MECHANICAL SHOCK AND DROP RELIABILITY EVALUATION OF THE BGA SOLDER JOINT STACK-UPS FORMED BY REFLOW SOLDERING SAC SOLDER BALLS BGAs WITH BiSnAg AND RESIN REINFORCED BiSn-BASED SOLDER PASTES

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ABSTRACT
Printed circuit boards (PCB) used in the consumer electronic products such as smart phones, tablets and mobile client personal computers are commonly assembled by reflow soldering with lead-free SnAgCu (SAC) solder pastes with peak relow temperature in the 240C to 260C ranges. However, due to the decreasing size of electronic devices which demands lower z-height stackup, the ultra-thin flip chip ball grid array (FCBGA) often experienced SMT soldering challenges with typical lead-free solder reflow due to dynamic warpage on package substrate and PCB. As a result, low temperature solder pastes of the Bi-Sn metallurgical system have been proposed as alternatives to SnAgCu solder pastes for assembly of boards in the mobile consumer electronics market segments. Besides improvements in solder joint yield due to lower package and board warpages at the peak reflow temperatures, the lower melting points of these solder pastes will also enable significant cost savings.

However, presence of significant amounts of Bi in Sn based solder has previously been shown to induce embrittlement in the solder joints which leads to lower mechanical shock resistance. Hence, solder pastes, containing resin, have been developed recently to provide a post reflow polymeric reinforcement encapsulation around the mixed BiSn+SnAgCu BGA solder joints to mitigate this risk by enhancing the shock reliability of these solder joints.

This paper will investigate the Mechanical Shock and Drop Reliability of SnAgCu ball Flip Chip BGA solder joints soldered with BiSnAg (BSA), and Resin Reinforced BiSn system solder pastes (termed Joint Reinforced Pastes, JRP). This data will be compared to that obtained for SnAgCu ball Flip Chip BGA solder joints soldered with standard SAC solder paste, with and without board level adhesive reinforcement. Reflow processing conditions, the solder joint shape, microstructure, morphology and failure modes, for each of these cases, will also be described and discussed.

Based on in-situ failures recorded during shock event, JRP and SAC305 showed comparable performance, while BSA showed lowest number of drops to failure (less shock resistant). BSA leg showed more failure propagation on additional package locations while SAC305 and JRP legs did not show additional failures at other package locations other than the first two rows of solder joints from the package corners. In summary, BSA shock margin was significantly improved after the addition of L-shaped corner glue on all four package corners. No failures were seen on the BSA+CG leg. Hence board level adhesive and polymeric joint reinforce pastes, JRP both showed promising result to mitigate shock margin loss due to the brittle nature of BSA paste.

Key words: BGA solder joints, low temperature solder, Bi-Sn metallurgy, Mechanical Shock Reliability, polymeric reinforcement

INTRODUCTION
Recently there has been a driver from most ODMs and some OEMs to adopt low temperature soldering for consumer electronic products, such as cell phones, tablets, and mobile computers. The motivations for this driver have been economic and environmental. 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. The iNEMI Board Assembly roadmap has acknowledged this and incorporated low temperature solders in their Roadmap [1].

Another technical driver for low temperature soldering is related to the increasing demand for slimmer and lighter electronic products. This demand has fostered the use of ultra-thin electronic packages. Reduction in package thickness increases the warpages of these ultra-thin packages due to various mismatches in the CTE of the packaging materials. 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.

The warpage characteristics of Flip Chip Ball grid Array (FCBGA) packages are dynamic throughout the reflow soldering process due to the differential expansion of materials comprising the FCBGA package. Previous publications by the authors [2.3] have explained this dynamic nature of the warpage. Essentially, FCBGA packages 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. But the PCB warpage magnitude is significantly less than that of the package.

These dynamic warpage characteristics will lead to a gap being created between the BGA solder ball and the solder paste on the land, which can lead to solder joint such as Head on Pillow (HoP) [4], HoP Open, where no physical contact occurs between the solder ball and the post reflow solder paste mass, Non-Wet Open (NWO) [5,6], 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 and Solder Bridging, where two or more neighboring solder joints are connected together.

