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Lead Free Assembly of Chip Scale Packages

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Abstract
Chip scale packages (CSPs) are widely used in portable electronic products where there is also a growing trend to lead free assembly. Many CSP designs will meet the thermal cycle or thermal shock requirements for these applications. However, mechanical shock and bending requirements often necessitate the use of underfills to increase the mechanical strength of the CSP-to-board connection. Three underfill options compatible with lead free assembly have been evaluated: capillary underfill, fluxing underfill and corner bond underfill. CSPs with eutectic Sn/Pb solder were used for control samples. Without underfill, lead free and Sn/Pb eutectic drop test results were comparable.

Capillary flow underfills, dispensed and cured after reflow, are commonly used in CSP assembly with eutectic Sn/Pb solder. With capillary flow underfill, the drop test results were significantly better with lead free solder assembly than with Sn/Pb eutectic.

Fluxing underfill is dispensed at the CSP site prior to CSP placement. No solder paste is printed at the site. The CSP is placed and reflowed in a standard reflow cycle. A new fluxing underfill developed for compatibility with the higher lead free solder reflow profiles was investigated. The fluxing underfill with lead free solder yielded the best drop test results.

Corner bond underfill is dispensed as four dots corresponding to the four corners of the CSP after solder paste print, but before CSP placement. The corner bond material cures during the reflow cycle. It is a simpler process compared to capillary or fluxing underfill. The drop test results with corner bond were intermediate between no underfill and capillary underfill and similar for both lead free and Sn/Pb eutectic solder assembly.

The effect of aging on the drop test results with lead free solder and either no underfill or corner bond underfill was studied. This test was to simulate drop performance after the product has been placed in service for some period of time. There was degradation in the drop test results in both cases after 100 and 250 hours of storage at 125^{o}C prior to the drop test.

The assembly processes, drop test results and failure analysis are presented.

Introduction
Portable products face the challenges of ever increasing functional density, shorter product cycles, and pressure to reduce cost. Increasing functional density has lead to the explosive growth in chip scale package (CSP) usage.

The expected product life for a portable product is typically short compared to many other product categories; however, portable products must survive multiple drops. The decreasing I/O pitch of CSPs and the resulting smaller pads and solder joints, make the drop requirement more challenging. There are two approaches to improving drop reliability. The first is the mechanical design of the product to minimize the shock and flexing of the printed circuit board that occurs when the product is dropped. This approach places pressure on the time-to-market constraint. The second approach is to use underfills to mechanically reinforce the CSP solder joints.[1-3] This adds cost and cycle time to the manufacturing process.

With the proliferation of portable products and the short product life, there is growing concern over the resulting waste stream. Whether through legislative activity in Europe or global market pressure, a growing percentage of portable electronics are lead free.

This paper examines CSP assembly and drop test reliability with capillary, fluxing and corner bonding underfills used in conjunction with SnAgCu solder (solder paste and solder balls on the CSP). Eutectic Sn/Pb assemblies were also tested for comparison.

Test Vehicle
The test vehicle was a four-layer test board with ten CSP attachment sites per side. In these experiments, CSPs were only assembled on one side of the board. Standard technology (FR4) was used for board fabrication, no build-up or HDI layers. The board was 2.95" by 7.24" by 0.042" thick. The pads were 0.010” in diameter, non-solder mask defined with an immersion silver finish.

The CSP was an 8mm, 0.5mm pitch, 132 I/O TapeArray manufactured by Amkor Technology and purchased from Practical Components (A-TArray132-.5mm-8mm-DC-LF). The I/O were on a 14 x 14 array with only the outer three rows populated. The lead free solder ball composition was 95.5%Sn/4.0%Ag/0.5%Cu. CSPs with eutectic 63%Sn/37%Pb solder balls were used for comparison. The CSP was a daisy chain test part for continuity measurements. The silicon die was 3.98mm x 3.98mm.

Multicore LF300 lead-free solder paste (type 3, 95.5%Sn/3.8% Ag/0.7%Cu) was used for the lead free assemblies. Multicore MP200 63Sn/37Pb, type 3 solder paste was used for the Sn/Pb assemblies.

