The Effect of Pb Mixing Levels on Solder Joint Reliability and Failure Mode of Backward Compatible, High Density Ball Grid Array Assemblies

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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. 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. The influence of partial mixing on reliability was evaluated because full Pb mixing is more challenging as the package size and board complexity increase. To complete the reliability comparisons and provide experimental controls, SAC405-SAC405 and SnPb-SnPb assemblies were included. Post-cycling failure analysis was performed on representative test samples. The thermal cycling data and failure analysis are discussed in terms of the initial Pb mixing levels, mixed alloy microstructures, and attachment failure modes. The results indicate that full Pb mixing provides acceptable reliability, but certain cases of partial Pb mixing have measurably lower reliability and may present a reliability risk.

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

INTRODUCTION
Regardless of the accelerating trend for design and conversion to Pb-free manufacturing, many high reliability electronic equipment producers continue to manufacture and support tin-lead (SnPb) electronic products. Certain high reliability electronic 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, which 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 [49-52]. 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, 48-52]. Although recent studies, including some by the current authors, have demonstrated acceptable fatigue performance of large BGA mixed alloy assemblies [49, 51, 52, 53], there have been studies that indicate additions of Pb degrade the reliability of Pb-free solder joints.

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 soldering profiles designed to produce several different levels of Pb mixing in the BGA solder balls. In addition to the mixed alloy samples, the test program included SAC405-SAC405 and SnPb-SnPb assemblies for reliability comparisons. Failure analysis and microstructural characterization was performed on representative test samples to assess the relationship between the thermal cycling data, Pb mixing levels, mixed alloy microstructures, and attachment failure modes.

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

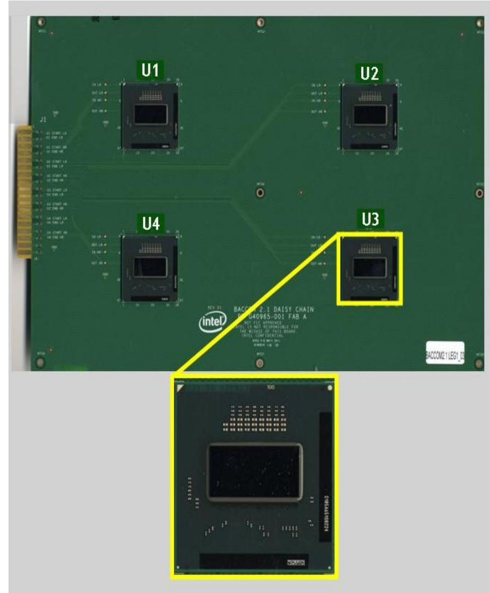

Figure 1: Top views of the populated printed circuit board and the BGA Package Test Vehicle.

Mixed Assembly Process Development and Assembly

The primary objective of this experimental study was to evaluate the effect of various Pb mixing levels on solder joint thermal fatigue reliability in a large, high density BGA component. The experimental strategy to meet this goal was to design multiple experimental legs using assembly profiles that would create different Pb mixing levels.

The various Pb mixing levels were defined and selected based on experience obtained from previous studies [48, 50-52] on large BGA package test vehicles. In the previous work, there were three experimental mixing levels defined as follows: low partial Pb mixing (<30%), medium partial Pb mixing (50 to 70%) and full Pb mixing (100%). Repeated test trials showed that the low partial Pb mixing target of <30% was difficult to control in the large BGA. Solder joint quality and standoff height varied across the BGA package to the extent that it would reflect an unstable SMT manufacturing process in practice. Minor profile changes when attempting the low partial mixing often affected significant changes in Pb mixing that were manifested as inconsistent solder joint quality and ultimately, a narrow or unstable assembly process window. Based on those previous experiences, the current study increased the threshold for low partial Pb mixing leg to 40%. The medium partial Pb mixing was set at 60-75% and full Pb mixing set at 100%.

The reliability comparisons were completed by including a SAC405-SAC405 leg and a SnPb-SnPb leg in the test matrix. An initial sample size of either 16 or 32 was used for the various Pb-free, SnPb and mixed legs. Table 2 lists the details for each of the 5 basic experimental legs in this study.

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

Leg #	BGA Solder Ball	Solder Paste	Test Cell	Target %Pb Mixing	Sample Sizes	
					BGA	PCBA
1	SAC405	Eutectic SnPb	Low Pb Mixing	>40	32	8
2			Medium Pb Mixing	60-75	32	8
3			Full Pb Mixing	100	16	4
4		SAC 305	Lead Free Control	N/A	16	4
5	Eutectic 63Sn37Pb		63Sn37Pb Control	N/A	16	4

Low magnification optical metallography was used to characterize the Pb mixing during profile development. The Pb mixing was documented along a diagonal plane through the BGA as shown in Figure 2.

