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THE SOLDER JOINT RELIABILITY OF CONFORMAL COATED WLCSP COMPONENTS

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ABSTRACT

The compatibility of PWB coatings with assembly materials such as solder pastes, fluxes, component adhesives, underfills and conformal coatings is important issue to achieve the reliable quality in board assembly. In this work was evaluated the coating adhesion and solder joint reliability for assemblies with different conformal coatings, solder masks and underfill. The daisy chain wafer level CSP components were assembled on PWB with Pb-free solder paste. The conformal coating materials were jet dispensed on WLCSP components. The PWB specimens of three different types of solder masks, four different coating materials and one type of underfill were stressed by thermal cycling. Under thermal cycling conditions, solder joints are subject to strain and stress because of the mismatch among the coefficients of thermal expansion (CTE) in the board, component, conformal coating and solder. The samples were subjected to 1000 temperature cycles starting from -40 ^{o}C to +125 ^{o}C. The solder joint lifetime was electrically monitored by resistance measurement and the metallurgical characteristics of solder joints were analyzed by cross-section samples. Results indicate that there is clear effect on solder joint reliability of WLCSP components depending on combination of conformal coating, solder mask and underfill. Statistically components coated with coatings: B and C gave higher solder joint reliability than uncoated components, and components coated with type D have lower solder joint reliability than uncoated components. Coating E has no significant effect on solder joint reliability. Solder mask and underfill were shown to have a stronger effect than coating type. Coating performance is related to material compatibility. It is important that all materials (solder pastes, solder masks, components, underfills) are carefully screened for compatibility before applying conformal coating on PWB assembly.

Key words: conformal coating, WLCSP

INTRODUCTION

Conformal coating is defined as a thin polymeric layer which conforms to the topography of the PWB and components. The primary reason for using conformal coatings is to shield specific areas of the assembly against environmental factors that can damage and shorten useful product life. Properly applied, conformal coatings offer protection from electromigration, vibration, moisture, dendrite growth, oxidation, dirt, solvents and other corrosive elements. Conformal coatings provide a thin dielectric and protective moisture barrier to the device leads and other conductors on the board. Conformal coatings provide a high degree of insulative protection and are usually resistant to many types of solvents and harsh environments encountered in the product life cycle. The coating materials also act to immobilize various types of particulate on the surface of the PWB and function as protective barriers to the various devices on the board. They are extremely resistant to moisture and humidity and are often applied as an after thought (not originally part of the initial design), to quiet down electrical bias and potential arcing during high humidity operating conditions, especially on fine pitch assemblies. Conformal Coatings are classified into types based upon their cured chemistry. They are available in a large variety of chemistries, including silicones, acrylics, urethanes, epoxies, parylene, and fluorocarbon.

All conformal coatings used in this work are dual cure materials. First curing mechanism is curing of ultraviolet (UV) light. The UV curing process requires a light source which directs UV onto the coated product. Photoinitiators in the coating material absorb the UV energy from the light source, setting in motion a chemical reaction that quickly, in seconds, converts the liquid formulation into a solid, cured film. The bulk of the formulation is made up of monomers and oligomers. Monomers are low molecular weight materials. They can be mono- or multifunctional molecules, depending on the number of reactive groups they possess. Functional monomers become part of the polymer matrix in the cured coating because their reactive functional groups undergo polymerization during exposure to UV light. Monomers also function as diluents in the formulations, used to adjust system viscosity, and are sometimes referred to as reactive diluents. Oligomers have higher molecular weight, viscous materials where the molecular weight ranges from several hundred to several thousand grams/molecule or even higher. Usually, the type of oligomer backbone determines the final properties of the coating such as flexibility, toughness, etc. These backbones can be epoxy, polyether, polyester, polyurethane etc.

However, should the coating thickness be excessive, or the coating be shadowed from UV light, then a secondary curing mechanism is required. The second curing mechanism in coating materials used in this work is moisture cure. The coating material is tack free after exposure to UV light and a secondary moisture cure mechanism will fully cure any unexposed areas of the coating in couple of days at ambient conditions.

Underfills are products designed to relieve thermal stresses which result from the brittleness of Pb free solder materials. Underfill adhesives help to redistribute stress away from solder joints and also improve the mechanical integrity.

