

Vibration Durability of Mixed Solder Interconnects

Gustavo Plaza, Dr. Michael Osterman, Prof. Michael Pecht
Center for Advance Life Cycle Engineering (CALCE)
Mechanical Engineering Department
University of Maryland, College Park, MD 20742, USA

Abstract

While the majority of consumer based electronics has converted to lead-free materials, a portion of the industry that provides electronics for critical applications, such as aerospace and defense, has resisted this change due to uncertainty in reliability. For these equipment manufacturers, limited availability of tin-lead parts has resulted in the potential use of lead-free parts in a tin-lead assembly process. However, reliability concerns remain with lead-free parts assembled with tin-lead solder (mixed solder interconnects). While some studies have examined the reliability of mixed solder interconnects under temperature cycling, very little data is present on the mixed solder interconnect reliability under vibration loading. This study presents the results of a random vibration test applied to mixed solder joint assemblies. A test assembly with a common layout was used which included surface mount components: 256 IO PBGAs, 100 IO TQFPs, 2512 and 1210 resistors. Lead-free board finishes examined included Organic Solderability Preservative (OSP), (Electroless Ni over Immersion Gold (ENIG), Immersion Silver (ImAg) and Immersion Tin (ImSn). TQFP lead finishes included Sn, Sn0.7Cu and Sn2Bi. Test assemblies were subjected to step-stress tests for a total of thirty six hours and a peak vibration input of 14 Grms at room temperature.

Key Words: Mixed Solder, Vibration, SnPb, SAC,

Introduction

Eutectic tin-lead (SnPb) has been the most widely used solder material in the electronics industry for different interconnects at different usage conditions. However, legislations imposed by the Restrictions of Hazardous Substances Directive (RoHS) in the European Union, as well as the China RoHS, have forced the electronics industry to transition toward lead-free electronics. [1][2] Consequently, by restricting the lead content on different solder materials, suppliers and manufacturers have been forced to change their products and manufacturing processes away from lead for the past 10-15 years in order to comply with the directives as well as to satisfy the demand of the market as companies. Exemptions, however, have been given to some sectors of the electrical and electronics equipment industry to use lead-based and other “hazardous” materials for scientific and technical purposes where the substitution of the material is not possible, such as those for aerospace, military, and space applications.[3] In some cases, those companies that have been granted exemptions to use lead-based materials on their manufacturing processes have encountered limitations due to cost and availability of lead-based components. Therefore, most of these companies are attempting to combine lead-free components with lead-based solder paste and assembly process yielding to the so called Mixed Solder assembly.

Solder joint reliability has been a concern in the electronics industry, solder fatigue being one of

the most influential factors. In addition to such concern, special worry has arisen in that sector of the electronics industry that is using the mixed solder joint and exposing the assemblies to harsh vibration environments such as avionics and ground vehicles. Different studies conducted in the academia and electronics industry are performed in an attempt to understand and evaluate the reliability of these assemblies. Studies [4][5] have looked at the homogeneous properties of the mixture between SAC and SnPb materials when reflowed with different profiles. Zbrzezny et al. reported the need of reflow temperatures between 218°C and 222 °C to achieve complete mixing between the two materials [4]. Addressing the same issue of finding the appropriate reflow temperature for a specific assembly, Pan developed a software to estimate the liquidus temperature of a mixed solder ball grid array (BGA) assemblies [5].

Although optimization of the assembly process is of great concern when dealing with the mixed solder interconnects, the presence of Pb in the structure of the assembly constitutes reliability concerns that are still unclear. Studies [6][7][8] have reported reliability evaluation of mixed solder assemblies including thermal cycling, shear stress, and pull strength. Ting-biao et al. studied the reliability of mixed solder BGA interconnects using an FEA model and applied the Coffin-Manson model to predict the thermal fatigue life of these assemblies. They found that the lead-free assemblies had a better reliability than the mixed solder; however, the lead

solder joints were found to have the worst reliability. Limaye et al. studied the creep behavior of Sn4.0Ag0.5Cu mixed with Sn37Pb solder under shear creep loading in an effort to compare this assembly with mode studied SAC and SnPb solder systems [6]. Choubey et al. reported pull strength results performed on mixed, lead-free and SnPb assemblies [8]. The pull strength of the mixed solder assembly was found to be lower than the SnPb and SAC assembly by 7% and 2% respectively.

