Challenges in Reflow Profiling Large and High Density Ball Grid Array (BGA) Packages Using Backward Compatible Assembly Processes

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ABSTRACT

Backward Compatibility of Pb free SnAgCu (SAC) solders with conventional SnPb soldering has been a subject of considerable interest since the introduction of Pb free solders earlier in this decade. Most BGA package suppliers have converted their BGAs ball alloys to Pb free, using SAC solder. Some customers for these BGA packages, whose products have exemptions from the use of Pb free solders, are still employing SnPb solder paste for reflow soldering their products. The two main concerns with Backward Compatibility are the quality and reliability of the solder joints formed when mixing SAC solder balls of the BGA with eutectic SnPb solder paste. Acceptable mixing of the two alloys is critical for solder joint yields during high volume manufacturing, as well as for long-term solder joint reliability in the field.

One key challenge to maximizing both the solder joint yield and reliability has been to achieve adequate collapse of the SAC solder balls and sufficient Pb mixing when the reflow soldering process is performed at temperatures below the Pb free solder liquidus temperature. Backward Compatible reflow profile development has always been a challenge, but recently, this challenge has been further exacerbated by the increase in size and complexity of high density BGAs.

This paper will illustrate the challenges encountered in reflow profiling of a thick (>90mils), printed circuit board test vehicle, which contains four each of two large (>37mm, >1200 balls), high density BGAs. The ball collapse and the percentage of Pb mixing achieved in the solder joints of these BGAs during the various iterations of the reflow profile development will be presented. The impact of package dynamic warpage during the reflow soldering process, on the solder joint shape, collapse and percentage of Pb mixed within a solder joint will also be described As part of the study, recommendations will be made for an optimum reflow window that can be used to achieve acceptable degree of mixing in solder joint formation.

INTRODUCTION

The Pb-in-solder exemption of the European Union RoHS (restriction on certain hazardous substances) directive [1] was implemented to allow time for the development of reliable Pb free processes in advance of full-scale Pb free implementation. The use of this exemption has allowed high reliability electronic equipment producers to comply with the RoHS directive while continuing to use tin-lead (SnPb) manufacturing processes. Those high reliability equipment producers (e.g., telecommunications, avionics, medical, and defense) now face additional manufacturing and reliability challenges due to the restricted availability and significantly higher cost of a growing number of SnPb ball grid array (BGA) components [2]. When a SnPb BGA component is unavailable, it may be necessary to use the Pb free version of that component with an existing SnPb assembly process. Using a Pb free BGA in a SnPb assembly process (SnPb paste/Pb free BGA) is referred to as mixed alloy or backward compatible soldering. Mixed alloy assembly provides an alternative to immediate, complete product conversion to Pb free manufacturing, but its implementation has been limited due to concerns about the assembly quality and long term attachment reliability of the mixed solder joints.

Various aspects of mixed alloy processing have been addressed in a significant number of studies [3-44]. A large fraction of the work has been driven by companies representing the electronic manufacturing services (EMS), universities, and national laboratories [e.g., 4-12, 14-17, and 19-23]. The primary focus of most of those studies has been related to the optimization of process parameters that produce acceptable solder joint quality and the microstructures that develop with SnPb paste and a Pb free component. There has been far less work published with regard to characterizing mixed solder joint reliability using thermal fatigue testing [3]. Some studies have incorporated accelerated temperature cycling (ATC) to assess thermal fatigue but most test programs typically have been limited and are not as rigorous or thorough as those performed on SnPb or Pb free solder assemblies. Consequently, there is a common perception that the literature contains fundamental inconsistencies and gaps that limit the understanding of mixed alloy reliability [4, 15, 16, 18, 32, and 35].

From a metallurgical perspective, there are some basic disagreements regarding the influence of Pb on the reliability, failure mechanisms and characteristics, and quality of Pb mixing required for adequate reliability of mixed assemblies. The most striking inconsistency found in the literature is that, depending on the specific details of the experiments, studies have shown mixed assemblies to have reliability better than, equal to, or worse than either SnPb or SAC (Pb free) assemblies.

Some of the earliest mixed alloy studies were motivated by a need to understand both forward compatibility (Pb free solder assembly with SnPb components) and backward compatibility. Vianco et al. used plug-in-ring shear testing and pull testing of gull wing leads to determine that Pb contamination reduced the strength of Sn-Ag-Cu-Sb and Sn-Ag-Bi solder joints [44]. Their results suggested that the degradation due to Pb was measurable but not sufficient to impair performance. Both Zhu et al. [43] and Choi et al. [42] studied mixed microstructures and suggested that the formation of a low melting point Pb phase at the grain boundaries could reduce fatigue life of Pb free solder in high temperature applications (>125 °C). Neither of those studies was able to corroborate the low melting phase hypothesis with fatigue test data. Chung et al., performed ATC using a temperature cycle of -40/+80 C on area array samples but the test was limited to 1000 cycles (not tested to failure) and did not include in situ monitoring [37]. They predicted that Pb ultimately would reduce the fatigue life on the basis of microstructural evolution and incipient cracking. Oliver et al. showed that Pb reduced the fatigue life of SAC357 using a ring and pin test but determined that the degradation was not caused by a low melting Pb phase [39]. Oliver also reported the very interesting result that at very high Pb contents (up to 20%), the fatigue life was unaffected. Seelig and Suraski studied both the forward and backward mixes in both a leadframe and an area array component using ATC and reported the lowest reliability for the forward compatible case [40]. Their leadframe failed due to gross Pb segregation at solder interfaces and the authors hypothesized (but did not confirm) that a similar mechanism might be operating in the area array. Many of these early studies suggest strongly that Pb reduces the reliability of Pb free solder joints, but collectively, the work suffers from a number of inconsistencies including the absence of any rigorous ATC testing and subsequent failure analysis to assess thermal fatigue reliability. The results from a very recent ATC study of ceramic chip resistors by Coyle et al. indicate that small amount of Pb introduced from the resistor metallization has no measurable effect on the thermal fatigue life of the resistor solder joints [45].

Additional ATC data sets have emerged from other mixed alloy studies but experimental inconsistencies and the absence of critical failure analyses continue to hinder comparisons of test data from different reliability studies. In 2003, Hua et al. published results of backward compatible studies that emphasized drop testing but also included some ATC testing at -40/+125 C to assess thermal fatigue reliability [35]. Hua was the first to suggest that complete melting of the SAC BGA ball followed by full mixing of the SnPb paste was required for adequate board level reliability. Those data were limited by relatively small sample sizes and the fact that the testing was performed in a two-zone chamber, making it difficult to assess dwell time effects.

Prior to 2005, much of the accelerated testing was conducted under high stress conditions and shorter test durations with the goal of obtaining rapid results for purposes of assembly qualification or alloy comparison [31]. In 2005, results from a number of more detailed mixed alloy reliability studies began to appear in the literature. Both Snugovsky et al. [22] and Bath et al. [23] demonstrated that complete mixing and acceptable solder joint quality can be achieved at reflow temperatures below the liquidus temperature of a SAC solder. Both studies used ATC testing at 0/100 C and in situ event detection monitoring to assess fatigue life. Snugovsky reported that the mixed solder fatigue life was component dependent and could be better, equal, or worse than the fatigue life of SnPb. Bath extended testing to include the standard short, 10 minute dwell and a longer, 60 minute dwell. At the short dwell time, the SnPb and SAC outperformed the mixed assemblies but at the longer dwell time the mixed assemblies and SAC were roughly equivalent. Although there are a few gaps or inconsistencies in these two studies, they agree on two important findings: 1) it is possible to achieve acceptable fatigue life with some mixed alloy assemblies, and 2) mixed alloy fatigue life is sensitive to package characteristics and test conditions, including ATC dwell time.

Although it is difficult to make exact comparisons, the results from the most recent studies are qualitatively consistent with those of Bath and Snugovsky. The two studies by Nguyen et al. [9, 10] show that complete mixing can be obtained at lower temperatures in SAC without a significant reliability penalty. The results from a large study by McCormick and Snugovsky also indicate that partial mixing outperforms full mixing [4, 7]. In the most inclusive ATC study to date, Nandagopal et al. confirmed that full mixing can be obtained below the SAC liquidus [26]. That work showed that the distribution of the Pb phase is finer with a higher temperature reflow and that a finer Pb distribution produced slightly better mixed reliability in 0/100 C (10 minute dwell) testing but the effect was not as prominent in -40/125 C testing. Nandagopal also reported all the mixed conditions outperformed SnPb but not Pb free in the 0/100 C testing and outperformed both SnPb and Pb free in the -40/125 C testing. The recently published results from the iNEMI consortium mixed alloy project [6] indicate that full mixing is not a reliability prerequisite and that mixed assembly reliability is package dependent and can be better, equal, or worse than the fatigue life of SnPb and SAC. The results from the work by Snugovsky et al. [5] are qualitatively in agreement with the iNEMI results and further suggest that mixed reliability is sensitive to microstructure which in turn, is sensitive processing conditions and alloy composition.

Based on the body of research literature cited above, at least two major reliability gaps can be identified in the mixed alloy data. Firstly, additional clarity is needed regarding the reliability of partial versus fully mixed joints, relative to both pure SnPb and pure SAC assemblies. The work of Coyle et al. [4] demonstrated acceptable reliability for the cases of partial and full mixing but that study did not address mixing levels below approximately 70%. Secondly, the Coyle study was limited to a relatively small, 21 mm x 21 mm PBGA. There is a growing need to perform mixed assembly testing on larger body packages because practical assembly time and temperature restrictions may limit the amount of mixing to less than 50%. Therefore, there is a need to establish performance limits for the combination of lower levels of mixing in larger-body packages.

Some implicit assumptions in this current study are that reflow parameters should not deviate drastically from typical SnPb conditions and that full mixing will not always be achievable in product manufacturing. Partial mixing may be unavoidable in practice, so it is essential to recognize and characterize any reliability limitations inherent to partial mixing.

This paper presents the results of the initial phase in the development and evaluation of a backward compatible, mixed alloy process for two thermally massive, high densities, large-body Pb free BGA components. Both BGA components have a body size larger than 37mm, with pin counts exceeding 1200. The results include the development and characterization of the surface mount profile, assembly parameters, and the subsequent analysis of the mixed alloy solder joints. Mixing is defined in terms of Pb mixing and ball collapse and is characterized using standard cross-section techniques and optical metallography. Finally, recommendations are made for an optimum reflow window that can be used to achieve acceptable degree of mixing and solder joint formation for these large BGA packages.

EXPERIMENTAL STRATEGY

Complete, 100% Pb mixing can not always be achieved within the parameters of a typical SnPb surface mount processing profile. This has been documented in a recently published study [46] as well as through direct product experience within Alcatel-Lucent and Intel. The current experiments were designed to simulate situations involving incomplete mixing and to generate samples to study the relationship between the Pb mixing level in backward compatible assembly, solder joint quality, and long term fatigue reliability.

Development of acceptable mixing parameters is more complicated with large-body, high thermal mass components. Process development becomes even more challenging when mixed assembly is required for more than a single component on a given printed circuit board assembly. The experimental approach described in the following sections uses a test vehicle to enable development of several sets of surface mount profile parameters corresponding to two specific levels of partial mixing in addition to full mixing. The test vehicle is an 8-up design that uses two different high density BGA components (four each). Nominal SnPb processing parameters are used for all assemblies with the following constraints: 60-120 seconds Time Above Liquidus (TAL) and 215-230C maximum peak temperature (measured at the center of solder joint). The peak temperature is restricted to less than 230C to simulate application conditions that require protection for temperature sensitive components and PCB materials that are qualified only for SnPb assembly. If the temperature is kept below 230C, there also is less chance of deactivating the flux before complete solder wetting. For the partially mixed test cells, the TAL and peak temperature are adjusted to produce the required levels of mixing.

TEST VEHICLE AND SOLDER PASTE DESCRIPTIONS

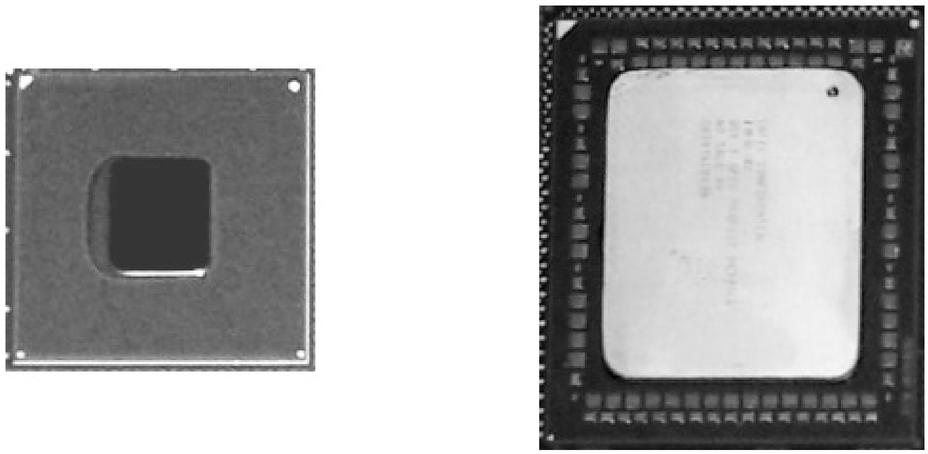
Package Test Vehicle Designs

The package test vehicle attributes and details for TV1 and TV2 are listed below in the Table 1.

