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CSP Underfill, Processing and Reliability

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Abstract

The use of Chip Scale Packaging (CSP) is rapidly expanding, particularly in portable electronic products. 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. This paper examines the assembly process with capillary and fluxing underfills. Issues of solder paste versus flux only, solder flux residue cleaning and reworkability are investigated with the capillary flow underfills. Fluxing underfills eliminate the issues of flux-underfill compatibility, but require placement into a predispensed underfill. Voiding during placement is discussed.

To evaluate the relative performance of the underfills, a drop test was performed and the results are presented. All of the underfills significantly improved the reliability in the drop test compared to non-underfilled parts. Processes such as cleaning or rework that improved the adhesion of the underfill to the PWB solder mask further improved drop test reliability

Introduction

As the pitch of CSPs continues to decrease and the corresponding solder volume and pad size decreases, the susceptibility of CSPs to fail in mechanical drop tests increases. The two options to address product failure when dropped are to improve the mechanical design or use underfills. Improving the mechanical design of the final product to minimize the magnitude of the shock on the CSP/PWB and the flexing that occurs will improve reliability in a drop situation. This type of design is complex and time consuming. In portable products, where time-to-market is a critical parameter for profitability, underfill is often chosen to mechanically couple the CSP to the PWB. By coupling the CSP to the PWB, the assembly can withstand larger mechanical shock, vibration and bending forces.

Capillary flow underfills provide one underfill option.[1-3] Capillary underfills are dispensed and cured after the completion of the reflow process. In a no-clean assembly, flux-underfill interactions must be considered due to the relatively large volume of flux residue from the printed solder paste. One of the advantages of CSPs over flip chip-on-laminate assembly is the ability to rework if a defective component is placed. Conventional underfills do not permit rework. In this investigation, a thermally reworkable underfill was studied. Details of the assembly process with capillary underfills including rework are presented along with drop test results.

A second option for CSP underfill is fluxing or no-flow underfills. In this process 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. The underfill provides the fluxing action for good solder wetting. The underfill may cure during the reflow cycle or a post reflow cure may be required. Fluxing underfills eliminate the issue of flux residue-underfill compatibility. In addition, as the electronic density in portable products increases, the spacing between components decreases, making underfill dispense after CSP placement and reflow more difficult. Fluxing underfill reduces the component spacing limitations. Assembly issues with fluxing underfills include CSP placement, CSP floating, solder wetting, and reflow profile. Experiments have been performed to optimize the assembly process and the results will be presented along with drop test data.

Test Vehicle

The test vehicle was a four-layer test board with 10 CSP attachment sites per side. The board was designed for a 12mm CSP on one side and an 8mm CSP on the other. In this work, only the 8mm CSP was used. The board was 2.95" by 7.24" by 0.042" thick. Drill holes (0.013” drill) under the 12mm CSP were plugged and tented to prevent underfill from flowing through the hole during dispense. The pads were 0.010” in diameter, non-solder mask defined with an electroless nickel/immersion gold finish. During the testing, no evidence of failure associated with ‘black pad’ was observed[4].

The CSP was a 8mm, 0.5mm pitch, 132 I/O TapeArray from Amkor Technology. The I/O were on a 14 x 14 array with only the outer three rows populated. The CSP was a daisy chain test part for continuity measurements. The silicon die was 3.98mm x 3.98mm.

Assembly – Capillary Underfill

Two approaches were investigated for the assembly of the CSP to the PWB: no-clean solder paste and flux only. The use of solder paste is standard in SMT assembly. While solder paste is 88-90% by weight metal, it is only 48-52% metal by volume. Thus, with a flux that leaves only 25% residue after reflow, the flux residue is equal to approximately 12-13% of the original solder paste print volume. With underfill, the flux residue is a concern since it may affect the underfill flow during dispense and it may interact chemically and mechanically with the underfill. To evaluate this, test samples were fabricated with no-clean solder paste. Test vehicles were then underfilled both 'as-assembled' and after cleaning to compare the results.

The 'flux only' assemblies were to examine two factors: reduced flux residue and reduced final solder volume. Using a dip flux approach similar to that used to assemble flip chip die, less flux is used compared to a solder paste. Solder paste does add solder volume to the CSP joint. The effect of a smaller solder volume on performance is important if 'flux only' rework process is used or for comparison to fluxing underfill assembly where no solder paste is used.