This study has conducted high cycle fatigue testing exposing mixed-solder surface-mount assemblies to random vibration in order to evaluate the different interconnect structures under such stress loading. Recent studies performed in the industry and academia have used random vibration loading to assess the reliability of the assemblies [9]-[15]. The study discusses the effect of random vibration on mixed solder joints assembled with different pad finishes and exposed to isothermal aging for 100 hours at 125°C prior to testing. In addition to the mixed solder durability test, lead-based and lead-free assemblies have been tested in order to compare the durability performance of the mixed solder interconnects.

The vibration durability test was performed on a test vehicle that consists of various common surface mount components soldered onto a test PWB. The solder system, plating system and thermal pre-conditioning are systematically varied. Thirty printed wiring assemblies are tested at a time in a specially designed fixture on an electrodynamic shaker. The test setup is first characterized before conducting the durability experiment, by collecting strain histories at different sites on the PWB, mounted at different locations on the fixture, under different loading conditions. These strain results are useful to be able to compare the performance of the assemblies at different strain conditions and as inputs for subsequent finite element analysis (FEA) to estimate acceleration factors for various field environments. Destructive failure analysis (cross-sectioning, polishing and microscopy) was used to confirm that the failure was by solder fatigue.

Test specimen and fixture

Components were selected as a representative for area array and peripheral array components: BGA (Sn3.0Ag0.5Cu balls) was selected as representative of area array components and QFP (Finish Sn, Sn0.7Cu, Sn2.0Bi) as a representative for peripheral array components. A photo of a test assembly used in this study is shown in Figure 1. Each test assembly included some surface mount technology components (SMT) such as four 256 IO BGAs which represented the area

array type, sixteen 100 IO quad flat packs (QFPs) which represented the peripheral array components and ninety-six (forty-eight 2515 and forty-eight 1210) resistors assembled on a single side of a FR4 printed wiring board (PWB). The SMT test board used in the study was a High Tg FR4 (constructed with a glass transition temperature of 220 °C) of dimension 177.8 mm by 203.2 mm and an overall thickness of 1.64 mm. The parts were non-functional but constructed to create low electric resistance paths across the individual soldered interconnects when soldered to the PWB. Failure under the test load was determined by monitoring individual resistance paths. Table 1 shows the number of components and the daisy chained nets per component that are assembled in each of the test vehicles that were exposed to the random vibration test.

Table 1: Part/Nets for Test Vehicle

Name	Number of Components	Number of Daisy Chains
BGA (256 balls)	4	8 per BGA
QFP (100 leads)	16	4 per QFP
1210 LCR	48	8
2512 LCR	48	8

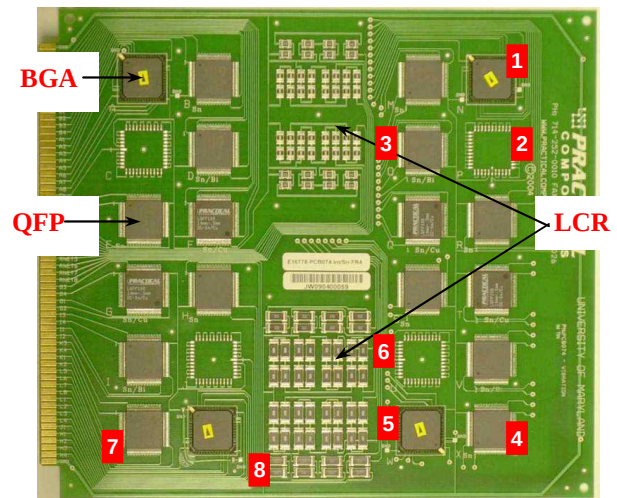


Figure 1: Test vehicle

In this study, the mixed assemblies were made with no-clean-type 3-Kester 256 paste (Sn37Pb). Board finishes included Immersion Tin-lead Hot Air Solder Leveling (HASL), Immersion Tin (ImSn), Immersion Silver (ImAg), Electroless Nickel with Immersion Gold (ENIG), and Organic Solderability Preservative (OSP). For comparison purpose, tin-lead assembly and lead-free assemblies were included. The tin-lead assemblies were composed of tin-lead finished parts, tin-lead HASL finished boards, assembled with the same tin-lead

paste. The lead-free assemblies as well as the mixed assemblies were made with no clean-type 3-Kester R905 solder paste (Sn3Ag0.5Cu). For the mixed solder assemblies, peak-temperatures of the PBGA parts were measured to be 220°C with a time above tin-lead eutectic melt point (183°C) between 66 to 79 seconds. For the lead-free Sn3Ag0.5Cu solder assembly, the peak PBGA temperature was 246°C with a time above Sn3Ag0.5Cu solder melt temperature (217°C) of 78 seconds. For the tin-lead assemblies, the peak PBGA temperature was 215°C with a time above tin-lead solder melt temperature (183°C) of 67 to 71 seconds.