Table 1: Package Test Vehicle Information

TV Description	Package TV1 attributes	Package TV2 Attributes
Package Size	37.5 x 37.5 mm	51.0 x 59.5 mm
Die size	13.58 x 10.4 mm	22.4 x 29.5 mm
Substrate thickness	1.162 mm	1.500 mm
Solder ball diameter	0.6 mm	0.508 mm
Ball Pitch	1.1016 mm	1.1016 mm
Solder ball metallurgy	SAC 405	SAC405
Ball count	1295	3162
Ball Pattern	Fully populated grid (corner depop)	Fully populated grid (corner depop / die shadow depop)

The top views of the TV1 and TV2 packages are shown in Figure 1a and 1b, respectively.



a) TV1 Package b) TV2 Package

Figures 1a and 1b: Top View of a) TV1 Package and b) TV2 Package

Board Test Vehicle Design

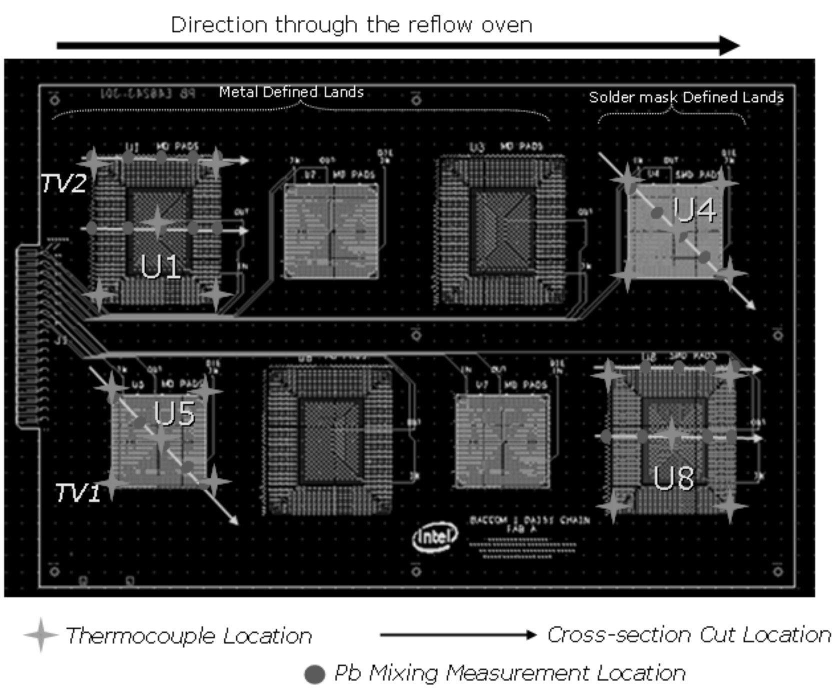


Figure 1c: Diagram of the Board Test Vehicle used for this Study. The Thermocouple locations during reflow profiling, the cross-section cuts and the solder joint locations where Pb mixing levels were measured are shown

The board test vehicle drawing is shown in Figure 1c. Its dimensions are 12 inches x 8 inches x 0.093 inches. There are 4 land patterns for each of the two components, arranged in alternating order. Six of the total eight component land pattern sites have metal defined (MD) or non-soldermask defined (NSMD) Lands. Two component land patterns, one for each package test vehicle type, located on the extreme right in Figure 1c, have soldermask defined (SMD) lands. The MD lands for TV2 are 17 mils in diameter, whereas those for TV1 are 18 mils in diameter. The SMD lands for the both components are 24 mils in diameter but the soldermask openings on these lands are 17 mils for TV2 and 18 mils for TV1.

There is one daisy chain net for each land pattern. However, for the TV1 land pattern, lands in the die shadow region can be tested independent of the others, using a test point brought out from within the daisy chain net. The lands on the corner areas of both components' land patterns are not connected within the daisy chain. The outer two rows of lands of the larger component are also not connected to the daisy chain nets. These corner and die shadow ball locations are typically not electrically functional on product packages.

Daisy chain nets from each of the 8 components' land patterns are brought out to a card edge connector, shown on the extreme left in Figure 1c. There are a total of 16 connections to card edge connector, which were used to monitor the resistances of the daisy chain nets.

The surface finish of the lands on the board test vehicle is OSP. There are 8 layers in this board. The top and bottom layers had 0.5 oz copper, whereas the 6 inner layers had 1 oz copper thickness each.

Solder Paste

A no clean, Halogen-free, Type 4, ROL0 solder paste was used in this study. This solder paste was recommended by its manufacturer for backward compatibility soldering. The metal composition of the paste was nominally SnPb eutectic.

REFLOW PROFILING

Experimental

Test Vehicles Design Review for Assembly and Stencil Printing Process

Before mounting the ball grid array (BGA) packages on the printed circuit board (PCB) for reflow, we performed a review of design for assembly on both BGA test vehicles, TV1 and TV2 and the test board to verify compliance with PCB assembly guidelines. The review exercise revealed TV1 ball size to be 0.024 inches (0.61mm) in diameter with a corresponding test board soldering pad diameter of 0.18 inches', corresponding to 25% pad size reduction. For TV2 package, the ball diameter was found to be 0.020 inches (0.508mm) with a test board soldering pad diameter measuring 0.017 inches' (a 15% pad size reduction).

For solder paste printing, a 0.006 inch thick laser-cut stencil with a circular opening, measuring 0.018 inches was used for both BGA packages. However, based on the known performance of the TV2 package, increased amount of solder paste was required for the three outer peripheral rows and therefore a 0.022 inch stencil opening was used for these rows only. A no-clean near eutectic SnPb Type 4 solder paste was used for mounting the BGA devices onto the board.

Reflow Profile Development

Figure 2 shows a schematic of the profile board with the thermocouples locations, labeled as TC2, TC4, and TC5. Three fine tip (diameter = 0.005 inches) thermocouples were placed at the center of solder joints along the diagonal line of each of the selected profile test vehicle BGA package, U1, U4, U5 and U8 through holes drilled from the bottom side of the test board. A forth thermocouple was placed on top of each profile BGA to monitor the maximum temperature reached during reflow. The direction of travel of the test board through the reflow oven is shown in Figure 1c.

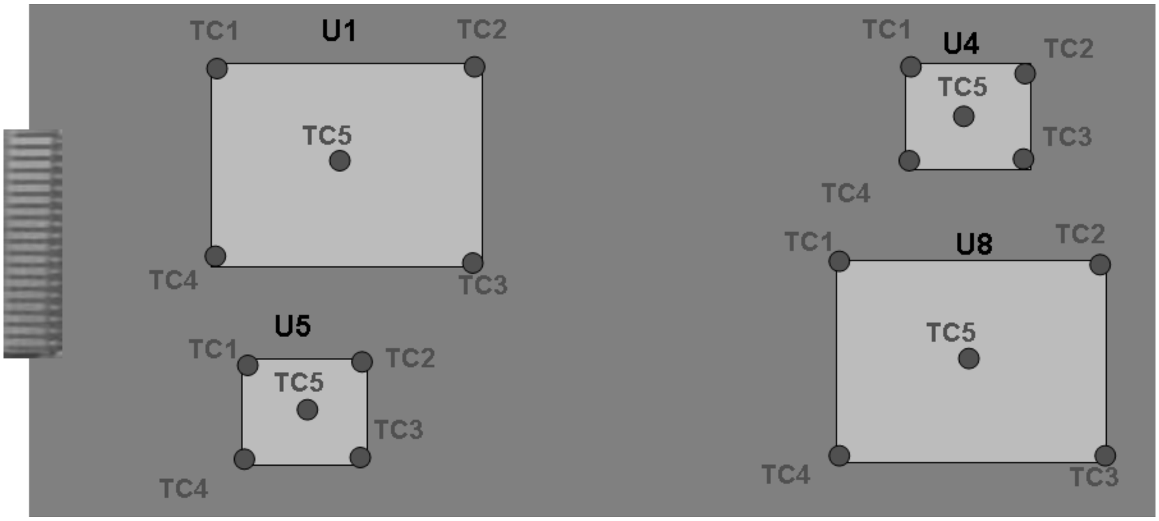


Figure 2: A schematic of the profile board showing the thermocouple locations. Four BGA locations were profiled including U1, U4, U5 and U8. The U4 and U8 are on the leading edge and U1 and U5 are on the trailing edge of the profile board direction of travel through the reflow oven.

Four different reflow profiles were used to obtain different levels of Pb mixing in the Pb free Sn-Ag-Cu solder joints. Table 2 shows the different DOE Leg numbers, which were designed with different peak temperature and time above liquidus targets. The first two DOE Legs (1&2) were designed with reflow profile target parameters selected in order to provide partial Pb mixing. DOE Leg 3 reflow parameters were set to provide full Pb mixing. DOE Leg 4 was included as a pure Pb free control. The target peak temperature and time above the SnPb eutectic liquidus temperature (TAL) values corresponding to each DOE Leg are also included in the table. The target values for DOE Leg 1 were set at the lowest limit in the DOE in order to provide the lowest level of mixing between the two solder alloys while DOE Leg 3 targets values were chosen to maximize the level of Pb mixing.

Table 2: Reflow Profile Matrix

DOE Leg #	DOE Leg Definition	Target Reflow Process Window (Peak Temp; TAL)	Reflow Oven Obtained Peak Temp & TAL Process Window	Peak Temp & TAL Ranges Obtained for each BGA Type	
				TV1	TV2
1	Low Partial Mixing	210-215oC; 60-70secs	211-216oC; 53-65secs	212-216oC; 62-64secs	211-214oC; 53-65secs
2	Medium Partial Mixing	215-220oC; 60-70secs	212-220oC; 61-76secs	214-220oC; 69-73secs	212-217oC; 61-66secs
3	Full Mixing	220-225oC; 90-100secs	220-228oC; 86-101secs	223-228oC; 93-101secs	220-223oC; 86-93secs
4	Pb-free Control	230-250oC; 60-120secs	244-248oC; 82-90secs	247-248oC; 87-90secs	244-245oC; 82-83secs

Table 2 also provides the experimental values obtained from the reflow oven for each DOE Leg. Further, the peak temperature and TAL ranges for each test vehicle, TV1 and TV2 are provided.

At the completion of reflow profile development exercise, we examined the reflow profile values obtained for each BGA test vehicle in order to understand the challenges posed in obtaining the target mixing levels established in the test DOE. To do this, we reviewed the maximum temperature values obtained at the reflow profile peak temperature across the diagonal of each test vehicle. Figure 3 shows a plot of ΔT, the change in temperature across each test vehicle at the maximum reflow process temperature corresponding to each DOE profile Leg designated in Table 2. From Figure 3, we observe that for the first three DOE profile Legs, the ΔT values for TV1 are higher than those found for TV2. But the same ΔT across the two BGA test vehicles was recorded at the forth DOE Leg. This observed trend, where TV1 has a slightly higher peak temperature values than TV2 for the same profiles highlights the thermal challenges of assembling two significantly different packages on the same test board.

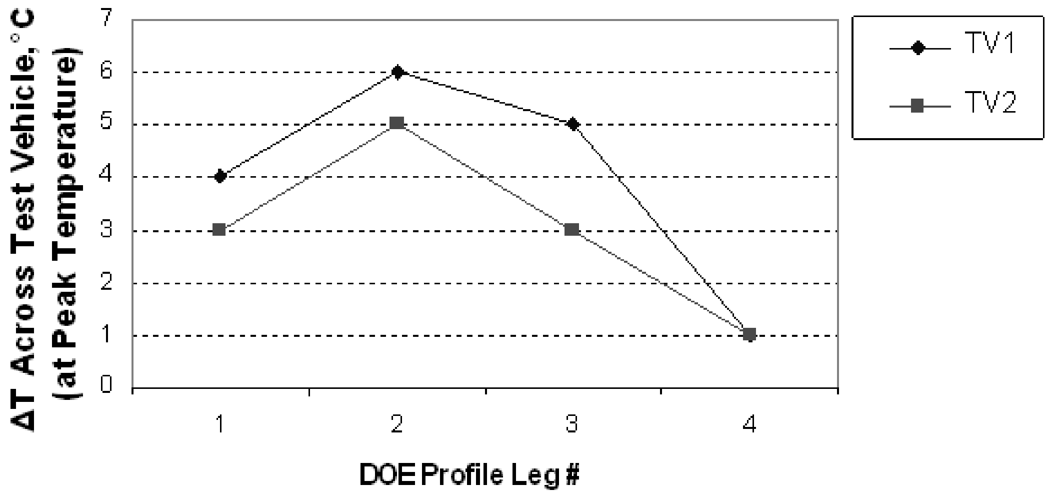


Figure 3: A comparison of the ΔT(C) across each BGA test vehicle at the peak reflow temperature corresponding to each DOE profile Leg. TV1was observed to have higher ΔT(C) values than TV2 for all the profiles but the forth where the two BGA show the same ΔT at peak reflow temperature.

Assembly and Electrical Inspection

Twelve boards were mounted on test boards, three for each DOE Leg shown in Table 2 and reflowed in a twelve-zone reflow oven with a controlled cooling capability in the last two zones. After reflow, each assembled BGA was electrically tested to determine the daisy chain continuity. This test served as a first check for solder joint connection between the PCB and BGA pads. The electrical results from the continuity test are provided in Table 3. In the table, U2, U4, U5, U7 refer to TV1 components while U1, U3, U6, U8 refer to TV2 components

Table 3: Electrical Continuity Test Result. The symbol Y used in the table indicates a pass after test.

	COMPONENT LOCATION ON BOARD							
Board Number	U1	U2	U3	U4	U5	U6	U7	U8
LEG1 BOARD1	Y	Y	Y	Y	Y	Y	Y	OPEN
LEG1 BOARD2	Y	Y	OPEN	Y	Y	Y	Y	OPEN
LEG1 BOARD3	Y	Y	OPEN	Y	Y	OPEN	Y	OPEN
LEG2 BOARD1	Y	Y	Y	Y	Y	Y	Y	OPEN
LEG2 BOARD2	Y	Y	Y	Y	Y	Y	Y	OPEN
LEG2 BOARD3	Y	Y	Y	Y	Y	Y	Y	OPEN
LEG3 BOARD1	Y	Y	Y	Y	Y	Y	Y	Y
LEG3 BOARD2	Y	Y	Y	Y	Y	Y	Y	Y
LEG3 BOARD3	Y	Y	Y	Y	Y	Y	Y	Y
LEG4 BOARD1	Y	Y	Y	Y	Y	Y	Y	Y
LEG4 BOARD2	Y	Y	Y	Y	Y	Y	Y	Y
LEG4 BOARD3	Y	Y	Y	Y	Y	Y	Y	OPEN

Noteworthy from Table 3 is that only test vehicle TV2 exhibited open solder joints including those located at U3, U6 and U8. The U8 location had the most open solder joints. It is also noted that six of the seven U8 open locations were all assembled using either DOE Leg 1 or DOE Leg 2, the two DOE Legs with the lowest profile targets values.

