As originally published in the SMTA International Conference Proceedings.

THERMAL SHOCK AND DROP TEST PERFORMANCE OF LEAD-FREE ASSEMBLIES WITH NO-UNDERFILL AND CORNER-UNDERFILL

Bankeem Chheda and S. Manian Ramkumar, Ph.D.
Rochester Institute of Technology-CEMA
Rochester, NY, USA
bankeemchheda@gmail.com and smrmet@rit.edu

Reza Ghaffarian, Ph.D.
Jet Propulsion Laboratory
Pasadena, CA, USA
reza.ghaffarian@jpl.nasa.gov

ABSTRACT
With ROHS compliance the transition to lead-free is inevitable. Several lead-free alloys are available in the market and its reliability has been the main concern. The results from this experimental research aims at making a comparison of different lead-free alloy combinations. Thermal shock and drop tests are a part of this experimental study.

The test vehicle considered for this study contains a variety of components such as ultra chip scale package (UCSP), package on package (PoP), plastic grid array (PBGA-676 & 1156), very thin chip array BGA (CVBGA), thin small outline package (TSOP-40 & 48), dual row micro-lead frame (DRMLF), micro-lead frame (MLF-36 & 72), and chip resistors (0201, 0402, 0603). The scope of this paper is limited to the performance evaluation for area array packages only. Solder ball alloy combinations for the area array packages include SAC305, SAC405, SAC105 and SnAg. The solder paste used for assembly is SAC305 with Type 3 particle size. Three different PCB surface finishes, electroless nickel immersion gold (ENIG), SnPb hot air solder level (HASL), and immersion silver (ImAg) are used. Different solder ball alloys and surface finish combinations will provide good comparison data for investigating the assembly performance.

Preliminary investigations have been carried out on PCB assemblies subjected to mechanical shock in the as-soldered condition and also after 200 and 500 thermal shock cycles at -55 to 125°C. The mechanical shock test was conducted by subjecting the assemblies to 30-drop cycles from a height of 3ft. After each drop cycle the daisy chains were checked for continuity for the solder joint evaluation. The number of drops for the first daisy chain failure is used in analyzing the performance of the solder joints.

Since each component has many independent daisy chains, the failure of the individual daisy chains was later used in determining the location of the failure and its progression. The preliminary investigations revealed consistent failure in the corner daisy chains of the area array components attributable to the flexing of the PCB resulting in the solder joint strain when subjected to the shock event.

Initial results indicate SnAg alloys for the solder balls to be performing better than the SAC 305 and 405 alloys in the no-underfill condition, irrespective of the PCB finish. After 200 cycles of thermal shock UCSPs showed marked improvement in drop tests but were found to fail after 500 cycles of thermal shock. PoP assemblies were found to survive all 30 drops for all combinations of PCB finishes. This paper will provide a detailed analysis of these findings including the results to be investigated with corner underfilled assemblies.

INTRODUCTION

With the advent of lead-free it is essential to evaluate several possible alloy combinations and select the most appropriate substitute for lead-based solder. In surface mount technology (SMT) lead is widely used in components, solder paste, and board surface finishes, hence eliminating lead would involves changes to the entire assembly process. A complete lead-free transition would require careful modification of several process parameters. Any lead-free alloy replacing lead-based solder should qualify with requirements such as low melting point, adequate wetting characteristics, comparable cost, consistent manufacturability (at the component level and the board level), wide availability, acceptable reliability, ease of reworkability and reparability etc [1].

Several possible combinations for lead-free are available in the market. Most commonly used lead-free solder paste is SAC305. Many alloys in this family typically have melting points ranging from 217°C to 222°C. Lead-free solder bumps comprises of combinations such as SAC105, SAC305, SAC405, SnAg, etc. Choosing a combination of lead-free solder bump and lead-free solder paste would dictate the reliability of the assembly.

Today's hand held devices are subjected to many stresses and hence requiring them to have to reinforce mechanical strength. For superior protection of solder joints against mechanical strains such as shock, drop and vibration, underfill technology should be adopted. Underfill technology aims to ensure that area array packages assembled on PCBs can withstand mechanical and thermal shock [2]. In order to prevent the solder joint strain at corner balls it was decided to underfill only the four corners of the package.

