Investigation of Low Temperature Solders to Reduce Reflow Temperature, Improve SMT Yields and Realize Energy Savings

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Abstract

The miniaturization of electronic devices demands the continued shrinking of system z-height. A significant consequence of these ultra-thin systems is yield loss due to high temperature warpage during SMT reflow. This warpage results from the Coefficient of Thermal Expansion (CTE) mismatch between the key materials, such as Si, organic substrates, and Cu in the SoC-to-PCB system stack up. Warpage impacts the solder joint formation, and can result in both bridging and open defects due to the compressive and expansive forces experienced during solder joint collapse at high temperatures. Solutions typically consist of mechanical reinforcement such as molding compounds or metal stiffeners applied to the substrate, and while successful, these solutions can be expensive. In this study, we investigate the impact of temperature on the system warpage profile and find that reducing the reflow peak temperature from 245C to <180C appreciably reduces the amount of warpage, thus improving SMT yields. To reduce the reflow temperature, we have used Bi-Sn-Ag solder alloys with a M.P. of 138C. Although reduced reflow temperature improves SMT yield, Bi containing solders have been previously shown to induce brittleness [1] that can jeopardize joint reliability. To overcome this, we further investigate a class of Bi-based solders that also contain epoxy resins to mechanically reinforce the solder joint. This paper describes the yield improvements and defect mechanisms as a function of temperature as well as the impact of epoxy based solder reinforcement materials on SMT process yields. Lower reflow temperatures bring added environmental benefits and we have conducted an analysis of the potential energy and cost savings in HVM due to lowering reflow temperatures by 65C-80C.

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 SnAgCu (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 [2]. 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. This higher warpage generates solder joint yield loss because the SMT reflow process using solder paste is predicated on a contact being maintained between the solder paste deposit on the PCB lands and the termination of components to be soldered during the time the component and the board are in the reflow zone of the oven, where the solder paste is molten.

Some packages, such as Flip Chip Ball grid Array (FCBGA) packages, however do not always meet this requirement due to their dynamic warpage during the SMT reflow soldering process. This dynamic warpage occurs due to the differential expansion of materials comprising the FCBGA package. 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. 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 [3], 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 [4,5], and Solder Bridging, where two or more neighboring solder joints are connected together .

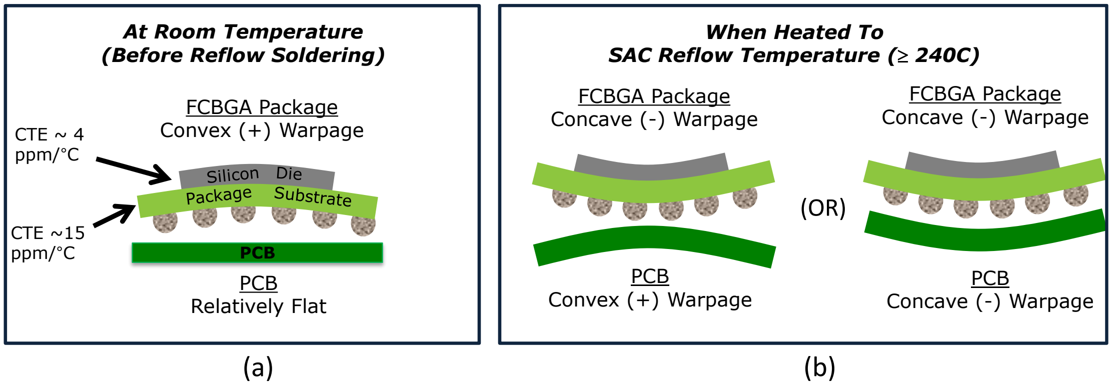


Figure 1-Typical warpage shapes of FCBGA packages (a) at room temperature and (b) at SAC solder paste reflow temperatures

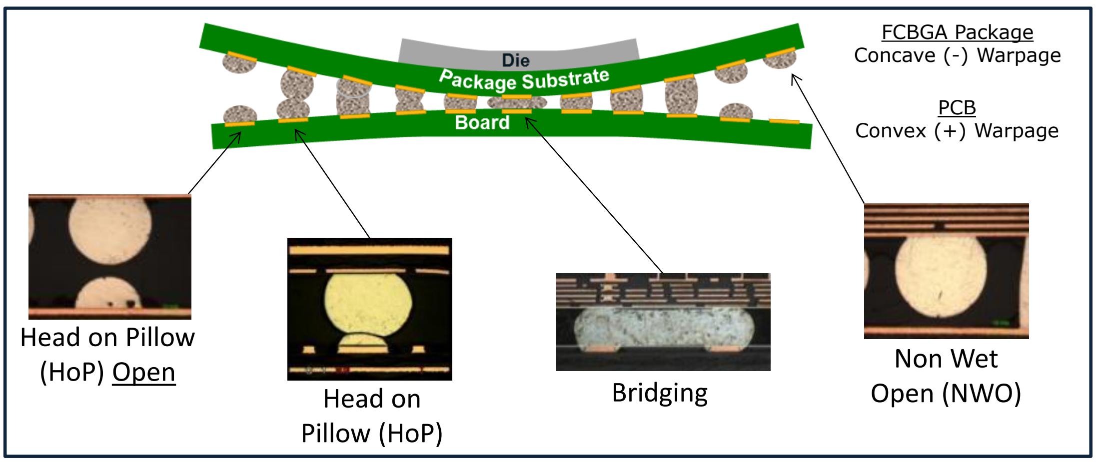


Figure 2 - Description of defects that can be caused by dynamic warpage of FCBGA components and/or PCBs during the reflow soldering process

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 packages 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 `Flip Temperature` range, which is the temperature range where the FCBGA package warpage `flips` from convex (+) to concave (-) 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, the `Flip Temperature Range` is typically between 125C and 160C.

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 [6]. There are many other advantages with the Bi-Sn metallurgy in addition to it's melting point falling in the desired Flip 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 [7,8,9]. Today, solder pastes with this Bi-Sn-Ag (BSA) metallurgy are widely available from many solder paste suppliers [10]. 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.

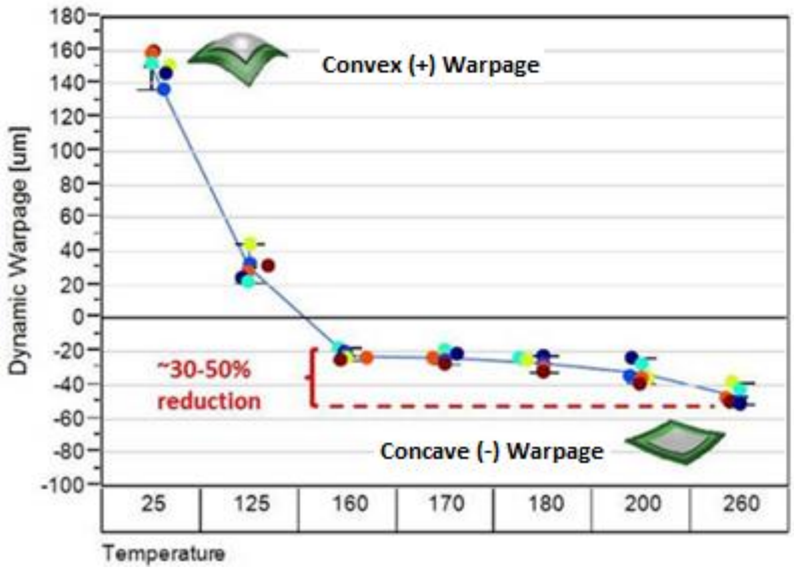


Figure 3 – Dynamic Warpage plot with temperature for a FCBGA package. The amount of dynamic warpage reduction if soldering in the 160-180C peak reflow temperature range is indicated

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 [11, 12, 13]. 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. 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 [14,15, 16]. Solder Pastes with these ductile Bi-Sn metallurgies are presently under development by a few solder suppliers.

The polymeric path to strengthen the solder joint at the macro level is by using cured polymeric materials such as epoxy as an external reinforcement. Such polymeric reinforcement is already in use for BGA and other area array components, in the form of board level underfills. These underfills are dispensed at specific locations where the BGAs are present after the board has been reflow soldered. The underfills are then cured in a subsequent post reflow step. These two additional steps, dispensing and curing, adversely impact the throughput time in high volume manufacturing environment as well as require expenditure of more energy for the curing ovens. Therefore, high volume manufacturers, such as ODMs, are reluctant to use these materials. Moreover, underfills are applicable mainly to area ar ray devices and hence only strengthen part of the solder joints on a typical product board. The solder joints of other components on the board, such as leaded devices and chip components, also need strengthening.

The better polymeric option to strengthen the Bi-Sn solder joints is to use low temperature resin reinforced (LTRR) solder pastes. These are solder pastes that contain an un-cured resin. During the reflow process, when the solder paste melts, this resin is displaced away from the molten solder and coats the molten solder externally. As the reflow process proceeds further, the resin starts to cure. Eventually, after the reflow process is completed, the cured resin forms a fillet around the solder joints, providing the necessary mechanical reinforcement. This concept of resin reinforced solder paste is not new. Epoxy fluxes, which have been on the market for some time now [17,18,19, 20,21] are a forerunner to it. The difference is that epoxy fluxes require a dipping process to apply the material to the component terminations or a dispensing step to apply the material to the printed board lands, whereas the resin reinforced solder pastes apply the resin to the lands during the stencil printing process. Today, LTRR solder pastes have been developed and available for evaluation from at least five solder paste suppliers, four of which are in the Far East.

Figure 4 compares the process steps and the resultant solder joint stack-up and structure for the metallurgical and polymeric enhancement solution paths to strengthen a typical mixed alloy (SAC ball + BiSn paste) BGA solder joint.

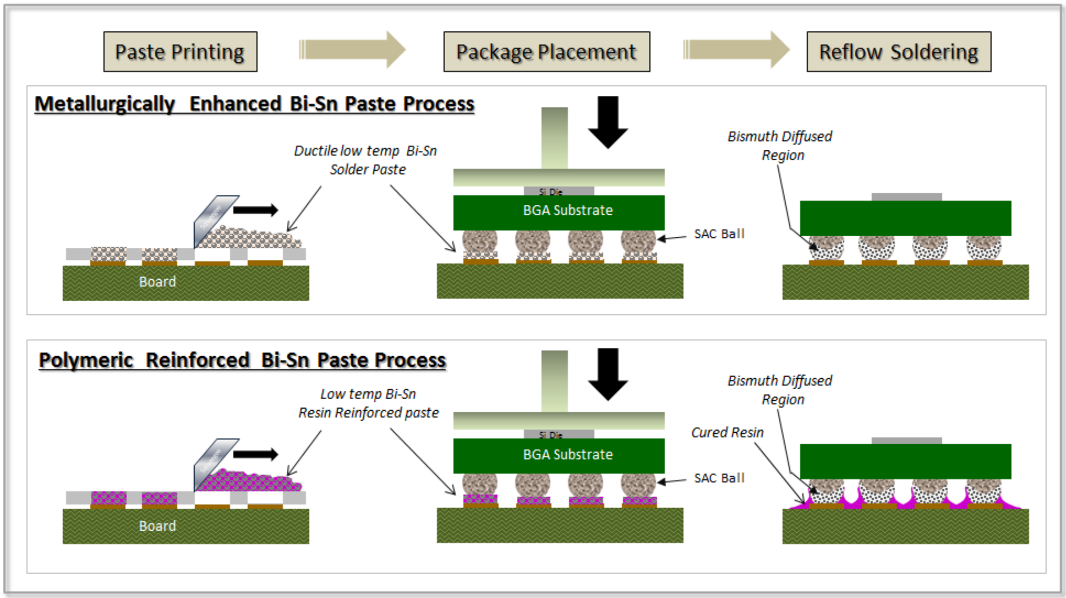


Figure 4 – Comparison of Assembly Process Steps for Metallurgical and Polymeric Enhancement of Low Temperature Bi-Sn Solder Joints for BGA components

This paper will focus on the solder paste printing processability, reflow profile comparison and SMT solder joint yield when using standard BSA and LTRR solder pastes. Evaluation of the ductile metallurgy Bi-Sn solder pastes, as well as the mechanical shock, temperature cycling reliability, as well as the reworkability of BSA and LTRR assembled boards will be covered in future papers.

Solder Pastes

Table 1 lists the description of the solder pastes used in this study. There are two LTRR solder pastes listed and each has a different manufacturer. In this paper, only the stencil printing results for LTRR2 pastes will be elaborated. Some differences between the solder pastes are evident. The LTRR1 paste has a Type 5 particle size (10-25um) , the other have Type 4 (20-38um). Both LTRR pastes have a higher flux % than the BSA and SAC pastes. This is due to the presence of the reinforcing resin within the flux. The LTRR paste has a storage requirement of -20C, which entails that it needs to be stored in a freezer. The other three solder pastes can be stored in a refrigerated environment.

Table 1 – Various Properties of the Solder Pastes Evaluated

	Solder Paste Type			
Property	**SAC305**	**BSA**	**LTRR1**	**LTRR2**
Alloy Composition, wt %	**Sn96.5/Ag3.0/Cu0.5**	**Bi57.6 /Sn42.0/Ag0.4**	**Bi58/Sn42**	**Bi58/Sn42**
Melting Point, C	**217-219**	**138-140**	**139**	**139-141**
Power Particle Size	**Type 4**	**Type 4**	**Type 5**	**Type 4**
Flux Content, wt %	**11**	**10**	**18**	**15**
Flux Type	**ROL1**	**ROL0**	**REL0**	**REL0**
Viscosity, Pa-S @25C	**200+/- 30**	**190 +/- 30**	**200**	**205+/- 10**
Halogen Content, %	**0.05**	**0**	**0**	**0.02**
Storage Temperature, C	**0 to 10**	**0 to 10**	**-20**	**0 to 10**

Reflow Profiles

Figure 5 depicts the reflow profiles for the three types of solder pastes evaluated. The SAC reflow profile is a typical ramp to peak reflow profile, with a peak temperature in the 240-245C range. The BSA reflow profile is a typical ramp-soak=-peak reflow profile but with a peak temperature in the 170-180C range.

The LTRR reflow profile is significantly different from the other two. It is a `trapezoidal` reflow profile, with 160C-165C being the peak temperature, and it extends out to over 600 seconds, which is twice the duration of the other two profile. Per the solder paste manufacturer, this extended time is required for the reinforcing resin to cure sufficiently and harden.

