THE APPLICATION OF BI-BASED SOLDERS FOR LOW TEMPERATURE REFLOW TO REDUCE COST WHILE IMPROVING SMT YIELDS IN CLIENT COMPUTING SYSTEMS

Scott Mokler, Ph.D., P.E., Raiyo Aspandiar, Ph.D., Kevin Byrd, Olivia Chen, Satyajit Walwadkar, Kok Kwan Tang, Mukul Renavikar and Sandeep Sane
Intel Corporation
Hillsboro, OR, USA
scott.mokler@intel.com

ABSTRACT

The continued miniaturization of personal computing systems has a significant impact on the ability to surface mount high I/O density component devices with high yield. To ensure complete solder joint melting, typical SnAgCu (SAC) solder reflow temperatures peak in the 245 to 260C range. At these temperatures, the mismatch in Coefficient of Thermal Expansion (CTE) of the key constituents in the system, primarily the PCB and BGA components, results in dynamic warpage that leads to both bridging and open solder joint defects. The use of low temperature Bi-based solder paste reduces the peak reflow temperatures below 200C at which point The magnitude of the dynamic warpage is reduced and this improves SMT yield. Additionally, there are further positive by-products of low temperature reflow such as measurable energy savings, reduced carbon footprint and the opportunity to use lower cost components. Although Bi-based solders are common in adjacent markets such as flat screen TVs and appliances, it has been avoided in mobile computing applications due to the brittle nature of Bi alloys. This brittleness needs to be overcome before the use of such Bi-Sn low temperature solders can be extended to other market segments. These three aspects of the use of low temperature solder pastes for electronic assembly were evaluated in the present study. Firstly, the impact of lower FCBGA package warpage at the lower peak reflow temperatures on FCBGA package solder joints was determined by assemblying packages with both nominal and excessive warpage using BiSnAg and SAC305 solder pastes. Secondly, a practically study was undertaken to assess the extent of power use savings by using BiSn-based solder pastes instead of SAC305 solder paste. Thirdly, to improve the ductility of the brittle of Bi-Sn solders, some solder paste manufacturers added dopant elements to the alloy to modify their microstructure. The lower peak reflow temperatures with BiSn based solder paste resulted in significantly better solder joint yield for both the nominal and excessive warpage FCBGA packages, even though the SAC solder ball did not fully collapse at these low temperatures. The estimated cost savings of the low temperature operation was determined to be \$168/oven/week or \$8,749/oven/year. The ductile BiSn solder metallurgy compositions were found to be better in cold ball pull and component shock/drop exposures but still not up to par with the SAC solder joints.

Key words: Bismuth, low temperature reflow, collapse, ductile, dynamic warpage, carbon footprint, energy saving

INTRODUCTION

Currently, printed circuit boards used in consumer electronic products, such as cell phones, tablets, mobile computers, are assembled with components by reflow soldering with lead-free SAC solder pastes at peak temperatures in the 240 to 260C range. The desire to lower this reflow temperature has existed for some time now and has been identified as one of the paradigm shifts within the electronics manufacturing industry in the 2015 iNEMI Roadmap [1]. The two main drivers for this have been environmental and economic. The environmental driver is related to the electronic products' life cycles and the economic driver has been related to the reduction in manufacturing assembly costs, particularly the energy costs for operating the soldering equipment.

Recently however, a technical driver for low temperature soldering has surfaced due to demands for slimmer and lighter electronic products with increasing performance. This has fostered the use of ultra-thin electronic packages. Reduction in package thickness creates new challenges for their reflow soldering assembly. Due to various mismatches in the CTE of materials comprising these electronic packages, their resultant warpage increases markedly at the current SAC reflow temperatures. Reducing the reflow peak temperature improves the SMT margin by reducing the dynamic warpage and keeping the ball and paste in contact during reflow.

Dynamic warpage occurs due to the differential expansion of materials. Essentially, during the heating of the package in the reflow oven, the silicon die expands much less than the package substrate laminate. This results in the warpage configurations shown in Figure 1(a) and 1(b). FCBGA packages typically have a convex (positive) warpage at room temperature and a concave (negative) warpage at the reflow temperatures when using SAC solder pastes. Likewise, the shape of the PCB warpage can vary based on the PCB layer construction and whether pallets are used or not, and the design of the pallets, if used, during the reflow soldering process.

These dynamic warpage characteristics will lead to a gap being created between the BGA solder ball and the solder paste on the land. This in turn can lead to solder joint defects that affect the yield of the board after reflow soldering. The types of solder joints defects, generated due to the dynamic warpage of such packages, are shown in Figure 2. They include Head on Pillow (HoP), where, though there is physical contact, there is no coalescence of the ball with the solder mass from the solder paste [2], HoP Open, where no physical contact occurs between the solder ball and the post reflow solder paste mass, Non-Wet Open (NWO), where there is no contact between the solder ball and the printed board land with little or no evidence of solder wetting on the land [3,4], and Solder Bridging, where two or more neighboring solder joints are connected together.

