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Implementation of No-Flow Underfills on Chip Scale Packages

Corey B. Franzo
Georgia Institute of Technology
Manufacturing Research Center
Atlanta, Georgia

Daniel F. Baldwin, Ph. D.
Engent, Inc. – Enabling Next Generation Technologies
Advanced Assembly Technology
Norcross, Georgia

Larry Crane, Ph.D.
Henkel Loctite Corporation
Industry, California

Abstract

Chip Scale Package (CSP) technology is growing at a rapid pace since its emergence in the electronics manufacturing industry. As the solder joint size decreases, it has become apparent that underfill is necessary to meet certain reliability standards with CSPs, specifically drop testing. The need to underfill the CSP package has exerted the same drawbacks that are involved in flip chip assembly. No-flow underfills pose serious potential in this area as they can be incorporated into the standard SMT process with no post reflow processing. Most new materials simultaneously reflow and cure in the same reflow process used for standard SMT solder pastes. This work presents a reliability study of several commercial no-flow underfills and compares these CSPs to CSPs assembled without underfill and CSPs assembled with conventional fast-flow, snap-cure underfills. Samples were built using solder paste only, flux only, combinations of conventional underfill and solder paste or flux, and no-flow underfills. The reliability tests include liquid-to-liquid thermal shock (-40°C to 125°C) and board level drop tests (6-feet). Samples assembled with underfilled were benchmarked against the samples that were not underfilled. The CSP test vehicles consisted of a printed circuit board with 10 CSPs having 84 I/O and a 0.5-mm pitch. Through these tests, it has been determined that no-flow underfills can pass over 1000 cycles in liquid-liquid thermal shock, the typical standard for package/product qualification. Samples assembled with no-flow underfills also exhibited an increase in reliability during drop testing as compared to non-underfilled samples. The reliability data shows that no-flow underfill implementation on CSP increases reliability as compared to non-underfilled samples.

Introduction

This paper summarizes the experimental work performed at the Georgia Institute of Technology for Loctite on the implementation of no-flow underfills on chip scale packages (CSP). The goal of the project was to develop a CSP no-flow underfill process and compare the reliability of that process to a standard CSP process and a standard CSP process utilizing conventional underfill. Test vehicles were assembled using only solder paste, only dip flux, a fast-flow underfill with solder paste, a fast-flow underfill with dip flux, and a no-flow underfill. The process development included screen-printing, underfill dispensing, chip placement, and reflow. A process was developed to achieve high yield and high reliability CSP test vehicles. A test vehicle is illustrated in Figure 1.

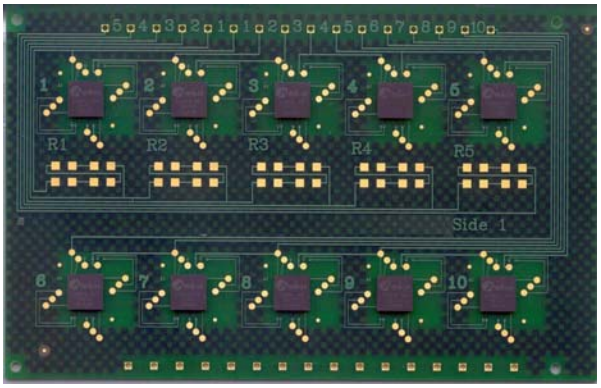


Figure 1: Image of the ten-site CSP test vehicle.

Screen printing was performed on an MPM 3000 screen printer for the paste boards while the flux boards were dip fluxed on the Siemens F5 placement machine. Boards from the solder paste and dip flux builds were either left alone or were underfilled with one of two fast-flow snap-cure underfills.

The underfill was dispensed using a Camalot 3700 dispensing system. The test vehicles that were assembled using a fast-flow underfill dispensed material along the topside of the device with a single pass line-pattern. The material flowed under the chip via capillary action. The no-flow underfill was dispensed as a dot in the center of the site. The underfill then spreads out as the CSP was placed with the placement machine.

Placement of the CABGA 84 CSPs was performed on the Siemens F5 pick and place machine. The boards assembled with paste utilized the simplest pick and place process. The parts were picked, visioned, and then placed. The boards assembled with flux were dip fluxed by the placement machine prior to being visioned and placed. The no-flow boards used the basic pick and place process although a dwell time was provided to ensure that the CSP balls penetrated the liquid polymer underfill and made contact with the substrate bond pads.

The reflow process was different for every material based on differences in the manufacturers recommended reflow profiles. All test vehicles were reflowed in a BTU Paragon 7-zone reflow oven. The flux, solder paste, and no-flow underfills all had different reflow profiles that were programmed into the oven and then verified using a KIC thermal profiler. All parameters for the reflow profiles were obtained from the specifications listed on the material data sheets.

Assembly Process

There were four different assembly processes used to assemble the test vehicles. The assembly processes are shown in Figure 2. The fast-flow conventional underfill process (Figure 2 (b)) is just added to the end of Figure 2 (a).