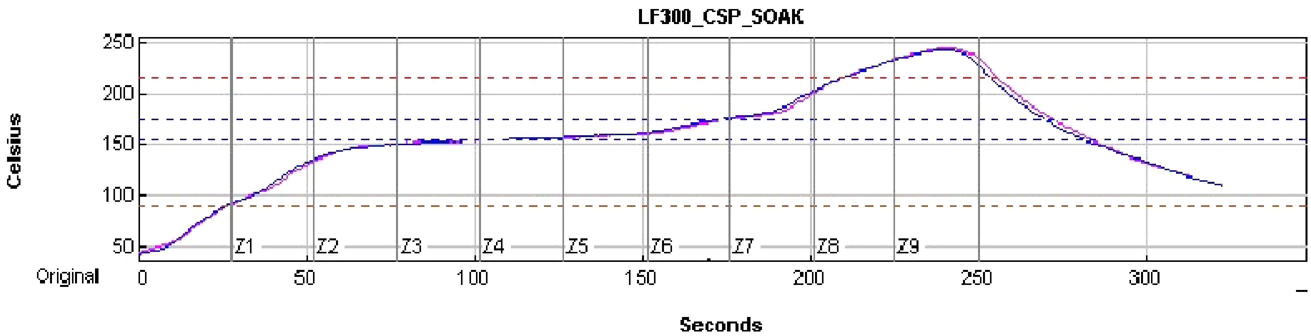
Table 1 lists the properties of the underfills investigated. The table also indicates which materials were used for Sn/Ag/Cu and/or eutectic Sn/Pb assembly

Table 1 - Properties of Underfill Materials Used

Material	3593	FP6101	CNB933-25	3515	CNB951-01
Underfill Type	Capillary - A	Capillary - B	Fluxing	Corner Bond	Corner Bond
Solder Alloy	Sn/Ag/Cu & Sn/Pb	Sn/Ag/Cu & Sn/Pb	Sn/Ag/Cu	Sn/Pb	Sn/Ag/Cu
Tg (°C)	110	10	83	122	150
CTE Below Tg (ppm/°C)	50	83	77	47	60
CTE Above Tg (ppm/°C)	160	211	190	165	155
Modulus (MPa)	2069	50	2600	2297	3800

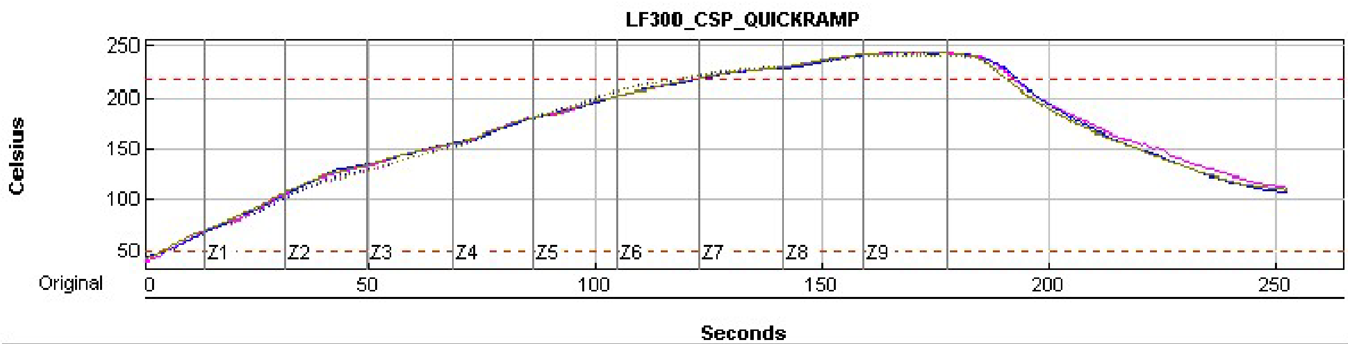
Assembly
No-Underfill
The test vehicles were assembled on an automated SMT line at Auburn University. The solder paste was printed with an MPM AP25 stencil printer using a 4 mil thick, laser cut, electro-polished, nickel plated stencil. The aperture opening was a 10 mil square. The solder paste print was inspected with an MVT 3-D solder paste inspection system. Assembly was performed with a Siemens F5 pick & place system.

A Heller 1800 reflow furnace was used to evaluate two reflow profiles for the lead free assembly. The first profile shown in Figure 1 is a ‘traditional soak’ profile. Figure 2 is a straight ramp-to-peak profile, often used in portable electronics assembly since the overall reflow time is shorter. CSPs assembled with both profiles were examined with a Phoenix X-ray system. While there was some minor voiding in the solder joint (Figure 3), there was no significant difference in voiding between the two reflow profiles. The ramp-to-peak profile was used for all subsequent lead free assemblies. A ramp profile with a peak temperature of 221^{o}C was used for the eutectic Sn/Pb assembly (Figure 4).



TCs	Max Rising Slope	Soak Time 155-175C	Reflow Time /217C	Peak Temp
2	2.1	70.8	46.2	246.2
3	2.2	70.4	43.9	244.1

Figure 1 - ‘Soak’ Reflow Profile for Lead Free Assembly



TCs	Max Rising Slope	Reflow Time /217C	Peak Temp	Tot Time / 50C
2	2.1	71.6	245.4	251.2
3	2.1	71.8	244.9	251.0
4	2.1	70.7	244.9	249.3