The test boards were clamped along two opposite long edges on a fixture which was connected to an electrodynamic vibration shaker, for motion in the direction normal to the boards. The fixture is divided into four quadrants and each quadrant can hold five boards (see Figure 2). The fixture is welded together with an aluminum plate and the plate is bolted on the slip table of an electrodynamic shaker. The excitation is applied in the z (out-of-plane) direction, as shown in Figure 1. This fixture is characterized before the durability test. Aluminum cross bars (not pictured) were added to increase the stiffness of the fixture. The frequency response of the fixture is very important since it influences the dynamic response of test boards. Based on simulation, the first frequency of the board as fixture was estimated to be 200 Hz. To avoid the resonance of the shaker, the first natural frequency of the fixture should be greater than the highest excitation frequency (500Hz, in this study). Accelerometers are used to measure the frequency response. Three accelerometers are attached at different key locations of the fixture, as depicted in Figure 2.

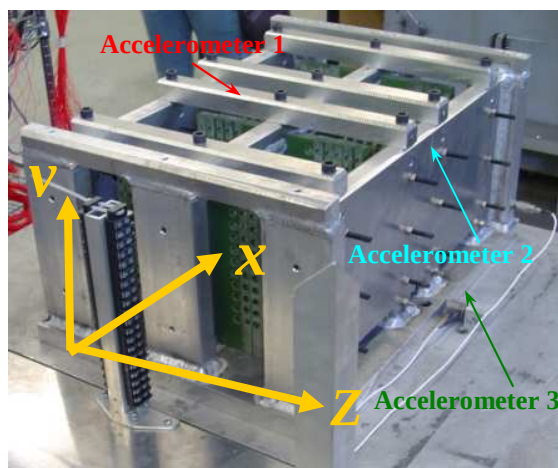


Figure 2: Vibration test fixture

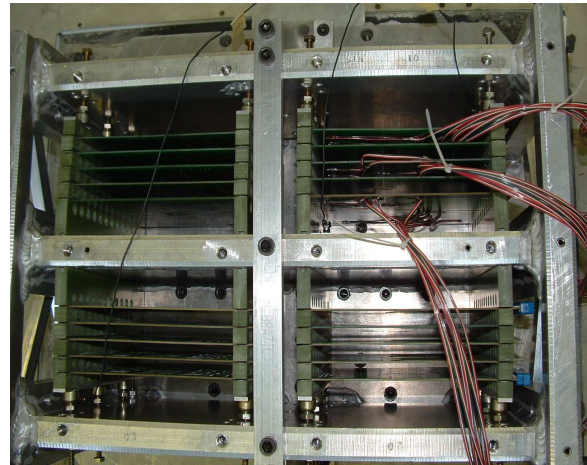


Figure 3: Test vehicle layout in the fixture

The results from the characterization step show that the first natural frequency of the fixture is around 800Hz. This frequency range is higher than the upper limit of frequency range applied in the durability test; therefore, the dynamics of the fixture are avoided.

Vibration Test

A broad-band random vibration loading is applied in the vibration durability test. The frequency range of the broad-band excitation is from 10 Hz - 500 Hz, which includes the first three natural frequencies of the test vehicle. The frequency range was selected to avoid significant influence of the fixture. To compress test time, the random vibration load was held constant for six hour intervals then increased. Four random vibration load levels were used that range from 0.02 G²/Hz to 0.2 G²/Hz with a 4dB/octave roll-off on both sides. The random vibration loads, defined by power spectral density (PSD) input profiles, used in the tests are shown in Figure 4.

Prior to the durability test, the populated test boards were characterized. Eight strain gages were attached to the back side of the test board below the components whose durability is of interest in this study. The strain response of the test vehicle was measured under eight different excitation levels. The instrumented boards were switched from location 1 to 5 in different quadrants. Strain measurements were collected using StrainBook/616 that was able to collect 2000 data points per second. The strain gages location as used in the test are shown in Figure 1.

