

Grain Orientation and Microstructure Evolution in Sn-Ag-Cu solder joints as a Function of position in Ball grid array Packages

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Abstract

Thermally cycled PBGA packages with 196 full array solder joints after various pre-conditions are examined to observe the microstructure evolution of Sn-Ag-Cu solder joints during aging and thermal cycling, focusing on Sn grain orientation. Each PBGA package was polished to obtain plan view cross sections of every solder joint, and characterized them using both Polarized Optical microscopy and Orientation Imaging Microscopy. Based on observations using polarized optical images, a single grain solder joint distribution map shows that thermal aging has a relatively small impact on the overall single grain solder joint fraction, but with thermal cycling, many single crystal joints transform to multi grained solder joints. A combined study and observation of Polarized light images and OIM provides further understanding about deformation and microstructure evolution processes that occur during thermal cycling.

Keywords: Pb free solder, Sn grain orientation, polarized image, microstructure, Orientation image microscopy (OIM), Corresponding author contact: Tae-Kyu Lee, taeklee@cisco.com

Introduction

It is well known that Sn-Pb based solder alloys are homogeneous and deform in a relatively uniform manner. As shown in Figure 1(a), a 4x4 joint ball grid array (BGA) sample with eutectic SnPb solder balls was deformed using shear deformation until reaching its ultimate tensile strength (UTS). Before shear deformation, one side of the 16-joint sample was polished to reveal the cross section of four of the solder joints. The deformation characteristics after shear deformation are evident on

the prior polished surface in Figure 1. The zone of high deformation near the top indicates considerable grain boundary sliding, but these features are also evident throughout the joint, not only in a certain localized region. This can be explained by considering the Sn and Pb dual phase nature of the joint. Grain boundary sliding occurred at the interface between Sn and Pb, providing additional slip systems beyond existing Sn slip systems. In addition, the orientation imaging microscopy (OIM) image shown in Figure 1(b) from the same joint shows that the Sn

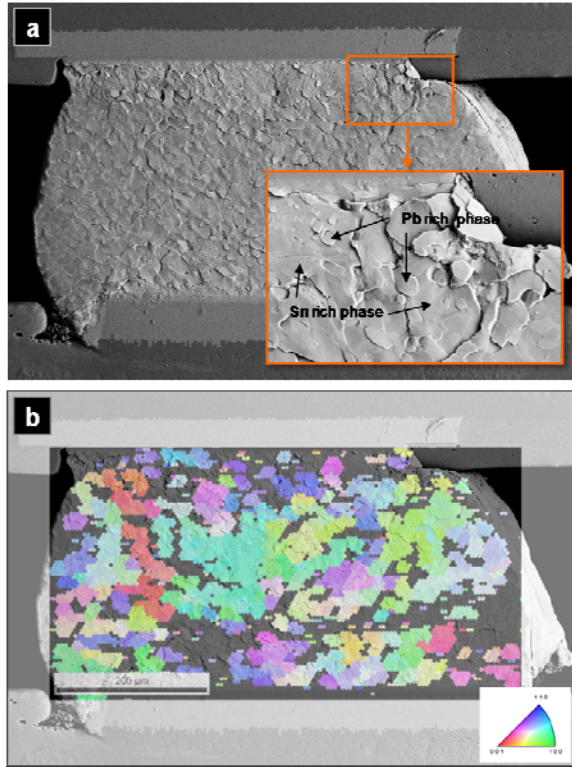


Figure 1. SEM image and OIM image overlap showing the microstructure of shear deformed Sn-Pb solder joints (a) and orientation image microscopy (b) taken after shear deformation with 0.01mm/min. displacement rate.

grain orientation is random and resides in small pockets compared to the mostly single grained Sn grain orientation in lead-free solder joints. Thus, the Sn grain orientation in the Sn-Pb solder alloy has relatively little impact on the properties of joint.