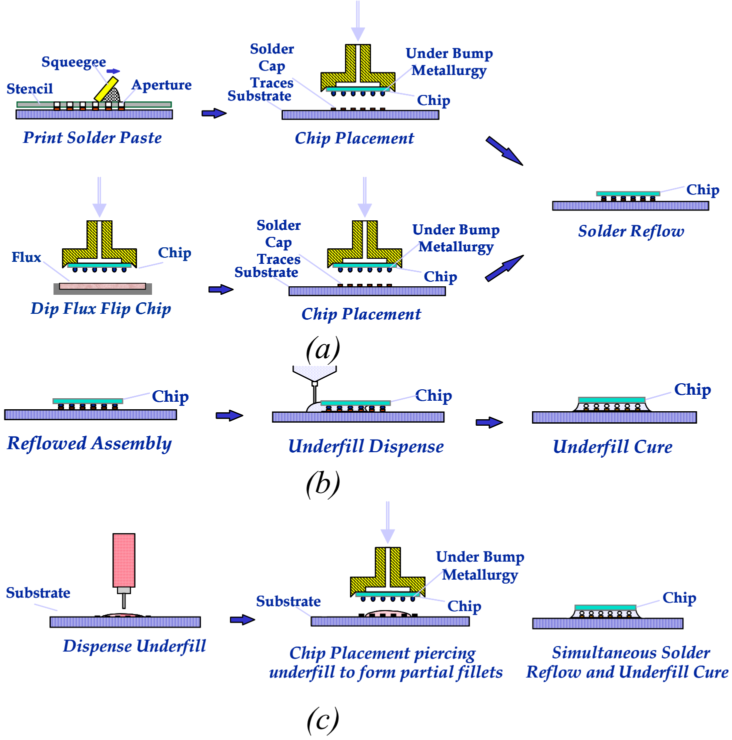


Figure 2: Flow charts of the builds (a) paste and flux only (b) fast-flow conventional underfill (c) no-flow underfill.

Dispensing Process

Two dispensing processes were used to assemble the test vehicles. The first process was dispensing of the fast-flow underfills in a straight line along the top of the CSP. Capillary flow allowed for the underfill to spread beneath the CSP and self-fillet around the perimeter of the component. The second dispensing process was dispensing no-flow underfill in the center of the site where a CSP was to be placed. This process required 12-16 milligrams of underfill be dispensed to form adequate fillets that reached up to 50% of the CSP height. The dispense patterns used for each type of underfill are illustrated in Figure 3. The underfill dispense ranges are listed in Table 1.

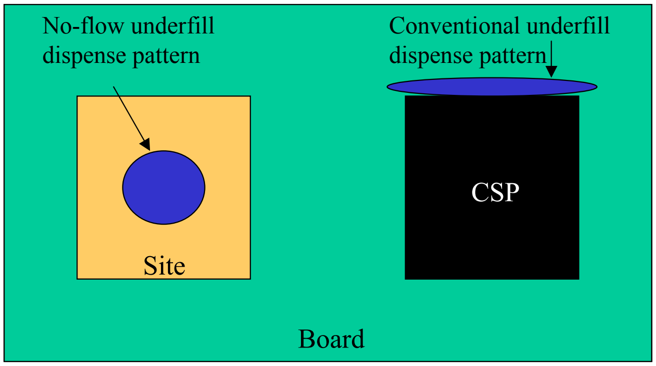


Figure 3: Fast-Flow and no-flow underfill dispense patterns.

Table 1: No-flow Underfill Dispense Ranges

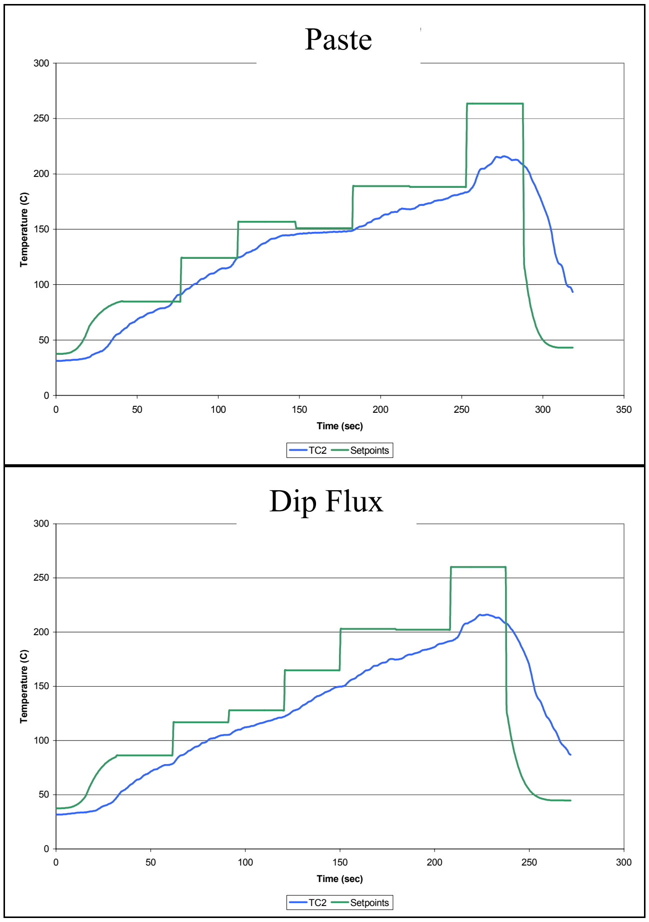
No-Flow Underfill	Underfill Weight Range
No-Flow I	12-16 milligrams
No-Flow II	12-16 milligrams