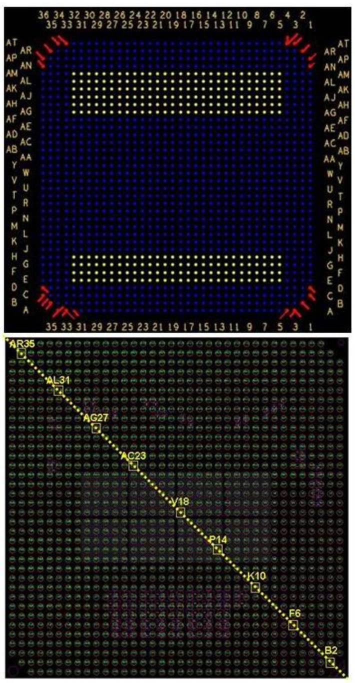

Figure 2: The pin diagram for the 1284 I/O BGA and location of the diagonal cross sectional plane used for Pb mixing characterization.

Figures 3 through 5 show optical photomicrographs obtained from profile development samples for the three mixed alloy legs of the matrix. In the Low Pb mixed, Leg1 samples shown in Figure 3, there is significant variation in the Pb mixing despite establishing the target threshold for low mixing at above 40%. This finding reinforces the results from the previous studies [50-52] that demonstrated the risk of inconsistent solder joint quality associated with a narrow or unstable assembly window when processing under conditions that generate low partial Pb mixing levels. There is variation in the Pb mixing in the Medium Pb mixed, Leg2 samples shown in Figure 4, but it appears to be within the target mixing level of 60-75%.

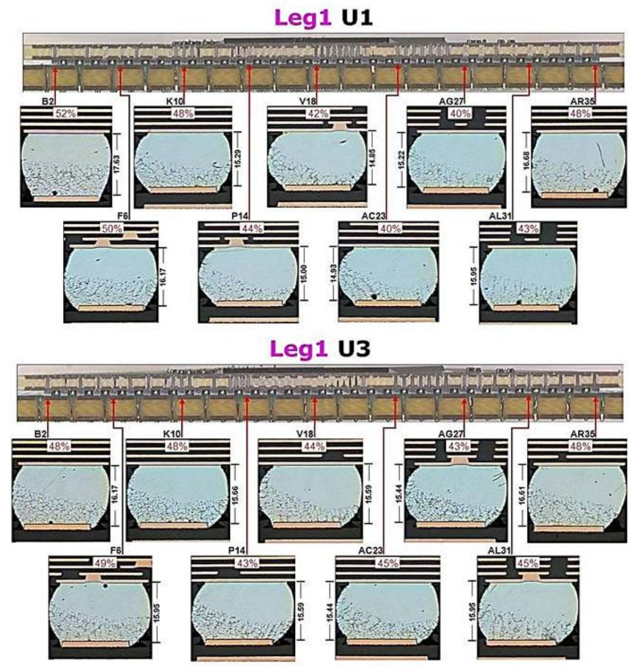

Figure 3: Multiple photomicrographs along the diagonals of two Low Pb mixed, Leg 1 samples. The Pb mixing ranges from 40 to 50% across the diagonal and often is not uniform across the solder ball.

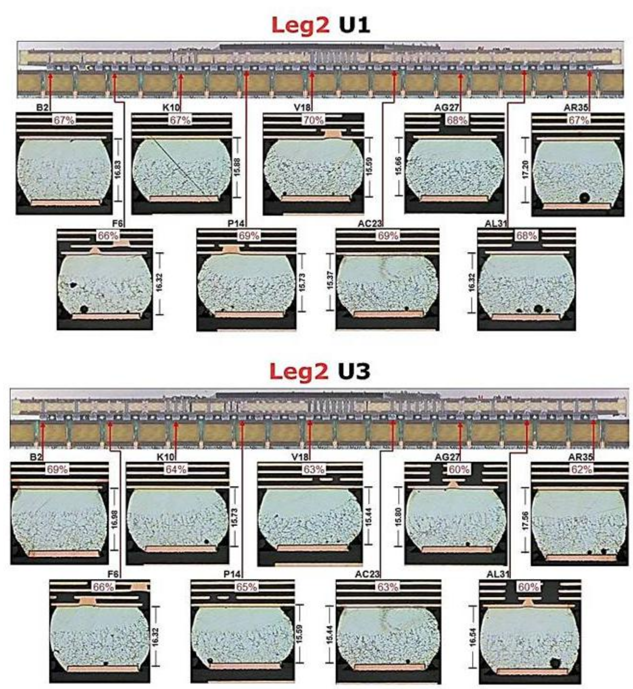

Figure 4: Multiple photomicrographs along the diagonals of two Medium Pb mixed, Leg 2 samples. The Pb mixing ranges from 60 to 70% across the diagonal and the Pb mixing is more uniform in the individual balls compared to Leg 1 shown in Figure 3).

