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Citation: GONG, J...et al., 2006. Grain features of SnAgCu solder and their effect on mechanical behaviour of micro-joints. IN: Proceedings of the 56th Electronic Components and Technology Conference, San Diego, CA , 30 May-2 June, 8pp.

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Metadata Record: https://dspace.lboro.ac.uk/2134/5335

Version: Published

Publisher: © IEEE

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Grain Features of SnAgCu Solder and their Effect on Mechanical Behaviour of Micro-joints

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Abstract

SnAgCu alloy, which promises compatible properties with Sn-Pb solder, has been identified as one of the most potential Lead-free solders for electronic interconnections. However, due to the miniaturization of solder joints, a micro-joint of this material contains only few grains. In this case, the mechanical behaviour of solder alloys shifts from the polycrystal-based to single-crystal based. Since β-Sn, the matrix of SnAgCu solder, has a contracted body-centred tetragonal structure, its grains is expected to have anisotropic properties, which are important the reliability of a micro-joint. The present paper studies the inelastic anisotropic behaviour of this material. In order to analyse the effect of grain features, solder joints at different size are formed under the different cooling rate. An In-situ shear test is then performed to correlate the mechanical behavior of a joint to its microstructural features. The results show that the decrease in the joint’s dimension results in the diminishment of the number of grains, and that the inelastic behaviour of SnAgCu grains is orientation-dependent.

Introduction

Due to the appreciation of ‘green’ electronics, the replacement of SnPb solder used in consuming electronic products with Pb-free alloys has drawn a great attention to the electronics packaging engineers and academics worldwide. As one of the potential alternatives, SnAgCu solders promise compatible properties compared to those of the SnPb solders in terms of melting temperature, wettability and reliability, therefore have been recommended by NEMI [1, 2]. However, due to demands for high-density assembly, solder joints in electronic package has been miniaturized to dimensions that are comparable with the characteristic size of microstructural features of this material [3, 4]. For instance, a micro-joint with a diameter less than 100 μm, which has been already in the commercial flip chip assemblies, may contain only one or few grains. In this case, the mechanical behaviour of solder alloys at such small scale is expected to shift from the polycrystal-based to inter- or intragranular-based. Since β-Sn, the matrix of SnAgCu solder, has a contracted body-centred tetragonal (BCT) structure (as shown in Fig. 1), resulting in a considerably anisotropic behaviour, crystal features, such as grain size and orientation, may become key factors to reliability of a micro-joint. When solder joints are further miniaturized, the effect of the local lattice of β-Sn on the mechanical behaviour could be more significant, and therefore requires a further investigation.

Serving as interconnections between components, solder joints usually experience a temperature change, and consequently suffer a thermal-induced mechanical load due to the mismatch of the coefficient of thermal expansion (CTE) for these components. At the same time, the melting temperature of SnAgCu solder is relatively low, leading to inelastic behaviour at the service temperature. In this case, three types of the lattice-dependent behaviour are expected for a micro-joint: elastic, thermal expansion and inelastic. The first two types arise from different interatomic potentials in different crystal orientation and the change of these potentials varies with temperature. While the last type is due to the non-uniform distribution of potential slip systems in 3D, and their different ability to be activated or to slide. All these mechanisms are assumed to determine the response of a SnAgCu crystal and make a contribution to reliability of a micro-joint. Recently, M. A. Matin investigated the response of an unconstrained solder alloy under the isotropic thermal cycling load and attributed its fatigue damage to the anisotropic thermal expansion and elastic properties of β-Sn matrix [5]. In the present paper, the grain-based inelastic behaviour for a Sn-Ag-Cu alloy is studied. Firstly, solder joints with the different geometry and cooling rate are fabricated for the microstructural analysis. Then an In-situ shearing test is conducted to study the relationship between their grain features and the local mechanical behaviour of solder joints.

1 Specimen preparation

A commercial solder paste, Sn3.8Ag0.7Cu, is adopted for the test. The diameter of solder balls ranges form 8 μm to 12 μm, and the flux comprises 13% of the paste. It is specially
designed for a fine pitch flip chip assembly, and therefore suitable for the small joint geometry in the test. The solder joints are formed between two substrates using a Planer T-TRACK© reflow oven. Beside the temperature control system from the oven, an assistant air control system is used to obtain a fast cooling rate. Two cooling conditions are adopted. Figure 2 shows two temperature curves that solder joints experience in the oven. To obtain different size of joints, the distance between two substrates is defined at 1 mm and 0.1 mm, which correspond to the scale of solder joints for ball grid array (BGA) and flip chip. The substrates are made of copper plates (99.9% purity) so that they can get a reliable bonding with the solder while the substrate is rigid enough for the following mechanical test. The dimensions of the substrates are 15×15 mm² with a thickness of 1 mm. Figure 3a gives the sample configuration. After the reflow, the sample is cut into several specimens with their longitudinal axes perpendicular to the welding line as shown in Fig. 3b. The depth of the specimens (d in Fig.3b) is approx 1 mm. Finally, one of the specimen’s cross-sections is carefully ground and polished for the in situ observation.

