray background). There is insufficient contrast to resolve the Ag_3Sn intermetallic precipitates at this magnification, but the randomly dispersed Cu_6Sn_5 precipitates appear as very small dark regions.

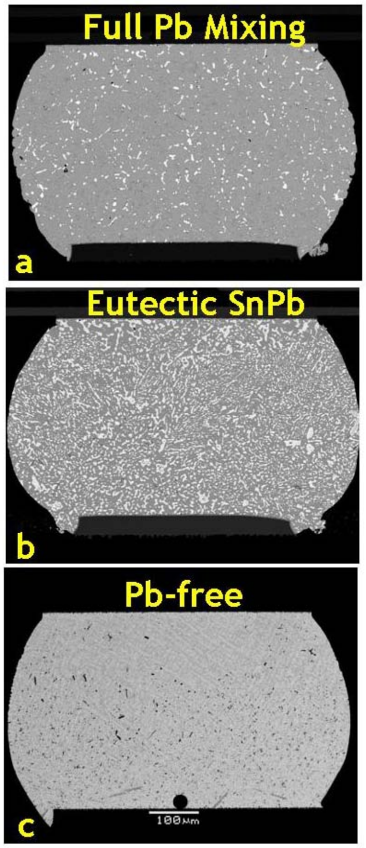


Figure 2: SEM backscattered images showing the basic microstructures of the BGA balls at low magnification for a) Full Pb Mixing, b) eutectic SnPb, and c) Pb-free.

A comparison of the detailed features of the SAC microstructures for the Full Pb mixed and Pb-free SAC405 samples is shown in the backscattered electron micrographs of Figure 3. There are marked differences in the time-zero SAC microstructures, in addition to the obvious addition of Pb to the mixed sample. The Pb-free SAC405 microstructure consists of primary Sn dendrites surrounded by wide regions containing very small equiaxed Ag_3Sn intermetallic particles and Sn that are the result of a binary eutectic decomposition reaction. The Full Pb Mixed microstructure also contains primary Sn dendrites but in contrast, has fewer, substantially larger Ag_3Sn intermetallic particles at the Sn dendrite boundaries. The Ag_3Sn particles in the Full Pb Mixed sample also tend to be elongated with an almost lamellar morphology. There is no definitive correlation in the literature between particle size and reliability but some results have suggested that larger diameter or lamellar shaped particles may be more resistant to particle coarsening or ripening, which is the precursor to recrystallization and fatigue crack propagation [45, 58].

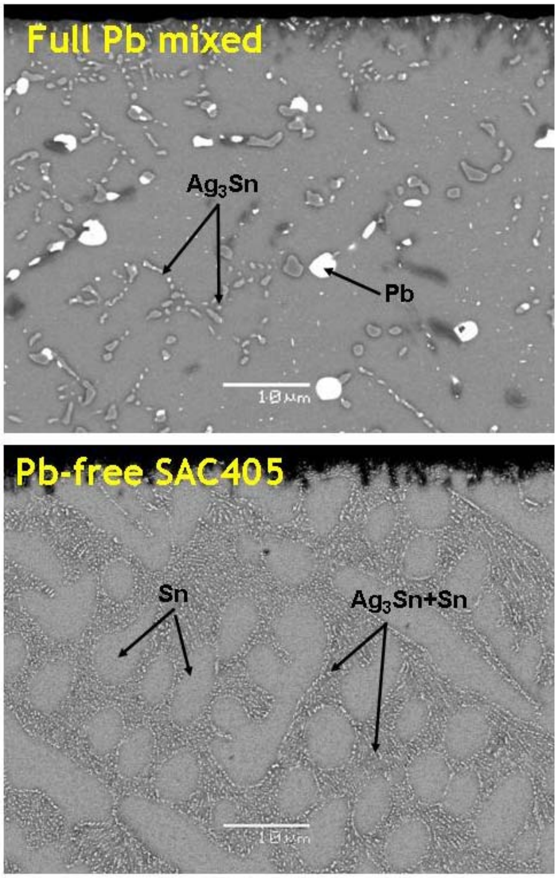


Figure 3: High magnification backscattered electron images illustrating the different basic solder microstructures in the Full Pb mixed and Pb-free SAC405 BGA solder balls [53].