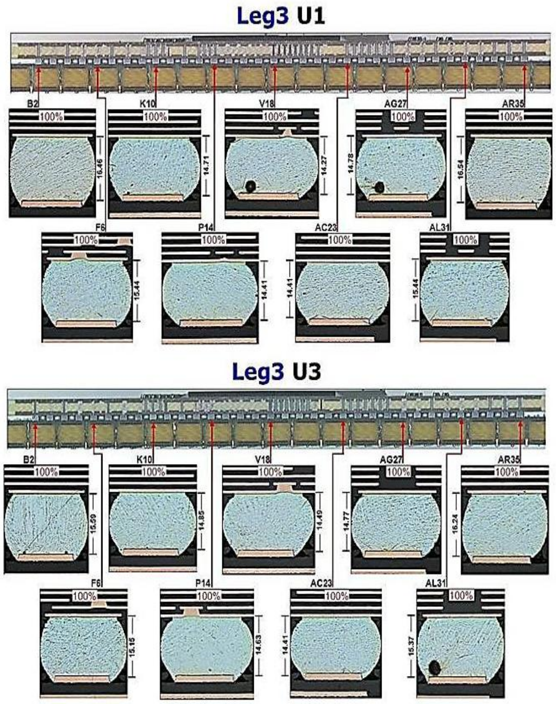

Figure 5: Multiple photomicrographs along the diagonals of two Full Pb mixed, Leg 3 samples. Compared to the partially mixed Legs 1 and 2, the standoff height is slightly lower for the fully mixed Leg 3 due to the complete melting and collapse of the solder balls.

The details of the Pb mixing are illustrated better in Figure 6, which shows backscattered electron images (BEI) of the Pb mixing for the Low and Medium Pb partial mixed legs and the Full Pb mixed leg. The BEI compositional mode is effective for differentiating phases in mixed alloy samples because the intensity of the backscattered electron signal is strongly related to the atomic number (Z) of the specimen. With backscattered imaging, the high density Pb-rich phase has a bright white appearance in contrast to the gray appearance of the Sn matrix. The effectiveness of the BEI method was demonstrated in previous mixed alloy studies [3, 49-52].

Figure 7 shows backscattered images of the SAC405 Pb-free and SnPb control legs. The dark phase in the SAC405 ball is the Cu_6Sn_5 intermetallic; the Ag_3Sn intermetallic particles cannot be resolved at this magnification. In BEI, the Sn-rich phase appears gray and the Pb-rich phase white. The regions of SnPb eutectic solidification cannot be resolved at this magnification.

Table 3 contains the details of the surface mount assembly profiles for all of the experimental legs.

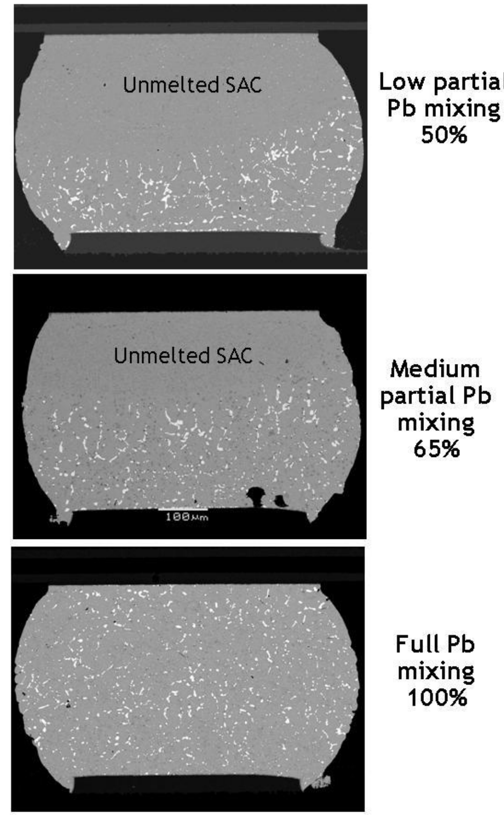

Figure 6: Backscattered SEM images illustrating the differences in Pb mixing levels. The Pb-rich phase appears as fine, bright white particles in the BGA balls.

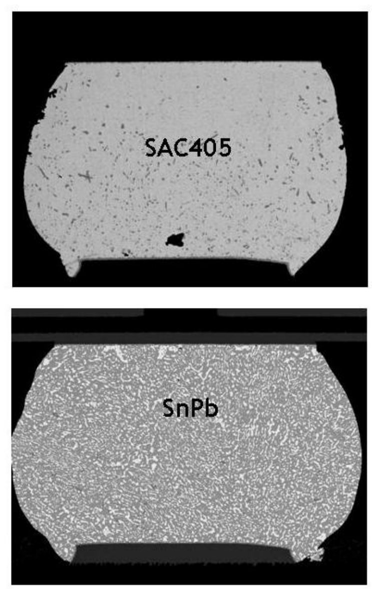

Figure 7: Backscattered SEM images for the SAC405 Pb-free and SnPb eutectic control legs. The dark phase in the SAC405 is the Cu_6Sn_5 intermetallic; the Ag_3Sn intermetallic particles cannot be resolved at this magnification.

Table 3: Reflow profile data showing peak temperature and time above liquidus (TAL) for the three mixed alloy legs and the pure SAC and pure SnPb control legs.