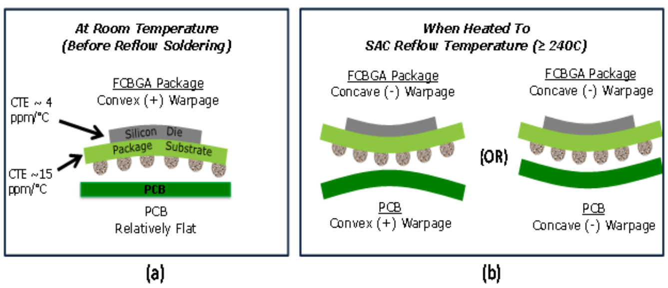


Figure 1: Typical warpage shapes of FCBGA packages and PCBs (a) at room temperature and (b) at SAC solder paste reflow temperatures

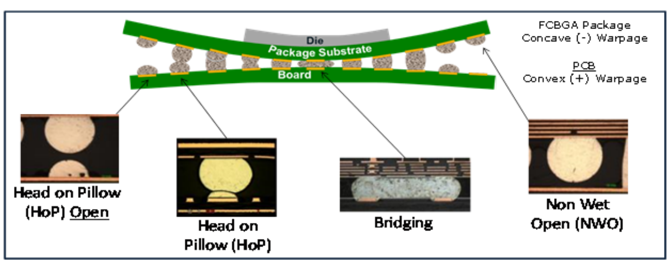
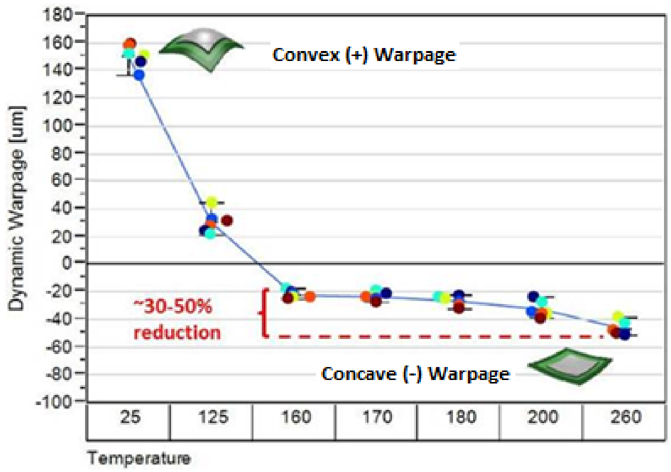


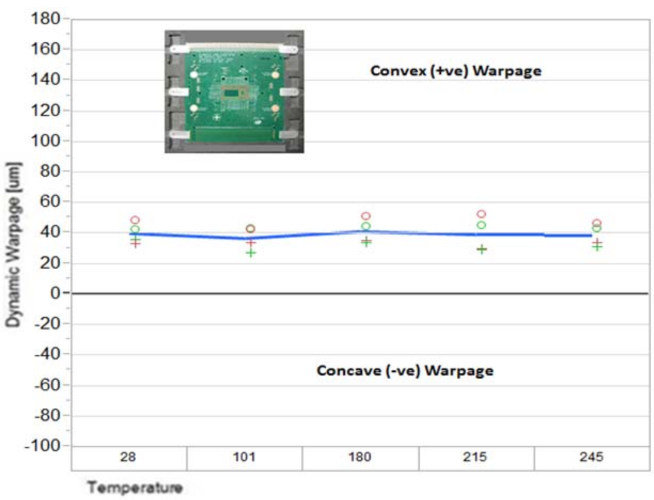
Figure 2: Description of defects that can be caused by dynamic warpage of FCBGA components and/or PCBs during the reflow soldering process

One way to mitigate the generation of these defects and the resulting reduction of the solder joint yield for FCBGA components becomes apparent by inspecting their dynamic warpage vs temperature plot. Figure 3 typifies such a plot, with the data points in the plot showing the measured warpage of (a) packages and (b) boards by the Shadow Moire technique. Note that the Temperature scale is specific and not continuous. If the peak reflow soldering temperature is lowered to the 160-180C range, the warpage of the FCBGA component at the peak reflow temperature is reduced by 30-50%. However, the `Inversion Temperature` range, which is the temperature range where the FCBGA package warpage `inverts` from convex (+) to concave (-) and the package and board are in closest contact, is also of some importance for solder joint yields. If the metallurgical composition of the solder paste is such that its solder melting point falls within this flip temperature range, the FCBGA component warpage profile is flat, and therefore the contact between the FCBGA solder ball and the solder paste is maintained when the solder paste first becomes molten. This significantly reduces the propensity for the formation of the defects shown in Figure 2. From Figure 3(a), the `Inversion Temperature Range` is typically between 125C and 160C for current high density FCBGAs. The dynamic warpage for a land pattern area of an FCBGA on a typical PCB test vehicle is shown in Figure 3(b). There are four sets of data in this plot, for two different FCBGA land patterns coupled with the two cases where pallets are used or not. In contrast to the large change in dynamic warpage of FCBGAs, the dynamic warpage of the corresponding FCBGA land pattern area on PCBs is fairly constant across the temperature range shown and its warpage shape does not `invert`. However, though the example in Figure 3(b) shows a concave warpage profile measurement, there is no consistent shape across the gamut of board designs. Depending on the board layer stack-up design, materials of construction, designs of support pallets during reflow, the board profiles can be flat, convex or concave.

