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Abstract

During the solidification of solder joints comprised of near eutectic Sn-Ag-Cu alloys, the Sn phase grows rapidly with a dendritic growth morphology, characterized by copious branching. Notwithstanding the complicated Sn growth topology, the Sn phase demonstrates single crystallographic orientations over large regions. Typical solder Ball Grid Array (BGA) joints, 900 µm in diameter, are comprised of 1 to perhaps 12 different Sn crystallographic domains (Sn grains). When such solder joints are submitted to cyclic thermomechanical strains, the solder joint fatigue process is characterized by the recrystallization of the Sn phase in the higher deformation regions with the production of a much smaller grain size. Grain boundary sliding and diffusion in these recrystallized regions then leads to extensive grain boundary damage and results in fatigue crack initiation and growth along the recrystallized Sn grain boundaries.

The electronics industry will make substantial progress toward a full manufacturing transition to Pb-free soldering technology in the near future. The leading candidate alloys to replace the Sn-Pb eutectic alloy are near ternary-eutectic, Sn-Ag-Cu, alloys. The ternary-eutectic composition is now thought to be close to the composition Sn-3.5Ag-0.9Cu [1-2] with a melting point of 217 °C. The near-eutectic, commercially available alloys are exemplified by the Sn-3.8Ag-0.7Cu and Sn-3.0Ag-0.5Cu compositions. The electronics industry has begun to study the processing behaviors, microstructures and the thermomechanical fatigue properties of these alloys in detail in order to understand their applicability in the context of electronic assembly reliability requirements [4].

The near-eutectic ternary, Sn-Ag-Cu, alloys yield three phases upon solidification, β-Sn, Ag_3Sn and Cu_6Sn_5. Attempts to characterize the solidification behavior [1-3, 5-7, 8] and to define the ternary eutectic composition [1-3] in the Sn-Ag-Cu system have been reported by several investigators. In the solidification of these alloys from the fully liquid state, the equilibrium eutectic transformation is inhibited. The intermetallic compound phases, Ag_3Sn and Cu_6Sn_5, nucleate with minimal undercooling; but, the β-Sn phase requires 15 to 30 °C undercooling to nucleate in typical solder joints [5]. Because of this disparity in the required undercooling for nucleation, plate-like (Ag_3Sn) and rod-like (Cu_6Sn_5) intermetallic structures can grow to large size in the solder joint in the liquid phase, if the cooling rate is sufficiently slow. After nucleation, the β-Sn phase grows by a dendritic growth mechanism. The solidification of the β-Sn phase is rapid, because of the significant undercooling and because of the intrinsically-rapid growth kinetics of Sn [8]. A typical solder joint fully or substantially solidifies in less than a second after initiation of the growth of the β-Sn phase, which comprises more than 90 wt. % of the solder joint [5]. The rapid solidification and the associated liberation of the latent heat of fusion causes the temperature of the solder mass to rise and so suppress the nucleation rate of all three phases. Notwithstanding, there may be nucleation and initial growth of the two intermetallic compound phases in the supersaturated liquid phase in close proximity to the β-Sn dendritic growth fronts. This intermetallic compound growth would probably be manifested as small particulates. If intermetallic compound particulates have nucleated and grown to any appreciable size, they must be swept aside of the growing β-Sn dendrite arms, because intermetallic compound particulates are not found in the interior of the pure β-Sn dendrite arms. Most of the nucleation and certainly most of the growth of these particulates probably occur, when these dendrite arms impinge on each other, during the final stages of local solidification. Consequently, the intermetallic compound particulates decorate the impingement zones. This growth sequence is illustrated in Figures 1a and 1b, which show the final microstructure in images of a typical BGA solder ball attached to a Ni pad at two magnifications. These images depict microstructures which are typical of solidified solder joints. The light colored regions define the β-Sn phase. The darker, network-like, regions, surrounding the dendrite arms of the β-Sn phase, are comprised of high densities of intermetallic compound particulates, both Ag_3Sn and Cu_6Sn_5, in the β-Sn phase. It should be noted that the overall composition of these network-like regions clearly exceeds the eutectic composition in both Cu and Ag concentrations.