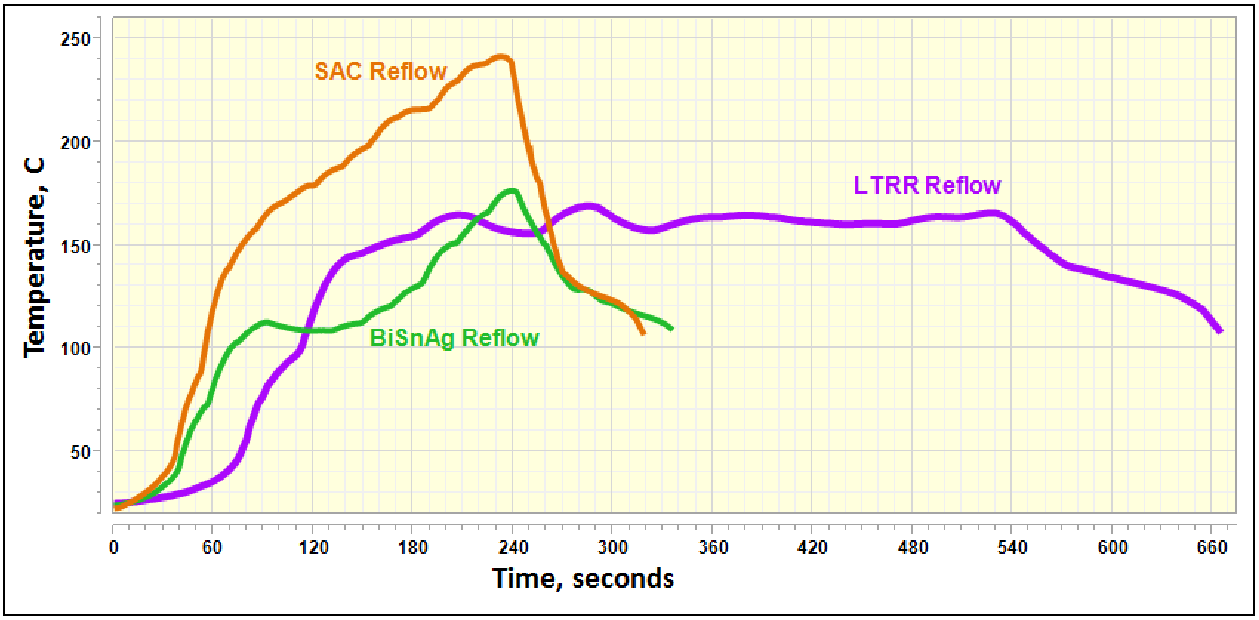


Figure 5 – Comparison of Reflow Soldering Profiles for the Three Types of Solder Pastes (SAC, BSA, LTRR) evaluated.

However, there are other drawbacks to this LTRR Trapezoidal reflow profile besides its extended time above liquidus, which increases the electrical power required to run it on the reflow ovens. Developing the reflow profile in the standard 14 zone reflow oven is quite difficult as compared to the ramp-soak-peak reflow profile. Though the solder paste suppliers recommend a narrow peak temperature range (5C), it was difficult to keep the peak temperature range constant, as seen in Figure 5. The challenge that needs to be addressed here is the requirement that the resin in the solder paste must initiate the gelling and curing process after the solder has melted and wetted the board land and component terminations, and then subsequently there is sufficient time given above the cure temperature for the resin to harden. Nevertheless, based on these inputs, the solder paste manufacturer has developed another shorter, peak-ramp-soak reflow profile for the LTRR paste. This will be discussed in the Future Work section later.

Stencil Printing Capability of Solder Pastes

The capability of printing two low temperature resin reinforced solder pastes through stencils was evaluated first and compared with that of the standard SAC305 metallurgy solder paste and a non-resin reinforced BiSnAg solder paste. The test land pattern for this evaluation was that of a BGA with 1191 circular lands. Figure 6 shows the board and BGA pattern layout. The lands were placed on mixed pitches, with 0.65 mm being the finest pitch. Table 2 lists the number of lands for each diameter (12 mils vs 15 mils) and each design (solder mask defined vs metal defined). The 15 mils lands were mainly in the corner regions of the land pattern and under the die shadow. All soldermask defined lands were in the corner regions.

The stencil aperture diameter: land diameter ratio was 1:1. The stencil thickness was 4 mils (101.6 µm). Hence, the area ratio (AR) of the 12 and 16 mils diameters corresponds to 0.75 and 1.0, respectively. The stencil comprised of a laser-cut, Stainless steel foil, on a 29x29 inches frame, with a single image, center justified. The solder paste was printed on a DEK Galaxy printer. The critical to function parameters, such as squeegee angle, print pressure and speed, separation distance and time, were set to the optimum values derived for the SAC305 solder paste. The solder paste volume was measured using a Koh Young KY3030 VAL solder paste Inspection (SPI) machine, set at a 40 µm height threshold. For each solder paste evaluated, four boards were printed, once each in the forward and reverse direction.

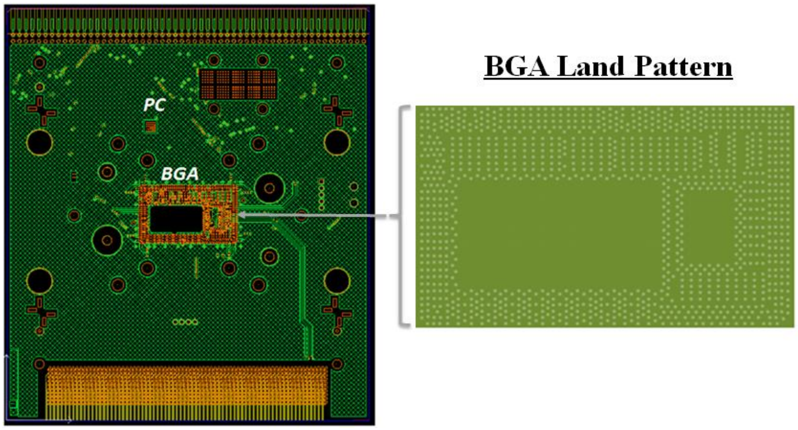
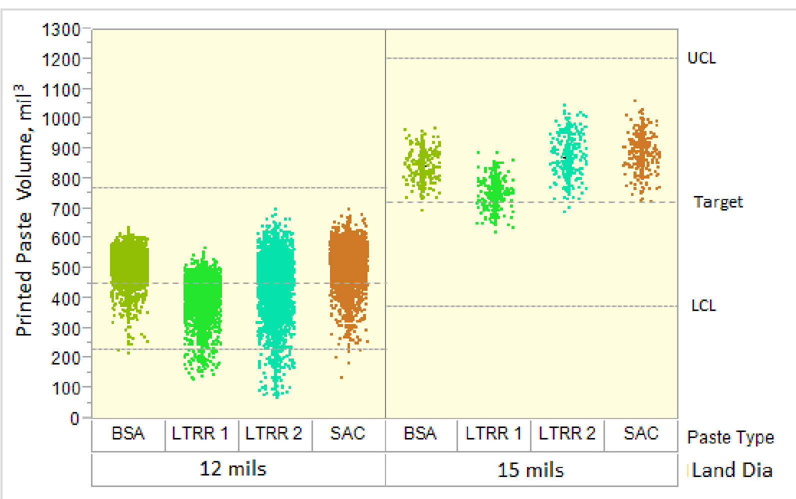


Figure 6 - The printed circuit board test vehicle used and a magnified view of the BGA land pattern used for evaluation of the printing capabilities of the solder pastes.

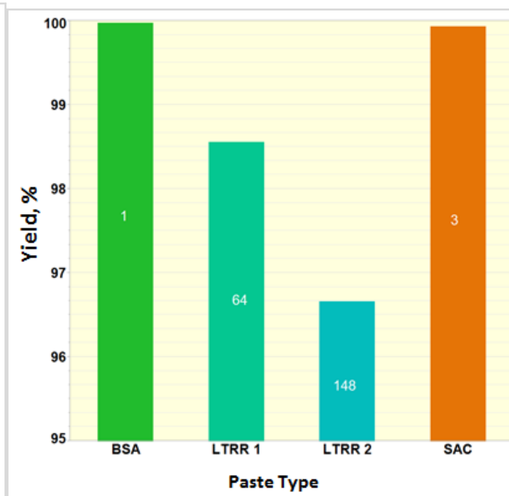
Table 2 –Design Parameters for BGA Land Pattern used for Stencil Printing Capability Study

Land Diameter	Metal Defined	Solder Mask Defined
12 mils (304.8 μm)	1072	35
15 mils (381.0 μm)	78	6

Figure 7(a) depicts the printed paste volumes for all four solder pastes evaluated and also shows the control limits set for the printing process. Figure 7(b) depicts the yield % of the BGA lands that met these control limits, for the 12 mils diameter lands. All four solder pastes met the process capability requirements for the 15 mils diameter lands, with yields being 100%. However, for the 12 mils diameter lands, the two LTRR solder pastes had a significantly lower yield than the other solder paste. The BSA solder paste yield was equivalent to the standard SAC305 solder paste.



(a)

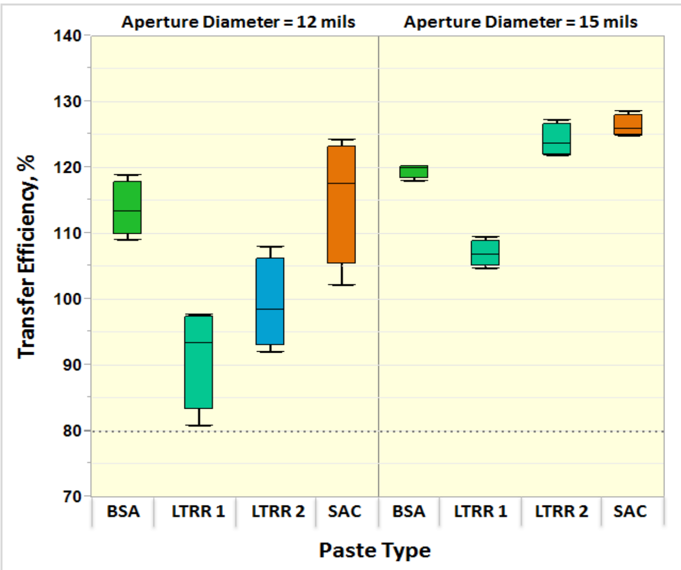


(b)

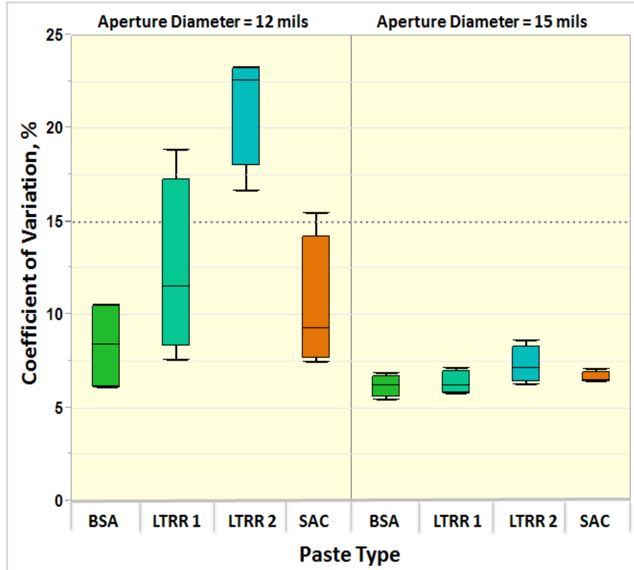
Figure 7 - (a) Printed Paste Volume in cubic mils for each solder paste evaluated on 12 and 15 mils diameter lands; (b) % Yield at the land level, for each solder paste evaluated for the 12 mils diameter lands.

Further data analysis was conducted to determine the Transfer Efficiency (TE) and Coefficient of Variation (CV) of the solder paste volumes for each of the four solder pastes evaluated. The Transfer Efficiency is the ratio of the volume of solder paste deposited on the printed board land to the volume of the stencil aperture. This parameter should be maximized, with a 100% or higher value being desirable. 80% is set as a minimum in this study. The Coefficient of Variation is the standard deviation of the data distribution as a % of the mean. These are two of the basic statistical parameters used to compare data sets for solder paste printing [22].

Figure 8(a) presents the Transfer Efficiency for each of the solder pastes on the two different stencil aperture diameters. As expected the TE for the 15 mils apertures was higher, since the 15 mils apertures have a higher AR. The two LTRR solder pastes had significantly lower transfer efficiency than the BSA and SAC solder pastes. Figure 8(b) presents the Coefficient of Variation for each of the solder pastes on the two different stencil aperture diameters. As expected the CV for the 15 mils apertures was significantly lower. However, for the 12 mils aperture diameter, the two LTRR solder pastes were significantly higher than the standard SAC paste, and the LTRR2 paste did not meet the 15% maximum CV requirement. Another point of note is that the BSA paste outperformed the standard SAC solder paste in both TE and CV metrics.



(a)



(b)

Figure 8 - (a) Mean of Transfer Efficiency for each solder paste evaluated on 12 and 15 mils diameter lands; (b) Mean of the Coefficient of Variation for each solder paste evaluated for the 12 mils diameter lands.

The stencil printing capability evaluation results above indicate that the resin reinforced solder pastes have a lower capability to the standard SAC and BSA solder pastes used in this study. The presence of the resin component in the solder paste is one obvious cause of this. The critical printing parameters used in this study were optimized for the SAC solder paste. Hence, it is obvious that with the resin component in the solder paste, the printing parameters will need to be modified to get better TE and CV, particularly as the AR of the stencil aperture decreases. The LTRR solder paste manufacturers are also modifying the particle sizes to improve the TE and CV of their solder pates to enhance its capability for lower ARs which will be needed for finer pitch (<0.4mm) BGA and other component land patterns.

Validation of Package Warpage Effects Mitigation by Low Temperature Reflow

Experiments were conducted to determine whether reflow soldering with BSA solder paste at lower peak reflow temperatures can lead to higher solder joint yield for FCBGA components with excessive dynamic warpage magnitudes. FCBGA package Test Vehicles (TV1), with daisy chain structures, 40x24mm in body size with a total of 1191 balls, 16 mils in diameter, at 0.65mm pitch, and package warpage levels in the 245 to 290 µm range at 260C, were used for this study. The excess dynamic warpage of these test vehicles was generated by bending these packages in a lab before reflow soldering.

Two sets of these TV1 packages were reflow soldered, each set with a different solder paste, on an printed board test vehicle which had land patterns designed such that the electrical continuity of the solder joints could be measured using daisy chain structures. One set was soldered with SAC solder paste, in the 245°C to 250°C peak reflow temperature range. The other set was soldered with the BSA solder paste in the 175 to 180°C temperature range. A 1:1 stencil aperture to land diameter design was used for solder paste printing to forcibly precipitate open defects, such as HoP and HoP Open. These board assemblies were then tested with a Flying Probe Tester to determine the number of open solder joints in each package.