A potential solder metallurgy system that meets the requirement of having the melting temperatures in this 125 and 160C range is the Bi-Sn system. The eutectic temperature is this system is 138C [5]. There are many other advantages with the Bi-Sn metallurgy in addition to its melting point falling in the desired Inversion Temperature range. Solder pastes with the Bi-Sn metallurgy are widely available from leading solder paste manufacturers. Soldering BGAs with SAC solder balls using BiSn based solder pastes, with small amounts of Ag added to increase the solder strength and ductility, has been evaluated more than a decade ago, and even proposed for use in consumer electronic products by Hewlett Packard [6,7,8]. Today, solder pastes with this Bi-Sn-Ag (BSA) metallurgy are widely available from many solder paste suppliers [9]. These solder pastes are used for the assembly of low cost consumer electronics products, such as CD players, TVs, and even the electronics within kitchen appliances, mainly in the Far East countries. Solder paste of this composition is also used for a pin-in-paste process to eliminate the wave solder step in the process. The lower reflow temperatures with this BSA pastes avoids the SAC solder joints from becoming molten during the secondary pin-in-paste reflow process.



(a) FCBGA Package



(b) PCB Warpage

Figure 3: Dynamic Warpage plots with temperature for (a) a FCBGA package and (b) PCB. The amount of dynamic warpage reduction if soldering in the 160-180C peak reflow temperature range is indicated for the FCBGA package

One of the drawbacks of using the Bi-Sn metallurgy system as a solder material in consumer electronics products has been its brittleness under mechanical shock conditions. Due to rigors of daily use, cell phones, tablets and other mobile devices can be subjected to multiple drops during field use and therefore the solder joints formed with the BSA solder paste have to withstand strict mechanical shock and drop requirements. Recently published results confirmed that Mixed Alloy BGA solder joints formed by soldering BGA solder balls with BSA solder paste exhibited significant reduction in mechanical drop reliability when compared with solder joints formed using SAC based solder pastes [10, 11, 12]. This reduced drop resistance was deemed to have been caused by the bismuth presence in the solder joint stiffening the solder and embrittling the intermetallic compound (IMC) at the Solder-to-land interface.

To overcome this brittleness, two solution paths are available. One is metallurgical and the other is polymeric. Recently we have focused on the metallurgical path to strengthen the solder joint at the micro level is by making the Bi-Sn alloy more ductile with the addition of metallic dopants. These dopants refine the alloy's microstructure to impart improved mechanical properties even beyond that achieved initially by the addition of 0.4 to 1 wt% Ag [13,14, 15]. Solder Pastes with these ductile Bi-Sn metallurgies are presently under development by several solder suppliers.

IMPROVED SMT YIELDS

Collapse model

It is well know that the SAC metallurgy exhibits complete melting at eutectic temperature of 217 C however in case of a mixed alloy (or hybrid) solder joint formed with SAC solder ball and low temperature solder paste, this is not true. There is a large temperature gap in melting behavior of the two metallurgies. Low temperature solder paste typically melts first followed by the SAC solder ball melting. Due to the differences in melting characteristics of these two metallurgies, understanding the collapse and mixing behavior of a hybrid assembly as it goes through the SMT reflow is important.

Prior to performing surface mount experiments, the collapse dynamics of the low temperature mixed metallurgy system was studied to characterize the collapse behavior. To do this, we examined an isolated single joint controlled collapse as a function of temperature using SAC 405 spheres and SnBi paste printed on a Cu Organic Solderability Preservative (OSP) pad. The assembly was reflowed in a small chamber at varied reflow temperatures encompassing the temperature range between melting points of the low temperature paste melting and that of the SAC paste. The collapse height and Bi mixing were measured on cross sections of the samples while inspecting through an optical microscope The extend of Bi mixing in the SAC solder ball was calculated as a function of Bi penetration into the solder joint using the following equation:

$$Bi(\%) = \frac{[Hjh - (0.25 * Hul + 0.25 * Hur + 0.5 * Hmid\ )]}{Hjh}$$

Where H_{jh}, H_{ul}, H_{ur} and H_{mid} are shown in Figure 4.

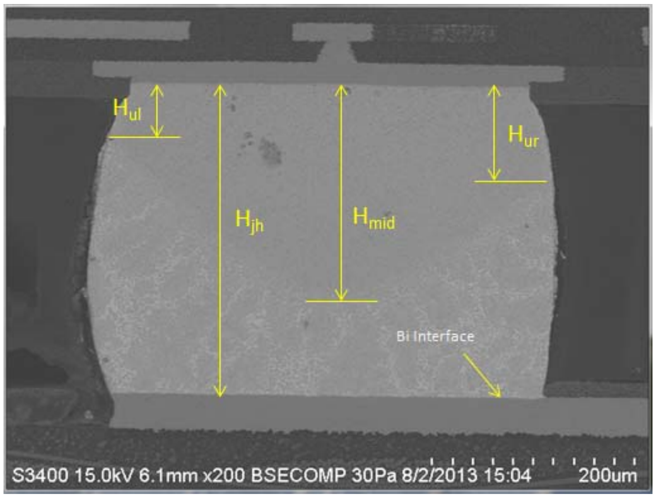


Figure 4: Cross section of a mixed SAC305 + SnBi solder joint indicating the height of diffusion of the Bi region into the joint