Placement Issues

The pick and place machine was used for placement of all test vehicles assembled. The parts were picked, visioned, and placed on the circuit board. The test vehicles assembled with the paste utilized a placement procedure without dipping or dwell time giving it the shortest cycle time. The test vehicles assembled with the dip flux were dipped and then placed. The no flow underfills are viscous so a dwell time during placement was incorporated to ensure the solder bumps were pushed through the underfill material to the substrate bond pads. There was only one CSP out of three hundred twenty that did not yield because of a placement error.

Reflow Experiments

The use of four different fluxing materials required that four different reflow profiles be used for the assembly process. All four of the reflow profiles were very similar to a standard eutectic reflow profile. The reflow profiles for the dip flux, the solder paste, and the two no-flows were created according to manufacturers specifications. The four profiles used are shown in Figure 4. The parameters used for the reflow profiles are listed in Table 2.



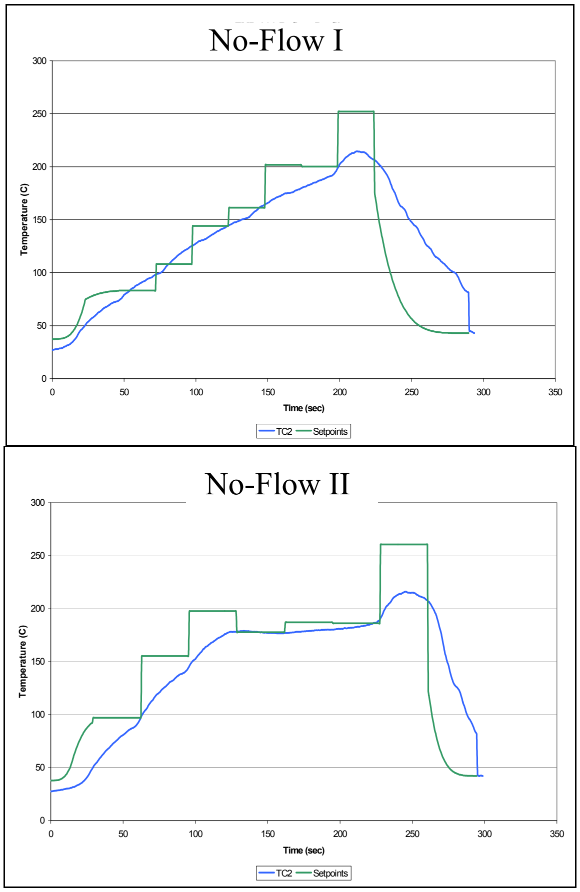


Figure 4: Reflow profiles used for CSP assembly.

Table 2: Important Reflow Parameters.

Material	Maximum Rising Slope	Time between 150 and 170	Time above 183	Peak Temperature
Solder Paste	1.8-2.2 degC/sec	60-120 sec	30-60 sec	208 degC
Dip Flux	1.3-1.7 degC/sec	60-90 sec	40-60 sec	210 degC
No-Flow I	1.3-1.7 degC/sec	60-90 sec	40-60 sec	210 degC
No-Flow II	1.8-2.2 degC/sec	110-130 sec	50-65 sec	210 degC

An interesting phenomenon was discovered after reflow of the first no-flow assembled boards. The first several boards built with no-flow underfill experienced large amounts of outgassing. It was determined that the CSPs were the source of the outgassing. The solution to this problem was baking out the CSPs for 2 hours at 80°C to drive out all of the moisture prior to assembly. The boards built with baked CSPs and baked boards did not experience any outgassing. There were four no-flow test vehicles that did not yield because of outgassing and they were placed in thermal shock testing. This was done because there were thirty test vehicles for thermal shock testing and only ten for the drop tests so the impact of the four failed test vehicles would be minimized.

Yield and Reliability Results

The experimental matrix for this work yielded eight different material combinations. A total of five boards were built for each material combination. Three of the boards were designated to undergo liquid-liquid thermal shock testing while the other two were going to undergo drop testing. There were a total of fifteen boards assembled with paste and another fifteen boards assembled with dip flux. Of the fifteen boards in each of these sets, five were left as is, five were underfilled with conventional underfill I, and the remaining five were underfilled with conventional underfill II. There were a total of ten no-flow underfill boards assembled. Five were assembled with no-flow I and five were assembled with no-flow II. Processing for the paste boards achieved 97.5% while the dip flux boards achieved 100% yield. The paste device was the only yield loss due to errors in the processing. The no-flow boards achieved 100% yield for the no-flow I devices and 90% yield for the no-flow II devices. In Table 3, a breakdown of the yields for each of the material combinations is shown.

Table 3: Yields for all material combinations assembled.