In Pb-free SAC solder alloys, Sn is the major component of the alloys and β-Sn, which has a tetragonal unit cell, displays large anisotropies in its physical and mechanical properties [59-60]. Thus, it is reasonable to hypothesize that the orientations of the Sn grains are critical in determining the thermomechanical response of SAC solder joints [61, 62]. Large scale BGA solder joints generally display one to three large Sn grains, each with a number of dendrites with the same crystallographic orientation [63]. Frequently this is called the "beach ball" morphology. A fine grain interlaced twinned morphology also may form depending on the solidification conditions [64]. Figure 4 shows examples from the literature of these different Sn grain morphologies in metallographic cross sections of Pb-free SAC solder balls obtained with polarized light microscopy (PLM) or cross polarized imaging [65,66]. The PLM technique is useful for identifying basic Sn microstructures following reflow and solidification.

For eutectic SnPb solder, which solidifies with a two phase microstructure, Sn grain morphology is not a factor. However, mixed alloy solder joints solidify as Pb-free joints, albeit with a significant contamination of Pb. The PLM images in Figure 5 compare the Sn grain morphologies of a pure SAC405 Pb-free solder joint to a Full Pb mixed, SAC405 solder joint from the current experiment. In both cases, the Sn grain morphologies are single grain or beach ball, and there is no indication that the presence of Pb has a significant effect on Sn grain solidification.

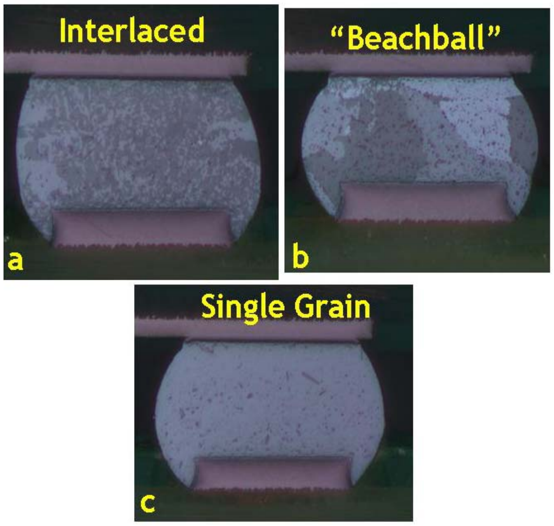


Figure 4: Polarized light micrographs of SAC microstructures illustrating three different Sn grain morphologies: a) interlaced twinning, b) "beach ball", and c) single grain.

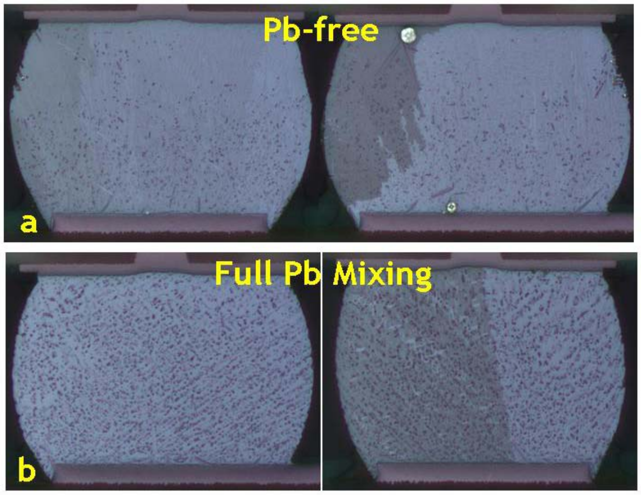


Figure 5: Polarized light micrographs of a) Pb-free SAC405 and b) Full Pb mixed Sn grain morphologies. The morphologies are single grain or beach ball independent of Pb content.

Accelerated Temperature Cycling

The components and the test circuit boards were daisy chained to allow electrical continuity testing after surface mount assembly and in situ, continuous monitoring during thermal cycling. The resistance of each loop was independently monitored during the temperature cycle test. All assembled circuit boards were thermally cycled from 0 °C to 100 °C or from 20 °C to 80 °C. Both cycling profiles used a 10 minute ramp time between temperature extremes and 10 minute hot and cold dwell times in accordance with the IPC-9701A industry test guidance [56]. The solder joints were monitored continuously during thermal cycling with an event detector set at a resistance limit of 1000 ohms. A spike of 1000 ohms for 0.2 microseconds followed by 9 additional events within 10% of the cycles to the initial event was flagged as a failure. The failure data are reported as characteristic life η (typically the number of cycles to achieve 63.2% failure) and slope β from a two-parameter Weibull analysis.