It was found at temperatures below the SAC melting point, that the material mixing in the joint is driven primarily by diffusion kinetics and exhibits a strong dependence on reflow peak temperature. Figure 5 shows that below 200C, Bi mixing is moderate and joint collapse is incomplete. This can be directly observed in the cross section images in Figure 6. This data indicates that both mixing and collapse are complete at reflow temperatures above 220C. However, from the BGA package warpage profile shown in Figure 3a, at temperatures above 200C the concave warpage increases which is known to increase both open and bridging defect generation during high temperature reflow. In order to maintain high SMT yields, we established 200 C as the maximum reflow peak temperature, and used the single joint data to calibrate final solder joint heights and mixing across the BGA array on the package.

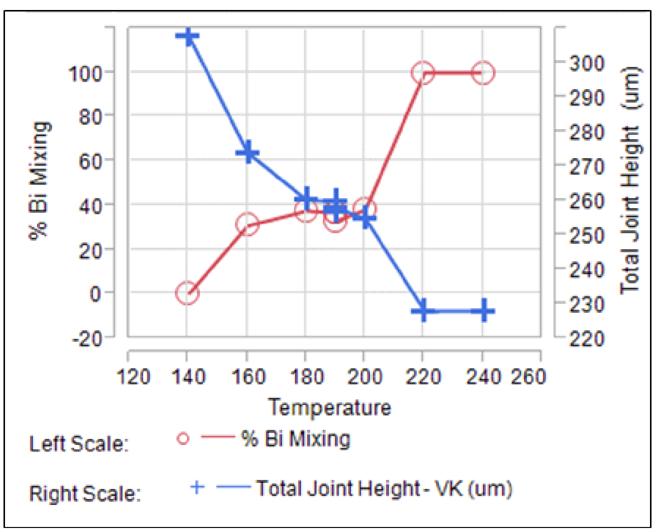


Figure 5: Bismuth mixing and solder joint collapse height as a function of peak reflow temperature

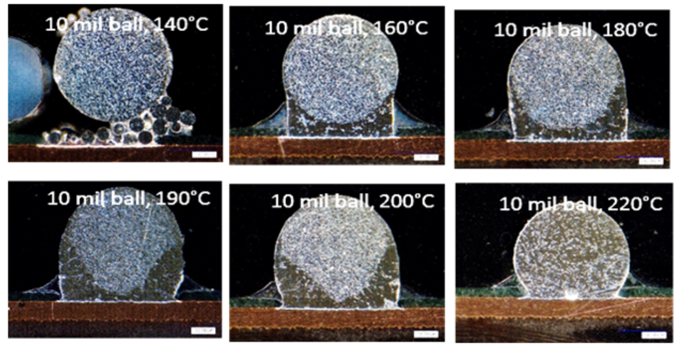


Figure 6: Cross section images of mixed SAC305 + SnBi solder paste solder joints after melting at the indicated temperatures.

Assembly Process and Yields

SMT experiments were conducted on large FCBGA packages that typically present SMT challenges due to their size. Table 1 lists the package parameters used in this study. To ensure observation of yield fallout due to warpage, excess dynamic warpage was induced by bending a subset of packages prior to reflow soldering. These are referred to as " "Excessive" in plot in Figure 7, whereas the subset of packages that were not bent are referred to as "Nominal" in the same plot. Both the excessive and the nominal packages were reflow soldered, with either Bi-based or SAC solder paste, on a printed board test vehicle with land patterns designed for X-ray and Dye-and-Pry (D-n-P) analysis. Solder paste was applied to the BGA lands on these board test vehicles via a 100micron thick stainless steel laser etched, electro-polished stencil. The stencil aperture design for the SAC solder paste legs was a variable aperture design optimized to account for the concave warpage of the package at the high reflow peak temperatures. But, for the Bi-based solder paste legs, the stencil apertures were uniform across all lands since the package warpage is reduced at the lower peak reflow temperatures needed for these legs of the experiment. The settings of the print parameters had previously been optimized for both the SAC305 and Bi-solder paste [16]. All experimental legs resulted in equivalent post-print solder volume distributions.

Each sample was reflowed with a universal reflow carrier in order to control PCB warpage at reflow temperatures. Reflow was completed in an air ambient with reflow profiles developed to match the solder supplier recommendations. The PCBs were 8 layer boards with dimensions 5.6 inches x 4.6 inches x 0.028 inches. The boards were designed for a single FCBGA component. The component land pattern pads were 13 mils in diameter and the surface finish on the PCB was OSP. Half the boards used solder mask defined (SMD) pads and half used metal defined (MD) pads in order to detect any influence of pad design on SMT yield. One set was soldered with SAC solder paste at 245°C peak reflow temperature range while the other set was soldered with the Bi-based solder paste at 175°C. These board assemblies were then tested using X-Ray and D-n-P procedures to determine the number of open or bridged solder joints in each package.

Table 1: The package attributes BGA test vehicle used in the experimental study.

