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HALT Testing of Backward Soldered BGAs on a Military Product

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Abstract
The move to lead free (Pb-free) electronics by the commercial industry has resulted in an increasing number of ball grid array components (BGAs) which are only available with Pb-free solder balls. The reliability of these devices is not well established when assembled using a standard tin-lead (SnPb) solder paste and reflow profile, known as a backward compatible process. Previous studies in processing mixed alloy solder joints have demonstrated the importance of using a reflow temperature high enough to achieve complete mixing of the SnPb solder paste with the Pb-free solder ball. Research has indicated that complete mixing can occur below the melting point of the Pb-free alloy and is dependent on a number of factors including solder ball composition, solder ball to solder paste ratio, and peak reflow times and temperatures. Increasing the lead content in the system enables full mixing of the solder joint with a reduced peak reflow temperature, however, previous research is conflicting regarding the effect that lead percentage has on solder joint reliability in this mixed alloy solder joint.

Previous work by the authors established a protocol for soldering Pb-free BGAs with SnPb solder paste based on solder ball size and target lead content in the final solder joint. The units from that testing were subjected to thermal cycling between -55°C and 125°C and compared to a SnPb baseline assembly. Results showed that mixed alloy joints performed as well as or better than standard SnPb joints under these conditions.

This study continues the previous work with evaluation of reliability in a production design. Functional assemblies were built using Pb-free BGAs in a SnPb solder process and subjected to life testing including accelerated aging and highly accelerated life testing (HALT). Results from this testing are compared to SnPb baseline units and previous product development test results.

Introduction
Europe's Restriction of Hazardous Substances (RoHS) and similar lead-free directives from nations outside the European Union have caused the electronics industry to move towards lead-free soldering. Some manufacturers building high-reliability electronics and/or products with a long service life which are outside of the scope of these directives continue to use conventional tin-lead (SnPb) solder due to the uncertain reliability of lead-free solder joints. Because component manufacturers are moving to lead-free production, many components are no longer available in SnPb.

As availability of SnPb BGAs and chip scale packages (CSPs) continues to diminish, fabricators who continue to use a SnPb process will be compelled to accommodate lead-free versions of these packages by either reballing the package, or using them as-is in a backward compatible process. Reballing is currently an acceptable process for many, but carries with it the disadvantages of potential damage to the package, voiding of the component manufacturer's warranty, and/or significant cost impacts. Soldering of lead-free components with SnPb solder, called backward compatibility, has therefore become an area of particular interest.

The mixing of metallurgies can induce new reliability concerns because solder joint reliability depends on loading conditions, material properties and microstructure of the solder joint. Furthermore, the microstructure of the solder joint continues to evolve over time depending on temperature and mechanical loading conditions. One of the microstructural features known to influence the reliability of conventional SnPb solder is the lead (Pb) phase, which coarsens with time, temperature and mechanical loading, causing reliability concerns [1][2]. It is therefore important to understand any impact to reliability resulting from the mixing of solder alloys, particularly in the use of components which have a volume of lead-free solder that is significant to the final solder volume in the joint, such as BGAs and CSPs.

Numerous studies have been conducted to investigate the reliability of the mixed solder joints subjected to various loading conditions and metallurgical combinations. In general, results from these studies indicate that for lead-free

BGA components assembled with lead-based solder, the reliability is equivalent to completely lead-free assemblies, provided that the Pb is distributed evenly throughout the joint [3-9]. Correspondingly, several studies found that the reliability of solder interconnections degraded when a SAC solder ball is only partially mixed with SnPb solder paste [4][6][10].

The degree of mixing in backward compatibility assembly is expected to be a function of the reflow peak temperature, time above liquidus (183°C), the alloys used (ball and paste), and the mix ratio of those alloys[3][7][11-18]. In previous studies, the authors developed processing guidelines for lead-free BGAs and CSPs with SnPb solder paste based on lead content, reflow peak temperature, and time above liquidus (TAL)[19]. The result was the chart shown in Figure 1, which is used by the assembler to ensure that full alloy mixing in the BGA solder joint is achieved, thus providing a reliable joint, while allowing the assembler to adjust the desired parameters of their process to optimize for design-specific restrictions.

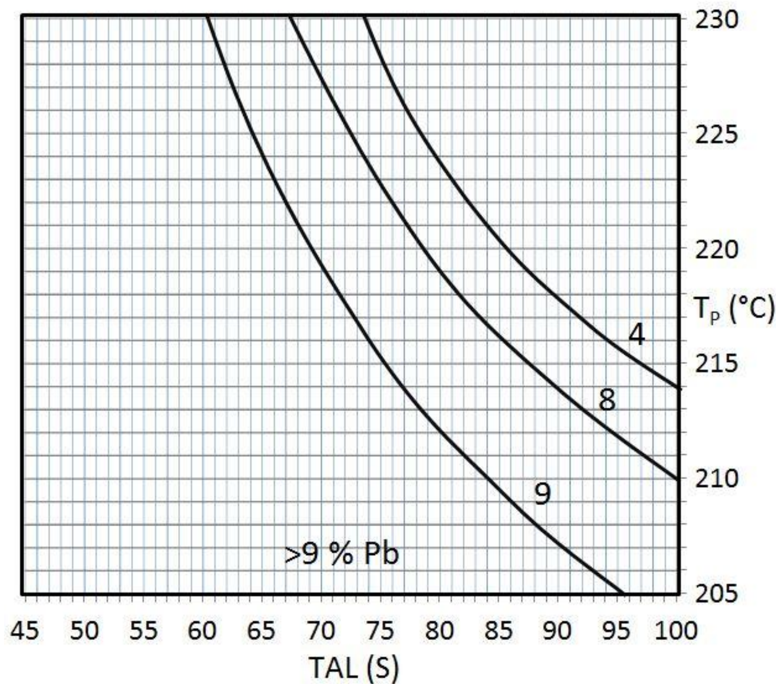

Figure 1 - Pb content (% wt.) curves for predicting full mixing of backward compatible solder joints based on T_P and TAL (183°C)