Miniaturization of components along with smaller ball diameter creates greater concern over reliability of the solder joints. This can be attributed to the low component standoff and large intermetallic to solder ball ratio when compared to a standard area array package. This study will provide a good understanding of the performance of different solder ball materials with three different PCB surface finishes when assembled with SAC305 solder paste. PCB assemblies without underfill will be compared with assemblies with corner underfill.

BACKGROUND RESEARCH

Packages such as CSP and BGA, particularly those in handheld devices require high level of reliability. As these devices are exposed to higher than normal stress capillary flow underfills would be the choice of material **[3]**. Capillary underfills are low viscosity liquids designed to flow under a component by capillary action. Underfill is applied close to the edge of the component to enable capillary forces to flood the gap between the component and the board [4].

Substrate temperature can be used with great effectiveness to control the flow of underfill under the die. Flow velocity and wetting to package surface can be improved if the substrates are preheated. Typical pre-heat temperatures range from 40°C to 90°C, depending on the package geometry and the encapsulants used [5].

Many dispensers are available with heaters to warm the syringe containing the underfill material. Heating of the syringe can lower the underfill viscosity to provide easier and more precise dispensing. Viscosities are designed to be sufficiently low to enable precise dispensing without heating aids [6].

The binary alloy system SnAg has been extensively studied in the past for various reasons. This alloy has been used in the industry for many years in module assembly. The reliability of this alloy is comparable to eutectic SnPb alloy, and the primary difference between SnAg and SAC alloys is the addition of copper, which lowers the melting temperature by 4°C. SAC alloys have been considered as the most probable substitute for SnPb. iNEMI, the International Tin Research Institute (ITRI), European Department of Trade and Industry (DTI), JEIDA have all recommended SAC to be the mainstream lead-free alloy for the electronics assembly [7].

Underfill is supposed to protect solder joints and make the end product last longer. Previous research indicates that for some applications underfill may result in thermal-cycle failure sooner than if no underfill was used at all. In order to achieve improved reliability under both thermal and mechanical conditions, underfill material properties need to be optimized for the type of package and its intended environment [8].

Handheld electronic devices are prone to be dropped in their lifespan [9]. These drops may result in cracking of these solder joint. Hence it is important to study the drop test reliability of the lead-free solder joints. Past experimental research have stated that a SAC alloy performs poorly in comparison to low Ag content alloys, it has also been mentioned that edge bonding improves the life of a solder joint [9]. This experimental study comprises of different lead-free alloys for the solder balls and surface finishes and hence will prove beneficial in correlating the results. Performance evaluation for area array packages with corner underfill will be compared to without underfill.

EXPERIMENTAL DESIGN

The experiment was designed in such a way that maximum possible comparison data would be obtained. This experimental study compares lead-free solder paste (SAC305) with other lead-free solder bumps. The solder bump comprises of lead-free alloy such as SAC305, SAC405, SAC105, SnAg, SAC125Ni. The combination of solder paste to solder bump for each area array package is provided in Table 1. For comparison purpose three different surface finishes were examined in this study as shown in Table 2. This experimental study will compare performance of area array packages with corner underfill and without underfill.

Component	Solder Ball Alloy Composition		
UCSP192	SAC305		
PBGA1156	SAC305		
PoP152	Top-SAC105	Bottom*SAC125Ni	
CVBGA432	SAC105	SAC305	SAC405
PBGA676	SnAg	SAC305	SAC405
*SAC125Ni (1.2%Sn/0.5%Ag/0.05%Cu/98.25%Ni)			

Table 1: Lead-free components assembled with SAC305

PCB Surface Finish		
ENIG	HASL	ImAg

Table 2: PCB Surface Finishes

TEST VEHICLE

A custom designed test vehicle was used for this experiment. The design incorporated the following components as marked in Figure 1: (1) UCSP192; (2) PoP152; (3) PBGA676; (4) PBGA1156; (5) CVBGA432; (6) TSOP40; (7) TSOP48; (8)-DRMLF; (9) MLF36; (10) MLF72; (11) 0201; (12) 0402; (13) 0603; (14) LCCC. Table 3 provides component specification pertaining to area array package components considered for this study.