TV Description	Package TV attributes
Package Size	28mm x 42mm
Die Amount	Two
Substrate thickness	0.702 mm
Solder ball diameter	16 mils
Ball Pitch	0.65 mm
Solder ball metallurgy	SAC 405
Ball count	1440
Ball pattern	Balls Anywhere
Package surface finish	NiPdAu

Figure 7 shows the plot of the passing and failing units as a function of their high temperature warpage after soldering with SAC (245C) and Bi-solder (175C). From the graph, it is evident that reflow at 175C results in approximately 100 micronm less warpage on average for both the nominal and excessive warpage packages. It can also be seen that BGA packages assembled with the Bi-paste paste showed just one solder joint defect whereas BGA packages assembled with SAC solder paste metallurgy showed a large amount of both open and bridging solder defects. The data in Fig. 7 is representative of defect observations made across a wide array of BGA packages and PCB platforms in our lab. In every instance, the high temperature SAC joint formation showed significantly greater defects than the corresponding system formed at low temperature. These results indicate that reflow soldering at lower temperatures enhances FCBGA solder joint yields when compared to SAC lead-free solder reflow temperatures for packages with similar package dynamic warpage characteristics.

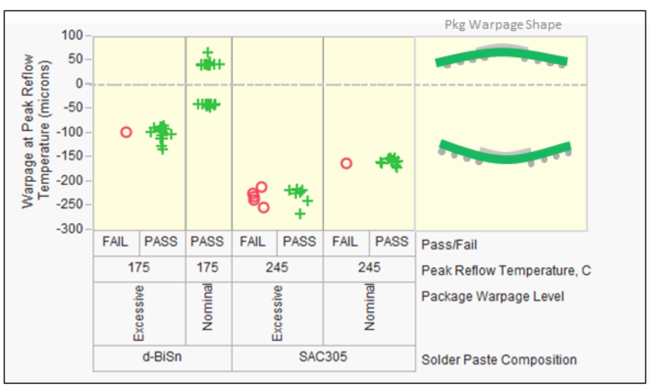


Figure 7: SMT yield and warpage comparison at 245C and 175C peak reflow temperatures

REDUCED MANUFACTURING COST

Power Use Savings

A prominent motivation for electronics manufacturers to use lower melting temperature solders is the cost savings realized by reflow soldering at lower peak temperatures. The cost savings are expected to primarily from the smaller current draw required to operate the ovens during reflow, which is a direct consequence of the set temperatures of the zones in the oven being at a lower value. Holzer and Mok [17] had shown that energy consumption can be decreased from the 20-24 killowatts/hour range when reflow soldering SAC solder paste at 245C peak reflow temperatures to the 15-17 kilowatts per hour range when reflow soldering BiSn solder paste at 190C peak reflow temperatures.

A similar study was undertaken to assess the extent of power use savings realized by using BiSn based solder pastes instead of the standard lead free SAC305 solder pastes, at Intel's Hillsboro, Oregon SMT manufacturing facility. In this investigation, the benefits of lower temperatures during reflow soldering were quantified by directly measuring the current load during a typical SAC solder paste reflow soldering process at a peak temperature of 243.8C and comparing that to the current load during a typical BSA solder paste reflow soldering process reflow at a peak temperature of 179.7 C.

Figure 8 depicts the two reflow profiles used in a 14 zone Furukawa XNK-1245PC in-line reflow oven. The values for each of these reflow profiles was calculated by averaging the temperature recorded by 9 thermocouples placed at specific locations on a test board, either on the surface of the board or within a solder joint of the BGA component in the center of the board.

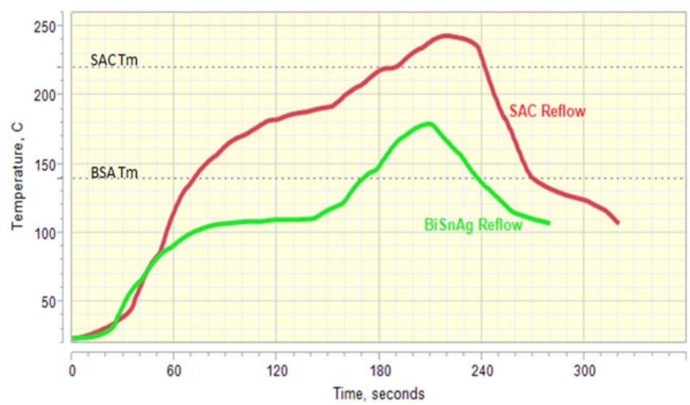


Figure 8: The Two Reflow Profiles used for the Power Use Savings Study

To measure the current load, an Amprobe DM II Data Logger Recorder was connected onto the 3-phase, 408V source that feeds the ovens. This was configured to take amperage readings at one minute intervals for the full duration of a typical six hour operation. Figure 9 shows the resultant current readings for low (BiSnAg) and high (SAC305) temperature reflows. Each data point in the plot denoted each amperage reading taken.

The average current draw during SAC reflow was measured to be 60.4A, while the average low temperature BSA reflow current was measured to be 36.7A. This difference represents a 39% reduction in current flow and is both statistically and technically significant. Using Watts Law for three phase systems, the power required to drive the ovens in the two states is calculated using equation (1).

$$Kw = \sqrt{3} \cdot V \cdot I \cdot Pf/1000, \quad (1)$$

In equation (1), V is the line voltage, I is the line current and Pf is the power factor of conversion. Based on the operational mode, a Pf =0.75 was used. From this calculation, the reduction in power consumption is found to be 11.7 kW. Table 2 lists the calculated Current and Power Usage during the two reflow profile settings for the in-line reflow oven.