SOLDER JOINT MICROSTRUCTURE

Pb Mixing in the Mixed Alloy BGA Solder Joints

Figure 3 shows an optical micrograph of a cross-section of a typical mixed BGA solder joint. The Pb mixed region is shown towards the printed circuit board side of the solder joint. The Sn-Pb solder paste printed on the board land has melted in the reflow zone of the soldering oven and resulted in Pb diffusion upwards within the lead-free SAC solder ball. The solder joint shown in Figure 3 is considered to have partial or incomplete mixing of Pb. For a fully mixed solder joint, the Pb mixed region would encompass the entire solder joint, right up to the package land.

The Pb mixing of mixed alloy solder joints can be quantified by measuring the height to which the Pb has diffused up into the SAC solder joint and calculating this height as percentage of the solder joint height. Equation 1 gives the formula for % Pb mixing in the mixed alloy solder joint

$$\%\ \text{Pb Mixing} = 100*(H_1-H_2)/H_1 \quad \ldots\ldots\ldots\ldots\ldots(1)$$

Figure 4 defines H_1 and H_2. H_1 is the distance from the top of the package land to the top of the board land and is essentially the solder joint height. H_2 height is calculated by measuring the distance from the top of the package land to the average height location of the Pb-mixed region.

To determine the Pb mixing in the solder joints of the assembled board test vehicle, solder joints of the two package test vehicles assembled at various locations on the board test vehicle were cross-sectioned. Figure 1, shown earlier in this section, shows the locations of the cross-section cuts on four package test vehicle locations whose solder joints were inspected. For TV1, U4 and U5 locations were cross-sectioned through one of the diagonal rows. For TV2, U1 and U8 locations were cross-sectioned through an outer row and the middle inner row.

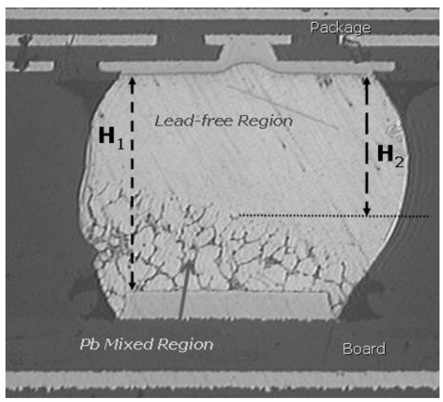


Figure 3: Metallographic cross-section of a typical mixed alloy SnPb-SnAgCu solder joint illustrating how Pb mixing levels were calculated.

Figure 4 is a plot of Time in seconds above the SnPb eutectic Liquidus temperature (183C) and the Peak Reflow Temperature in degrees Celsius of the solder joints during the reflow soldering process. The target windows for the four legs in this experiment are identified as shaded rectangles in this plot. Also identified as unshaded rectangles are the actual measured windows for each of the two legs, with rectangles corresponding to TV1 solder joints having dashed border lines and with rectangles corresponding to TV2 having solid border lines. It is apparent from Figure 4, that the actual measured windows are not exactly centered on the target windows, but there is some overlap in each case between the measured and the target windows.

The target range of %Pb mixing for each of the three backward compatibility legs is also indicated in this plot. These target ranges were determined by previous studies on single SAC405 balls with Sn-Pb solder paste, using Differential Scanning Calorimetry (DSC) to simulate a reflow profile. The solder paste used for these DSC experiment was however, different from the solder paste used for reflow soldering the test vehicle boards.

Figure 5 below displays the variability plot for %Pb Mixing on the BGA Test Vehicle solder joints that were measured after cross-sectioning. The data is partitioned by Reflow Profile Leg number and by Package Test Vehicle. For Leg 1, the Low Peak Temperature/Short TAL leg, a *large majority* of the measured %Pb mixing data is *above* the target %Pb mixing range (<30%). For Leg 2, the Medium Peak Temperature/Short TAL leg, *all* measured %Pb mixing data is *above* the target %Pb mixing range (50 to 80%). In contrast, for Leg 3, the High Peak Temperature/Long TAL leg, *almost all* the measured %Pb mixing data is *within* the target % Pb mixing range (100%, full mixing). These results for Leg 3 confirm the mixing effectiveness when the Peak Temperature is consistently above the Pb free liquidus temperature.

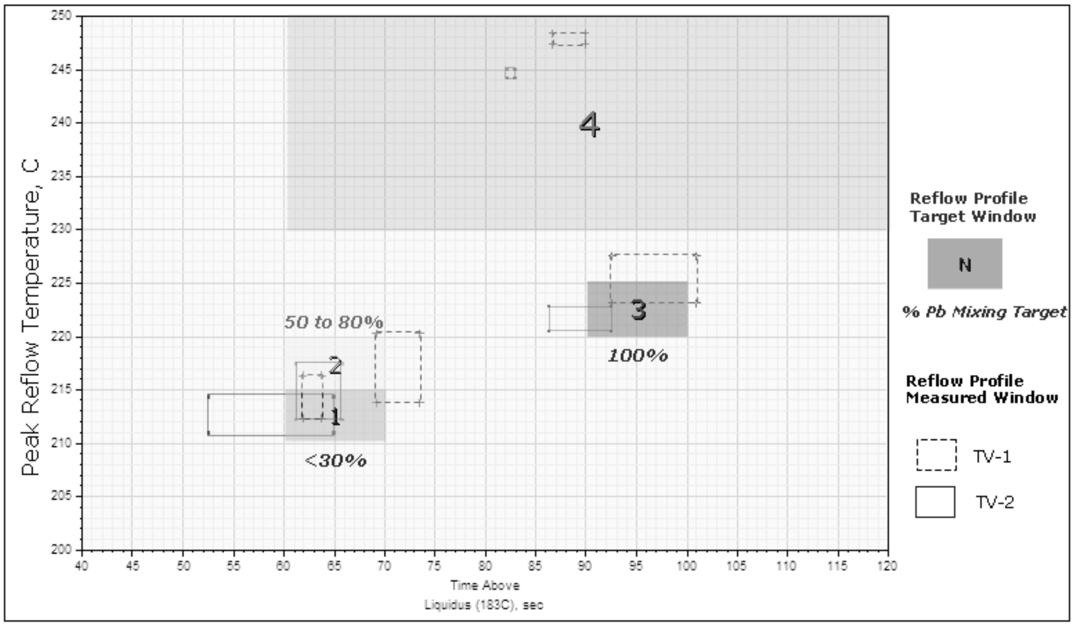


Figure 4: Plot of Time above Liquidus (183C) in seconds vs Peak Reflow Temperature in Degrees C for the Reflow Profiles of the 4 experimental legs used to assemble the board test vehicle in this study.

Further analysis of the %Pb mixing data with location of the solder joints within the package ball array indicates that solder joints within the inner rows of the array have less %Pb mixing that the outer rows. This is consistent with the known observations that the outer BGA rows generally heat faster and reach higher temperatures than inner rows.

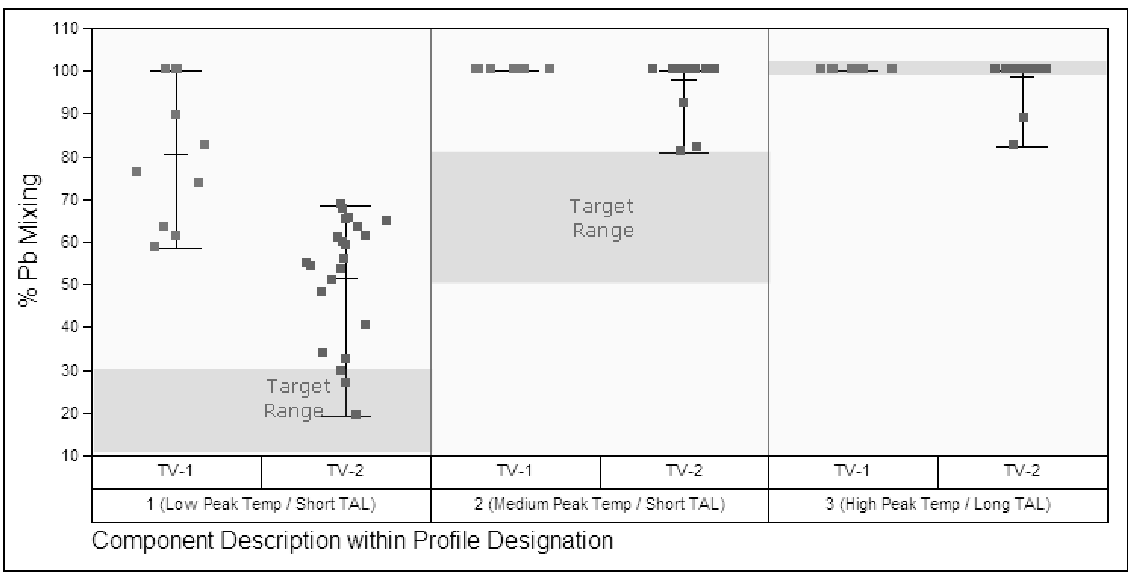


Figure 5: Variability Chart of the %Pb Mixing for each of the two BGA Test Vehicles across all three Backward Compatibility Profiles studied

Figure 6 below depicts the location within the ball array of the BGA Solder Joints which were measured for %Pb Mixing for both Package Test Vehicles. For TV1, five locations, spaced equidistance from each other, along the diagonal cross-section cut were measured. For TV2, six locations along the outer row and five locations along the inner row cross-section cut were measured. One extra location was measured along the outer row at the center part of the package since significant variation in %Pb Mixing was noted for TV2 in the %Pb in this region of the ball array for Leg 1.

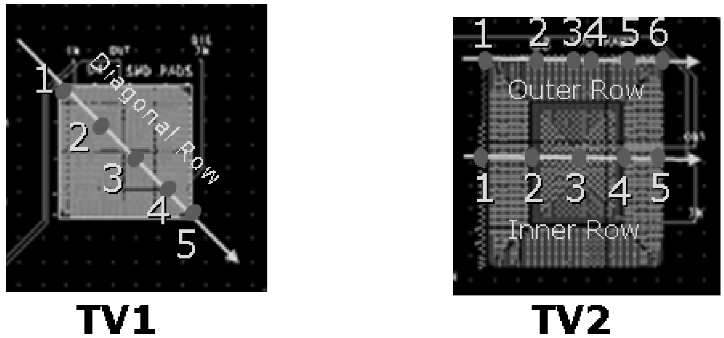


Figure 6: Diagram indicating the location of the BGA Solder Joints which were measured for % Pb Mixing for both Package Test Vehicles

Figure 7 plots the variability chart for %Pb with ball location within the cross-section cut array as shown in Figure 7. This plot is for Leg 1, Low Peak Temperature/Short TAL, and is shown for both package test vehicles at two different locations for each on the board. Leg 1 was the only leg that had significant variation in the %Pb mixing from the outer to the inner rows for both package test vehicles. The other reflow profile legs had very few solder joints with less than 100% Pb mixing.

From Figure 7, two aspects of %Pb variation within the solder joints with respect to their spatial location within the package ball array are obvious. One, the %Pb mixing is higher for the TV1 solder joints when compared to TV2 solder joints. This is to be expected since TV1 is smaller than TV2 and though the reflow profile window of TV1 solder joints overlaps some of the reflow profile window for TV2 solder joints, the former has higher Peak Reflow Temperature ranges and longer TAL ranges than the latter. Two, the solder joints in the central region of the package ball arrays have much lower %Pb mixing than on the outer region. This is true for both package test vehicles and is caused by the lower peak temperatures and TALs prevalent for the solder joints in the central region of these high density BGA packages.

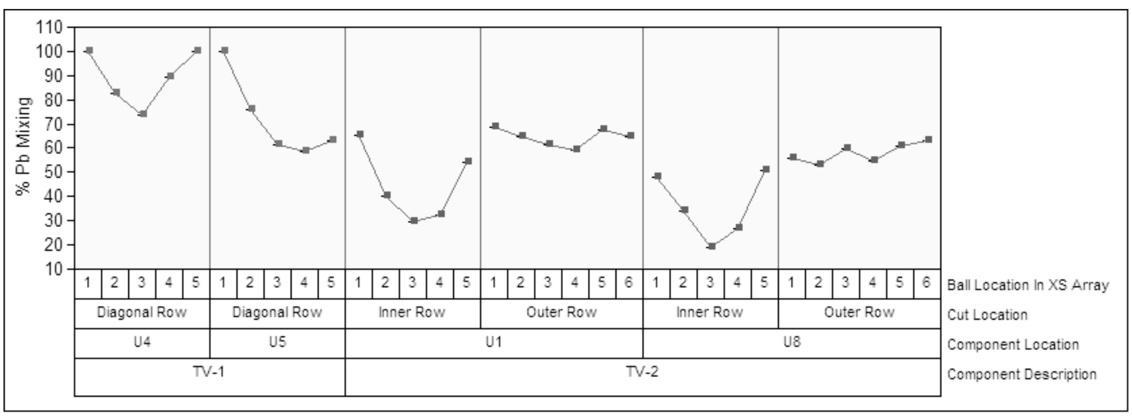


Figure 7: Variability chart of %Pb mixing with Ball Location with the Cross-section Cut Array for both package test vehicles at two locations on the board. This chart is for boards assembled using the Leg 1 (High Peak Temperature /Short TAL) reflow profile.

Figure 8 below contains a series of cross-section photographs, arranged in a matrix format, of the solder joints of the package TV1 at the U5 location on assembled boards. The rows of this matrix depict each Reflow Profile Leg, going from 1 (Low Peak Temperature/Short TAL) at the top to 4 (Pb free SAC) at the bottom. The columns depict the spatial location of the solder joints within the diagonal cross-section cut, with the two outer columns being for the edge solder joints and the center column being for the center solder joint along the diagonal cut.

Complete Pb mixing is noted for all solder joints for Leg 2 and Leg 3. For Leg 1, only the outer solder joint on the left has 100% Pb mixing. The other four solder joints have partial Pb mixing with the amount of Pb Mixing being about 60% for the center solder joint, as also seen by the data in Figure 7. The Leg 1 profile is the one with the lowest peak temperature and shortest TAL and hence there is insufficient temperature and/or time with the Sn-Pb paste in the molten state for the Pb to diffuse up the ball, towards the lower Pb concentration region within the SAC solder joint. Reflow Profiles corresponding to Leg 2 and leg 3, as depicted in Figure 4, reach a sufficiently high peak temperature for an adequate time to result in complete mixing of the Pb in the SAC solder ball.