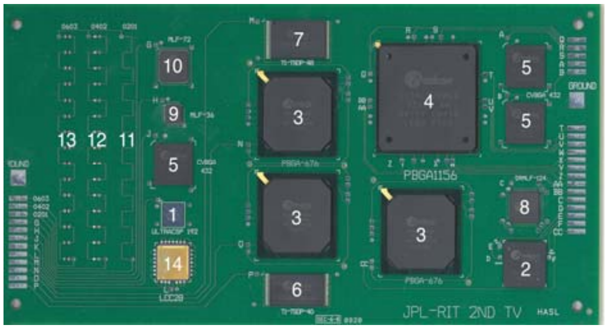

Figure 1: Test Vehicle

Component	I/O Count – (Area array configuration)	Ball Dia (mm)	Pitch (mm)	Body Size (mm)
UCSP192	192 (*P)	0.25	0.4	7
PBGA	676 (*F)	0.63	1.0	27
CVBGA432	432 (*P)	0.25	0.4	13
PBGA	1156 (*F)	0.63	1.0	35
PoP-top	152 (*P)	0.3	0.65	14
PoP-bottom	353 (*P)	0.5	0.5	14
*P – Peripheral area array				
*F – Full area array				

Table 3: Component Specifications

UNDERFILL MATERIAL

The underfill material used was Loctite 3536. It's a reworkable adhesive. This material was chosen as it has been designed to enhance the reliability of hand-held devices, especially those manufactured in lead-free environments. The physical properties of the material are shown in the Table 4.

Physical Properties	
Color	Black
Viscosity at 25°C, mPa	2200
Reflow cure temp/time	150°C / 1 minute
Tg (°C)	26
Specific gravity (g/cc)	1.25

Table 4: Physical Properties of Loctite 3536

ASSEMBLY PROCESS DEVELOPEMENT

The board assembly task included stencil design and setting up the SMT line (screen printing, placement machines & reflow oven). The designing of the stencil was complex due to the mix of components, which included chip resistors such as 0201, 0402 along with area array packages whose pitch varied from 0.4 mm (UCSP192) to 1 mm (PBGA).

The test vehicles were assembled on a fully automated SMT assembly line at Center for Electronics Manufacturing and Assembly (CEMA) at Rochester Institute of Technology. SAC305 No-Clean, type 3 solder paste, was printed using a 4-mil-thick, electroformed stencil. The solder paste volume was inspected using a laser inspection system. The components were placed using a placement force of 2N. The reason for selecting a placement force of 2N was due to the fact that during some of the preliminary test runs we found out that higher force was causing placement issues for PoP packages, this supports the findings from other published work [10]. It was also decided to use the flux dip method for placing the top-PoP package. The PCB assemblies were then reflowed with the established reflow profile.

The PoP assembly was very critical among the mix of components on the test vehicle. Placement accuracy was found to be a very important factor for successful assembly of PoP packages. One of the primary reasons for placement inaccuracy was improper board fiducial recognition, due to varying PCB finishes during the course of the assembly runs for the experiment. The flux dip height for the top package was maintained at 60%, of the solder ball height in order to achieve adequate wetting, which supports the findings from other published work [10].The dip time for the top package in the flux was 5 seconds. Slightest misalignment of the bottom package was corrected due to self-centering ability of BGA packages, whereas misalignment of top-package resulted in fallouts due to the absence of solder paste. No package warpage related issues were noticed with PoP assembly. Even with a complex mix of components no other assembly related issue was experienced.

For this experimental study Capillary flow underfill methodology was used. Dispensing was done using a jetting technology. For achieving sufficient and consistent flow rate, the needle, seat and the nozzle size had to be carefully selected. The dispensing program was designed in such a way that sufficient fillet of underfill was formed. The board design accommodated well for the underfill process.

REFLOW PROFILE

Reflow profile specifications for SAC305 solder paste is provided in Table 5. The actual profile is shown in Figure 2. These profiles was developed taking into account the paste manufacturer's specifications and component temperature limitations.