The materials present on the solder mask surface may also chemically interfere with curing mechanisms of some conformal coatings. These materials may include the residues of no-clean solder pastes and non-reacted materials from the solder mask itself. Coverage and adhesion of even properly cured conformal coatings may still be unsatisfactory if the surface tension of the as-applied liquid conformal coating is not properly matched to the surface energy of the solder mask and/or intermediate materials. A mismatch in these two properties can result in dewetting of the liquid conformal coating from the solder mask surface. Dewetting may occur immediately following conformal coating application or later during solvent loss or curing stages. Adhesion may also be affected by surface topography. Rougher, matte-finish solder mask surfaces may be difficult to adhere to if the conformal coating as applied does not wet and penetrate the peaks and valleys of the solder mask surface. A proper match between conformal coating surface tension and solder mask surface energy is critical to achieve proper coating quality.

Understanding the material characteristics of the PWB and components is critical. Mismatches in CTE between the PWB and the coating can be a problem (see Table 1). The question marks in table 1 indicate that there were no data available for parameter in question. Mismatching CTE can also result from applying too much coating, as CTE is volume-dependent, and the thicker the coating, the larger the change in volume with temperature changes. CTE is critical parameter affecting the solder joint reliability during thermal cycling. It is good to keep in mind that the modulus (compressive or expansion forces) of conformal coatings gives also a high impact for results. A material like silicone based coatings can have a high CTE and low modulus. As a result, silicones in general do not cause significant stresses on sensitive components. This is because low modulus materials are more rubbery as to absorb the energy of deformation. On the other hand, urethane and epoxy based coatings are high modulus materials [1].

Table 1. The glass temperature (Tg) and CTE values below and above Tg of materials used in this work.

	CTE, α_1 (ppm/ °C)	Tg (°C)	CTE, α_2 (ppm/ °C)
Solder Mask			
A	-	-	-
B	39	100 - 105	132
C	-	-	-
Conformal Coating			
B	-	-	-
C	66	-18	130
D	85	45	197
E	100	10	160
Underfill			
F	-	15	75
Silicon	-	-	3 - 4

Temperature Cycle Test determines the ability of parts to resist extremely low and extremely high temperatures, as well as their ability to withstand cyclical exposures to these temperature extremes. It consists of exposing the device to many cycles (usually 500 to 1000 cycles) of high and low temperatures, and primarily tests the device's resistance to fatigue failure. A mechanical failure resulting from cyclical thermomechanical loading is known as a fatigue failure, so temperature cycling primarily accelerates fatigue failures.

Under thermal cycling conditions, solder joints are subject to strain and stress because of the mismatch among the coefficients of thermal expansion (CTE) in the board, component, solder and conformal coating. In addition to CTE mismatch, the cyclic thermal strains can also be created by transient temperature gradients resulting from rapid heating and cooling. As the ramp rate increases, transient temperature gradients and the resulting transient strains become larger. Constraint of thermal expansion causes thermal stresses that may eventually initiate and propagate fatigue cracks. In general, thermal fatigue is related to the ambient conditions, including the rate of change of temperature (ramp rate), the temperature range, and the dwell times at the extreme temperatures.

In this work the printed circuit assemblies were stressed in temperature cycling testing. The objective of the work was to evaluate the coating adhesion and solder joint reliability for assemblies with different coatings, solder masks and the presence of underfill. The assemblies were stressed by thermally cycling the assemblies, and evaluated by analysis of the break in electrical continuity and visual inspection of the coatings.

EXPERIMENT

Thirty assemblies (10 boards, 3 modules in each board and 12 components in each module) were thermal cycle tested (Fig. 1). There were two solder pastes (A and B), 3 solder masks (A,B and C), 4 conformal coatings (B, C, D and E) and one underfill (F) used for the assemblies. The capital letters are used to identify the combinations in this article. The letters in the code (for instance ACBF) from first to fourth represent the type of solder paste, solder mask, conformal coating and underfill respectively. Each assembly had 12 identical components assembled. Six components (1-6) were assembled without underfill and six components were assembled with underfill. The underfill used in this work is reworkable, capillary flow, underfill for CSP applications. The curing condition for underfill was 10 minutes in 110 °C. There were totally 50 material combinations for these 30 assemblies.