RESULTS AND DISCUSSION

Test Results

The thermal cycling test results are summarized in Table 3 and shown graphically in the Weibull plots in Figure 5 for the standard 0/100 °C thermal cycle [53], and Figure 6 for the Mild Acceleration 20/80 °C thermal cycle.

Table 3: Summary of temperature cycling failure statistics.

Leg	Characteristic Life η (cycles)	Slope (β)	Correlation Coefficient (r^2)	Sample Size
Standard Thermal Cycle (TC1): 0/100 °C				
Full Pb Mixing	7938	12.2	0.968	16
Pb-free SAC405	6510	21.8	0.899	16
63Sn37Pb	2682	20.8	0.96	16
Mild Acceleration Factor Cycle : 20/80 °C				
Full Pb Mixing	31595	17.8	0.946	16
Pb-free SAC405	31235	19.9	0.917	16
63Sn37Pb	6802	11.6	0.929	8

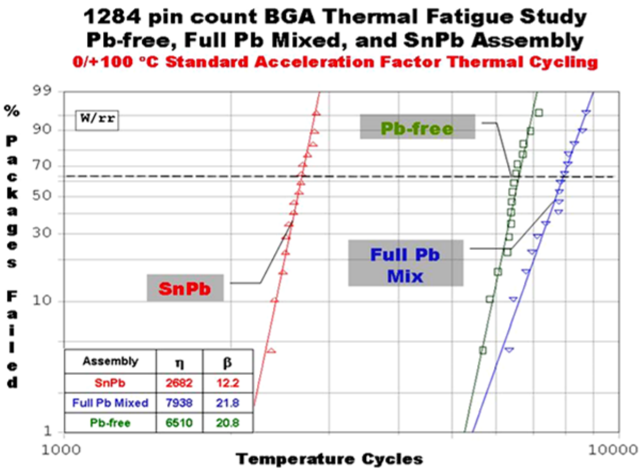


Figure 6: Weibull plot for the 1284 I/O PBGA comparing the performance of SAC405 solder balls to SAC405 with Full Pb Mixing for the standard 0/100 °C thermal cycle. The plot also includes the results for the eutectic SnPb solder leg.

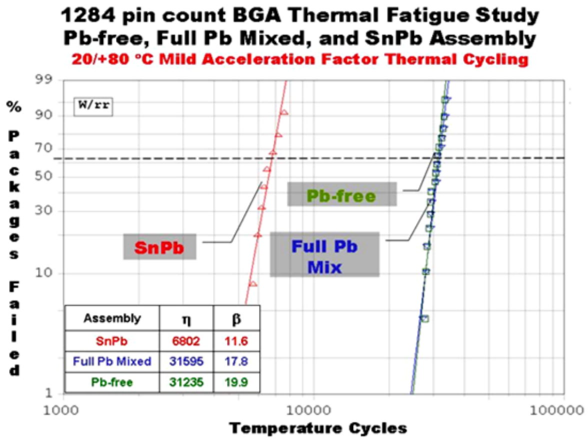


Figure 7: Weibull plot for the 1284 I/O PBGA comparing the performance of SAC405 solder balls with and without Pb mixing. The plot also includes the results for the eutectic SnPb solder leg.

In the standard 0/100 °C thermal cycling test, the Full Pb Mixed and Pb-free legs outperform the eutectic SnPb by factors of 2.5 and 3 respectively. In the mildly accelerated 20/80 °C test, the Full Pb Mixed and Pb-free legs outperform the eutectic SnPb almost by a factor of 5. The performance of the Full Pb Mixed leg is comparable to the Pb-free leg and *substantially* better than the SnPb eutectic leg using the smaller temperature ranges (△T) characteristic of many service conditions. These results provide a strong indication that the acceleration factor for mixed alloy assemblies is comparable to or greater than Pb-free or SnPb.

The 0/100 °C cycle accelerates failures in Pb-free and Full Pb Mixed about 4 times faster than in 20/80 °C testing, and about 2.5 times faster in eutectic SnPb. Both of these results are consistent with previously published work using the identical 20/80 °C thermal cycle [57].

In the 0/100 °C cycle, the Full Pb Mixed leg outperforms the Pb-free leg by about 20% based on the characteristic lifetimes. While it can be argued that this difference is statistically significant, there is a large difference in Weibull slope (β) between these two data sets and this should be taken into account when making characteristic lifetime comparisons between the data sets. A comparison based on first failures for example, does not show much of a difference. Note also that with the 20/80 °C testing, the characteristic lifetimes of the Full Pb Mixed Pb-free legs are indistinguishable. Additionally, this study used a sample size of only 16 components per leg (the preferred number is 32 [56]) due to resource limitations in the experimental plan.