The use of low temperature solder pastes can mitigate the generation of these defects by significantly reducing the dynamic warpage of the FCBGA components at the peak reflow temperatures. The `Inversion Temperature` range, which is the temperature range where the FCBGA package warpage `inverts` from convex (+) to concave (-) is of some importance in this case. Most FCBGA components have inversion temperatures between 125C and 160C. If the reflow soldering temperature is within or close to this range, the package warpage profile will be essentially flat and the contact between the BGA solder ball and molten solder paste deposit will be maintained through most of all of the reflow soldering process. This is schematically illustrated in Figure 1, which compares the typical warpage shapes of FCBGA packages during the reflow soldering process for SAC and BiSnAg solder pastes. Components assembled by reflow soldering with lead-free SnAgCu (SAC) solder pastes has peak temperatures in the 240 to 260C range.

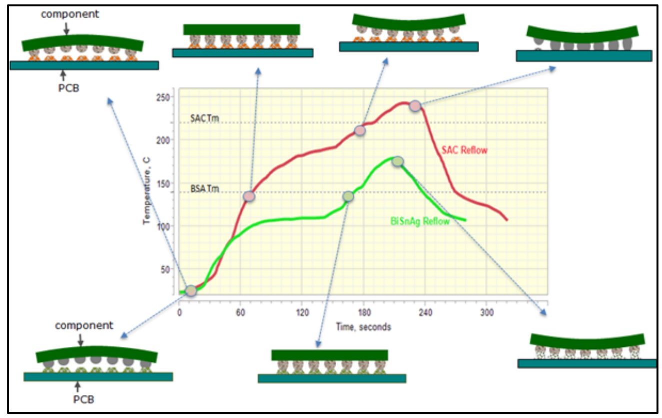


Figure 1:. Comparison of typical warpage shapes of FCBGA packages during the reflow solder process for SAC and BiSnAg solder paste soldering Time-Temperature profiles

The eutectic temperature of this Bi-Sn metallurgy system is 138C [7]. Ag is added in small amounts (<1wt%) to the Bi-Sn to improve the mechanical properties of the solder and BiSnAg (BSA) solder paste is widely available in the industry [8]. As seen in Figure 1, the FCBGA component warpage profile is flat, when at the liquidus temperature of the BSA solder paste and therefore the contact between the FCBGA solder ball and the solder paste is maintained when the solder paste first becomes molten. Maintaining this contact at this juncture in the reflow process enables the molten solder to wet the FCBGA solder balls and significantly reduce the propensity for the formation of the defects such as HoP and NWO. In contrast, during the SAC solder paste reflow process, the contact between the solder ball and solder paste is lost due to the dynamic package warpage much before the SAC solder paste becomes molten, as also seen in Figure 1.

There are other advantages for using BSA metallurgy solder pastes for consumer electronics products. These solder pastes are already being used for the assembly of low cost consumer electronics products, such as CD players, TVs, and 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.

However, the Bi-Sn metallurgy system as a solder material in consumer electronics products has a major drawback. Bi is a brittle metal [12]. The brittleness of Bi-Sn based solder alloys can limit their use in cell phones, tablets and other mobile devices, which can be subjected to multiple drops during field use. Mixed Alloy BGA solder joints formed by soldering BGA solder balls with BSA solder paste have been shown to exhibit significant reduction in mechanical drop reliability when compared with solder joints formed using SAC based solder pastes [13,14,15]. This reduced drop resistance have been caused by the bismuth presence in the solder joint stiffening the solder and making the intermetallic compound (IMC) at the solder-to-land interface more brittle.

One avenue to overcome this brittleness, which has been developed recently, entails using polymeric reinforcements, such as epoxy materials, around the solder joints to enhance their mechanical shock and drop resistance. 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, ODMs, are reluctant to use these materials. Moreover, underfills are applicable mainly to area array 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 when using BiSn based solder pastes.