Material Combination	Number Assembled	Number Functional	% Yield
Flux Only	40	40	100
Flux Fast-Flow I	40	40	100
Flux Fast-Flow II	40	40	100
Paste Only	40	40	100
Paste Fast-Flow I	33 *	33	100
Paste Fast-Flow II	25 *	25	100
No-Flow I	40	40	100
No-Flow II	40	36	90

* Forty of each type were built and yielded, but x-ray inspection revealed defects.

Upon completion of placement, the boards underwent X-ray inspection on the Nicolet X-ray system to verify alignment prior to reflow. Some post reflow X-ray analysis revealed that several solder joints had bridged in the test vehicles assembled with paste. Although they yielded they were removed from reliability testing. X-ray analysis was the only inspection performed on the test vehicles since underfill delamination cannot be viewed under CSP devices with the acoustic microscopy equipment at Georgia Tech. Some X-ray images taken of test vehicles are shown in Figure 5.

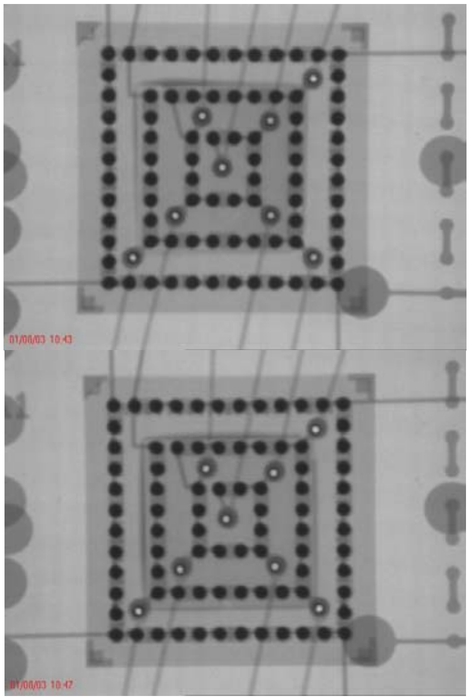


Figure 5: Post placement x-ray images.

When assembly and probing were completed the boards were subjected to liquid-liquid thermal shock (LLTS) testing (JESD22-A106-A) and board level drop testing. These tests would investigate thermomechanical and mechanical reliability of the material combinations used. Three boards of each material combination were placed in LLTS and subjected to temperatures of – 40^{o}C in the cold bath and 125^{o}C in the hot bath. Samples were in each bath for five minutes resulting in a total cycle time of ten minutes. The boards were taken out and tested for electrical continuity every one hundred cycles. CSPs were determined to fail if they reached a resistance equal to or greater than one and a half times their original resistance. The reliability results for the LLTS testing are shown in Table 4.

Table 4: Liquid-Liquid Thermal Shock Reliability Statistics.

	Flux Only	Flux Fast-Flow I	Flux Fast-Flow II	Paste Only	Paste Fast-Flow I	Paste Fast-Flow II	No-Flow I	No-Flow II
First Failure	800	3400	1400	400	2500	2600	2000	2300
MTTF	906	5805	3901	820	4462	3983	4290	4627
Final Failure	1100	6500	6100	1000	5600	5000	6500	5300
Total CSP	30	30	30	30	23	15	30	16

The data in Table 3 indicates that a total of 40 fast-flow II test vehicles were assembled and 36 of those yielded. In Table 4, only 16 are listed because these test vehicles were assembled with CSPs that were pre-baked. The other ten assemblies did not undergo a pre-bake and had a much lower reliability than the pre-baked assemblies did. A comparison of the reliability statistics for these two sets of test vehicles show a large decrease in reliability for the unbaked CSPs. This data indicates that assembly of no-flow underfill on CSPs requires that both the board and the CSPs be baked out to achieve high reliability. The reliability statistics for these two sets of data are shown in Table 5.

Table 5: Reliability statistics for unbaked and baked CSPs assembled with fast-flow II.

	No-Flow II - No Pre-bake	No-Flow II - No Pre-bake
First Failure	900	2300
MMTF	1264	4627
Final Failure	1500	5300
Total CSP	10	16

A statistical analysis was performed to determine the reliability of the material combinations used. The data was fit to a parametric Weibull distribution for the statistical analysis. The non-underfilled boards had a much lower mean time to failure than the underfilled boards as was expected. The flux only boards were found to have a slightly better performance than the paste only boards in reliability testing. The boards that were underfilled with fast-flow I and used flux achieved a mean time to failure of over 1000 cycles better than the fast-flow I boards that were assembled with paste. The performance of the paste and flux boards underfilled with the fast-flow II underfill was determined to be equal. The no-flow underfill analysis showed that the no-flow II had a higher mean time to failure than the no-flow underfill. A comparison between the two no-flow underfills and the two conventional underfills with flux showed that the conventional underfills with flux achieved a higher mean time to failure. Since the mean time to failure was well over 1000 for both no-flow underfills, both materials proved to have an adequate reliability for use in CSP assembly. The Weibull probability plot for the LLTS tests is shown in Figure 6.

