MECHANICAL RELIABILITY OF UNDERFILLED CSP ASSEMBLIES

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ABSTRACT

Chip Scale Packages (CSPs) are widely used in portable and hand-held electronic devices. They offer robust interconnects and higher standoffs than flip chips. The reliability of CSPs in portable devices is questionable due to the mechanical stresses experienced during their service lifetime. The stresses are primarily generated due to impact, shock, vibration, mechanical bending, and thermally induced fatigue due to CTE (Coefficient of Thermal Expansion) mismatch between the CSP and the Printed Circuit board (PCB). Applying an underfill material between the CSP and PCB can significantly reduce these stresses. The underfill reduces the shear strain due to CTE mismatch and absorbs stresses by coupling the device and the PCB. This paper presents a study of different CSP underfill materials and their effect on the reliability of the CSP assemblies.

A capillary flow underfill was used to underfill the space between the CSP and the PCB. The underfilled CSP assemblies were subjected to accelerated testing conditions: torsion tests, vibration tests, and air-to-air thermal cycling. Non-underfilled assemblies were also subjected to similar reliability experiments and their results were compared to the underfilled assemblies.

INTRODUCTION

Some of the major reliability concerns in today's electronics are the mechanical handling and dynamic loading conditions applied to packages during fabrication and operation in the field. These concerns are best reflected in Chip Scale Packages (CSPs) used in portable electronics such as PDAs, cell phones, pagers, etc[1]. CSPs have a larger solder ball size (as compared to flip chips) and, typically, are less affected by thermal cycling fatigue. These packages, however, show reduced resistance to mechanical stresses[2]. CSP underfilling provides adhesion between the CSP body and the motherboard. Forces that occur during impact or vibration are distributed over the entire array of solder bumps and the underfill material. This approach of reinforcing the CSP assembly improves its mechanical reliability[2].

The process of underfilling CSPs is similar to that of flip chips. Gap height is inversely proportional to the time required to underfill the assembly[1]. Thus, the time required to underfill CSP assemblies is less in than that required for flip chip assemblies, provided the viscosity, flow distance, wetting angle, and surface tension of the liquid underfill material is constant.

Improving thermal cycle fatigue resistance is not the primary motivation for underfilling CSPs. Published literature has indicated that voids trapped close to the solder joints will have little or no effect on the reliability of the package[1]. However, experimentation has shown solder extrusions and component failure with underfilled CSP assemblies when subjected to JEDEC preconditioning.

Different types of CSPs were assembled on 62 mil (1.57 mm) and 76 mil (1.93 mm) thick multilayered boards with either Cu-OSP, Electroless Nickel/Immersion Gold (ENIG) or Electroless Nickel/Immersion Palladium (ENIP) surface finish. Seven different underfills were used in this study, including reworkable capillary flow underfills, non-reworkable capillary flow underfills, and two-part epoxy material. The CSP assemblies were underfilled using different dispense patterns based on the dimensions of the component and the volume of underfill material required. The dispensing parameters were 'optimized' for all CSP-underfill combinations. The reliability of non-underfilled CSP assemblies in torsion testing, vibration testing, and air-to-air thermal cycling was compared to that of underfilled CSP assemblies.

CSP ASSEMBLY

Eight different packages (Packages A, B, C, D, E, F, G and H) were considered in this study. One CSP package utilized lead-free solder balls and the remaining utilized eutectic tin-lead solder balls. The component details are summarized in Table 1. All the packages possess daisy-chained structures to facilitate electrical monitoring during reliability evaluation.

Two different board thicknesses were considered in this study. Packages A, B, C, F, and G were assembled on 76.0 mil (1.93 mm) thick multilayered FR-4 boards with ENIG A, B, D, and E were assembled on 62.0 mils (1.57 mm) thick multilayered FR-4 boards with ENIP H was assembled on 62.0 mils (1.57 mm) thick multilayered FR-4 boards with Cu-OSP surface finish. All the test vehicles contained had Non-Solder Mask Defined (NSMD) pads. Table 2 summarizes the details of the assembly.