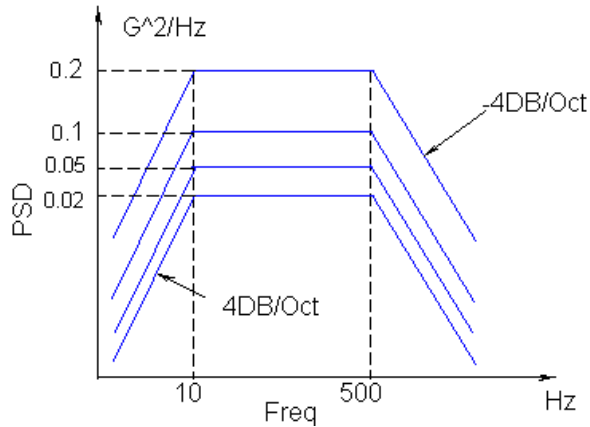


Figure 4: Vibration loading profile

A step-stress profile was applied on fully populated test vehicles to assess their random vibration durability. PSD level starts at 0.02 and continues at 0.05, 0.1 and stops at 0.2 G^2/Hz . The excitation magnitude was held constant for six hours at each load level while the highest excitation level was applied for eighteen hours in periods of six hours each. Data loggers, shown in Figure 5, are used to measure the daisy-chain resistance and monitor the health of the interconnects on each component.



Figure 5: Failure monitoring system

Failure Analysis

Failure is defined as a maximum of 20% increase of the nominal resistance in 5 consecutive readings based on the recommendations provided in the standard IPC-9701 for reliability evaluation on surface mount attachments [16]. A failure signature from the test is depicted in Figure 6.

Since step-stress excitation is applied in the durability test, different components experienced a different loading history, which makes the direct durability comparison very complex. Furthermore, there are also difference in other parameters that affect the durability of test component, such as the location of the board, solder material, pad finish and aging conditions. Ideally, the comparison of durability should be based on identical experiment conditions. Some durability test results and comparison between different kind of solder joints and different loading conditions are provided in next section.

In order to have a better understanding of the physics of failure of the failed mixed solder BGAs, failure analysis has been conducted. Failure site, mode and mechanism are identified through a two-step procedure. Initially, after the random vibration test was performed, the resistance data collected to monitored the health of the interconnects was used to identified the components that had failed during the test. In order to confirm the existence of failures and rule out experimental and monitoring errors, static electrical measurements were performed individually attaching probes from the daisy-chained interconnects that show failures to a multi-meter. The second step after the accelerated vibration durability test was the destructive failure analysis carried out on selected failed components to confirm that the failure modes and failure sites were related to solder interconnect failure. The failure analysis is conducted by cross-sectioning and E-SEM.

The microstructure of the BGA assemblies cross-sectioned, as seen in Figure 7, revealed a complete mixing between the SnPb solder paste and the SAC305 solder balls. Literature has shown that a high concentration of Pb will present toward the copper pad in the board side for this type of assembly [4]. Figure 8 clearly depicts the Pb phase present near the copper pad on the board side for the assemblies used in this study. Although mixed solder reliability studies under thermal cycling loading have related the Pb concentration with the failure site [4], a different observation was found in this study. As seen in Figure 9 and Figure 10, crack propagation induced by random vibration loading is not affected by the high Pb-phase near the copper pad on the board side.