For test vehicles assembled with solder paste, a no-clean Multicore CR-36 solder paste was used. The paste was Type 4 for uniform paste transfer through the 4mil thick electropolished, Ni plated, laser cut stencil. The aperture in the stencil was 0.010". An MPM AP 25 automatic stencil printer was used. The paste was visually inspected after printing to insure print quality.

The CSPs were placed with a Siemens F5 pick & place machine. For the parts assembled with 'flux only', a rotating dip fluxer on the F5 was used. The flux depth was set at 55 µm and Kester 6502 flux was used.

After placement, the parts were reflowed in an air atmosphere using a Heller 1800 convection reflow oven. The reflow profile was developed to minimize solder voids as measured using a Phoenix X-ray microfocus x-ray system.

Two capillary flow underfills were evaluated. Underfill A (Loctite 3563) is a filled, fast flow, snap cure underfill. Underfill B (Loctite 3568) is a filled, thermally reworkable underfill.

The boards were not underfilled immediately after reflow, as time was required for underfill process development. Voids were observed in the cured underfill due to moisture absorbed by the boards after reflow. Figure 1 shows a flat-section of underfill A (the PWB has been polished away). The solder ball serves as a nucleation site for the water vapor.

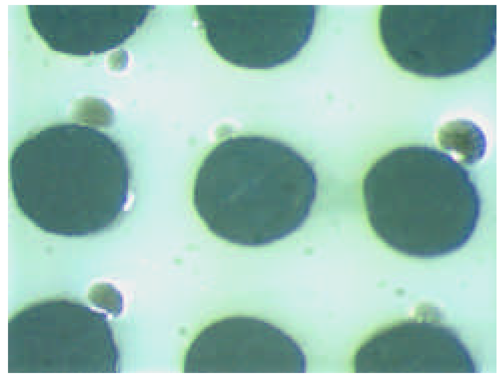


Figure 1 - Flat-section Showing Voids in Underfill a Due to Moisture in the PWB

Subsequently, the PWBs were dehydrated for 4-6 hours at 125^{o}C. Figure 2 is a flat-section of Underfill A after dehydration. The larger, random voids are no longer present, but smaller voids along the solder ball perimeter can be seen. These voids are due to solder flux residue at the base of the solder joint. During the polishing process, the flux residue is dissolved, leaving an apparent void. Figure 3 is a cross-section also showing a void due to flux residue.

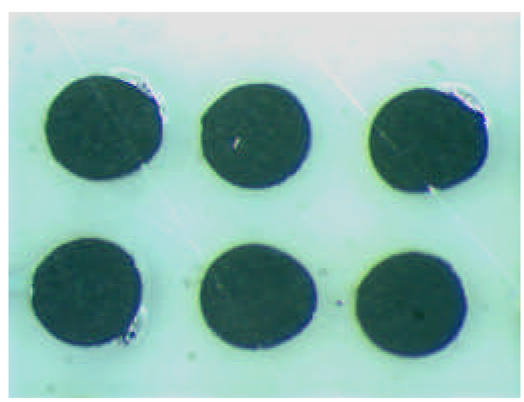


Figure 2 - Flat-section Showing Voids at the Perimeter of the Solder Ball Due to Flux Residue from Solder Paste. Sample was Dehydrated Prior to Underfill

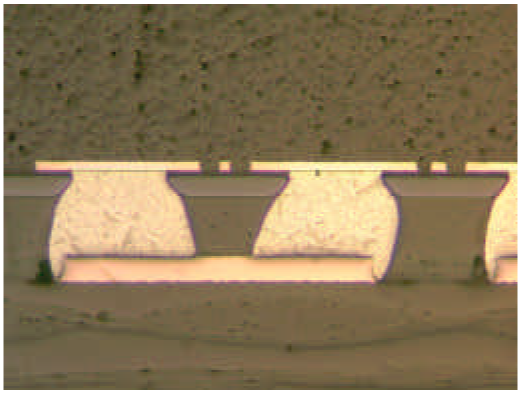


Figure 3 - Cross-section Showing Void at the Base of the Solder Ball Due to Flux Residue (Solder Paste Assembly). Sample was Dehydrated Prior to Underfill

A cross-section of a 'flux only' assembly underfilled with material A is shown in Figure 4. There is very little voiding at the base of the solder ball. This was expected, as the quantity of flux residue was less. Note the good solder wetting achieved.