Solder Paste	Max Preheat Slope (°C/sec)	Soak Time (sec)	Peak Temp (°C)	*TAL (sec)
SAC305	1-1.5	12-20	240-250	65-85
*TAL- time above liquidus				

Table 5: Reflow Profile Parameters

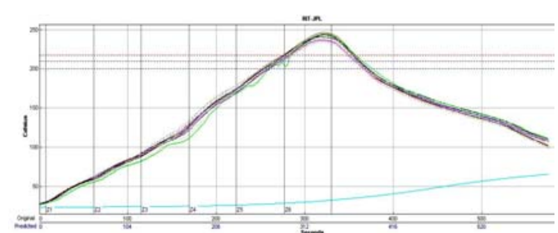

Figure 2: Reflow Profile for SAC305

TEST SAMPLE SIZE

This experimental study involved assembling 18 PCBs, which included 6 each with ENIG, HASL, and ImAg surface finish. Nine PCBs were subjected to corner underfill while the other nine were not underfilled. This selection was made in order to draw comparison of no-underfill with corner underfill. Out of the nine PCBs, that were underfilled, 3 were drop tested in as-soldered condition, 3 after 200 cycles of thermal shock, and 3 after 500 cycles of thermal shock. Similar was the selection for the nine PCB assemblies, which did not undergo underfill process.

RELIABILITY TEST METHODS

To evaluate the solder joint reliability, PCB assemblies were subjected to thermal shock (-55°C to 125°C) followed by drop test Table 6. The thermal shock equipment had to undergo defrosting after completion of every 75 cycles for proper functioning. During this defrost period the PCB assemblies were maintained at +125°C.

Parameter	Setting
Average Peak Load	485 G
Time period	3 ms
Height of drop	36 inches
Maximum drop cycles	30
Stand-off height	2 inches

Table 6: Drop test parameters

The PCB assemblies were mounted in the horizontal orientation with components facing down for the drop test. The board was held in place for the drop test, using the tooling holes. This orientation is recommended since it provides the most severe board deflection as identified by JEDEC Standard No. 22-B111. After every drop the component solder joint integrity was evaluated using continuity measurement in the daisy chains.

OBSERVATION & ANALYSIS

After assembly the boards were subjected to thermal shock and mechanical shock tests, while some were directly tested for mechanical shock as discussed in the experimental design. The results of these tests are discussed in this section.

From the Table 7, it is conclusive that corner underfill improved the package performance. UCSP did not fail for 30 drops for both the as-soldered condition and the 200 cycles of thermal shock. It however failed during the 200 cycles for the PCB assembled with ImAg finish. From the above data it can also be concluded that the UCSP could not withstand 500 cycles of thermal shock irrespective of whether it was underfilled or not.

With corner underfill it was observed that the package was able to withstand more number of drops as compared to without underfill for the as-soldered condition. With underfill, the package seems to have a better mechanical shock resistance than thermal shock resistance. This is evident with 200 and 500 cycles of thermal shock as shown in Table 8.

UCSP drops to failure			
Solder paste (SAC305) – Solder ball (SAC305)			
Test Condition	PCB surface finish	Without Underfill	Corner Underfill
As soldered	ENIG	24	*DNF
	HASL	14	DNF
	ImAg	13	DNF
200 *TS	ENIG	11	DNF
	HASL	2	DNF
	ImAg	10	*0
500 *TS	ENIG	0	0
	HASL	0	0
	ImAg	0	0
*TS – Thermal Shock Cycles			
*DNF – did not fail for 30 drops			
*0 – failed during the thermal shock cycle			

Table 7: UCSP drops to failure (SAC305-SAC305)

PBGA1156 drops to failure			
Solder paste (SAC305) – Solder ball (SAC305)			
Test Condition	PCB surface finish	Without Underfill	Corner Underfill
As soldered	ENIG	1	29
	HASL	6	16
	ImAg	5	14
200 *TS	ENIG	5	7
	HASL	11	8
	ImAg	5	7
500 *TS	ENIG	5	11
	HASL	9	11
	ImAg	12	13
*TS – Thermal Shock Cycles			

Table 8: PBGA1156 drops to failure (SAC305-SAC305)

PBGA676 drops to failure			
Solder paste (SAC305) – Solder ball (SAC305)			
Test Condition	PCB surface finish	Without Underfill	Corner Underfill
As soldered	ENIG	3	5
	HASL	3	8
	ImAg	4	3
200 *TS	ENIG	3	3
	HASL	5	2
	ImAg	2	2
500 *TS	ENIG	2	4
	HASL	3	3
	ImAg	3	3
*TS – Thermal Shock Cycles			

Table 9: PBGA676 drops to failure (SAC305-SAC305)