Figure 2 - Ramp-to-Peak Lead Free Reflow Profile

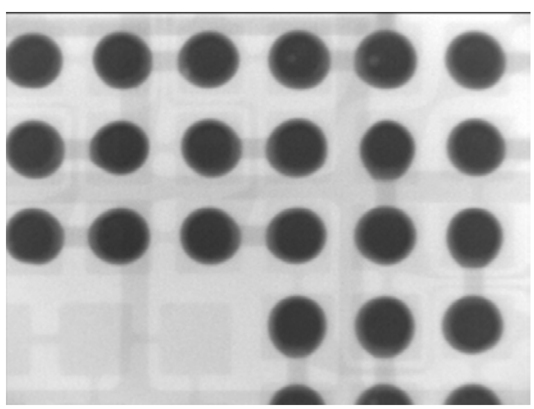
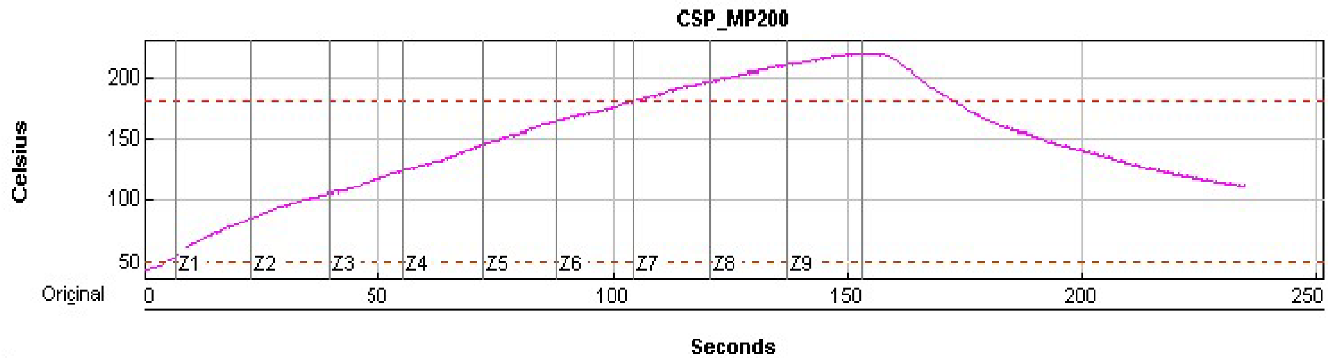


Figure 3 - X-Ray Image of Lead Free Solder Joints (Ramp-to-Peak Profile)



TCs	Max Rising Slope	Reflow Time /183C	Peak Temp	Tot Time / 50C
2	1.9	67.1	221.4	231.6

Figure 4 - Eutectic Sn/Pb Reflow Profile

The wetting characteristics of Sn/Ag/Cu solders are typically not as good as for Sn/Pb solder. To evaluate the self-centering capability of the Sn/Ag/Cu alloy, CSPs were intentionally placed 50% off-pad (5 mils) in both the X and Y directions as shown in Figure 5. After reflow the CSP had self-centered as shown in Figure 6.

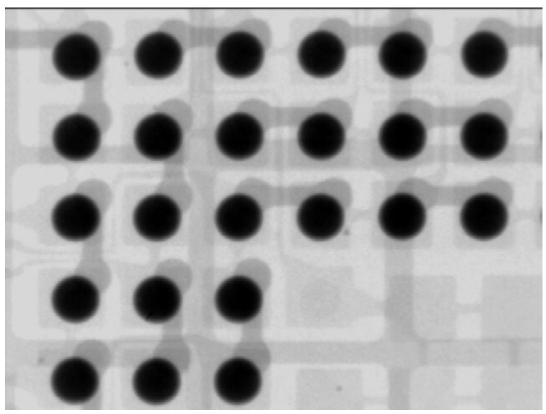


Figure 5 - X-Ray Image of CSP Intentionally Placed 50% Off-pad in both the X and Y Directions

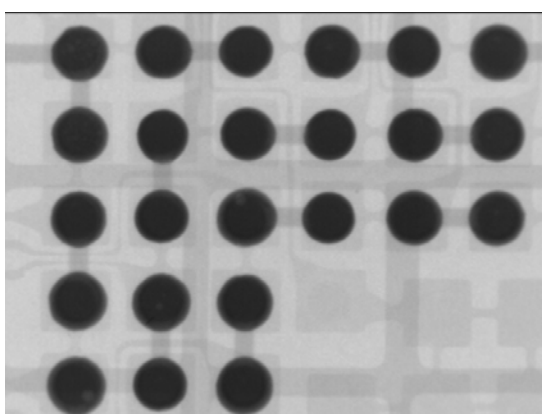


Figure 6 - X-Ray Image after Reflow

Capillary Underfill

Assembly of CSPs for capillary underfill followed the same assembly process as the no-underfill CSP assemblies up through the reflow step. Both eutectic Sn/Pb and lead free assembles were made. Following reflow, the assembled boards were dehydrated for 12 hours at 125^{o}C to remove absorbed moisture. In a continuous assembly process, this dehydration step may not be necessary since most of the moisture absorbed by the PCB would have been removed during the reflow cycle. In this experiment, there was a significant lag time between reflow and underfill.