Failure Analysis

Metallographic failure analysis was performed to document the solder joint failures and characterize the thermal fatigue failure mechanism. The backscattered electron images in Figure 8 show solder joint cracking in failed BGA solder joints from the Pb-free SAC405, Full Pb mixed, and SnPb eutectic legs for the standard 0/100 °C cycle and the mild 20/80 °C cycle. The failures in all three legs occur at the package side of the solder joint and under the die edge, which is a common location for BGA fatigue cracking. The lands on the BGA package substrate are solder mask defined , and this design feature is more prone to cracking than the metal defined lands that exist on the PCB side in this study.

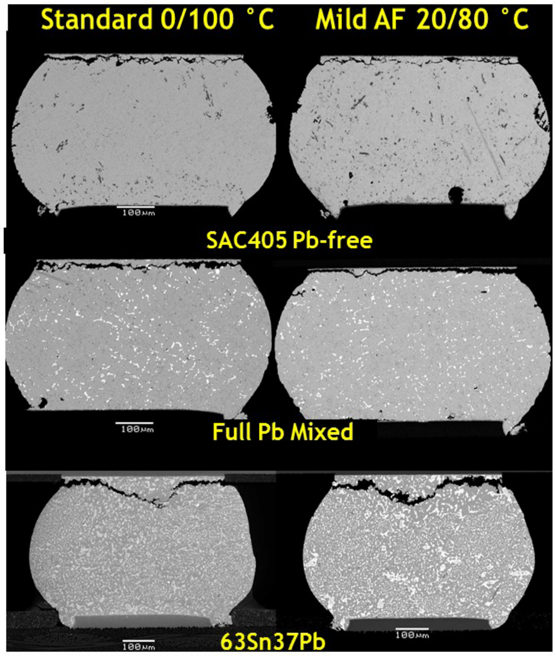


Figure 8: Low magnification backscattered electron images showing thermal fatigue cracking in the Pb-free, Full Pb Mixed, and SnPb samples for the 0/100 °C and 20/80 °C thermal cycling profiles.

Figure 9 compares higher magnification images of thermal fatigue cracking in the Pb-free and Full Pb Mixed solder assemblies. The crack paths are near the package-side intermetallic layer but through the bulk solder in all samples. All of the samples have Ag_3Sn precipitate coarsening in the strain-localized region surrounding the fatigue crack and show signs of recrystallization of Sn grains. The fracture modes are typical of thermal fatigue in Pb-free solders and are similar for the Pb-free and Full Pb mixed samples in both the standard and mild acceleration factor tests. In the Full Pb Mixed samples, there is no evidence of an interaction between the Pb phase (white) and the propagating fatigue crack. This observation indicates that the low Pb content from mixed assembly has no appreciable influence on the fatigue cracking of the Pb-free solder. These results are consistent with the Weibull statistics and with results from previous investigations [e.g., 52-54].

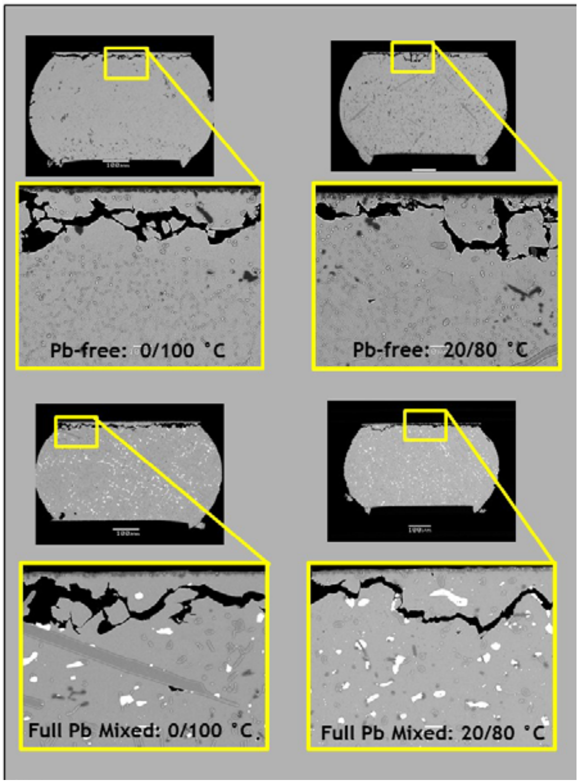


Figure 9: Higher magnification images of thermal fatigue cracking in the Pb-free and Full Pb Mixed solder assemblies. The fracture modes are similar for the Pb-free and Full Pb mixed samples in both the standard and mild acceleration factor tests.