Figure 9(a) shows the plot of the number of open solder joints per component for the BSA and SAC solder pastes. BGA packages assembled with BSA metallurgy paste showed zero solder joint opens whereas BGA packages assembled with SAC solder paste metallurgy showed a large amount of open solder joints per package, with the range varying from 5 to 200 joints. Figure 9(b) contains photographs showing examples of the solder joint open failures after components have been through the Dye and Pry procedure. The HoP signature of the solder joint opens is evident from the photographs.

These results indicate that by eliminating HoP defects, 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.

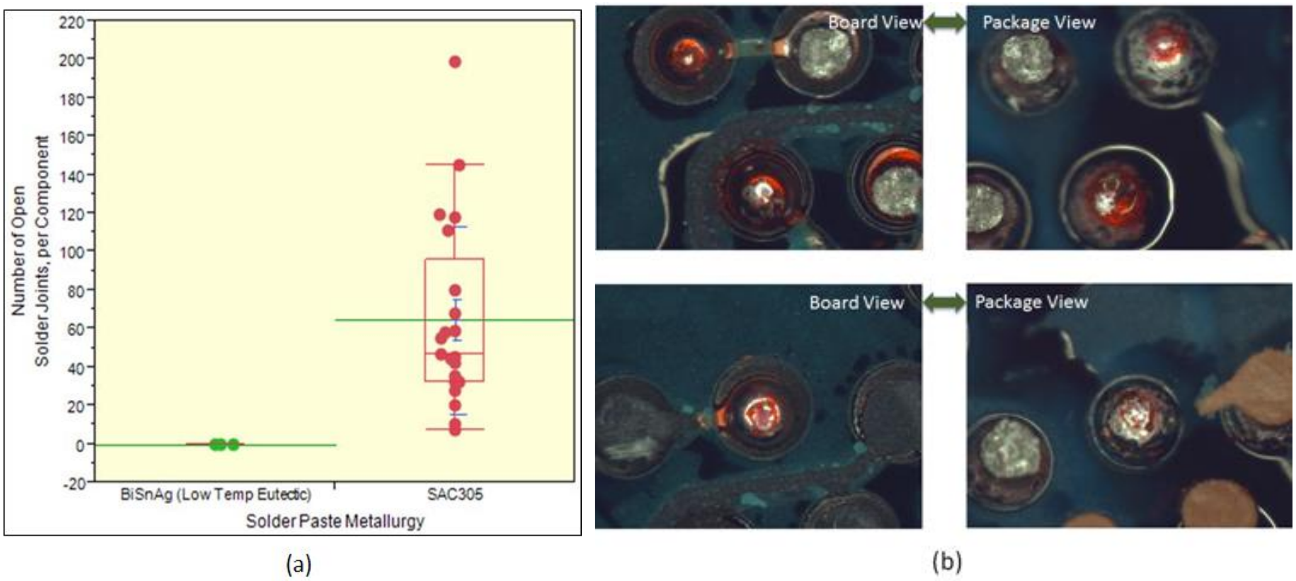
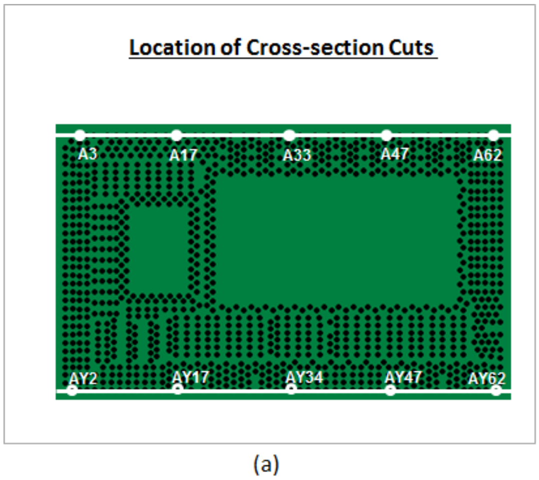


Figure 9 - (a) Number of Open Solder Joints per component for eutectic BiSnAg and SAC305 solder paste metallurgies; (b) Optical Micrographs of the surfaces of boards and components, post Dye and Pry, for two failed components.

Cross-sections of one package in each solder paste case, were made to determine solder joint heights and microstructures. Two cross-section cuts were made for each package. Figure 10(a) shows the location of these cuts within the ball array. The mixed BSA-SAC solder joints formed when using the BSA solder paste have a higher mean solder joint height than the homogenous SAC solder joints. This is to be expected since there is only partial collapse of the SAC solder balls when subjected to the lower peak temperature BSA reflow profile. However, the SAC solder balls do collapse fully when subjected to the standard SAC reflow profiles with peak temperatures above the SAC solder melting point. The mean difference between the two data sets is 2 mils (~50 µm).

Another difference between the two distributions for the solder joint heights is that the range for the BSA-SAC mixed solder joint is much smaller than that for the homogenous SAC solder joints. This result reflects the warpage profile of the package at the peak reflow temperature during the corresponding reflow process. For the lower temperature BSA solder paste reflow profile peak temperature the warpage of the package is much lower, as pointed out in Figure 3. Close examination of the SAC305 data distribution reveals that a bimodality. This is due to the concave (-) package warpage where the corners bend upwards from the board at the SAC reflow profile peak temperature.



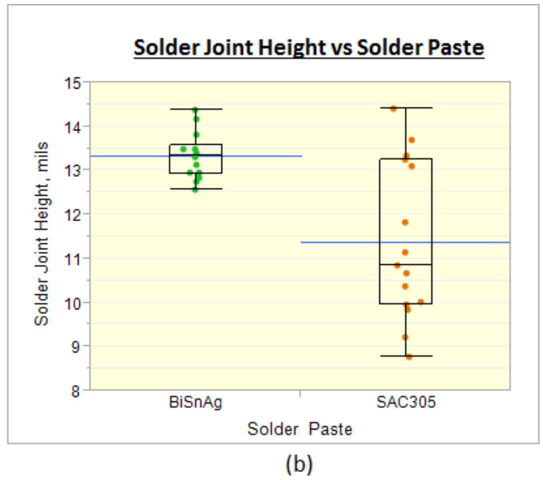


Figure 10 - (a) Location of the two cross-section cuts made within the ball array of the BGA package TV1; (b) Solder Joint Heights for the BGA package TVs vs the solder paste type used to assemble them.

The optical microscopy images of the cross-sections for both mixed BSA-SAC and homogenous SAC solder joint cases, shown in Figure 11, make these points clear. These are images of the four corner solder joints of the package. These four corner solder joints are in regions where the package exhibits the highest dynamic warpage and hence, the largest distance between the package substrate and the board, resulting in the largest solder joint height. The stretched nature of these solder joints is easily apparent, resulting in a columnar or hour-glass shape, rather than the more common barrel shape exhibited by fully collapse BGA solder joints.

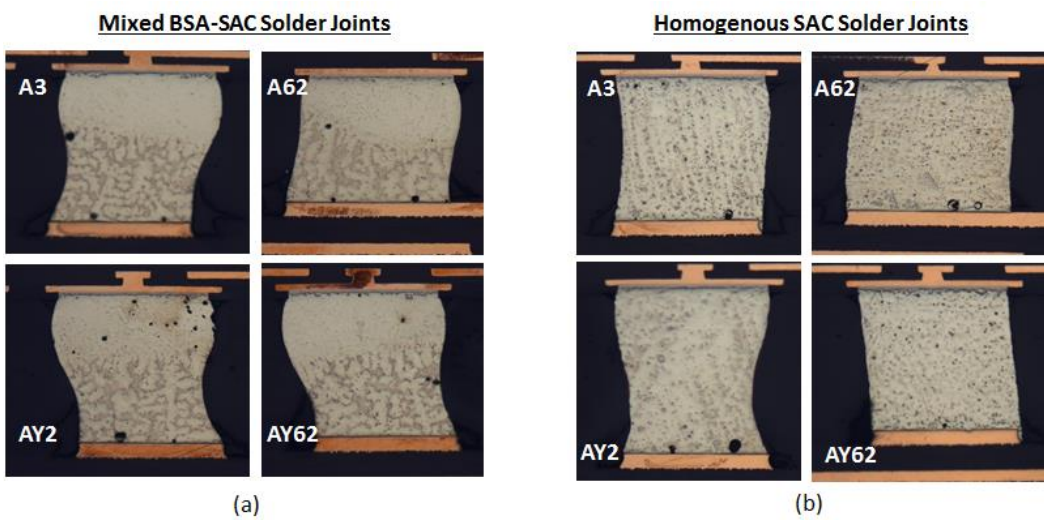


Figure 11 – Optical Microscopy Images of Solder Joint Cross-sections at the Four Corners of the BGA TV1. (a) BSA solder paste and reflow profile was used to form these solder joints; (b) SAC solder paste and reflow profile was used to form these solder joints

Figures 10 and 11, in conjunction with the solder joint yield data in Figure 9, provide a good indication on the solder joint formation sequence for the corner solder joints of high dynamic warpage FCBGA components. In the case of the of the BSA solder paste, the paste melts (at 138-140C) when the package is relative `flat` and therefore there is contact between the solder ball and the molten paste, even though the SAC solder ball has not started the melt at this point. The molten paste wets the lands and the SAC305 solder ball as the temperature is on its way up to the peak reflow zone of 175-180C. As the temperature rises, the package corners rise up due to the dynamic warpage characteristic of the package. However, since the BSA solder paste has already wet the SAC solder ball and bismuth diffusion into the SAC ball has initiated, driven by the Bi concentration difference within it, the molten solder paste mass will stretch with the movement of the ball above the board.

On the other hand, for the SAC solder paste reflow profile case, the SAC solder paste is not yet molten when the package is relatively flat. When it does become molten at around 220C, the solder ball would have already lost contact with the paste due to the high dynamic warpage of the package at this temperature. Hence, the solder joint will not form initially between the solder ball and solder paste in the corner regions.

When the package begins to cool, the package warpage will begin to reduce and eventually the solder ball and the solder mass on the board land will come in contact. If both are molten at this time, which can be the case due to undercooling, sometimes quite significantly, of SAC solder joints, then the solder ball and solder paste will coalesce. If either is not molten when they touch during the cool down period then a HoP defect will form. This is the cause of the high solder joint fall out for SAC solder paste reflow profile case, as shown in Figure 9.

Surface Mount Assembly

To quantify any differences in surface mount yield between a SAC305 paste, BiSnAg, and low temperature resin reinforced options, a custom "high density test board" was used. The test board was an eight layer (8L) design with a thickness of 0.8mm. Components included passives from 01005 to 0805, 0.4mm BGA, QFN, TDFN, CSP, TSOP, and SMT connectors. Component body to body spacing varied from 0.100mm (4 mil) to 0.300mm (12 mil) for the small passives, passive component to BGA body spacing was 0.150mm (6mil) and 0.200mm (8mil). Passive component to other surface mount components were placed at 0.200mm (8mil), 0.375mm (15mil), and 0.750mm (30mil) spacing.

Two boards were processed for each paste type. One board was fabricated with Cu OSP surface finish, while the second utilized ENIG surface finish. Paste print was completed using a DEK Galaxy paste print tool and a 0.100mm (4 mil) thick stencil. The ambient atmosphere in the reflow oven was air. The reflow profiles for the SAC (control leg), BSA solder pastes were as shown in Figure 5. The trapezoidal profile was used for LTRR1 solder paste. As mentioned in the Reflow Profile Development section, subsequent to this assembly experiment, the LTRR1 reflow profile was changed to a ramp-peak-soak reflow profile.

Due to the requirement that the LTRR1 paste be stored at or below -20C, the paste was removed from the freezer four hours before building the boards. BSA and SAC pastes were removed from the refrigerator 2 hours before the build and allowed to warm to room temperature. Build order was set as LTRR1 first, BSA next, and finally SAC. As reported in the section on Stencil Printing Capability, the DEK stencil printer parameters needed to be modified from those employed for SAC solder paste printing to increase solder paste volume yields. These were therefore modified for the LTRR1 paste and these modified parameters as well as the original parameter settings employed for printing SAC and BSA solder pastes are shown in Table 3.

Table 3 - Comparison of Initial Paste Print Set-Up Parameters For SAC/BSA vs. LTRR Paste

Paste	Squeegee Angle	Print Speed (mm/sec)	Print Gap (mm)	Separation Speed (mm/sec)	Print Pressure (Kgm)
SAC/BSA	45°	60	0	5	7
LTRR	45°	50	-0.25	3	9

Each board was printed with paste and then each pad location was measured for paste area and volume using a Koh Young paste inspection tool. Passing paste area and volume were set as +/- 50% of theoretical paste volume for a given aperture size and are identified as "GOOD" in the paste volume results. Paste volume results were comparable for each of the paste types, as shown in Figure 12.

Print data was analyzed for percentage of pads with insufficient paste and excessive paste. There was no significant difference in the level of excessive paste volume between the three paste options. For pads identified with post-print pad to pad bridging, LTRR1 was significantly worse than the BSA paste. However SAC results were comparable to both low temp pastes. The BSA paste was found to have a significantly higher level of insufficient paste volumes compared with LTRR1 or SAC. These insufficient results appear to have been the result of stencil aperture clogging as previous BSA printing results have consistently demonstrated high quality print results.

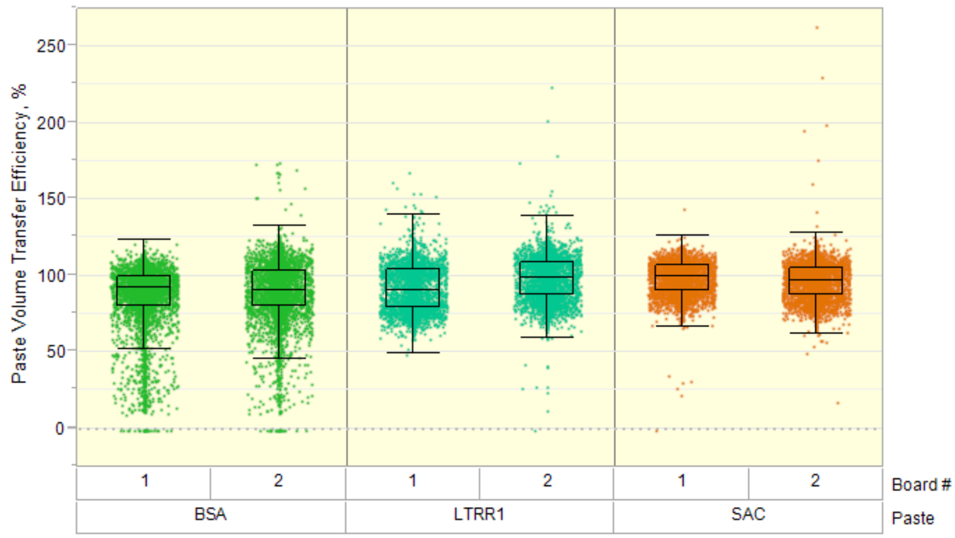


Figure 12 - Paste Print Volume Comparison For Each Paste

After completing reflow, each board was visually inspected and any defects were logged per IPC standard 610 criteria [23]. Absolute defect counts as well as specific failure mechanism were then analyzed for each combination of paste and board surface finish across the component to component spacing. For component to component spacing down to 0.150mm (6 mil), no statistical significance for SMT defects was found between any of the three paste options. At 0.100um (4 mil) component to component spacing, the two low temperature solder pastes produced statistically significant defect results when compared with the SAC paste. At 0.100mm spacing BSA paste has a larger number of bridge defects when compared with the LTRR or the SAC pastes, as shown in Figure 13(a). The LTRR paste produced significantly more skew defects at 0.100mm spacing than the BSA or SAC pastes, as shown in Figure 13(b). The resin component of the LTRR paste appears to pull the components towards each other creating the skew. The gap between the parts is filled with the epoxy resin, but it was not determined if there was any electrical contact between skewed parts. No difference in defect performance was observed between the Cu OSP and ENIG surface finishes.