In this study, the guidelines developed in that previous work were used to fabricate hardware of an existing production design where the SnPb-balled BGAs are replaced with components which have SAC305 balls. This hardware was then be subjected to HALT and accelerated aging in a fashion similar to the tests used to validate other design changes, to demonstrate the reliability of the Pb-free components used in the backward compatible process.

Experimental Procedure

The test vehicle chosen for this study was a 9” x 5”, two-sided, multi-layer surface mount (predominantly) circuit card with a variety of component package types (see Figure 2). Three of these components are BGA packages with the properties shown in Table 1.

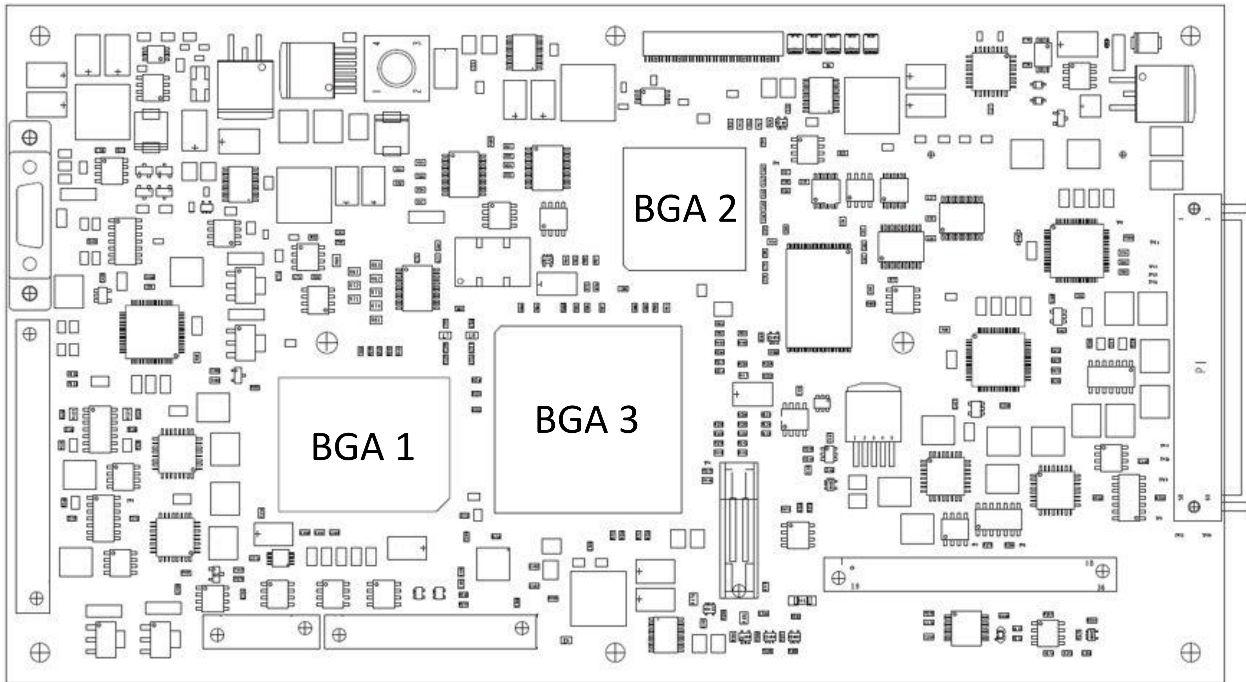

Figure 2 – Circuit card test vehicle top side layout

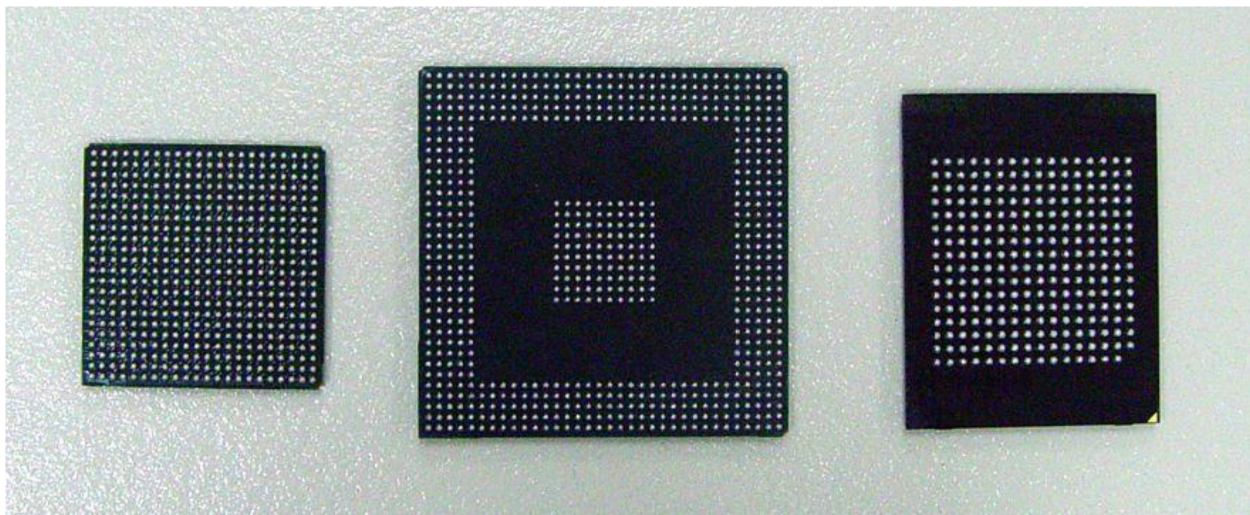

Figure 3 – BGAs used on test vehicle

Table 1 – BGA component properties

BGA #	Length (mm)	Width (mm)	Ball Count	Ball Ø (mm)	Array Type	Pitch
1	32	25	255	0.762	Full	1.27
2	23	23	484	0.6	Full	1
3	35	35	680	0.6	Island	1

The existing design includes SnPb balls on the BGA components, so the Pb-free versions on these components were procured from the manufacturer and inserted into the assembly. The Pb-free version of each component has SAC305 balls.

For each BGA, the size of the ball and the existing stencil design was evaluated to determine the expected Pb content that would be present in the final joint, assuming full mixing in the joint (see Table 2). Using the current stencil design, the Pb content in the joints was expected to be quite low. Because there are