Experimental Legs and Reflow Profiles						
Leg #	BGA Solder Ball	Solder Paste	Test Cell	Target %Pb Mixing	Reflow Profiles	
					Peak Temp (°C)	TAL (sec)
1	SAC405	Eutectic SnPb	Low Pb Mixing	>40	212	60
2			Medium Pb Mixing	60-75	214	70
3			Full Pb Mixing	100	226	90
4		SAC 305	Lead Free Control	N/A	240	75
5	Eutectic 63Sn37Pb		63Sn37Pb Control	N/A	225	90

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 with a 10 minute ramp between temperature extremes. The hot and cold dwell times were each 10 minutes in accordance with the IPC-9701A industry test guidance [54]. The solder joints were monitored continuously during thermal cycling using 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 were reported as characteristic life η (typically the number of cycles to achieve 63.2% failure) and slope β from a two-parameter Weibull analysis.

Failure Analysis

The failure mode characterization employed the same basic sample preparation and analytical techniques described earlier for characterizing the profile development samples. The scanning electron microscopy (SEM) operating in the backscattered electron imaging compositional mode was used to the differentiate phases and characterize the extent of Pb mixing throughout the basic SAC microstructures. Imaging using polarized light microscopy (PLM) was added to study Sn grain morphology.

RESULTS AND DISCUSSION

Thermal Cycling Test Results

The thermal cycling test results are shown graphically in the Weibull plot in Figure 8 and are summarized in Table 4. The four test legs assembled with Pb-free solder balls (low, medium, and full mixed and SAC405) outperform the leg assembled with eutectic SnPb balls by more than a factor of two. The leg with full Pb mixing outperforms the legs with low and medium Pb mixing by 25-35%. The latter result contradicts results from several recent studies that indicate the performance of partially mixed microstructures is comparable to full Pb mixed microstructures and pure SAC microstructures containing no Pb [3, 6, 49-53]. This finding was unexpected because the low Pb concentrations typical of mixed assembly have not been associated with accelerated fatigue failure.

Based on the calculated characteristic lifetimes, the full Pb mixing leg also outperforms the Pb-free SAC405 leg. However, there is a significant difference in Weibull slope (β) between these two data sets and this should be taken into consideration when making characteristic lifetime comparisons between the data sets. Additionally, the full Pb mixed and Pb-free legs use an initial sample size of only 16 components per cell (the preferred number is 32 [54]) resulting from resource limitations imposed by the experimental plan.

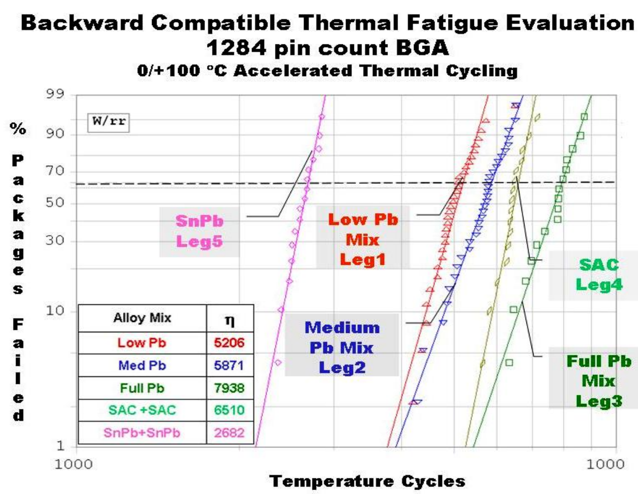

Figure 8: Weibull plot for the 1284 I/O BGA comparing the performance of SAC405 solder with various levels of Pb mixing. The plot also includes the eutectic SnPb results.

Table 4: Temperature cycling failure statistics.

1284 I/O BGA Thermal Cycling Data				
SMT Assembly	Sample Size	Characteristic Lifetime η (cycles)	Slope β	Correlation Coefficient r^2
Low Partial Pb Mixing	32	5206	14.1	0.895
Medium Pb Mixing	32	5871	11.3	0.989
Full Pb Mixing	16	7938	12.2	0.968
Pb-free SAC405	16	6510	21.8	0.899
SnPb	16	2682	20.8	0.960

Failure Analysis and Microstructural Characterization

Metallographic failure analysis was performed to confirm the thermal fatigue failure mode and determine the failure location. The backscattered electron images in Figure 9 show solder joint cracking in failed BGA solder joints from each of the three Pb mixed assembly legs, and the control legs with Pb-free SAC405 and SnPb eutectic solders.

The failures in the SAC405 and SnPb eutectic BGA solders occur at the expected location for BGA fatigue cracking at the package side of the solder joint. In contrast, the failures for the Low and Medium Pb mixed legs are at the printed circuit board side of the solder joint. More detailed failure analysis was conducted because the board-side failures and lower reliability of the Low and Medium Pb mixed legs (Figure 8 and Table 4), are not consistent with results reported previously [3, 6, 49-53].