The capillary underfills were dispensed with a Camalot 3700 dispense system. The FP6101 and 3593 underfills were cured for 5 minutes at 165°C in a box oven. In-line conveyor ovens have also been used in the past.

Fluxing Underfill

Prior to assembly, the PCBs were dehydrated for 12 hours at 125°C. With fluxing underfill, no solder paste was printed. Instead, the fluxing underfill was dispensed at the CSP sites on the board and then the CSPs were placed and reflowed. Differential scanning calorimetry (DSC) was used to evaluate the underfill cure with the lead free ramp-to-peak profile. A DSC plot of an uncured sample was also made. As shown in Figure 7, there is no exotherm associated with the reflow cured sample, indicating a high degree of cure.

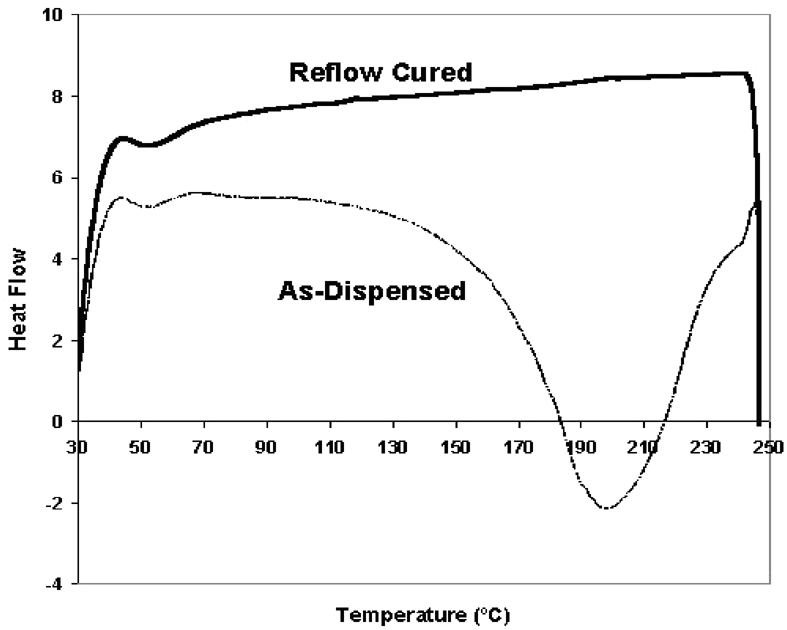


Figure 7 - DSC Curves for Uncured and Reflow Cured Fluxing Underfill

Only lead free assemblies were built with fluxing underfill. Eutectic Sn/Pb CSP assembly with fluxing underfill has previously been studied.[4] Figure 8 shows a flat section (the CSP has been polished away) of an initial assembly after reflow. Significant placement voids were observed. This voiding has been noted with fluxing underfills for eutectic Sn/Pb CSPs.[4] In that study, the voids did not degrade drop or liquid-to-liquid thermal shock performance. A DOE was performed to optimize the placement parameters, minimizing voids. While voiding was not eliminated, it was significantly reduced (Figure 9).

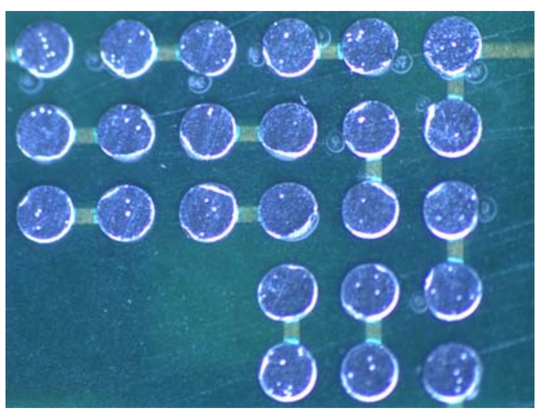


Figure 8 - Flat Section (CSP Polished Away) of Fluxing Underfill Showing Voiding before Placement Optimization

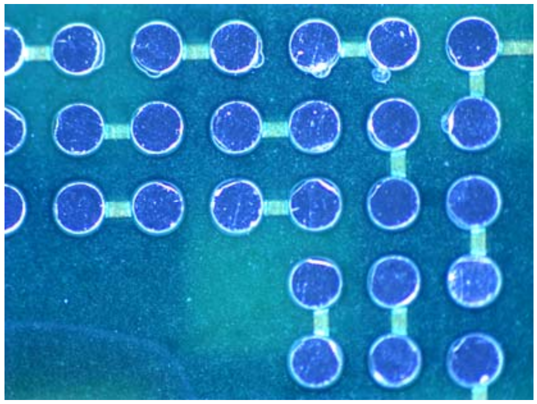


Figure 9 - Flat Section of Fluxing underfill Showing Reduced Voiding with Placement Optimization

Self-centering with the fluxing underfill was also studied. CSPs intentionally placed off-set by 50% in both the X and Y directions self-centered during reflow.