some component types used in SMT assembly which have temperature sensitivities beginning around 230-235°C, it was desirable to keep the reflow profile below 230°C. To stay above the appropriate curves for these Pb levels in Figure 1, a long reflow profile or a tight process window would be required. In order to enlarge this process window, the stencil apertures were enlarged to increase the volume of solder paste applied and therefore increase the expected Pb content in the final joint.

Table 2 – Pb content, with and without stencil design modifications

BGA #	Initial Stencil Aperture (mm)	Aperture Type	Expected Pb%	Updated Stencil Aperture (mm)	New Expected Pb%
1	0.57	Square	3.8%	0.84	6.4%
2	0.43	Square	4.3%	0.64	7.4%
3	0.48	Square	5.2%	0.64	7.4%

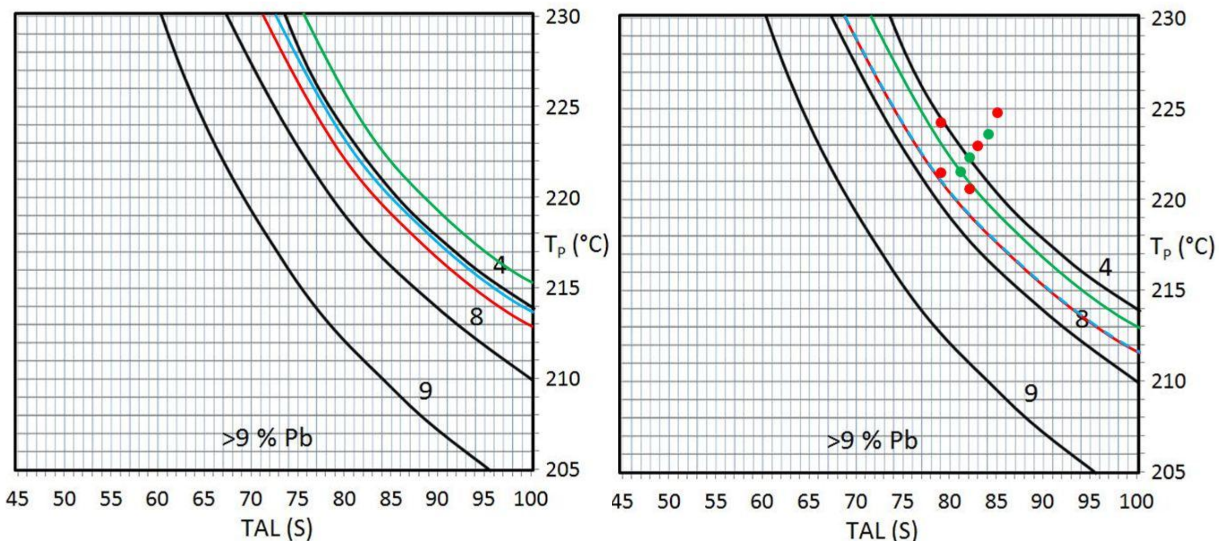

Figure 4 – Initial expected Pb curve levels applied to process chart (left) and updated Pb curve levels applied to process chart (right). Actual thermocouple values are plotted on the updated chart.

After SMT assembly, the required plated through hole components were installed, followed by application of conformal coating (Type UR). Inspection was performed throughout the process to ensure that the hardware met all quality requirements.

On completion of assembly, the test vehicles were divided into two groups; three assemblies were subjected to thermal and vibratory extremes, commonly referred to as Highly Accelerated Life Testing (HALT). The remaining six units were subjected to accelerated aging through humidity and thermal exposure, along with another four units built in a standard production process with SnPb-balled BGAs.