The results from this SMT assembly study indicate that the LTRR1 paste capability at 100mm component-to-component spacing is lower than that for the standard SAC solder paste. One avenue for improvement in this capability is the modification of the LTRR1 solder paste reflow profile from a trapezoidal profile to a ramp-peak-soak reflow profile. This is being evaluated presently.

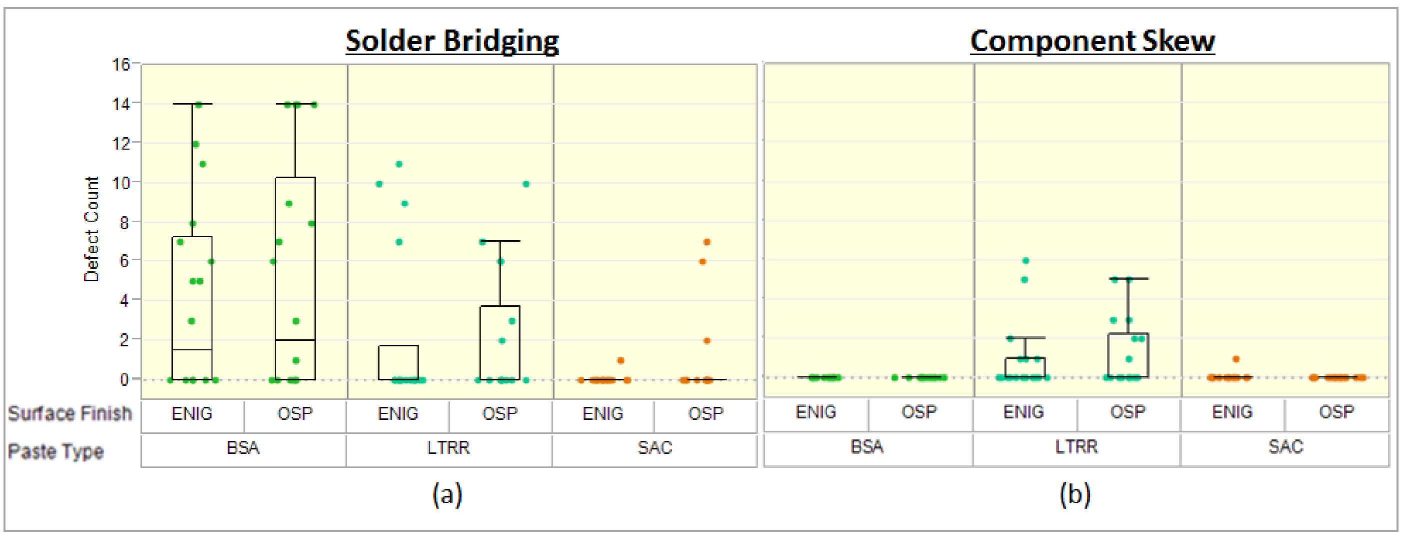


Figure 13 - Comparison of Defects at 0.100mm Component Spacing due to (a) Solder Bridging and (b) Component Skew

Optical Micrographs of LTRR solder Joints

Cross-sections of solder joints formed using LTRR solder paste will have a polymer fillet around the solder joints near the board land. However, to detect this polymer fillet requires the optical image to be viewed in the dark field mode where the sample is dark but the background is light. This is exemplified by Figure 14.

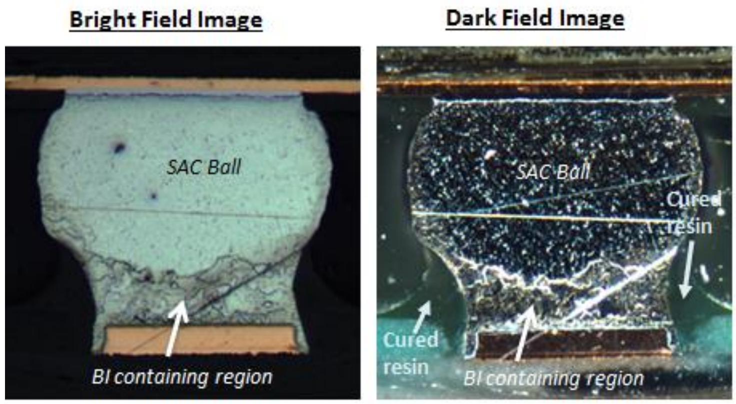


Figure 14 – Bright Field and Dark Field Optical Micrographs for a BGA LTRR solder joint

Figure 15 shows examples of LTRR solder joints for various types of the components. The cured resin is seen to form a fillet around the solder joint. This resin adheres to the solder joint, the component terminations as well as the solder mask or board laminate in areas where there is no solder mask. For BGA solder joints the resin adheres to the solder ball in the region where the bismuth has diffused into the un-melted SAC solder ball. For BGA solder joints the fillet appears uniform across the solder joint, but for chip and leaded component solder joints, the uniformity is difficult to gauge from the cross-sections and warrant further inspection and investigation.

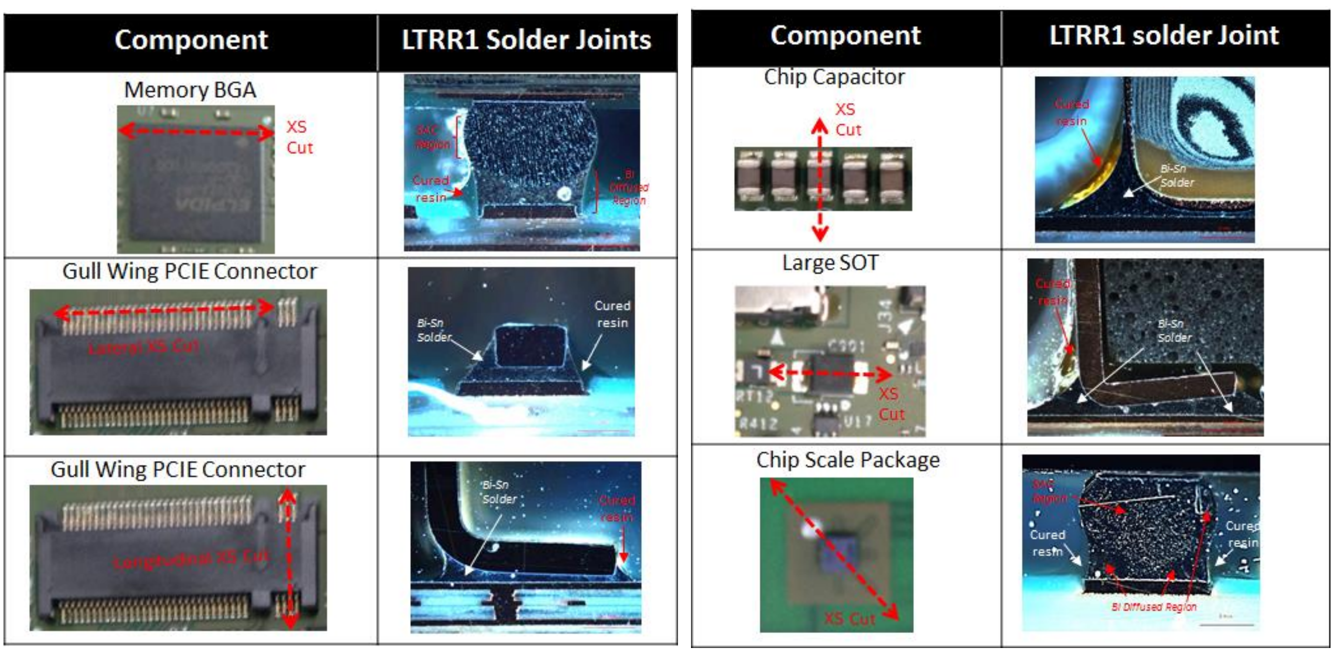


Figure 15 –Dark Field Images of Optical Micrographs for a BGA solder joint formed using LTRR solder paste.

Power Use Savings

A previous study [24] has shown that considerable energy savings can be realized by lowering the peak soldering temperature when manufacturing electronic assemblies. These savings result 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. 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 16 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.

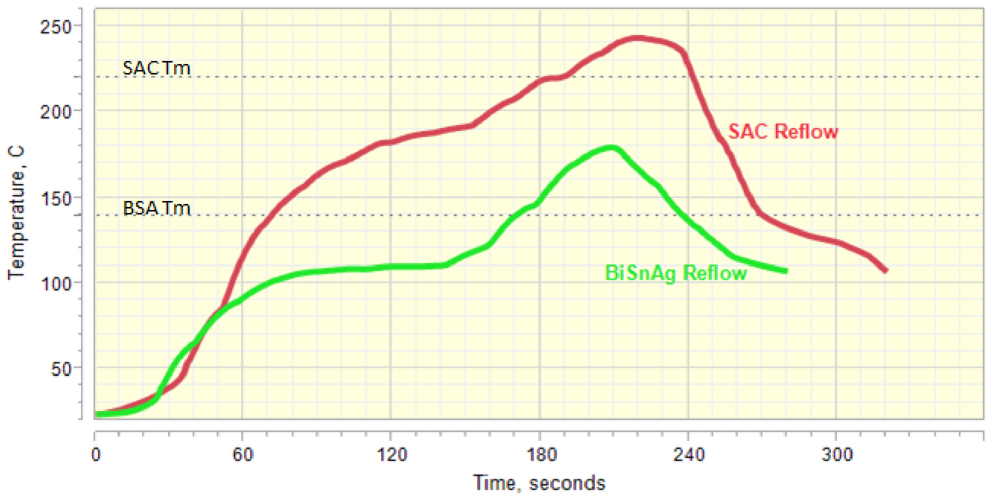


Figure 16 - The Two Reflow Profiles used for the Power Use Savings Study

Table 4 shows the temperature settings for each zone to achieve these two reflow profiles. It is apparent that the temperature settings for the BSA reflow profile are significantly lower than that for the SAC reflow profile.

Table 4 - Temperature (in C) Setting for each zone and Belt Speed (in cm/min) setting for the Reflow Oven during the Current Load measurements

		Zone # of the In-line Reflow Oven														Belt
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	Speed
Reflow	SAC	120	160	170	180	190	195	195	215	230	245	250	235	150	100	115
Profile	BiSnAg	95	100	110	110	110	110	110	125	155	185	185	145	120	100	115

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 17 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) and shown in Table 5.

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

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 5 lists the calculated Current and Power Usage during the two reflow profile settings for the in-line reflow oven.

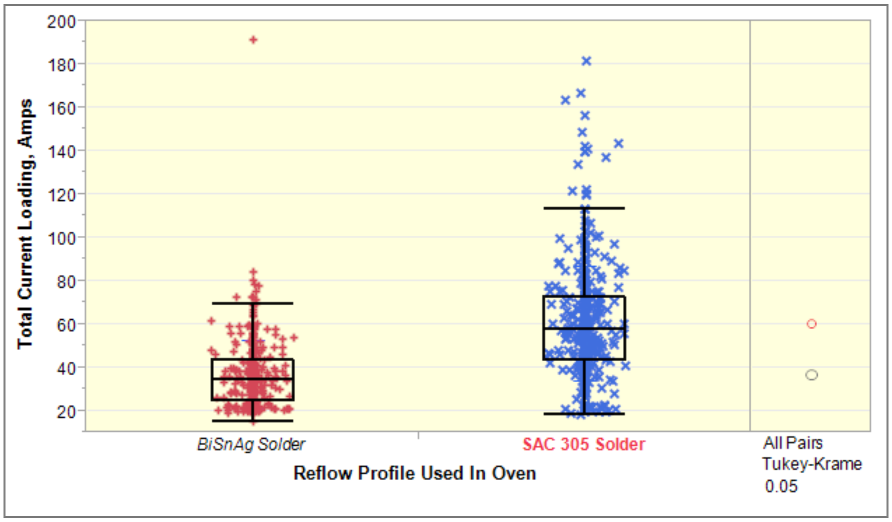


Figure 17 – Comparison of Current Loading for a Reflow Oven when running a Low Temperature BSA soldering vs a standard SAC soldering reflow profiles

Table 5 - 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 [25] and the high end of China energy estimates [26], 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 6. For a large HVM factory that is continuously running hundreds of ovens, this use of low temperature soldering with Bi-Sn based solders can result in significant cost savings.

Table 6 - 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 [27] 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 [27]. For large HVM production, low temperature reflow soldering using Bi-Sn based solder pastes results in a significant reduction in the emissions of greenhouse gases.

Conclusions

Stencil printing capability of BSA solder paste is equivalent to that of SAC solder pastes, but LTRR solder pastes, due to the resin component in the flux, have a lower capability compared to the standard SAC solder paste used in this study. To achieve similar printing capability as the SAC solder pastes, the critical printing parameters for LTRR pastes need optimizing, particularly as the area ratio of the stencil aperture decreases.

Lower peak temperatures of 175-180C during SAC solder paste reflow soldering diminishes solder joint yield loss due to the flatter package warpage profiles of typical FCBGA components, with SAC balls, ,when compared with the 240C+ peak reflow temperatures during SAC solder paste reflow. The SAC solder balls do not fully collapse but the molten BSA solder paste wets the SAC solder balls and a partial collapse occurs as the bismuth diffuses into the SAC microstructure. Solder joints at the corners of the FCBGA packages are stretched and some have an hour-glass shape due to the concave (-) warpage shape of the component at the reflow temperatures.