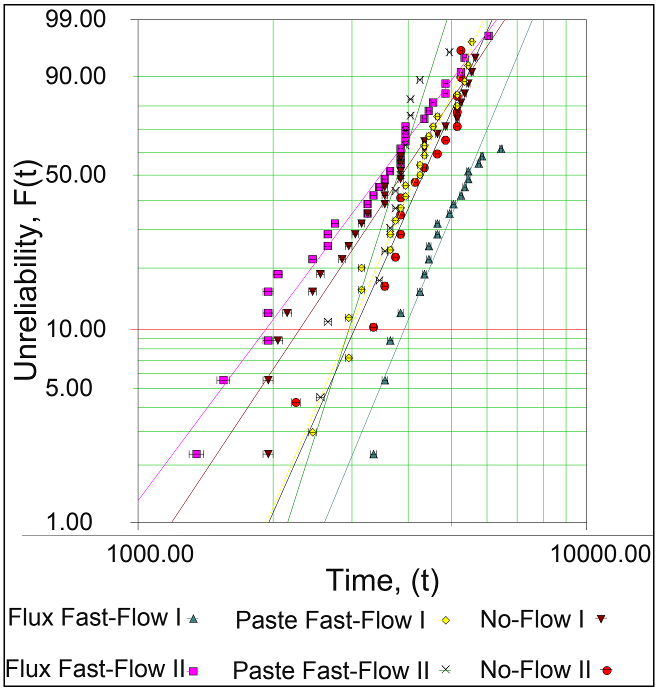


Figure 6: Weibull plots of the underfilled boards from liquid-liquid testing.

Drop testing was performed on one board of each material combination. The drop tests consisted of a 6-foot vertical drop through a PVC pipe onto a concrete floor. These drops were performed on the same side of the board for every drop. Further multi-sided drop testing is planned for one board in each material combination. Electrical continuity testing was used to determine if the integrity of the electrical connections was compromised during drop testing. The non-underfilled boards were tested for electrical continuity after every drop to determine an acceptable interval for probing the underfilled boards. It was determined that electrical continuity testing should be performed on the underfilled boards after every twenty-five drops. The reliability results for the board-level drop tests are shown in Table 6.

Table 6: Drop Test Reliability Results.

	Flux Only	Paste Only	No-Flow I	No-Flow II
First Failure	27	33	325	200
MTTF	100	109	2085	840
Final Failure	332	247	3400	2600
Total CSP	10	10	10	10

The same statistical analysis was performed to determine the reliability of the material combinations used for the drop tests. The data was fit to a parametric Weibull distribution for the statistical analysis. The two conventional underfill materials did not experience any failures through 3000 drops. It was determined that there was no need for further testing of the conventional materials and they are not included in these results because they did not experience any failures. It was concluded that the flux only and the paste only boards showed no statistical difference in drop test performance. The no-flow materials were tested and the no-flow I had over 1000 cycles higher mean time to failure than the no-flow II material. The no-flow materials had a much better performance than the non-underfilled boards, but were not as good as the boards assembled with the conventional underfill. The Weibull probability plot of the drop test boards is shown in Figure 7.

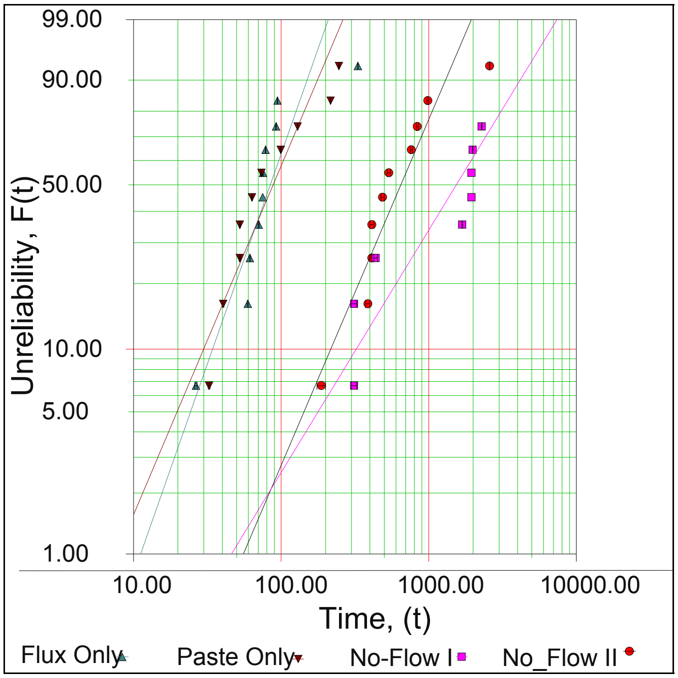


Figure 7: Weibull plot of no-flow and non-underfilled boards from drop testing.