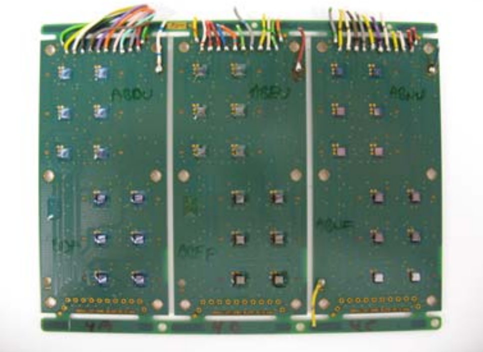

Fig. 1. The test board for temperature cycle test.

There were two basic chemistries in conformal coating materials: acrylated polyurethane and acrylate (Table 2). Coating E is copolymerisate of polyurethane and polyacrylate. The curing process occurs via two different cross-linking mechanisms: UV curing of acrylate part and moisture curing of polyurethane part. The moisture cure leads to complete cross-linking in the shadow zones where UV radiation cannot initiate the cross-linking effect. Coating D is a one-part, low viscosity, high solids dual cure acrylated polyurethane conformal coating. The material is tack free after exposure to UV light and the secondary moisture cure mechanism will fully cure any unexposed areas of the coating within 2-3 days at ambient conditions. Coating B is a one component, UV/moisture curing lead encapsulant adhesive. This single component adhesive cures in 5-15 seconds with a 300 W/in UV lamp.Coating C is UV curing radical type acrylic resin.

Table. 2. The chemistry of coating materials used in this work.

Conformal Coating	Basic chemistry
B	acrylate
C	acrylate
D	acrylated polyurethane
E	copolymerization of polyurethane and polyacrylate

The test boards were 0.8 mm thick FR-4 substrates with a size of 148 mm by 114 mm metalized with Cu. The board pads had 260-micron diameter, non-solder mask pad defined geometry. The copper pads on PWB were covered with Organic Solderablity Preservative (OSP). The functions of OSP are to prevent the oxygen and humidity to effect the solderbility. The solder paste used for surface mount purposes on the board was printed using a 100 um thick stencil.

The assembled components were all daisy chain type WLCSP components. There were 36 components assembled per board. The components were 0.4mm pitch WLCSP having 49 I/O and with a size of 3 mm by 3 mm. The CSP has daisy-chained connections with an input and output trace located at one package corner (Fig. 2).

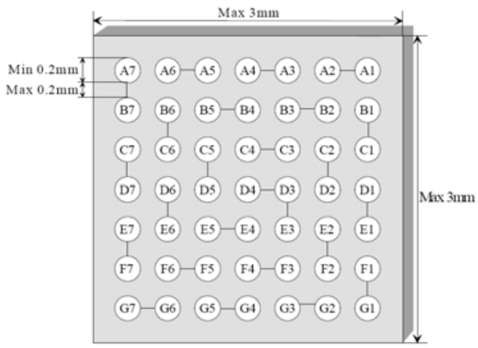

Fig. 2. The footprint of WLCSP used in temperature cycle test.

Air to air thermal cycling was ramped up from -40 ^{o}C to 125 ^{o}C at a heating rate of 16.5 ^{o}C /min and then held for 5 min at the maximum temperature of 125 ^{o}C (Fig. 3). Next, it was ramped down at the same rate to -40 ^{o}C and held for another 5 min at the this minimum temperature, before the repetition of the next cycle. This resulted in a cycle time of 30 min.

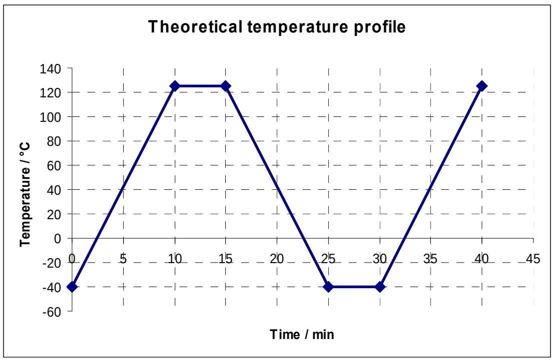

Figure 3. The theoretical temperature profile.