Unlike Sn-Pb solder joints, lead-free solder alloys have strong anisotropic thermal expansion and plastic deformation characteristics, resulting in different mechanical properties.[1,2] Solder joints with various crystal orientations will have significantly different tensile, compressive, and shear characteristics, giving each lead-free solder joint in a given package an unique mechanical property. As shown in Figure 2 each lead-free solder joint has its own unique characteristics. The sample in Figure 2 is a 4x4 BGA with Sn-3.0Ag-0.5Cu (wt%) (SAC305) solder alloy, shear deformed with the same method as the Sn-Pb sample mentioned above. Figures 2(a)-(c) are SEM images taken of three different joints after shear deformation, at a displacement rate of 0.01mm/min. Deformation striation bands are

observed near the package side in the joint. The striations in Figure 2(a) are more horizontal than in Figure 2(b). Polarized light images in Figures 2(d,e) show that both solder joints are single-grain oriented solder joints. In contrast, Figures 1(c,f) show multi-grain orientation structure with a different orientations of striation bands. Based on these three solder joint examples, it is clear that deformation characteristics vary even between single-grained Sn solder joints, and the strain differs in multi-grained joints according the arrangement of crystal orientations and grain boundaries. A detailed analysis of this phenomenon can be found in other publications [3,4].

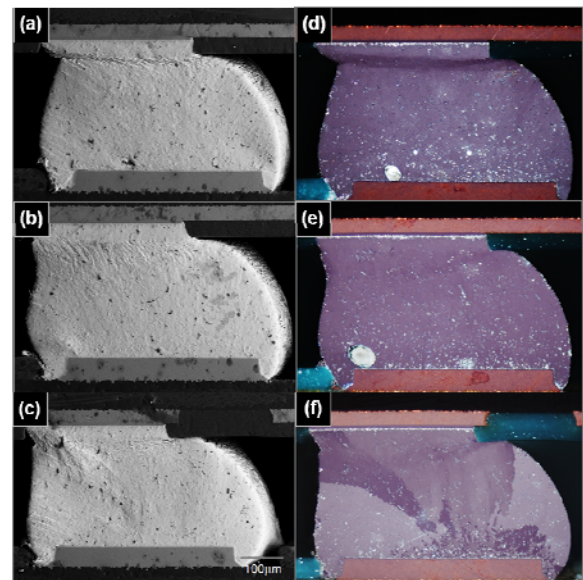


Figure 2. SEM images showing the microstructure of shear deformed SAC305 solder joints (a)-(c) and (d)-(f) polarized light micrographs taken after shear deformation with 0.01mm/min. displacement rate.

Many active research efforts seek to understand the general deformation mechanisms of solder joints [5-11]. However, given the large difference in character between various solder joints, it is becoming more important to understand the distribution of individual grain orientations and the impact of this distribution on the package. A macroscopic view of the distribution of likely deformation mechanisms is needed and in this paper, we focus on the overall distribution of single and multi-grained structures in order to investigate

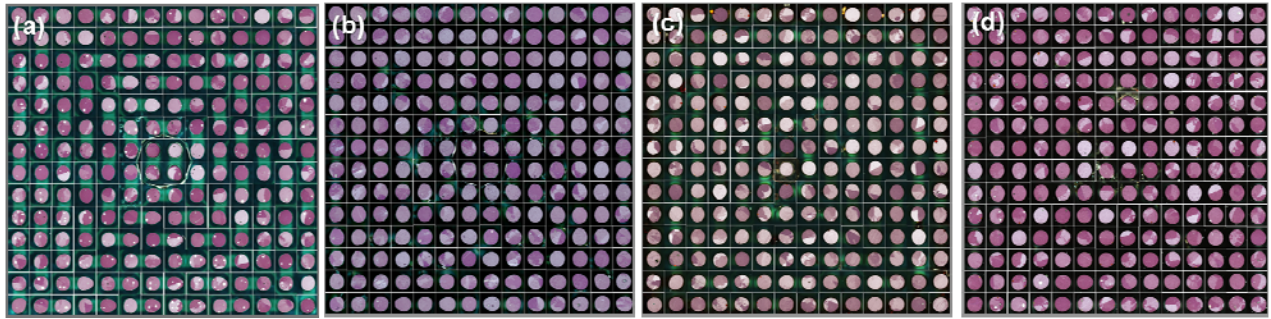


Figure 3. Selected polarized images of PBGA samples (a) un-aged, as-assembled (b) aged at 150°C for 1000 h (c) un-aged sample after thermal cycling for 2500 cycles (d) aged at 150°C for 1000 h and thermal cycled for 2500 cycles.

patterns in the solder joint grain structure present before and after thermal cycling. Both polarized light microscopy and orientation imaging microscopy are used to study the solder joint microstructure.

