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Application Methods and Thermal Mechanical Reliability of Polymeric Solder Joint Encapsulation Materials (SJEM) on SnAgCu Solder Joints

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Abstract
With each new generation, the complexity in the design of flip chip devices, as exemplified by thinner package stack-ups, larger device sizes, and multiple die configurations, is increasing significantly. This is creating new challenges in their surface mount manufacturing and their solder joint reliability. To improve surface mount solder joint reliability under mechanical stresses, such as those imposed under shock, drop, and vibration during transportation and end user handling, the use of polymeric materials to provide added reinforcement to the second level solder interconnects on flip chip ball grid arrays (FCBGA)and package-on-package (POP) solder joints has been proposed as a solution. Some of the common examples of such polymeric reinforcement applications in manufacturing include, but are not limited to, corner glue edge bonding, underfill (UF) application, and epoxy-containing solder pastes. However, as the solder joints' pitch size and height decreases, control of the extent and uniformity of polymeric encapsulation of second level solder joints becomes more challenging. As a result, solder joint encapsulation materials (SJEM) have been developed to provide a better controlled and localized application process. Unlike other polymeric materials in use today, these SJEMs do not require an additional step for cure, since they are applied before the reflow soldering process step and cure during the reflow soldering process step.

Based on past studies on polymer reinforced solder joints, mechanical shock performance generally improved with the application of the polymer reinforcement and was less sensitive to the polymeric material properties as long as the material has acceptable application, curing, adhesion and fracture strength properties. However, thermal cycling reliability is more sensitive to certain material properties of the reinforcing polymer. The glass transition temperature (Tg) and the coefficient of thermal expansion (CTE) are two such properties [1-2]. Materials with a low Tg and a high CTE often lead to accelerated solder joint failure from thermal fatigue. Therefore, the material properties of SJEM and the extent of material coverage on the solder joint both play important roles in optimizing solder joint reliability performance under mechanical and thermal conditions.

In this paper, two SJEM material application methods, dispensing and dipping, will be studied for the extent and uniformity of their encapsulation of high density BGA solder joints. The solder joint mechanical shock and thermal cycling reliability from these two SJEM dispensing techniques, which correspond to different encapsulation coverage, will also be analyzed and discussed.

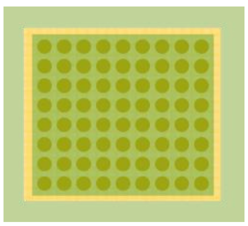
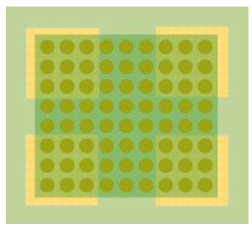
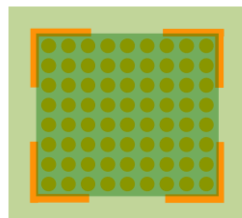
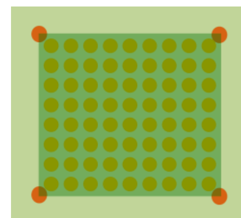
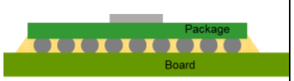
From the assembly and reliability test results, both SJEM materials showed process feasibility to be applied, reflowed, and cured with SAC305 solder paste. Both SJEM application methods showed promising mechanical shock and temperature cycle reliability. These materials can be considered as a solution to replace underfills and corner glues for smaller, finer pitch components in the future.

Introduction
Area Array components, particularly those for microprocessors, memory and chip sets, are in a continuous miniaturization trend [3,4]. As an example, the physical volume of the company microprocessor Flip Chip Ball Grid Array (FCBGA) packages have reduced from 1440 cm^3 for the device generation introduced in 2010 to 330 cm^3 for the device generation introduced in 2015. Also, the z heights of these packages have decreased in half from 2 mm for the device generation in 2010 to 1 mm for the device generation in 2015 [5]. The decrease in the size of such area array components, as Ball Grid Arrays (BGA), Chip Scale Packages (CSP), and Wafer Level Packages (WLP), concomitantly decreases the size of their solder joints and thereby drives the need to enhance their robustness when exposed to mechanical stresses experienced under

vibration and shock impact, as well as thermomechanical stresses experienced under temperature and power cycling [6].Additionally, the field use temperatures of these solders are very high on their homologous temperatures scale[7]. Hence, polymeric reinforcement of area array solder joints become a necessity to lower the risk for solder joint failure in the field.

Four alternatives are commonly used today for polymeric reinforcement of BGA solder joints. These are shown in Table 1. Full underfill and partial underfill reinforcement has been in use for some years now [8 - 13]. These polymeric underfills flow under the BGAs through the action of capillary forces. Since the time to fill the entire space under the BGA package is proportional to the square of the flow distance [14], the processing time when using the full underfill alternative can increase substantially for BGAs with a large body size (>30 mm). Furthermore, as area array components get smaller in stand-off height and ball pitch, the underfill flow time increases exponentially, particularly below a 20 microns gap between the board and the component substrate [15-18]. As this gap and pitch decrease, the size of fillers in the underfill critically also impacts its flow under the component [19].

Table 1 –Pictorial Description of Various Strategies used today for Polymeric Reinforcement of BGA Solder Joints

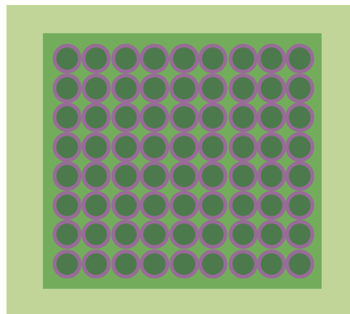
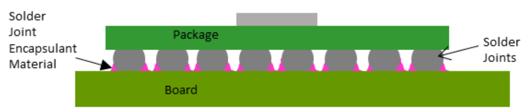
	Full Underfill	Partial Underfill	Edge Bond	Corner Bond
Top View				
Cross-section				

To reduce this processing time, the partial underfill process was developed, where only corner areas under the BGAs were filled but the central areas were left unfilled. These two alternatives provide the most enhancement in reliability under mechanical and thermomechanical stresses provided the materials are chosen have optimum values for three key properties, namely modulus, coefficient of thermal expansion (CTE) and glass transition temperature, Tg. However, underfills have a few drawbacks. Besides the increase in processing time for underfills dramatically impacting the board throughput rate in a high volume manufacturing (HVM) operation, incompatibility between the underfill and the flux residue from the solder paste after reflow creates voids in the underfill and leads to subsequent delamination and solder extrusion [20-21]. Reworking BGAs with partial or full underfills is difficult and requires a highly skilled operator to avoid damage to the PCB lands when removing the remnants of the underfill after the defective BGA has been desoldered [12,22].

To overcome these disadvantages of the underfill options, edge bond adhesive and corner bond adhesive alternatives were developed for use in applications where the solder joint reliability enhancement required is modest, as in the case of notebook computers [6]. Edge bond adhesives are typically applied around the corners of the BGAs, where the stress imparted on the solder joints is the highest during component shock and drop. The corner bond adhesive configuration comprises of a much smaller amount applied at the corners of the package [23]. In addition to decreasing processing time, since, unlike the underfill, the edge bond and corner bond adhesives do not have to flow under the component, less material is used in these cases. Reworkability is easier because there is less material to remove from under the component and the risk for PCB land damage is negligible because the edge bond and corner bond adhesives are not present in the land array area on the PCB. Edge bond and corner bond adhesives are primarily used to enhance the solder joint reliability during mechanical shock and drop events. But, one potential drawback is that some edge bond and corner bond adhesives can compromise the solder joint reliability in temperature cycling and even shift the location of failing solder joints due to an interaction between adhesive material properties and geometric parameters of the board assembly [24-25].

Solder Joint Encapsulant Materials (SJEM) were developed to address these drawbacks of underfills, edge bond and corner bond adhesives. SJEMs are also called fluxing underfills, epoxy fluxes, or polymer fluxes. Many papers have been published on SJEMs [26-34]. A pictorial illustration of SJEMs after application and cure is shown in Table 2. The SJEM partially or fully covers each solder joint of the BGA, forming an adhesive bond where it contacts the solder joint and the printed circuit board (PCB) laminate and solder mask. This adhesive bond, together with the cohesive strength of the cured SJEM, forms the basis for the reinforcement the SJEM provides to the solder joints. There is significantly more flexibility in the application of SJEMs to the BGA solder joints than there is for underfills or corner glues. BGA components can be dipped into a reservoir of the material before being placed on the board, a process similar to that for application of tacky fluxes for PoP assembly. SJEM can be dispensed or jetted on the BGA lands of the PCB before component placement. SJEMs can also be screen printed on the BGA lands. However, the rheology of the SJEMs, will need to be optimized by these different application methods.