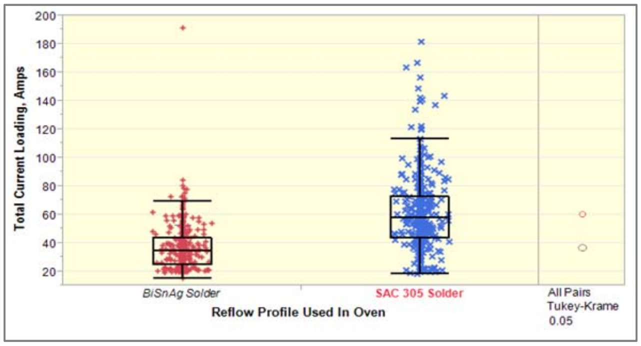


Figure 9: Comparison of Current Loading for a Reflow Oven when running a Low Temperature BSA soldering vs a standard SAC soldering reflow profiles

Table 2: Calculated Current and Power Usage

Measured Parameter	SAC Reflow	BiSnAg Reflow
Current (Root Mean Square), amps	60.4	36.7
Power (Average), Kilowatts	29.3	17.8

To evaluate the economic benefits of this power reduction, a cost estimate, on a per oven basis, is calculated assuming an 80% utilization of the oven and an energy cost of USD \$0.11 per kWh. This, of course, is an estimate since energy prices vary widely by country and even by region within the same country. However, \$0.11 per kWh, which is on the low end of US energy estimates [18] and the high end of China energy estimates [19], appears to be a good representative of world-wide costs. Based on these assumptions, the cost savings of low temperature operation is estimated to be \$168/oven/week or \$8,749/oven/year as shown in Table 3. This evaluation was repeated at both an ODM and supplier site with consistent results. For our OEM partner, to support their market share of world-wide notebook production this is a direct operational savings of \$3.8M per year. Furthermore, low temp solders contain less silver (Ag) content resulting in material cost savings of approximately 10%.

Table 3: Estimated Cost Saving Comparison for SAC vs BiSnAg Soldering Reflow Processes

SAC 305 Paste		Sn/Bi/Ag Paste	
Oven Energy Consumption (kWh)	**29.5**	**Oven Energy Consumption (kWh)**	**17.8**
80% Utilization (Hours/week)	134.4	80% Utilization (Hours/Week)	134.4
Energy Cost-\$/KWH (PRC -2013)	\$0.11	Energy Cost/KWH (PRC - 2013)	\$0.11
Oven Cost/week	\$424	Oven Cost/Week	\$256
BiSnAg Savings (per oven/week)			**\$168**
BiSnAg Savings (per oven/year)			**\$8,749**
CO2 Metric ton per kWh (EPA est.)	0.0007		0.0007
CO2 emission per week	2.78		1.67
CO_2 Savings (metric tons per oven/week)			**1.1**
CO_2 Savings (metric tons per oven/year)			**57.2**

Furthermore, the environmental benefits due to the reduction of CO_2 greenhouse gasses can be estimated for low temperature reflow. Based on EPA estimates [20] that 0.0007 metric tons of CO_2 are produced for every kWh consumed, an 11.7 kW power reduction due to low temperature reflow equates to 1.1 metric tons of CO_2 that will not be produced per oven each week relative to high temperature reflow, assuming 80% oven utilization. This is approximately 57.2 metric tons of CO_2 per oven per year. For reference, 57 metric tons of CO_2 is the green gas equivalent of burning nearly 6000 gallons of gasoline, or the average monthly CO_2 production of 60 US households [20]. Based on evaluations that were conducted by our OEM and ODM customers at their production sites it is estimated that these single oven energy savings are estimated to scale to a CO_2 reduction in excess of 25,000 metric tons per year based on a modest 20% share of the world wide mobile laptop market.

IMPROVING RELIABILIY OF BISMUTH CONTAINING SOLDERS

In previous sections, the benefits of improved solder joint yield and significant economic benefits realized by using low temperature melting bismuth-tin based solder paste, were elucidated Indeed, Bi-based solders are common in adjacent markets such as flat screen TVs and appliances, but their use been avoided in mobile computing applications due to the well-known brittle nature of Bi alloys that can result in failure during component drop shock testing.

The inherent brittle nature of bismuth, particular at the high strain rates prevalent in mechanical shock and drop events, is largely attributed to its rhombohedral crystal structure [21], which has very few of the slip planes that are necessary for material ductility. In fact, bismuth has only 1/3 the slip planes found in Sn and 1/6 the slip planes found in Cu, Ni, Al and Pb [22]. To overcome this brittle nature of

Bi-based solder paste, collaborations were initiated directly with key material suppliers to increase the ductility of the Bismuth-tin solder.