An alternative polymeric option to strengthen the Bi-Sn solder joints is to use low temperature joint reinforced pastes (JRP). 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.

Epoxy fluxes [16,17,18,19] are a forerunner to this concept of JRP materials. One 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. JRP solder pastes are also available commercially from multiple suppliers.

To determine whether JRP pastes provide sufficient mechanical shock resistance to mixed SAC-BSA FCBGA solder joints by providing resin reinforcement is the goal of this paper. A previous paper by the authors [2] focused on the solder paste printability, reflow profile comparison and SMT solder joint yield when using standard BSA and resin reinforced solder pastes. Another paper by the authors [3] presented preliminary shock results on FCBGA solder joints using JRP pastes. This paper will continue the evaluation of mechanical shock resistance of the JRP formed mixed SAC-BSA FCBGA solder joints and compare with standard SAC solder joints, mixed SAC-BSA solder joints, with and without corner glue reinforcement at the package level. Table 1 shows the cross-section diagrams of the four cases compared for mechanical shock resistance in this paper.

EXPERIMENTAL

Package Test Vehicle

The attributes of the Package Test Vehicle are listed in Table 2 and images of the top view of the package and populated printed circuit board test vehicle are shown in Figure 2.

The printed circuit board test vehicle for shock testing is an 8 layer board with dimensions 12 inches x 12 inches x 0.032 inches. The board contains one FCBGA component. The component sites have metal defined (MD) land patterns that range from 10-12 mils in diameter and the surface finish on the test vehicle is organic solderability preservative (OSP).

There is one daisy chain net for each land pattern. Daisy chain nets from each of the components patterns are brought out to a card edge connector and soldered connections are used to monitor the resistances of the daisy chain nets during drop testing.

Table 1: Cross-sectional Diagram showing the Solder Joint Configuration for the Four Legs evaluated for Mechanical Shock Resistance

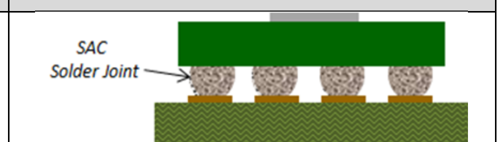
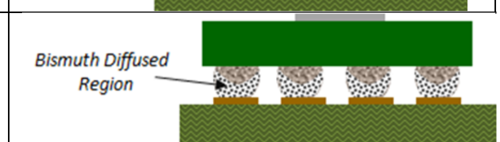
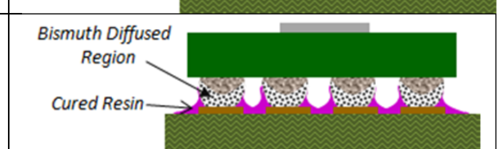
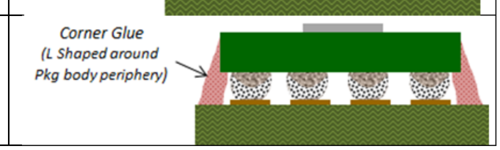
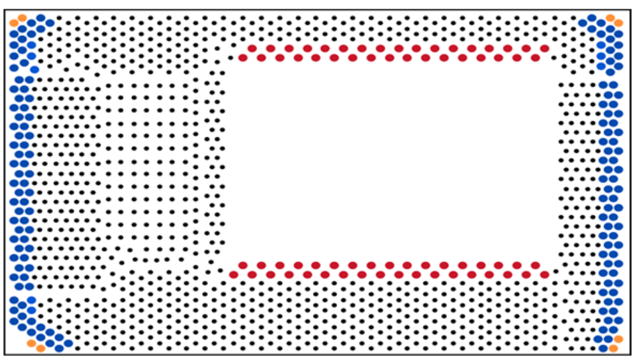
Experimental Leg name	Cross-sectional Diagram
SAC	
LTS/BSA	
JRP	
LTS/BSA + L shaped Corner Glue	

Table 2: The package attributes BGA test vehicle used in the experimental study.