PBGA676 drops to failure			
Solder paste (SAC305) – Solder ball (SAC405)			
Test Condition	PCB surface finish	Without Underfill	Corner Underfill
As soldered	ENIG	3	2
	HASL	2	8
	ImAg	1	3
200 *TS	ENIG	2	2
	HASL	4	3
	ImAg	4	2
500 *TS	ENIG	3	4
	HASL	3	5
	ImAg	5	4
*TS – Thermal Shock Cycles			

Table 10: PBGA676 drops to failure (SAC305-SAC405)

For PBGA676 with SAC305 and SAC405 solder bumps, it was observed that there was no significant improvement in performance of the component after it was corner underfilled. Table 9 and Table 10 provide the drops to failure for PBGA676 with SAC305, SAC405 as the solder bump. The failure of the PBGA676 with SAC305 and SAC405 can be attributed to the deflection of the PCB and the location of the component on the PCB when mounted for drop test.

PBGA676 drops to failure			
Solder paste (SAC305) – Solder ball (SnAg)			
Test Condition	PCB surface finish	Without Underfill	Corner Underfill
As soldered	ENIG	12	DNF
	HASL	18	DNF
	ImAg	8	DNF
200 *TS	ENIG	12	DNF
	HASL	13	DNF
	ImAg	7	17
500 *TS	ENIG	*DNF	DNF
	HASL	13	25
	ImAg	22	18
*TS – Thermal Shock Cycles			
*DNF – did not fail for 30 drops			

Table 11: PBGA676 drops to failure (SAC305-SnAg)

On comparing the drops to failure for PBGA676 (SnAg-solder bump) with and without underfill, it was observed that the component performed better with the underfill (Table 11). The performance was better for the as-soldered condition and for the thermal shock cycles. With and without underfill SnAg solder bump seems to be performing better than SAC305, SAC405 bumps this could be attributed to the location of the component on the PCB [7].

CVBGA drops to failure			
Solder paste (SAC305) – Solder ball (SAC305)			
Test Condition	PCB surface finish	Without Underfill	Corner Underfill
As soldered	ENIG	15	DNF
	HASL	26	DNF
	ImAg	12	DNF
200 *TS	ENIG	27	DNF
	HASL	*DNF	DNF
	ImAg	DNF	DNF
500 *TS	ENIG	DNF	DNF
	HASL	*0	DNF
	ImAg	DNF	DNF
*TS – Thermal Shock Cycles			
*DNF – did not fail for 30 drops			
*0 – failed during the thermal shock cycle			

Table 12: CVBGA drops to failure (SAC305-SAC305)

CVBGA drops to failure			
Solder paste (SAC305) – Solder ball (SAC405)			
Test Condition	PCB surface finish	Without Underfill	Corner Underfill
As soldered	ENIG	27	DNF
	HASL	*DNF	DNF
	ImAg	DNF	DNF
200 *TS	ENIG	DNF	DNF
	HASL	16	DNF
	ImAg	13	DNF
500 *TS	ENIG	DNF	DNF
	HASL	30	DNF
	ImAg	DNF	DNF
*TS – Thermal Shock Cycles			
*DNF – did not fail for 30 drops			

Table 13: CVBGA drops to failure (SAC305-SAC405)

CVBGA drops to failure			
Solder paste (SAC305) – Solder ball (SAC105)			
Test Condition	PCB surface finish	Without Underfill	Corner Underfill
As soldered	ENIG	17	DNF
	HASL	29	DNF
	ImAg	*DNF	DNF
200 *TS	ENIG	28	DNF
	HASL	DNF	DNF
	ImAg	DNF	DNF
500 *TS	ENIG	DNF	DNF
	HASL	DNF	DNF
	ImAg	DNF	DNF
*TS – Thermal Shock Cycles			
*DNF – did not fail for 30 drops			

Table 14: CVBGA drops to failure (SAC305-SAC105)

The test vehicle comprised of three CVBGA components. The solder bumps comprised of SAC305, SAC405, and SAC105. It was observed that the performance of the CVBGA component was better with corner underfill than without underfill, irrespective of the solder bump composition. The drops to failure results for CVBGA are shown from Table 12 to Table 14.On comparing solder bump SAC105, SAC305, SAC405 for CVBGA, it was not decisive as which one is performing better than the other.