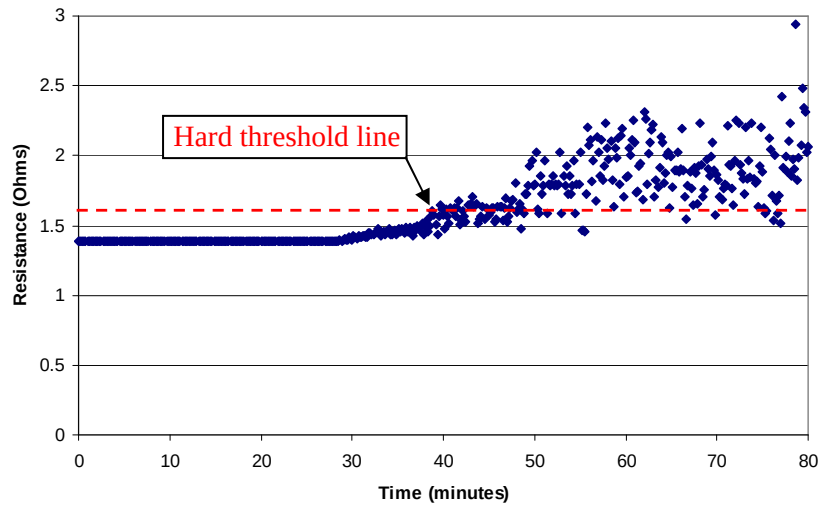


Figure 6: Example of Failure Signature

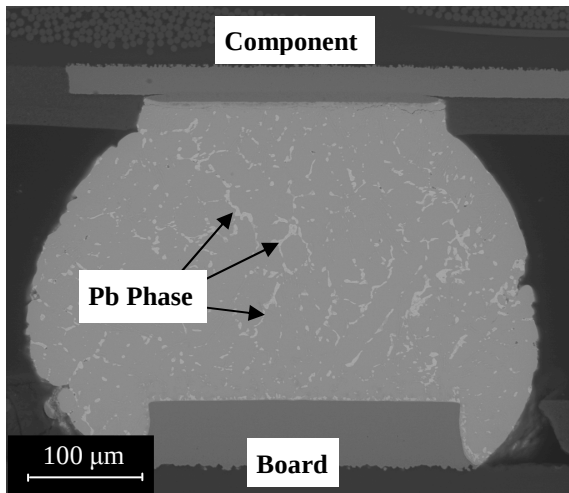


Figure 7: Mixed Solder BGA

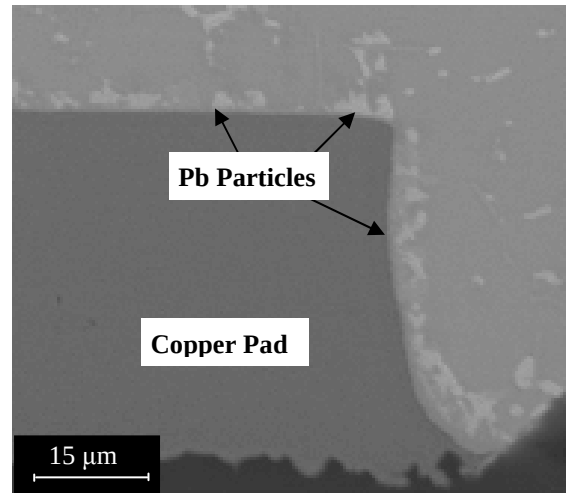


Figure 8: Pb concentration near Cu pad on a BGA's board-side

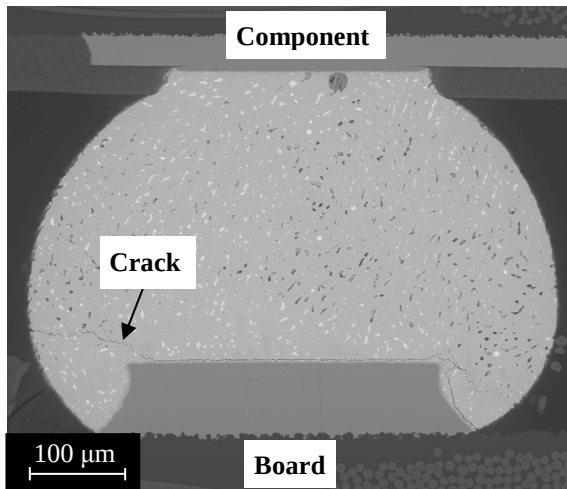


Figure 9: Board-side crack propagation path

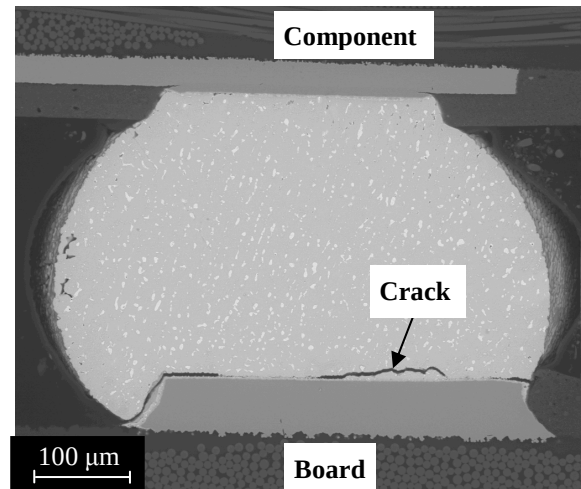


Figure 10: BGA Board-side crack propagation path

Results

During the step-stress test, each board failed at a different excitation levels. For purposes of comparison, durability of BGA interconnects is quantified by pseudo strain-life curves. In these curves, the vertical axis shows the PWB strain measured close to the failed BGA. Based on the location of the BGA on the PWB and the location of the PWB in the fixture, different components experienced different flexural PWB strains. Because of the step-stress excitation, the strain value used in the plot is only a reference value for comparison, measured at the highest excitation level ($0.2 \text{ G}^2/\text{Hz}$). The horizontal axis shows the TTF (time to failure) but the damage accumulation rate is not constant during this time, because of the step stress excitation. Thus, while such graphs allow good qualitative comparisons, they are clearly not true strain-life fatigue curves for quantitative comparisons.

Figure 11 through Figure 14 show the durability comparison between the three groups of solder systems. Figure 11 shows a comparison between all mixed assemblies. Out of all the assemblies, Mixed-ImAg appears to have the best performance through the entire time range. Mixed-ImSn, Mixed-ENIG and Mixed-HASL performed similarly as the pseudo S-N curve remain with a similar slope and with comparable TTF as seen in the graph. Finally, Mixed-OSP started off with a good durability performance at the high micro-strain levels, but it decayed faster than the other assemblies with a faster failure rate. Figure 12 shows that SnPb assemblies are more durable than mixed-HASL assemblies. On the other hand, Figure 13 and Figure 14 show that it is hard to conclude what assembly is more durable between the SAC and Mixed assemblies. This trend in the comparisons repeated among the other surface combination of assemblies.