Because of its tetragonal crystal structure, β-Sn is birefringent in reflecting light from a polished surface. Using polarized light microscopy (PLM) and a nearly crossed polarizer to view polished cross sections, it is possible to discern different crystallographic orientations for the

β-Sn phase, because different crystallographic orientations will exhibit distinguishable contrast [4, 8, 10]. Great care must be exercised in producing the polished sections to avoid unwanted artifacts produced by recrystallization of the β-Sn phase, induced during polishing. Figure 2 is a PLM micrograph of a region within a 20 mg solder mass, comprised of the Sn-3.8Ag-0.7Cu alloy, which was solidified at a cooling rate of 1.0 °C/s in a DSC.. The micrograph shows a region of this solder mass where several contrasting domains converge and are made visible, when viewed through a crossed polarizer. The β-Sn dendritic arm structure and the surrounding impingement zones are clearly visible within the contrasting domains. It is clear that the domains encompass many dendrite arms.

To show that these PLM contrasting domains represent single crystallographic orientations or grains of the β-Sn phase, comparison of PLM and Electron Backscatter Diffraction (EBSD) was used. Figures 3a, 3b, and 3c are crossed polarizer PLM and EBSD images of the same field of a small, Sn-3.8Ag-0.7Cu alloy, tensile test sample. The images have the same magnification. Constant color or contrast in the EBSD image represents constant crystallographic orientation. The identity of the domains and their boundaries shown in these micrographs clearly indicates that the β-Sn crystallographic orientations are preserved over very large distances, despite the complexity of the dendritic growth. The correspondence of the EBSD and PLM images clearly shows that these visible PLM domains are essentially single β-Sn grains, which have the two intermetallic compound phases infused throughout their structure. Comparison of the crossed polarizer and EBSD techniques indicates that most, *but not all* , crystallographic orientations may be visible as distinct contrasting regions, using PLM with a specific polarizer - specimen - analyzer geometry. However, reorientation of the specimen or analyzer usually allows substantially all of the different β-Sn orientations found by EBSD to be optically defined. Figure 3c shows an image of the same field, but viewed with a different crossed polarizer orientation. The β-Sn grain, which is not visible in Figure 3b (but, which is visible in the EBSD image of Figure 3a), was made visible in Figure 3c by a small change in analyzer orientation.

Based on these analytical techniques, we have found that typical, as solidified, BGA solder joints, approximately 900 μm (0.035 inches) in diameter, are comprised of only 1 to perhaps 12 independent β-Sn grains. The average is estimated at approximately 8 grains. The number of grains is insensitive to the cooling rate, imposed during solidification within the range of 0.5 to 3.0 °C/s, examined experimentally. Because there are so few grains and because of the anisotropy of the β-Sn phase, these solder joints cannot be viewed as being homogeneous and isotropic structures. On that basis it is anticipated that the mechanical properties of the solder joints will vary from joint to joint.

It has also been found that under cyclic thermomechanical deformation, the β-Sn phase dynamically recrystallizes in the regions of higher plastic deformation. This recrystallization process leads to a dramatically reduced grain size in the recrystallized regions. Figure 4a is a crossed polarizer image of a polished section of a BGA solder joint that failed due to fatigue in an accelerated thermal cycle (ATC) test with a cycle time of 45 minutes and temperature excursions from -40 to 125 ° C. A ceramic, 0.8 mm thick, BGA module attached to a 1.5 mm thick card was used for this test. Figure 4a clearly shows recrystallization of the solder joint near the card and module solder pads. A single β-Sn grain was found in the central region of this