Package E, the lead-free CSP, was assembled using tin-silver (96.5%Sn/3.5%Ag), Type 4, no-clean solder paste. The remaining packages were assembled using eutectic tin-lead (63%Sn/37%Pb), Type 4, no-clean solder paste. The solder paste was deposited using a 5 mil thick laser-cut stencil and a metal squeegee. The component was placed on the test vehicle and reflowed. A reflow profile with a peak temperature of 221^{o}C and a time above liquidus of 72 seconds was used for the tin-lead CSPs. Package E was assembled using a reflow profile having a peak reflow temperature of 246^{o}C and a time above liquidus of 81 seconds.

The assemblies were electrically inspected to record the resistance of the daisy chain structure. X-ray and cross-sectional analysis were also performed. No instances of open joints or solder bridging were observed. The standoff heights of the assemblies were measured using a laser profilometer. Table 1 provides the average standoff heights that were measured for all the CSPs.

CSP UNDERFILLING

Table 3 contains the characteristic properties of the underfills utilized in this study. The underfills were dispensed using an automatic dispenser. The diameter of the auger used for dispensing was 0.091 inches. A 25-gauge needle having an internal diameter of 10 mils and an external diameter of 20 mils, with a polypropylene hub and a stainless steel tip was used to underfill the CSPs. The

Package	I/O	Dimensions (mils)	Pitch (mm)	Type	PCB Pad Size (mils)	Assembly Standoff (mils)
A	48	323 x 244	0.8	Flex	12,16	12.0
B	180	477 x 477	0.8	Flex	12,16	12.0
C	328	560 x 560	0.5	Flex	10	8.0
D	36	240 x 240	0.8	Rigid	12,14	12.0
E*	46	310 x 228	0.75	Elastomer with Polyimide	11, 13, 15	5.5
F	20	107 x 89	0.5	Wafer level	9	8.5
G	8	57 x 57	0.5	Wafer level	6,7,8	5.0
H	64	315 x 315	0.8	Flex	15	16.0

* Second level solder interconnects lead free (96.5%/3.5%Ag)

Table 1. Component Details

	Board Thickness	Pad Metallurgy	Packages Assembled
Test Vehicle 1	76.0 mil (1.93 mm)	Electroless Ni/ immersion Au	A, B, C, F, G
Test Vehicle 2	62.0 mil (1.57 mm)	Electroless Ni / immersion Pd	A, B, D, E
Test Vehicle 3	62.0 mil (1.57 mm)	Cu-OSP	H

Table 2. Assembly Details

Underfill	Viscosity	Tg	Modulus	Filler Content
UF1	3100 Cps	0°C	58 Mpa	0%
UF2	910 Cps	70° C	1380 Mpa	30%
UF3	4800 Cps	NA	276 Mpa	0%
UF4	25800 Cps	NA	25 Mpa	0%
UF5	4400 Cps	41° C	25 Mpa	0%
UF6	600 Cps	150°C	NA	NA
UF7	150000 Cps	NA	NA	NA

NA – Not Available

Table 3. Underfill Material Properties

needle was placed at a distance of 15 mils from the edge of the package body for the capillary flow underfills. This distance was calculated from the outer edge of the package body to the center of the needle. The height of the needle was equal to the mid-line of the package body.

Dispense Volume Calculation

The theoretical volume of underfill required to completely underfill an assembly was calculated based on the external dimensions of the package, the assembly standoff height, and the density of the underfill material. This volume includes the amount of material required to fill the entire area between the package and the PCB and to form fillets along the package perimeter.

The formulae used to calculate the theoretical amount (mg) are:
L = Chip Length (mils)
W = Width of Chip (mils)
T = Thickness of Package (mils)
S = Standoff Height of Component (mils)
I = Number of I/Os
D = Underfill Density (mg/mil^3)
Extent of Fillet (E) = T + S (mils)
Amount Beneath the Component = L x W x S x D ---(i)
Amount in Fillet = ½ x E^2 x (2 x L + 2 x W) x D ----(ii)
Amount in Fillet Corners = 3.14159/3 x E^3 x D------(iii)
Amount in joints = 4/3 x 3.14159 x $(S/2)^3$ x I x D---(iv)
Total Amount Required = (i) + (ii) + (iii) – (iv) ------(v)

It was assumed that length ‘L’ is the longest dimension and was used as the dispense edge. The total amount of volume dispensed in the dispense pass must be at least equal to the volume required under the package and the amount of material required in the entrance fillet.
Total Amount in Dispense Pass = {(ii) x L / (L + B) / 2} + (iii)/2 + (i) – (ii)}-----(vi)
Total Amount in Close-up Pass = (v) – (vi)
This calculated volume was used as a starting point. The amount of underfill that was finally dispensed was decided after further optimization and was based on the formation of adequate fillets on all sides of the component.

