THE IMPACT OF CONFORMAL COATING ON WLCSP THERMAL CYCLE PERFORMANCE : DEGRADATION MECHANISM AND MITIGATION METHOD

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ABSTRACT
Conformal coating is commonly used for harsh environments to protect electronics from moisture and chemical contaminants. But the stresses imparted by the conformal coating can cause degradation to the package's thermal cycle performance. In this study, $8x8mm^2$ wafer level chip scale packages (WLCSP) were thermal cycled from -40ºC to +125ºC with and without conformal coating applied. The correlation between crack propagation and localized recrystallization were compared in a series of cross section analyses using polarized imaging. Mapping the localized recrystallization was found to be a useful analytical method for characterizing the stress-induced degradation mechanism of the solder interconnects. Partial and full coverage of conformal coating show different thermal cycling performance. A reworkable edgebond adhesive was investigated, to determine if it can mitigate the negative effect of conformal coatings on thermal cycle performance.

Key words: Edgebond, Conformal coating, WLCSP, thermal cycling, recrystallization.

INTRODUCTION
Electronic products and devices are used in a wide range of environments for various applications and can be subjected to a diverse array of extreme conditions.[1,2] The amount of data concerning the corrosion properties of electronic products are continuously growing but still limited. It is well established that tin-based interconnections like solder joints are less problematic because of their relatively strong corrosion resistance.[2-4] It has been reported that the main component of solder alloys, tin (Sn), resists corrosion because of the passivity of the film that forms on its surface.[5] The results of various studies show that Sn–3.0Ag–0.5Cu (wt%) (SAC305) solder exhibits better corrosion resistance than other Sn-based alloy compositions due to its high content of noble or inert elements (Ag and Cu) and its theorized stable structure.[5,6] In earlier publication, where the corrosion resistance of SnPb and several Pb-free solders were investigated in 3.5 wt.% NaCl solution, through potentiodynamic polarisation measurements, it was shown that, in NaCl solution, Pb-free solders were more resistant to corrosion than SnPb solder due to their lower passivation current density, lower corrosion current density after breakdown of the passivation film and more stable surface passivation film.[7] It was reported that SnPb solder joints have thin SnO films less than 2 nm thick and, furthermore, that Pb is oxidized only if there is no Sn at the surface.[8,9] The same oxide layer structure applies to SAC305 solder joints where the amount of Sn is much greater than that of SnPb, i.e., > 96.5%. Even though Sn is protected by a stable passivation layer of SnO and exhibits relatively good resistance to corrosion, it is still

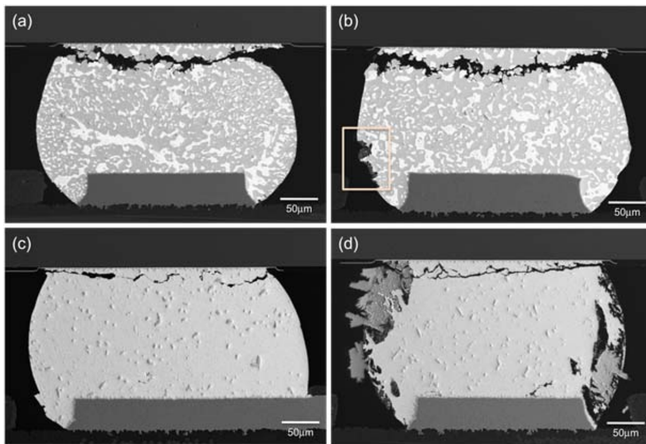

Figure 1. Cross section SEM microstructure after thermal cycling : (a) SnPb solder joint as assembled and thermal cycled (b) SnPb solder joint after salt spray treatment and then thermal cycling. Corrosion area indicated as a box. (c) SAC305 solder joint as assembled and thermal cycled (d) SAC305 solder joint after salt spray treatment and then thermal cycling. [11]