Table 2 – Pictorial Description of Solder Joint Encapsulation Material (SJEM)

	Solder Joint Encapsulant Material
Top View	
Cross-section	

Curing of the SJEMs is achieved during the reflow soldering process and hence an additional post reflow step for cure is not required. This characteristic imparts the main processing advantage to SJEMs when compared to underfills or corner glues, which as mentioned before, require an additional curing process that is typically done off-line, slows down the assembled board throughput and increases manufacturing cost due to the need for additional equipment, electrical power and labor. The SJEM has to be optimally engineered to ensure that it will cure during the reflow soldering process step without impeding the BGA solder joint formation processes. The resin within the SJEM should not begin gelling (i.e., no longer being a liquid and having lost its ability to flow)until the solder in the paste has melted, wetted the PCB land and the solder ball and the solder joint has collapsed fully. If the SJEM is used in conjunction with solder paste printed on the PCB lands (for instance, if the need arises to accommodate substantial dynamic warpage of FCBGA components during reflow), the fluxes in the SJEM should have sufficient miscibility with the solder paste. This combination of SJEM and solder paste requires `venting channels` within the solder joint array for the volatiles evolving from the SJEM and solder paste to escape during the reflow soldering process. But, generally, this is not an issue since, unlike underfills, SJEMs encapsulate individual solder joints only rather than the entire area under the BGA component substrate, thereby leaving interconnected channels for the emitted gases to escape [30-31].

The aim of this study was to evaluate the processing and reliability of SJEMs that were either commercially available or in the latter stages of development at their suppliers. Two SJEMS optimized for dipping and three SJEMs optimized for dispensing were selected for evaluation. A POP component was used as the Test Vehicle. These POP components were assembled to PCBs with the selected SJEMs and subsequently subjected to standard mechanical shock and temperature cycling reliability tests to assess the efficacy of the SJEMs. A control leg, without any resin reinforcement, was added to the experimental plan to gauge the improvement provided by the SJEMs. Another experimental leg, with a common underfill applied to the test components, was also added for comparison.

Experimental Strategy

Various aspects of the experimental strategy in this study are expounded below.

Package Test Vehicles

Figure 1 depicts the top, bottom and side views of the POP component, which was chosen for the evaluations in this work. Table 3 and 4 list the various attributes of the POP shown in Figure 1.

A JEDEC standard memory package was mounted on the top of the POP package during surface mount assembly to form a package-on-package structure. This memory package had a 14x14mm body size, with 220 balls at 0.5mm pitch.

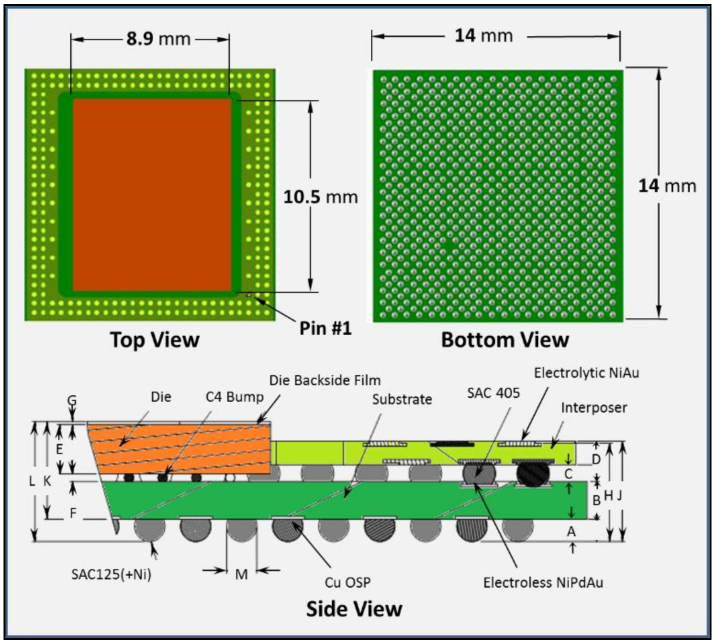


Figure 1. **Detailed Top, Bottom and Side Views of the POP package**

Table 3 - Attributes for the POP package in Figure 1

Item	**Attribute**	**Dimension (mm)**
A	BGA Balls Attached	0.116
B	Substrate Thickness	0.262
E	Die Thickness	0.270
F	Die Gap Height	0.055
G	Die Backside Film (DBF)	0.020
J	Interposer Height (pre-SMT)	0.605
H	Substrate ball to Interposer Top Metal Plate	0.594
K	Substrate Ball to Interposer Solder Resist Top	0.605
L	Bottom of Substrate to Top of DBF	0.611
M	Bottom of ball to Top of DBF	0.727

Printed Circuit Board Test Vehicle

The printed circuit board test vehicle for shock testing was designed in accordance to JEDEC JESD022-B111 specification [35] which is a widely used industry standard to assess mobile product drop use conditions. The test board, which is shown in Figure 2, had dimensions of 132mm x 77mm x 1mm with 8 layers design. The board contained (15) POP components with10mil metal defined (MD) land patterns and 13mil round solder resist opening (SRO) and an organic solderability preservative (OSP) surface finish.

Table 4 - Attributes for Substrate and Interposer in Figure 1

Item	Attribute	Top	Bottom
Substrate	Solder Resist Opening (mm)	0.25	0.28
	Ball Pitch (mm)	0.4	0.483
	Pre-Attach Solder Ball (mm)	n/a	0.203
	Ball Count	276	760
Interposer	Solder Resist Opening (mm)	0.28	0.25
	Ball Pitch (mm)	0.5	0.4
	Pre-Attach Solder Ball (mm)	n/a	0.254
	Ball Count	220	276

There were a total of four monitoring daisy chain nets on each component. The location of the daisy chains are shown in Figure 3. Daisy chain nets from each of the components patterns were brought out to a card edge connector and soldered connections were used to monitor the resistances of the daisy chain nets during drop and temp cycle testing.

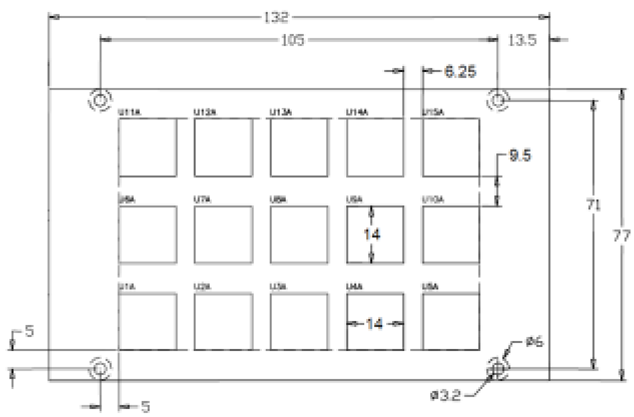


Figure 2.JEDEC Test Board Size and Layout

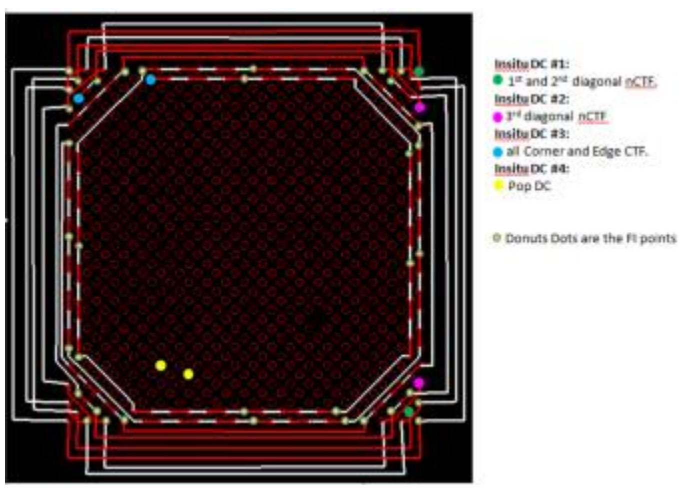


Figure 3.Daisy Chain Coverage for Monitoring the POP Component

SJEM Descriptions

Various SJEMs were evaluated in this study. Table 5lists the designations used for identifying these SJEMs and an underfill in this manuscript and distinguishes them based on the method of their application to the POP components.Dip2 and Dis1 are the same material but are designated differently due to their different method of application. Descriptions of the method of application are given in a later section. All these materials are available commercially.

Table 5 – Descriptions of Materials Evaluated

Designation	Material Type	Manufacturer	Application Method
Dip1	SJEM	A	Dipping
Dip2	SJEM	B	Dipping
Dis1	SJEM	A	Dispensing
Dis2	SJEM	B	Dispensing
Dis3	SJEM	A	Dispensing
UF1	Underfill	C	Dispensing

Experimental Design

The main objective of this study is to evaluate different dispensing methods that can achieve optimized SJEM material coverage for mechanical shock and temperature cycling reliability.