Experimental Procedure

In this study, 15x15mm plastic ball grid array (PBGA) samples with a 14x14 full array of Sn-3.0Ag-0.5Cu (wt%) (SAC305) solder joints (600 μm in diameter) with 1.0 mm pitch between each solder joint are used. All PBGAs have a 5x5 mm silicon die attached, and the package side substrates have an electrolytic NiAu surface finish. Parts are attached to a 2.4 mm thick high T_g FR4 printed circuit board with organic surface preservative (OSP) surface finish. Sn-3.0Ag-0.5Cu (wt%) (SAC305) solder paste was used for the reflow and a typical peak temperature of 240°C, with 60 seconds above the liquidus temperature reflow, was used for board assembly.

To investigate the impact of microstructural changes pre-treatment conditions with aging temperature of either 100 or 150°C, with a holding time ranging between 500 and 1000 h, in ambient air are selected. For thermal cycling, we subjected samples to a 0 to 100°C thermal cycle, with a ramp rate of 10°C per minute and a 10 min dwell time. In this paper, the results are based on samples after 0, 1400 or 2500 cycles. The most accurate way to observe the grain orientation of each pre-conditioned sample is to look at a side view cross section, a tedious and inefficient process. As an alternative, in this study, a z-axis cross section (bottom view sample

preparation) is used for analysis. The mounted samples are polished from the printed circuit board (PCB) side to the solder joint. The z-axis cross section is taken at 50% of each solder joint's height. Given the fact that the solder joint is very sensitive to sample preparation, sample preparation studies (e.g. serial sectioning) confirmed that the sample microstructure has not been altered during the sample preparation process and leads to good polarized light optical and OIM observations. Images of each individual solder joint were taken in high resolution format with Optical polarization microscope and OIM for subsequent analysis.

Results and Discussion

Figure 3 shows the individually taken and then arranged polarized images of individual solder joints that were subjected to different preconditions. Figure 3(a) shows the microstructure directly after board assembly, Figure 3(b) after an aging period of 1000 h at 150°C. Each set of images shows a combination of single-grained structures and multi-grained structures. From Figures 3(a,b), it is not easy to single out the dominant grain orientation structure distribution. Figures 3(c,d) show the arrays after thermal cycling from 0 to 100°C for 2500 cycles.

As it is difficult to see the difference in the overall distribution, a relatively simple systematic approach to reveal patterns in the grain structure was used to categorize each solder joint as shown in Table 1. Each solder joint is assigned to one of five categories, (1) single grain (2) near two grain structure, that is mainly a single grain with a small

Image	Category/type	Indicator
	Single Grain structure Solder joints with a single grain under the polarized filter	
	Near single grain structure Solder joints with a second grain orientation occupies less than 20% of the joint area	
	Two grain structure Solder joints with two grain orientation	
	Near three grain structure Solder joints with two dominant grain orientations and a minor third orientation	
	Three grain structure Solder joints with a clear beach ball structure or more than three grain orientations	

Table 1. Grain structure Category

fraction of second grain orientation structure (3) two grain structure (4) near three grain orientation structure that have two strong grain orientations with an additional small fraction of a different grain orientation structure and (5) three grain orientation

joint, that either show a clear beach ball structure or include more than three grain orientations.

Figure 4 shows the categorized grain structure distribution for selected joints before and after thermal cycling for two different aging conditions in Figure 3. As shown in Figure 4, each array has a mixture of single and multi-grained solder joints. The distribution of single grain solder joints in Figure 4 (e)-(h) are extracted from Figure 4(a)-(d), where the un-aged, as-assembled array samples and the thermally aged samples show a majority of single-grained solder joints. The number of these single-grained solder joints decreases after thermal cycling. The sample thermal cycled after aged at 150°C shows higher reduction rate in single grain joints. This trend is clearly seen in Figure 5, where the percentage of single-grained structure solder joints is plotted against each precondition. As shown in Figure 5, the fraction of single grain joints decreased right after the board assembly by ~16%. Prior to assembly, the sample is a freestanding PBGA sample, just after ball attachment. A possible driving force for this change is the build-up of internal stress during reflow. Typically, during high temperature reflow, the package experiences thermal expansion and has a tendency to warp, introducing additional internal stresses during the assembly process. The cooling, followed by the exposure to a high peak