The assemblies were thermally cycled between –40 and 125 °C with 30 minute cycle time for 1000 cycles. The temperatures on assemblies were measured with two thermocouples attached using thermally conductive adhesive to the assemblies. The continuity of solder joints for each component was monitored using event detector system. The detection point was set at 5 kΩ, and the system continuously detected when any circuit went above the detection point with a 200ns response time.

The coating and underfill was applied by Asymtek Axiom X-1020 dispenser using jetting head DJ9000. Jet dispensing is a non-contact process that shoots coating to form droplets of material. The system consists of a gantry xyz robot that moves the dispensing valve to pre-programmed areas. After moving the dispensing valve to the proper location, the valve is actuated and coating is jetted. Then, the valve moves to a second location and the process is repeated. A matrix of dots is dispensed in this fashion until the programmed pattern is covered with coating material. Jet dispensing has many advantages for selective coating of small parts, especially when coating needs to be applied in hard-to-reach spaces. The jet can shoot small volumes of material without touching the substrate and without concern for substrate warpage.

The parameters of jet dispensing were very much material related. As an example of parameters for coating material B is given in table 3.

Table 3. The jet dispensing parameters for B type conformal coating.

Nozzle:	0.125mm
Seat:	0.75mm
Needle:	2.4mm
Fluid pressure:	4psi
Valve pressure:	75psi
Nozzle temperature:	70 °C
Pre-stroke setting:	7 increments
Valve on / of time:	3ms / 5ms
Dispensing area:	6 x 6mm x 25 lines
Line spacing:	0.25mm
Dot spacing:	0.4mm
Dispense gap:	2.0mm
Speed:	25.4mm/sec
Purge:	1sec. after every 3 comp.
Flow measure rate:	0.020mg/dot (before run)
Flow measure rate:	0.025mg/dot (after run)

The fluid temperature is controlled in the valve to maintain uniform flow and drop sizes. The valve is moved in the XY plane in pre-programmed patterns, guided by optical recognition equipment.

After the dispensing process the coated boards were cured by UV light. In the UV curing process ultraviolet light interacts with coating chemistry to cure coatings. The material is tack free after exposure to UV light. The curing process optimization is key to achieve a good quality film of conformal coating. The most important paremeters in UV curing process are the conveyor speed and the UV light energy. All coating materials have been cured by Asymtek Select Cure UV-5 curing oven.

RESULTS AND DISCUSSION

The assemblies were visual inspected under a microscope after the thermal cycle test to evaluate the coating adhesion. Figure 4 clearly shows that the coatings flipped on top of the components on all assemblies coated with B after 1000 cycles. Furthermore the coatings showed some cracks for all assemblies with coating of C. However there was no visual damage after 1000 thermal cycles on assemblies coated with coatings of D and E.

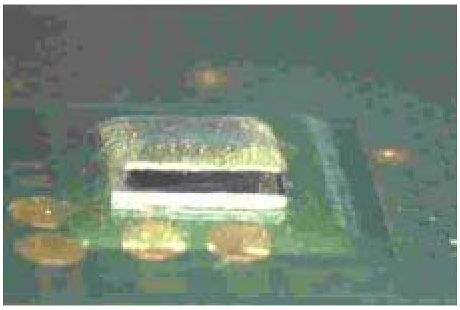

Fig. 4. The combination AABU after 1000 cycles.

The reason for coating flip off is due to combination of two mechanism. First, during coating dispensing there is always possible to create microbubbles inside coating material. The bubbles will start to accumulate next to sharp edges of WLCSP component. The amount of material near component edges is getting lower and the film thickness is getting very thin. During thermal cycling the CTE will cause the system (solder mask, coating, component, solder paste) to move up and down. The stress will finaly crack the coating around the WLCSP corners. When this is combined together with second mechanism, poor adhesion on top of component, the coating will flip off.

There were made 50 cross section samples. It was choosen one component of every combination for cross sectioning. Thermal fatigue failures of WLCSPs are driven by coefficient of thermal expansion mismatches. Since the CTE mismatch between component and the combinations: solder mask, conformal coating and underfill is high the first failures were observed after 400 cycles. The failure mode was solder joint cracking on the package side (Fig. 5). The solder joint crack is always initiated near top of solder joint on component side no matter what combination. Same kind of failure mode due to CTE mismatch has been reported due to large CTE mismatch between die and solder compared to solder and organic PWB [2].