One group of test vehicles was cleaned prior to underfilling with material A. The clean was aqueous based using a 10% HYDREX DX solution in deionized water at 65-70^{o}C. Due to the water exposure, the test vehicles were dehydrated at 125^{o}C for 24 hours before underfilling. Flat-sections and cross-sections (Figure 5) of cleaned parts revealed no voiding around the solder ball.

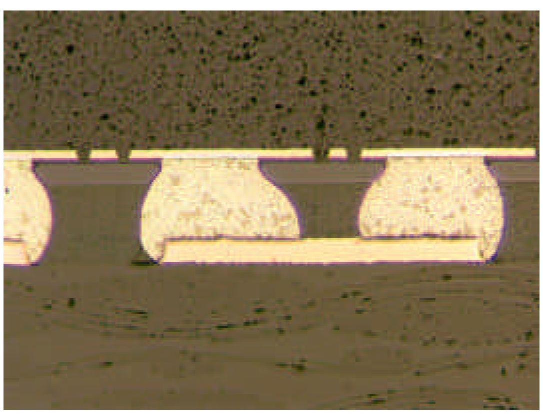


Figure 4 - Cross-section Showing Minimal Voiding at the Base of the Solder Ball Due to Flux Residue (Flux Only Assembly). Sample was Dehydrated Prior to Underfill

The dispense and flow times for Underfill A are shown in Table 1. The stage temperature for dispense was 100^{o}C and a "L' shaped dispense pattern at one corner was used. The underfill was cured for 5 minutes at 165^{o}C in a box oven. With a 5 minute cure, a conveyorized convection oven can be used in production.

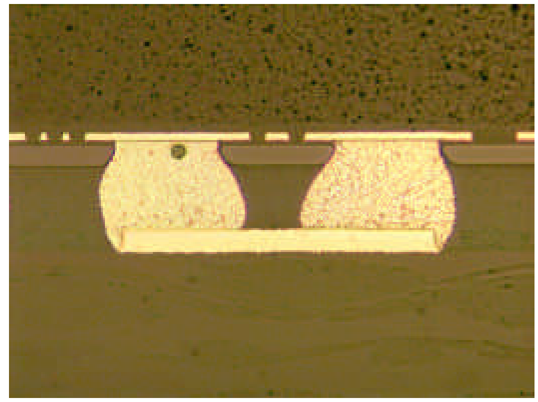


Figure 5 - Cross-section Showing No Voids at the Base of the Solder Ball Due to Flux Residue after Cleaning. Sample was Dehydrated Prior to Underfill

Reworkable underfill B was investigated only with solder paste and without cleaning. The test vehicles ere dehydrated for 4-6 hours at 125^{o}C just prior to underfill dispense. For the 'as-built' condition, the dispense and flow times are shown in Table 1. An "L" shaped dispense pattern was used in one corner and the stage temperature was 100^{o}C. The cure of 15 minutes at 150^{o}C was performed in a box oven.

Table 1 - Underfill Dispense and Flow Times

Underfill	Dispense Time (sec.)	Flow Time (sec.)
A, with Solder Paste	5	10
A, Cleaned	5	7
A, Flux	5	13
B, As-built	6	3
B, Reworked	6	3

An AirVac DSR 24 rework station was used to rework the underfilled CSPs. Underfill B is designed to breakdown when heated to solder reflow (rework) temperature. This breakdown of the thermoset network is a result of the incorporation of a patented monomer which has a special linkage designed to break apart upon heating. The breakdown of the network reduces the adhesion allowing easy removal of the CSP. After CSP removal, the underfill is also ready for easy removal due to the network breakdown.

The board was heated to 90^{o}C and the CSP was heated with a nozzle air temperature of 250^{o}C. The CSP was then easily removed with a custom developed hand tool used to gently lift the CSP from one side producing a peeling action. The tool was smooth on the face contacting the PWB to avoid any potential for solder mask damage. Figure 6 shows a CSP site after removal of the CSP. Underfill residue is seen in the figure. A two-step process was used to remove the underfill residue. First, a modified dressing tool was used on the AirVac system to remove the excess solder and most of the epoxy residue. Second, the remaining epoxy residue was removed with a rotating flat-tipped brush in a rotary tool. An automated brushing system has been developed.[1] The rework times are given in Table 2. A cleaned site is shown in Figure 7.