Further insight into the performance of the Pb mixed assemblies can be obtained by comparing the microstructural evolution and damage mechanism to that of Pb-free assemblies. The recrystallization of Sn during thermal cycling has been related directly to crack propagation in SAC solder joints [67-69]. Yin et al have proposed a damage accumulation model that correlates the evolution of the solder microstructure and thermal cycling fatigue [68]. A fatigue crack begins to propagate along the network of grain boundaries through the recrystallized area until failure. The recrystallization is found mainly adjacent to high strain regions on the component side of the solder joint. This recrystallization varies systematically with the density of precipitates in a solder joint. Arfaei et al has studied the microstructural evolution in Pb-free solders during thermal cycling with the mildly accelerated conditions of the 20/80 °C thermal cycle [70]. They found that process of precipitate coarsening, recrystallization, and fatigue crack propagation in the 20/80 °C thermal cycle, shown in the polarized light micrograph in Figure 10, is the same as in the 0/100 °C cycle.

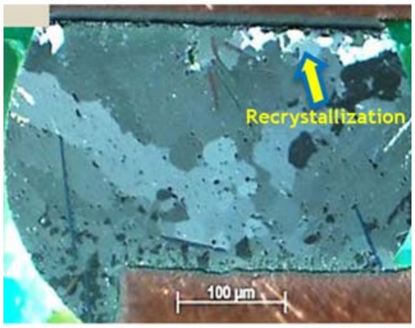


Figure 10: A polarized light image showing Sn recrystallization in a Pb-free BGA thermally cycled to failure using the 20-80°C mild acceleration factor profile. From Arfaei et al [70].

The fracture characteristics from the current metallographic failure analysis (Figure 9) indicate that the failure mode is the same in the Pb-free and Full Pb mixed samples from either the standard or and mild acceleration factor tests. The series of images shown in Figures 11 through 13 provide further evidence that the characteristic Pb-free failure mode is not altered by the presence of Pb and is the same with the standard and mild acceleration thermal cycling test profiles. Figure 11 shows optical (a) and polarized light (b) images of a Pb-free BGA thermally cycled with the 0/100°C profile. These images illustrate the process of microstructural evolution, which consists of precipitate coarsening and recrystallization in the high strain region followed by fatigue crack propagation along recrystallized Sn boundaries.

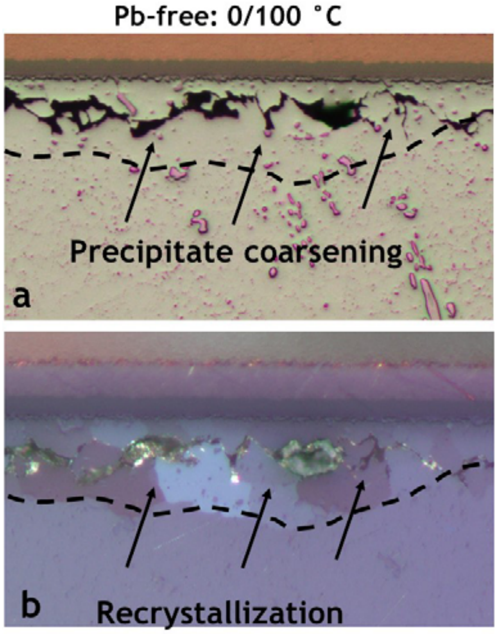


Figure 11: Optical (a) and polarized light (b) images of a Pb-free BGA thermally cycled with the 0/100°C profile. The failure process in Pb-free solder consists of Ag_3Sn precipitate coarsening in the high strain region followed by and recrystallization and fatigue crack propagation.

Figures 12 and 13 show optical and polarized light images of Full Pb Mixed samples from the 0/100°C test and the 20-80°C test respectively. These images confirm that the Full Pb Mixed samples fail according to the microstructural evolution and damage mechanism proposed by Yin for Pb-free solder assemblies [68]. These samples have the same characteristics as the Pb-free failure shown in Figure 11, with precipitate coarsening and recrystallization in the high strain region followed by fatigue crack propagation along recrystallized Sn boundaries.

