Effect of Localized Recrystallization Distribution on Edgebond and Underfilm Applied Wafer-level Chip-scale Package Thermal Cycling Performance

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Abstract: The correlation between crack propagation and localized recrystallization are compared in a series of cross section analyses on thermal cycled edgebond and underfilm material applied wafer level chip scale package (WLCSP) components with a baseline of no-material applied WLCSP components. The results show that the crack propagation distribution and recrystallization region correlation can explain potential degradation mechanisms and support the damage accumulation history in a more efficient way. Edgebond material applied components show a shift of damage accumulation to a more localized region, thus potentially accelerated the degradation during thermal cycling. Underfilm material applied components triggered more solder joints for a more wider distribution of damage accumulation resulting in a slightly improved thermal cycling performance compared to no-material applied components. Using an analysis on localized distribution of recrystallized areas inside the solder joint showed potential value as a new analytical approach.

Keywords: solder, thermal cycling, edgebond, underfilm, recrystallization, grain structure, microstructure

1. Introduction

The mechanism, leading to crack initiation and propagation during thermal cycling by sub-grain boundary development can be observed as a general trend in various solder joints.1,2) The rate that this process occurs depends on the package design and configuration, but using the crack propagation path and region, which are recrystallized during thermal cycling can explain additional phenomenon and mechanism associated with the certain package configuration and associated thermal cycling process.1) For example, Fig. 1 show three packages with each die size information and solder joint arrangements indicated in the figure.1) A correlation between the crack propagation and localized recrystallization area analysis is summarized in Fig. 2 on selected joints, shown in Fig. 1 indicated in red. The selected joints are also categorized into five stress/strain levels. For instance, the two WLCSP corner joints experience the highest stress/strain during thermal cycling compared to the joints next to the corners. The joint position number is identified with respect to the magnitude of the shear strain, with position 1 having the highest amount of shear strain and 5 the lowest. The same categorization can be applied to the PBGA, which represents the lowest stress/strain package among those selected. In case of the PBGA, the highest shear stress/strain joints are not at the package corners but under the edge of the die shadow, and hence they are labeled as position 1. After thermal cycling these samples to failure, the microstructural features are quantified shown in Fig. 2.3) The extent of cracking is identified using the red markers, which shows that the WLCSP samples have the highest stress/strain package design of these designs, and that the crack propagation at the corner solder joints is well developed. The associated recrystallized regions indicated in orange are also well distributed with a slightly larger recrystallized region in the corner joints, which is expected since those are the most strained joints.3-5) Most of the crack propagation paths are near the package side interface and also the recrystallized regions are well developed near the package interface, which identifies that most of the deformation and damage accumulation occurred near at the package side interface region. As dislocations are pumped into the boundaries they gradually become high angle boundaries. In regions with the greatest strain energy, faster coarsening occurs, leading to conditions that facilitate particle-stimulated nucleation (or other processes) to form of discontinuous nuclei.6-9) During thermal cycling, the differential CTE mismatch conditions at

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Fig. 1. Locations of joints examined with optical, electron, and orientation characterization in packages with high stress (WLCSP) to low stress (PBGA) designs. The position of the die is indicated with an orange line. The numbers beneath the ball positions that were investigated provide a qualitative measure of CTE induced strain where 1 indicates highest strain and 5 lowest.\textsuperscript{11}