Table 2 - Rework Times

Process	Time (minutes)
CSP removal	3
Dressing with modified Air Vac Nozzle	1
Brushing	2

After rework the sites were inspected. There was some roughening of the solder mask surface, but no solder mask damage (deep scratches, peeling, etc.) was observed. The test vehicles were then re-build using solder paste. Figure 8 shows x-ray images of 'as-built' and reworked CSPs.

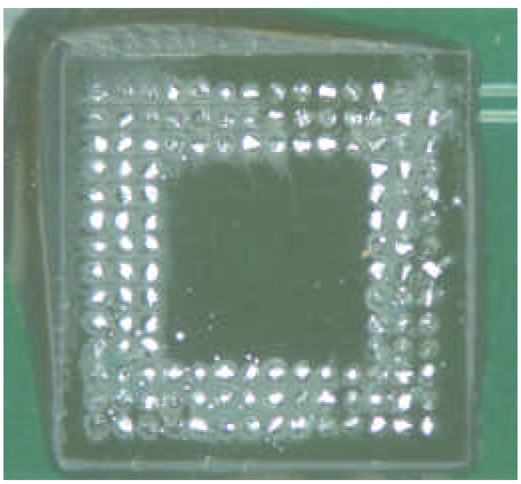


Figure 6 - Photograph of a CSP Site after CSP Removal

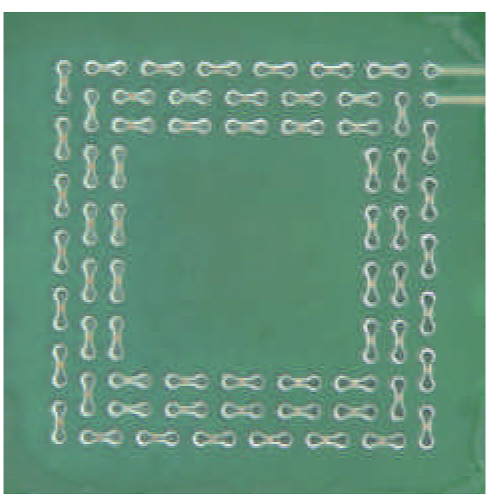
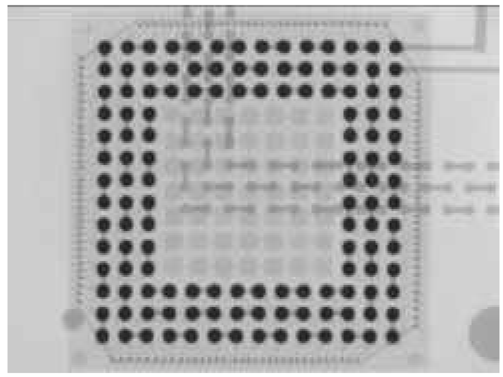


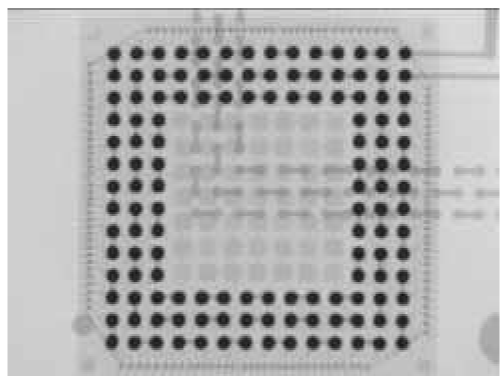
Figure 7 - Photograph of a CSP Site after Clean-up

The underfill dispense and flow times were the same after rework as in the 'as-built' condition (Table 1). The dispense pattern for the reworked samples was a single line along one side of the CSP. The line was ½ the length of the CSP side.

Figure 9 shows a cross-section of a reworked CSP. The solder wets well to the pad, but does not wet around the edges of the pad. This is likely due to a small amount of residual underfill in the gap between the copper pad and the solder mask. In a brushing process it is difficult to remove all of the material in this area without damaging the solder mask.