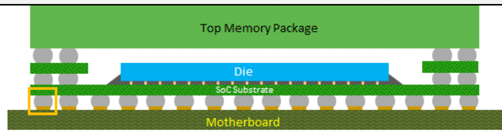
There were two main variables for the experimental design. One was the type of reliability test - mechanical shock and temperature cycling. The other was the solder paste (or attachment material) used –the plan of record (POR) SAC305 solder paste, and two different types of SJEM materials which were optimized for application by component dipping and application by dispensing through a needle dispenser applications. The Experimental Design Matrix is given in Table 5. The sample sizes for each leg are also listed in the table.

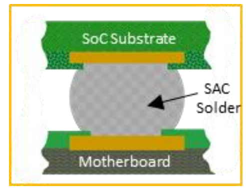
The two specific reliability tests were chosen since these are the two primary reliability tests that are required for all company package platforms. SAC305 solder paste without any SJEM adhesive was used as the control leg, and three different SJEMs from dipping to dispensing were used for comparison. One leg with corner glue was added since, presently, some BGA components on product boards have corner fill adhesives applied after reflow soldering. This leg was tested under temperature cycling to understand the relative impact on temperature cycling fatigue life. If the SJEM reinforced solder joints showed improved or comparable shock and temp cycle requirements were comparable to those with underfill, then the underfill step in production could be replaced by SJEM in the future for localized and focused applications on finer pitch components.

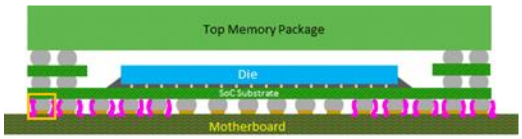
Table 6 - Experimental Design Matrix

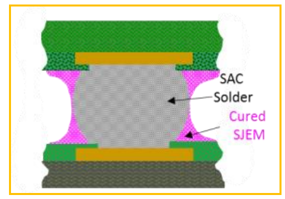
Leg #	Reliability Test	Solder Joint Reinforcing Material	Sample Size	
			Boards	Components
T1	Temp Cycle	Dip1	3	45 (12 monitored)
T2		Dip2	3	45 (12 monitored)
T3		Dis1	3	45 (12 monitored)
T4		Dis2	3	45 (12 monitored)
T5		Dis3	3	45 (12 monitored)
T6		UF1	3	45 (12 monitored)
S1	Mechanical Shock	Dip1	1	15
S2		Dip2	1	15
S3		Dis1	1	15
S4		Dis2	1	15
S5		Dis3	1	15
S6		UF1	1	15
Control	Both Shock and Temp Cycle	None (SAC305 solder Paste only)	4 (3 Shock, 1 Temp Cycle)	Shock: 45 (12 monitored) Temp Cycle 15

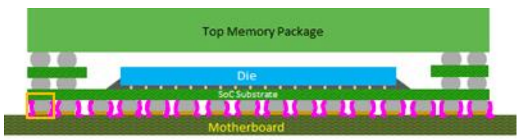
The POP component area array solder joint stack up after reflow soldering varied for each of the legs depicted in Table 6. Figure 4 shows a cross-sectional diagram of the POP assembly as well as a close up of an individual solder joint in the corner region of the POP array, for each of the legs in Table 6.

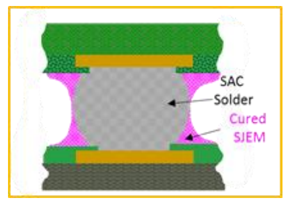
<table>
<tr><th>Leg Name</th><th>Package and Solder Joint Stack-ups</th><th>Single Solder Joint Cross-section</th></tr>
<tr><td>SAC
(No SJEM or Underfill)</td><td>

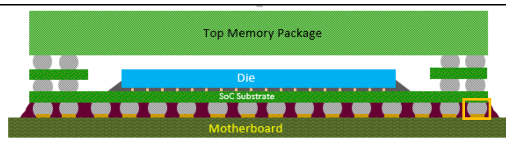
Typical Package on Package Stack Up</td><td>

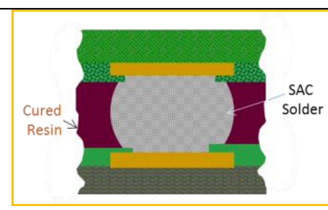
SAC Solder Joint With No Resin Reinforcement</td></tr>
<tr><td>SJEM Dip</td><td>

Typical Package on Package Stack Up
with outer rows of SoC Package Solder Joints
covered with cured SJEM</td><td>

SAC Solder Joint
covered with cured SJEM resin</td></tr>
<tr><td>SJEM Dispense</td><td>

Typical Package on Package Stack Up
with most rows of SoC Package Solder Joints
covered with cured SJEM</td><td>

SAC Solder Joint
covered with cured SJEM resin</td></tr>
<tr><td>Underfill</td><td>

Typical Package on Package Stack Up
With Bottom SoC Package solder joints underfilled</td><td>

SAC Solder Joint
Fully encapsulated with Resin</td></tr>
</table>

Figure 4. Cross-sectional Diagrams of the POP Assembly for the experimental legs evaluated.

SJEM Application Methods Descriptions

Two methods were employed for application of SJEMs. One was dipping and the other was dispensing. The rheology of the specific SJEM was optimized for each of these two application methods to enable adequate coverage of the solder joints after curing of the resins.

SJEM Application Method

Two different SJEM material types with material properties optimized for dipping and dispensing, were evaluated in this study. The application process and applied amount are different between dipping and dispensing SJEMs. Therefore, the weight of the material needed to achieve best solder joint coverage needs to be determined first.

The dipping application process steps are depicted in Figure 5. The POP component was dipped into a reservoir containing the SJEM. The SJEM wicks up the solder balls. The target was to achieve 65% solder ball height coverage of the SJEM during the dipping process. This height was controlled by the depth to which the component balls were placed in the SJEM and the amount of time the component was held in the reservoir. Table 7 lists these parameters for the two SJEMs that were evaluated by this dipping process. The SJEM dipping took place within the Pick and Place machine on the production SMT manufacturing line. This Pick and Place machine was already equipped with the capability for dipping components into a reservoir containing a fluxing liquid and had been used for assembly of the memory package on top of the POP System-on-Chip (SoC) component using a tacky flux. After the component was removed from this dipping operation, it was placed on to its land pattern on the board which had solder Paste printed on the lands. Subsequently, the board was reflow soldered in an in-line oven using a typical reflow profile for SAC305 solder paste. During this reflow soldering step, the SJEM cured and encapsulated the solder joints of the components

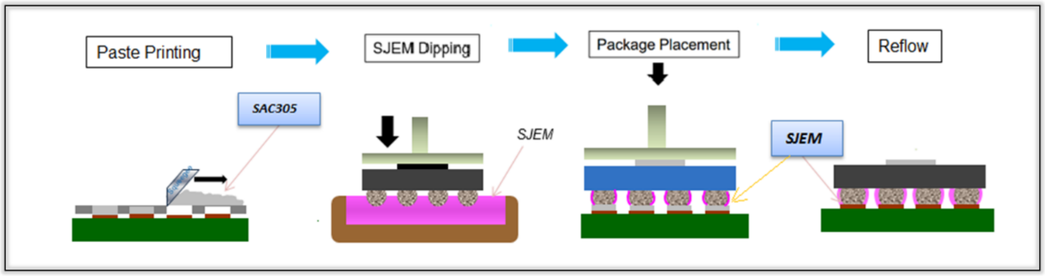


Figure 5. SJEM Dipping Process

Table 7 - Dip Materials and Process Comparison

Material	Material/ Parameter Comparison			
	Viscosity	Cure Profile	Dipping Height	Others
Dip1	5-20k cps (Production Viscometer, 0.5 rpm)	SAC305	0.075mm (65% solder ball hgt post SMT)	Part is held for 0.5 secs at placement before nozzle release
Dip2	1050cps (Production Viscometer, 20 rpm)	SAC305	0.075mm (65% solder ball hgt post SMT)	Part is held for 0.35 secs at placement before nozzle release

One issue was discovered during the dipping process development. The SoC substrate was warped slightly at room temperature due to the presence of the silicon chip on the substrate. When the POP components were dipped into the reservoir, the covered of the SJEM across all the rows was not uniform due to this substrate warpage. Figure 6 illustrates this issue. The outer rows were covered adequately with the SJEM but the central rows were devoid of the SJEM after the dipping operation. Dipping the component deeper into the SJEM reservoir would lead to excessive application of the SJEM on the other rows and would sometimes even make it difficult to pull the component out of the reservoir. Therefore, the dipping process acceptance limit was changed to ensure that at least three outer rows of solder balls were covered to the target limit by the SJEM on each side of the package, as shown in Figure 6.