HALT:
The three units for HALT were exposed to the combined thermal and vibratory environment. The profile consisted of thermal cycling from -67°C to 106°C at a rate of 25°C/min, with 10 minute dwells once the BGA components reached temperature. Vibration input was escalated with each thermal cycle. The expected vibration input levels were to be at least 6 Grms at the holding fixture at the maximum level. Actual vibration responses of the BGA locations were determined during the process, and functional testing was performed periodically.

Accelerated aging:
To induce electronic failures that could be exhibited in the lifetime of fielded hardware, the test units were exposed to increased temperature and humidity levels. An estimate of the amount of life acceleration that this environment induced was calculated using a variation of the Arrhenius equation with a humidity stressor applied. This equation is the Hallberg-Peck Model:

$$AF = (RH_T / RH_A)\ 3 * \exp\{(Ea/k)*(1/T_T-1/T_A)\}$$

Given:

RH_T	Relative humidity in the test environment
RH_A	Relative humidity in the application environment
Ea	Activation energy
k	Boltzmann's constant ($k = 8.617 \times 10^{-5}$ eV/Tk)
T_T	Temperature in Kelvin in the test environment
T_A	Temperature in Kelvin in the application environment

A conservative value of 0.7 was chosen for Activation Energy. For this study, a relative humidity of 60% and temperature of 30°C was assumed for the application environment. The above formula for test acceleration factor completed for these values is shown below. Table 3 shows other Acceleration Factors for determining simulated life based on a range of application conditions.

$$AF = (0.85/0.60)^3 * \exp\{(0.7/8.617E\text{-}5)*(1/358-1/303)\}$$
$$AF = 2.8 * 61.5 = 174.8$$

The goal of this study was to fully evaluate the performance of the mixed alloy solder joint over an extended life. In many aerospace and defense products, this life can be more than 20 years, even 30 years or more. This aging test was conducted for 63 days to simulate 30 years of aging.

Test time unit:	1 day
Acceleration Factor:	174.8
Simulated Life per day:	174.8/365 = 0.48 years/day
Total test time:	63 days
Total Simulated Life:	30 years

Table 3 – Acceleration factors for various expected service life conditions and the given test conditions.

		Expected temperature (K) in Application Environment						
		20	25	30	35	40	45	50
Expected RH in Application Environment	0.25	6034.4	3789.7	2416.8	1564.0	1026.2	682.4	459.5
	0.30	3492.1	2193.1	1398.6	905.1	593.9	394.9	265.9
	0.35	2199.1	1381.1	880.8	570.0	374.0	248.7	167.5
	0.40	1473.2	925.2	590.0	381.8	250.5	166.6	112.2
	0.45	1034.7	649.8	414.4	268.2	176.0	117.0	78.8
	0.50	754.3	473.7	302.1	195.5	128.3	85.3	57.4
	0.55	566.7	355.9	227.0	146.9	96.4	64.1	43.2
	0.60	436.5	274.1	174.8	113.1	74.2	49.4	33.2
	0.65	343.3	215.6	137.5	89.0	58.4	38.8	26.1
	0.70	274.9	172.6	110.1	71.2	46.7	31.1	20.9
	0.75	223.5	140.4	89.5	57.9	38.0	25.3	17.0
	0.80	184.2	115.7	73.8	47.7	31.3	20.8	14.0
	0.85	153.5	96.4	61.5	39.8	26.1	17.4	11.7
	0.90	129.3	81.2	51.8	33.5	22.0	14.6	9.8

Table 4 – Simulated years of life for various expected service life conditions and the given test conditions and duration

Expected RH in Application Environment		Expected temperature (°C) in Application Environment						
		20	25	30	35	40	45	50
	0.25	1041.5	654.1	417.1	269.9	177.1	117.8	79.3
	0.30	602.7	378.5	241.4	156.2	102.5	68.2	45.9
	0.35	379.6	238.4	152.0	98.4	64.6	42.9	28.9
	0.40	254.3	159.7	101.8	65.9	43.2	28.8	19.4
	0.45	178.6	112.2	71.5	46.3	30.4	20.2	13.6
	0.50	130.2	81.8	52.1	33.7	22.1	14.7	9.9
	0.55	97.8	61.4	39.2	25.4	16.6	11.1	7.4
	0.60	75.3	47.3	30.2	19.5	12.8	8.5	5.7
	0.65	59.3	37.2	23.7	15.4	10.1	6.7	4.5
	0.70	47.4	29.8	19.0	12.3	8.1	5.4	3.6
	0.75	38.6	24.2	15.4	10.0	6.6	4.4	2.9
	0.80	31.8	20.0	12.7	8.2	5.4	3.6	2.4
	0.85	26.5	16.6	10.6	6.9	4.5	3.0	2.0
	0.90	22.3	14.0	8.9	5.8	3.8	2.5	1.7

The second environment used in the aging sequence was periodic instances of 50 temperature cycles. The profile consisted of temperature swings from -43°C to 85°C, with a ramp rate of approximately 2.7°C per minute, and with 15 minute dwells at each extreme, for a time of approximately 1 hour per cycle.