The PoP package survived all the 30 drops of the mechanical shock irrespective of the reliability test method. The results were similar for PoP package with and without underfill. A probable reason for this could be the location of the package on the PCB (Figure 1)

DAISY CHAIN FAILURE PROGRESSION

For PBGA676 and PBGA1156 it was found that the daisy chain failed in a particular pattern. However, this was not observed in the case of CVBGA432 and UCSP192.

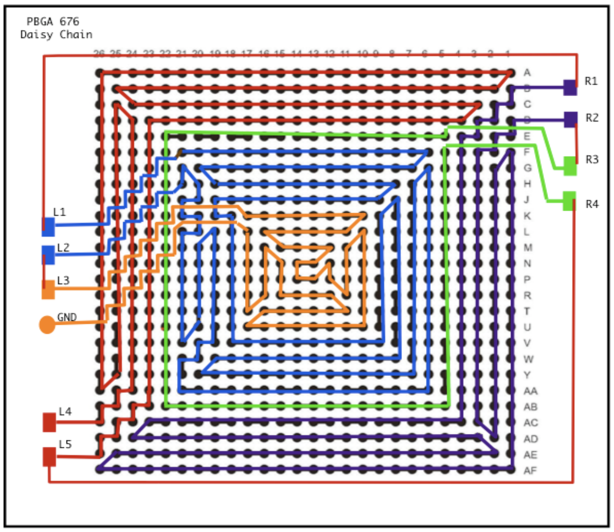

Figure 3: Daisy Chain Pattern for PBGA676

In the case of PBGA676, in all three locations the failure started with the daisy chain L4-L5, this was followed by daisy chain R3-R4, followed by R1-R2 and L1-L2. The innermost daisy chain L3-GND never failed. The various daisy chains are labeled as shown in Figure 3.

In the case of PBGA1156 the failure started with daisy chain (Figure 4) Z-Z, followed by daisy chain AA-AA, followed by BB-BB or Q-Q, followed by T-T. Daisy chains R-R, S-S, U-U, V-V, W-W, X-X, Y-Y never failed. Based on the failure of the daisy chains it appears that the orientation of the component plays a considerable role.

SOLDER JOINT ANALYSIS

The two failure modes observed after the drop tests show were pad lifting (Figure 5 to Figure 7) and solder joint crack. The pad lifting was primarily observed in PBGA 676 assembled.

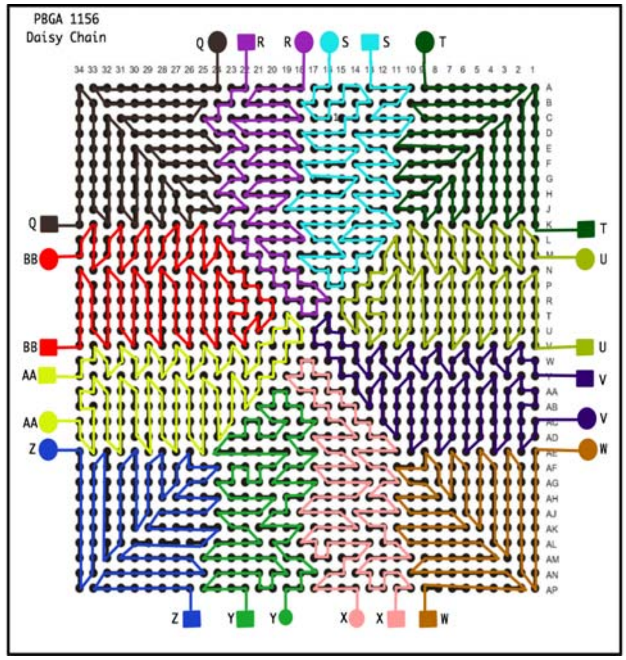

Figure 4: Daisy Chain Pattern for PBGA1156

with SAC305 and SAC405 solder bumps. The pad lifting indicates that the solder joint was intact.