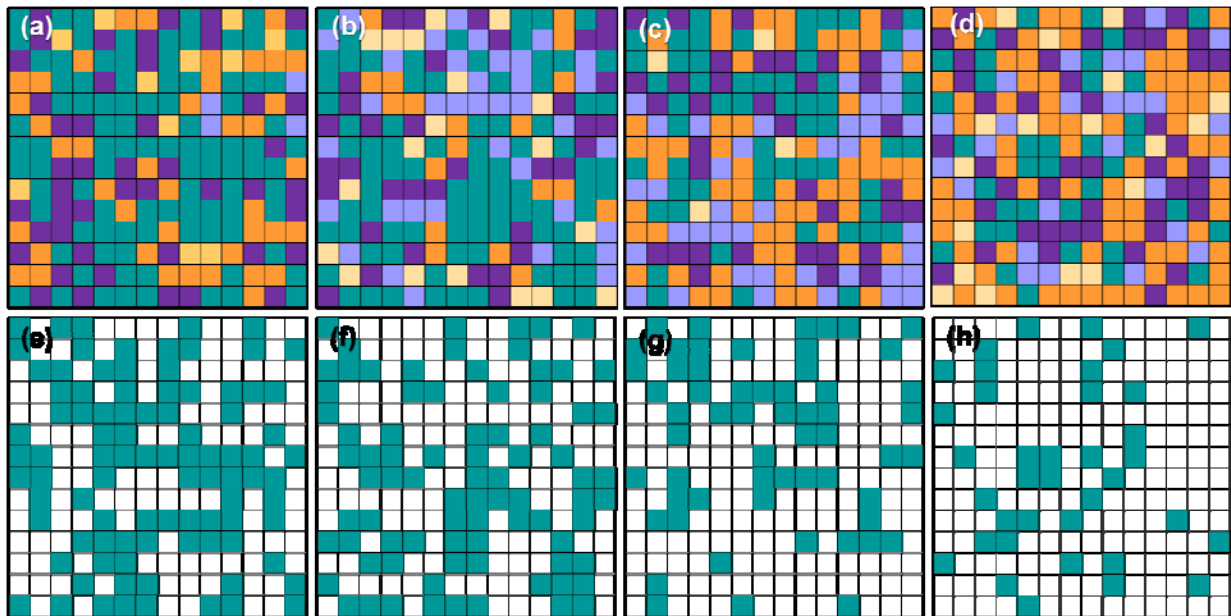


Figure 4. Grain structure distribution map and Single grain structure distribution map (a)(e) un-aged, as assembled (b)(f) aged at 150°C for 1000 h (c)(g) un-aged sample after thermal cycling for 2500 cycles (d)(h) aged at 150°C for 1000 h and thermal cycled for 2500 cycles.

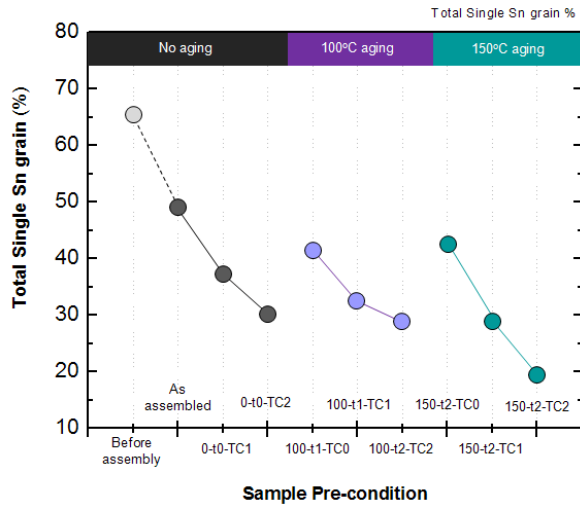


Figure 5. Total single grain orientation joint number percentage for each pre-condition. Specimen names indicate precondition, e.g. PL-100-t1-TC1 indicates plan view section aged at 100°C for 500 h and thermally cycled 1400 times (t0 = un-aged, t1 = 500 h, t2 = 1000 h, TC1 = 1400 cycles TC2 = 2500 cycles).

temperature results in internal stresses in the solder joints that could later trigger the growth of a minority twin orientation during heating or cooling. This process results in a lower fraction of single-grained joints.