Utilizing the Coffin-Manson equation, these thermal cycles are equivalent to approximately 0.25 years of aging for each 50 cycle period. This equation is the following:

$$AF = (\Delta T_L / \Delta T_F)^{1.9} * (F_F / F_L)^{1/3} * \exp\{Ea/K\ (1/Tmax_F - 1/Tmax_L)\}$$

Given:

ΔT_L Lab temperature difference between highest and lowest operating temperature
ΔT_F Field temperature difference between on and off state
F_F Cycle frequency in the field (cycles per 24 hours), minimum number of six
F_L Cycle frequency in the lab
$Tmax_F$ Max temperature in Kelvin in the application environment
$Tmax_L$ Max temperature in Kelvin in the lab environment

This thermal cycling does not add a significant amount of simulated life time to the test; its main purpose is to expose the hardware to the thermal cycles that could be experienced over the life cycle in an attempt to cause failures in solder joints that may have been weakened through the aging process.

Results

All units built were built using standard production processes with in-process checks; inspection, x-ray evaluation and functional test. No issues were identified through these processes. Cross-sections were made of one unit for an evaluation of the as-built condition and verification of full solder joint mixing in the BGA solder joints. These cross-sections are shown in Figure 5. The Pb content of the joints was measured through SEM/EDX and found to be 6.4%, 7.4%, and 7.4% by weight for BGAs 1, 2, and 3, respectively. As seen in the images, mixing of the alloys in the solder joint is good, with Pb-rich areas uniformly distributed through the ball. As expected, the Pb-rich areas are not as dense as they would be in a standard Sn63Pb37 solder joint, and they have a stringy appearance.

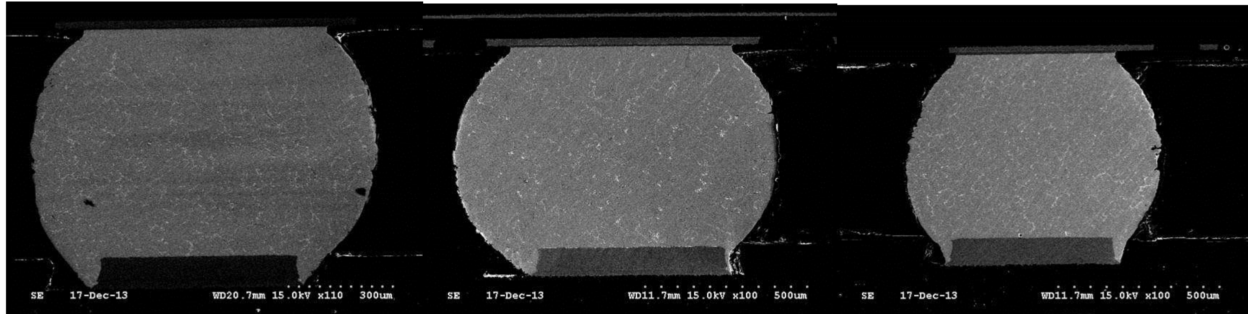

Figure 5 – Micrographs of cross-sections for BGAs 1, 2, and 3 in as-built condition.

The three assemblies subjected to HALT were built into a representation of a higher level assembly and mounted in the HALT chamber as shown in Figure 6. A vibration survey was performed on each unit to determine the vibration response at the BGA sites. At the lowest vibration input, the BGAs experience about 5 Grms, and they saw progressive increases in response as the input was increased, with maximum values of 20, 22, and 27 Grms experienced at the three BGA sites.

The assembly was exposed to the combined thermal and vibration profile as shown in Figure 7. A thermocouple located on top of one of the BGAs (the green line in Figure 7) demonstrated good temperature tracking and was used to ensure that the desired dwell period was reached. At the completion of the fourth thermal cycle, two of the three units were subjected to the addition period of vibration shown, at the maximum level for 60 minutes. The entire test lasted for a little over three hours. Units were tested functionally at the end of each dwell period, and during each transition. Units were also tested approximately every ten minutes during extended vibration. All tests were passed successfully.

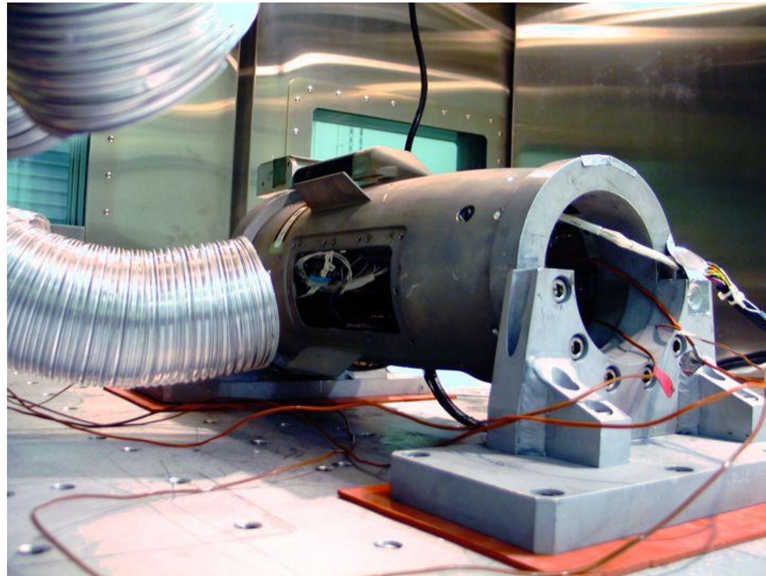

Figure 6 – Unit assembled into test fixture and mounted in the HALT chamber.