BGA solder joint. In the "as solidified" state, this solder joint may have been comprised of only a single β-Sn grain. Figure 4b is an enlargement of the lower right hand side of the view of the solder joint, shown in Figure 4a. As shown in the crossed polarizer image in Figure 4b, a multiplicity of small grains have been formed by recrystallization and a fatigue crack was initiated and propagated along the recrystallized grain boundaries. The finer grain size associated with the local recrystallization of the β-Sn phase facilitates grain boundary sliding, as a dominant deformation mechanism. Strain localization in these recrystallized regions is probable, because of plastic deformation augmentation provide by grain boundary sliding. Clear evidence of fatigue damage due to grain boundary sliding was observed in these regions, giving rise to significant triple point cavitation and grain boundary cracking, as shown in Figure 5. In the present study the degree to which the recrystallized zones penetrate into the solder joint varied markedly from joint to joint after fatigue failure. Because the degree of penetration often changes at β-Sn grain boundaries, the local crystallographic orientation of the Sn phase, in association with the applied stress field, may strongly influence the recrystallization process. *Except for interfacial crack propagation at the pad-solder interface, fatigue crack growth through the solder was always characterized by intergranular fracture with crack propagation along recrystallized grain boundaries*. These results were verified in a wide range of test temperatures and BGA module types. EBSD was used to confirm the recrystallization of the β-Sn matrix. Large angular rotations, from the parent β-Sn matrix and between neighboring recrystallized grains, were found in many instances.

The applicability and utility of the EBSD and particularly the PLM techniques in defining the microstructure of the β-Sn phase in the SAC alloy system is apparent. Using these techniques, we have been able to demonstrate that SAC alloy solder joints are typically comprised of only a few β-Sn grains in the "as solidified" state, that the β-Sn phase dynamically recrystallizes under typical thermomechanical fatigue conditions and that the smaller recrystallized grain structure, in combination with continued cyclic fatigue strains, fosters enhanced grain boundary sliding, ensuing grain boundary damage and intergranular crack initiation and growth which leads to final joint failure. We believe this to be the typical thermomechanical fatigue failure mode of BGA, SAC alloy, solder joints and perhaps a wider range of SAC alloy solder joint structures.

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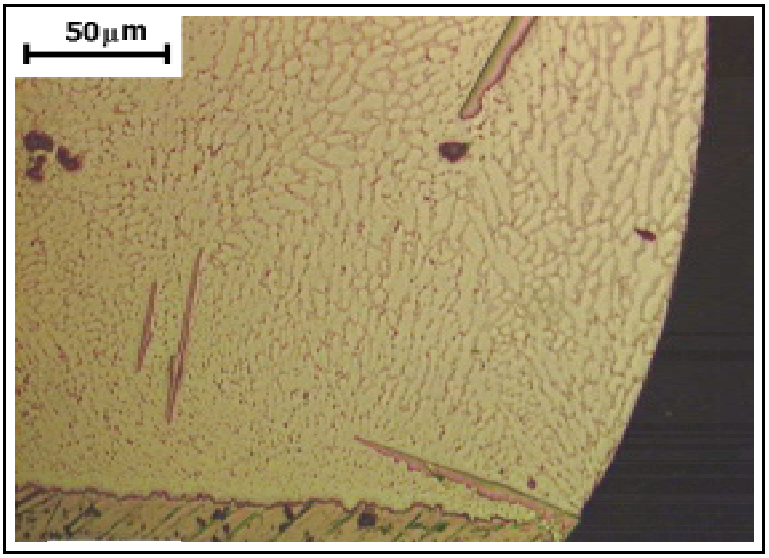
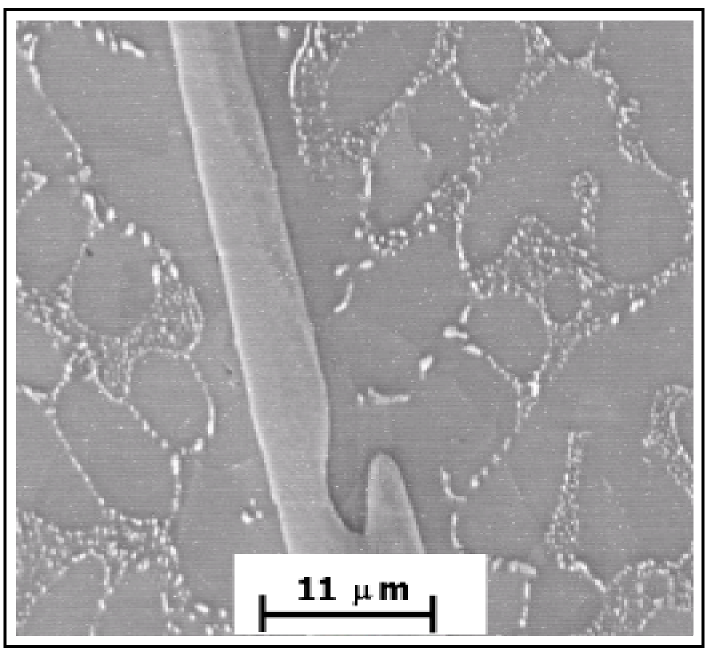