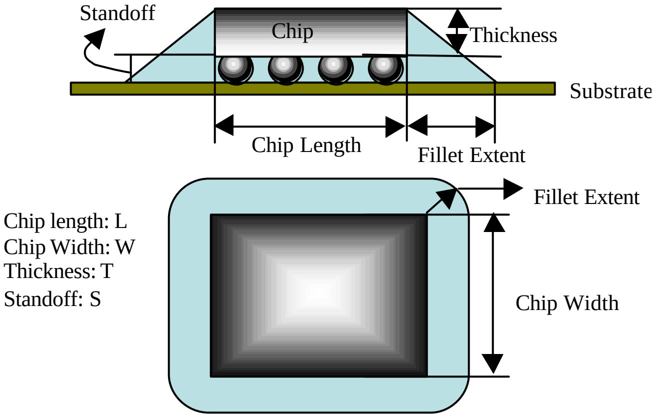

Figure 1. Calculation of Theoretical Underfill Volume

Dispense Patterns

‘Single pass with close-up pass’ and ‘multiple passes with close-up pass’ were the two dispensing patterns used to fully underfill the samples. The dispense pattern was selected based on the volume of underfill material required for a particular component assembly. Dispensing from multiple sides of a component will increase throughput, but if the opposing wave fronts meet at an acute angle, the underfill may trap voids[3]. Hence, the underfills for all the packages were dispensed along a single package edge.

Figure 2 shows a schematic of the single pass with close-up pass dispense pattern. The underfill material is first dispensed along a single dispense edge. The underfill is allowed to flow beneath the package body through capillary action. Once the material is observed from the opposite edge, a close-up pass is performed along the other three edges of the package body. The close-up pass helps in obtaining uniform fillets along the package body. Packages A, D, E, and F were underfilled using this pattern.

Packages B, C, and H were underfilled using the multiple pass with close-up pass dispense pattern. These packages require a larger volume of underfill owing to their larger dimensions and/or higher standoff. It was found that the entire amount is dispensed in a single pass, a pool of

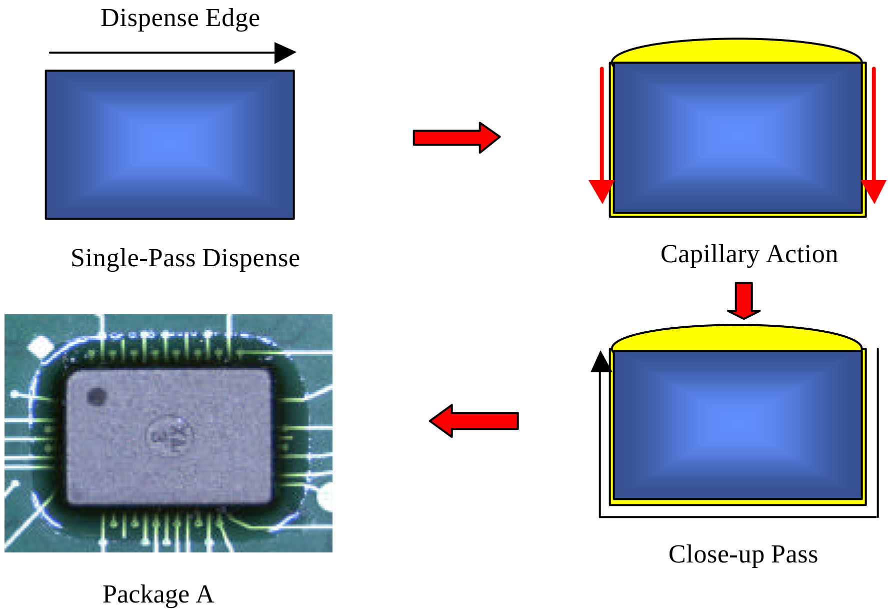

Figure 2. Single Pass with Close-up Pass Pattern

underfill can form at the dispense edge of the package. Increasing the number of passes increased the time required to underfill a component, however, the process gave better fillet control and tighter process control.