The capability of LTRR pastes for eliminating solder bridging and component skewing for chip components at 0.100mm body spacing is lower than that for the standard SAC solder paste. Reflow profile modifications may improve this capability and plans are in place to verify this.

LTRR solder pastes after reflow soldering create a fillet of cured resin around the solder joints with the resin adhering to solder mask and/or board laminate as well as the component terminations or the solder ball of BGA components. The height of resin covered by the solder joint depends on the termination and solder joint shape. The cured resin is best detected in a dark-field mode when observing solder joint cross-sections through an optical microscope.

When comparing the power usage of an in-line reflow soldering oven running low temperature Bi-Sn based reflow profile to that of a SAC reflow profile, the cost savings were estimated to be $168/oven/week or $8,749/oven/year. this corresponds to approximately 57 metric tons of CO2 per oven per year. This showed that significant reduction in the energy cost is feasible when converting to a lower temperature solder process in high volume production.

Future Work

Future planned work at Intel can be categorized into process development, and reliability assessment. Listed below are the efforts planned in each of these categories, which will be executed in conjunction with solder paste suppliers and ODM partners.

Process Development

- Validate a new, ramp-peak-soak reflow profile for LTRR solder paste as shown in Figure 18. This new LTRR solder paste reflow profile was proposed by the LTRR paste manufacturers after some drawbacks of the trapezoidal reflow profile, also shown for comparison in Figure 18, were conveyed to them.
- Determine % Bismuth mixing and resin height variation for different BGA ball size to printed paste volume ratios.
- Determine assembly feasibility of the various BGA solder joint configurations shown in Figure 19. The dynamic package warpage limit for each of these configurations will be different. Homogeneous solder joints collapse fully, as opposed to the mixed SAC-BSA solder joints and will have a higher dynamic package warpage limit before HoP types of defects are generated, but the risk of solder bridging is increases due to the lower expected solder joint stand-off.

Reliability Assessment

- Mechanical Shock and Drop Reliability Evaluation of the BGA solder joint stack-ups shown in Figure 19 and comparison with presently used resin reinforcement processes in high volume manufacturing, such as corner glue and board level underfill.
- Thermal Fatigue comparison of the various stack-ups shown in Figure 19.
- Assessment of the enhancement of Plated Through Hole Via reliability and reduction in Conductive Anodic Filament (CAF) growth by reduction in the reflow soldering temperature that the printed circuit boards are exposed to during assembly

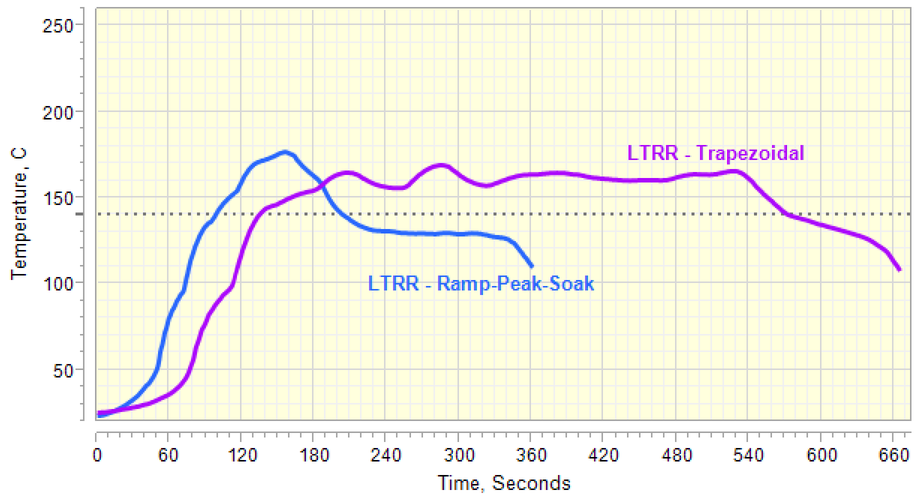


Figure 18 – Comparison of the Ramp-Peak-Soak Reflow Profile to the Trapezoidal profile for LTRR solder pastes

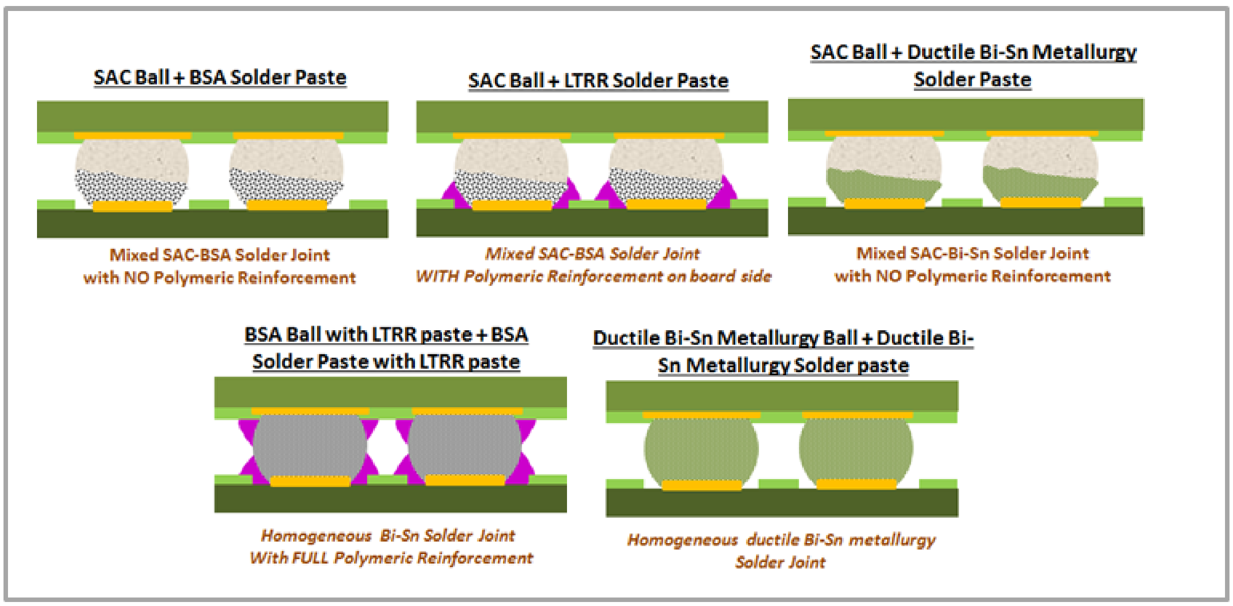


Figure 19 – Various BGA Solder Joint Configurations, using low temperature Bi-Sn solder pastes, which will be evaluated for assembly feasibility and reliability as part of future work

Acknowledgement

The authors are grateful to Olivia Chen, Kesete Kahsay, Abhishek Prasad, Tim Swettlen, Yoshihiro Tomita, and Bite Zhou for their contributions to the work reported in this paper.

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Investigation of Low Temperature Solders to Reduce Reflow Temperature, Improve SMT Yields and Realize Energy Savings

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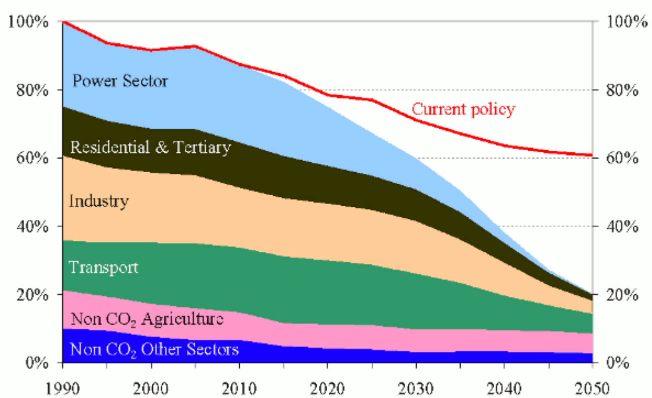
Contents

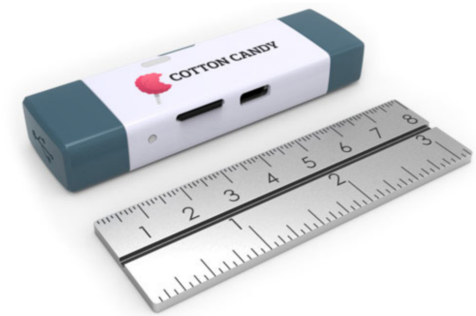
- Drivers for Low Temp electronic assembly
- Mitigation of warpage defects by low temperature soldering
- Energy Savings and Emission Reduction
- Process Development for Low Temp Solders
  - Stencil Printing
  - Reflow Profiles
  - LTS Component Impact
- Summary & Future Work