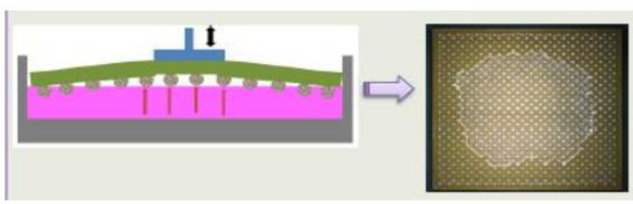


Figure 6 - Preferred Dipping SJEM material area coverage

The dispensing application process steps employed in this study are shown in Figure 7. The first three steps are identical to that of a typical SMT process, and include printing of the solder paste on the lands, placement of the component on the land pattern site and reflow soldering. The next step is to dispense the SJEM on one side of the package edge and then reflow solder the board once again. This process step is similar to that for applying and underfilling. However, there are two key differences. One is that the underfill requires a batch oven cure at a specific temperature and time. The other is that the SJEM flows during its curing process, which is the reflow cycle. When dispensing underfill, time has to be set aside for the underfill to flow into the gap between the package substrate and the board before it can be cured.

The dispensing process described above was chosen for this study after investigation of some other alternative process steps for the dispensing application option. Initially, as recommended by the SJEM suppliers, the SJEM was dispensed on to each individual land of the package. However, there were three unacceptable drawbacks to this method.

Firstly, due to the large number of lands for the POP component (220), the time taken to individually dispense each land was deemed to be unacceptably long for a high volume production environment. Jetting of the SJEMs could alleviate this issue since the jetting process is quicker than the needle dispensing process, but there was no jetting equipment on the SMT manufacturing line at the time this study was being conducted.

Dispensing equipment was in existence. Secondly, if the SJEM was dispensed on to the component lands after solder paste was printed on them, a significant amount of yield loss was obtained mainly due to extrusion of the solder during the reflow process step. The third drawback resulted due to the significant dynamic warpage of the POP component during reflow. Besides the resin, SJEMs do also contain fluxes with activators. Hence, solder paste is not necessary to form a solder joint between the solder ball and the PCB lands. However, the solder volume generated when the solder paste melts during the reflow process fills the gap between the component solder ball and the PCB land. This gap is created due to the component dynamic warpage during reflow. Without the presence of this solder on the land, the incidences of Head-on-Pillow (HoP) and Non-contact Open (NCO) defects were unacceptably high. Hence, the typical pre-reflow SJEM dispensing process on PCB lands was dropped.

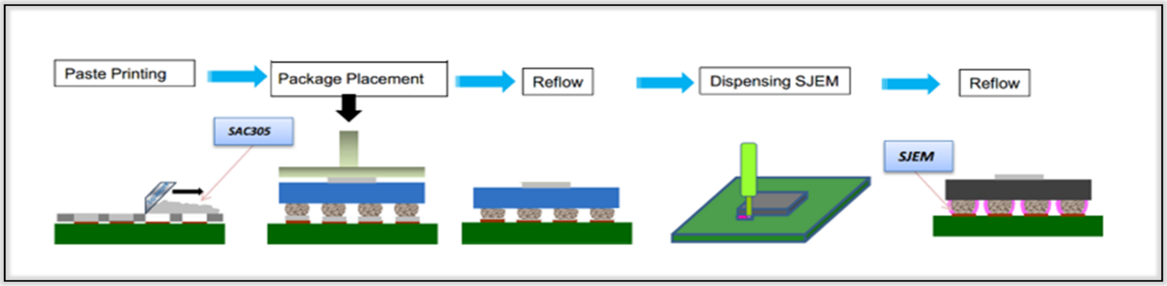


Figure 7. SJEM dispensing process

The next application process sequence evaluated was dispensing the SJEM immediately after placement of the POP component on the board, before the board was reflow soldered. However, the needle of the dispensing machine would sometimes jar the edge of the POP package and misalign the component since it was held in place just by the tackiness of the solder paste on the lands. This misalignment led to large, unacceptable solder joint yield losses. Thus, this process sequence was also dropped. Eventually the process step sequence depicted in Figure 7 was explored and adopted for further evaluation since the solder joint yield was acceptable.

Three dispensing type SJEMs and one underfill were evaluated in this study using the dispensing application method. The material and process parameters for each are compared in Table 8. Depending on the viscosity and material properties, the ease of dispense also varies.

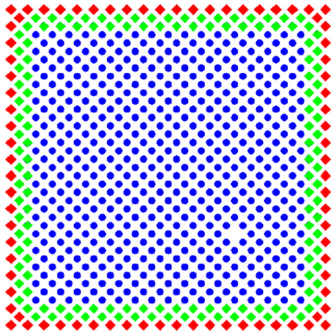
Table 8 - Dispense Materials and Process Parameter Comparison

Material	**Material/ Parameter Comparison**			
	Viscosity	**Cure Profile**	**SJEM Weight**	**Others**
Dis1	1050cps (Production Viscometer, 20rpm)	SAC305	20mg	Easy to dispense
Dis2	100-200 cps (Production Viscometer, 100rpm)	SAC305	20mg	Need a proper nozzle
Dis3	50k cps (Production Viscometer, 20rpm)	SAC305	20mg	Hard to dispense
UF1	394cps (Production Viscometer, 20rpm)	SAC305	36mg	Easy to dispense

When comparing the two application methods, the dipping method provides better control on SJEM coverage through in-line dipping height, but, as mentioned above, it was very sensitive to the component room temperature co-planarity. It also requires an additional feeder to carry out the application process. For the dispensing method, it is easier to ensure sufficient SJEM material can be applied to encapsulate each solder joint and is also less sensitive to component warpage. However, it requires dispensing equipment on the manufacturing to carry out the application process in-line. One important difference between the dispensing of the SJEMs and the underfill was that lesser volume of SJEM was needed to encapsulated the solder joints with the SJEM Volume/Underfill volume = 0.25.

Stencil Design

Solder Paste was applied to the POP component lands using a stencil. The Stencil aperture design is shown in Figure 8. The outer rows have lands have larger stencil aperture than the centrally located lands. This is due to the level of dynamic warpage for this POP component at the peak reflow temperatures of the SAC solder reflow profile used to solder the components on the boards. The stencil thickness was 0.08 mm.



Pad Color	Stencil Aperture Shape	Stencil Aperture Size, microns
Red	Square	305 per side
Green	Square	280 per side
Blue	Circle	280 diameter

Figure 8. Stencil design of BGA Test Vehicle paste print

Mechanical Shock Test Protocol

Samples were tested under mechanical shock based on the JEDEC JESD022-B111 specification. These shock conditions are listed in Table9.

Table 9- Shock Test Condition Used for SJEM DOE

Input	Level	# of drops	Orientation
Half-sine shock pulse	1500 g's +/- 10%	Up to 100 drops	Top Down
Pulse Duration	0.5ms		

Though each board test vehicle sample had 15 total POP components mounted on it, only 4 components were monitored for solder joint failures during the shock test. The location of these 4 components is shown in Figure9. These components were monitored electrically (in-situ) during the duration of the test using the daisy chain design shown in Figure 3. The daisy chain designators are shown in 10.

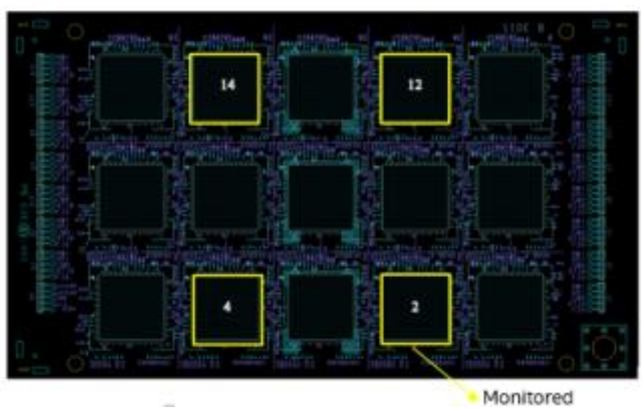


Figure 9. Components Monitored in-situ during Shock Testing (four components/board)

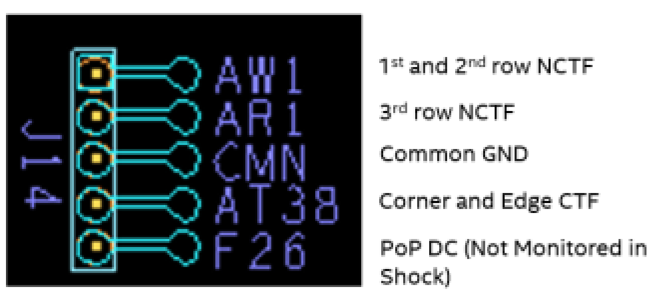


Figure 10. Daisy chain net designators for Shock and Temp cycle coverage. NCTF = Non critical to function; GND = Ground; CTF = Critical to function

The shock test samples were setup with the board placed in a fixture in the top down orientation on a High-G shock table. This setup is shown in Figure 11.