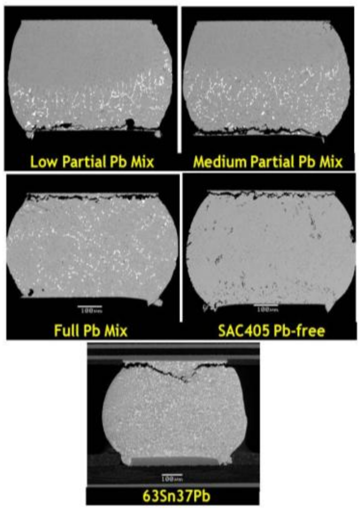

Figure 9: Backscattered electron images of thermal fatigue failures in the Low, Medium, and Full Pb mixed legs and the SAC405 Pb-free and SnPb eutectic control samples.

Examples of solder joint fractures in the Low and Medium Pb mixed ATC samples are shown at higher magnification in Figures 10 and 11. The fractures are characteristic of thermal fatigue in SAC with intergranular crack propagation generally along Sn boundaries. The crack path is in proximity to the PCB-side intermetallic interface. However, several of the images show a distinct accumulation of Pb on many sections of the fracture path. In one of the earliest mixed alloy thermal cycling studies, Seelig and Suraski attributed reduced reliability to gross Pb segregation at soldered interfaces [40]. A similar argument can be made that crack initiation or propagation is assisted by the accumulation of Pb shown in the images in Figures 10 and 11. The baseline images in Figure 12 show that the Pb accumulates at the PCB interface during reflow solidification. Regions of high Pb accumulation could stimulate a subtle mixed fracture mode consisting of the expected Sn creep fatigue mode coupled with random sections of grain boundary sliding typical of SnPb solder or interfacial decohesion caused by an extraordinary amount of Pb. There appears to be more Pb accumulated at the interface of the Low Partial Pb mixed sample, which is consistent with its slightly lower characteristic lifetime. In either case, the Pb accumulation appears sufficient to produce a measureable reduction in reliability of the partial Pb mixed legs but not sufficient to induce complete interfacial separations and catastrophic early failures. Further, this hypothesis is consistent with the uncharacteristic fractures observed at the board side of the joints.

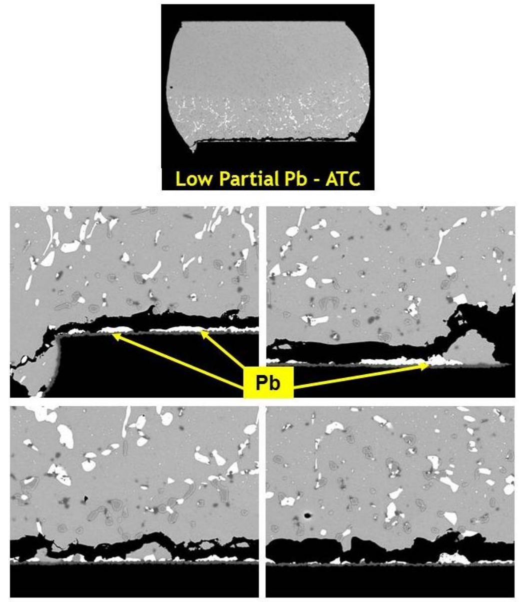

Figure 10: Backscattered electron images of thermal fatigue failures at the PCB side of the solder joint in the Low Pb mixed leg. Note the Pb (bright white phase) accumulated at the soldered interface and along the crack path.

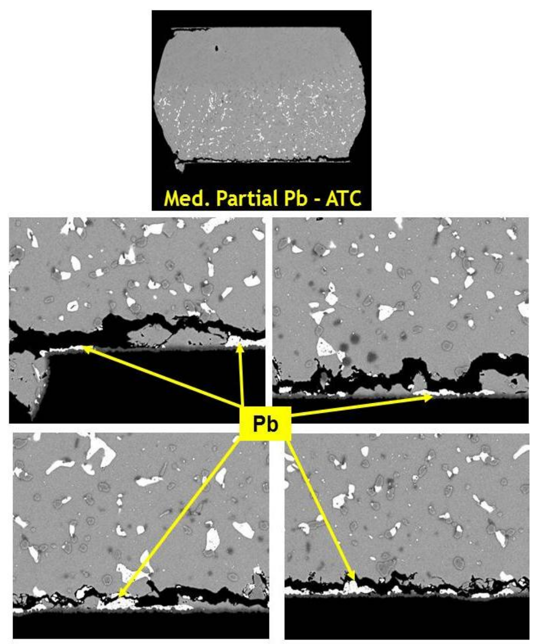

Figure 11: Backscattered electron images of thermal fatigue failures at the PCB side of the solder joint in the Medium Pb mixed leg. Note the Pb (bright white phase) accumulated at the soldered interface and along the crack path.

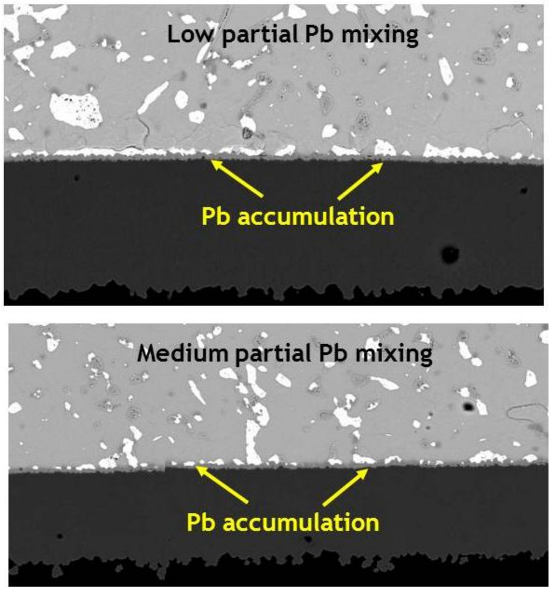

Figure 12: Backscattered electron images of Pb (bright white phase) accumulated at the PCB soldered interface after reflow solder assembly.