TV Description	Package TV attributes
Package Size	30.0 mm x 16.5 mm
Die Amount	Two
Substrate thickness	0.557 mm
Solder ball diameter	12 mils
Ball Pitch	0.5 mm
Solder ball metallurgy	SAC 405
Ball count	1234
Ball pattern	Depopulated in the Central Regions
Package surface finish	NiPdAu

Assembly Process

All test samples were paste via 100um thick stainless steel laser etched, electro-polished stencil. The stencil employed a variable aperture design (Figure 2). Print tool parameters had previously been optimized for the SAC305 POR paste and were not adjusted for the candidate BSA low temperature solder pastes. Previous print studies had indicated that modified print tool parameters were required to obtain equivalent print quality with the JRP paste. Starting print tool settings for the JRP paste are given in Table 3. All paste legs resulted in equivalent post-print solder volume distributions (Figure 3). Each sample was reflowed with a universal reflow carrier (Figure 4) 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 recommendation (Figure 5, 6, 7).



Stencil Proposal	Color Code	PCB Pad Size	Thickness	Aperture Size	Design	Volume
Overprint Stencil	Orange	12	4	12X16	Rectangle	754
	Blue	12/10	4	12.7	Round	507
	Black	10	4	12	Round	452
	Red	11	4	15	Round	707

Figure 2: Stencil design of BGA test vehicle paste print

Table 3: Starting print tool settings for JRP paste

Squeegee Angle	Print Speed (mm/sec)	Print Gap (mm)	Separation Speed (mm/sec)	Print Pressure (Kgm)
45°	50	-0.25	3	9

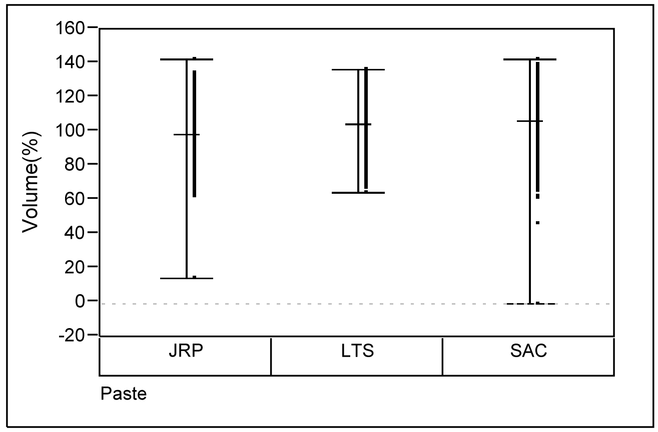


Figure 3: Post solder print volume distribution by paste

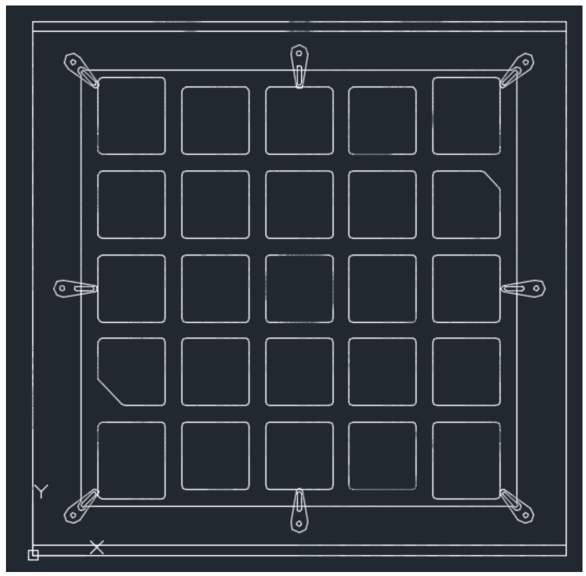
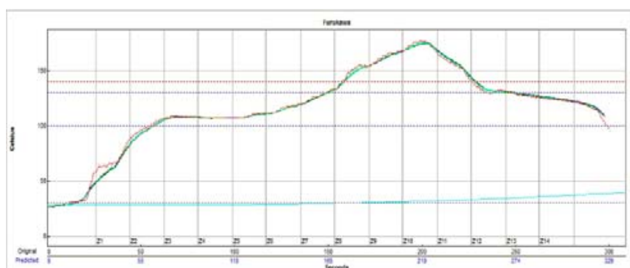
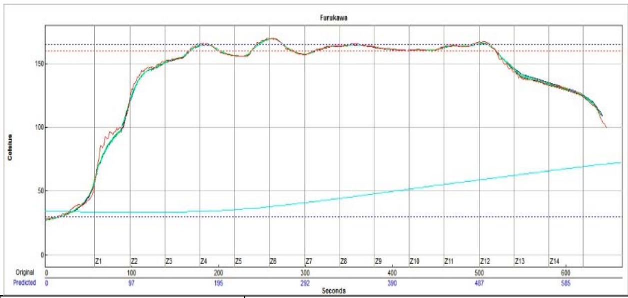