Package G was the smallest package evaluated in this study. The external dimensions of the package are 57.0 mils x 57.0 mils (1.45 mm x 1.45 mm). Using a single pass with close-up pass dispense pattern to underfill this package resulted in an excessive amount of underfill material around the package. Hence a dot dispense pattern was used to underfill the package. The underfill was dispensed as a dot at a distance of 15 mils from the center of the dispense edge. The amount of underfill material dispensed using the dot dispense pattern was sufficient to fully underfill Package G and form good fillets on all sides of the package. After dispensing the underfill, the assemblies were cured in an oven as per the curing conditions specified by the manufacturer.

Post - Cure Inspection

There was no change in the electrical resistance of the assemblies after underfill dispensing. Sample cross-sections were obtained to study the underfill formation beneath the package and to evaluate any voids within the underfill. The use of C-mode Scanning Acoustic Microscopy (C-SAM) proved to be unsuccessful in detecting the presence of voids in the underfill due to the multilayered complexity of CSP devices. Hence, the samples were flat-sectioned through the board side to expose the underside of the assembly. Any voids present in the underfill were than visible. Cross-sections of the assemblies showed good solder joint formation and wetting around the PCB pads. In addition, all the underfills had flowed completely underneath the package.

Excessive voiding within the underfill was observed for assemblies underfilled using UF7. A substantial amount of voiding was observed in packages underfilled using underfill UF7. This underfill is a two-part epoxy underfill that is stored at room temperature and mixed using a static mixer. The preparation of the underfill traps a significant number of voids in the material. Figure 3 shows a flat-section of Package G that was underfilled using underfill UF7. The figure shows voids that were trapped near the corner bumps.

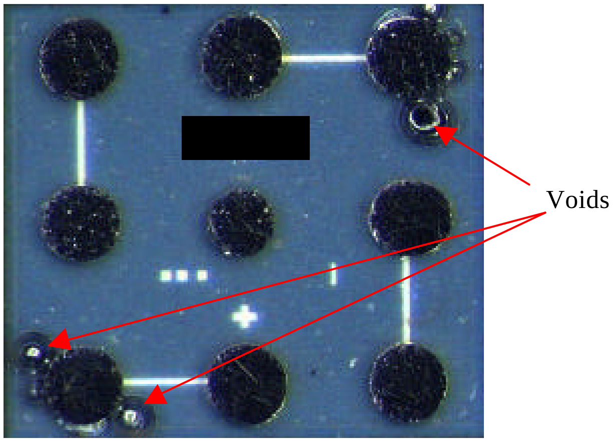
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Figure 3. Flat-Section of Package G using UF7

The fillet thickness of the underfilled packages was measured as the shortest distance from the lower corner of the package to the edge of the fillet using a laser profilometer. Eight scans were performed on each package, i.e. two scans at each corner. There was a large variation in fillet thickness observed for all the packages; no combination of component and underfill resulted in a significant improvement in fillet thickness consistency. For example, the minimum fillet thickness measured for Package A was 9.9 mils and the maximum fillet thickness was 18.0 mils. On average, the variation in fillet thickness was 5.0 to 10.0 mils. This variation may be a result of a combination of factors including differences in assembly standoff height, spread of underfill on the solder mask of the substrate, change in material properties, and the ability of the underfill dispenser to dispense accurate amounts of underfill material.

RELIABILITY TESTS

Reliability testing is an integral part of assembly process development. For some conditions, data from reliability testing can be a useful indicator of the performance of a product under actual service conditions. Reliability testing was performed under accelerated testing conditions. The underfilled assemblies were subjected to various thermal and mechanical stresses using air-to-air thermal cycling, torsion testing, and vibration testing. Non-underfilled assemblies were also subjected to similar testing conditions and compared to the underfilled assemblies. Solder extrusions are a concern in flip chip assemblies. Hence the underfilled samples were also subjected to JEDEC level 3 moisture sensitivity testing to evaluate the likelihood of solder extrusions.