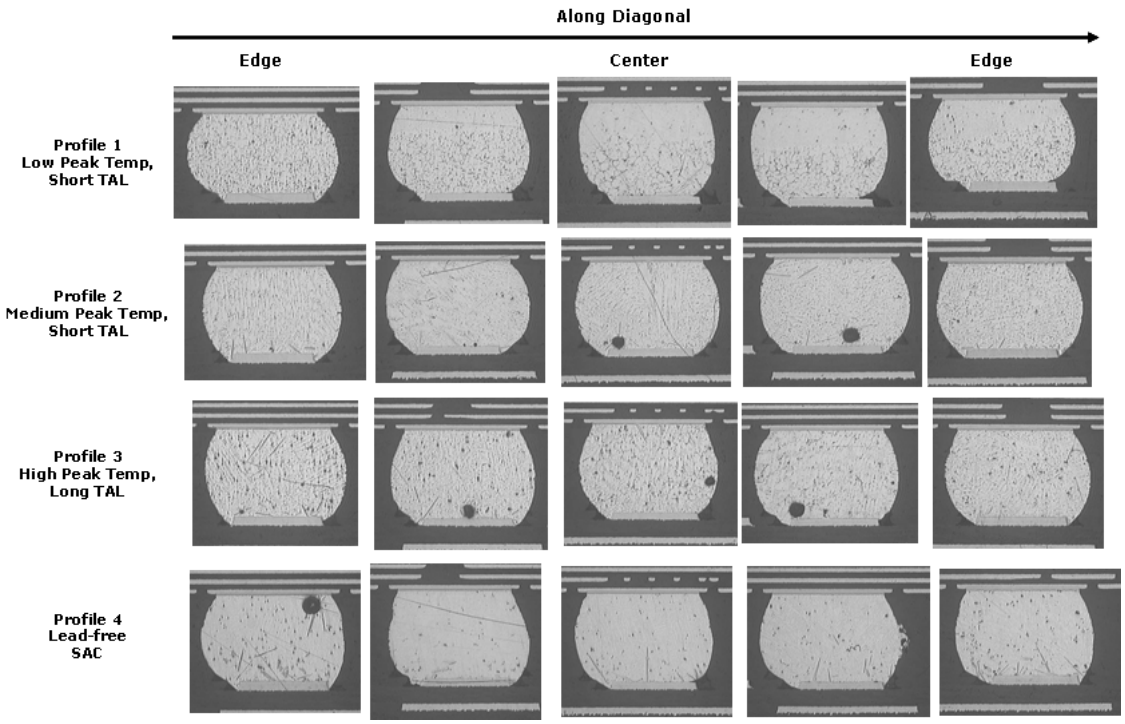


Figure 8: Optical Micrograph photographs of cross-sections, arranged in a matrix format, of the solder joints of the BGA package TV-1 at the U5 location on assembled boards.

Figure 9 below contains a series of cross-section photographs, arranged in a matrix format, of the solder joints of the package TV2 at the U8 location on assembled boards. The rows of this matrix depict each Reflow Profile Leg, going from 1 (Low Peak Temperature/Short TAL) at the top to 4 (Pb free SAC) at the bottom. The columns depict the spatial location of the solder joints within the two cross-section cuts, one through an inner row and one through an outer row of the package ball array. The two outer columns for each cross-section cut are the edge solder joints along that cut row and the center column for each cross-section cut is center solder joint along that cut row.

All solder joints for Profile 3 have 100% Pb mixing within them. All but the center solder joint of the inner row have 100% Pb mixing for Profile 2. This solder joint has the lowest peak temperature within all the solder joints whose cross-section photos are shown above and hence it has less than 100% Pb mixing. Similarly, Profile 1, the coolest profile, has less than 70% Pb mixing for every solder joint whose cross-section photos are shown.

One aspect of the inner row solder joints for TV2 apparent in Figure 9 is that the edge solder joints are stretched whereas the center solder joints are compressed. These anomalous shapes of the solder joints is caused by the severe dynamic warpage of the TV2 component, particularly above the melting point of the Sn-Pb solder paste. The backward compatibility nature of the solder joints is *not* responsible for this stretching, since even the lead-free SAC solder joints (Profile 4) exhibit similar solder joint shapes. Remarkably, the stretching of the edge joints is so severe that in one case it caused a `hanging ball` open defect as seen in the top right photograph.

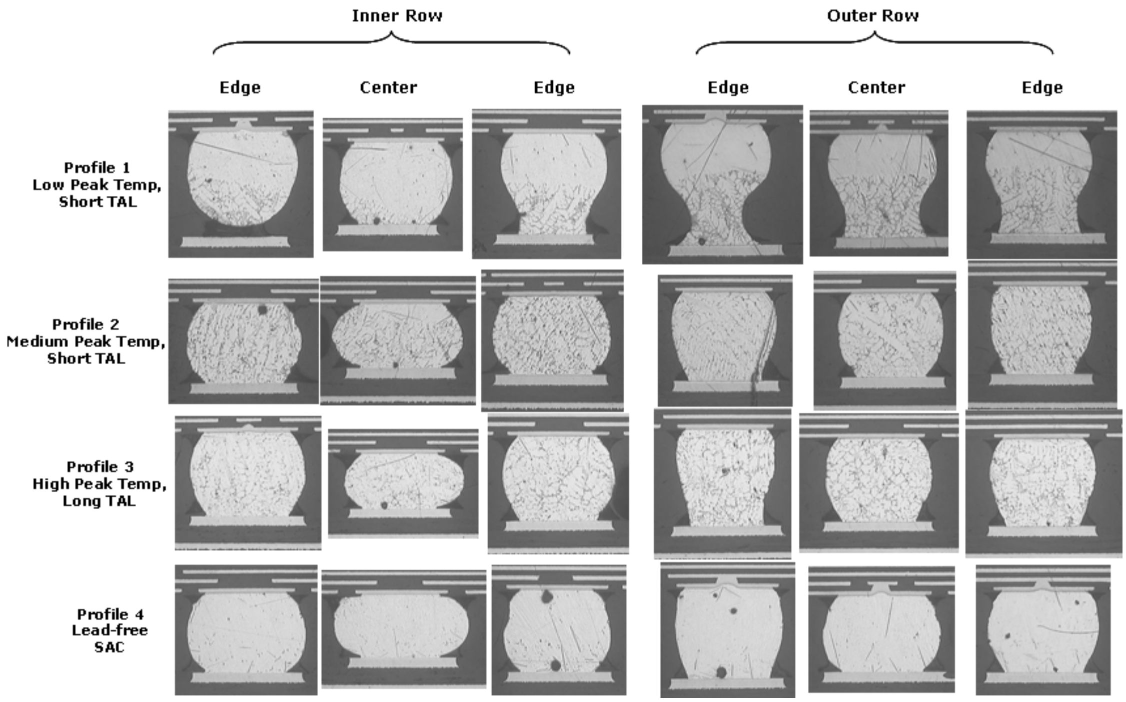


Figure 9: Optical Micrograph photographs of cross-sections, arranged in a matrix format, of the solder joints of the BGA package TV-2 at the U8 location on assembled boards.

Ball Collapse of the Package Solder Joints

In general, BGA Ball Collapse during the reflow soldering process is essential to attain high solder joint yields and adequate solder joint reliability. Ball Collapse during the lead-free backward compatibility solder process is even more important, since in a large part of the backward compatibility reflow window the SAC solder balls do not melt and a pseudo ball collapse is achieved by the molten Sn-Pb solder paste diffusing into the SAC solder ball and lowering its melting point.

The extent of ball collapse for the package test vehicle solder joints in this study was determined by measuring the solder joint height. This solder joint height is defined by the length H_1, as shown in Figure 4. This is essentially the distance between the top of the board land and the top of the package land.

Figure 10 depicts the Variability Chart of the solder joint heights for a) Package TV1 and b) Package TV2, with reflow profile, location on the board, and ball location across the cross-section cut row. A good measure of the extent of ball collapse for the backward compatibility solder joints can be obtained by comparing their solder joint heights to that of the solder joints obtained when using a lead-free reflow profile (Profile 4). The lightly shaded bands in both variability charts define the range of the solder joint height for lead-free solder joints formed using profile 4. As seen in the figure, the solder joint heights of all backward compatibility reflow profiles for Package TV1 and all except Profile 1 solder joints for Package TV2, fall in the same range as that for the lead-free profile. Hence, except for one leg for TV2, all solder joints appear to have achieved close to full collapse during the backward compatibility reflow profiles.

The variation of the solder joint heights across the diagonal of the package can give a fair indication of the warpage profile of the package substrate. From Figure 10, it can be noted that TV1 substrate has a slight "`frown" warpage profile with the solder joints in the center being taller than those at the edges. This warpage profile is more accentuated for the coolest reflow profile, Profile 1, and shows signs of changing to a "smile" warpage profile, for the package at location U4, which is the first to enter the reflow oven, as the peak reflow temperature increases to the lead-free SAC window.

It is evident from Figure 10 that the warpage profile of the TV2 package substrate is a "smile" profile with the edge solder joints taller than the central solder joints for both inner and outer rows. The magnitude of this "smile" warpage profile is larger for the inner rows than the outer rows. The U8 package location "smile" warpage profile is slightly larger than that for the U1 package location. This indicates that the packages on the leading edge of the board through the reflow oven reach slightly higher temperatures than those at the trailing edge of the board. Moreover, the U8 location has soldermask design lands with a large copper plane which causes a different solder reflow profile than the other package locations for TV2.

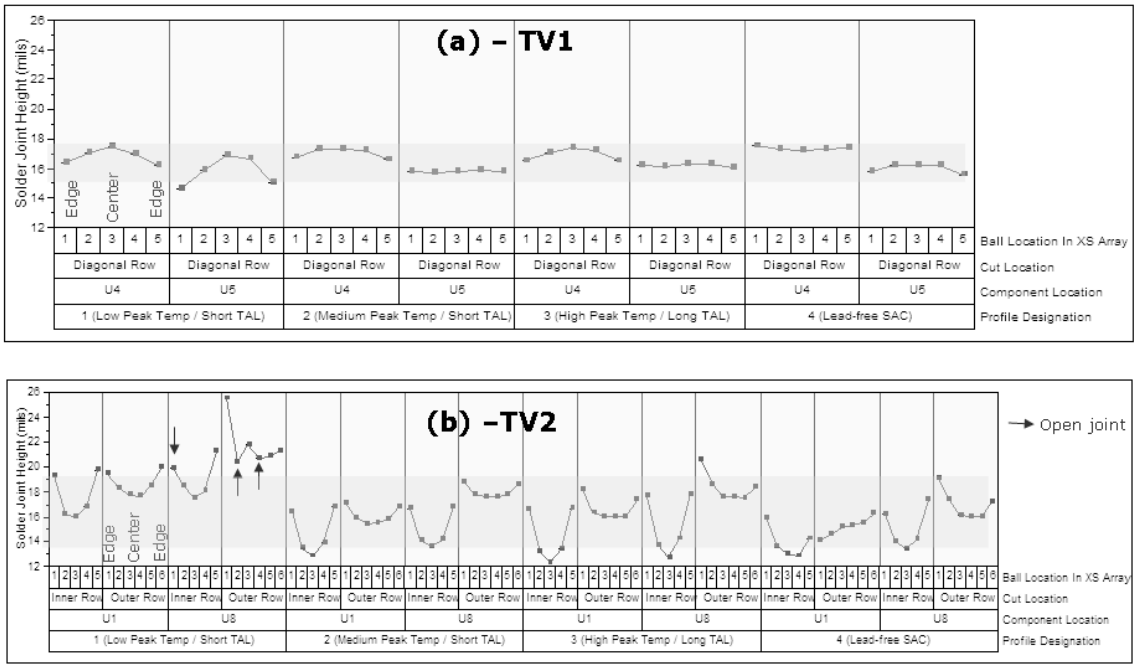


Figure 10: Variability Chart Of The Solder Joint Heights For a) Package TV1 and b) Package TV2 With Reflow Profile, Location On The Board, And Ball Location Across The Cross-Section Cut

Discussion

Logterman and Gopalakrishnan [46] published a plot of Time above Liquidus (183C) in seconds vs Reflow Temperature in Degrees C and identified the full mixing (100% Pb) line for three ball diameters. This plot is reproduced in Figure 11.

Package TV1 has 0.6mm diameter solder balls, so its interesting to compare where the reflow window that produced 100% Pb mixing within the solder balls of Package TV1 resides in this chart with respect to the Full mixing line for 0.6mm ball (maroon line in Figure 11.As seen in Figure 11, this reflow window falls *below* the 0.6mm ball Full mixing line. Assuming all the temperature measurements during the reflow profiling tasks are accurate, two possible reasons for this discrepancy could be a) the SnPb solder paste used in this study has faster wetting with the SAC solder balls of the BGA Package TV1 than that used by Logterman and Gopalakrishnan or b) the solder ball oxidation and surface morphology for Package TV1 promotes faster wetting than the solder balls of the package test vehicles used by Logterman and Gopalakrishnan. These two factors need to be studied further.

The overall SMT yield and solder joint quality is a function of multiple parameters including**,** reflow profile parameters, paste characteristics, PCB board and package warpage characteristics. The PCB board and warpage characteristics impact on overall SMT yield has been discussed in several papers [47-49]. The focus of this paper is to achieve desired Pb mixing level, understanding the factors affecting SMT yield is important.

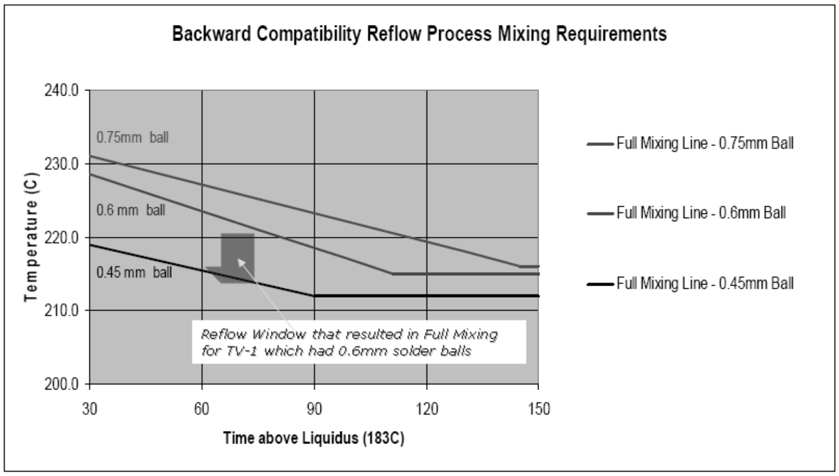


Figure 11: A Plot of Time above Liquidus (183C) in seconds vs Reflow Temperature in Degrees C with the full mixing (100% Pb) line for three ball diameters. From Logterman and Gopalakrishnan [46].