Figure 4: Universal reflow carrier



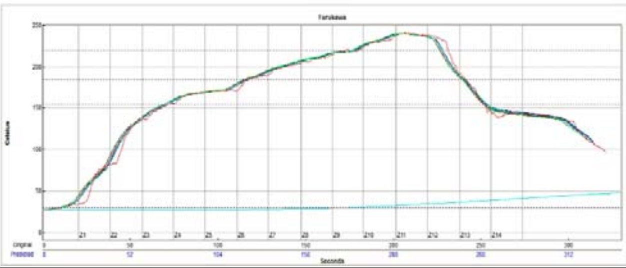
Peak Temperature	171.10 – 176.37°C
Time above 140°C	70 seconds

Figure 5: Reflow profile of BSA LTS solder paste samples



Peak Temperature	169°- 170°C
Time above 140°C	440 seconds

Figure 6: Reflow profile of JRP solder paste samples



Peak Temperature	240.45 – 241.06°C
Time above 220°C	70 seconds

Figure 7: Reflow profile of SAC solder paste samples

Shock Test Board Test Vehicle

To evaluate the mechanical shock performance of FCBGA packaged assembled using low temperature solder, the following samples (Table 4) were subjected to 140g's 2ms half-sine shock loading for 30 drops on each test board.

Table 4: Shock test DOE Matrix

DOE leg	# of brds/ DOE	Board thickness (mil)	# of pkg/brd
POR (SAC305)	10	32	1
LTS/BSA	9	32	1
JRP	10	32	1
LTS/BSA + L-shaped Corner glue	10	32	1

The shock test board design is shown in Figure 8. Package A was monitored electrically (in-situ) during shock impact to determine the first package location to show failure. The two monitored package corners are shown in Figure 9.

RESULTS AND DISCUSSION

In-situ Shock Test Result

Based on the 2-P Weibull distribution data, BSA LTS showed lowest characteristic life (drop to failure) when compared to SAC305 and JRP assembled packages (Figure 10 – 11). Table 5 showed a summary of the characteristic life on all DOE legs from both A1 and CY45 outer most row ball grid array.

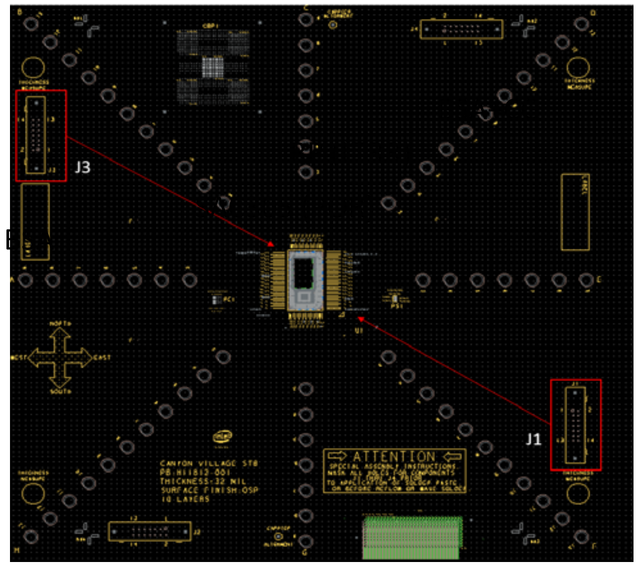


Figure 8: Top views of the printed circuit board used for the Mechanical Shock tests.