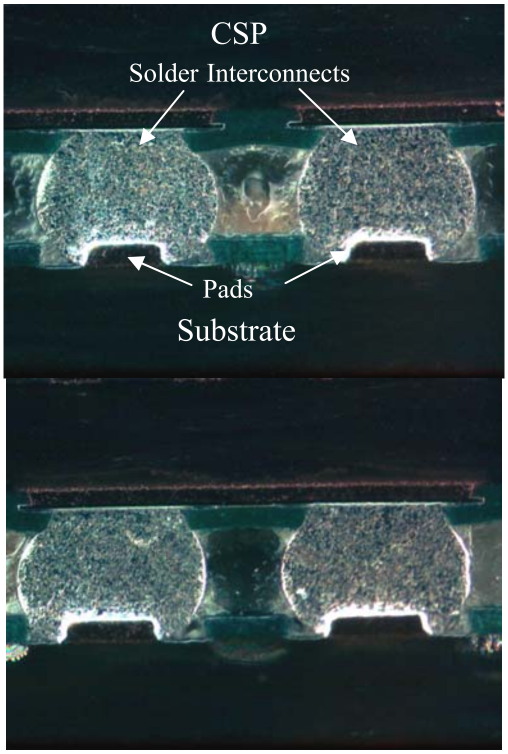
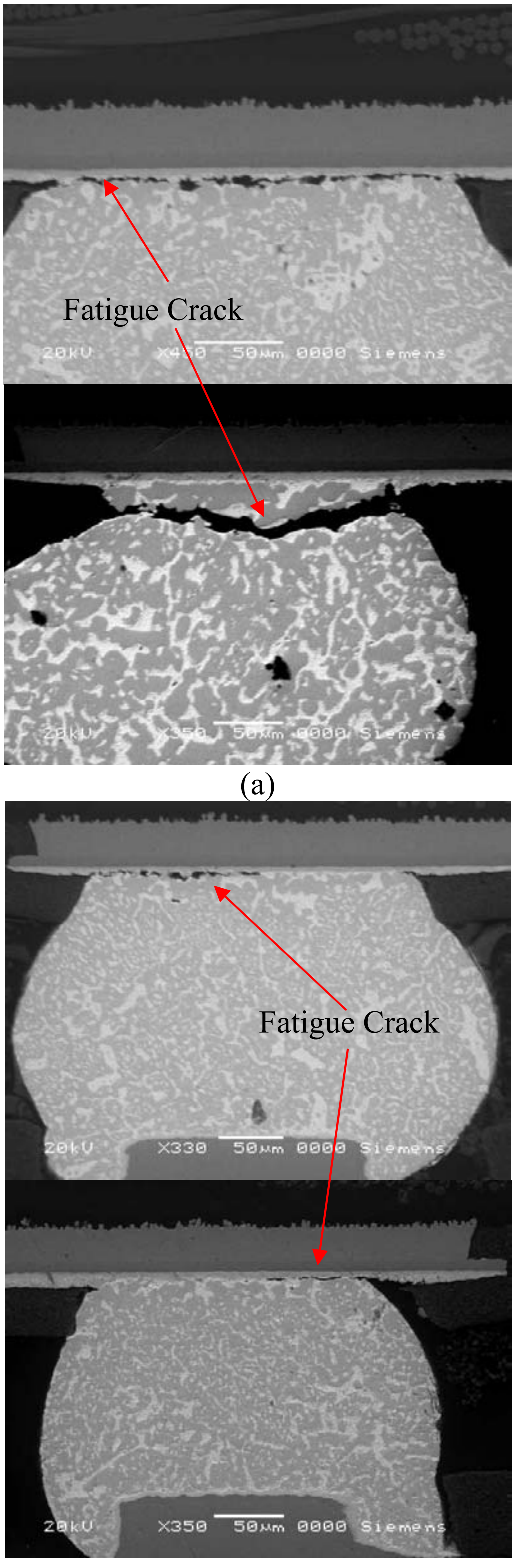


Figure 8: Images of fully wetted solder interconnects.

Failure Mode Analysis

Once thermal cycling and drop testing were complete, samples from each type of material combination were cross-sectioned. The finely polished cross-sections were then analyzed using optical microscopy and scanning electron microscopy (SEM) to determine the failure modes. Every material combination built yielded well with fully wetted interconnects. Figure 8 shows two images of good wetting from a paste only cross-section.

The most common form of failure was solder fatigue cracks in the liquid-liquid thermal shock boards. Solder fatigue results from the CTE mismatch between the composite CSP structure and the organic substrate. Underfill cracking and delamination can accelerate the rate of fatigue crack propagation. In every material combination, cross-sectional analysis revealed component level cracks in the solder joints. Figure 9 (a) shows SEM images of component side solder fatigue cracks while Figure 9 (b) shows cracks that have not fully propagated across the solder interconnect.

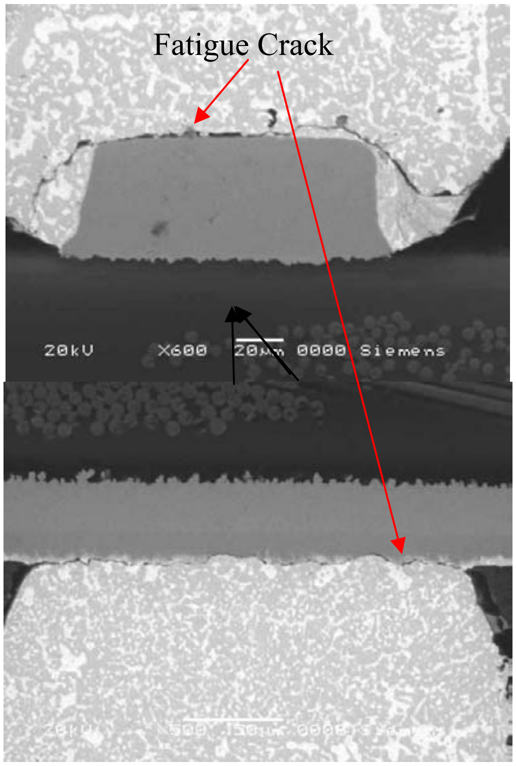


(a)