The observations that the single grained joints percentages decrease after thermal cycling

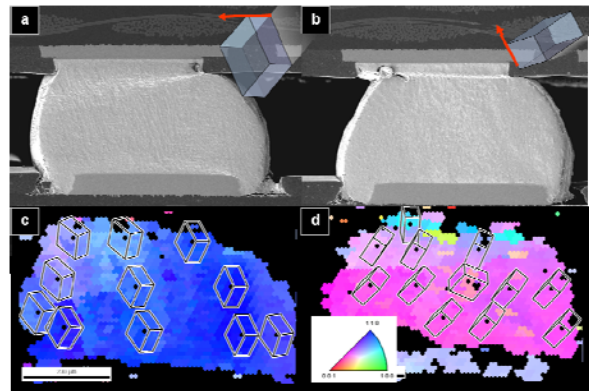


Figure 6. (a)(b) SEM image and (c)(d) OIM images of shear deformed SAC305 solder joints taken after shear deformation with 0.01mm/min. displacement rate. (c) and (d) OIM image from joint (a) and (b) respectively.

provide a new insight about what really happens during thermal cycling. Dominant Sn orientations, in other words, joints with different mechanical characters are going to transform to a stable state or homogenized state which is driven by other factors like silicon die and substrate material and the overall package structure. Polarized light micrographs give detailed geometrical understanding of microstructure, but OIM provides accurate crystal orientation

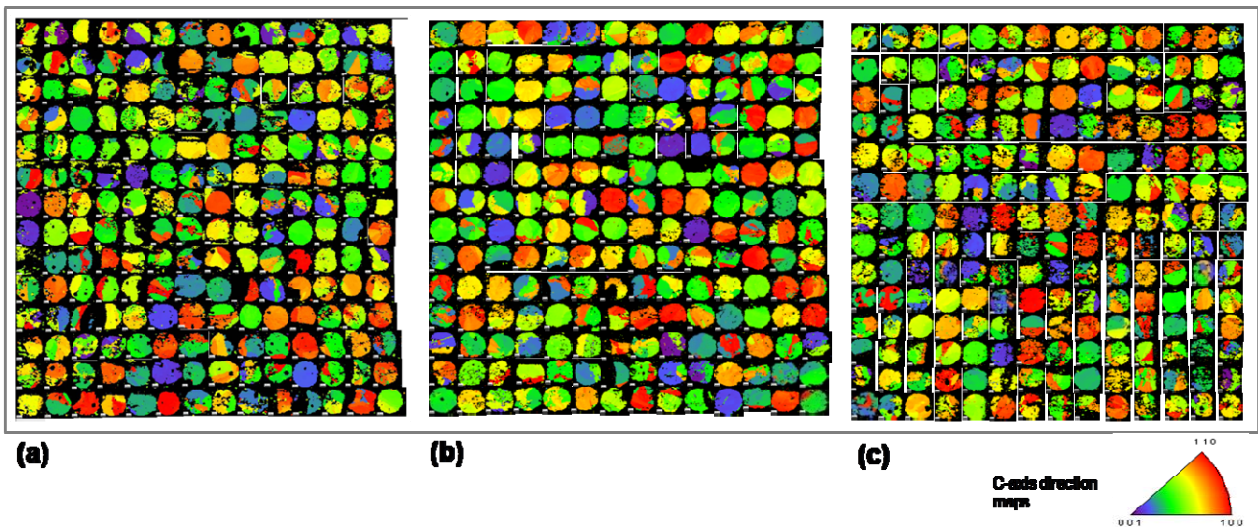


Figure 7. OIM c-axis Sn grain orientation maps for : (a) no aged no thermal cycled (b) no aged and thermal cycled for 2500 cycles and (c) aged at 150°C for 1000 h and thermal cycled for 2500 cycles. When the c-axis is parallel to the board, it is red, and when perpendicular to the board, it is blue.