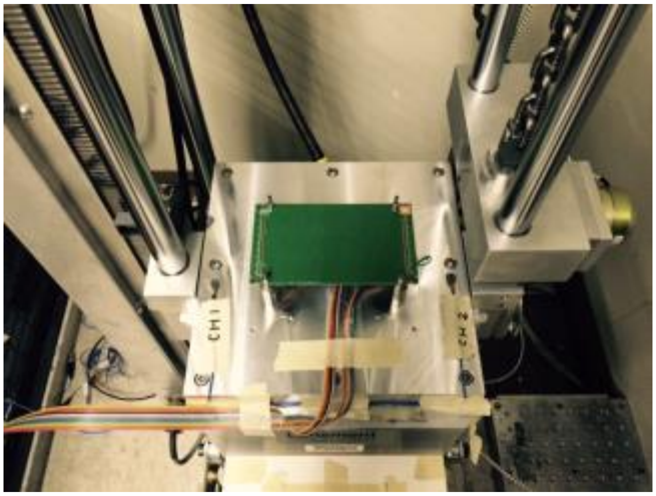


Figure 11. Shock Test Setup

Temperature Cycling Test Protocol

The temperature cycling test profile is shown in Figure 12. It entailed dwell temperatures of -40C and 125C, with a 5min soak at each dwell temperature and a 15C/min ramp between the dwell temperatures. The total cycle time was ~32min/cycle. Temp cycle data collection was carried out per the JEDEC JESD22-A104E specification. The component is deemed failed when the resistance of the daisy chains being monitored exceeded 1 MΩ.

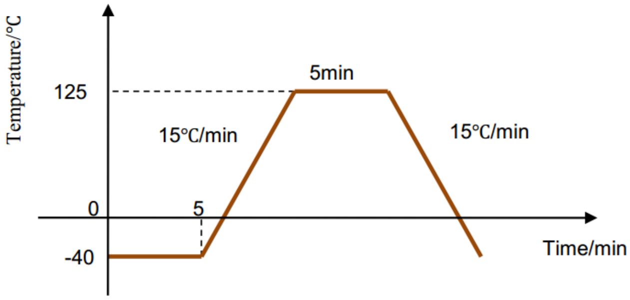


Figure 12. Temp Cycle Test Profile

A production thermal shock ramp tester was used was used to conduct the experiment. All 15 assembled POP components on the test board were monitored for solder joint failures. These 15 locations are shown in Figure 13.

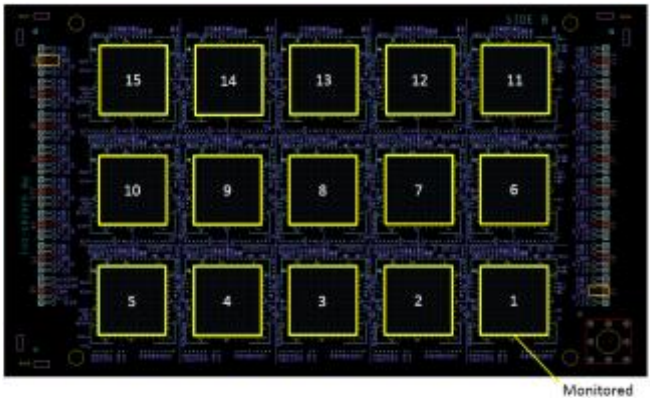


Figure 13: Components monitored in-situ during Temp Cycle testing

Results and Discussion

SJEM Assembly Results

The components were inspected for coverage of the solder joints by the SJEM after it was cured. For dipping packages, a cross section was done on the third row of solder joint from the package edge. For dispensing packages, two cross section cuts were made, one on the center row of the package, and the other across the diagonal row of the package. The cross section locations are shown in Figure 14.

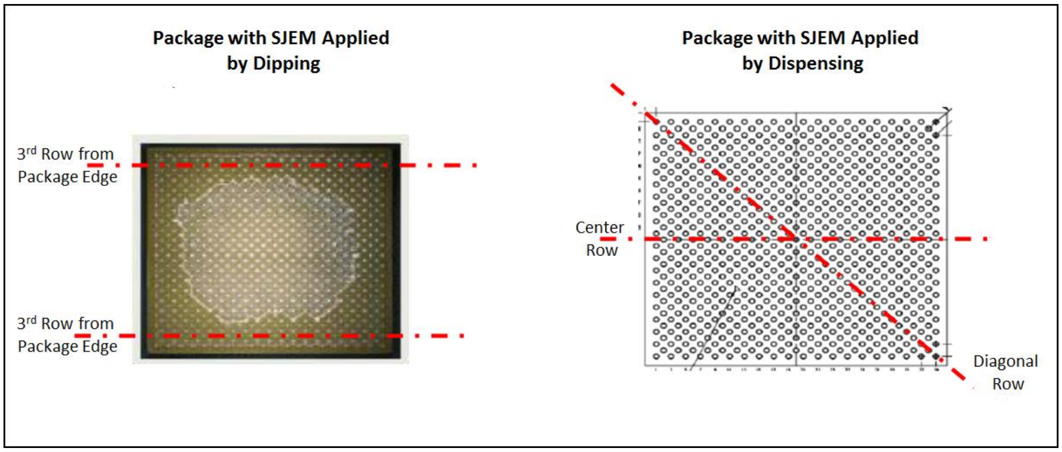


Figure 14. Cross section locations for SJEM coverage inspection on packages assembled with Dipping and Dispensing materials

X-ray inspection was done on the boards after SJEM application to calculate the area void percentage. Overall, dipping type material showed higher average area void up to 18% compared to dispensing type material at a maximum of 7% (Figure 15). Both SJEM materials showed higher void percentage compared to the baseline board without SJEM (~4%).

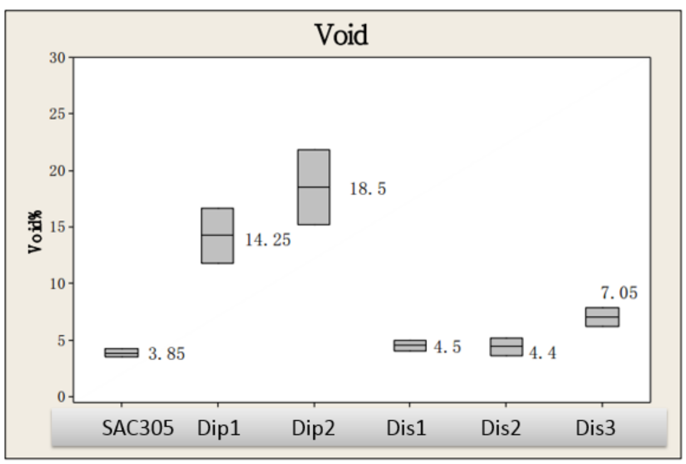


Figure 15. SJEM Void Average

When comparing SJEM material coverage, Dip1 SJEM did not show uniform coverage across the first three rows of solder ball from the component edge after reflow curing, although pre-SMT application covered 65% of the solder ball. On the other hand, Dip2 SJEM showed better uniformity in material coverage, where the first three row of solder joints showed clear epoxy coverage. However, the component center has visibly less epoxy coverage then the corner and edge locations. The pry test results comparing SJEM coverage can be found on Figure 16.

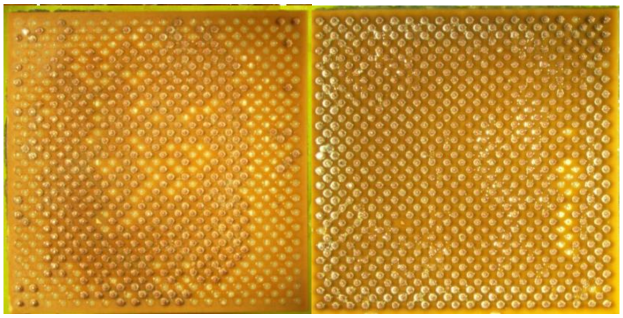


Figure 16. SJEM Dipping Material Coverage (Left: SJEM Dip1; Right: SJEM Dip2)

Dispensing type SJEM material showed more epoxy encapsulation around the solder joints overall compared to dipping type material. The localized dispensing offered more material coverage. Dis1 and Dis2 SJEM both showed full material coverage on all solder balls across the package after curing (Figure 17). Pry test was unsuccessful on Dis3 samples after five attempts due to strong adhesion to the PCB, so the coverage amount is unknown. This observation also indicated that Dis3 material processability and reworkability could be a potential challenge.