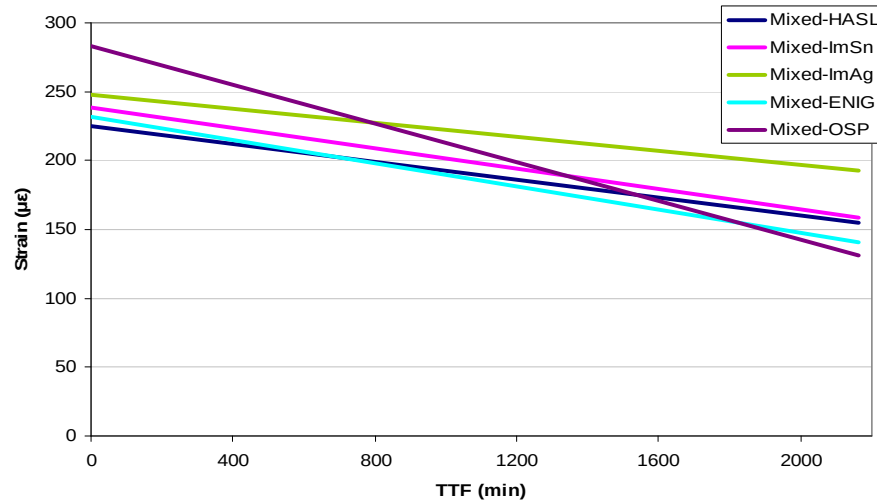


Figure 11: Mixed Solder Assemblies Tested at Room Temperature

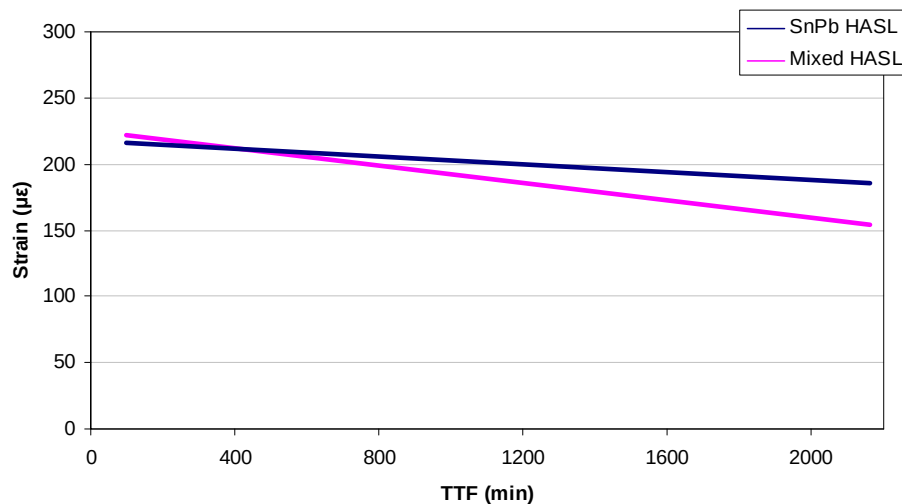


Figure 12: Comparison of Mixed-HASL and Tin-lead Assemblies

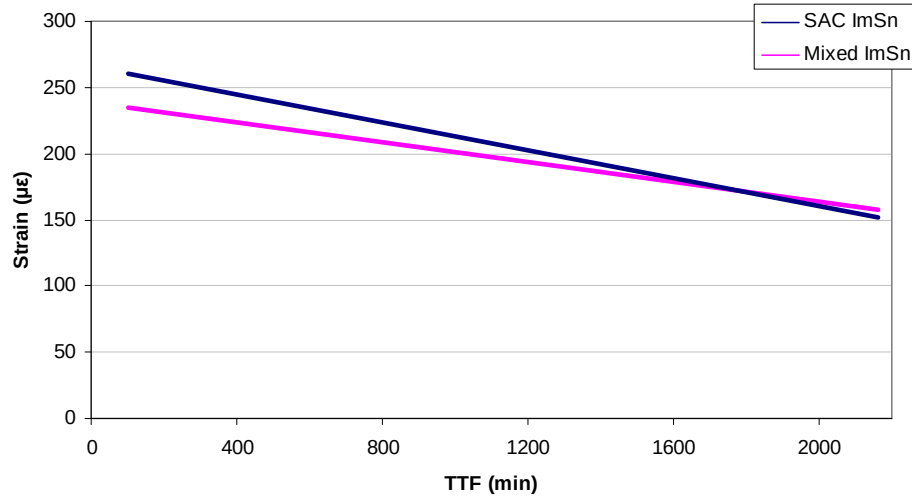


Figure 13: BGA TTF Comparison SAC vs. Mixed on ImSn finish

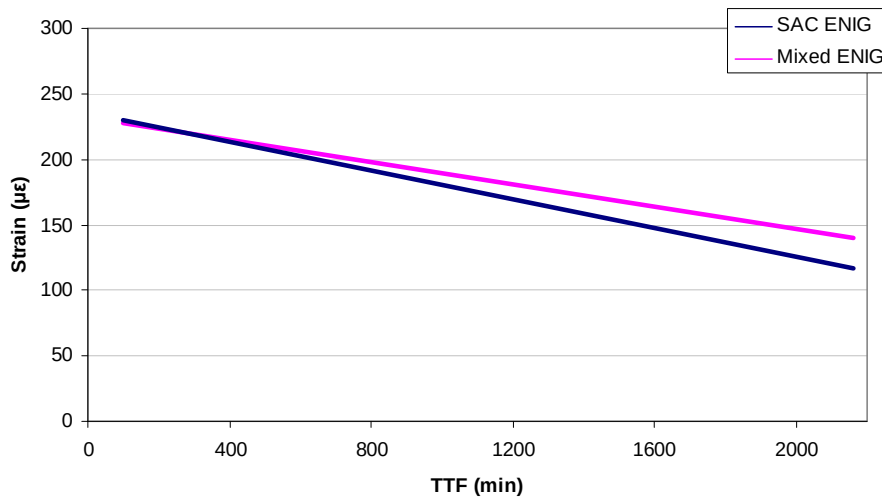


Figure 14 - BGA TTF Comparison SAC vs. Mixed on ENIG finish

Summary

Accelerated vibration fatigue tests have been conducted on three different solder system groups. The results provide insights regarding the HCF durability of SnPb, SAC and mixed solder assemblies with various plating systems, after thermal pre-aging. Based on test results, the following preliminary observations can be made, in spite of the scatter in the data:

- ◆ Failure analysis conducted on selected specimens revealed a different failure mechanism from the one found on studies conducted using thermal cycling loading. Pb-concentration near the copper pad on the board side does not influence the crack propagation path.
- ◆ SnPb/HASL assemblies are found to have better vibration durability than most mixed

assemblies with the same pad finish (HASL) when these are aged at 125°C for 100 hours.