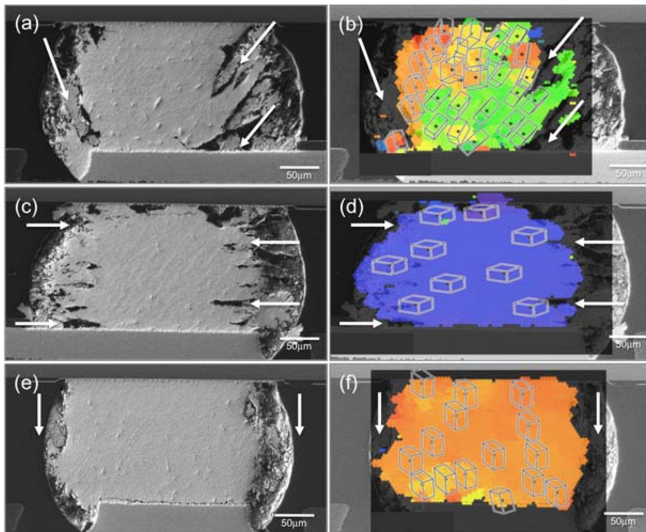

Figure 2. Enlarged SEM images and OIM maps for 5% NaCl preconditioned joints show how the corrosion attack is correlated with the Sn lattice basal planes. [11]

possible for localized corrosion to occur. However, the existence of Cu_6Sn_5 and Ag_3Sn intermetallic precipitates in the solder provided unique settings to the solder joint corrosion mechanism. These intermetallic precipitates, in addition to functioning as noble materials, may also react with the base material Sn to form galvanic couples. In their recent study, Jung et al. showed that the dissolution of Sn from the SnAg alloy was actually accelerated by the presence of Ag.[6] Even though the NaCl condition did not affect the whole Sn based solder joint, only a localized reaction can degrade the joint stability. Figure 1 shows SnPb and SAC305 solder joints from packages experienced 5% NaCl treatment and thermal cycling. Figure 1(a) is a SnPb solder joints after thermal cycling to failure without NaCl pre-treatment, a crack were initiated and propagated at the interface between the package side interface. The solder joints after NaCl treatment and thermal cycling show a localized reaction area at the lower left side surface (indicated in a box), but little effect to thermal cycling induced crack propagation and initiation was observed. Compared to the SnPb joint in Figure 1(b), the NaCl pre-treatment thermal cycled SAC305 joints show localized corrosion near the package side interface and crack propagation from the corrosion-developed area (Figure 1(d)). The crack propagation occurred through the corrosion area, the same as the no-NaCl pre-treated and thermal cycled solder joint in Figure 1(c). But it is easy to identify that the corrosion area accelerated the crack initiation and thus, resulted in a lower characteristic life cycle number for SAC305 NaCl pre-treated solder joints. The corrosion reaction product is a complex oxide chloride hydroxide of tin, $Sn_3O(OH)_2Cl_2$, which is also reported in other references.[7,10] It is a brittle material, which provide an earlier than expected crack initiation. The overall impact of a 5% NaCl salt spray treatment did not alone produce a serious and imminent challenge to the reliability of the whole joint. However, given the fact that the corroded areas were near the interface between the package surface and the bulk solder, such localized corrosion pose a potential risk to the long-term reliability of the solder joint because it can accelerate the initiation of a crack. The corrosion path is also identified that it follows certain grain orientations. Figure 2 shows the correlation between the corrosion path and the c-axis direction of the Sn lattice after solder joints under 5% NaCl test. It revealed that the Corrosion path followed and aligned with the Sn lattice basal plane. [11] Given the examples above, even if the overall solder joint did not experience severe corrosion, it shows that the joint can suffer accelerated thermal fatigue crack initiation due to the brittle nature of the oxide phase at the stress concentration point, which, in this case, is at the corner of the solder joint. Thus, preventing such localized corrosion in Pb-free solder joints is critical to assure their long-term reliability in marine environments or in similarly harsh corrosive atmospheres. In this study, partial and full cover of conformal coating material were applied to 8x8mm WLCSP components to effectively mitigate any localized corrosion due to NaCl reaction, to observe and confirm any potential thermal cycling performance and finding the

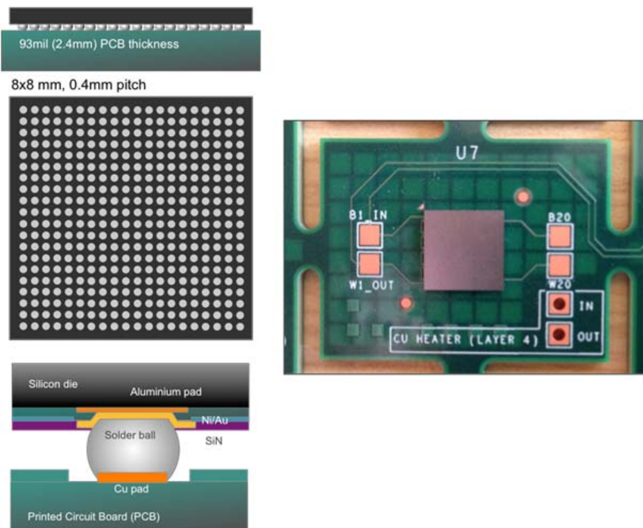

Figure 3. Test component and schematic configuration.