The failed samples were analyzed through cross-sectional analysis to observe the failure mechanisms and locations. Weibull distribution plots were used to obtain the expected lifetimes of the package assemblies.

Torsion Test

A torsion test was used to simulate the bending and twisting motion experienced during the service life of CSP assemblies used in hand held device applications. During this test, the assemblies were mechanically twisted for a specified displacement. In general, the value of deflection used is 0.75° for an inch of printed circuit board length[4]. The test coupons were twisted by a specially designed fixture that uses an air cylinder to control the deflection angle and cycle frequency. A 256-channel event detector was used to monitor the CSP assemblies. Electrical failure was based on IPC-SM-785 (daisy chain resistance exceeding 300 Ω for a period of at least 200 nanoseconds) failure criteria. Initially, the underfilled samples were subjected to 0.5 or 1.0 degrees of deflection. However, none of the underfilled samples failed the torsion test at these levels and the torsion testing was increased to 3.0 degrees of deflection to obtain failures.

Moisture Extrusion

The components were subjected to JEDEC level 3 pre-conditioning followed by three reflow cycles. Five samples of Package C in combination with all the underfills were tested in this study. The moisture soak conditions for JEDEC level 3 are 192 hours at 30^{o}C and 60%RH. The components were then subjected to three consecutive reflow cycles 15 minutes after removing them from the moisture chamber. A standard eutectic tin-lead reflow profile with a peak temperature of 215°C was used. The assemblies were probed for electrical continuity and x-rayed to check for solder extrusions.

It was observed that packages underfilled using UF7 (the two-part epoxy underfill) extruded and bridged after the first reflow cycle. The solder extruded into the voids located close to the bumps and at some locations, solder bridging was also observed. All UF7 packages were electrically open. Figure 4 shows a x-ray image of Package C underfilled using underfill UF7. No solder extrusions or electrical opens were observed in any of the assemblies underfilled with the other materials.

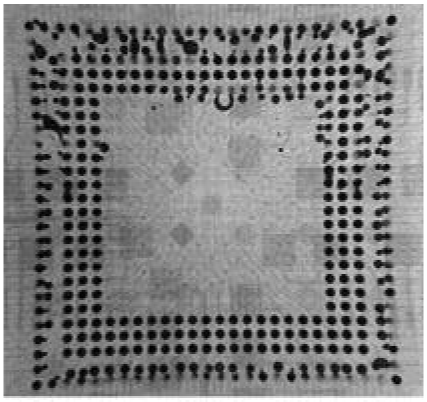

Figure 4. X-ray Image of an Extruded Package C Assembly

Vibration Test

The vibration test was performed using a 10 to 1000 Hz random vibration signal at ambient temperature and humidity. Nine samples were tested in this experiment. Two test profiles were used. Profile #1 was a 24 hour profile with 8 hour out-of-plane (z), 8 hour in-plane (x), and 8 hour in-plane (y) vibrations. Profile #2 was a 32 hour profile with 8 hour out-of-plane (z), 8 hour in-plane (x), 8 hour in-plane (y), 4 hour out-of-plane (z), and 4 hour in-plane (x) vibrations.

The test was performed on a dynamic vibration table connected to a 10K amplifier. The event detection system was set to record events characterized by a 30Ω change in resistance for a duration of one millisecond. The test vehicles were prepared by applying a double-sided tape to the backside of the test board and laying the boards in a specially designed fixture. The tape was used to minimize the board oscillation. Two clamps were used to provide additional support.

Thermal Cycling Test

Air-to-air thermal cycling was performed between 0°C and 100°C as measured on the assembly solder joint/PCB surface. A 20 minute long cycle with 5 minutes ramp and 5 minutes dwell was used in the study. The failure criterion was based on the IPC-SM-785 specification of a loop resistance exceeding 300Ω for a duration of 200 nanoseconds.