FIGURES 1a and 1b

Optical (Figure 1a) and back scattered electron SEM (Figure 1b) micrographs at two different magnifications, showing the typical solidified microstructure of Sn-3.8Ag-0.7Cu alloy in a BGA solder ball. Sn dendritic arms (light colored phase) are surrounded by Ag_3Sn and Cu_6Sn_5 particulate arrays. These arrays decorate the zones of growth impingement of the dendrite arms.

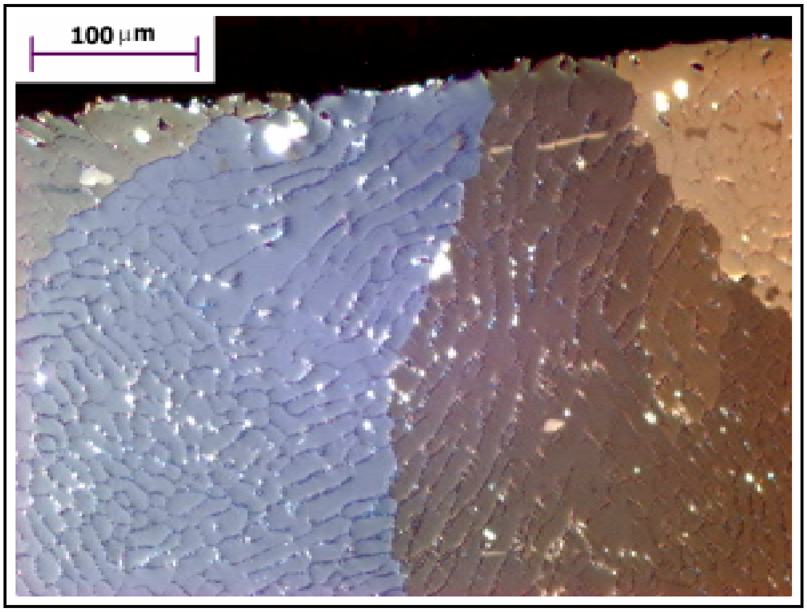
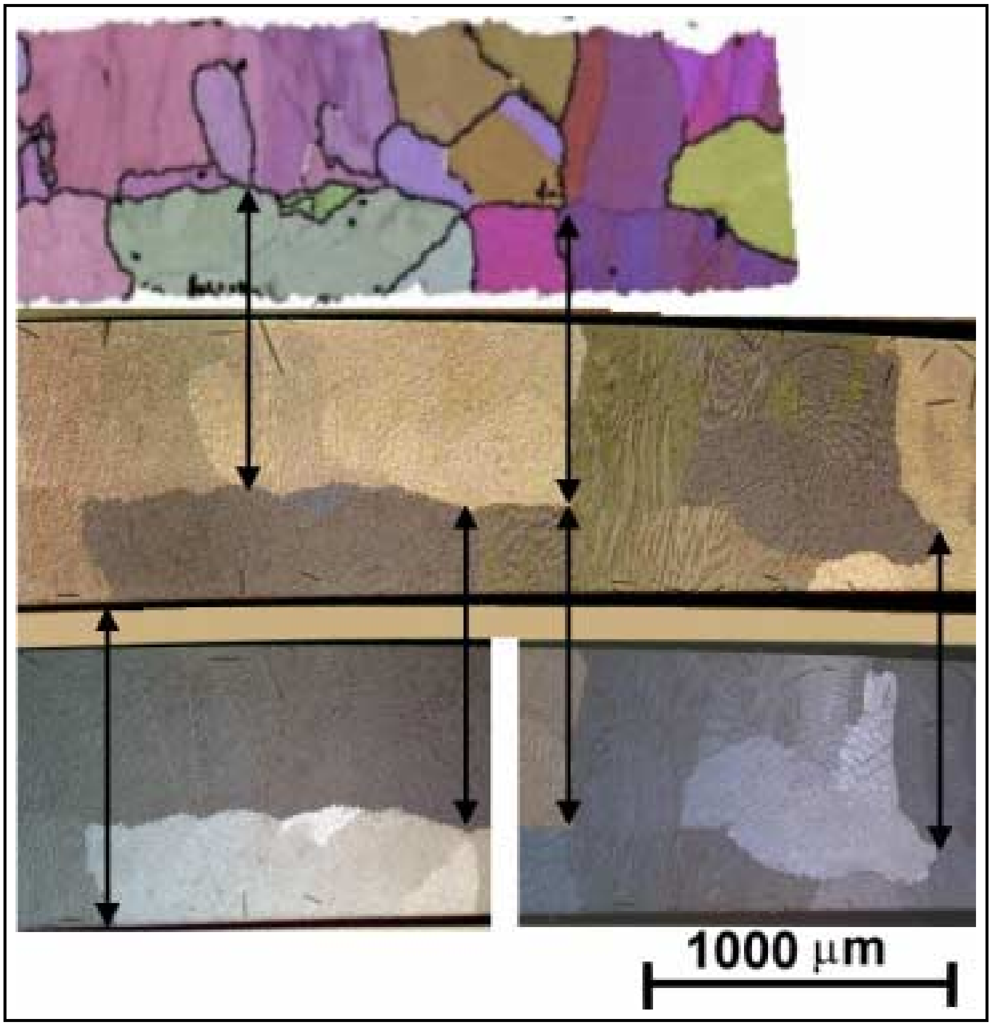