Figure 5: Pad lifting – PBGA676 (SAC305) – 200TS

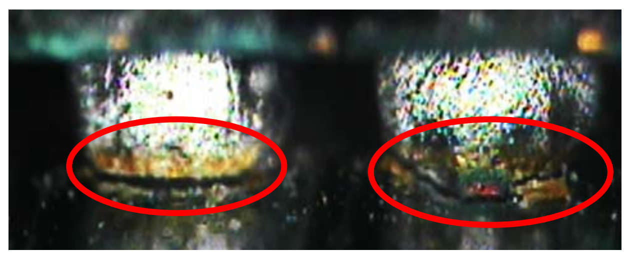

Figure 6: Pad lifting – PBGA676 (SAC305) – 200TS

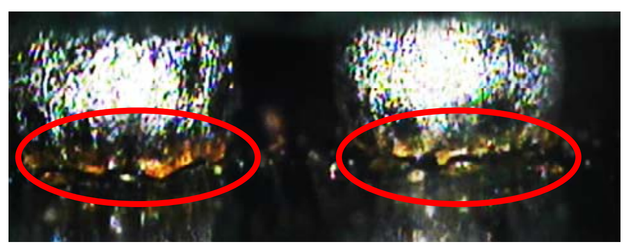

Figure 7: Pad lifting – PBGA676 (SAC405) – 200TS

Figure 8: Crack formation – CVBGA (305) – 200TS

Crack formation is evident in Figure 8. This is an image of a solder joint of a CVBGA component with SAC305 solder bumps. The component was subjected to 200 cycles of thermal shock followed by 30 drops of mechanical shock. This component however did not fail for all the 30 drops of mechanical shock.

CONCLUSION

This experimental study provided good comparisons for performance evaluation of area array packages, with and without the use of underfill. Some of the research findings are as follows.

1. PoP package survived all 30 drops of mechanical shock test for the as-soldered condition and after 200 and 500 cycles of thermal shock. Similar results were observed with and without the use of underfill.
2. The performance of UCSP was better with corner underfill when compared to without underfill.
3. UCSP with corner underfill provided better results for the as soldered and the 200 cycles of thermal shock, but it could not withstand 500 cycles of thermal shock. This was observed with and without the use of underfill.
4. Significant improvement in reliability was observed for PBGA1156 in the as-soldered condition with the use of corner underfill when compared to without corner underfill.
5. For PBGA676 the performance of SnAg solder ball was better than SAC305 and SAC405 solder balls. This result holds good with and without the use of corner underfill. This is possible due to the location of the component on the test vehicle.
6. SnAg solder balls of PBGA676 showed marked improvement with use of corner underfill than without corner underfill. However SAC305, SAC405 solder balls did not have any such improvements in performance with corner underfill.
7. Corner underfill improved the performance for CVBGA when compared to no underfill. Improvement was observed for SAC305, SAC405, and SAC105 solder balls.
8. There was a specific pattern observed in the failure of daisy chains for PBGA676 and PBGA1156 components. This daisy chain failure pattern was observed to be linked to the solder joints undergoing the most deflection during the drop.
9. Pad lifting and crack formation were the root cause for failure of the packages.

REFERENCES

[1] Sanka Ganesan, Michael Pecht, Chapter 3, "Lead free electronics".

[2] Press release, Loctite 3536, Henkel Corporation, Feb 2007.

[3] Brian Toleno, "Advanced Underfill Technology", SMT, May, 2008.

[4] Benjamin Salomon, "Capillary Underfill Manufacturing Development and Characterization for 2nd Level Electronic Interconnect Processes", University of Puerto Rico, December, 2004.

[5] Alec J. Bariarz, Alan R. Lewis, Robert L. Ciardella, "Automating Underfill for Non-Traditional Packages, Secondary CSP Underfill, Stacked Die, and No-Flow Underfill", SMTA Pan Pacific, Jan 2000.

[6] Staychip Capillary Underill Encapsulants, Cookson Electronics.

[7] Edwin Bradley, Carol A. Handwerker, Jasbir Bath, Richard D. Parker, Ronald W. Gedney, Chapter 1, "Lead-free electronics" IEEE press.

[8] Kelly Barett, "To underfill Or Not To Underfill", Findarticles.com, August, 2000.

[9] Andrew Farris, Jainbiao Pan, Albert Liddicoat, Brian J. Toleno, Dan Maslyk, Dongkai Shangguan, Jasbir Bath, Dennis Willie, David A. Geiger, "Drop test reliability of leaf-free chip scale packages," IEEE 2008.

[10] John Sprovieri, "POP Goes the future," Assembly magazine, September 30, 2008.