RESULTS AND DISCUSSIONS

Torsion Test

Four underfilled samples of Package G were initially subjected to 0.5 degrees of deflection. No failures were recorded for the underfilled samples through 7800 cycles. An additional four samples of Package G were then subjected to 1.0 degree of deflection. No failures were recorded through 3000 cycles. However, the non-underfilled samples failed when subjected to similar testing conditions. The non-underfilled assemblies had a characteristic life (N_{63}) of 2761 and 518 cycles at 0.5 and 1.0 degrees of deflection respectively. In order to obtain failure results, underfilled samples of Packages A, B, and D were subjected to 3.0 degrees of deflection. A sample size of eight was used for this test. The characteristic lifetime values of the packages for the different underfills are summarized in Table 4.

Underfill	**A** $^{(3)}$	**B** $^{(3)}$	**D** $^{(3)}$	**H** $^{(1)}$
UF1	2366	1333	4147	>3000
UF2	1024	2610	3001	>3000
UF3	----	----	----	>3000
UF4	----	----	----	>3000
UF5	2815	1527	1488	----
UF6	----	----	----	>3000
UF7	----	----	----	>3000
Non-underfilled	297	232	257	518

$^{(3)}$ Tests performed at 3 degrees of deflection

$^{(1)}$ Tests performed at 1 degree of deflection

Table 4. Cycles to Failure for Torsion Test

From the reliability data obtained based on a sample size of eight, it can be concluded that underfilling the CSPs increases torsional reliability by 300 to 1100% depending on the type of package and underfill material. Cross-sectional analysis of failed assemblies found cracks within the solder joint along the component side of the assembly. Figure 5 shows an image of a non-underfilled sample of Package H that failed in torsional testing. The crack initiated from the interface of the solder mask and the pad of the component. Figure 6 shows a cross-section of Package D, underfilled using UF1, which failed after 1825 torsion cycles.

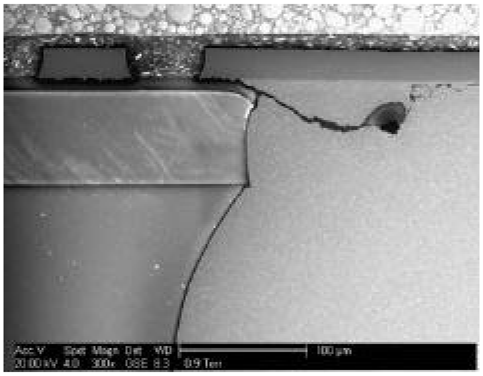

Figure 5. Failed Non-underfilled Assembly of Package H

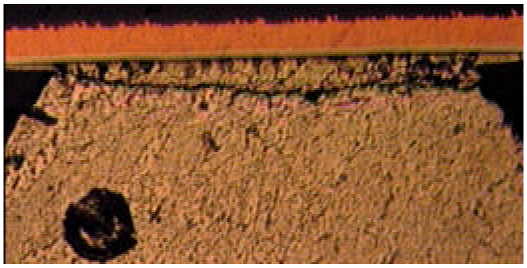

Figure 6. Cross-sectional Image of Failed Package D Assembly (UF1)

Vibration Test

Eight underfilled samples of Package F were subjected to Profile #1 followed by Profile #2. Nine non-underfilled assemblies were subjected to the less severe Profile #1 test. None of the underfilled samples failed in the vibration test. However, four of the non-underfilled assemblies showed failures. Table 4 summarizes the results of the vibration test for the non-underfilled assemblies. It should be noted that the vibration profile used were more "duration" oriented and that the difference between non-underfilled and underfilled assemblies may be more pronounced in a "force" oriented test.

Air-to-Air Thermal Cycling Test

Samples of every package and underfill combination were subjected to 2300 air-to-air thermal cycles. Early failures were recorded in packages underfilled using underfills UF1 and UF7. The sample size used in this experiment varied from 6 to 8 samples. All the assemblies underfilled with UF1 failed before 1500 cycles, while only two assemblies underfilled with UF7 failed at 632 and 850 cycles. Packages D, A and B underfilled using UF1 had characteristic lifetimes of 1208, 946, and 1435 cycles respectively. No failures were recorded for the other underfills or the non-underfilled samples. Cross-sectional analysis of the underfilled samples found cracks through the solder joint on both the component side and the board side. Figure 7 shows a cross-section showing component side failure of a Package A assembly, underfilled using UF1, which failed after 848 cycles. Figure 8 shows a cross-section of Package D assembly, underfilled using UFI, which failed after 963 thermal cycles.