Fig. 2. Selected joints examined after thermal cycling to failure close the characteristic cycle number with OIM and corresponding characterization of observed crack length (indicated by red bars on corresponding grids) and locations of recrystallized grains (indicated by orange cells on corresponding grids) for four different package designs with (a) low (WLCSP) to (c) high (PBGA) stress designs. The joint positions are presented in order from most stressed on the left to least stressed on the right.\textsuperscript{11}
high energy boundaries lead to sliding and formation of cavities in boundaries particularly at triple lines. Cracks form along high energy boundaries to connect damaged locations between the discontinuously recrystallized boundaries. Wafer-level chip-scale packages (WLCSPs) are considered relatively short-lifetime packages under thermal cycling because of the high coefficient of thermal expansion (CTE) mismatch. In this study, localized recrystallization regions were observed on thermal cycled WLCSPs with and without edgebond and underfilm material application. The reason for applying additional materials at the corner or edge is to enhance the thermal cycling performance. With increasing importance of mechanical shock and bending, edgebond materials were developed for mechanical stability enhancement. But recently the material is also considered for improving the thermal cycling performance. Since WLCSP components show relatively short lifetime with thermal cycling, it is critical to improve the lifetime by applying an additive which is also easy to rework. Edgebond and underfilm materials are good candidates since the material is covering just a small area of the component. Edgebond is a composite material consists of epoxy polymer with filler silica added to increase modulus and reduce CTE. With using edgebond material, it is expected to enhance the thermal cycling performance. Along with Edgebond materials, Underfilm is a tape type solid film, made of thermoplastic material. Underfilm strips are picked and placed on sticky pads, which are located on the edge of BGA before assembly reflow. It forms an adhesive film between BGA substrate and PCB surface during reflow. The focus on this paper is to use the localized recrystallization microstructure observation technique to identify the degradation mechanism for each condition. Since edgebond and underfilm material have various CTE and transition glass temperature ($T_g$) properties based on the materials characteristics, different performance levels are expected for both mechanical shock and thermal cycling. A detailed correlation between various edgebond material properties and performance will be addressed in a different paper.

2. Experimental Procedure

A 7×7 mm WLCSP sample configuration was used for this study, which is also the same sample configuration used in other studies. The WLCSP packages had a 0.4-mm pitch size (i.e., the distance from one solder ball to the adjacent one) and the solder joint interconnection was 16×16 full array matrix of 250-µm-diameter solder balls composed of Sn-3.0Ag-0.5Cu (wt%) (SAC305). The package-side metallurgy had an electrolytic NiAu surface finish, and the parts were board-assembled on 2.4 mm thick, high glass transition temperature ($T_g$), FR4-printed circuit boards featuring Cu pads with organic surface preservative (OSP) surface finishes. Sn-3.0Ag-0.5Cu (wt%) (SAC305) solder paste was used for the SAC305 solder ball attached components with typical peak temperatures of 240°C, 60 seconds above the liquidus temperature reflow profile. For edgebond process, commercially available edgebond adhesive was selected. The $T_g$ and CTE were 30°C and 70 ppm/°C respectively. To prevent voiding due to moisture releasing from PCB material in curing cycle, test boards are prebaked for 4 hours at 125°C. The edgebond adhesives were dispensed at room temperature using a pneumatic, hand-held dispenser on each of the four corners. Each leg of adhesive was 1.8 mm in length, which covered 25% of the...
WL CSP edge. The board was then cured at 150°C for 30 minutes. For underfilm process, the pre cut underfilm material were placed between the PCB and the WL CSP component to cover the edge of the component before placing the component on to the board. Top view and cross section side view pictures after placing the edgebond and underfilm materials are shown in Fig. 3. Both edgebond and underfilm material did not penetrated into the BGA array under the component, only forming a bonding between the bottom side edge and corner of the component to the PCB surface. For thermal cycling, samples were cycled from 0 to 100°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 in situ monitoring during the test. The failure criterion in this study was based on the JESD22-A104D standard, a 20% increase of the peak resistivity for continuous five cycles relative to the initial value. The results were plotted as Weibull distribution plots. The failed samples were subjected to cross-sectional analysis to observe the evolution of the microstructures and the locations of the solder joint cracks. For microstructure analysis, selected joints were imaged using polarized light microscopy.

3. Results and Discussion

Fig. 4 presents the thermal cycling results. The characteristic lifecycle number, which is the 63.5% failure rate per condition, for no underfilm or edgebond material applied (no-material applied) components was 792 cycles with the first failure cycle number at 513 cycles. A relatively lower characteristic life cycle number was obtained for edgebond applied components with 307 cycles, a 38% degraded thermal cycling performance. Compared to Edgebond applied components, the underfilm material applied components show an improvement compared to the no-material applied component performance with a characteristic life cycle number of 898 cycles, but with a slightly lower first cycle number at 387 cycles. Since only one material set per edgebond or underfilm were used in this study, it is not suitable to conclude the performance gain or loss by these two weibull plots. Indeed, recent study on various edgebond material combinations with different CTE and Tₕ properties addressed significant improvement of both thermal cycling and shock performance, which can be found in other publications. To identify the damage accumulation history during thermal cycling, each condition components after thermal cycling were cross sectioned and observed using polarized microscopy, revealing the grain structure evolution and localized recrystallization regions. Fig. 5 are selected cross section side views of each condition components failed during thermal cycling at around the characteristic life cycle number. The polarized optical images reveal the region where microstructure evolution occurred, along with the crack propagation path for each solder joint associated with each condition. One significant difference can be observed in Fig. 5(d) and 5(e). Fig. 5(d) show joint A1 and A2 from a component, thermal cycled without material applied and Fig. 5(e) shows the same location joint for edgebonded component after thermal cycling. The no-material applied component joints show a continuous grain refinement and recrystallization and a crack propagation path at the package side interface. Compared to the no-material applied component joints, the edgebond-applied joint show relatively less microstructure evolution during thermal cycling and more localized microstructure evolu-