Corner Bond Underfill

In this assembly process, solder paste was printed as previously described. No board dehydration bake was used. The corner bond underfills (one for eutectic Sn/Pb and one for lead free) were then dispensed on the board as four dots corresponding to the four corners of the CSP. The CSPs were placed and then reflowed. Two different corner bond materials, one for each solder alloy, was required due to the different reflow profiles used. During reflow, the underfill must not cure before the alloy melts, to allow collapse. However, the underfill must cure during the final stages of the reflow profile. DSC was used to verify the underfill for lead free assembly cured during the ramp-to-peak reflow profile. Cross sections verified good collapse and solder wetting. The reflow profile for the eutectic Sn/Pb assembly had previously been verified.[5]

Self-centering of the CSPs with corner bond underfill was studied. CSPs intentionally off-set by 50% in either the X or the Y direction self-centered during reflow. However, a 50% off-set in both the X and Y directions resulted in the corner solder ball contacting the dispensed underfill. As shown in Figure 10, this resulted in a deformed solder joint (lower left corner). This CSP still self-centered. The alignment tolerance for solder balls contacting the dispensed underfill is a function of the CSP ball pattern design and the dispense volume.

If corner bonded CSPs are to be assembled on both sides of a board, the corner bond material on the first side assembled will be subjected to a second reflow cycle. To evaluate the effect of this, boards with corner bonded CSPs were inverted and passed thorough the reflow oven a second time. No CSPs were actually assembled on the second side, as this would have changed the mechanical structure of the assembly. During drop testing, this change in mechanical structure would be a second variable and not allow direct observation of the effect due to two reflow passes. CSPs assembled with no underfill were also subjected to a second, inverted reflow cycle for comparison.

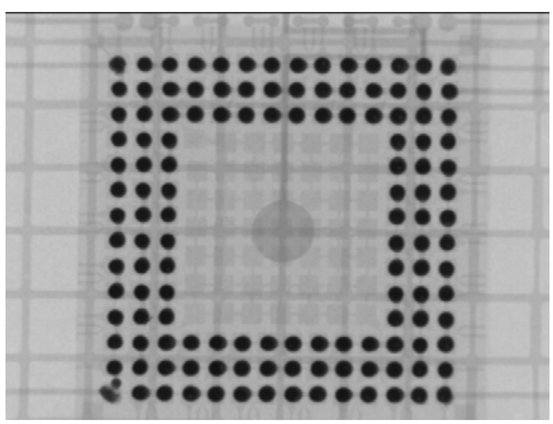


Figure 10 - X-Ray Image after Reflow for CSP Intentionally Mis-placed by 50% in both the X and Y Directions with Corner Bond Underfill

Drop Test Results

For drop testing, a 31.8 gram weight was attached to one end of the board as shown in Figure 11 to accelerate failure and simulate product weight. The board was then dropped through a six foot long, three inch diameter tube onto a concrete floor. The daisy chain resistance of each CSP was measured and a 10% increase in resistance was recorded as a failure.

Before making a final reflow profile selection, four Sn/Ag/Cu boards without underfill were assembled with each reflow profile and dropped. The results are shown in Figure 12. Based on these results, the ramp-to-peak profile was chosen for all subsequent test vehicles builds.

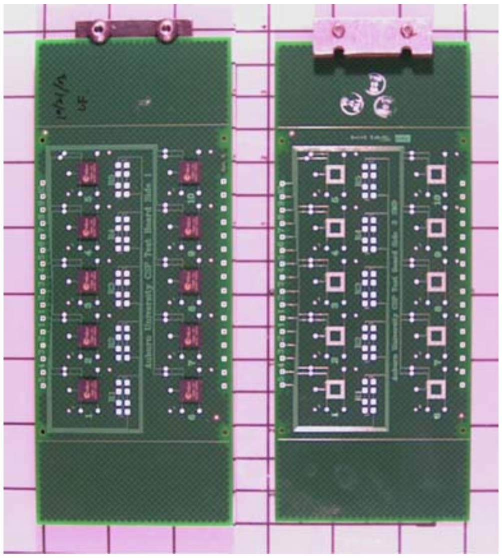


Figure 11 - Photographs of Test Board (front and back) with Weight (31.8g) Attached to Backside (non-CSP side) for Drop Test