Drivers for Low Temperature Soldering

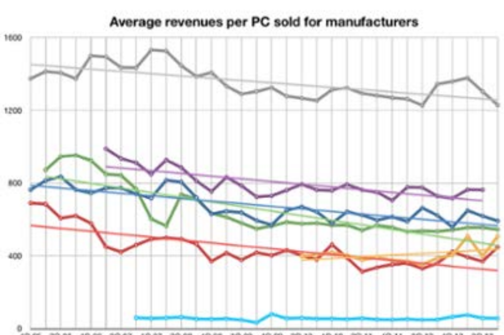
Green House Gas Reduction



SMT Margin for Thin Designs



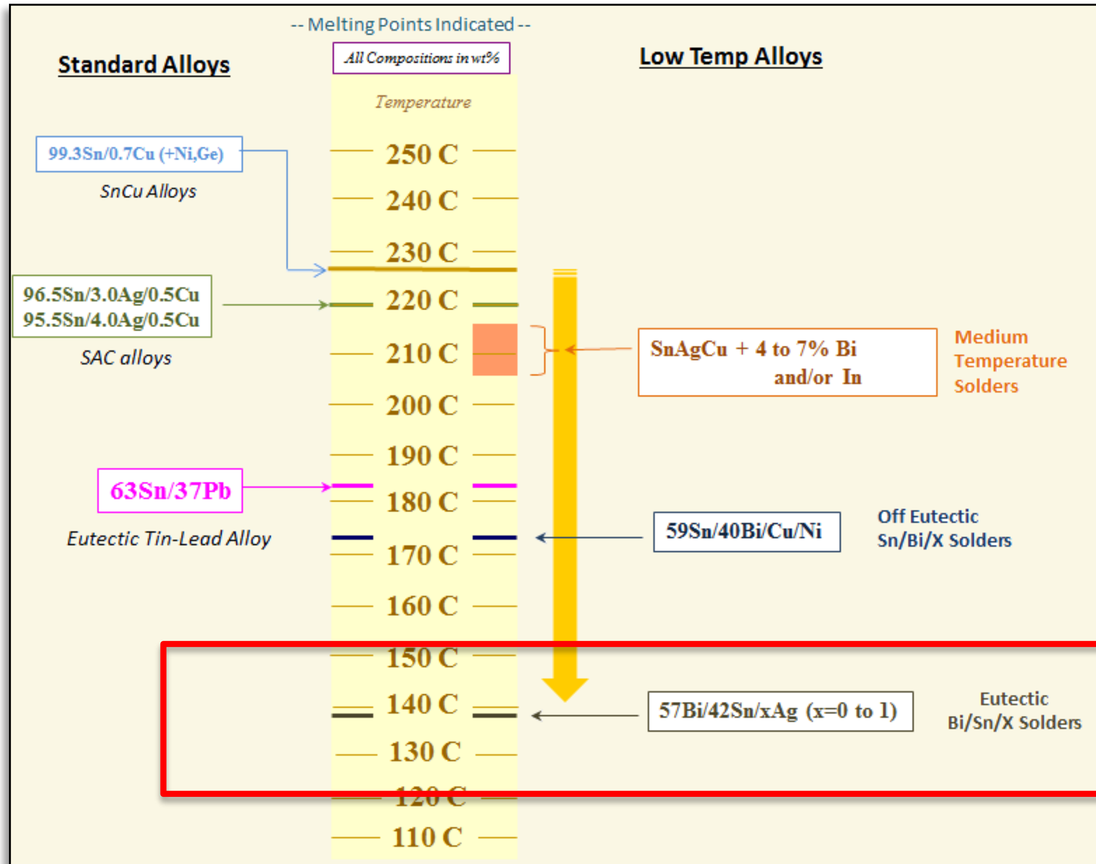
Lower Electricity Usage Reduces Cost



Reduced PLC Environmental Impact

Low Temp Solders Provide Benefit to Each of These Challenges

Low Temperature Solder Hierarchy

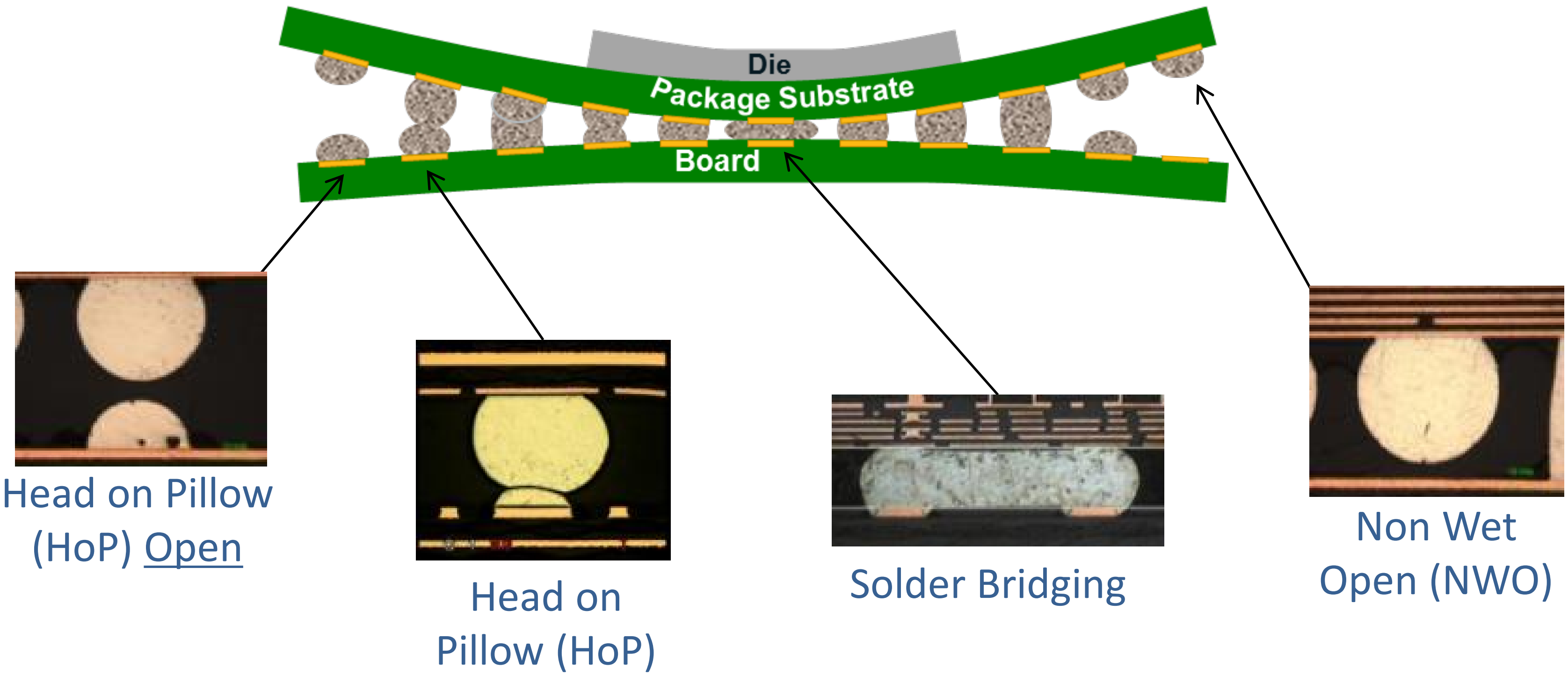


Medium Temperature Solders [SnAgCu+Bi,In]
- melt in the 210 to 220C range

Low Temperature Solders [Bi/Sn/X, X=Ag,Cu,Ni]
- melt in the 139 to 175C range

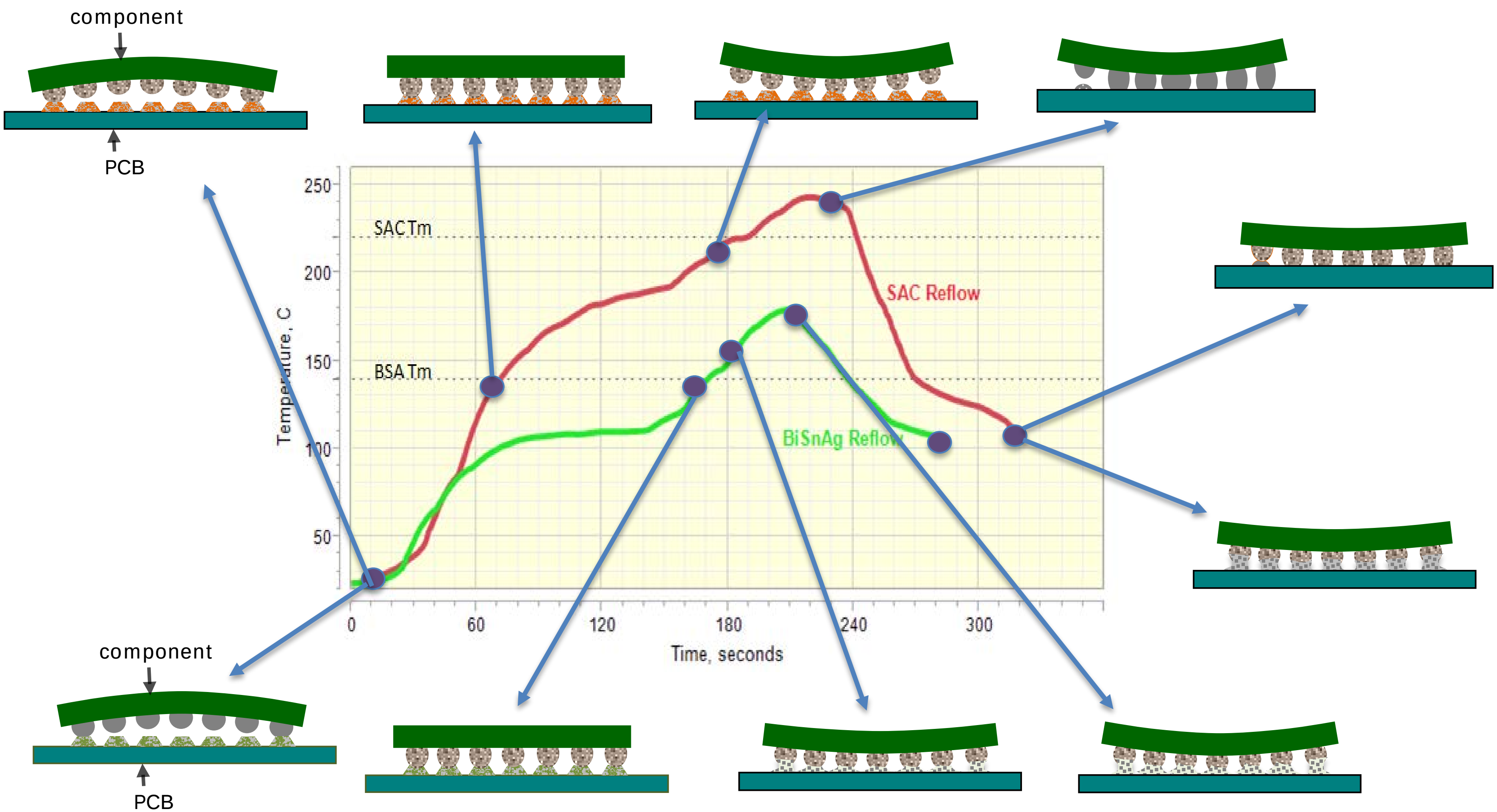
- **A variety of compositions and melting ranges for Potential Low Temperature Solders in Electronics Manufacturing**
- **Focus on 57Bi/42Sn Eutectic; MP=139 C**

Warpage – Induced Solder Joint Defect Signatures



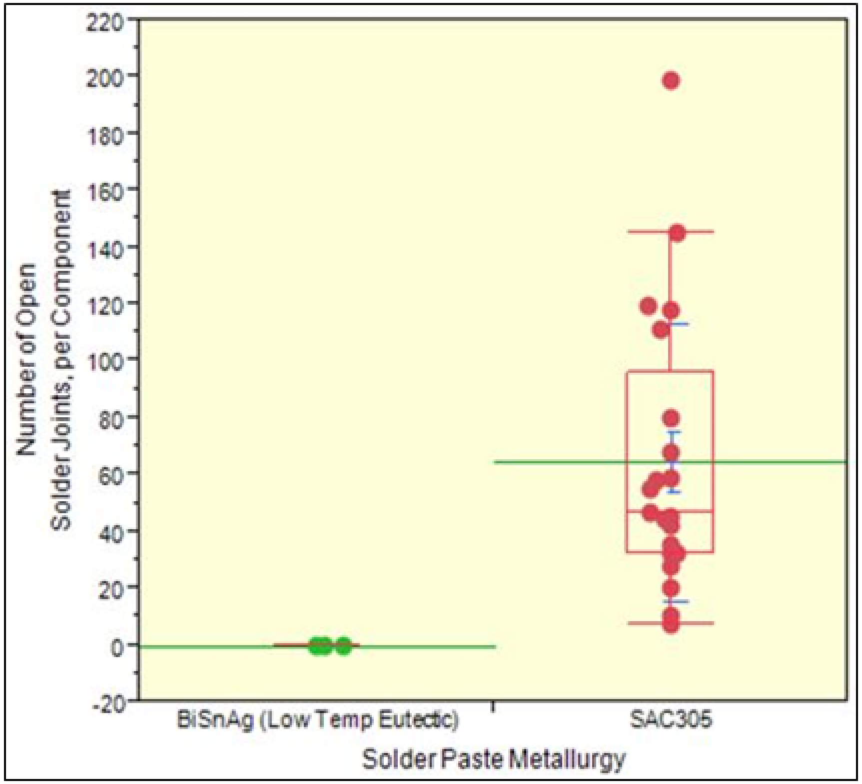
- Various solder joint defects can occur during SMT reflow soldering due to Package and/or PCB `dynamic` warpage

Yield Improvement Mechanism



LTS Shows Improved BGA Yield

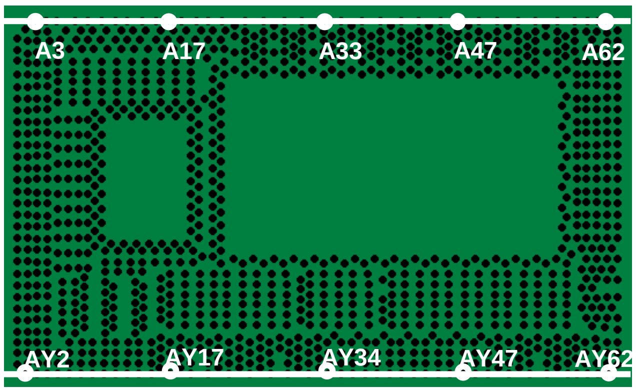
Open Solder Joints Per Component

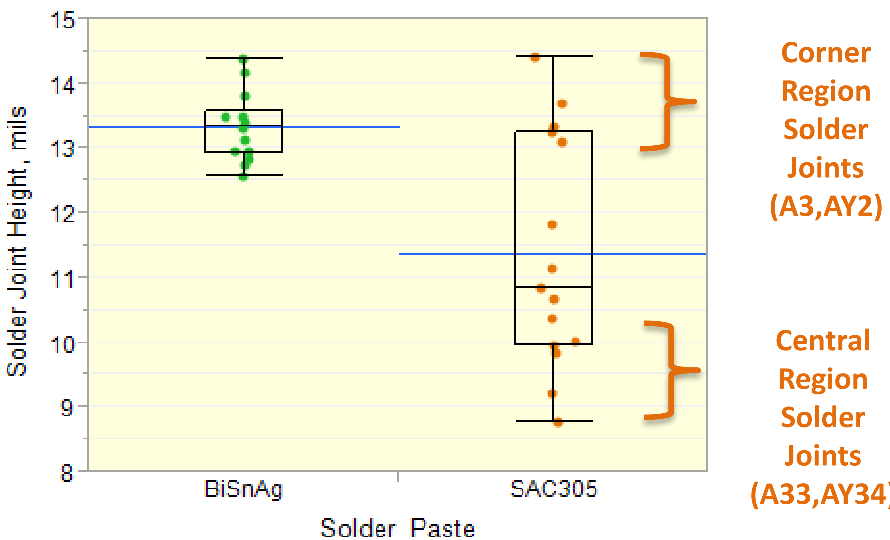


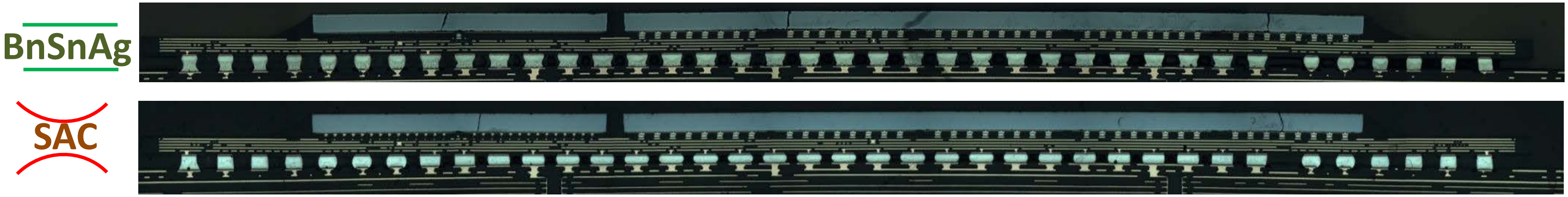
- ✓ BiSnAg Boards had Zero defects
- ✓ Most SAC305 boards had a large number of defects
- ✓ Consistent Result across multiple package and board platform combinations

➢ Low temperature Reflow Soldering significantly Reduces Solder Joint Opens on high density FCBGA packages

LTS Consistent Joint Height





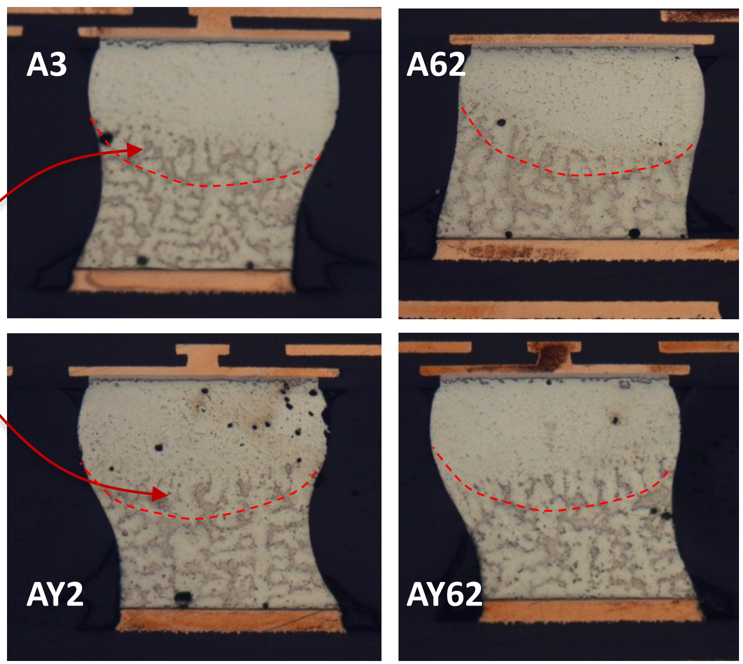


- Lower Mean solder joint heights (~2 mils/50 microns) for SAC solder paste and reflow profile due to SAC ball melting and collapse
- But wider range of solder joint heights due to higher package warpage at SAC peak reflow temperature

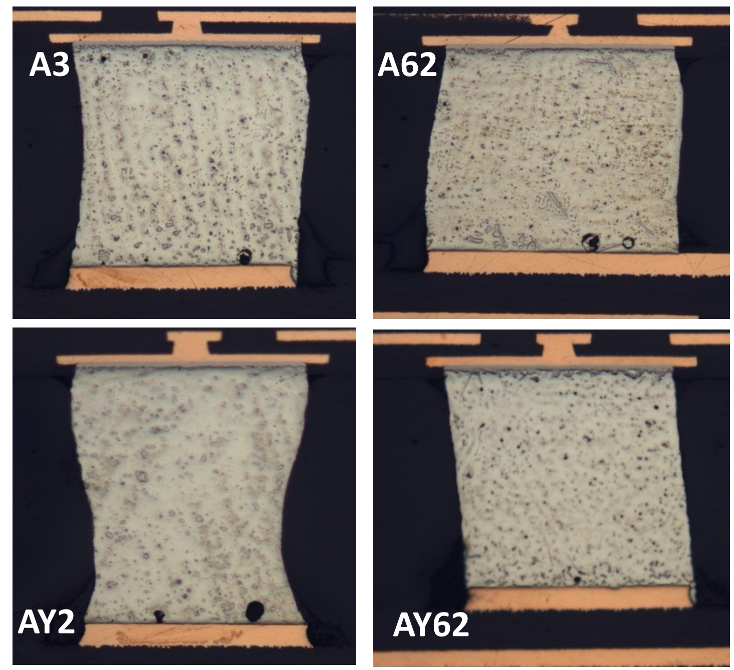
Micrographs of Corner Solder Joint Cross-sections