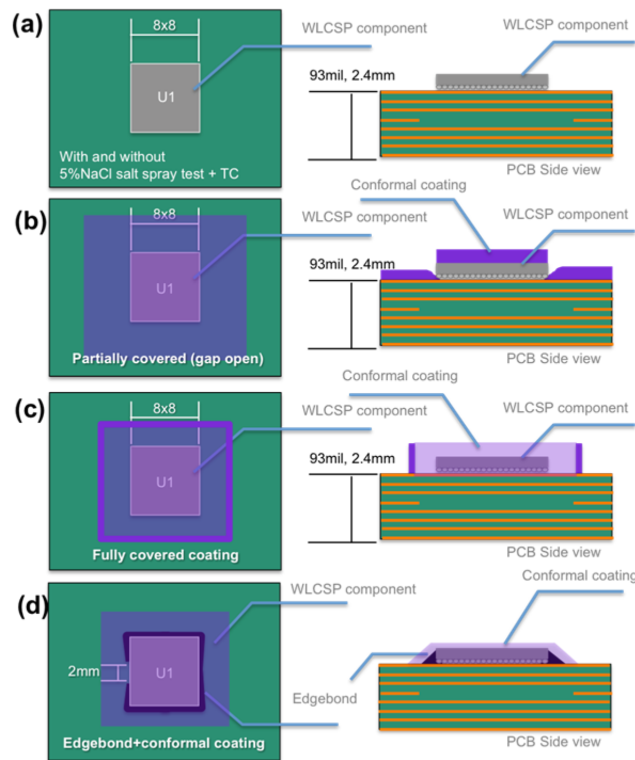

Figure 4. Test condition and sample configuration. (a) WLCSP 8x8mm without coating (b) Partially covered conformal coating. (c) fully covered conformal coating. (d) Edgebond and conformal coating combined configuration.

degradation mechanism due to the full coverage of the conformal coating. Additionally a combination of edgebond and conformal coating was tested to see a possible solution to enhance the thermal cycling performance. The extent of degradation, its microstructural evolution and possible mechanisms are discussed.

EXPERIMENTAL PROCEDURE

8x8mm with 0.4mm pitch, 250µm solder ball diameter WLCSP components were used in this study. A schematic diagram of the WLCSP sample configuration is shown in Figure 3. Solder balls attached to the packages were all composed of Sn-4.0Ag-0.5Cu (wt%) (SAC405). The parts were board-assembled on 93mil high glass transition temperature (T_g), FR4-printed circuit boards with OSP surface finishes with a thermal profile of peak temperatures of 240 °C, 60 seconds above the liquidus temperature. All components were assembled with SAC305 no-clean solder paste. For conformal coating, UV curable commercial product was used. The coating was applied with spray coating process, which covered the whole PCB but remained open at the gap between the WLCSP and the PCB. As schematically shown in Figure 4(b), this allowed some NaCl solution penetrated during salt spray testing. To prevent any open gap, the second configuration, a conformal coating dam was build around each component and filled with the coating material to have a fully covered configuration. (Figure 4(c)) The third configuration with the combination of edgebond and conformal coating is also presented in Figure 4(d). First a commercially available reworkable edgebond adhesive was selected, which has a T_g of 130°C and a CTE of 30ppm/°C. To prevent voiding due to moisture releasing from PCB material during the curing cycle, test boards are pre-baked for 4 hours at 125°C. The edgebond adhesives were dispensed at room temperature using a pneumatic, hand-held dispenser. The board was then cured at 150°C for 30 minutes. The edgebond adhesive covered three full edges and one side-edge partially opened as shown in Figure 4(d). After assembly, all the test boards were treated in a salt spray environment with 5% sodium chloride (NaCl) aqua solution (or fog) at 35 °C for 150 hours in an enclosed chamber. After the salt spray test, salt deposits were removed by a gentle rinse of deionized water at room temperature and dried in a dry chamber. For thermal cycling, samples were cycled from -40 to 125 °C at a ramp rate of 10 °C per minute with 10 minutes of dwell time. A continuous resistivity measurement using a data logger was applied for each channel with in-situ monitoring during the test. The failure criterion in this study was based on the JESD22-A104D standard [10], a 20% increase of the peak resistivity for continuous five cycles relative to the initial value. The thermal cycling results for each condition were plotted as Weibull distribution plots. Cross-sectional analysis using optical microscope with bright light and polarized light were applied to observe the evolution of the microstructures and the locations of the solder joint cracks.