The coating coverage was very thin at the edges of WLCSP component (Fig. 6). This is due to challenging dispensing process. It is very difficult to cover charp edges of WLSCP component with conformal coating.The thin layer of coating material on the component edges and microbubbles of air were the root cause for flipping of coating.

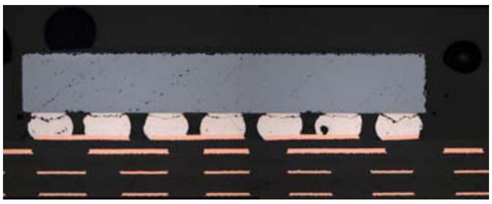

Fig. 5. The cross section of BADU combination.

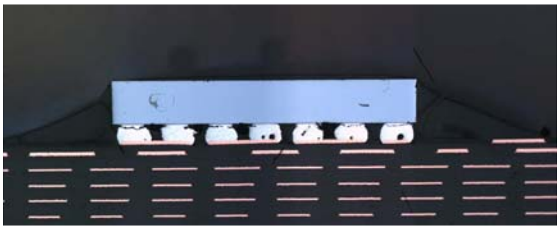

Fig. 6. The cross section of AACU combination.

In thermal cycle testing, the continuity of solder joints for each component was monitored, and the cycle number when an electrical failure occurred for each component on all assemblies was recorded. The results of average time for failure for each combination with solder paste A are given in Figures 7 and 8 for no underfilled and underfilled components respectively.

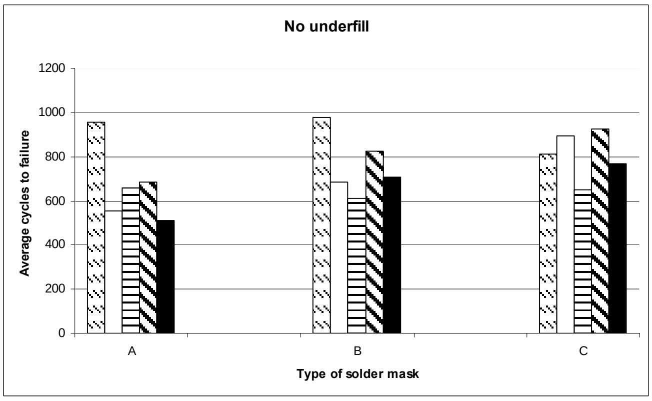

Fig. 7. The average cycles to failure of coatings as a function of the type of solder mask (A,B andC). There were no underfill and solder paste was type A. The results are grouped based on solder mask. In each group the order of coating is: first bar is for coating B, second for C, third for D, fourth for E, and last one for no coating.

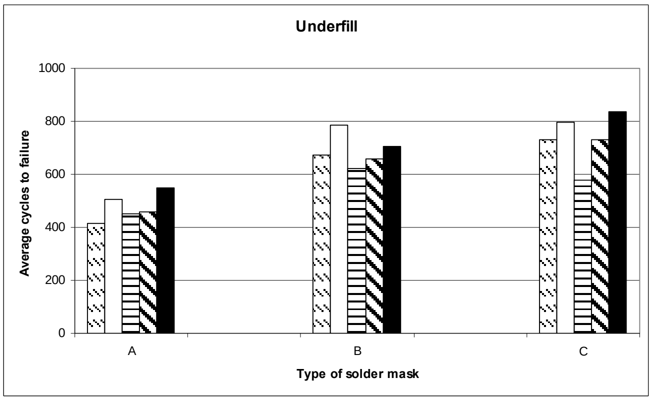

Fig. 8. The average cycles to failure of coatings as a function of the type of solder mask (A,B andC). WLCSP components were underfilled and solder paste was type A. The results are grouped based on solder mask. In each group the order of coating is: first bar is for coating B, second for C, third for D, fourth for E, and last one for no coating.

Figures 7 and 8 clearly show that the type of soldermask in all material combinations has a large influence for solder joint reliability of WLCSP components. The type C gives the best reliability and type A gives the lowest one. This tendency is much clearer in the case of underfilled and coated components (fig. 8). Generally can be said that if WLCSP components are underfilled and coated the solder joint reliability is decreased compared to underfilled components (black bars in fig 8). This is a clear indication of effect of CTE.