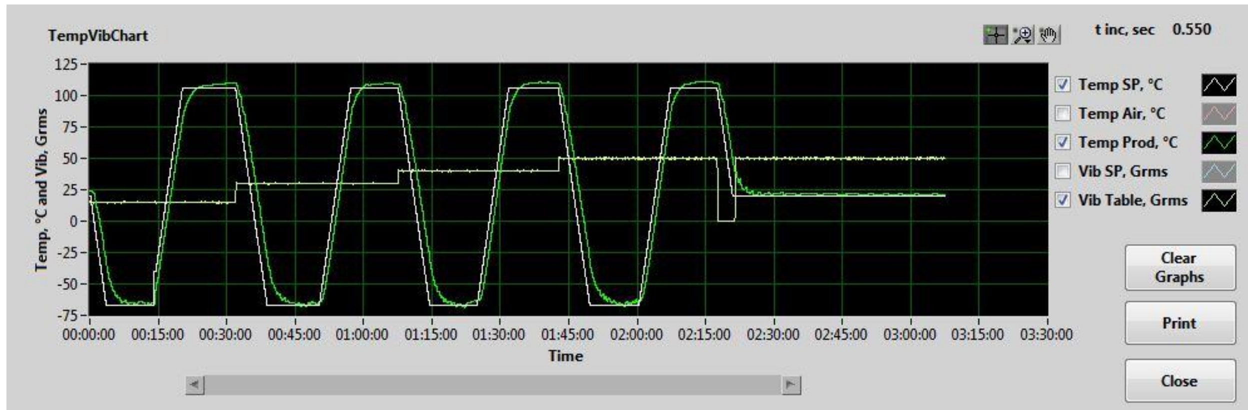

Figure 7 – Combined thermal and vibratory profile for units in HALT, with extended vibe. The yellow line shows vibration input levels at the table, the grey line is the thermal program, and the green line is the thermal reading on one of the BGAs.

One of the test units was cross-sectioned after HALT to examine the condition of the BGA solder joints. Although a standard Sn63Pb37 test unit was not exposed to HALT, there was another circuit card in the HALT setup which included such a BGA. This unit was also exposed to the thermal and vibratory conditions, and was cross-sectioned as a comparison. The cross-sections of these post-HALT units are shown in Figure 8. There is no significant change to the solder joints from the as-built conditions. Although the surfaces of these low-Pb solder joints are rough compared to the Sn63Pb37 joint, this roughness has not increased from the as-built condition. Similarly, the Sn63Pb37 solder joint has not changed significantly from the condition typically seen in an as-built joint; the grain structure is fine and there is no evidence of damage to the joint.