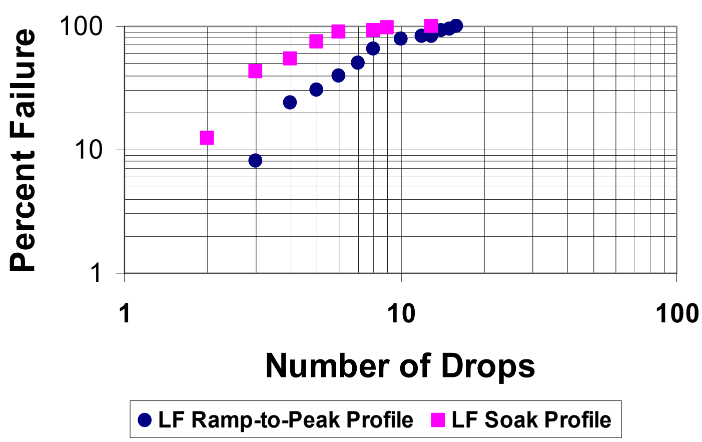


Figure 12 - Drop test Results for Non-Underfilled Sn/Ag/Cu CSPs with Two Reflow Profiles

Figure 13 shows the drop test results for each solder alloy and underfill combination tested. With the exception of the Sn/Pb corner bond test vehicle, five boards (50 CSPs) were dropped for each test combination. Four Sn/Pb corner bond boards were dropped.

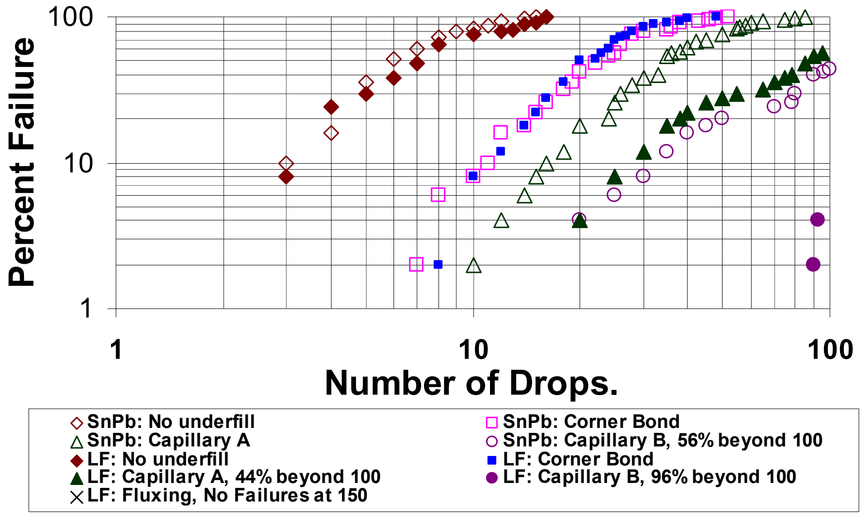


Figure 13 - Drop test Results for Sn/Pb and Sn/Ag/Cu Solders and Different Underfills

The earliest group to fail was the samples with no underfill. There was no significant difference between the Sn/Pb and the Sn/Ag/Cu CSPs.

The second group to fail was the corner bonded CSPs with a 3x improvement over the no underfill samples. This is consistent with earlier results with Sn/Pb and corner bond underfill.[5] Again, there was no significant difference between Sn/Pb and Sn/Ag/Cu.

The next group to fail was the capillary flow samples. For this group of samples, capillary underfill B performed better than capillary underfill A and Sn/Ag/Cu out performed Sn/Pb. The combination of Sn/Ag/Cu and capillary underfill B had only 2 CSPs failures out of 50 CSPs after 100 drops.

The best drop test results were obtained with the Sn/Ag/Cu alloy and the fluxing underfill – No failures (0/50) after 150 drops. The presence of voids in the underfill did not degrade the drop test performance of the fluxing underfill.

Figure 14 shows the drop test results for the double reflow (the board was inverted for the second reflow cycle) experiment with no underfill and with the corner bond underfill. There was some decrease in drop test performance of the corner bond samples with the second reflow cycle, as well as earlier failures in the non-underfilled samples with two reflow cycles.

Drop tests are typically performed on as-built samples. However, customers expect their portable products to survive dropping after some use time in the field. To begin to explore the effect of aging on drop test performance, Sn/Ag/Cu CSPs, with no underfill and with corner bond underfill was studied. Samples were aged at 125°C for 100 hours and 250 hours then drop tested. The results are shown in Figure 15. There is a significant decrease in drop test performance after 100 hours at 125°C. After 250 hours at 125°C, the drop test results for the corner bonded CSPs are approximately equal to the unaged, non-underfilled Sn/Ag/Cu samples. The decline in non-underfilled performance seems to stabilize after 100 hours.