![Fig. 2 Temperature change in tests. The cooling rates near the melting point are 0.13°K/s and 4.5°K/s, respectively. Heating and cooling condition are the same before 718 s (around 493°K, Point S) so that the difference in microstructure is defined by cooling conditions.](image)

2 Mechanical test

In order to apply an external load to the specimens, a strain-controlling device is designed. During the mechanical test, one of the copper substrate is fixed. The other substrate is fixed with regard to two directions and all rotations, and the displacement in the third direction can be controlled at the resolution of 1 µm. Figure 4 shows loading conditions for a specimen. As can be seen, a shearing mode of loading can be applied on the joint, which is similar to that of BGA and flip chip. Since the yield point of pure copper is much higher than that of Sn3.8Ag0.7Cu solder, the copper substrates remain in the elastic condition after the onset of yielding in the solder joint. At the same time, the Young’s modulus of SnAgCu solder is considerably less than that of copper. Under loading, nearly the entire movement of the second substrate is transferred to the joint, especially in the case of the large deformation. Therefore, the applied engineering shear strain γ on the joint is approximately:

\[
\gamma = \frac{U_{\text{substrate}}}{b},
\]

where \(U_{\text{substrate}}\) is the movement of the second substrate and \(b\) is the distance between substrates (it is the distance between the middle points of interfaces for the real specimens). Before the mechanical test, both scanning electron microscopy and optical microscopy with the polarized light are employed to examine grain features and other microstructural features of joints. Afterwards, an in situ observation is performed with an optical microscope to capture the mechanical behaviour of the specimens. This behaviour is subsequently compared with the local microstructure of the corresponding SnAgCu joints.

Moving direction for the second copper substrate in loading

![Fig. 4 Constraints and loading conditions for a joint in the shearing mechanical test. \(b\) is the distance between two substrates. It is 1 mm and 0.1 mm for large and small joints, respectively.](image)
Results

Fig. 5 Bright-field image of a large joint ($b = 965 \, \mu m$) formed at the slow cooling rate (0.13°K/s). (a) Image for the whole joint. (b) Local image near the interface.

Fig. 6 Polarized-light image of the whole joint corresponding to Fig. 5a

Figure 5a is an optical image of a large joint formed under the slow cooling rate. Besides the eutectics (bright area), large amounts of Sn dendrites are formed in the body of the joint, indicating that the solder composition is not at the eutectic point or that the cooling rate is still too high so that the alloy system deviates from the equilibrium phase transformation during solidification. Figure 5b focuses on an area at the interface. It shows that eutectics are composed of Sn matrix and small Ag$_3$Sn and Cu$_6$Sn$_5$ particles in the matrix. At the interface, there is a layer of Cu$_6$Sn$_5$ intermetallics between the solder joint and substrate. The needle-like phase near the interface is Ag$_3$Sn plate. These plates are also found at other places as shown in Fig. 5a. Figure 6 presents the corresponding image of the joint obtained with the polarized light microscope (PLM). Since the contrast of grains in a PLM image depends on the angle, the configuration of some grains is not very clear in an image common. But it still can be seen that there are mainly five grains formed in the joint.

Figure 7 shows the joint when $\gamma = 20\%$. From the slip bands in grains 3, 4 and 5, it can be seen that the inelastic behaviour of this solder joint is considerably microstructure-dependent. For each of these grains, there is only one major slip system that is activated. In fact, the direction of the maximum shear stresses is parallel to that of IMC interfaces under this loading mode. However, all of the activated slip systems have a large angle with this direction, especially for grains 3 and 5, which have an angle of nearly 90°. This indicates that there are few slip systems for the SnAgCu solder, or that the distribution of these slip systems is not uniform. Under loading, only some potential slip systems can be activated, even in an inconvenient direction. As a result, the inelastic behaviour of grains for this alloy is considerably anisotropic and lattice orientation-dependent. No clear slip bands are found in grains 1 and 2. This may be due to the crack in the upper-left corner of the joint and the void on its right side, which can release the stresses under loading.

Bright-field images for the joint with a distance of 82 $\mu m$ are given in Figs. 8a and 8b. Compared with the first joint, it has a similar substructure (Sn dendrites, eutectics and intermetallic particles) in terms of their shape and size in grains due to the similar processing parameters. Figure 8c is the polarized image for this joint, composed of two grains. This indicates that the reduction in the joint size does not significantly retard the grain growth and that the existence of interfaces does not facilitate heterogeneous nucleation so that the grain can reach the same size as that in the large joint. In other words, the smaller the joint is, the fewer grains it contains. With respect to the position of these two grains, they are separated by the grain boundary in the middle of the
Fig. 7 Bright-field image of a loaded large joint (corresponding to Figs. 5 and 6); $\lambda = 20\%$.