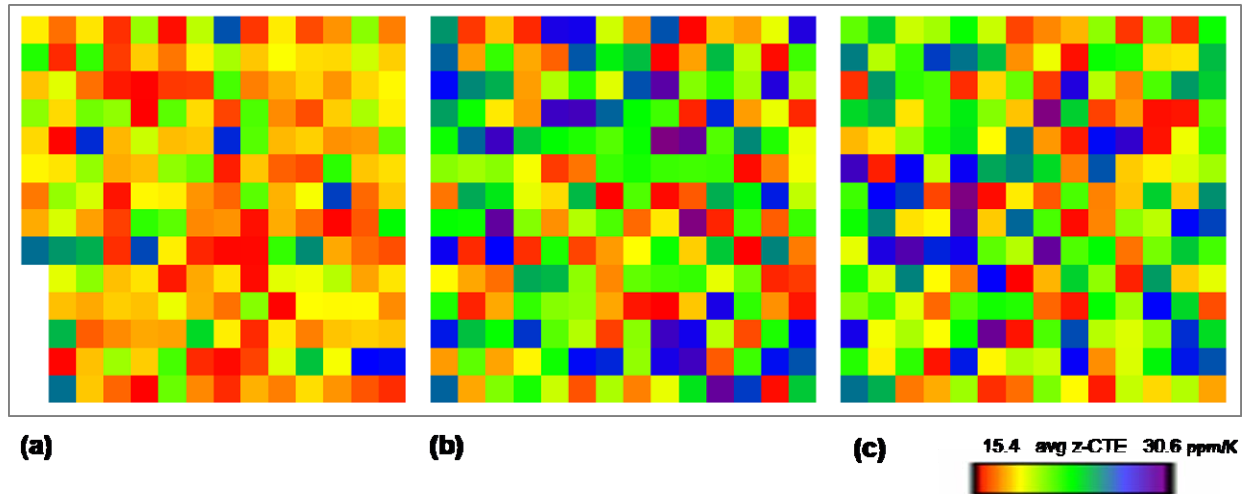


Figure 8. z-axis average CTE maps converted from Figure 7 : (a) unaged no thermal cycled (b) unaged and thermal cycled for 2500cycles and (c) aged at 150°C for 1000 h and thermal cycled for 2500 cycles. When the c-axis is parallel to the board, it is red, and when perpendicular to the board, it is blue.

information that is critical to understand the deformation mechanisms associated with this transition. It takes more time and effort to obtain a complete map, but better quantification of orientation combined microstructure information is possible. As shown in Figure 6, the sheared SAC305 solder joints show two different types of deformation striation bands. Similar to Figure 2, Figure 6(a) shows an overall uniform deformation in a single direction aligned roughly with the direction of shear. Compared to Figure 6(a), Figure 6(b) shows a highly localized shear deformation, that gives the appearance of a sharp line. From the OIM scan observations in Figure 6(c) and 6(d) for joints 6(a) and 6(b), respectively, we observe two different crystal orientations. In Figure 6(c), the Sn lattice c-axes is parallel to the package interface, and in Figure 6(d), the c-axis is inclined to the package interface in most of the joint, but in the shear deformed region, the c-axis is aligned with the interface. The concentrated shear band developed by a gradual spatial rotation of the crystal to an orientation where the c-axis is aligned with the maximum shear direction.

Figure 7 is the OIM map taken from an unaged sample, unaged and then after 2500 thermal cycles, and aged at 150°C aged for 1000 hours and then thermal cycled for 2500 cycles, respectively. Each solder joint image in these maps shows single grained orientations or a mixture of several