In the present case, the solder joint height of TV2 showed a larger variation than TV1. This can be attributed to lower temperature at the U8 location, which was a SMD land design with a large copper plane. Further, the TV2 has a larger body size which can cause higher warpage during reflow process.

The room temperature component and PCB coplanarity and flatness requirements have documented in industry specifications [50] to ensure component surface mount yield and quality. To better understand the relative warpage behavior between PCB and component at reflow temperature, high temperature warpage characteristics were studied and the typical technique used are shadow Moiré and 3-D imaging approach.. The dynamic warpage measurement technique is descried in JEDEC standard. Luke Garner and et. al., [49] have shown that understanding the high temperature warpage characteristics can be an alternative technique for a better indicator of SMT quality. They have also concluded that room co-planarity should be used as a factory monitor, however, understanding the high temperature warpage behavior along with coplanarity specification can be beneficial for solder joint quality.

Conclusions

The profile development for mixed alloy assembly (SAC BGA/SnPb paste) of the two large body, thermally massive BGA packages proved to be very challenging. The following conclusions and observations are drawn from the results of the profile development and mixed alloy solder joint characterization.

- Achieving high solder joint yields with complete 100% Pb mixing in large high density BGAs is a challenge due to temperature variations across the package.
- Complete mixing is best achieved and assured when the solder joint temperature exceeds the liquidus of the Pb free SAC solder.
- Packages characterized by a significant amount of dynamic warpage present additional challenges for Pb mixing and ball collapse. Mixing performance can not be anticipated based solely on room temperature coplanarity data.
- It can be difficult to obtain complete 100% Pb mixing on multiple components on the same printed circuit board assembly. This was demonstrated using the test vehicle from this study (Figure 1), which is less complex in many respects than actual product boards. There may be cases where process constraints limit mixing to less than 100%.
- Mixed alloy assembly has a very narrow processing window. The recommended mixed alloy reflow profile uses a peak temperature above Pb free liquidus (~220 C) but less than 230 C. A target peak temperature of 225 C is suggested, The recommended SnPb TAL is 60-120 seconds and it is suggested that the profile have ~30 seconds above SAC TAL.

Next Steps

The test boards will be assembled using the various reflow profiles described in the paper and the thermal fatigue reliability of TV1 and TV2 will be determined as a function of %Pb mixing using accelerated temperature cycling.

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Challenges in Reflow Profiling Large & High Density Ball Grid Array (BGA) Packages Using Backward Compatible Assembly Processes

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April 8th 2010

OUTLINE

- Background Information
- Goals of the Present Study
- Test Vehicles Design Attributes
    - Printed Circuit Board Design
    - BGA Packages Design Details
- Design Of Experiment Details
    - Peak Temperature
    - Time above Liquidus
- Results & Summary
    - Profile Development Result
    - Solder Joint Quality

Background Information

❖ Impact of RoHS Directive on End-of-Life (EoL)

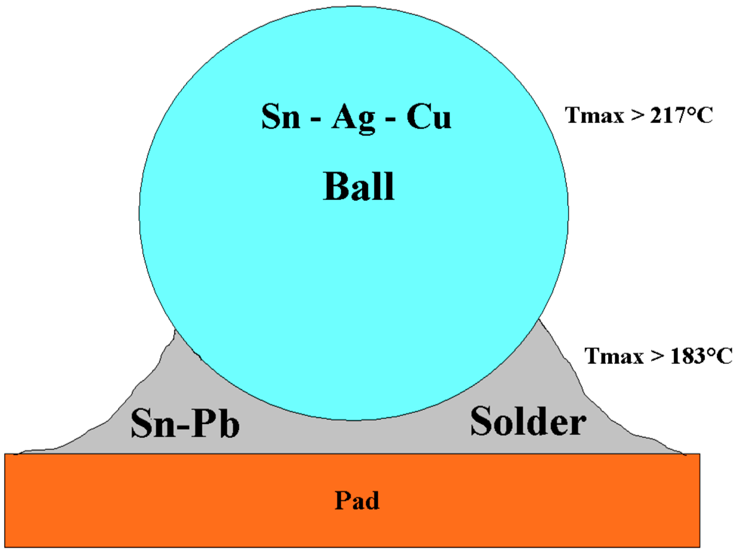
- One impact of the European Union (EU) directive on Reduction of Hazardous Substances (RoHS) is that it has created supply chain constraints or End-Of-Life issues for SnPb component availability.

  - This is especially true for the RoHS exempted sector of the industry which includes ***telecommunications, avionics, medical, and defense***.

- Due to restricted availability of certain SnPb BGA components, high reliability equipment suppliers may need to use ***mixed alloy (backward compatible) soldering*** to enable continued use of SnPb solder assembly

Background Information

➢*Mixed alloy processing provides an alternative to complete product conversion* to Pb free manufacturing but its implementation has been limited due to ***concerns about solder joint quality*** and ***long term attachment reliability***.



Courtesy Polina Snogovsky, Celestica, Inc.
Toronto, ON, Canada

Mixed Alloy or Backward Compatible Soldering

➢Pb free SAC solders melt in the range of 217-221° C, whereas a typical SnPb peak reflow temperature range for a large telecom PCBA is 215-220° C

❖***Mixed Alloy Solder Joints Quality Issues***

Background Information

❖Reliability of Mixed Alloy BGA Solder Joints

- Initially, Full Pb mixing (100%) was considered necessary for adequate Solder Joint Reliability under Temperature Cycling
- Later, empirical studies indicated that partial Pb mixing (minimum 70%) was sufficient to attain adequate solder joint reliability under temp cycle fatigue
- Further, these studies indicated that mixed alloy fatigue life is sensitive to package characteristics
- But, these studies were done on small body (<21 mm a side) components
- Very few studies have been conducted on large body (>30 mm a side) BGAs to assess fatigue life of their mixed alloy solder joints

Solder Joint Quality of Large & High Density BGA

Assembled in a Backward Process

Background Information

❖Impact of Large Body, High Density BGAs

- Large Body, High Density BGAs have two major effects during the reflow soldering process:

1) *Increased variation in temperature across* the solder ball array of the package
   - Larger variation in % Pb mixing within the solder joints of a single package
   - Outer row (hotter) solder joints can have full mixing but center solder joints can be below 50% Pb mixing

2) *Higher amount of warpage*
   - Pb Mixing is impacted due to potential loss of contact between Sn-Pb solder paste during reflow heating cycle

- Large Body, High density BGAs need further study with %Pb mixing below 70%, even preferably below 50%

Goals of the Present Study

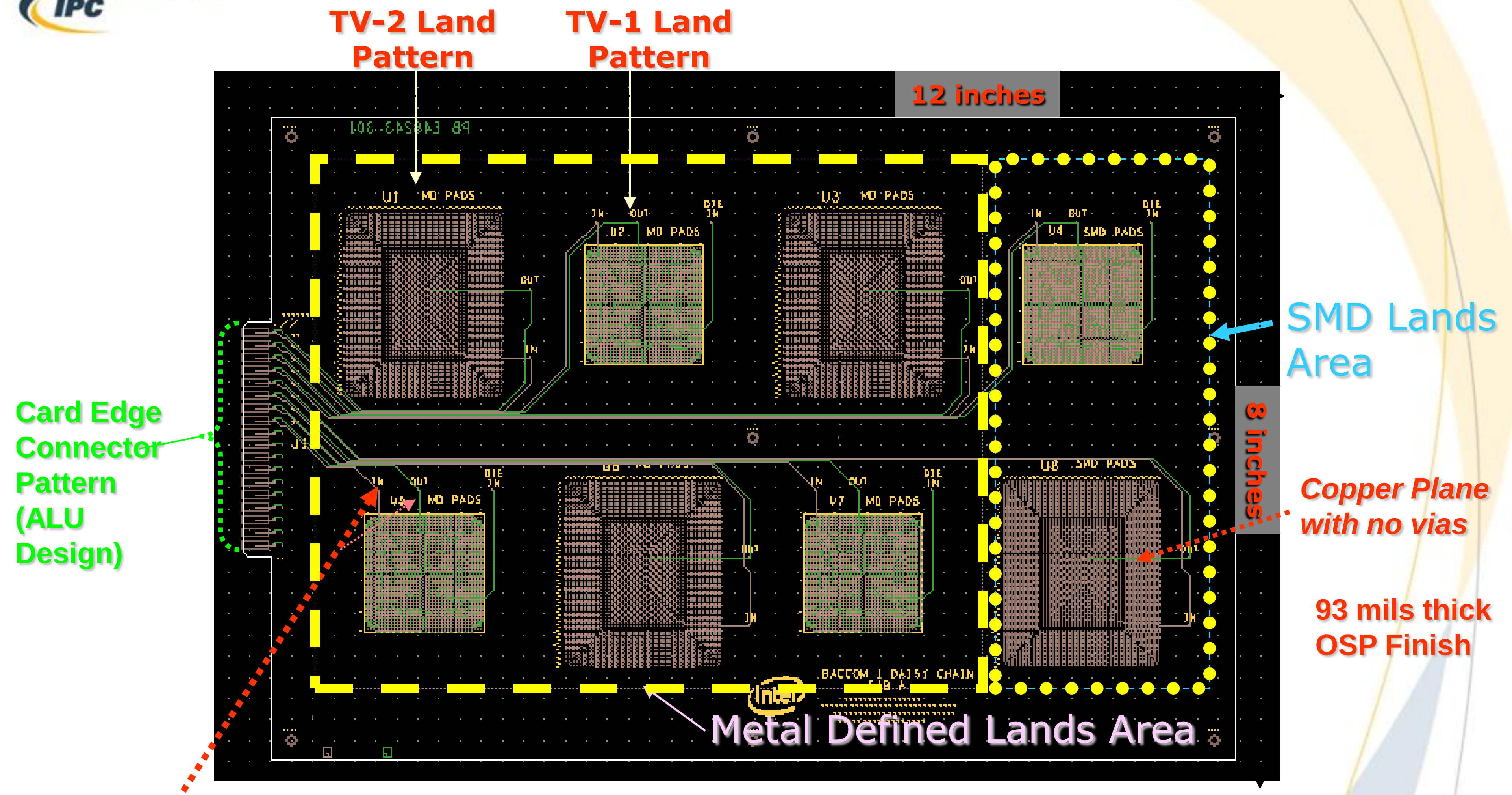
- Determine ***optimum reflow process windows*** that can be used to achieve acceptable degree of mixing and solder joint formation for large BGA packages

  - Assumption: Reflow profile parameters should not deviate drastically from typical SnPb profile conditions

- Concurrently, ***assess the extent of Pb mixing variation across*** the package solder joint arrays resulting from the large body sizes and dynamic warpage characteristics of these packages

Package & Board Test Vehicle Descriptions

Package and Board Test Vehicles Design



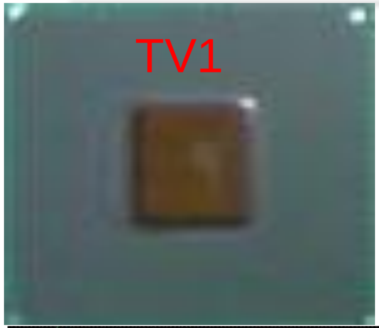
Daisy Chain Net
- *One per Component*

- **FOUR** BGAs per type were populated
- Each BGA has **ONE** Daisy Chain

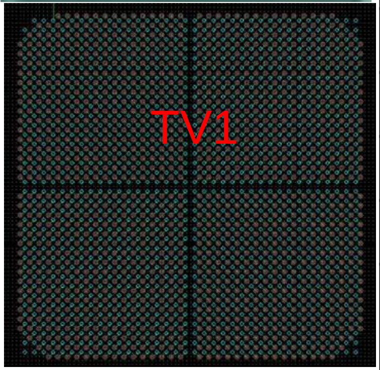
TEST VEHICLES DESIGN

BGA Test Vehicles Attributes

Top side

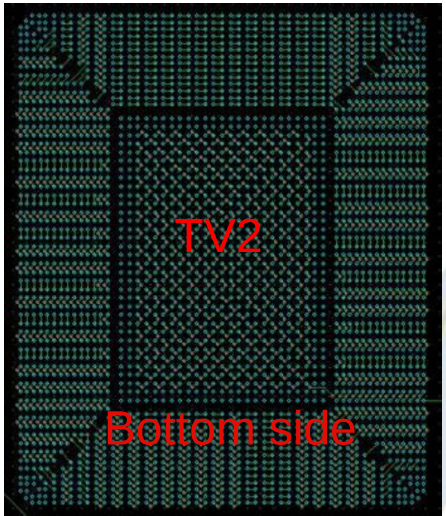


Bottom side



TV Description	Package TV attributes
Package Size, mm^2	37.5 x 37.5
Die size, mm^2	13.58 x 10.4
Substrate thickness, mm	1.162
Solder ball diameter, μm	600
Ball Pitch, mm	1.10
Solder ball metallurgy	SAC405
Ball count	1295
Pad Finish	NiPdAu
Ball Pattern	Fully populated grid (corner depopulated)

Package Attributes:
Size: 51 mm x 59.5 mm; 3162 balls,
Pad Finish: NiPdAu
Ball Pitch size: Multiple pitches (0.63, 0.79, 0.81 & 1.02mm)
Ball Metallurgy: SAC405