(b)

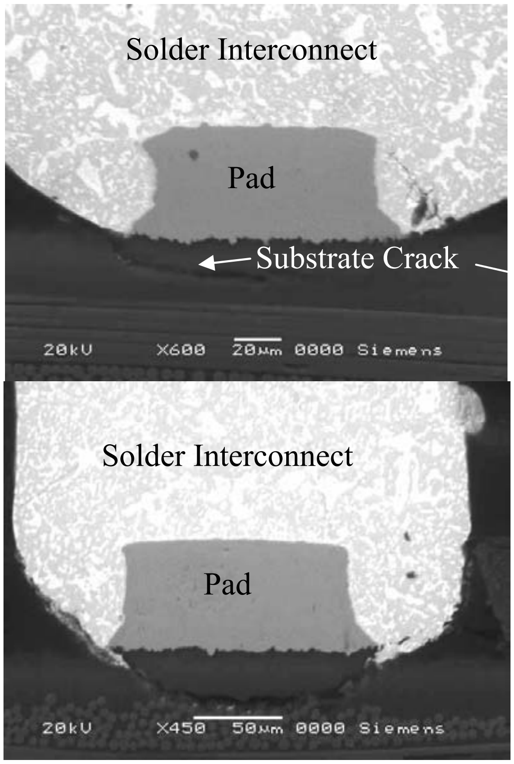
Figure 9: (a) SEM images of component level fatigue cracks (b) SEM images of propagating fatigue crack.

Failure mode analysis of the drop tests had some different results. There were no continuity failures in the boards assembled with the conventional underfill. Of the cross-sections from these boards, no fatigue cracks were found which supports the continuity test results. The non-underfilled boards experienced solder fatigue cracks on the component side of the solder joint and in the substrate beneath the pads. The no-flow underfilled boards experienced fatigue cracks at the component level, on the board side along the pad, and in the substrate beneath the pad. This unusual location beneath the pads incurred more cracks than there were at the component level. It should be noted that both types of cracks were observed in cross sections of both no-flow materials. SEM images of all three types of cracks are shown in Figures 10 (a) and (b).



(a)

Figure 10: (a) Solder fatigue cracks on the component and board levels. (b) cracks in the substrate under the pads.



(b)

Figure 11: (a) Solder fatigue cracks on the component and board levels. (b) cracks in the substrate under the pads.

The board level drop tests were conducted in such a way that the same side of the board impacted the ground during every drop. This resulted in the CSPs placed on sites closest to this edge to pop off of the board. Some no-flow devices popped off with a majority of the no-flow underfill that was under the CSP as well as many of the pads from the substrate. There were three paste only devices that popped off and one flux only device. The paste only devices popped of between 3 and 25 drops after they failed continuity testing and the flux only device popped off 200 drops after failing continuity testing. There were two no-flow II devices that popped off and three no-flow I devices that popped off during drop testing. The no-flow devices that popped of did so after about 350 drops after they failed electrical continuity testing for the no-flow I and about 700 cycles after they failed electrical continuity testing for the no-flow II. The devices that popped off were among the earliest ones to fail continuity testing. Figure 11 shows images of the component side and board side of the test vehicles after the CSP popped off during drop testing. It can be seen that all the pads came off of the board indicating the weakest interface is not at the solder interconnect but under the copper pads.

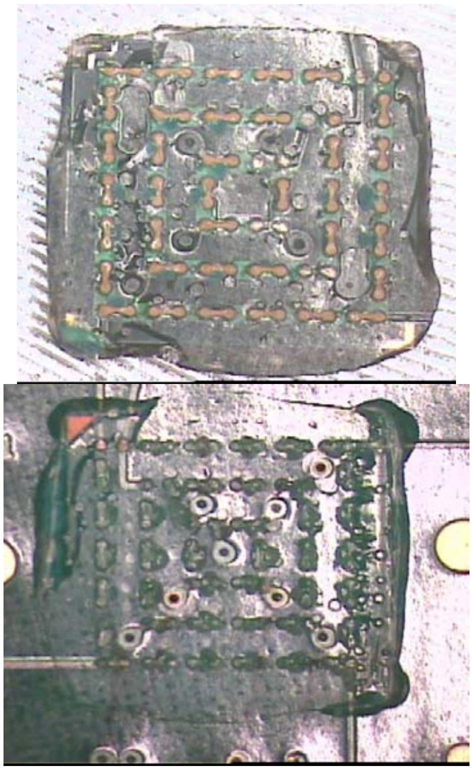


Figure 12: Component and board level images taken after drop testing.

The same phenomenon was seen with the non-underfilled boards. More components popped off of these boards because there was no underfill adhesive to distribute the stresses experienced by the solder joints. Every device that popped off came up with all of the solder balls and most of the pads from the substrate. The drop tests show that the interface between the solder ball and the component and the solder ball and the pad are robust. The weakest area of the package is actually beneath the pad where it breaks away from the substrate. Figure 12 shows that the pads were pulled from the substrate in non-underfilled test vehicles as well.