Weibull analysis methods, including the Contour Plot, were chosen for this paper for several reasons. The Weibull distribution is often the best fitting mathematical model for component fatigue data in reliability tests, and can be fit when the data are not complete (when some data are suspensions). Contour plots can be used for comparing data sets. Consider two data sets (old and new design) where we would like to determine if the two designs are significantly different and at what confidence. By plotting the contour plots of each data set in a multiple plot (the same distribution must be fitted to each data set), one can determine the confidence at which the two sets are significantly different. If, for example, there is no overlap (*i.e.* the two plots do not intersect) between the two 90% contours, then the two data sets are significantly different with a 90% confidence. If there is an overlap between the two 95% contours, then the two designs are NOT significantly different at the 95% confidence level.

A two-parameter Weibull distribution function is used to fit the failure data of temperature cycle test. In many cases, the two-parameter Weibull is found to yield the most conservative results [3]. From the analysis, two parameters are obtained, one is the characteristic life (η) at which 63.2% parts fail and the other is the shape parameter (β). The slope of the Weibull plot (β) determines which member of the family of Weibull failure distributions best fits or describes the data. The slope indicates which class of failures is present: $\beta < 1.0$ indicates infant mortality, $\beta = 1.0$ means random failures (independent of age), and $\beta > 1.0$ indicates wear out failures. The values of scale and shape parameters of Weibull plots for all combinations are presented in Figures 9 to 11. The Weibull parameters clearly indicate that all variables: solder paste, solder mask, conformal coating and under-fill influence the solder joint reliability to varying degrees but it is difficult to detect any overall trends. There is a good correlation between values of average cycles to failure and the scale parameter (Fig. 9). The scale parameter was much larger than 1 in all material combinations indicating wear out failures as a failure mechanism.

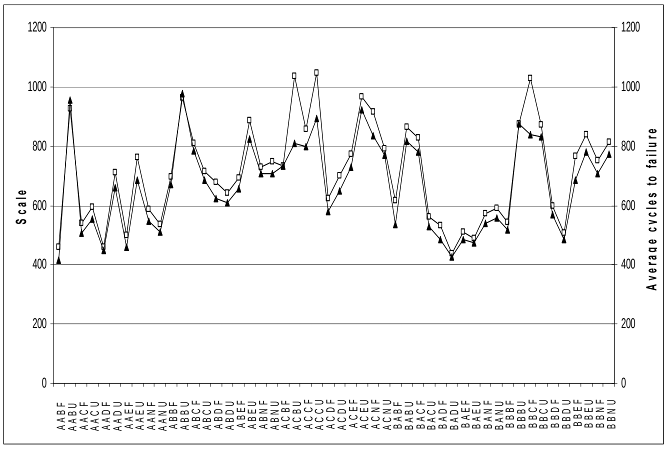

Fig. 9. The scale parameter (squares) of Weibull fit and the average cycles to failure (triangles) as a function of material combinations.

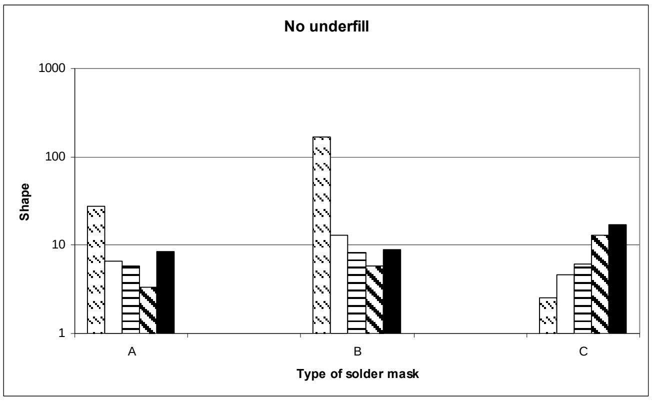

Fig. 10. The shape parameter of Weibull fit as a function of solder masks. There were no underfill and solder paste was A. The results are grouped based on solder mask. In each group the order of coating is: first bar is for coating B, second for C, third for D, fourth for E, and last one for no coating. Solder paste was type A and there was no underfill.