Three techniques were investigated. 1) Decrease Bi content which results in a reduction of the brittle phase (Bi) and increase of the ductile phase (Sn) and hence the ductility. This can be measured by elongation, which increases from 50% to 120% as the Bi content is reduced[23]. This however, also increases the liquidus temperature of the alloy and therefore, its peak reflow temperature. Reduction of the Bi content has limited viability since peak reflow temperatures above 200C show an increase HT warpage and a corresponding decrease in SMT yield. 2) The second approach is precipitation strengthening by creating lattice distortion in the vicinity of dopants, typically Cu or Ni. The distortion impedes dislocation motion and grain coarsening. Elongation increases from 120% to 170% [23]. Finally, 3) the third approach is to add dopant elements into the solder to induce grain size refinements, that change plastic deformation from classic dislocation slip to cooperative grain boundary sliding at finer grain sizes. Typically, Co, Mn, and Sb doping show increases in ductility [24].

Details of the alloy reformulations and specific dopants are proprietary, but fundamental measurements of the solder ductility and the corresponding improvement in the component drop shock reliability performance due to the alloy modification, are reported here. This investigation compared a standard BiSn Alloy (BSA) with a formulation modified specifically to increase the material ductility (referred to as Ductile BSA). Samples were prepared by depositing approximately 615 cubic mils mils of BSA or Ductile BSA paste on a OSP covered Cu pad and first placing, then reflowing a SAC 405 solder sphere sphere (appx. 900 cubic mils in volume) on the paste to form a single mixed alloy solder joint. All test systems were assembled at identical 190C peak reflow temperatures. The solder joint was then subject to a vertical Cold Ball Pull (CBP) test at a pull rate of 5mm/s, as shown in Figure 10. The Force-Displacement curve in Figure 11 shows that the solder ball joint formed using the modified ductile BSA paste exhibited a marked increase in displacement relative to the standard, brittle BSA. In fact, under the conditions of this CBP test, the hybrid solder ball joint formed with ductile BSA paste showed even a greater displacement than solder ball joint formed with the SAC alloy.

Additionally, following the CBP test, we examined the fracture interface to evaluate the type of disbond that occurred. Specifically, we studied whether the solder joint fractured at the IMC interface, indicative of a brittle material or within the bulk of the solder joint, suggestive of a more ductile material. Figure 12 shows that the ductile BSA material requires a mean disbond force similar to that of SAC with a few fractures occurring in the bulk solder at the mean disbond force suggesting that the modified material shows increased ductility relative to the standard BSA, and that it could be further improved to match the SAC failure modes through additional alloy reformulations.

The Cold Ball Pull results provide good insight into the change in ductility due to the solder modification, but do not provide a direct correlation to how the material will perform under drop shock conditions. This is primarily due to the dependence on strain rate on the joint fracture mechanics and the severe strain rate conditions experienced during shock tests.

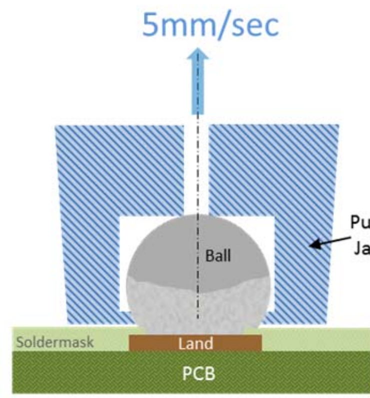


Figure 10: Schematic representation of Cold Ball Pull test condition

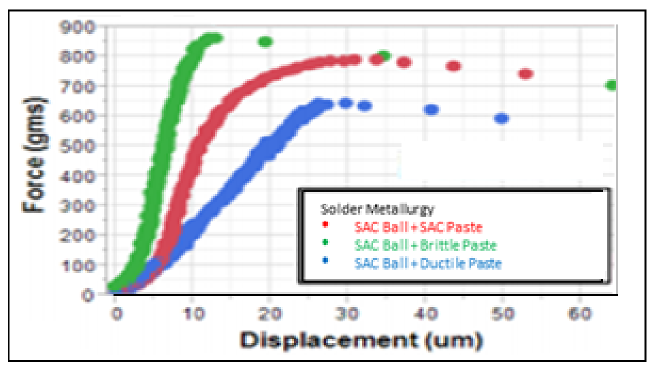


Figure 11: Force displacement curves comparing the SAC305/SAC305 system vs. SAC305/SnBi solder systems

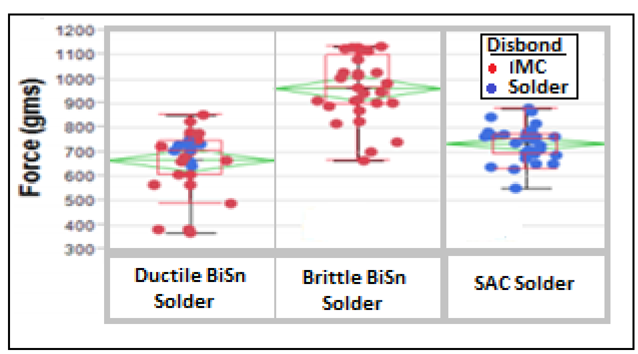


Figure 12: Cold Ball pull force and disband type for the SAC305/SAC305 and the SAC305/SnBi solder systems.