Fig. 4. Thermal cycling result weibull plot (a) and summary graph (b) per no-material applied, edgebond material applied and underfilm applied WL CSPs.
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These observations provide some insight related to the degradation mechanism difference between no-material applied and edgebond material applied component configurations. By simply marking a pixel mesh, which overlaps each solder joint polarized optical image, the region where the crack propagated and where recrystallization occurred can be presented in a simplified format. Fig. 6(a-c) shows the crack propagated regions per solder joint for each condition and Fig. 6(d-f) shows the recrystallized region per condition. By observing both crack propagation and the associated recrystallized region, the localized region where the main microstructure evolution occurred, in other words, the region where the defect accumulation occurred, can be identified. For example, the no-material applied WLCSP component distribution maps in Figs. 6(a) and (d), show strong activity at the corner of the cross section array and reduced its intensity toward the inner solder joints. Compared to the no-material applied components, the edgebond applied component had the main activity not at the corner joint but next to the corner joints. Joint A2 and A15 show more defect accumulation indication compared to A1 and A16 solder joints. The underfilm applied component cross section revealed an overall defect induced indication in the middle of the cross sectioned array (from A2-A15 solder joints), which explains the difference of the characteristic lifecycle number per condition. For a closer look into the location of the defect accumulation induced indications per solder joint, using the crack propagation path and distribution of recrystallized regions in each pixel mesh, segmented regions were designated per pixel mesh, dividing the region into three sections: package side, middle region and board side,

Fig. 5. Edge row cross section optical polarized images after thermal cycling. (a) no-material applied component, (b) edgebond material applied component and (c) underfilm applied component. (d), (e) higher magnification optical images from (a) and (b).

Fig. 6. Crack propagation path and recrystallization region distribution. Red boxes are where crack propagation occurred (a-c) and Orange boxes are where recrystallization microstructure were observed. (d-f) for each condition. (a), (d) no-material applied component, (b), (e) edgebond material applied component and (c), (f) underfilm applied component.
as shown in Fig. 7. Using this segmented pixel mesh, each solder joint mesh per condition can be plotted in a line graph as presented in Fig. 8. Fig. 8(a-c) shows the crack propagation path sites and Fig. 8(d-f) shows the recrystallized region distribution per solder joint. For the no-material applied components, the thermal cycling caused damage accumulation mostly near at the package side interface (Fig. 8(a) and (d)), which is different than the edgebond applied components. The edgebond applied components not only show a strong damage accumulation at the second to the corner joints, they also show a strong tendency of damage accumulation associate with crack propagation at the board side rather than at the package side interface region. The recrystallization occurred also in a higher rate at the board side compared to the package side, which indicates that the edgebond have strong bonding at the package interface and holding the package side solder interface rigid enough so that the damage accumulation mainly occurs at the board side region. It is hard to conclude the bonding force is a major factor in this mechanism since the bonding strength between the edgebond material and the Si interface compared to the PCB interface may show different values. More detailed analysis on the interface between the edgebond material and Si and PCB is needed to explain the dominant mechanism. But based on the observation alone it is clear that these two configurations show different degradation modes, which can be identified by localized recrystallization and crack propagation path correlation analysis. At the same time, these two observations based on the recrystallized region distribution provide a potential explanation why edgebond material applied components failed earlier than the no-material applied components. First, the rigidity provide by the edgebond material at the corner region shifted the damage accumulation to the next available joint (in this case A2 and A15) and accelerated the damaging process. Second, the edgebond provided strong bonding near at the package side and securely hold most of the solder joint rigid, so the deformation and defect

Fig. 7. Segmented region indicated in pixel mesh. As indicated in (a), top two rows are defined as package side region, middle four rows are middle section and bottom three rows are board side region. (b) is an example of the percentage value calculation from solder joint A16 in Fig. 6(f).