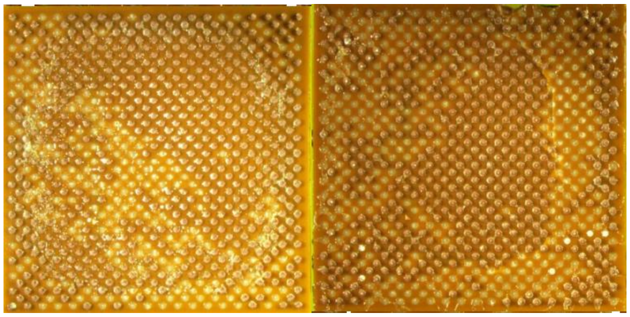


Figure 17. SJEM Dispensing Material Coverage (Left: Dis1; Right: Dis2)

In addition to the pry test, cross sectioning was also done on both dipping and dispensing samples on material coverage following the cross section location in Figure 14. No material coverage was found on the first row of solder balls on Dip1, which supported the non-uniformity found from the pry test. For Dip2, some voiding was found near the package, but material coverage can be found up to the thrid row of solder balls, showing better uniformity (Figure 18 and 19).

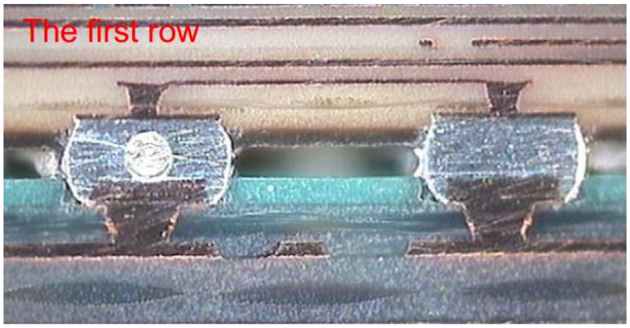


Figure 18. SJEM Dip1 cross section on the first row of package edge

Figure 19. SJEM Dip2 cross section on the third row of package edge

Among the three dispense type materials, Dis1 showed good material coverage on both the diagonal row and the middle row of the package, with minimal bubbles in the epoxy. Dis2 material showed more material coverage on the diagonal row, where the middle row showed less material coverage. Dis3 showed full coverage on both diagonal and middle row, but larger bubbles were found in the epoxy and some voiding was observed in the middle solder balls (Figures20,21 and 22).

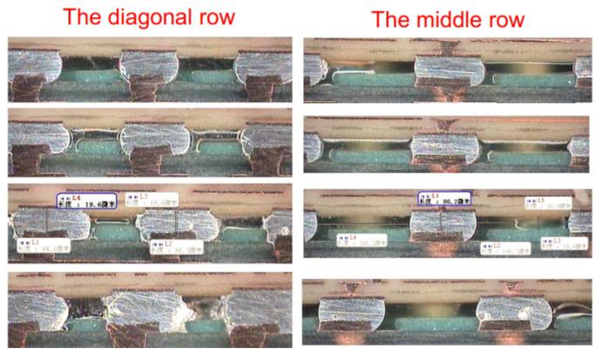


Figure 20. Dis1 material coverage

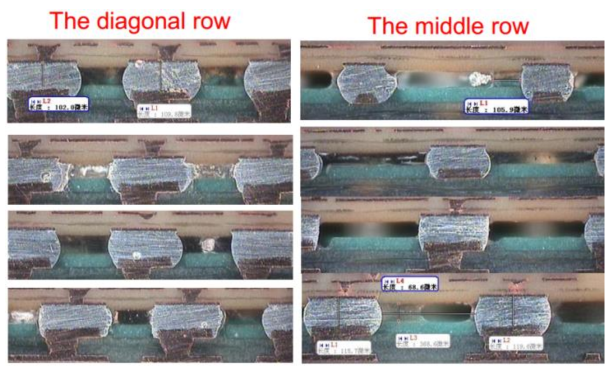


Figure 21. Dis2 material coverage

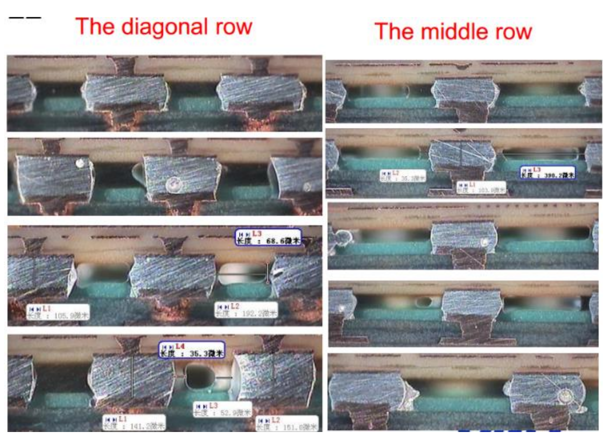


Figure 22. Dis3 material coverage

Based on the SJEM assembly results, dipping material showed higher voiding for the solder ball, and dispensing materials had higher material encapsulation amount around the solder joints. The solder joints all formed without issues with both SJEM materials application methods. The mechanical shock and temperature cycle reliability results will be discussed in the following sections.

In-situ Shock Test Results

The 1st and 2nd row NCTF daisy chain nets located in the package corners (AW1 net in Figure 10) were the first nets to show failure on all SJEM legs. A 2-P Weibull distribution plot was used to compare the characteristic life of the DOE legs based on the number of drops to failure (daisy chain open).

The 2-P Weibull distribution data plots for the 1st and 2nd row NCTF are shown in Figure 23. Table 10 lists these results in terms of the characteristics lives of the data, i.e., number of drops for 63.2% failure rate. In summary, both SJEM showed improved shock performance over bare component without SJEM (Control Leg). Dip1 and Dip2 material showed comparable characteristic lives, but Dip1 material has a larger data variation, which can be attributed to the coverage uniformity observed from Dip1 assembly results. Both Dis1 and Dis2 material showed comparable shock performance compared to dipping material, while Dis3 is the only SJEM that did not show in-situ shock failures. Underfill (UF1) material also performed better than most SJEM, with only 1 failed samples among a total of 45 samples. Based on the results, SJEM still has room for improvement to achieve shock performance parity to replace underfill material.

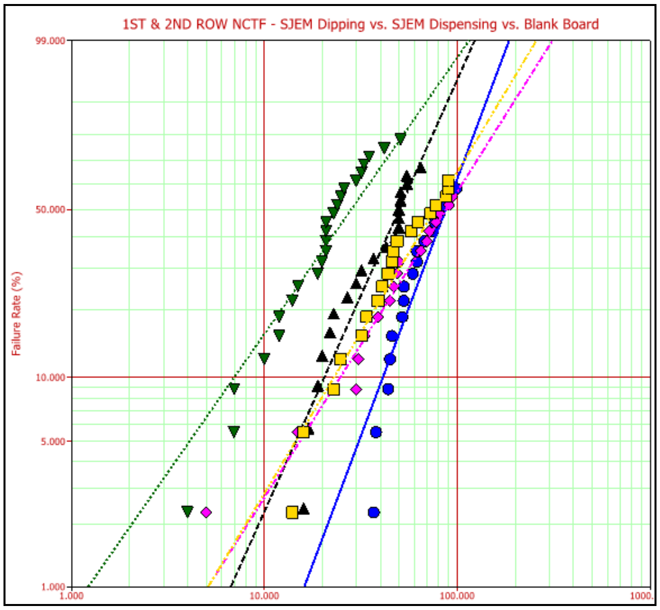


Figure 23: Weibull 2-P distribution of Net AW1 (1st and 2nd row NCTF) comparing Dipping SJEM, Dispensing SJEM, and Blank Board. Green: Blank; Black: Dis1; Yellow: Dis2; Pink: Dip1; Blue: Dip2

Table 10 - Shock Characteristic Life comparison for Various DOE Legs

DOE Leg	Characteristic Life (63.2% fail) in Number of Drops for the AW1 Net (1st &2nd Outer Rows)
Blank (Control)	37
Dip1	112
Dip2	101
Dis1	60
Dis2	97
Dis3	No Fail
UF1	No Fail

Overall, Dis1 material showed the lowest number of drops to failure when compared to the rest of the SJEMs evaluated. But it still showed a 62% improvement over boards without SJEM. The two dipping materials showed marginally better shock performance than two of the three dispensing materials. This can be attributed a larger amount of material around the solder joint, but this effect needs further study.

In general, these results highlight the necessity of additional work to optimize SJEM rheological properties and curing kinetics and ensure that the coverage of the SJEM cured resins is more uniform. Cured resin adhesion and cohesive properties also need improve to enable solder joints encapsulated with SJEMs have comparable shock resistance to underfilled solder joints.