Duration	Plane	Duration	Plane	Duration	Plane	Total Time to Failure
8 hr	Z	4 hr 42 min	X		Y	12 hr 42 min
8 hr	Z	8 hr	X	3 hr 27 min	Y	19 hr 27 min
8 hr	Z	8 hr	X	6 hr 31 min	Y	22 hr 35 min
8 hr	Z	53 min	X		Y	8 hr 53 min

Table 4. Results of the Vibration Test

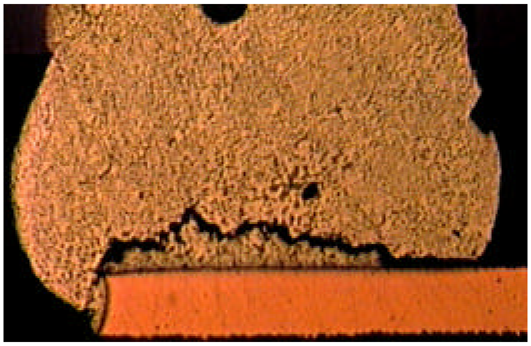

Figure 7. Cross-sectional Image of Package A

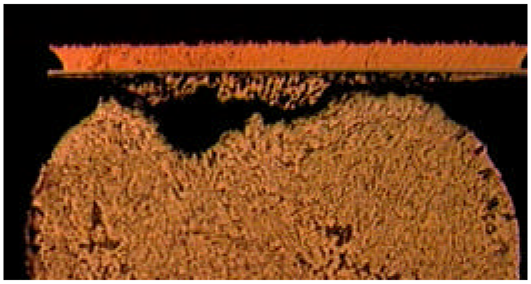

Figure 8. Cross-sectional Image of Package D

CONCLUSIONS

The underfilling process for CSP assemblies is similar to that for flip chip assemblies. It requires careful optimization to obtain good fillet control. The fillet thicknesses of similar assemblies using the same dispense volume and dispensing parameters varied significantly. While preliminary data suggests that there is no correlation between the failures and the fillet thicknesses, it was ensured that adequate fillets were obtained on all sides of the assembly. The dispensing parameters depend on the characteristics of the underfill material, the component, and the assembly parameters. Hence, the underfill dispense process should be optimized for each underfill/component/assembly combination.

All the UF7 underfilled samples had solder extrusions and solder bridging after the first JEDEC (level 3) reflow cycle. None of the samples underfilled with the other materials extruded. The UF7 underfill, a two-part epoxy, showed significant voiding and performed poorly in thermal cycling as compared to the non-underfilled assemblies.

Initial torsion results indicate that the underfilled samples survive between 3 – 11 times longer than non-underfilled samples, depending on the package and the underfill material. In the vibration test, no failures were recorded for the underfilled samples. However, failures were recorded for the non-underfilled samples. The underfilled samples were subjected to a more strenuous vibration profile than the non-underfilled samples.

In air-to-air thermal cycling, failures were reported predominantly in packages underfilled using UF1. This indicates that the use of UF1 decreases the thermal cycling reliability of the assembly. The cycles to failure for all the packages underfilled using UF1 were comparable and the average characteristic life was approximately 1196 cycles. No failures were recorded for similar non-underfilled samples up to 2300 cycles. Two failures were recorded in assemblies using underfill UF7.

From the reliability experiments, it was observed that underfilling of CSP assemblies enhance their mechanical reliability in terms of torsion and vibration. Variations in fillet thickness and voiding in the underfilled assemblies did not significantly affect their reliability performance. However, some underfills may negatively impact the thermal fatigue resistance of the CSP assemblies. In conclusion, an underfill material for CSP assemblies should meet thermal fatigue reliability requirements in addition to enhancing the mechanical robustness of the assembly. The selection of underfill material for CSP assemblies plays a critical role in the reliability performance of CSP assemblies.

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