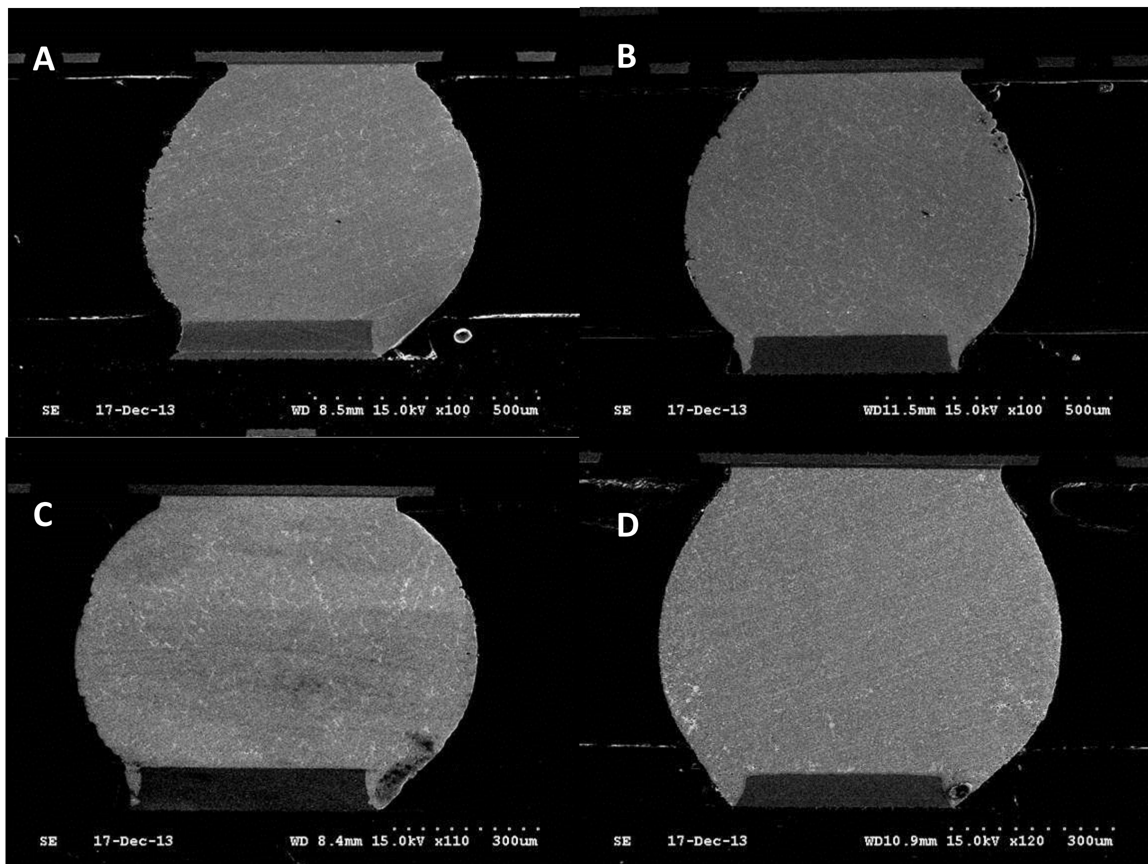

Figure 8 - Micrographs of cross-sections for BGAs 1 (A), 2 (B), 3 (C), and Sn63Pb37 (D) after HALT.

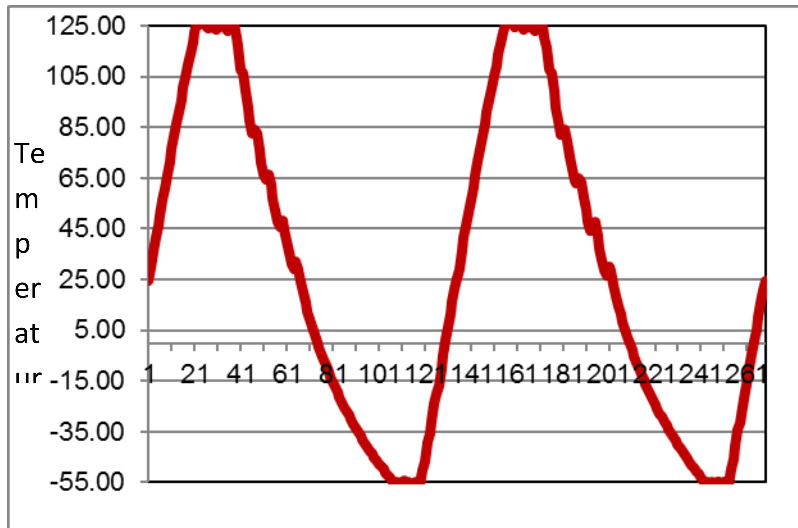

Figure 9 – Thermal cycling profile for accelerated aging test units.

Six test units and four control units (standard SnPb) were subjected to multiple sessions of accelerated aging and thermal cycling. Electrical acceptance testing was performed between these sessions to verify functionality. In all, the test units were exposed to 63 days temperature / humidity (85°C / 85% RH) and 200 thermal cycles (See Figure 9) for simulation of approximately 30 years relative to a 60%RH/30°C application environment. The overall flow for this process is shown in Figure 10.

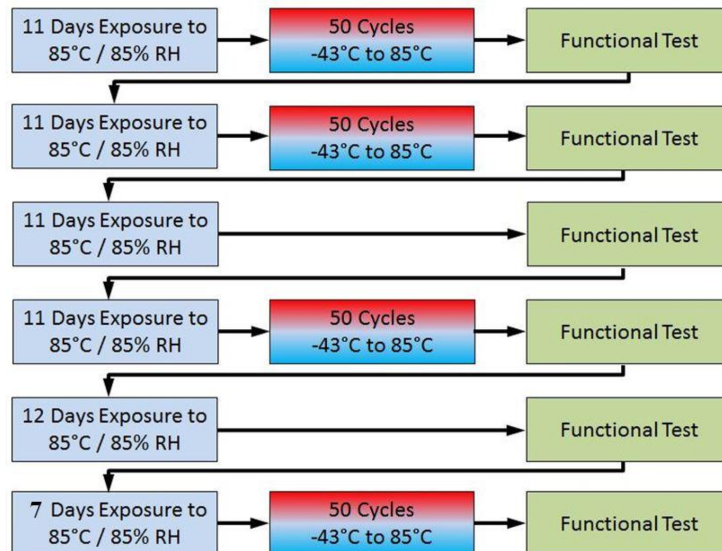

Figure 10 – Accelerated aging process flow

All ten test units successfully passed testing until the final round of aging. In the final test, two of the six mixed-alloy units failed a test, indicating a problem with BGA 1. One of the mixed-alloy units subjected to accelerated aging was cross-sectioned, as well as one of the Sn63Pb37 units, to evaluate the resulting condition of the solder joints (see Figure 11). The cross sectional images of the post-aging units do not show any significant anomalies in the solder joints; there were no fractured solder joints, no crack initiation sites, and generally no apparent deterioration of the solder joints. The mixed-alloy joints still display a uniform distribution of Pb-rich areas of relatively fine grain structure. In the post-aging image for the standard SnPb joint, however, there is a significant amount of grain growth. The grain structure of the joint is not as fine as in the as-built condition. Dye-and-pry was

used to evaluate the failed units, and there was no indication of solder joint failure from this inspection; the printed circuit board pad was partially or fully lifted at all joints as a result of the component removal.