Fig. 8. Crack propagation path and recrystallization region distribution plots per segmented regions for each solder joints. (a-c) crack propagation path per region and (d-f) recrystalization microstructure distribution per segmented region for each condition. (a), (d) no-material applied component, (b), (e) edgebond material applied component and (c), (f) underfilm applied component.
accumulation occurred at a smaller localized region near at the board side interface. Accumulated stress at the localized region during thermal cycling will also play a role, which can be revealed during stress relaxation, in a form of recrystallization. These observations also pose potential solution to the problem. If the edgebond material is capable of providing balanced bonding strength at both package and board side interface, which can be available by controlling the CTE and associated Tg of the material, by allowing the whole solder joint to absorb the external deformation, the thermal cycling performance can be improved. In recent studies, low CTE and high Tg edgebond materials are introduced, which can improve the performance. Compared to the edgebond material applied components, which show a strong damage accumulation at the board side interface region, the underfilm applied components show an opposite phenomenon, damage accumulation strongly at the package side interface region. Fig. 8(c) and (f) showed both crack propagation and recrystallization near at the package side interface. This phenomenon is actually the same damage accumulation distribution, which no-material applied components presented. But the underfilm applied components show a damage accumulation at the package side interface on a wide range of solder joints, whereas the no-material applied components show an accumulated activity at a few solder joints near the corner joints, and not in the middle of the array. In Fig. 8(f), the recrystallized regions were mainly at the package side interface but more emphasized at the middle section of the array compared to the corner most solder joints, which can be clearly seen with the comparison of no-material applied component recrystallization distribution plot in Fig. 8(d). The crack propagation associated with damage accumulated regions also show the same trend: a wide distribution of crack propagation along the solder joint array, not localized crack distribution limited to the corner joints as shown in no-material applied components (Fig. 8(a)). The observation on underfilm material applied components after thermal cycling present the explanation why underfilm applied components show a similar but a slightly improved thermal cycling performance. The first is the more widely distributed damage accumulation in the array of solder joints. More solder joints are affected during thermal cycling where limited number of solder joints are affected in no-material applied components. The second factor is the localized activity of damage accumulation at the package side interface. Unlike the edgebond material applied condition, the bonding at the board side seems to be stronger than the package side bonding. This actually can pose a negative impact on thermal cycling performance, which can be seen in edgebond applied components: localized damage accumulation accelerated the crack propagation resulting in a degraded thermal cycling performance. But the underfilm material was able to allow the solder joint middle section to absorb the damage accumulation (shown in Fig. 8(f)) which shows a similar percentage to no-material applied component distribution plot (Fig. 8(d)). These two observations are suggested to be the reason why the thermal cycling performance with underfilm material show similar but slightly improved results compared to no-material applied components.

4. Conclusions

The mechanism leading to crack initiation and propagation during thermal cycling by sub-grain boundary development is observed as a general trend in various solder joints in earlier publications. By using a method based on damage accumulation induced recrystallization region observation, more detailed mechanisms can be obtained. The correlation between the crack propagation and localized recrystallization areas are compared in a series of cross section analyses on thermal cycled edgebond and underfilm material applied WLCSP components with a baseline of no-material applied components. The results show that the crack propagation distribution and recrystallization region marking can explain potential degradation mechanisms and support the damage accumulation history in a more efficient way. Edgebond material applied components shift the damage accumulation to a more localized region thus accelerated the degradation during thermal cycling. Underfilm material applied components triggered more solder joints for a wider distribution of damage accumulation resulting in a slightly improved thermal cycling performance compared to no-material applied components. Even though the evaluation of edgebond material and underfilm material application is not sufficient to address the detailed mechanism and bonding strength correlation due to lack of variety of material property combination in this study, the method of observing the distribution of indicators (recrystallized regions in this case) during thermal cycling can be an effective analytical method and approach for future microstructure based analysis.

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