Mixed BiSnAg-SAC Solder Joints

Bismuth Mixing Region



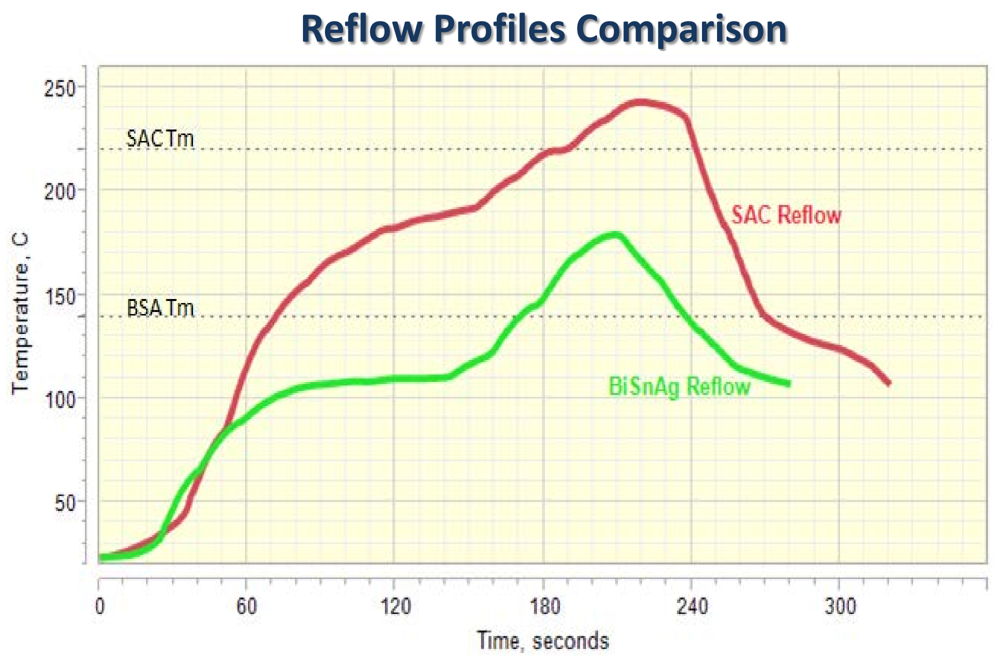
Homogenous SAC Solder Joints



➢ **Cross-sections show bismuth diffusion into SAC ball region**

Low Temp Reflow Profile

- Reflow Oven: Furakawa XNK 1245PC In-line
- Number of Zones: 14
- Thermocouples on test Boards: 9
- Average Temperature readings for all 9 thermocouples shown

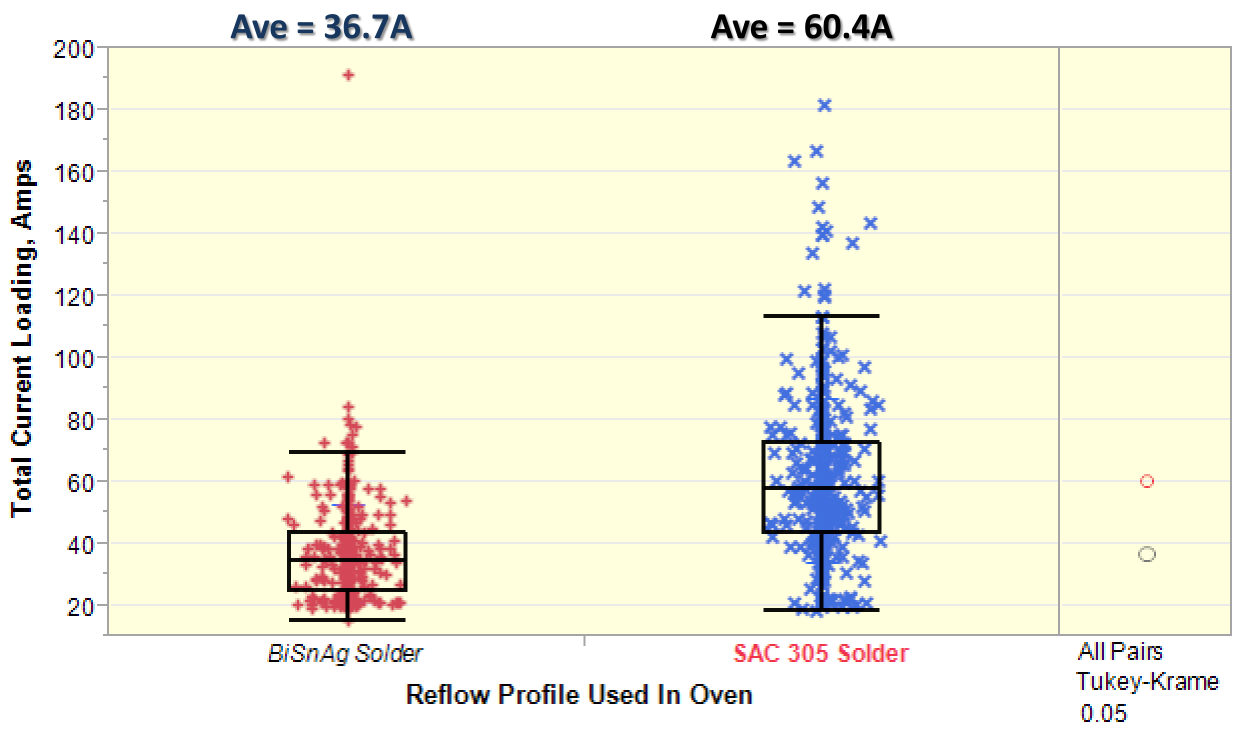


Zone Temperature(C) and Belt Speed (cm/min) Settings for Reflow Oven

		Zone # of the In-line Reflow Oven														Belt Speed
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	
Reflow Profile	SAC	120	160	170	180	190	195	195	215	230	245	250	235	150	100	115
	BiSnAg	95	100	110	110	110	110	110	125	155	185	185	145	120	100	115

Low Temp Reflow Reduces Power Consumption

Current Load into the Oven when running Reflow Profiles



Lower Calculated Power Consumption

- Current measured using a Amprobe Data logger Recorder

Equation

$$kW=(\sqrt{3}\cdot V\cdot I\cdot Pf)/1000$$

$$Pf = power\ factor = 0.75$$

$$V = Line\ Voltage = 408\ V\ (3\ phase)$$

$$I = Line\ Current = as\ measured$$

Power Consumptions Results

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

- **39% reduction in Power Consumption when converting to BiSnAg solder paste from SAC solder paste**

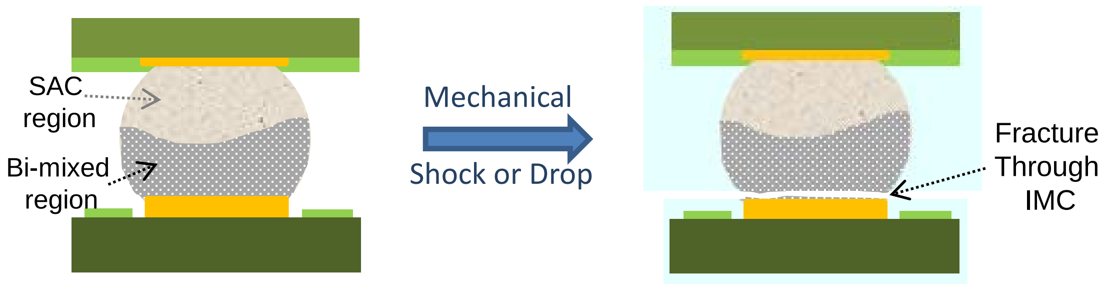
Estimated Cost Saving and CO_2 Emission Reduction

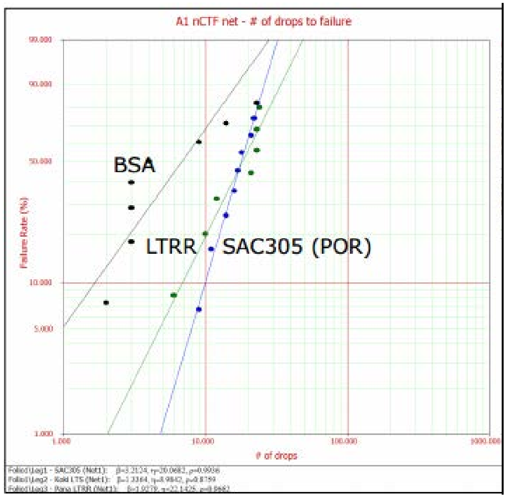
SAC 305 Paste		Sn/Bi/Ag Paste	
Oven Energy Consumption (kWh)	**29.5**	**Oven Energy Consumption (kWh)**	**17.8**
80% Utilization (Hours/week)	134.4	80% Utilization (Hours/Week)	134.4
Energy Cost-$/KWH (PRC -2013)	$0.11	Energy Cost/KWH (PRC - 2013)	$0.11
Oven Cost/week	$424	Oven Cost/Week	$256
BiSnAg 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**

- Significant Cost and CO_2 emission reduction for typical High Volume Factory
- Approx $1M USD per 55 SMT lines per year
- CO_2 equivalent of 11,000 gallons of gasoline per SMT line per year

Risk of Bi-based Solder

- **Due to brittleness of BiSn solders, mixed SAC-SnBi BGA solder joints are prone to brittle fractures under mechanical shock and drop forces**

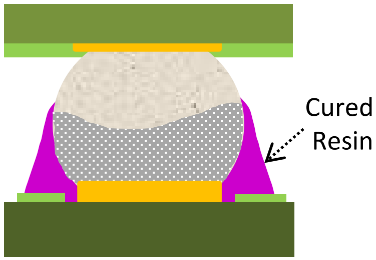




Two Primary Solution Paths

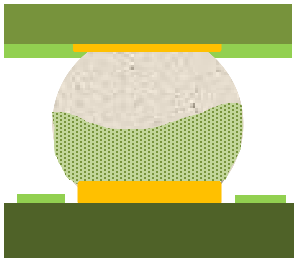
Resin Reinforcement

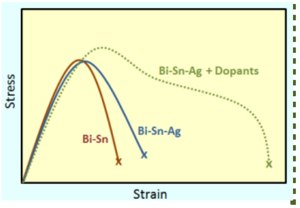
- **Resin added to the solder paste cures during reflow and provides reinforcement under mechanical stresses**



Ductile Bi-Sn Metallurgy

- **Addition of Elemental Dopants increases ductility of BiSn solder by modifying microstructure**

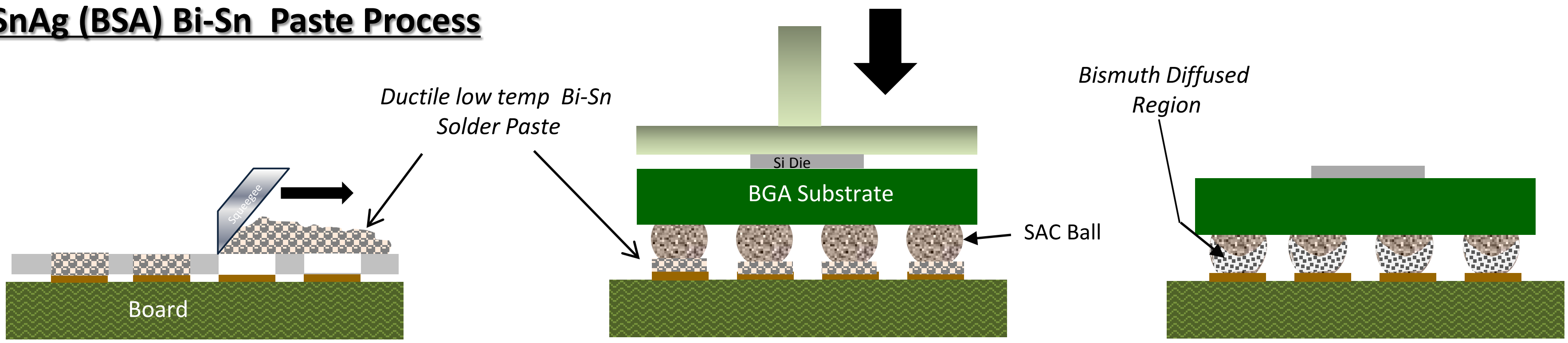




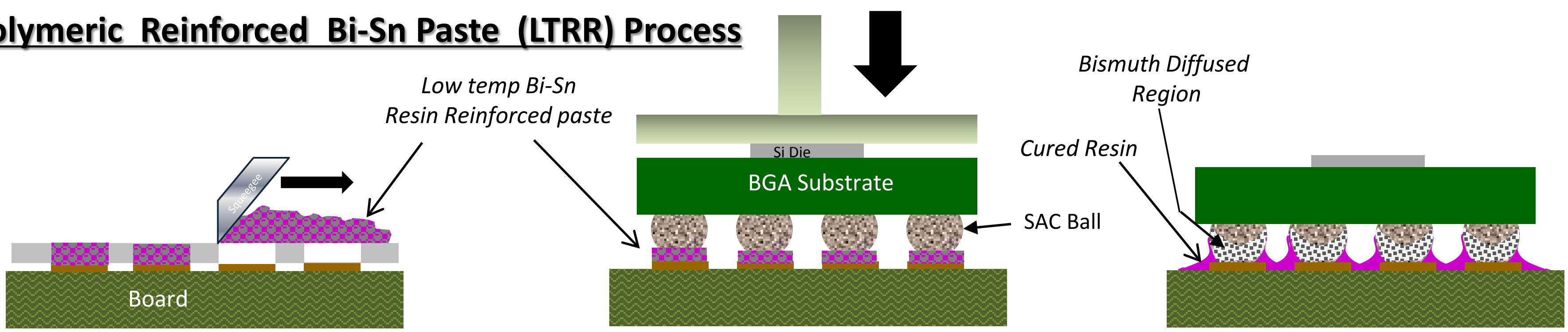
BiSnAg and Resin Reinforced Solder Pastes follow SAC Print Process