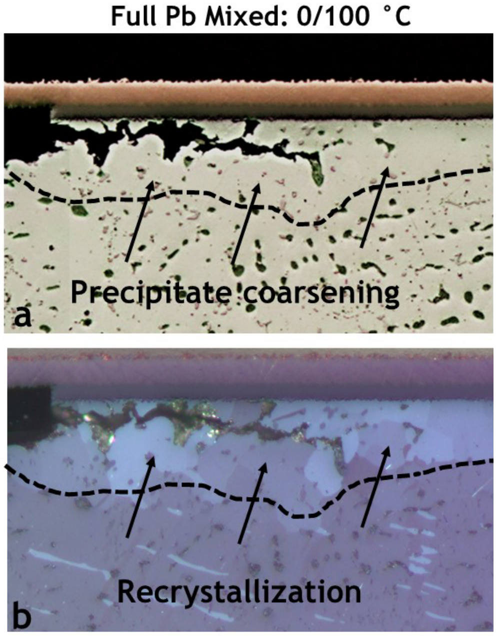


Figure 12: Optical (a) and polarized light (b) images of a Full Pb Mixed BGA thermally cycled with the 0/100°C mild acceleration factor profile.

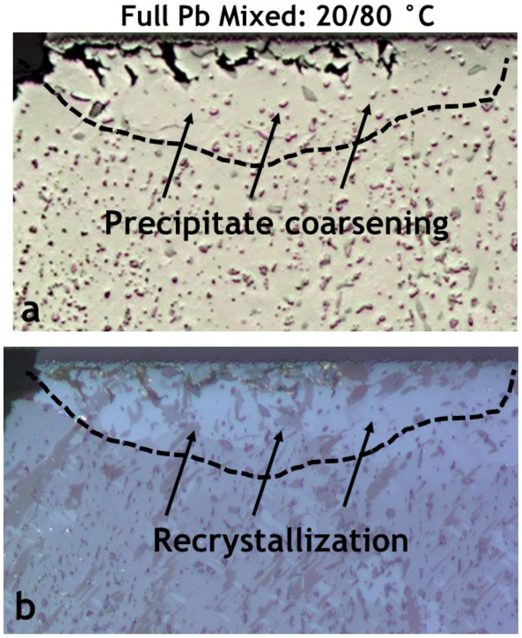


Figure 13: Optical (a) and polarized light (b) images of a Full Pb Mixed BGA thermally cycled with the 20/80°C mild acceleration factor profile.

These observations of microstructural evolution combined with the Weibull statistics from the two thermal cycling tests indicate that the resultant Pb content from mixed assembly has no appreciable influence on the thermal fatigue performance or thermal fatigue failure mode of the Pb-free solder.

CONCLUSIONS

The results from this experimental study show that the thermal fatigue performance measured by characteristic lifetime of the large-body 1284 I/O full array BGA with Full Pb Mixed solder joints, is comparable to that of the 1284 I/O BGA with Pb-free SAC405 solder joints. The Full Pb Mixed and the SAC405 Pb free assemblies perform equally well when tested with the standard 0/100 °C thermal cycle as with the mildly accelerated 20/80 °C cycle. Additionally, the mixed and Pb-free assemblies outperform the SnPb eutectic assemblies by a factor of 2.5 to 3 in 0/100 °C testing and by a factor of almost 5 in 20/80 °C testing. The latter result indicates that the acceleration factor for mixed alloy assemblies is comparable to or greater than Pb-free or SnPb.

There is no indication from the thermal cycling data or the metallurgical failure analysis that the Pb introduced by the mixed alloy assembly has a significant impact on thermal fatigue performance. The fracture features and failure modes of thermally fatigued mixed microstructures are the same as the fracture features of Pb-free SAC failures and the common fracture characteristics are consistent with their virtually identical fatigue performance.

Although these experimental results are consistent with some previous studies it is important to recognize that in practice, mixed alloy assembly is a custom process and its level of risk always should be assessed with respect to specific package construction, product design, and assembly parameters [49].

ACKNOWLEDGEMENTS

The authors want to acknowledge the following people for their valuable contributions: the management support of Marc Benowitz and Sherwin Kahn from Alcatel-Lucent Bell Labs Reliability; the management support of Michael Stark of Intel's Customer Platform Technology Development Team; the management support of Marco Gonzalez and Mulugeta Abtew of Sanmina and the PCB assembly support provided by the Sanmina (Guadalajara, MX) NPI team. Special thanks go to Dr. Babak Arfaei of Universal Instruments for helpful technical discussions.

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