orientations. Each distribution map has unique patterns and analysis is ongoing to identify statistical characteristics [12,13]. Using this series of OIM maps, we can see the evolution of the overall joint behavior and before and after thermal cycling based on the initial joint mechanical characters which came from the aging pre-treatment. For example, the thermal cycled samples after isothermal aging show a similar reduction of single grained joints in the package as observed with polarized light, but in addition, there is a certain c-axis distribution based on the package die and size configuration. As shown in Figure 7(c), the fraction of solder joints with the c-axis perpendicular to the package (indicated as blue) increased under the die compared to the unaged and thermal cycled sample in Figure 7(b). This distribution tendency can be seen more clearly when we convert the Figure 7 OIM map into a z axis average CTE map (the area fraction of each orientation times its CTE value along the z-axis) in Figure 8. As shown in Figure 8(b) and (c), the distribution of the blue colored joints are decentralized in Figure 8(b) and centralized in Figure 8(c), and furthermore, there is a noticeable tendency for the c-axis to be more inclined toward the z-axis (normal to the board), which is made visible as more green and blue orientations with aging and thermal cycling.

The changes in orientation distribution are correlated with changes in the joint microstructure.

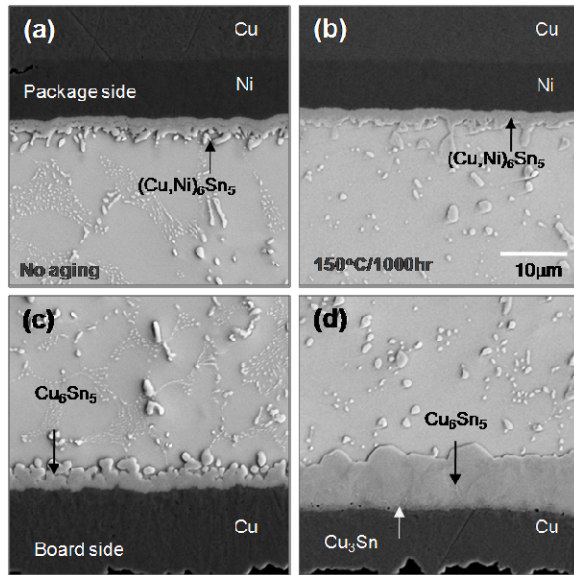


Figure 9. SEM micrographs of the solder joints, package side (a)(b) and board side (c)(d) : as-assembled and un-aged (a)(c), aged at 150°C for 1000 h (b)(d).

Also, a companion paper comparing statistics of polarized light and OIM measurements shows that the fraction of single crystals decreases in a similar manner as indicated by the polarized light measurements [13]. Furthermore, Figure 9 shows SEM images revealing the microstructure of the package side and board side. A relatively thick intermetallic layer is observed after aging, a common observation from aging for a long time at high temperature. In addition to this change at the interface, the bulk area shows fewer but larger precipitates. The precipitates in the aged sample (consisting predominately of Ag_3Sn intermetallic particles) coarsen and are less effective in pinning the Sn sub-grain boundaries between dendrite arms. This allows unpinning of low-angle grain boundaries that permits coalescence, leading to larger subgrains with larger crystallographic misorientations within the Sn grains, ultimately resulting in a softer material, as confirmed with measurements of decreasing hardness after thermal aging. Also, coarsening precipitates results in fewer pinning sites for grain boundaries, and should enable greater grain boundary mobility. More mobile grain boundaries could facilitate the transformation of single-grained structures to multi-grained structures. A possible mechanism for growing a minority orientation is the incremental recrystallization and/or grain growth driven by the

release of elastic strain energy. This is discussed in another publication [9] where growth of a minority orientation was shown to reduce the elastic strain energy that results from thermal cycling.

Conclusions

While this study cannot identify particular mechanisms operating during thermal cycling and grain structure evolution, it does provide data which permits models to be evaluated against in the future. Clearly, the overall distribution of single-grained and multi-grained solder joints is dependent on process history variables. Based on observations using polarized light microscopy and orientation image microscopy, a distribution map of single-grained solder joints and a detailed Sn grain orientation distribution shows that thermal aging has a relatively small impact on the overall fraction of single-grained solder joints, but with thermal cycling, many single-grained joints transform to multi-grained joints and at the same time alter the overall orientation pattern associated with the character of the solder material and microstructure evolution. A detailed study using polarized light microscopy and OIM provides further understanding about the deformation and microstructure evolution processes that occur during thermal cycling, which lays the groundwork for developing greater understanding of the effect of the grain orientation distributions on package reliability.

Acknowledgements

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