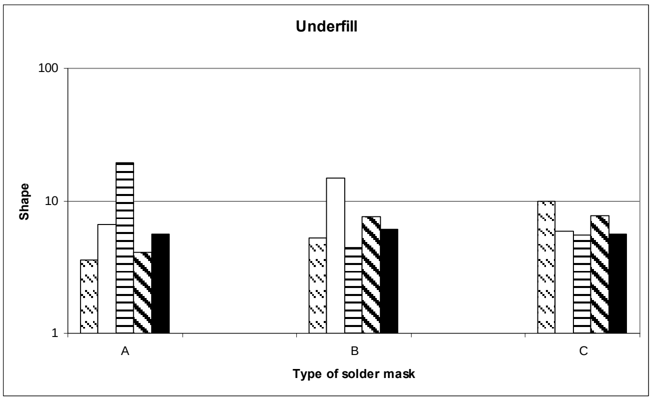

Fig. 11. The shape parameter of Weibull fit as a function of solder masks. Components were underfilled and solder paste was type A. The results are grouped based on solder mask. In each group the order of coating is: first bar is for coating B, second for C, third for D, fourth for E, and last one for no coating.

An example of contour plot is shown in Fig. 12. Three of material variables were kept constant and only variable was conformal coating. The 90% likelihood contours of B,C and E type coatings (third capital letter in material combination code) intersect. This means that the three material combinations are not significantly different at the 90% confidence level.

There is no overlap between no coated sample ACNU and coated ones. The data sets are significantly different with a 90% confidence. The cross section samples indicated the same failure mechanism for all combinations. This fact is also supported the Weibull contour plot. It is a good method to see differences between material combinations if there exist any.

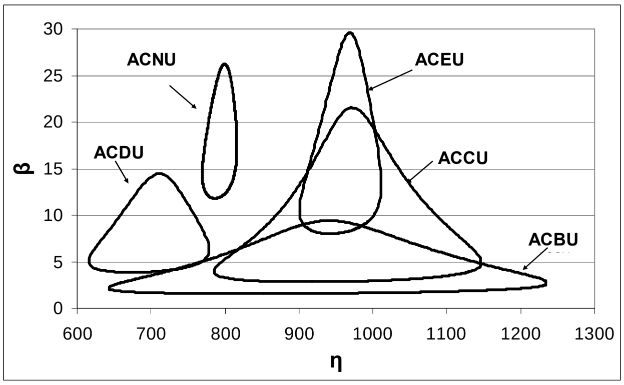

Fig. 12. The Weibull contour plot of parameters η and β. The only material variable is the type of coating.

The points where β are maximized and minimized do not necessarily correspond with the points where η are maximized and minimized. This is due to the fact that the contour plot is not symmetrical, so that the parameters will have their extremes at different points.

CONCLUSIONS

This work successfully evaluated coating adhesion and solder joint reliability of WLCSP components coated with four different conformal coatings using thermal cycle testing to see differences between material combinations. Large CTE mismatch between silicone die of WLCSP component and coating materials have been a concern. Visual inspection after 1000 cycles the components on all assemblies coated with B showed that the coating had flipped. There were some cracks for all assemblies that used coating C. However there was no visual damage on coatings for assemblies coated with coatings D and E.

The solder joint electrical failure results reveal a more complex picture, as solder joint reliability not only depended on coating material, but also other variables, solder paste, solder mask and underfill. Statistically components coated with coatings B and C, give higher solder joint reliability than uncoated components, and components coated with coating D have lower solder joint reliability than uncoated components. Coating E has no significant effect on solder joint reliability. Solder mask and underfill were shown to have a stronger effect than coating type. The type of solder paste did not have significant influence on solder joint reliability of WLCSP components.

Failure Analysis was conducted to determine the root cause for failure mechanisms of WLCSP components. Weibull analysis was conducted for failures with the main failure mechanisms. The main failure mechanism determined by cross section samples was solder joint cracking on component side. Coating performance is related to material compatibility. It is important that all materials (solder pastes, solder masks, components, underfills) are carefully screened for compatibility before applying conformal coating on PWB assembly.

Jet dispensing technology has many advantages for selective coating of small parts, especially when coating needs to be applied in hard-to-reach spaces. It is very demanding process. The process parameters of jet dispensing must be carefully found for different types of coating materials.

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