(a) As-Built



(b) After Rework

Figure 8 - X-ray Images of CSP

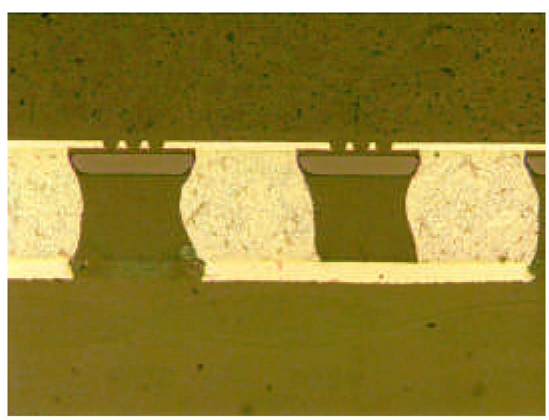


Figure 9 - Cross-section Showing Solder Wetting of a Reworked CSP

Assembly – Fluxing Underfill

The use of fluxing underfill eliminates the issues of flux residue and flow time. A dispense operation still remains and there is reduced total solder volume in the joint since solder paste is not used.

For assembly with the developmental fluxing underfill, a 12-hour dehydration bake at 125^{o}C was used to remove any moisture from the board and to ensure the solder mask was fully cured. Moisture and volatiles from under cured solder mask can cause bubbles (voids) in the fluxing underfill.

When placing a CSP or flip chip into a dispensed volume of fluxing underfill, ideally the fluxing underfill will make initial contact with the center of the part and flow radially outward as the part is placed. This would happen if the bottom of the CSP or flip chip were a flat plate. However, CSPs and flip chip die have solder balls that interfere with the ideal flow pattern. As the size of the solder ball increases, this non-ideality becomes more pronounced. Voids can be trapped in the underfill during placement near the solder balls. Figure 10 shows an example of voids in the fluxing underfill as initially placed.

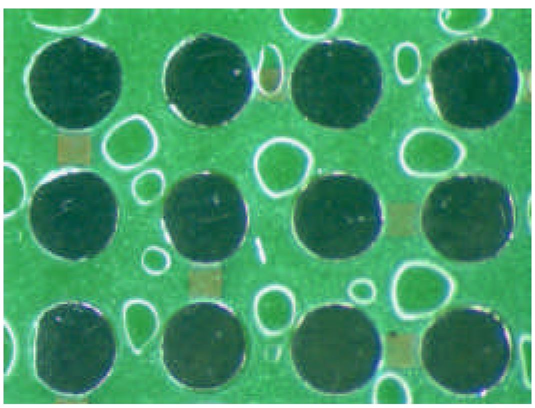


Figure 10 - Flat-section Showing Voids in Fluxing Underfill with Initial Placement Parameters

Experiments were performed to verify the voids were not due to moisture, solder mask volatiles, underfill outgassing or chemical reactions (fluxing) with the solder balls. Then the placement parameters (acceleration, force and dwell time) were examined to reduce the number of placement voids. The combination of placement force: 1N, placement acceleration: 0.1g and placement dwell time: 3s was selected. Figure 11 is a flat-section showing reduced voiding with this combination of parameters. Further work is required to optimize the placement process. Also, the impact of these voids on reliability, thermal cycling and mechanical shock, must be determined. In flip chip assemblies, voids adjacent to solder balls decrease thermal cycling reliability as solder extrudes into the void. The impact on CSP reliability has not been determined.

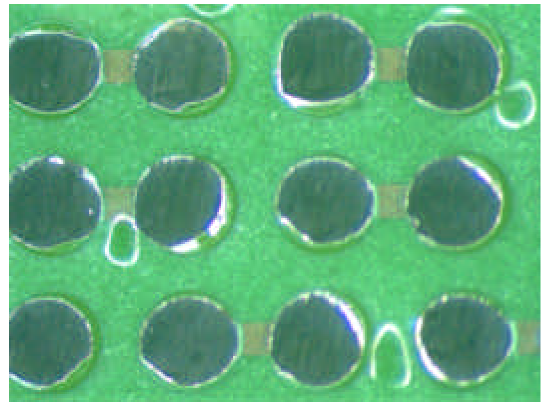


Figure 11 - Flat-section of Fluxing Underfill with the Final Placement Parameters

The reflow profile for the fluxing underfill is shown in Figure 12. The degree of cure after the reflow cycle is approximately 90%. This may be sufficient, but a 30-minute post reflow cure at 165^{o}C was used to ensure a complete cure. Further work is required to determine if the post reflow cure is required. A second side reflow process could also provide additional curing time depending on the process design and process sequence.