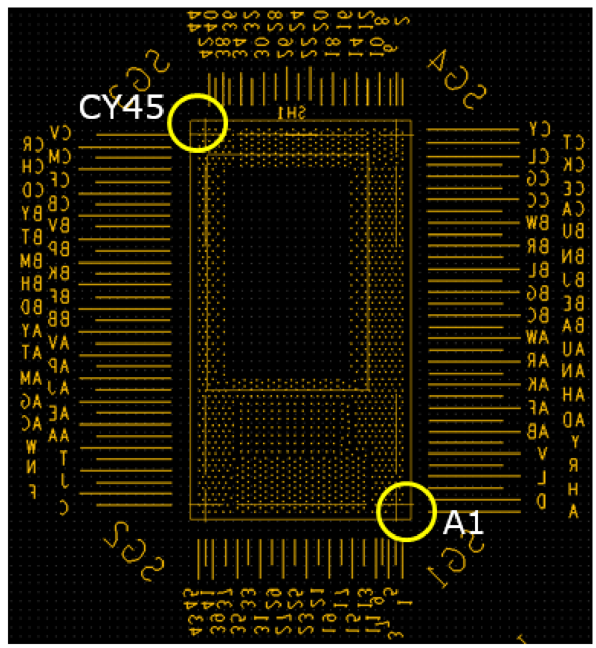


Figure 9: Top vies of the package Land Pattern on the Mechanical Shock test Board with the monitored package corners shown by yellow circles.