Temperature Cycle Test Results

The temperature cycle test was carried out to 500 cycles, with intermittent readouts taken at every 100cycles. Failure was observed on bare board, underfill and dispensing SJEM legs on the first two monitored daisy chain nets.

A 2-P Weibull distribution using Maximum Likelihood (MLE) method was used to analyze the intermittent resistance data collected per the JEDEC JESD22-A104-B specification. From the Weibull distribution shown in Figure 24, and Table 11, which lists the characteristic life for all legs, dipping material showed overall best temp cycle performance.

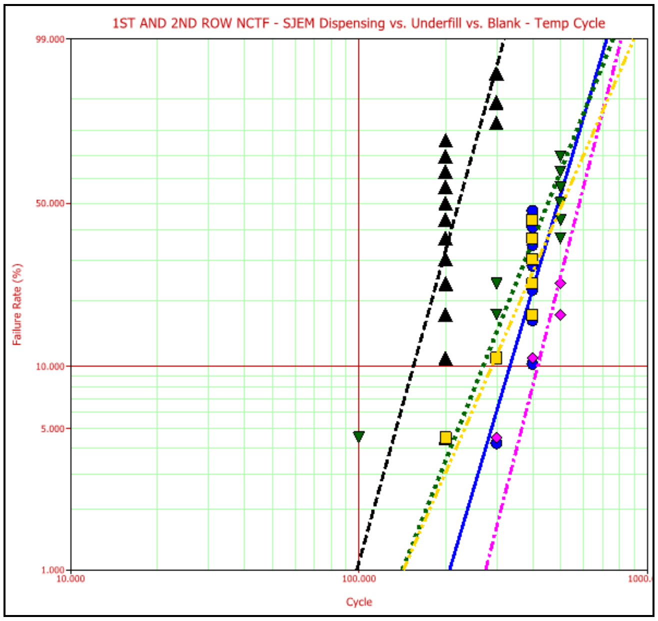


Figure 24. Weibull 2-P distribution of Blank versus SJEM Dispensing versus Underfill on AW1 (1st and 2nd row NCTF). Dipping leg is not plotted because no failures were detected (Black: UF1; Green: Dis1; Yellow: Dis2; Blue: Bare Board; Pink: Dis3)

The Weibull results showed that the reliability of SJEM boards can be material property and epoxy coverage dependent. Although dipping SJEM boards has less material coverage, the temperature cycle reliability is better than the dispensing material. The resin encapsulation amount surrounding the solder joint can play an important role on thermal cycle fatigue failure especially when the material properties such as Tg or CTE is not optimized for the temperature use condition. Accelerated temperature cycle test shows early failure due to CTE mismatch and exceeding the glass transition temperature. More will be discussed in the failure analysis section in this paper as we compare the failure location on different SJEM materials.

Table 12 lists the temperature cycle failures after each 100 cycle readout for each of the legs tested. Based on the results from this study, both SJEM material type showed at least 1.9x better temperature cycle reliability than underfill material. The underfill material evaluated in this study showed worse reliability than blank boards.

Table 11–Temperature Cycling Characteristic life comparison for various DOE Legs

DOE Leg	Characteristic Life (63.2% fail) in Number of Temperature Cycles for the AW1 Net (1st &2nd Outer Rows)
Blank (Control)	528
Dip1	No fail
Dip2	No fail
Dis1	499
Dis2	567
Dis3	619
UF1	238

Table 12 - Summary of TC SJEM results at each 100 cycle readout

Cyc	Blank - POR	UF1	Dip1	Dip2	Dis1	Dis2	Dis3
100	0	0	0	0	2 chips failed (net: AT38 1pcs) (net: AW1 1pcs)	1 chips failed (net: AT38 1pcs)	0
200	1chip failed (net: AT38 1pcs)	12 chips failed (net: AR1 2pcs) (net: AW1 12pcs)	0	0	2 chips failed (net: AT38 1pcs) (net: AW1 1pcs)	4 chips failed (net: AT38 3pcs) (net: AW1 1pcs)	0
300	3 chips failed (net: AT38 2pcs) (net: AW1 1pcs)	15 chips failed (all nets failed: 10pcs) (net: AW1 3pcs) (net: AW1 & AT38 2pcs)	0	0	5 chips failed (net: AT38 1pcs) (net: AW1 4pcs)	5 chips failed (net: AT38 3pcs) (net: AW1 2pcs)	1 chips failed (net: AW1 1pcs)
400	10 chips failed (net: AT38 2pcs) (net: AW1 8pcs)	15 chips failed (all nets failed: 14pcs) (net: AW1 & AT38 1pcs)	0	0	6 chips failed (net: AT38 1pcs) (net: AW1 5pcs)	9 chips failed (net: AT38 3pcs) (net: AW1 7pcs) (net: AR1 1pcs)	2 chips failed (net: AW1 2pcs)
500	10 chips failed (net: AT38 2pcs) (net: AW1 8pcs)	15 chips failed (all nets failed: 14pcs) (net: AW1 & AT38 1pcs)	0	0	11 chips failed (net: AT38 3pcs) (net: AW1 11pcs)	10 chips failed (net: AT38 4pcs) (net: AW1 7pcs) (net: AR1 1pcs)	4 chips failed (net: AW1 4pcs)

Failure Analysis on Mechanical Shock Samples

The post shock test cross section failure analysis results confirmed the failure trend from in-situ shock data. Figure 25 shows the various possible failure disbond interfaces. SAC305's dominant disbond mode is Type 4, between the PCB pad and PCB laminate which is sometimes termed `pad cratering`. Both SJEM legs show type4 disbonds with cracks initiated from the SJEM epoxy voiding area for dispensing type material (Figure 26,27,28,and 29). The cross section analysis does not show significant difference in the failure signatures between the two SJEM materials, which potentially indicated that the shock performance variation is more material properties dependent.

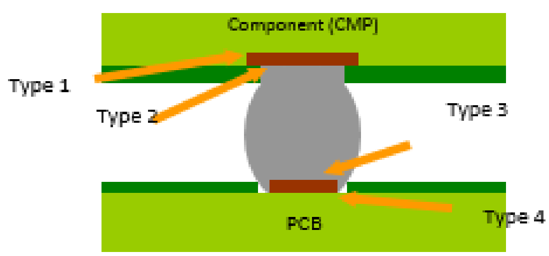


Figure 25. Failure disbond type categories

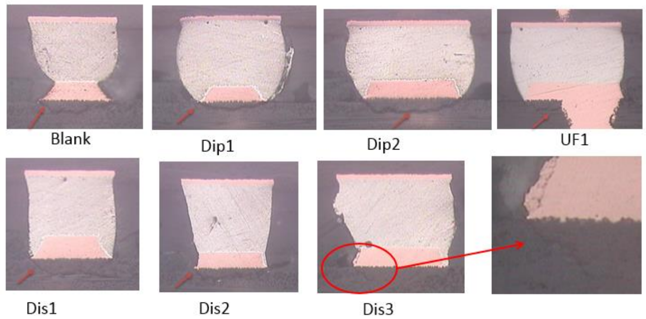


Figure 26. Post Mechanical Shock Cross section failure interface for All Experimental Legs

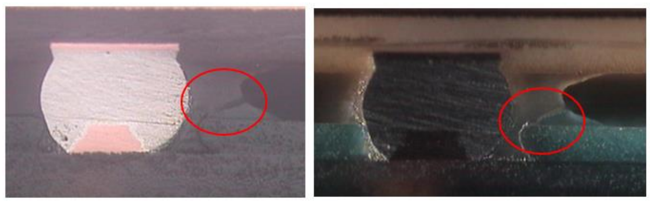


Figure 27. Evidence of Dis1 material crack initiation site in the SJEM cured Resin

Figure 28.Evidence of Dis2 material crack initiation site in the SJEM cured Resin

Figure 29. Evidence of Dis3 material crack initiation site in the SJEM cured Resin

Failure Analysis on Temperature Cycle Samples

Cross sections were done immediately after reflow soldering (i.e., pre temperature cycling) on package locations shown in Figures18,19,20,21, and22 in the earlier section of this paper to determine the extent of resin encapsulation height on the solder joints. More material coverage was found on corner/edge package location compared to package center on dipping material, whereas dispensing type material showed full coverage around all solder joints regardless of location on the package. This variation in resin coverage also lead to the temp cycle characteristic life margin differences observed on SJEM and SAC305 at 1st and 2nd NCTF net. More details will be discussed in the section below.