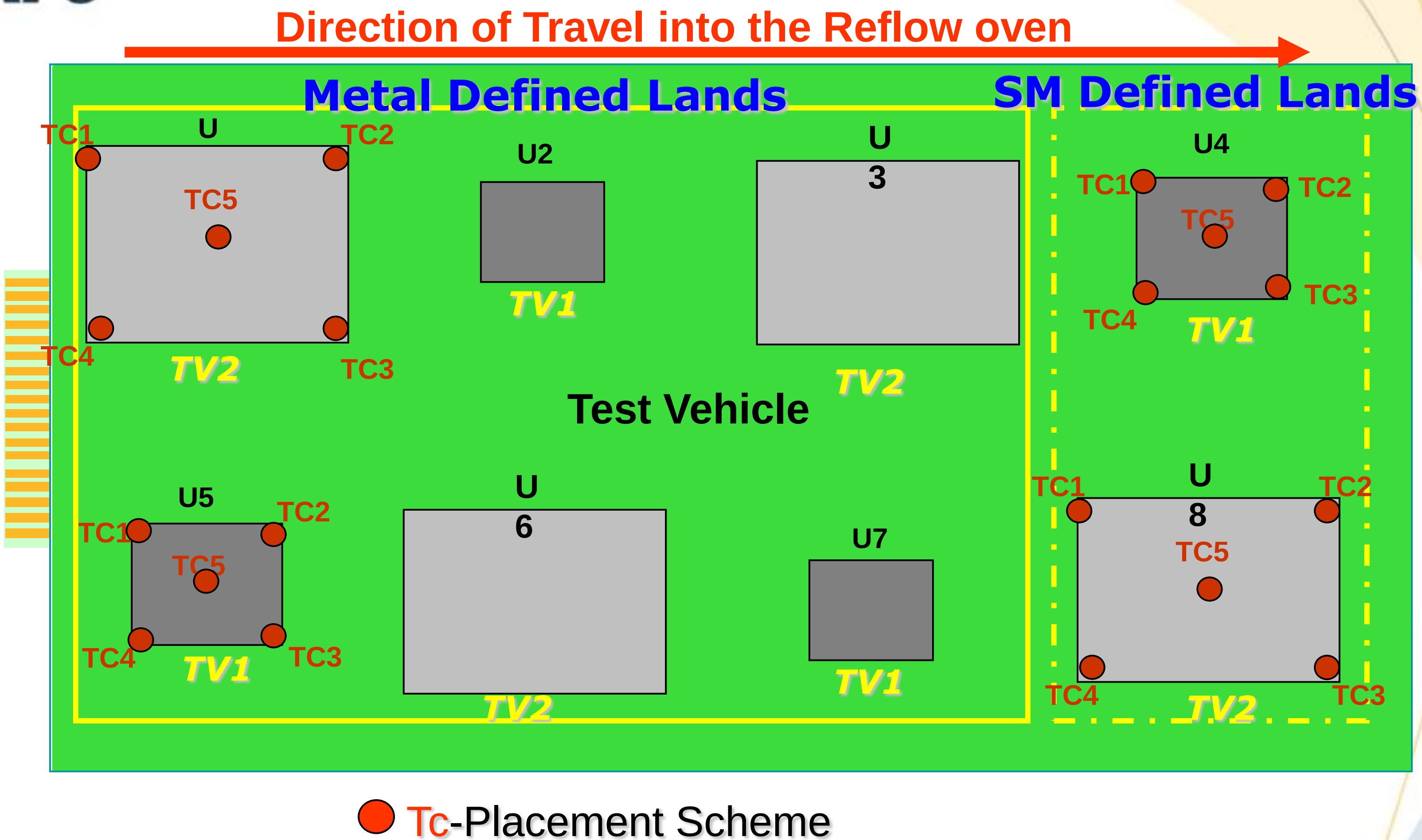
DOE TARGET REFLOW PROCESS WINDOWS

DOE REFLOW PROFILE MATRIX		
DOE Leg #	DOE Leg Definition	Target Reflow Process Window (Peak Temp; TAL)
1	Low Partial Mixing	210-215ºC; 60-70secs
2	Medium Partial Mixing	215-220ºC; 60-70secs
3	Full Mixing	220-225ºC; 90-100secs
4	Pb-free Control	230-250ºC; 60-120secs

DOE Target Profiles:

- THREE Mixed Alloy profiles and ONE Pb-free Control

Tc Location for Reflow Profile Development



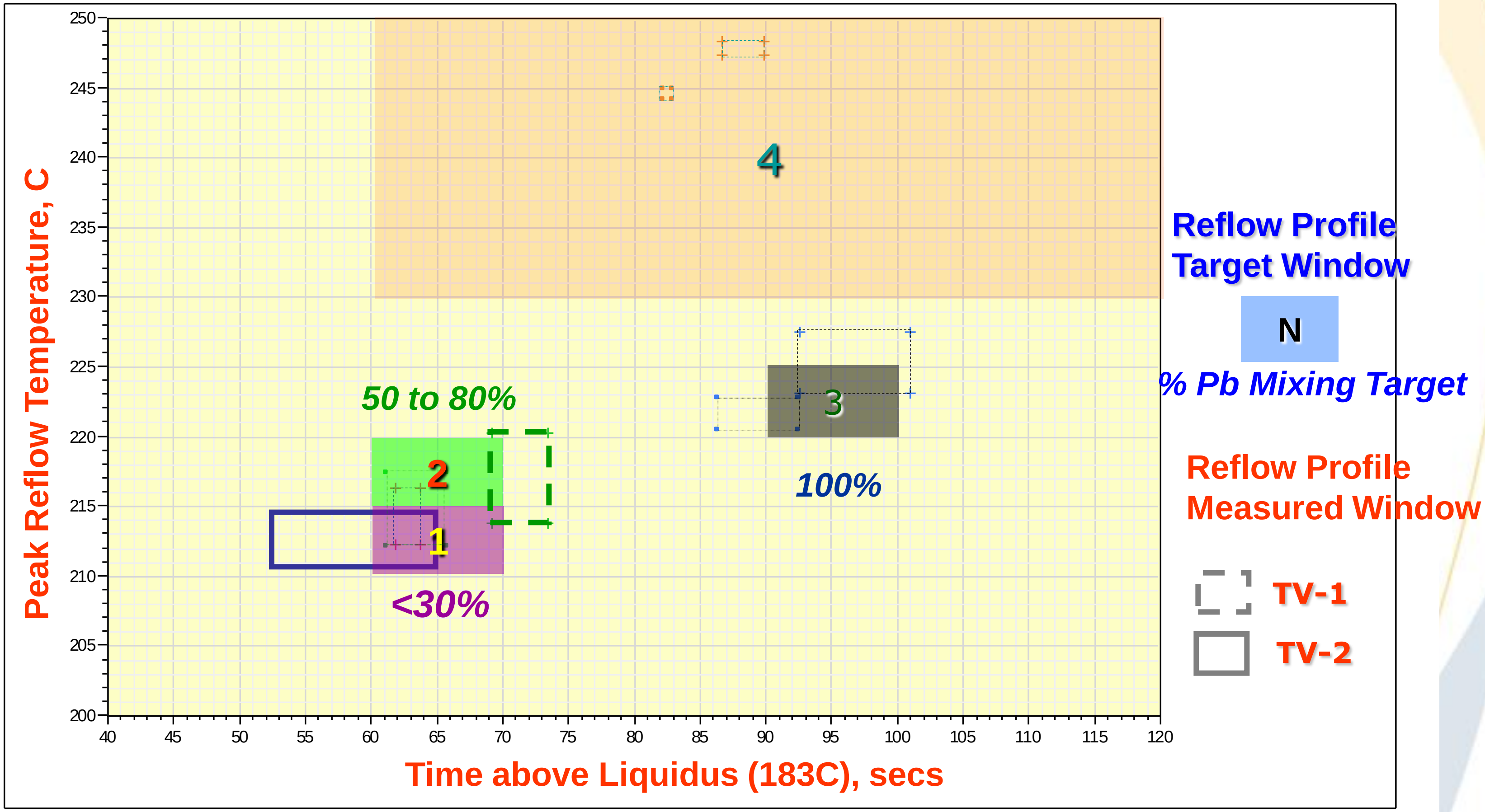
Thermocouples (5mil in tip diameter) placed on

- **Center and all FOUR corners of each package**
- **Two component Locations for each Package TV**
- **One each on a leading edge and trailing edge through the reflow oven**
- **One each on a Metal Defined and Soldermask Defined Lands**

- **Used Convection Reflow Oven with 12 Zone (including 2 cooling zones)**

Reflow Profile Windows for Each Package Type on the board

✓ All Measured Data Points fall within the indicated windows for the corresponding Package TVs



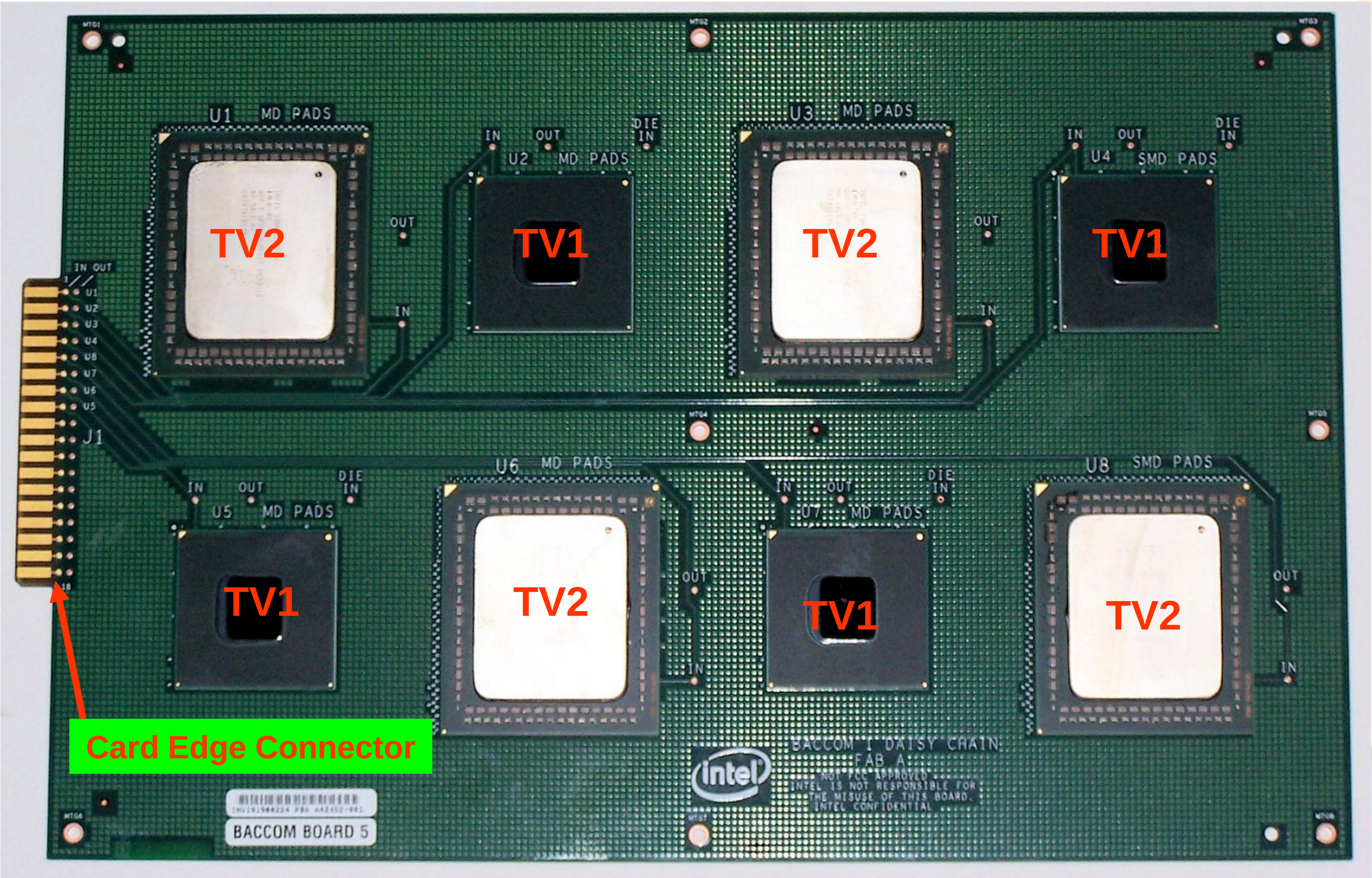
✓ Slight Off-set present for some Reflow Profile windows with respect to the Target

% Pb Mixing

&

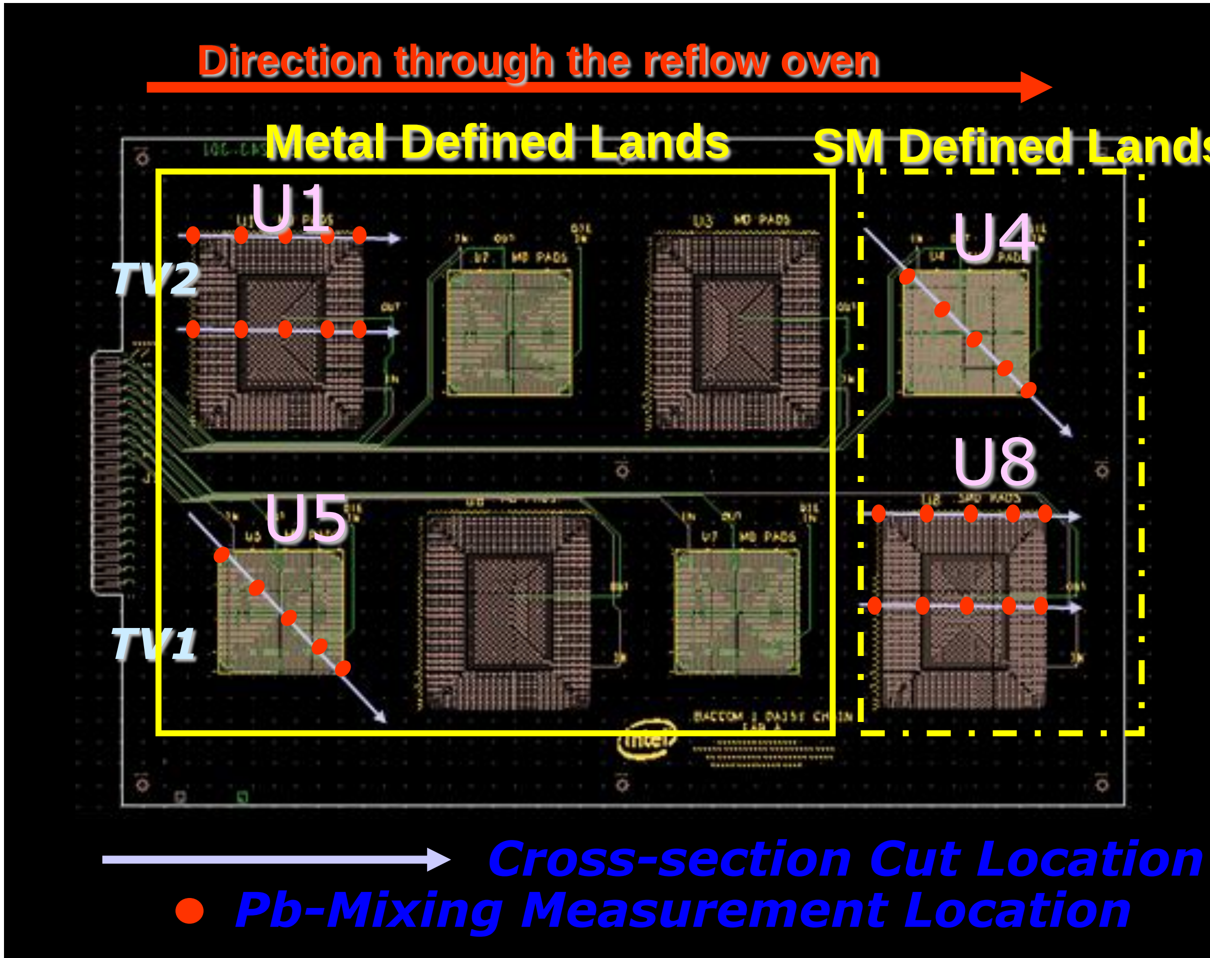
Solder Joint Quality Via metallographic Analysis