Examples of solder joint fractures in a Full Pb mixed sample are shown in the higher magnification images in Figure 13. The fatigue cracking in the bulk solder is located at the typical package side of the solder joint. Unlike the Low and Medium mixed samples, there is no significant Pb segregation along the fracture path that would indicate an interaction between the Pb phase (white) and the propagating fatigue crack. This is the anticipated finding based on the majority of the publications in the Pb mixed assembly literature.

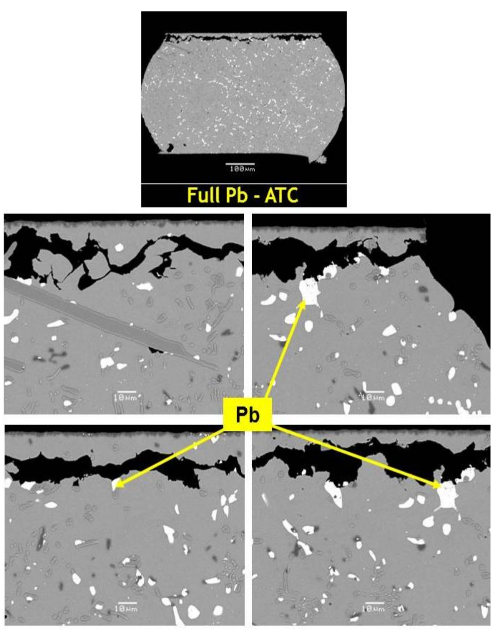

Figure 13: High magnification backscattered images near the fatigue crack in a full Pb mixed sample. There is minimal interaction between the Pb phase (white) and the propagating fatigue crack.

Examples of solder joint fractures in the Pb-free SAC405 and eutectic SnPb samples are shown Figure 14. The features of the crack path in the Pb-free SAC405 include intergranular crack branching, recrystallization, and cavitation at boundary triple points. All of these are characteristic traits of thermal fatigue cracking in Sn-based Pb-free solders [55-57]. The eutectic SnPb crack path is characterized by grain coarsening in the solder in proximity to the crack and boundary sliding between the Sn-rich and Pb-rich phases [58-59].

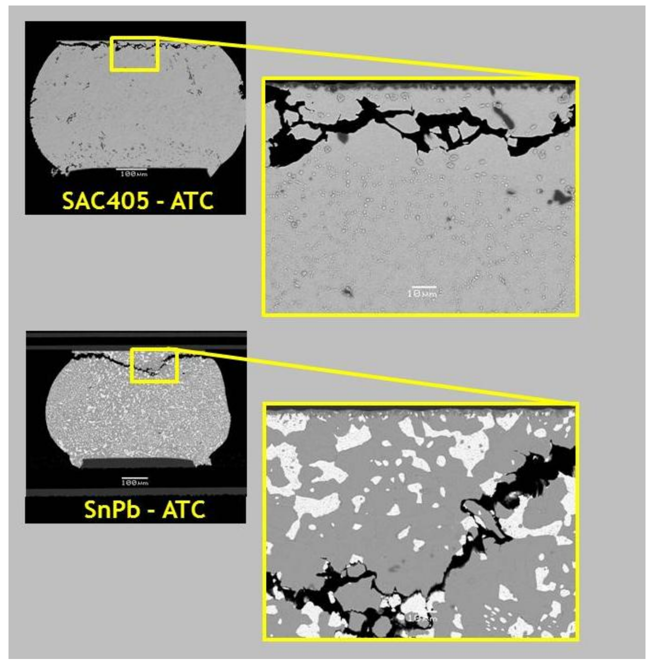

Figure 14: High magnification backscattered images of fatigue cracking in the SAC405 Pb-free and eutectic SnPb control samples.

The slightly better performance of the fully Pb mixed cell compared to the Pb-free SAC405 leg (Figure 8 and Table 4) very likely is not due to the presence of Pb but rather due to differences in the basic SAC microstructures in the two test legs. Numerous published reports such as those from the iNEMI Alloy Alternatives project [56, 57] have shown that thermal fatigue reliability is sensitive to microstructural features such as Sn grain size, intermetallic particle distribution, and interdendritic spacing. Because the reflow profiles for these two legs were very different, there could be significant differences in the SAC microstructures.

The Sn grain morphology can be characterized using polarized light microscopy (PLM), which is a technique that can highlight basic Sn microstructural features resulting from reflow and solidification. This is illustrated in Figure 15, which shows "beach ball" and interlaced twinned morphologies in a cross section of a SAC405 sample from the iNEMI Alloy Alternatives project [60]. Better thermal fatigue performance has been associated with the fine grain interlaced twinned morphology [61, 62].