Paste Printing → **Package Placement** → **Reflow Soldering**

BiSnAg (BSA) Bi-Sn Paste Process

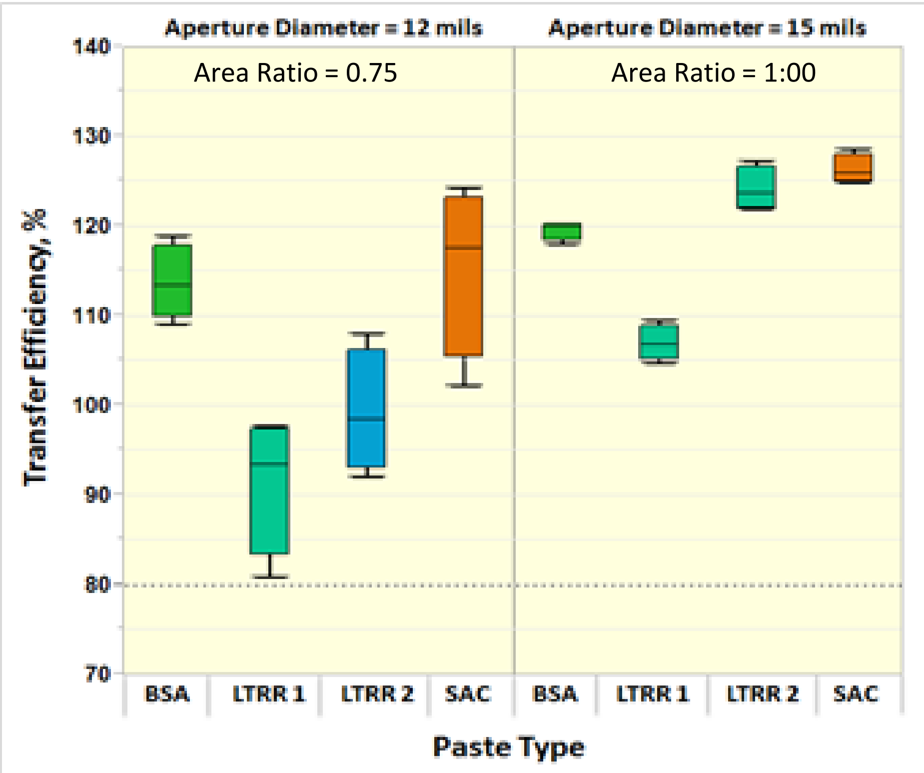


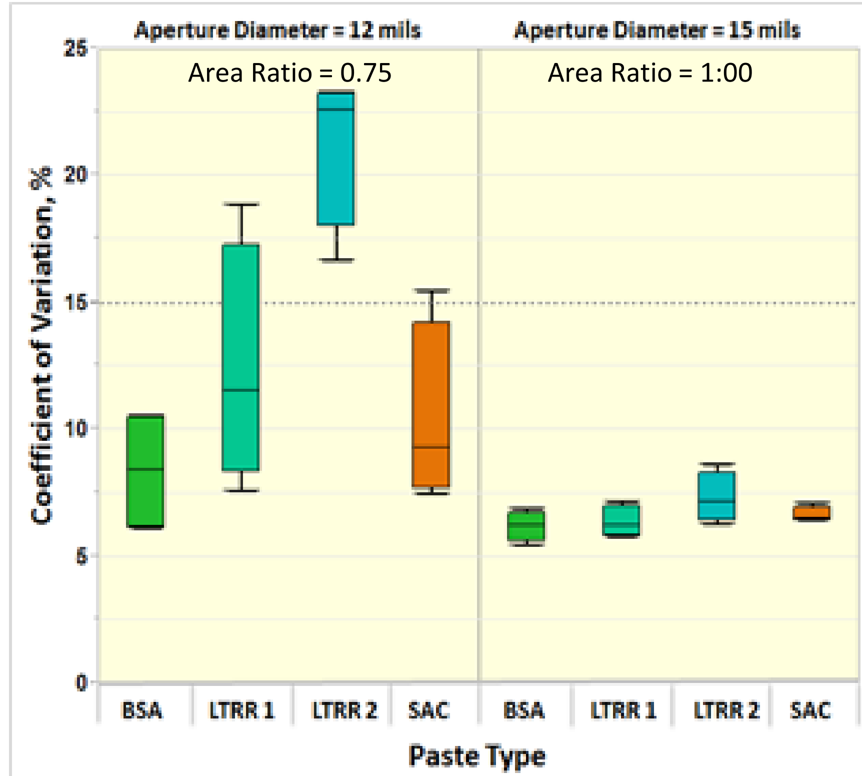
Polymeric Reinforced Bi-Sn Paste (LTRR) Process



BSA: BiSnAg LTRR: Low Temp (BiSn based) Resin Reinforcement

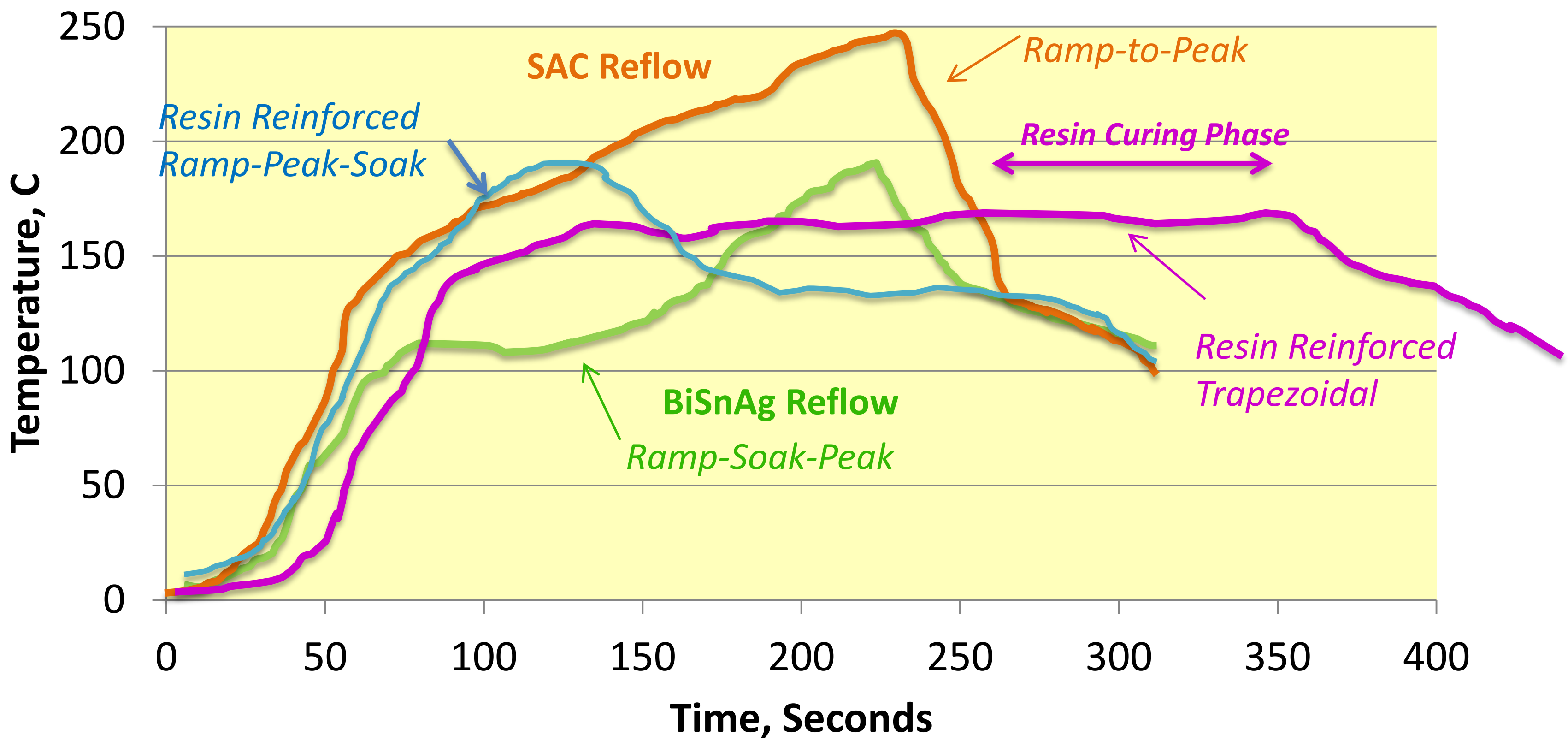
Transfer Efficiency (TE) and Coefficient of Variation (CV)





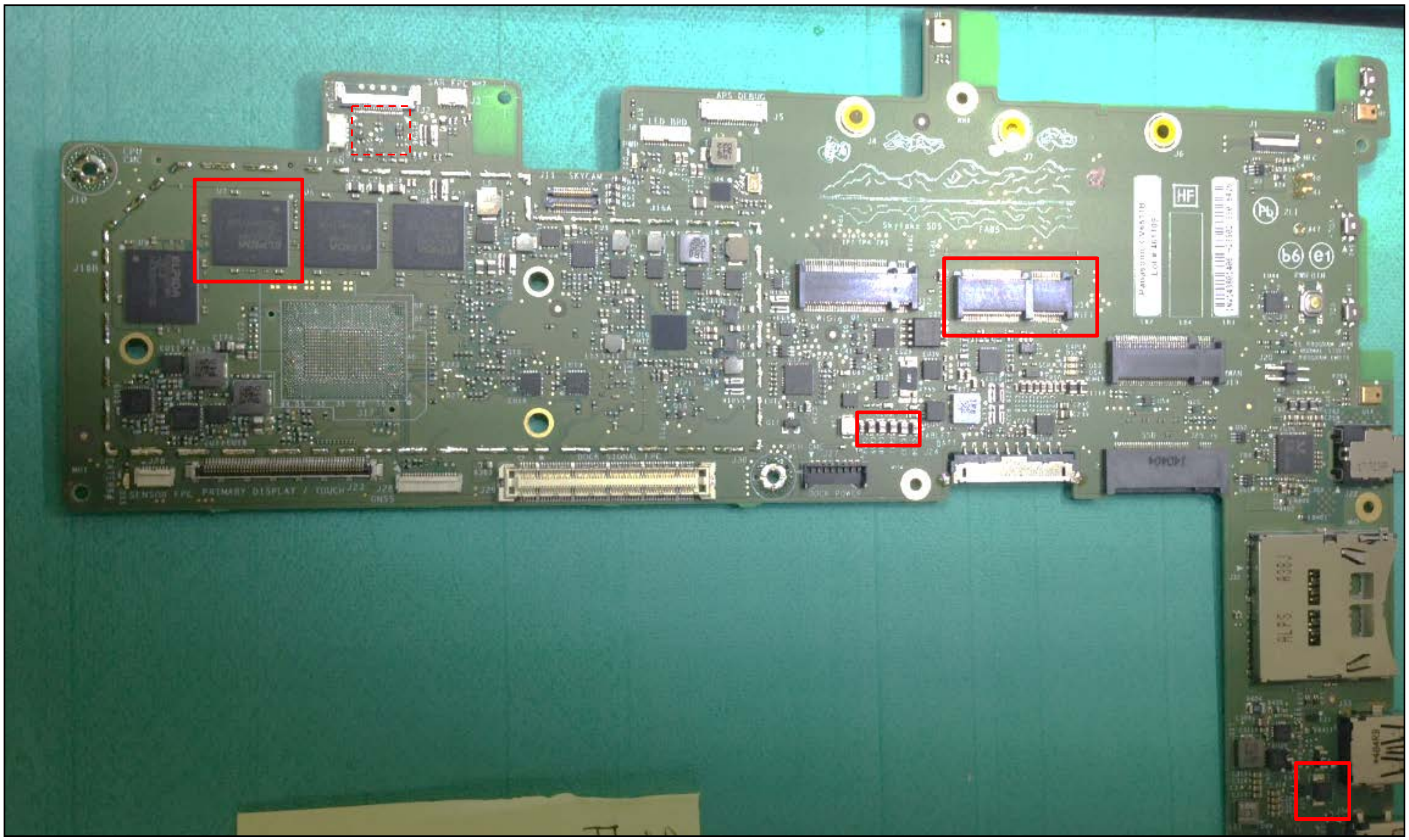
- ➢ Resin Reinforced solder pastes printing performance is worse than SAC and BSA paste based on TE and CV metrics
- ➢ Printing Process Parameters for Resin Reinforced pastes need optimization
- ➢ Adjustment of particle size and rheological modifiers needed for improvement

Reflow Profiles



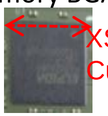
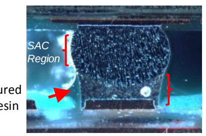
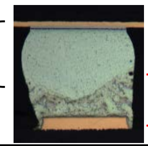
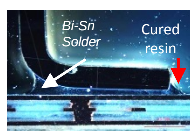
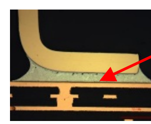
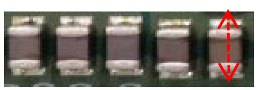
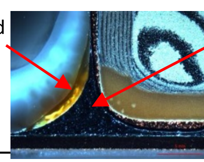
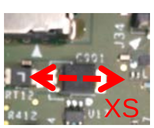
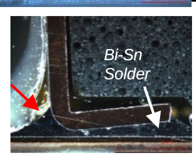
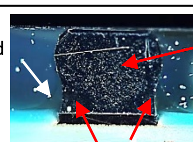
- Initial Resin Paste Reflow Profile was 2X Longer than the other Two Profiles
  - Trapezoidal Profile and Long Cure Time requirement for resin cure
- Revised Ramp-Peak-Soak Profile meets Mfg TPT requirements

Full BOM Assembly with Resin Reinforced Solder Paste



- Components outlined in red were cross-sectioned to inspect for solder joint resin reinforcement evidence

No Defects Identified across Typical Components

Component	LTRR Solder Joints	LTS Solder Joints
Memory BGA 		
Gull Wing PCIE Connector 		
Gull Wing PCIE Connector 		
Chip Capacitor 		
Large SOT 		
Chip Scale Package 		

Key risks:
- -small component "floating"
- -tombstoning
- -Resin epoxy "bleedout"
- -Resin voiding, outgassing
- -Resin rework

Status:
- -Global BOM yields equivalent to SAC
- -Resin rework studies underway

Summary

- The use of Bi-Sn based low temperature solder pastes:
  - Improves warpage related Yield
  - Reduces Reflow Oven Energy Costs
  - Reduces CO_2 emissions
  - Does not impact board component yields
- Bi-based solders risks can be mitigated by paste formulation
  - Resin Reinforced Pastes mitigate shock but require process development
  - High ductility Bi-based pastes can improve shock resistance but require further validation
- Low Temp Reflow provides opportunity, but requires further study and industry support

Future Work

-- Reliability, Yield & Manufacturability Assessment --

- ✓ Mechanical Shock and Drop
- ✓ Thermal Fatigue
- ✓ Plated Through Hole Via Reliability
- ✓ Rework
- ✓ Collapse Model & Microstructure Analysis