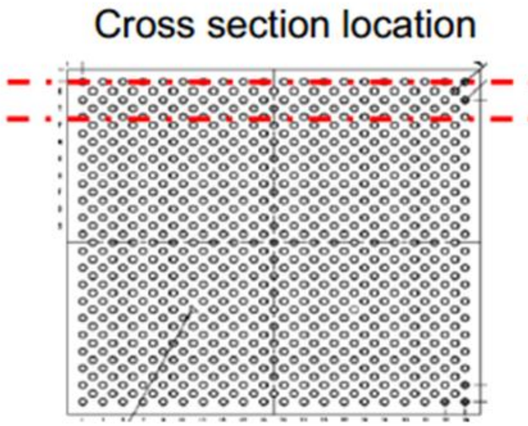


Figure 30. Post-Temp Cycle, cross section location on two package location.

In addition to pre-temperature cycling cross sections, dye and pull as well as end of test cross section were also done on selected units after thermal cycle test reached 500 cycles. The cross section cuts' location is shown in Fig. 30. The outer row and the 5th inner row were cross-sectioned to determine the failure mode and locations in the solder joints' stack-up.

Figure 31 shows the crack propagation in SAC305 joints at the end of test. Most cracks occurred in the bulk solder, at a mix of type 2 and type 3 interfaces through the intermetallic phase (IMC) closer to the PCB side. Compared to SAC305, solder joints with SJEM dipping material did not show any solder joint cracks. Dispensing type material showed less crack propagation compared to UF or bare board, but higher IMC formation on the PCB side is observed on the dispensing SJEM material. A summary of the average IMC thickness of the material is shown in Table 13.

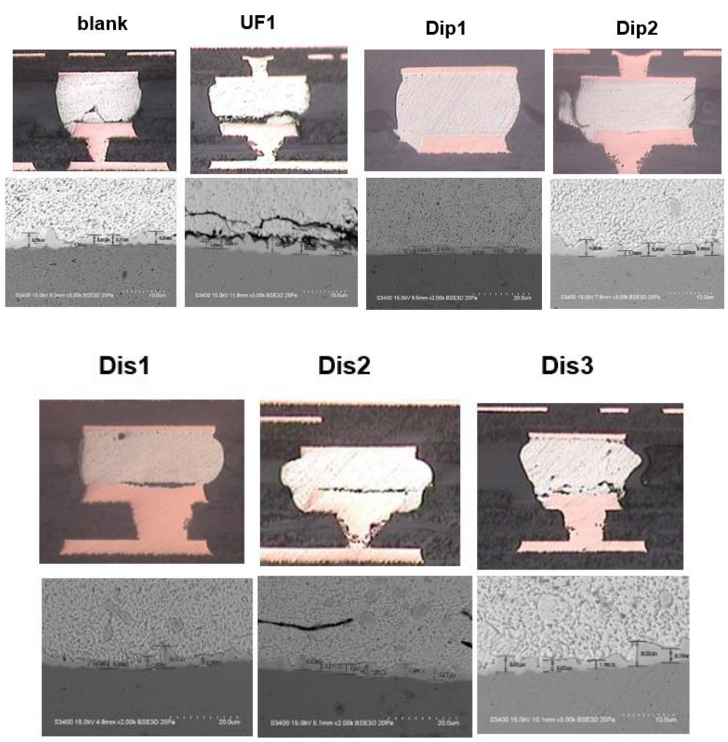


Figure 31. SJEMs post TC solder joint crack cross section compared to UF and SAC305 Bare board

In conjunction with the intermittent resistance results from temp cycle, dipping material showed best temp cycle performance overall, followed by dispensing materials, and underfill material showed worse temp cycle margin than bare SAC305 boards. The failure occurred on the IMC interface, with dispensing material showing thicker IMC growth after reflow curing. The variation in temp cycle reliability between the two types of SJEM materials can be attributed to the material properties differences where dipping material has more desirable CTE and Tg that will minimize temp cycle reliability risk. With dispensing material, although there was more material coverage, the properties might not be optimized for temp cycle reliability, which subsequently led to negative impact on temp cycle margin due to thicker IMC growth and worse CTE mismatch.

Table 13 - Post temp cycle IMC thickness comparison between SJEMs, UF, and SAC305

DOE	Average IMC thickness (µm)	Reflow Cycles Exposure
Blank (Control)	2.64	1
Dip1	2.65	1
Dip2	2.52	1
Dis1	3.81	2
Dis2	3.95	2
Dis3	3.06	2
UF1	2.45	1

CONCLUSIONS

This study set out to determine the processability, mechanical and temperature cycle reliability of SAC BGA solder joints reinforced by encapsulation using SJEMs. A total of 5 different SJEMs from two suppliers were evaluated. Three of these SJEMS were applied by dipping the BGA package balls into a reservoir containing these SJEMs and two others were applied by dispensing along one edge the package after it was initially reflow soldered. The solder joint reliability enhancement provided by the SJEMs was compared to a selected underfill material.

From the process assembly results, all SJEMs types can be successfully applied and cured with a typical SAC305 reflow process without solder joint defects. When comparing the two application methods, the dipping method provided a better control on SJEM coverage through in-line dipping height, but the number of solder balls covered by the SJEM in the BGA array was very sensitive to the room temperature coplanarity of the component. The dipping method requires an additional feeder to carry out the application process. The dispensing method ensured sufficient SJEM material coverage each solder joint and was less sensitive to component warpage. However, this method requires additional dispensing equipment to carry out the application process. The SJEMs covered solder joints formed by the dipping method contained slightly higher voiding when compared to the SJEM covered solder joints formed by the dispensing method. The dispensing method resulted in more volume of SJEM around the solder joints as well as better uniformity of this volume across the solder joint array for a package. However, this larger volume of SJEMs surrounding the solder joint can potentially make reworking the component more difficult.

Based on in-situ failures recorded during the shock event which the POP components were subjected to, solder joints reinforced with all SJEMs showed better mechanical shock margin when compared to the solder joints without any SJEMs (the control leg). This confirmed that use of SJEMs do enhance the shock reliability of POP components. Among the various SJEM materials evaluated, the Dis3 SJEM and the underfill material, performed the best and did not show any in-situ shock failures. SJEMs applied by the dipping method showed slightly better margin than those applied by the dispensing method. Based on the observed characteristic life on the1st and 2nd row NCTF nets, the ranking of the SJEMs according to the shock resistance of the solder joints formed when using them is: Bare board < Dis1 < Dis2 =< Dip2 < Dip1 <Dis3 & UF.

Based on in-situ failures recorded during temperature cycling of the POP components, solder joints at the package corners formed when using dipping SJEMs showed improved temperature cycle performance then the control sample which had no SJEM reinforcement (the control leg). But, solder joints applied with dispensing SJEMs, did not show any significant difference when compared to the control leg. The underfill material evaluated in this study showed a negative impact to temp cycle reliability, with the failure occurring even before the control leg. Based on the observed characteristic life on the 1st and 2nd row corner NCTF nets, the ranking of the SJEMs according to the enhancement they provide in improving the solder joint temp cycle failure resistance is: Dipping > Dispensing ≥ Bare Board > UF. Dispensing SJEMs showed thicker IMC formation on the PCB side compared to the rest of the DOE legs.

From these results, all SJEM materials evaluated exhibited feasibility to be applied, reflowed, and cured with SAC305 solder paste. The dipping method is sensitive to package coplanarity, but resulted in better reliability in mechanical shock and temperature cycle. The dispensing method provides more material coverage, but this does not translate to better shock or temp cycle reliability. The material properties of the cured SJEM resins and IMC thickness and morphology of the solder joints both play a role in optimizing reliability performance. Hence, further work is necessary to understand the effect of resin properties and the amount of resin coverage of the solder joints on their reliability performance. When comparing SJEM materials to underfills, though temp cycle reliability is shown to be equivalent or better for SJEMs, there is still room for enhancing the mechanical shock reliability.

In summary, the weighted matrix comparing all the DOE legs for various characteristics is shown in Table 14 below. From this table, dipping SJEM is the most favorable solution from this study, which showed improved reliability margin over bare boards. It can also be a potential solution to replace traditional underfill material to provide solder joint reinforcement as component pitch size decreases and body size increases.

Table 14 - Overall matrix comparison: 6 – Most desirable; 1 – least desirable

Polymeric Reinforcement	Ease of Processing and Solder Joint Yield	Temperature Cycling Reliability	Drop shock reliability	Mfg Line Loading level	Cost	Total
Control (Blank)	6	1	1	6	6	20
Underfill UF1	4	0.45	6	1	1	12.45
SJEM Dis1	4	1.07	1.6	4	4	14.67
SJEM Dis2	4	1	2.6	4	4	15.6
SJEM Dis3	2	2.4	6	4	4	18.4
SJEM Dip1	2	6	3	5.5	5.5	22
SJEM Dip2	4	6	2.7	5	5	22.7

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