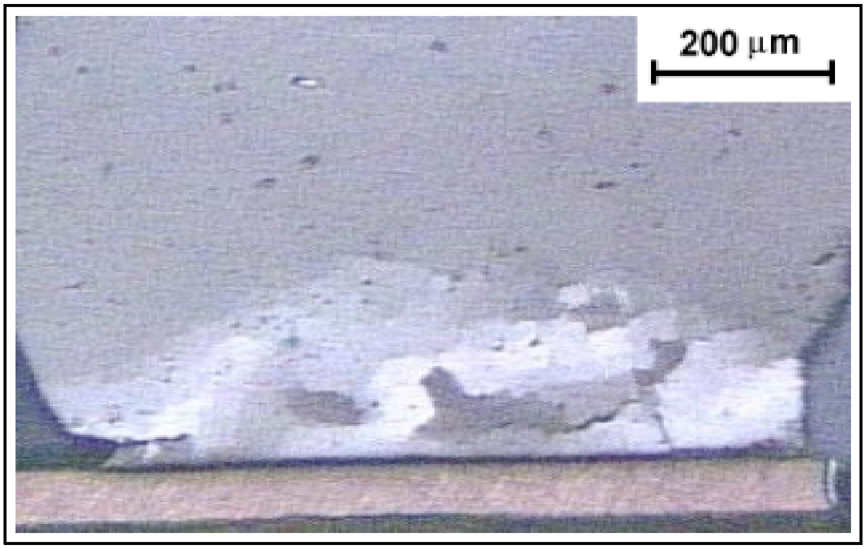
Figure 2

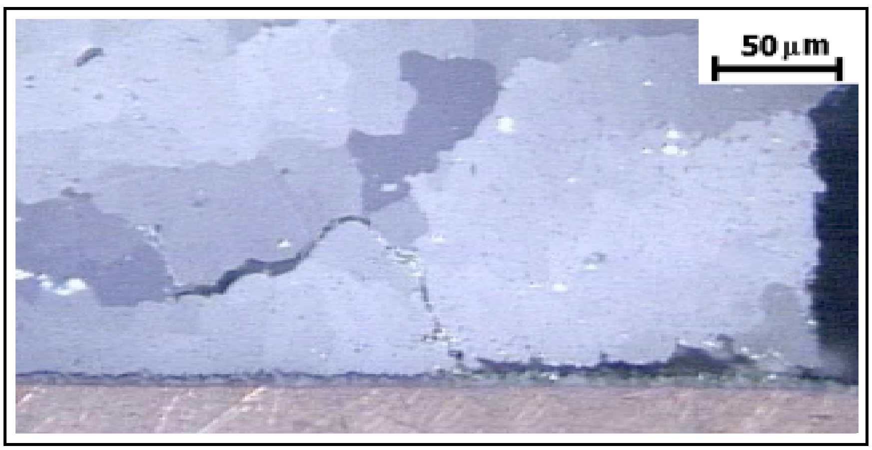
Figure 2 shows a crossed polarizer image of a segment of a small test sample comprised of the Sn-3.8Ag-0.7Cu alloy solidified with a 1.0 °C/s. Different contrasting regions define regions with different Sn crystallographic orientations of the Sn phase