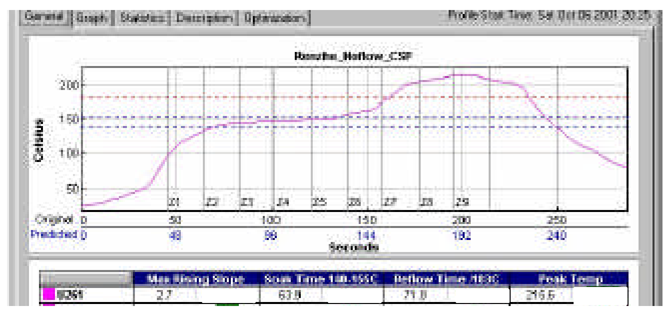


Figure 12 - Reflow Profile for Fluxing Underfill

CSPs assembled with the fluxing underfill were cross-sectioned to verify the wetting. Excellent wetting was observed as seen in Figure 13.

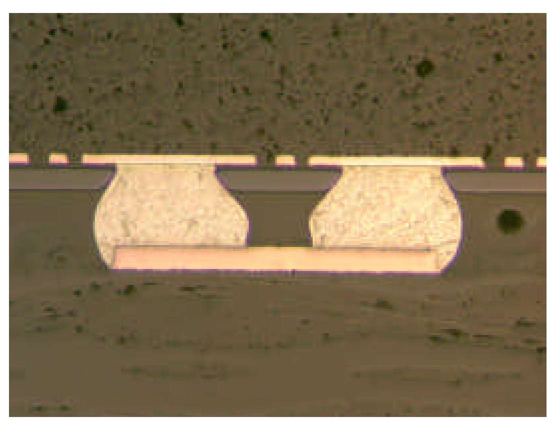


Figure 13 - Cross-section of CSP Assembled with Fluxing Underfill

Drop Testing

To evaluate the performance of the assemblies in mechanical shock, a drop test was performed. For a real product, the drop test is performed on the final product, not the individual PWB assembly. The mechanics of the product, how the board is held, etc. affect the drop test results. To accelerate the failure of an assembled PWB without a product housing, a metal weight (57.5grams) was attached to one end of the PWB as shown in Figure 14. The board was dropped lengthwise (weighted end up) through a 6-foot plastic tube. The non-weighted end impacted onto a concrete floor. The resistance was measured after each drop and an increase of 10% was recorded as a failure. The boards were dropped until all CSPs failed or a total of 80 drops were reached. Two (20 CSPs) or three (30 CSPs) boards were dropped for each underfill and assembly condition. The results are plotted in Figure 15.

From the data, it is clear that underfill significantly improves drop test performance as expected. There was no significant difference between solder paste and 'flux only' with either no underfill or with underfill A. Cleaning the flux residue did improve the performance of underfill A. The results for the fluxing underfill were between the cleaned underfill A and the solder paste, not cleaned with underfill A. The reworkable underfill B 'as-built' was comparable to the other underfills, but there were fewer failures after 80 drops. There was only one failure at 80 drops with the reworkable underfill, reworked. The process of reworking abrades the solder mask surface increasing underfill adhesion.

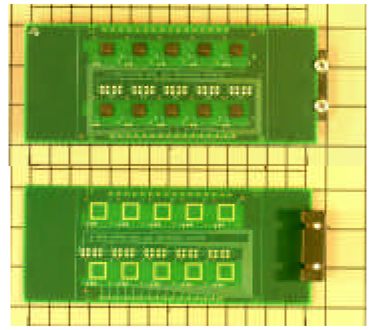


Figure 14 - Photographs of Test Board (front and back) with Weight Attached to Backside (CSP side) for Drop Test

Figure 16 shows a typical cross-section of a failure with no underfill. The failure is at the solder–to-board metallization interface. By comparison, Figure 17 shows a cross-section of a failure with underfill A solder paste, not cleaned. The failure is a crack that initiates in the underfill fillet and propagates through the solder mask and then trough a copper conductor trace.

Thermal shock test are scheduled to further examine the reliability differences in the assemblies.