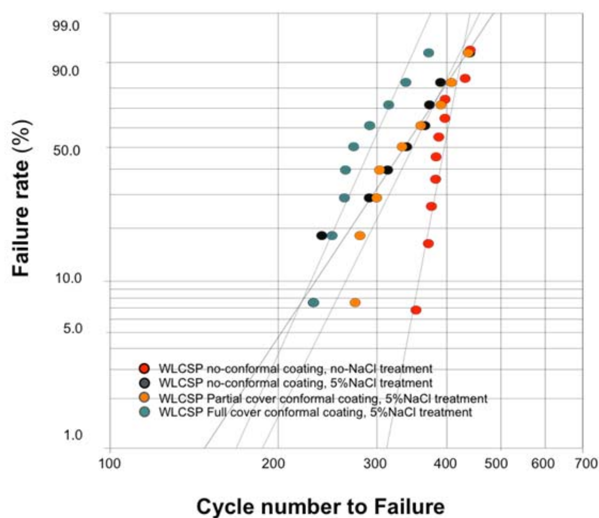

Figure 5. Thermal cycling test result Weibull plot

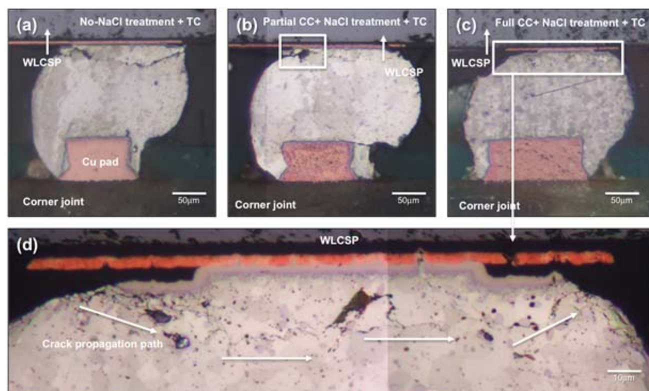

Figure 6. Optical microscopy polarized images of corner solder joint (a) non-coated, non-NaCl treated WLCSP after thermal cycling (b) Partially coated sample after NaCl treatment and thermal cycling (Box indicated the corrosion region). (c) Fully coated sample after NaCl and thermal cycling, (d) higher magnification region from Figure 6(c).

RESULTS AND DISCUSSION

Figure 5 presents the Weibull plots of the thermal cycling results per sample configuration. The sample configuration without conformal coating and edgebond material applied and not treated with 5% NaCl shows a characteristic life cycle number of 404 cycles with a first failure at 354 cycles. Characteristic life cycle number is the cycle number at 63.5% failure rate. Compared to this baseline data set, the 5% NaCl treated samples show a characteristic life cycle number as 361 cycles, a small degradation of 10%. But comparing the first failure cycle between those two sample configuration, the cycle number for the NaCl treated sample component is 232 cycles compared to the no-NaCl treated samples, which is a significant 34% degradation. It can be stated that the NaCl treatment did not modify the thermal cycling degradation mechanism but cause more early failures, which is also an indirect evidence that localized corrosion areas cause earlier crack initiation, which led to shorter life cycle numbers. For the partially coated samples, the characteristic life cycle number is similar to the NaCl treated samples, at 367 cycles. Also the first failure cycle number is similar but slightly higher with 276 cycles, compared to the NaCl treated samples without coating. This indicates that the coating layer provided little protection to the BGA joints, which is relatively obvious since the gap between the WLCSP components and the PCB is open, so the NaCl solution can penetrate and cause damage to the BGAs. Unlike the partially coated samples, the fully coated samples did not show any evidence of NaCl solution penetration and corrosion reaction. But the characteristic lifecycle number is 307 cycles, which is even lower than the NaCl treated WLCSP without any protection coating. Since it did not show any corrosion reaction at the BGA solder joints, the degradation seems to be caused by the conformal coating itself. The direct root cause is still under investigation, but compression stress is one of the potential reasons for a shortened life cycle number. The cross section and optical images are shown in Figure 6. The non-coated WLCSP, after thermal cycling, exhibits crack propagation at the package interface with a visually identifiable crack opening. (Figure 6(a)) The NaCl-treated, partially coated WLCSP exhibits crack propagation with a crack path identifiable with optical images in Figure 6(b). It is also important to indicate that the crack was initiated at the package side interface corner where a corrosion by-product is observed. The initiation point is indicated with a box in Figure 6(b). For the fully coated sample, after thermal cycling, Figure 6(c), the crack propagation is observed in a very tight and closed penetration path, which suggests that a compression stress was applied during the thermal cycling process. Figure 6(d) is a higher magnification optical image, which reveals the closed crack propagation path. Based on the observation above, the NaCl solution induced localized corrosion cannot be fully mitigated with partial conformal coating, but complete corrosion mitigation can be achieved with fully covered coatings. But, with the fully coated configuration, the compression stress caused by the thick coating layer can degrade the thermal cycling performance and cause further degradation. To find a possible solution to the corrosion and mechanical stress driven degradation, a combination of edgebond and conformal coating was considered and tested. As shown in Figure 4(d), a reworkable edgebond material was applied before