Figure 16 shows typical polarized light micrographs of full mixed and SAC405 BGA solder joints from the current study. The cross sectional images contain either a single Sn grain or the "beach ball" Sn grain morphology and there is no evidence of the interlaced twinned grain morphology. This is consistent with reports that beach ball microstructures tend to occur more often in larger BGA balls with higher Ag content. The slightly better performance of the fully Pb mixed cell cannot be due to the basic Sn microstructure, since it essentially is the same in the full mixed and SAC405 samples.

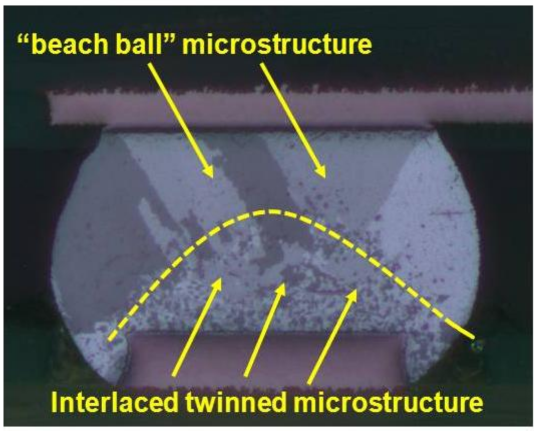

Figure 15: A polarized light micrograph illustrating regions that contain beach ball and interlaced twinned microstructures. This image was obtained from a SAC405 sample used in the iNEMI alternative Alloys project [60].

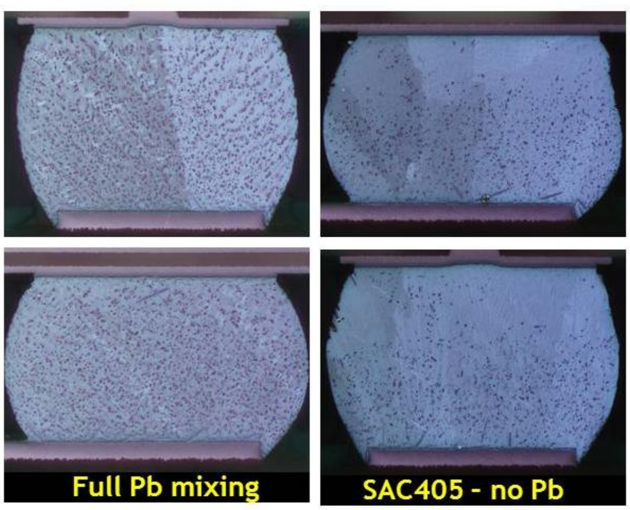

Figure 16. Polarized light micrographs of full Pb mixed and SAC405 BGA solder joints showing single grain and beach ball Sn microstructures.

The data in Table 3 indicate that full Pb mixing leg was achieved using a "hot" SnPb profile, with a peak temperature and TAL at the upper end of the acceptable SnPb assembly range. The SAC405 leg was assembled using a higher temperature Pb-free profile considered to be fairly standard for this type of a test vehicle. Representative photomicrographs for these two test legs are shown in Figure 17 and there are marked differences in the time-zero or starting microstructures. The Pb-free SAC405 microstructure consists of primary Sn dendrites surrounded by wide eutectic bands containing very small equiaxed Ag_3Sn intermetallic particles. In contrast, the full Pb mixing microstructure has primary Sn dendrites and fewer, substantially larger Ag_3Sn intermetallic particles at the Sn dendrite boundaries. The Ag_3Sn particles in the full Pb mixed sample 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 indicate that larger diameter or lamellar shaped particles may be more resistant to particle coarsening, the precursor to recrystallization and fatigue crack propagation [45, 63]. The difference in intermetallic size and shape in the full Pb mixed leg might account for the slightly better thermal fatigue performance of the Full Pb mixed test leg. Figure 18 shows comparisons of the microstructures at time zero and after thermal cycling (ATC). It is difficult to determine if the particle coarsening is greater in the SAC405 but the deterioration of the network of particles at the eutectic cell walls is very obvious.