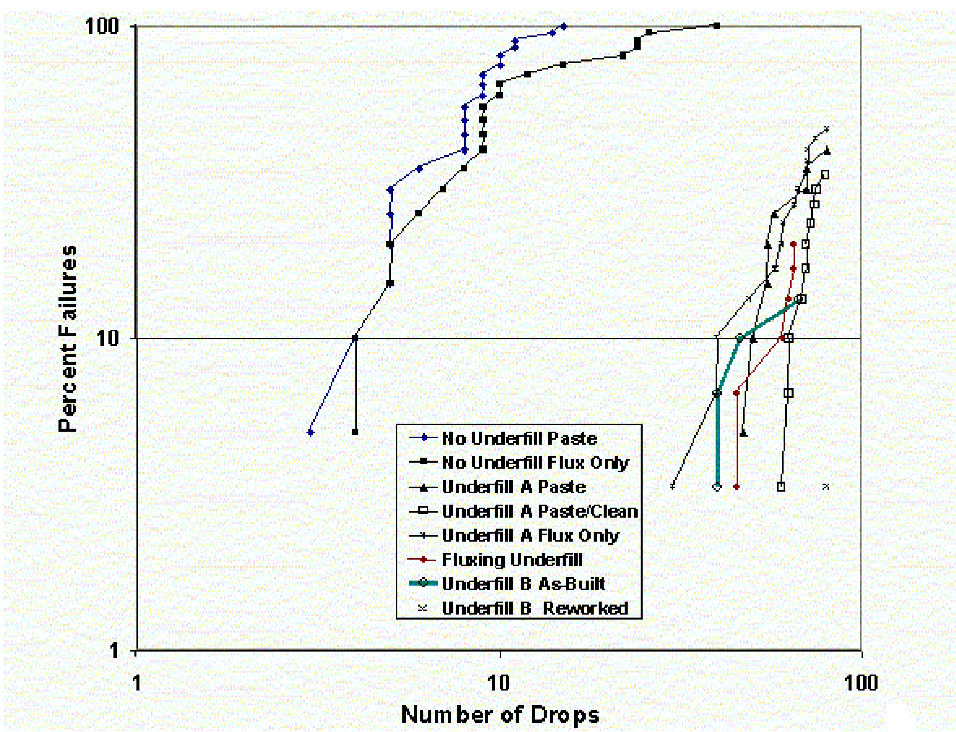


Figure 15 - Log-Log Plot of Drop Test Result

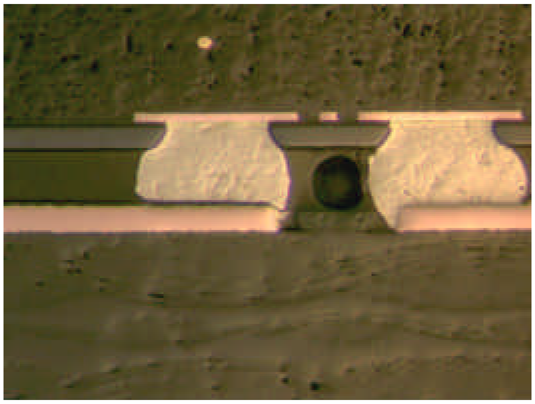


Figure 16 - Typical Cross-section of Failure in Non-underfilled CSP

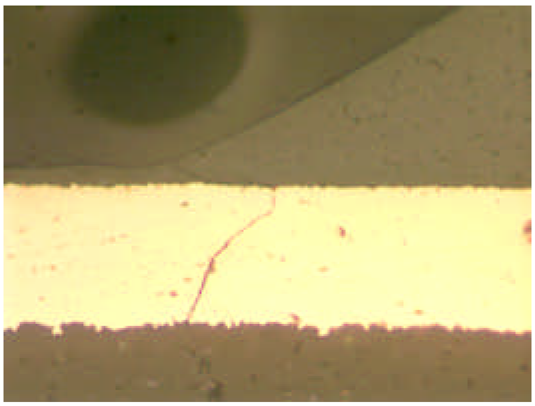


Figure 17 - Cross-section of Crack Propagating from Underfill Fillet to Solder Mask to Copper Trace and Finally into PWB Laminate

Summary

The use of underfill significantly improves the performance of CSPs in drop tests. Capillary (reworkable and non-reworkable) and fluxing underfills can all be used with comparable results. The selection of material can be based on the processing requirements. Improved performance can be achieved by increasing the underfill-to-solder mask adhesion by cleaning or abrading (rework). At least in drop testing, the use of solder paste or 'flux only' does not appear to make a difference.

Acknowledgements

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