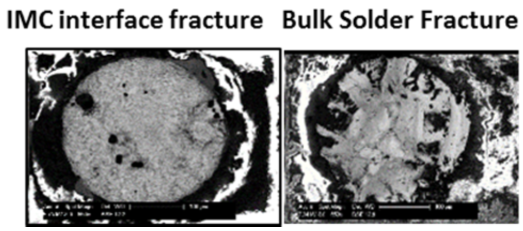


Figure 13: Images of the disband region after Cold Ball Pull joint fracture.

The shock performance of FCBGA test vehicles assembled using solder paste standard BSA (BiSnAg metallurgy) and d-BiSn (Ductile BiSn metallurgy) solder pastes were compared directly to FCBGA packages assembled using SAC305 solder paste and then subjecting each assembled test board to 140g's 2ms half-sine shock loading for 30 drops.

The shock test board was monitored electrically in-situ, during shock impact to determine the first package location to show failure. Based on the 2-P Weibull distribution data, standard BSA leg samples showed lowest characteristic life with only 8 drops to 63.2% failure at the monitoring location. The Ductile BiSn leg samples showed a 26% improvement in the characteristic life. While the shock performance is still not as robust as SAC305, it does provide clear evidence that material modification leads to enhanced shock performance.Further modifications are currently underway to establish a low temperature Bi-based solder paste that performs equivalently to SAC305 in all reliability metrics. Since most mobile laptop manufacturers use corner bond adhesive on BGA components, another leg was added to the shock evaluation experiment using a corner bond adhesive to a set of samples soldered with standard, brittle BSA as a check on the viability of these materials under practical conditions. This additional leg which had corner bond reinforcement added to these packages resulted in *no detectable failures* for any samples in the experiment. Table 4 lists the characteristic life of all 4 legs evaluated in this mechanical shock drop exposure experiment and Figure 14 depicts the Weibull plots for comparison.

Table 4: Shock Drop performance of the SAC305 and SAC Ball/SnBi solder paste formed mixed alloy solder joints.

SOLDER PASTE	CHARACTERISTIC LIFE (# DROPS TO 62.3% FAIL)
BiSnAg (Standard BSA)	12
d-BiSn (Ductile BiSn)	15
Standard BSA + Corner Glue	No Fail
SAC (SAC305)	28

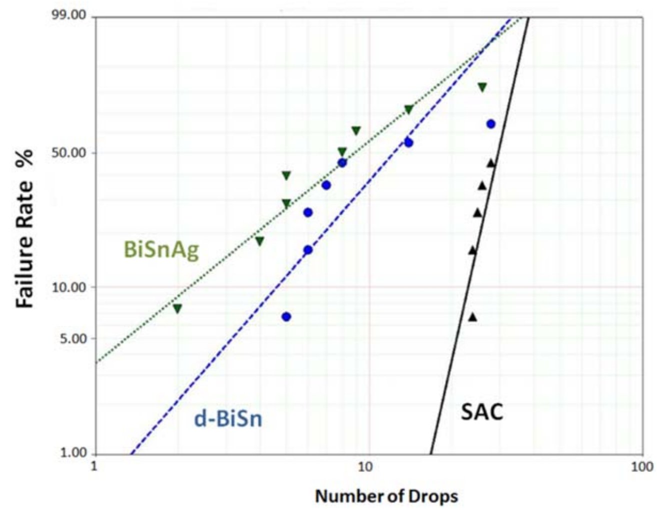


Figure 14: Weibull distribution of shock drop performance of the full SAC, SAC/BiSnAg and SAC/Ductile BiSn mixed alloy solder joints

To confirm the viability of using low temperature ductile BiSn solder pastes at the system level, in collaboration with industry partners, fully functional laptop systems were assembled by an OEM on an ODM's manufacturing line, and subjected to system level shock and temperature cycling stress tests The systems were tested under two sets of reliability conditions for mechanical shock and temperature cycling. One was the standard requirement for currently assembled product system and the other was at harsher stress levels than the standard requirements. The results indicated that the systems with low temperature solder paste assembled systems were equivalent to those assembled with the SAC305 solder paste for both reliability tests and at both the standard and harsher levels of the reliability test conditions [25].

CONCLUSION

The use of BiSnbased solder paste substantially improves the BGA solder joint yield relative to SAC based solder pastes, even when the BGA ball metallurgy remains SAC, and does not fully collapse during the low temperature reflow soldering process.

Low temperature soldering with Bi-Sn based solder pastes does result in measurable energy cost savings and a reduced carbon footprint. The estimated cost savings of the low temperature operation was determined to be \$168/oven/week or \$8,749/oven/year. The approximate carbon footprint reduction was 57.2 metric tons of CO_2 per oven per year

The characteristic life under mechanical shock/drop tests of SAC BGA solder joints formed with ductile BiSn solder pastes compositions were found to be 26% better than those formed the standard BiSnAg metallurgy solder pastes. But the characteristic life of the BGA solder joints formed using ductile BiSn solder pastes was still significantly lower than those solder joints formed with SAC solder paste (full SAC solder joint). Further enhancement in the BiSn solder metallurgy to increase the mechanical shock performance of BGA solder joints formed with SAC balls using these solder pastes is presently in progress and results will be reported in the future.

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