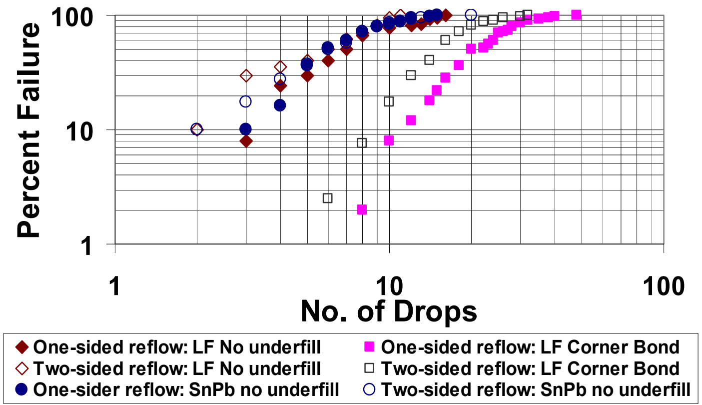


Figure 14 - Drop Test Results for Single and Double Reflow Cycles

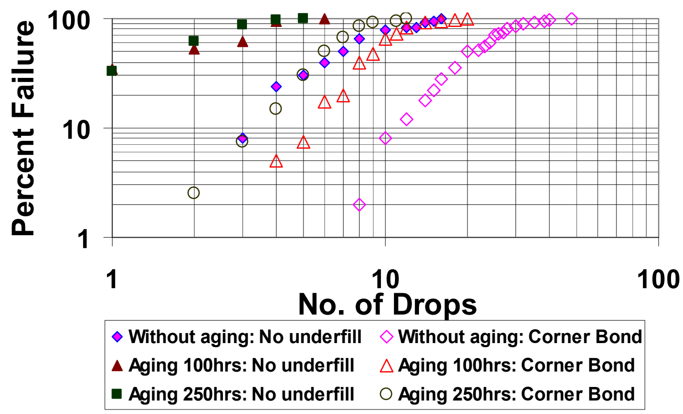


Figure 15 - Drop Test Results for Sn/Ag/Cu Solder with No Underfill and with Corner Bond Underfill after 0, 100 and 250 Hours of Aging at 125°C Prior to Dropping

Failure Analysis

Figures 16 and 17 show typical failures modes for the 'ramp-to-peak' and 'soak' lead free profiles, respectively. The predominate failure mode for the ramp-to-peak profile is in the solder near either the package or substrate interface. With the longer soak profile, the typical failure mode was fracture of the laminate under the pad with corresponding fracture of the copper trace. The drop test results for the soak profile were not quite as good as the results for the ramp-to-peak reflow profile (Figure 12), corresponding to the change in failure mode.

The corner bond underfilled Sn/Ag/Cu and Sn/Pb CSPs both failed by cracking of the corner bond adhesive and failure of the solder joint at the package or substrate interface. This is similar to the results previously reported for corner bonded Sn/Pb CSPs.[5]

Figures 18 and 19 show cross sections of Sn/Ag/Cu CSP failures with capillary underfills A and B, respectively.

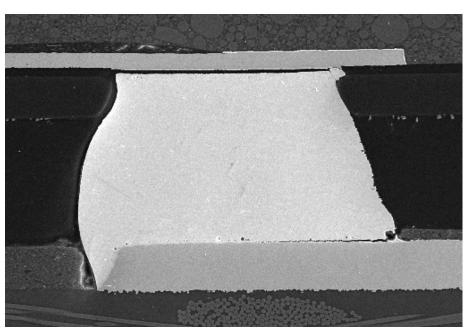


Figure 16 - Cross Section of a Typical Drop Test Failure of a Sn/Ag/Cu Solder joint (no underfill) Reflowed with the Ramp-to-Peak Profile

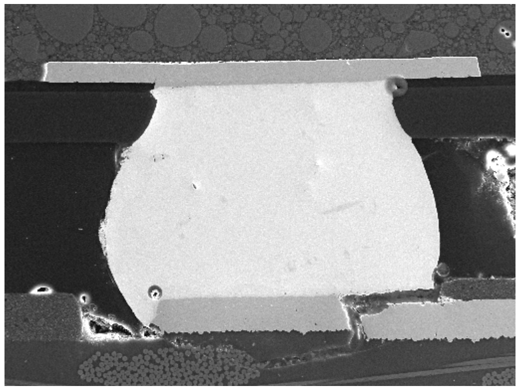


Figure 17 - Cross Section of a Typical Drop Test Failure of a Sn/Ag/Cu Solder joint (no underfill) Reflowed with the Soak Profile