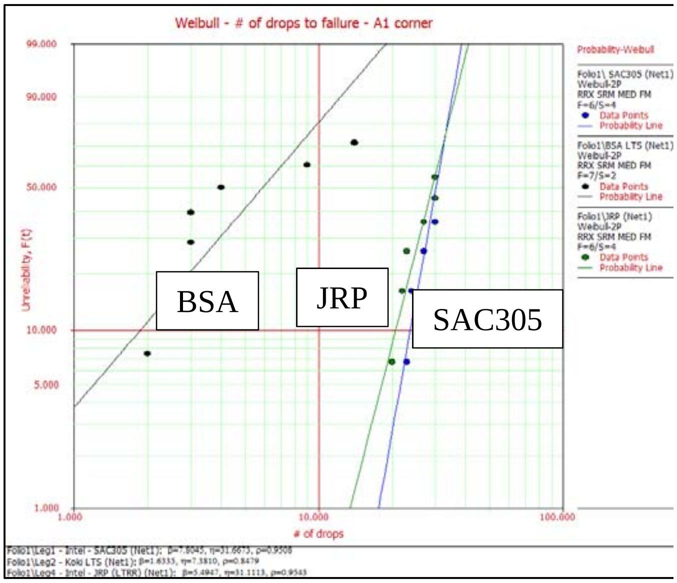


Figure 10: Weibull 2-P distribution of Net A1 comparing SAC305, BSA and JRP

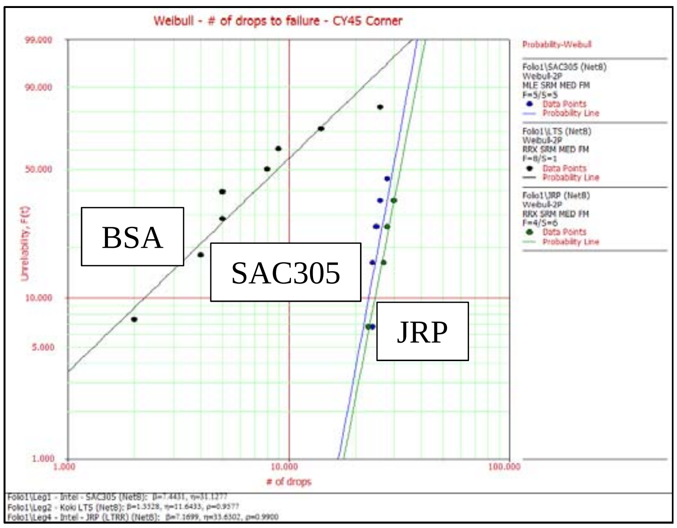


Figure 11: Weibull 2-P distribution of Net CY45 comparing SAC305, BSA and JRP

Table 5: Shock Characteristic life comparison between SAC305 (POR), BSA, JRP and BSA + Corner Glue

DOE	Characteristic Life (# of drops to 63.2% failure)	
	Net1 (A1 NCTF)	Net8 (CY45 NCTF)
POR	32	28
BSA	8	12
BSA + CG	No Fail	No Fail
JRP	31	34

Based on FCBGA outer most row in-situ failures, JRP and SAC305 showed comparable performance, while BSA showed lower number of drops to failure – First to show failure. Which is consistent with the theory of BSA embrittlement resulting in shock margin loss [13, 14, 15].

In addition to outer most row failures, BSA leg showed more failure propagation on additional package locations, i.e. Critical to Function (CTF) locations (Figure 12, Table 6) while SAC305 and JRP legs did not show additional failures at other package locations. Dye and Pull failure analysis results (Figure 13) confirmed the in-situ data failure, showing consistent failure trend. More dye penetration - solder joint crack was observed in BSA leg compared to SAC305 and JRP. Due to metallurgy differences from Bi segregation, BSA and JRP legs (both are Bi-Sn based) both showed dominant type3 disbond type , where solder joint crack forms between PCB pads and solder joint IMC at the brittle interface. SAC305's dominant disbond mode is type4, between the PCB pad and PCB laminate (Figure 14).

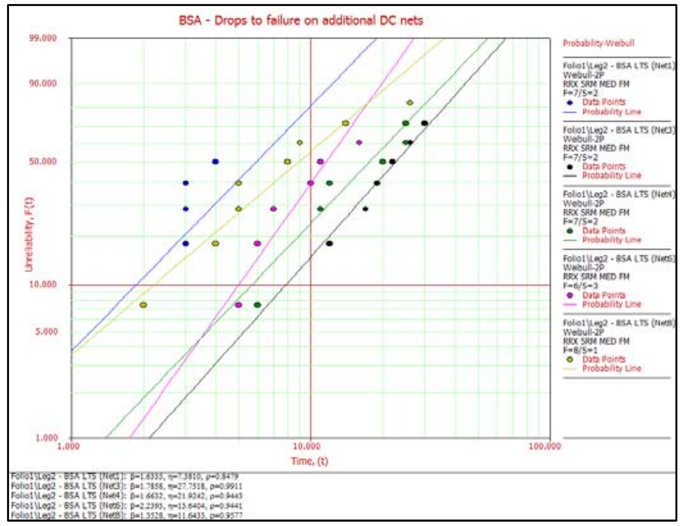


Figure 12: Weibull 2-P distribution of BSA leg across various monitoring daisy chain nets