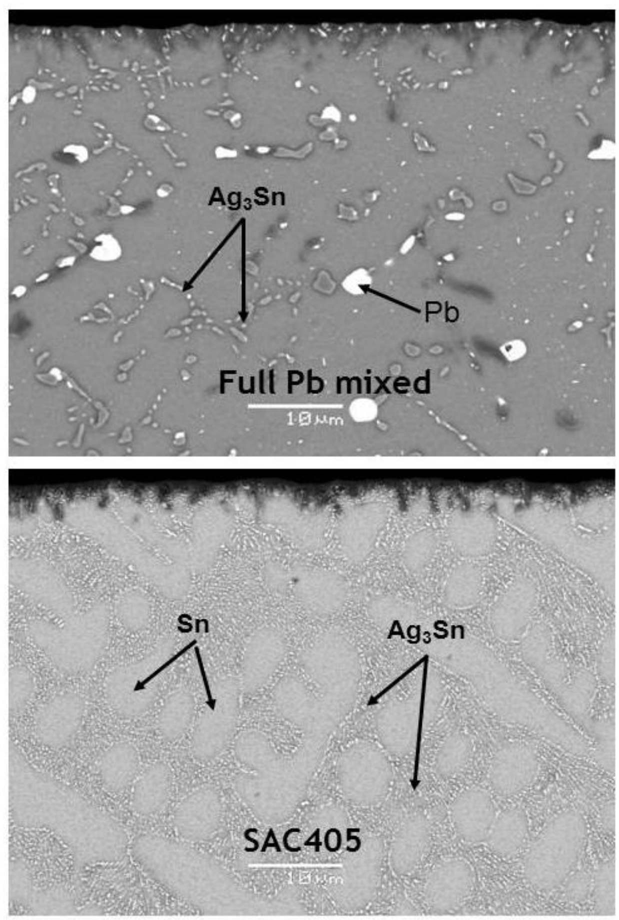

Figure 17. High magnification backscattered electron images illustrating the different solder microstructures in the full Pb mixed and SAC405 BGA solder balls.

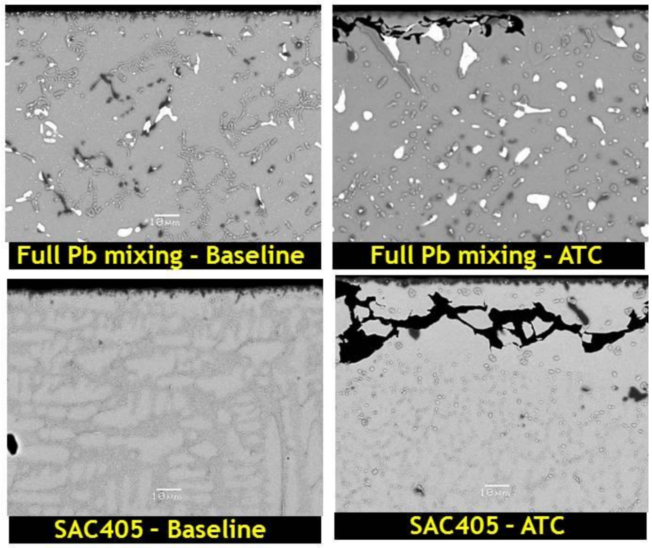

Figure 18. Comparisons of the microstructures for the Full Pb mixed and SAC405 test legs at time zero and after thermal cycling (ATC).

CONCLUSIONS

The results from this study demonstrate that the thermal fatigue performance of the Full Pb mixed, large-body, 1284 I/O BGA assemblies is acceptable and comparable to SAC405 Pb free assemblies within expected experimental error. The full Pb mixed test leg actually outperformed the SAC405 Pb-free test leg by a small margin. The better performance of the full Pb mixed leg is not likely due to the presence of Pb in the microstructure but to the mixed assembly profile and its resultant effect on solidification of the SAC solder. It is suggested that the size, morphology, and distribution of the Ag_3Sn particles in the microstructure of the full Pb mixed leg may be more resistant to particle coarsening, which would promote better thermal fatigue performance.

To the contrary, the fatigue performance with Low partial and Medium partial Pb mixing is about one third lower than the Full Pb mixed and pure SAC405 Pb free assemblies. Each of the four test legs based on SAC405 Pb-free solder outperforms the SnPb eutectic control cell by more than a factor of two.

Although the performance of the partial Pb mixed assemblies outperforms the SnPb control, there is a moderate reliability risk with partial Pb mixing in these large BGA assemblies. This finding contradicts results from several previous studies that have demonstrated acceptable reliability for the partial Pb mixing [3, 6, 49-53]. The findings from the current failure analysis provide support such a reliability risk assessment for partial mixing, at least for this specific component application. The metallographic analysis shows an atypical failure location at the PCB side of the solder joint and reveals a clear segregation or accumulation of Pb at the soldered interface and along the crack path. This analysis indicates strongly that the high concentrations of Pb are contributing to the lower fatigue resistance in the partial mixed assemblies. The exact mechanism causing the reduction in fatigue life is not clear nor is it clear if a high accumulation of Pb alters either the crack initiation or propagation processes.

In summary, these results demonstrate that it is possible to attain acceptable attachment reliability with mixed alloy, backward compatible assembly as long as complete, full Pb mixing is achieved. Mixed alloy assembly typically has a more limited process window than standard surface mount assembly and complete, full Pb mixing always is preferred in practice. Fully collapsed joints enable consistent alignment and are a key characteristic of acceptable solder joint geometry and quality. Unlike many previously published studies, the current findings show a measureable degradation in reliability with partial Pb mixing. The loss of reliability appears to be related to a high accumulation of Pb along the crack path which appears to be a direct consequence of partial mixed assembly. Despite previous favorable reliability test results, partial Pb mixed assembly is not recommended and if required, should be used with extreme caution due to the possibility of the Pb-assisted failure mode.

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