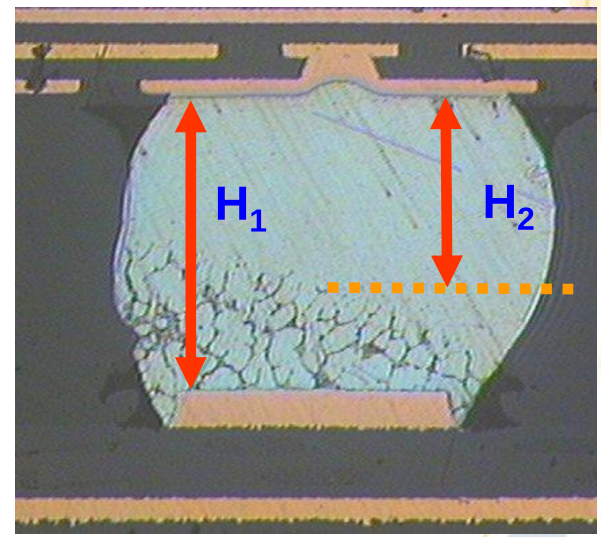
Photograph of Assembled Board Test Vehicle



Measuring the % Pb Mixing

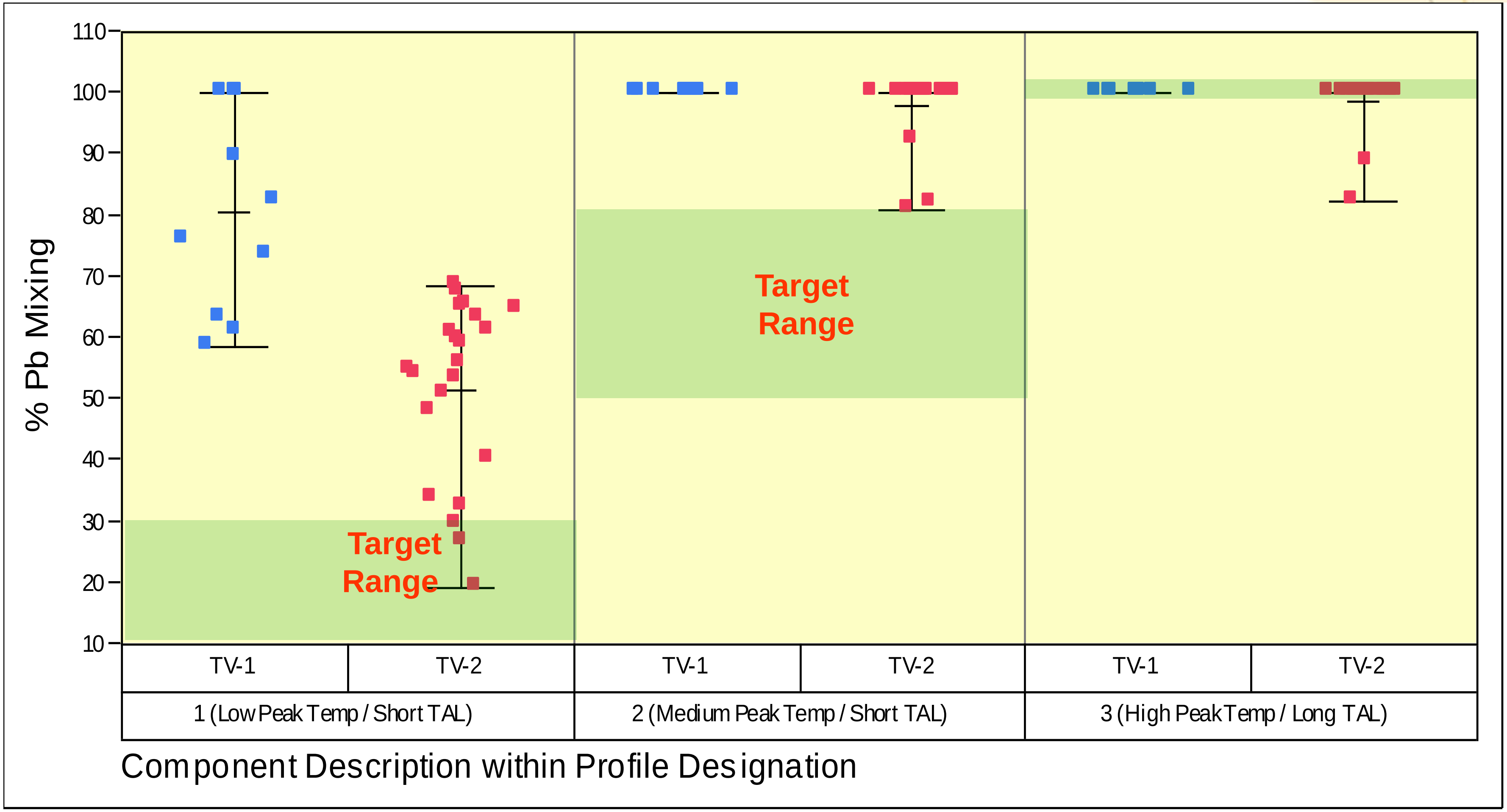
Cross-section Cut Locations





% Pb Mixing = $100*(H_1-H_2)/H_1$

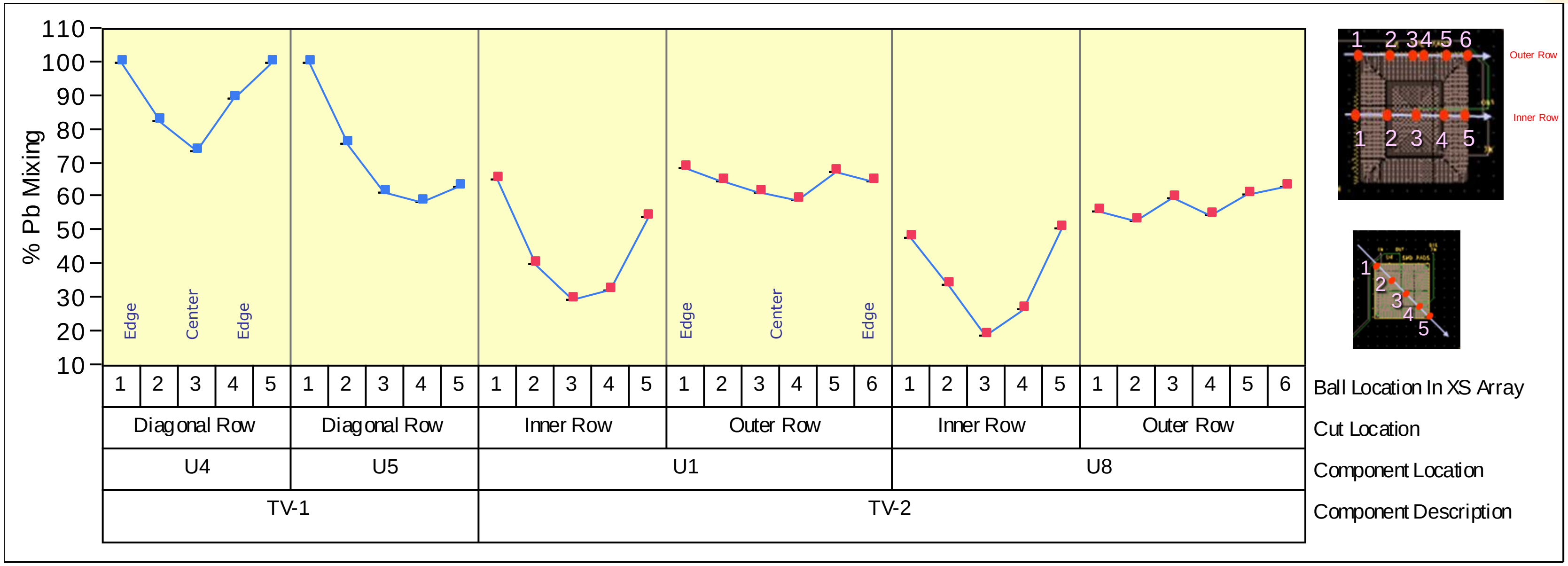
% Pb Mixing Levels Measured for each DOE Leg#



- ✓ Expected Trends observed for %Pb Mixing with Leg #
  - ✓ Increase in %Pb Mixing with Peak Reflow Temp and TAL
- ✓ But…..target ranges for Legs 1 & 2 are NOT being met

%Pb Mixing variability chart for Low Peak Temperature and Short TAL leg (Leg #1)

✓ *Variation shown for Each Component TV with location on the board and within the XS Row*



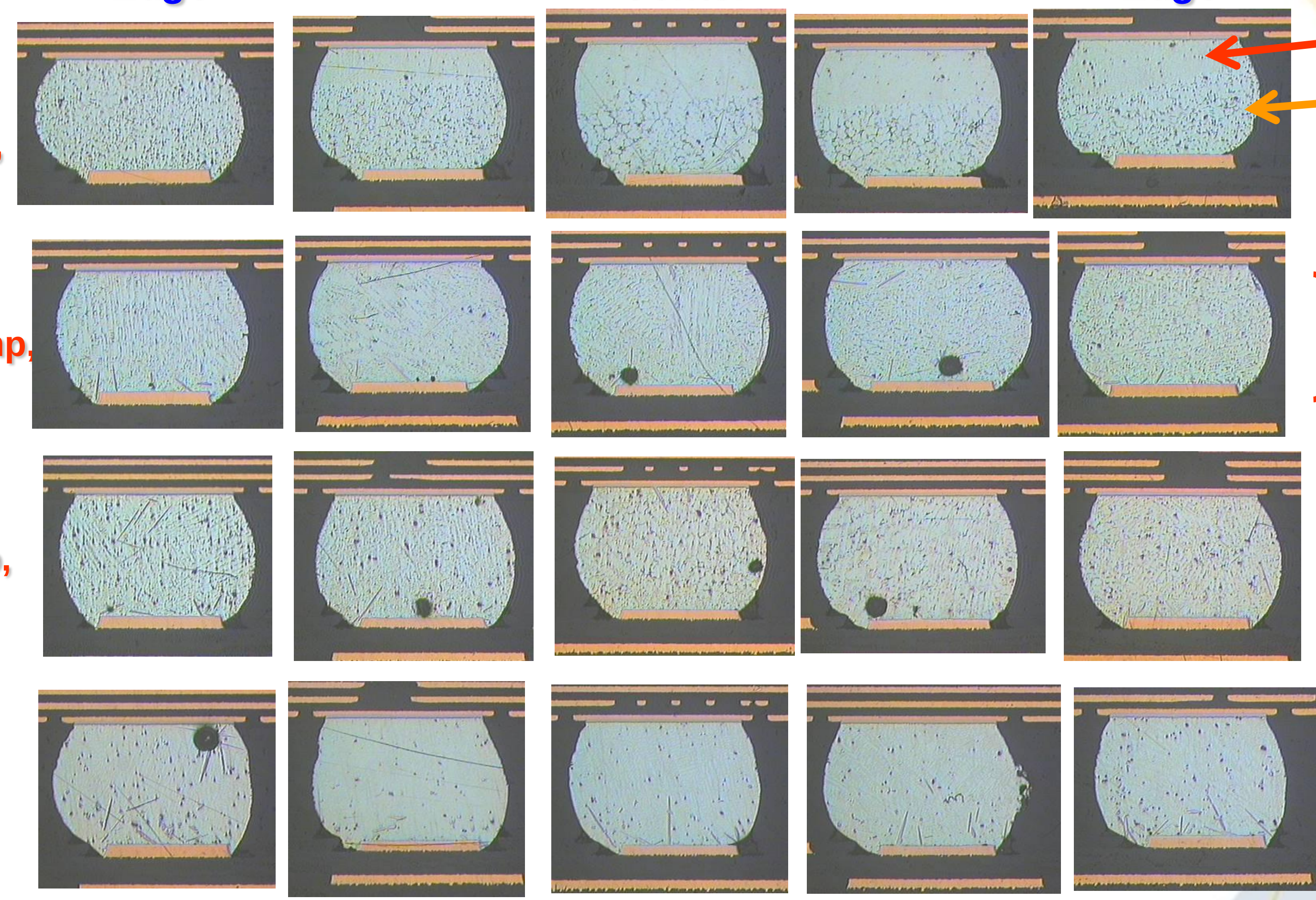
- **%Pb mixing is higher for the TV-1 solder joints**
  - ***TV-1 is smaller than TV-2***
  - ***TV-1 reflow profile has higher Peak Reflow Temperature and longer TAL ranges***
- **The solder joints in the central region of the package ball arrays have much lower %Pb mixing than on the outer region for both package TVs**
  - ***Caused by the lower peak temperatures and TALs prevalent for the solder joints in the central region of these high density BGA packages***