- ◆ On the other hand, it is harder to conclude what assembly between mixed and SAC have the best durability performance. The only conclusive statements that can be drawn from the graphs in section 6 are that SAC-ImSn performed better than Mixed-ImSn and that Mixed-ENIG performed better than SAC-ENIG throughout the entire time range.
- ◆ Finally, Mixed-OSP started off with a good durability performance at the high micro-strain levels, but it decayed faster than the other assemblies with a faster failure rate. This performance is consistent with SAC-OSP assemblies as compared to the rest of the solder-pad finish systems.

Acknowledgement

The authors would like to thank the industry sponsors of the CALCE Long-term Lead-free Reliability Study on mixed solder assemblies for sponsoring this work.

Reference

- [1] Ganesan, S., and M. Pecht, Lead-free Electronics, John Wiley and Sons, Inc., New York, 2006.
- [2] Pecht, M., Y. Fukuda, and S. Rajagopal, "The Impact of Lead-free Legislation Exemptions on the Electronics Industry," IEEE Transactions on Electronics Packaging Manufacturing, Vol. 27, No. 4, pp. 221-232, October 2004.
- [3] Official Journal of the European Union
- [4] A. Zbrzezny, P. Snugovsky, T. Lindsay, and R. Lau, "Reliability Investigation of Mixed BGA Assemblies", IEEE Transactions on Electronics Packaging Manufacturing, Vol. 29, No. 3, July 2006.
- [5] J. Pan, "Estimation of Liquidus Temperature when SnAgCu BGA/CSP Components are Soldered with SnPb Paste", International Conference on Electronic Packaging Technology, 2006. pp. 1-6, 6-29 August, 2006.
- [6] J. Ting-biao, D. Chao, and X. Long-hui, "Finite Element Analysis and Fatigue Life Prediction of BGA Mixed Solder Joints", International Symposium on High Density packaging and Microsystem Integration, pp. 1-6, 26-28 June, 2007.
- [7] P. Limaye, R. Labie, B. Vandeveld, D. Vandepitte, and B. Verlinden, "Creep Behavior of Mixed SAC 405 / SnPb Soldered Assemblies in Shear Loading", Electronics Packaging Technology Conference, pp. 703-712, 10-12 December, 2007.
- [8] A. Choubey, D. Menschow, S. Ganesan, and M. Pecht, "Effect of AgNi on Pull Strength of SnPb, SnAgCu, and Mixed Solder Joints in Peripheral Surface Mount Components", Journal of Surface Mount Technology Association, Vol. 19-2, April 2006.
- [9] T. Wong, H. Fenger, "Vibration and Thermo-Mechanical Durability Assessment in Advanced Electronic Package Interconnects", Electronic Components and Technology Conference, Vol. 1, pp. 1080-1087, 1-4 June 2004.
- [10] J. Pang, F. Che, and T. Low, "Vibration Fatigue Analysis For FCOB Solder Joints", Electronic Components and Technology Conference, Vol. 1, pp. 1055-1061, 1-4 June 2004.
- [11] Y. Chen, C. Wang, and Y. Yang, "Combining Vibration Test with Finite Element Analysis for the Fatigue Life Estimation of PBGA Components", Microelectronics Reliability (2007), doi:10.1016/j.microrel.2007.11.006.
- [12] S. Wong, P. Malatkar, C. Rick, V. Kulkarni, and U. Chin, "Vibration Testing and Analysis of Ball Grid Array Package Solder Joint", Electronic Components and Technology Conference, pp. 373-380 May 29-June 1 2007.
- [13] Y. Zhou, and A. Dasgupta, "vibration Durability Assessment of Sn3.0Ag0.5Cu and Sn37Pb Solders Under Harmonic Excitation", ASME - IMECE, November 11-16, 2007
- [14] H. Qi, "Plastic Ball Grid Array Solder Joint Reliability Assessment under Combined Thermal Cycling and Vibration Loading Conditions" Ph.D. Thesis, University of Maryland, 2006.
- [15] J. Gu, D. Barker and M. Pecht, "Prognostics Implementation for Electronics Under Vibration Loading" Microelectronics Reliability, Vol. 47, Issue 12, pp. 1849-1856, Dec. 2007.
- [16] IPC-9701, "Performance Test Methods and Qualification Requirements for Surface Mount Solder Attachments", The Institute for Interconnecting and Packaging Electronic Circuits, Northbrook, IL, January 2002.