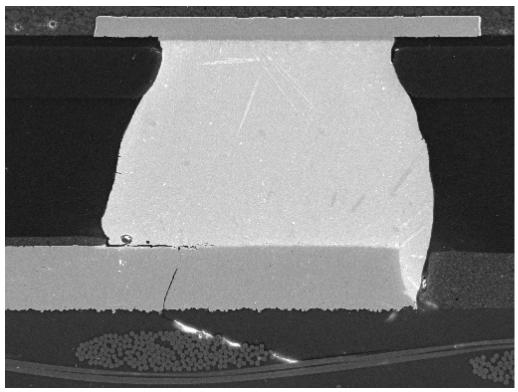


Figure 18 - Cross Section of Sn/Ag/Cu Failure with Capillary Underfill A

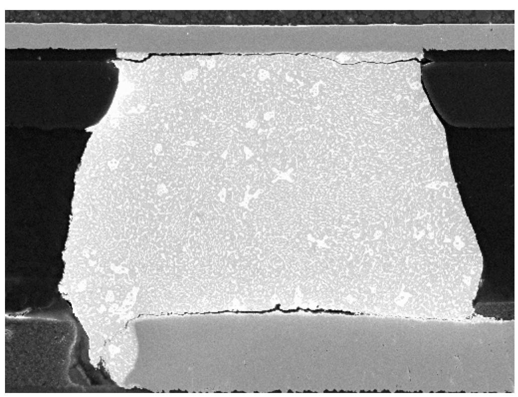


Figure 19 - Cross Section of Sn/Ag/Cu Failure with Capillary Underfill B

Capillary underfill A has a higher modulus, strongly coupling the CSP to the PCB. Thus the PCB is rigidized at the CSP locations. Flexing of the PCB during drop testing results in fracture of the underfill fillet. This crack propagates into the outer row of solder balls and then through the copper trace, into the laminate. This failure mode has been reported previously for Sn/Pb CSPs.[5]

The modulus of capillary underfill B is significantly lower, allowing more relative movement between the PCB and the CSP. This places more stress on the solder joint leading to failure in the solder. From the drop test results, the lower modulus underfill is better for both Sn/Pb and Sn/Ag/Cu CSPs.

Figure 20 shows a cross section of a Sn/Ag/Cu CSP failure (no underfill, two reflow cycles). The two reflow cycles were both ramp-to-peak. The exposure of the PCB to two lead free reflow cycles resulted in a change in failure mode (compare to Figure 16). This is consistent with the failure mode resulting from the longer soak profile.

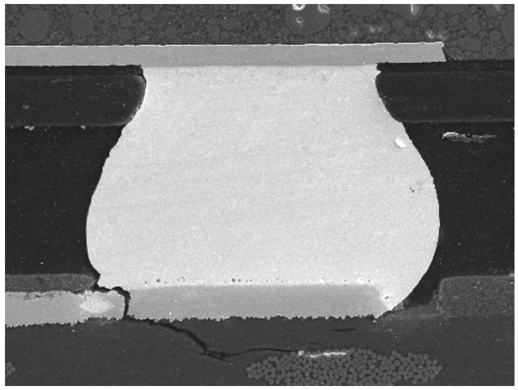


Figure 20 - Cross Section of Sn/Ag/Cu CSP (no-underfill) Failure Assembled with Two Reflow Cycles

Figure 21 shows the failure mode for the Sn/Ag/Cu CSP (no underfill) when aged at 125^{o}C for 250 hours before dropping. While the drop test performance was significantly degraded with aging, there is no change in failure mode (compare to Figure 16). This indicates the degradation mechanism is due to changes in the solder and/or intermetallic with aging.

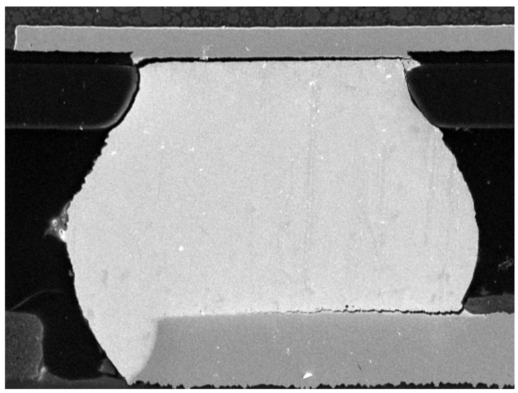


Figure 21 - Cross Section of Sn/Ag/Cu CSP Failure after 250 Hours at 125^{o}C Storage prior to Drop Testing

Summary

Three underfill options compatible with lead free assembly have been evaluated: capillary underfill, fluxing underfill and corner bond underfill. CSPs with eutectic Sn/Pb solder were used for control samples.

The reflow profile affected the drop test performance and failure mode with the Sn/Ag/Cu CSPs. The longer soak profile resulted in poorer drop test performance with failure in the laminate. The shorter, ramp-to-peak profile was used for all subsequent test vehicle builds.

Without underfill, lead free and Sn/Pb eutectic drop results were comparable. With capillary flow underfill, the drop test results were significantly better with lead free solder assembly than with Sn/Pb eutectic. The lower modulus capillary underfill performed better with both Sn/Pb and Sn/Ag/Cu CSPs in the drop test.

The fluxing underfill with lead free solder yielded the best drop test results. There were no failures after 150 drops.
The drop test results with corner bond were intermediate between no underfill and capillary underfill and similar for both lead free and Sn/Pb eutectic solder assembly.

There was degradation in the drop test results after 100 and 250 hours of storage at 125^{o}C prior to the drop test. Underfill improved the drop test performance of the CSP evaluated in this series of experiments. The different underfill types provide assembly process options, which must be weighed against the difference in drop test performance.

Acknowledgements
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