conformal coating. The coating covered the edgebond, which closed the gap between the WLCSP and the PCB. The thermal cycling test is still on-going with 300 cycles no failure. The final result needs to be thoroughly analyzed, but so far the combination of edgebonding and conformal coating enhance the thermal cycling performance by providing both corrosion resistance and enhanced thermo-mechanical stability to the component. Figure 7 is the data distribution plot per sample configuration. As explained above The 5% NaCl environment can cause localized corrosion regions at stress concentration area in each solder joints, which cause early failure cycle number to be very low. The characteristic life cycle number did not change much but the first failure indicates a 34% degradation in thermal cycling performance. The partially coated configuration can protect all the exposed metal areas on the PCB. But the exposed gap between the WLCSP components and the PCB can allow the 5%NaCl solution to be penetrate and cause the localized corrosion. The data distribution comparison between the NaCl treated non-coated samples versus the partially coated samples show similarity due to the similar degradation cause and mechanism. Compared to the partially coated samples, the fully coated samples were well protected from the corrosion environment, but show a degradation caused by the mechanical compression stress due to the thick conformal coating layer. A combination of edgebond adhesive and conformal coating to prevent the corrosion and also stabilize the joint structure is suggested and so far, shows an improved performance, which need confirmation after completing the test and analysis.

CONCLUSION

Conformal coating is commonly used for harsh environments, to protect electronics from moisture and chemical contaminants. The BGA components are difficult to be covered fully with the conformal coating material and are often exposed to the given environment due to the structure configuration with an open gap between the component and the PCB. In this study, partially covered components with an open gap which allows the NaCl solution to be penetrated, versus a fully covered component sample configuration were tested under thermal cycling from -40ºC to +125ºC. The correlation between crack propagation and localized recrystallization were compared in a series of cross section analyses using polarized imaging. Partial and full coverage of conformal coating show different thermal cycling performance. The partially coated components, after thermal cycling, show similar failure distribution as the non-conformal coated NaCl-treated samples. The fully coated samples show no evidence of corrosion but show degraded thermal cycling performance due to the coating induced compression stress. A reworkable edgebond adhesive was investigated, to determine if it can mitigate the negative effect of conformal coatings on thermal cycle performance and the test results so far show enhancement performance in thermal cycling without localized corrosion damage.

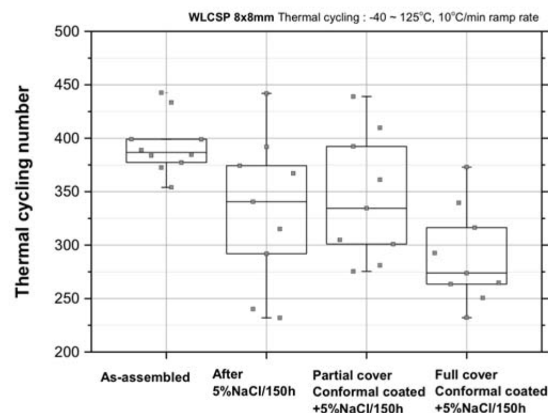

Figure 7. Thermal cycling test data distribution for each test condition and pre-conditioning samples

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