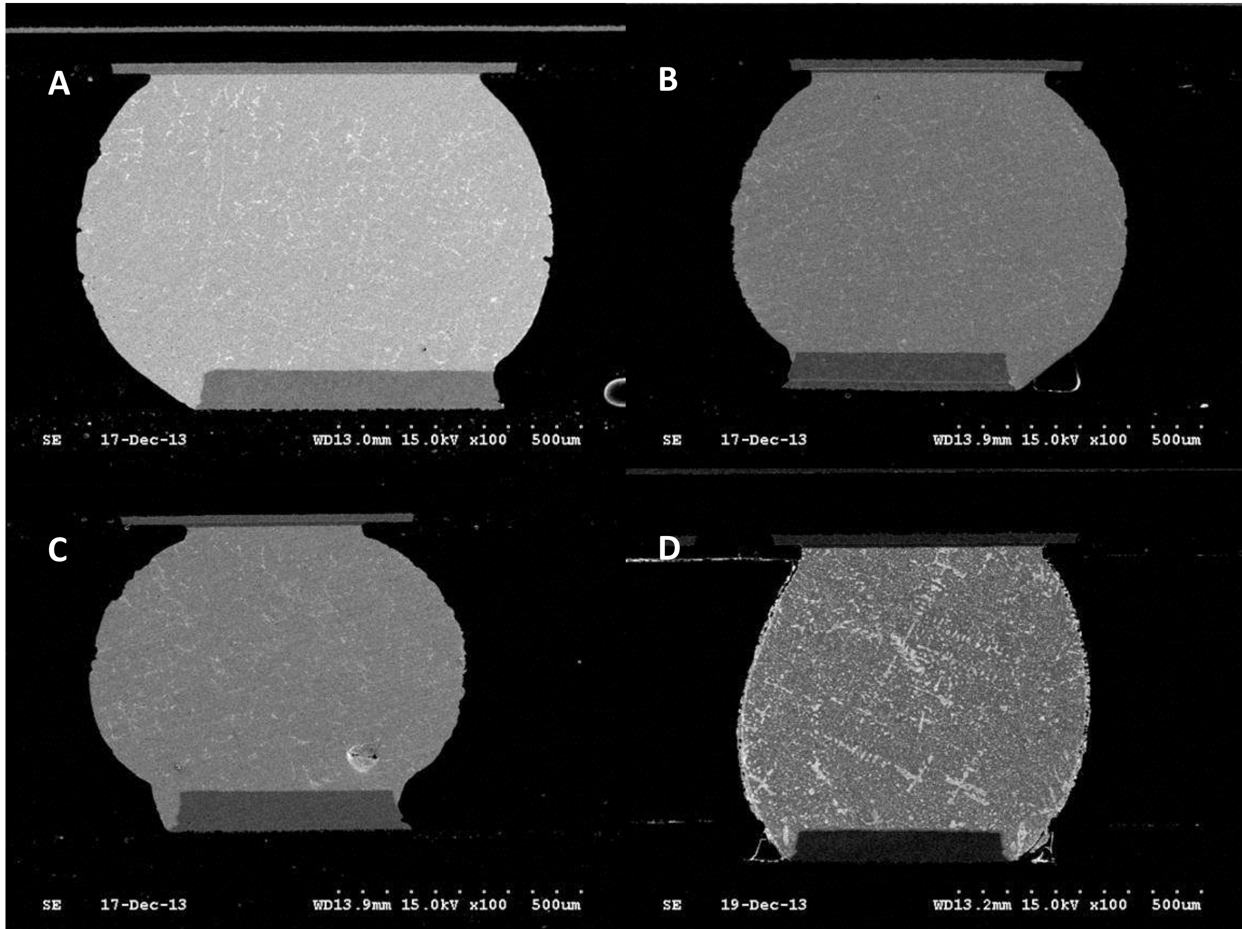

Figure 11 - Micrographs of cross-sections for BGAs 1 (A), 2 (B), 3 (C), and Sn63Pb37 (D) after accelerated aging.

Conclusions

BGAs with SAC305 balls were inserted into an existing military design and installed using a backward compatible process (SnPb solder). The assembly process was modified slightly (solder paste application and reflow profile) according to guidelines developed in previous studies to accommodate these Pb-free components, but kept within a window suitable for typical SnPb assembly. Cross-section evaluations of the base-line units validate that the process used resulted in complete mixing of the solder joints.

These assemblies were subjected to HALT and accelerated aging environments similar to those used in production development evaluations. The units survived nearly all functional testing through these environments, demonstrating survivability of the mixed alloy solder joints under exposure to humidity, temperature, vibration, and thermal cycling. The only failures exhibited came after a significant amount of aging and testing was complete, and were attributed to component failure, not solder joint failure.

This study shows that when the parameters of a backward compatible process are appropriately controlled and applied, the resulting BGA solder joint can have acceptable reliability in a military product for certain expected environmental conditions. We must keep in mind, however, that this relies on certain assumptions about the behavior of a low-Pb solder joint. Testing of Pb-free solder has demonstrated that reliability can be dependent on the parameters of the test and the order of certain testing. More studies should be performed to further investigate the point or range at which the Pb-content of a solder joint results in Pb-free-like behavior or standard SnPb-like behavior.

One observation of unique interest in this study is the lack of change in the morphology of the mixed-alloy solder joints. The Sn63Pb37 solder joints show a marked change in structure, with significant grain growth through both thermal cycling and accelerated aging in temperature and humidity. The mixed-allow joints do not show the same amount of change in shape of the lead-rich areas.

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