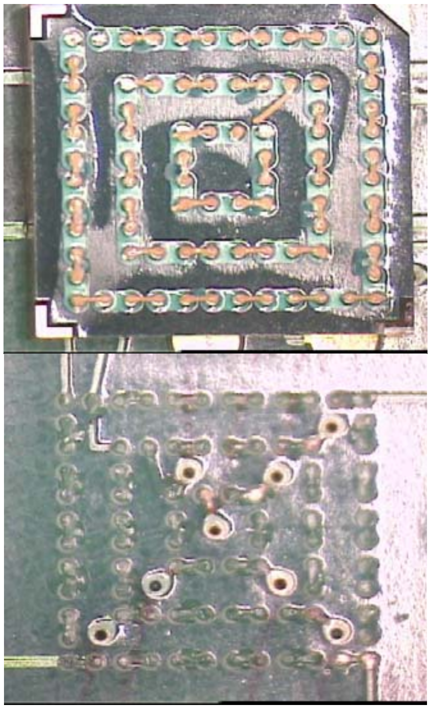


Figure 13: CSP and substrate from non-underfilled drop test board.

Fillet cracks were also observed during the failure mode analysis. All four underfill materials experienced cracks in the fillets of the underfill. These cracks were observed in both LLTS and drop test samples. The fillet cracks in the LLTS samples were typically perpendicular to the CSP running away from it and sometimes continuing into the substrate. The image shown in Figure 13 shows fillet cracks in an LLTS sample.

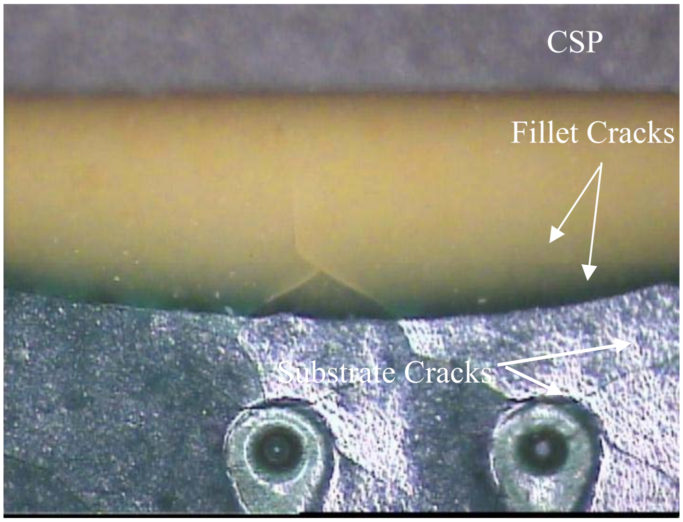


Figure 14: Fillet crack in a LLTS conventional underfill sample.

The fillets in the drop test samples tended to propagate around the perimeter of the CSP and did not run directly into it as seen in Figure 14. This pattern of fillet cracks propagating around the perimeter of the device may have contributed to the devices popping off of the circuit boards.

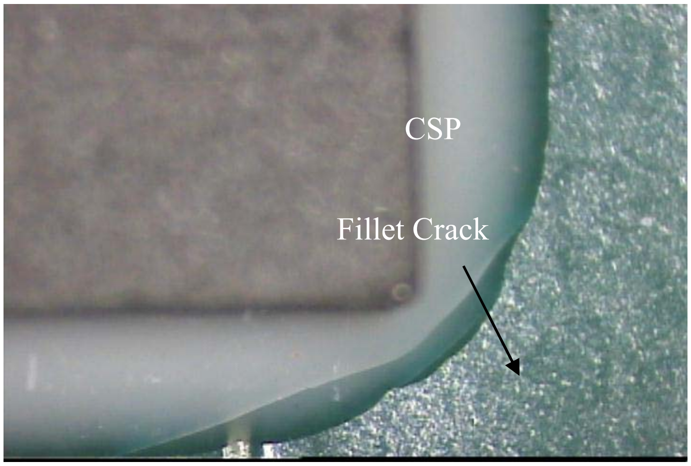


Figure 15: Fillet crack in a drop test conventional underfill sample.

Conclusion

The reliability of no-flow underfill CSP test vehicles was found to be adequate for package or board level reliability. Both no-flow materials were capable of reaching well over 1000 cycles in thermal shock testing. The performance of the no-flow material was not as good in the drop tests as the conventional underfill, but the no-flow I had a high mean time to failure of 2000 cycles. The no-flow II did not reach 1000 cycles indicating that the better no-flow material for processing CSPs is the no-flow I. The primary failure mode observed in all samples were solder fatigue cracks. A new failure mode previously not seen in work here at the Georgia Institute of Technology was the failure of the substrate under the pads during drop testing. This discovery shows that the solder interconnect and the underfill are more robust than the organic substrate. On the processing side, it was discovered that baking out the CSPs and boards before assembly significantly increased the reliability of the no-flow test vehicles. The results of this work have shown that no-flow underfills can perform at the required level for use in CSP assembly.