Table 6: Shock Characteristic life comparison on various BSA nets

Net	Characteristic Life (drops)
1	9
3	28 (CTF)
4	22
6	14 (CTF)
8	12

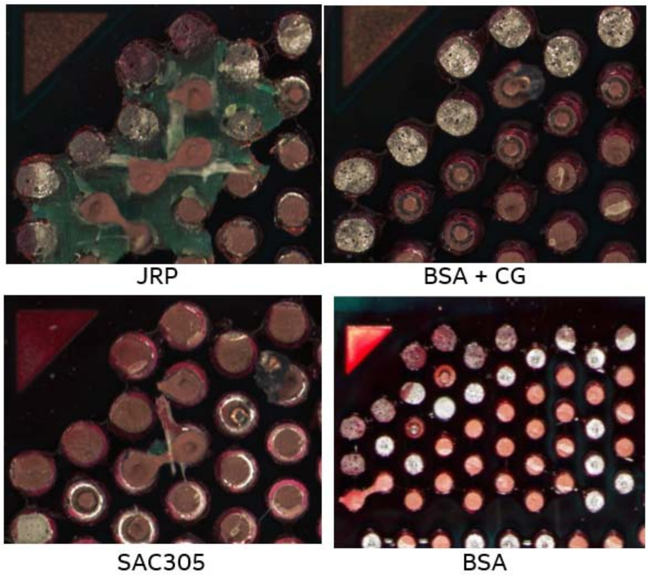


Figure 13: Dye and Pull Post Shock Failure analysis of JRP, BSA, BSA + CG and SAC305

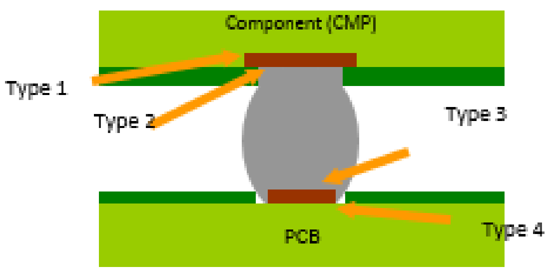


Figure 14: Failure disbond type categories

In summary, BSA leg showed more in-situ failures (including additional package location failure), consistent with what was shown in past literatures [13, 14, 15]. BSA also showed more sporadic failures across various DC nets (package locations) compared to JRP and SAC305 (Table 7-9. By adding polymeric reinforcement to BSA, making it a JRP, the shock performance is improved to almost equivalent as SAC305. Adding corner glue to the BSA paste, also showed promising margin improvement on BSA shock performance.

Table 7: BSA leg in-situ failure distribution

BSA LTS	Nets												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Board1	3							5				14	
Board2	2		22	6			7	9		27		18	
Board3	3		26	20				5					
Board4	23	3	17	6		6	11	26					
Board5	30					16		8	24	22		10	
Board6	14		19	11		10		14				26	
Board7	4		30	25		11		2	15	7		2	
Board8	9	2	12	25		7						29	
Board9	3		6	12		5		4		28			
Board10	SMT Defects												

Table 8: JRP leg in-situ failure distribution

JRP	Nets												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Board1	20							23					
Board2	22												
Board3	23							27					
Board4													
Board5								28					
Board6	30												
Board7	27												
Board8													
Board9	30												
Board10								30					

Table 9: SAC305 leg in-situ failure distribution

POR	Nets												
SAC305	1	2	3	4	5	6	7	8	9	10	11	12	13
Board1	23							24					
Board2								24					
Board3	24												
Board4													
Board5	30							26					
Board6	30												
Board7	30							28					
Board8								25					
Board9													
Board10	27												

CONCLUSIONS

The brittleness of Bi-Sn alloys, even after addition of Ag to the system, limits its use in consumer products where the risk of multiple shock impacts is high. Resin reinforcement solder pastes have been developed recently to provide a polymeric reinforcement around the mixed BiSn+SnAgCu BGA solder joints to mitigate the risk of embrittlement in Bi-Sn solder joints in order to enhance shock reliability.

In summary:

- Based on in-situ failures recorded during shock event, JRP and SAC305 showed comparable performance, while BSA showed lowest number of drops to failure (less shock resistant).
- BSA leg showed more failure propagation on additional package locations while SAC305 and JRP legs did not show additional failures at other package locations other than the first two rows of solder joints from the package corners.
- BSA shock margin was significantly improved after the addition of L-shaped corner glue on all four package corners. No failures were seen on the BSA+CG leg, outperforming both the SAC305 and JRP legs.

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