Figures 3a, 3b and 3c

Figures 3a, 3b and 3c are a comparison between an EBSD image (Figure 3a) and crossed polarizer images (Figures 3b and 3c) of the same field of Sn-3.8Ag-0.7Cu tensile test sample. The images have the same magnification. Markers are used to define the same positions in each image. The correspondence between the imaging techniques is self evident. The bottom micrograph shows a crossed polarizer image of the same field, but, with the slightly different analyzer orientation. Note the change in contrast of the β-Sn grains.





Figures 4a and 4b

Figure 4a. Crossed polarizer image of a sectioned BGA solder joint that failed by thermomechanical fatigue. Note that the recrystallized regions are associated with the areas of highest plastic deformation

Figure 4b. Crossed polarizer image with higher magnification of the same solder ball shown in Figure 4a. The image is of the lower right-hand side of the solder ball joint that failed by thermomechanical fatigue. The thermomechanical fatigue process recrystallized the original β-Sn structure, producing a finer grain size and altering the plastic deformation processes associated with thermomechanical fatigue.

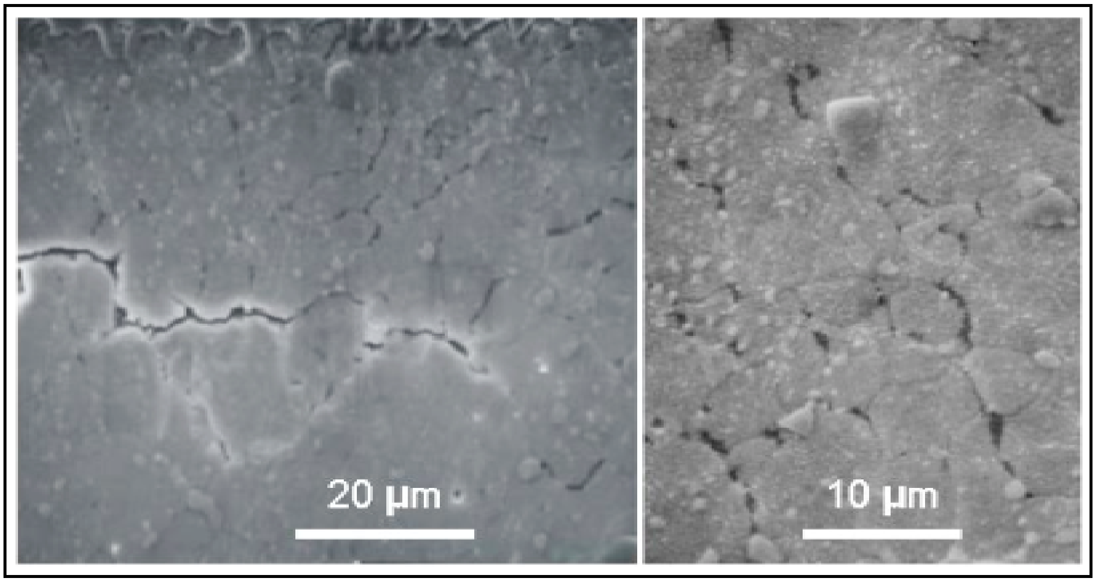


Figure 5

SEM micrograph of a section of a BGA solder joint that was tested under the same ATC test condition as that shown in Figures 3 and 4. Grain boundary sliding damage is evident in the recrystallized, region near the solder pad. Grain boundary sliding damage in the recrystallized structure leads to crack initiation and facilitates crack growth.