Optical Microscopy Analysis of Cross-Sectioned Samples

Cross-section Photos of Solder Joints from Package TV-1

Along Diagonal

Edge | Center | Edge



Profile 1
Low Peak Temp,
Short TAL

LF (SAC) Alloy Region

Mixed Alloy Region

Profile 2
Medium Peak Temp,
Short TAL

Mixed Alloy Region

Profile 3
High Peak Temp,
Long TAL

Mixed Alloy Region

Profile 4
Lead-free
SAC

LF (SAC) Alloy Region

Cross-section Photos of Solder Joints from Package TV-2

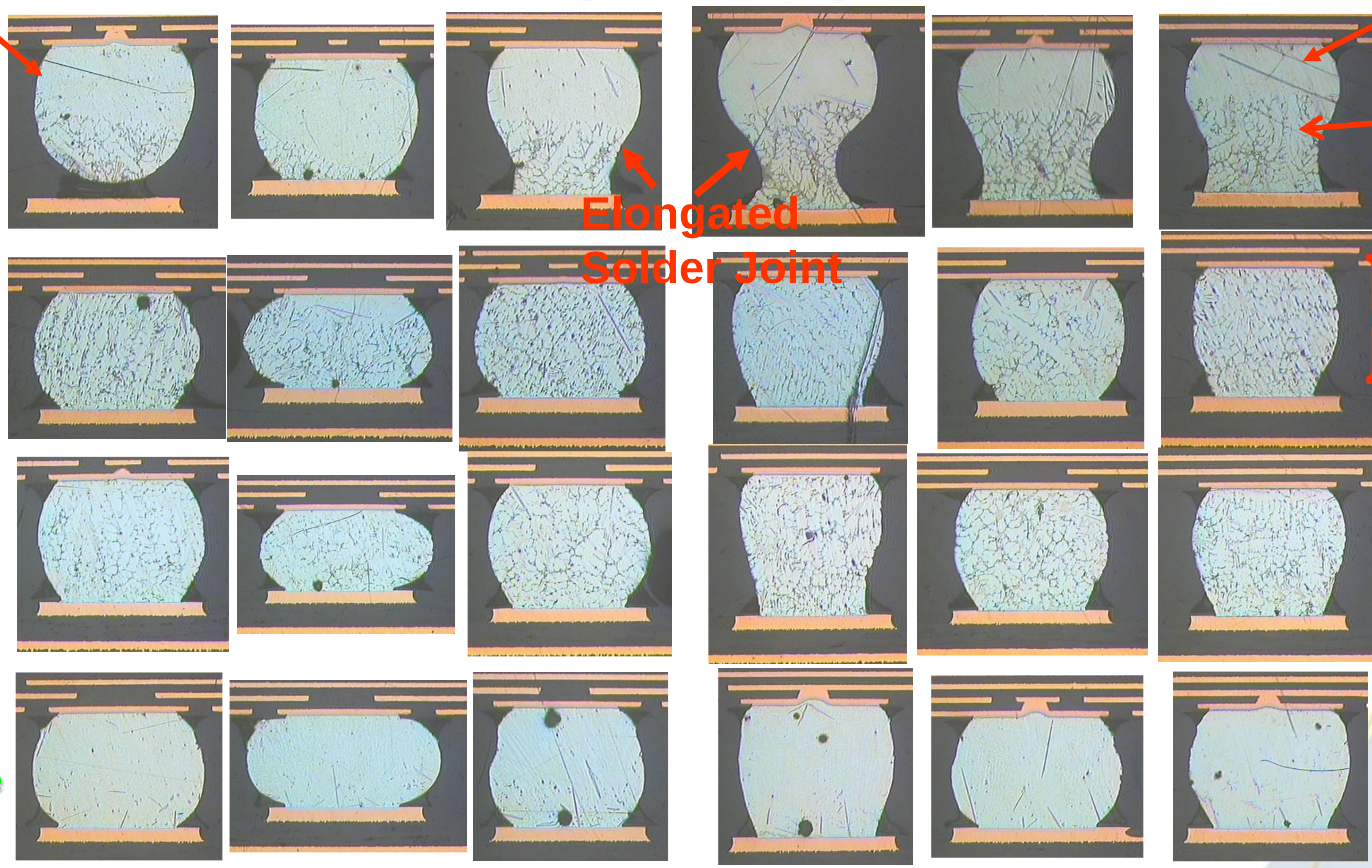
Inner Row | Outer Row

Edge | Center | Edge | Edge | Center | Edge

`Hanging` Ball

LF (SAC) Alloy Region

Mixed Alloy Region



Profile 1 Low Peak Temp, Short TAL — *Mixed Alloy Region* (Outer Row)

Profile 2 Medium Peak Temp, Short TAL — *Mixed Alloy Region*

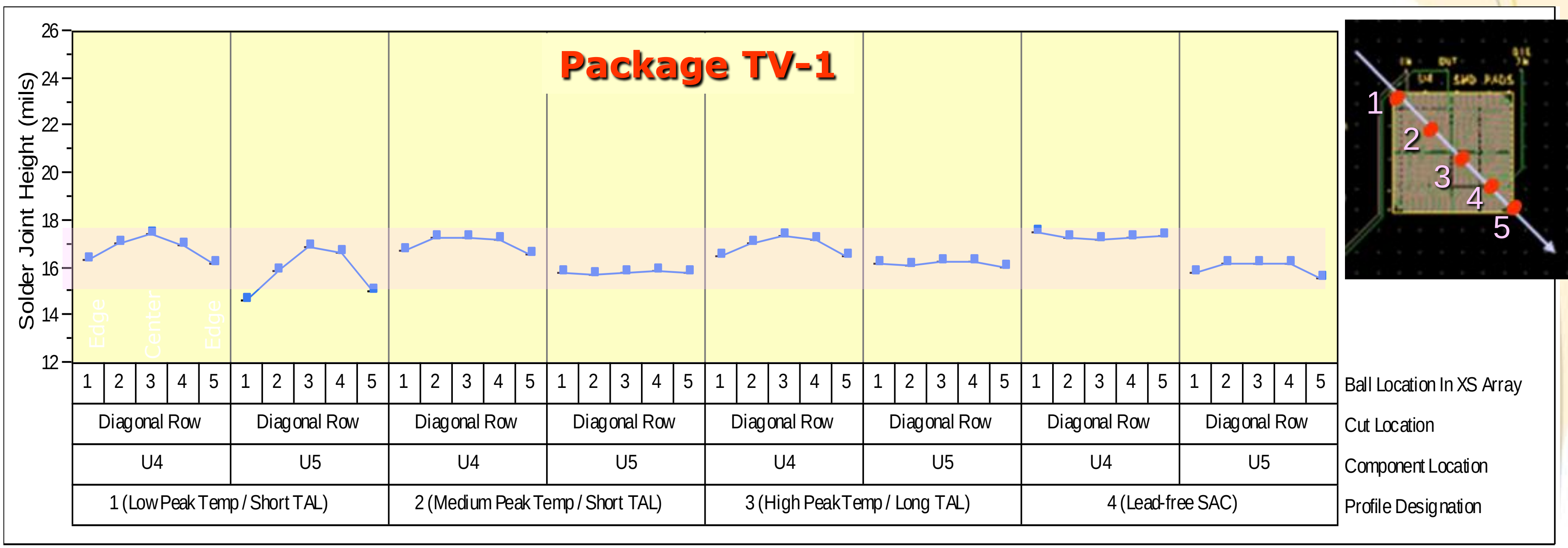
Profile 3 High Peak Temp, Long TAL — *Mixed Alloy Region*

Profile 4 Lead-free SAC — *LF (SAC) Alloy Region*

Solder Joint Collapse

Ball Collapse Variability Chart for Package TV-1

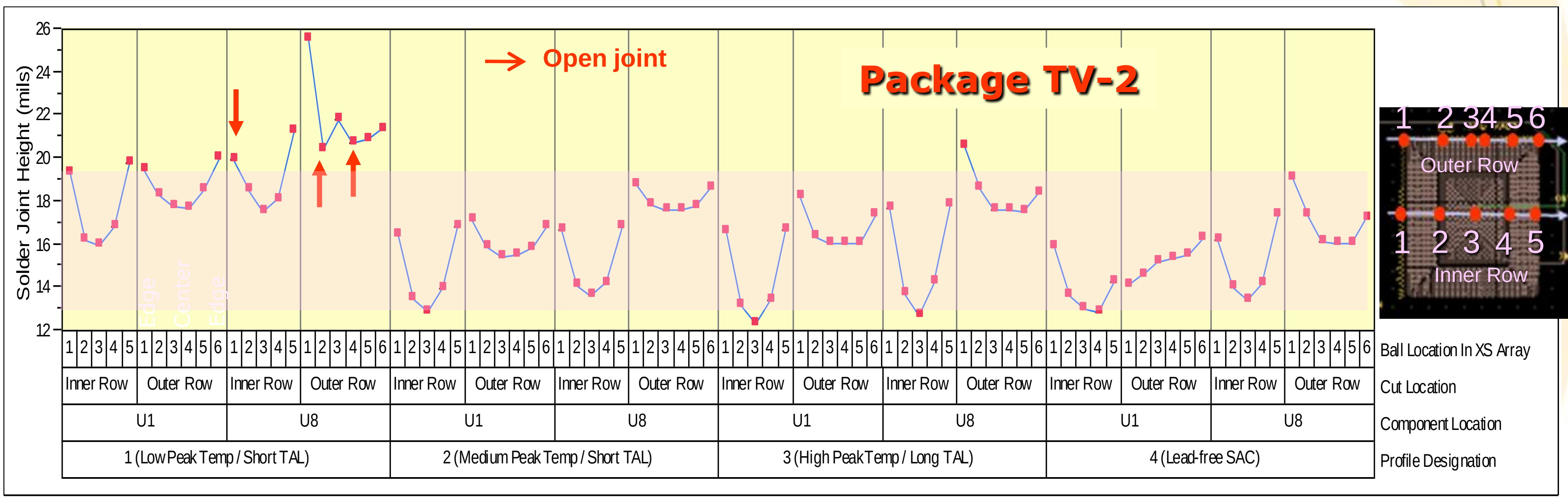
✓ ***Variation shown for Each Reflow Profile with location on the board and within the XS Row***



- **Package TV-1 substrate has a slight `frown` warpage profile with the solder joints in the center being taller than those at the edges**
- **The `frown` profile is accentuated for the coolest reflow profile, Profile 1**
- **This frown shows signs of changing to a `smile` warpage profile, as the peak reflow temperature increases from Profile 1, to 2 and to 3 and finally to 4, the lead-free SAC window, particularly for Location U4**

Ball Collapse Variability Chart for Package TV-2

✓ ***Variation shown for Each Reflow Profile with location on the board and within the XS Row***



- ➢ **Package TV-2 warpage profile is a `smile` profile with the edge solder joints taller than the central solder joints for both inner and outer rows**
- ➢ **The magnitude of this `smile` warpage profile is larger for the inner rows than the outer rows.**
- ➢ **U8 package location smile warpage profile is slightly larger than that for the U1 package location**
  - ▪ **U8 package is on the leading edge of the board through the reflow**
  - ▪ **Its land pattern is Soldermask Defined with no vias and a copper plane**

Comments on ΔT and ΔTAL Across BGA Package

❖ Factors Impacting the ΔT and ΔTAL Variations

- Package Size
  - Increased package size increases ΔT and ΔTAL
- Board Design
  - Thicker boards with more power and ground planes increases ΔT and Δ TAL
- Reflow Profile Type
  - Linear ramp-to-spike profiles increases ΔT and ΔTAL when compared to Ramp-Soak-Spike profiles
- Peak Reflow Temp
  - High peak reflow temperatures increase ΔT and ΔTAL

TV-1 Solder Joints Quality as a Function of Reflow Profile

- For Leg# 1, only the outer solder joint on the left has 100% Pb mixing.
    - The other four solder joints have partial Pb mixing with the amount of Pb Mixing being ~60% for the center solder joint.
- Complete Pb mixing is noted for all solder joints for Leg# 2 and Leg# 3.
    - Reflow Profiles corresponding to Leg# 2 and Leg# 3, reach a sufficiently high peak temperature for an adequate time to result in complete mixing of the Pb in the SAC solder ball.

TV-2 Solder Joints Quality as a Function of Reflow Profile

- Leg# 1, the coolest profile, has less than 70% Pb mixing for every solder joints
- For Leg # 2, all but the center solder joint of the inner row have 100% Pb mixing.
  - *Center solder joint has the lowest peak temperature within all the solder joints.*
- All solder joints for Leg# 3 display 100% Pb mixing.
- Inner row solder joints are *stretched* whereas the center solder joints are *squashed*.
  - These anomalous shapes of the solder joints are caused by the *severe dynamic warpage* of the TV-2 component.
    - The lead-free SAC solder joints (Leg#4) exhibit similar solder joint shapes (stretched and squashed).
- The stretching of the edge joints is so severe that in one case it caused **a** *"raised head-in-pillow" (the "Hanging ball" Phenomenon)*.

Summary and Conclusions

1) Achieving high ***solder joint yields*** with **100% Pb mixing in a large high density Pb free BGA Package (>37mm body size, >1200 solder balls) is a major challenge** due to ***temperature variations across the package***.
   a. Packages characterized by a **significant amount of dynamic warpage present additional challenges** for Pb mixing, ball collapse and stand-off height. Mixing performance cannot be anticipated based solely on room temperature co-planarity data.

2) **Deployment of Backward PCB assembly process for typical products present significant challenges.** This was demonstrated using the test vehicle from this study, which is less complex in many respects than actual product boards. There may be cases where process constraints limit mixing to less than 100%Pb.

3) **Backward PCB Assembly Process Window is Very Narrow**. The recommended mixed alloy reflow profile uses a peak temperature above Pb free liquidus (~220^{o}C) but less than 230^{o}C. The recommended SnPb TAL is 60-120 seconds and it is suggested that the profile have ~30 seconds above SAC solder liquidus temperature.

Next Steps

- The test boards will be assembled using the various reflow profiles described in the paper and the thermal fatigue reliability of TV1 and TV2 will be determined as a function of %Pb mixing using accelerated temperature cycling (IPC-9701, 0/100C).

Thank You!

Questions?