Fig. 8 Optical image of a small joint ($b = 82 \mu m$) formed at the low cooling rate ($0.13^\circ K/s$). (a) Bright-field image of the joint. (b) Local image. (c) Polarized-light image.
Fig. 11 Polarized-light image for the whole joint corresponding to Fig. 10

joint, and sandwiched between the substrates. Since the copper substrates are much more rigid, which can’t deform as the adjacent grains in a polycrystalline material during deformation; the mechanical response of these grains is similar to that of a single crystal. Figure 9 shows the joint at $\gamma = 39\%$. It is obviously that the mechanical behaviour of these grains is independent: the slip bands have the same direction inside a grain; however, there is a large angle between these bands for the two grains. If the difference in grain morphology under the surface of the sample is negligible, the loading condition is the same for the main body (excluding areas near grain boundaries) of these two grains since the copper substrates are parallel. Hence, the different bands demonstrate the lattice-dependent behaviour and, consequently, anisotropic properties for a SnAgCu single crystal.

Figure 10 is the bright-field image of a large joint exposed to the high cooling rate. It shows that the morphology of Sn dendrites, eutectics and intermetallic particles is similar to previous samples, but these microstructures become much finer since the rapid cooling condition restricts the movement of atoms during solidification. Also, there are fewer Ag$_x$Sn plates in the sample and the existing one becomes much smaller, indicating that it is mainly formed during solidification. Figure 11 gives a PLM image for this sample. It can be seen that the size of grains doesn’t reduce as much as the substructures inside grains, especially for grains 6 and 8. It indicates that the alloy’s ability to both grow and nucleate is
enhanced by the increased cooling rate, but the latter dominates for this geometry. This joint was exposed to a shear deformation $\gamma = 19\%$; its microstructure after this deformation is presented in Fig. 12. Similar to previous specimens, it shows a localized inelastic behaviour in most of the grains. An interesting phenomenon is that the direction of slip bands is the same as that of Sn dendrites in grains 5 and 6. This can be due to the existence of $\text{Ag}_3\text{Sn}$ and $\text{Cu}_6\text{Sn}_5$ intermetallics in eutectics. As well known, these particles can pin dislocation lines [6], making it difficult for dislocations to go through the eutectics. Therefore, the alloy system activates slip systems along the soft dendrites to minimize the required working during deformation. Another possible explanation is that the growth of SnAgCu grains is anisotropic during solidification. In other words, it grows along certain lattice orientations. In this case, the direction of Sn dendrites and orientation of a crystal correlate so that the crystal could have fixed potential slip systems along the dendrites.

A small joint after cooling with a high rate is shown in Figs. 13a and 13b. Its substructure is similar to that of the large joint in Fig. 10b. The PLM (Fig. 13c) shows that the joint is composed of two large and two small grains, this indicates that the reduced dimensions don’t decrease the grain size (in the direction parallel to interfaces) compared with the large joint in Fig. 10c. Two small grains (grains 3 and 4) demonstrate independent slip bands after deformation $\gamma = 60\%$ (Figure 14). For grain 1 in Fig. 14b, the slip band near the left end of the joint is independent, which is different from the other part of the grain. This may be due to the fact that it is actually two grains, which cannot be identified by PLM. In this case, the joint is composed of five grains. For grain 2 and the right side of grain 1, the directions of their slip bands are very close.

Discussion

From the PLM images and characteristics of slip bands in grains, it can be concluded that Sn dendrites and the adjacent Sn matrix for eutectics have the same crystal orientation within a grain. In this case, the formation of Sn dendrites and eutectics should be interrelated. A possible explanation is that the obtained alloy is composite eutectics, which is composed of two “phases”: Sn dendrites and Sn matrix with $\text{Ag}_3\text{Sn}$ and $\text{Cu}_6\text{Sn}_5$ intermetallics [7]. While pure Sn requires a

Fig. 12 Bright-field image of a loaded large joint (corresponding to Figs. 10 and 11); $\lambda = 19\%$.  

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considerable overcooling (about 30 degrees) to nucleate, Sn is considered as the initiative phase. During solidification, the interface between Sn dendrites and the liquid phase moves toward the liquid, releasing Ag and Cu atoms into the liquid. When the concentration of Ag and Cu is high enough at the interface, they begin to nucleate in the form of Ag$_3$Sn and Cu$_6$Sn$_5$. This process is controlled by the movement and supply of Ag and Cu atoms. Under a rapid-cooling condition, it is difficult for the released Ag and Cu atoms to move away. This results in a high density but narrow area along the interface. This layer reduces the ability of Sn atoms to deposit on the solid-liquid interface, obstructing the growth of Sn dendrites. Therefore, the size of Sn dendrites become smaller when the cooling rate increases. At the same time, the rapid solidification constrains the movement of Ag and Cu atoms in the liquid. Therefore, the intermetallics are unable to grow large, forming small particles in the Sn matrix. On the contrary, when the cooling rate is very low, the liquid alloy have enough time to supply Sn and Ag to the intermetallics to minimize the system’s energy, forming needle or plate Ag$_3$Sn and bulk Cu$_6$Sn$_5$. Considering the non-uniform temperature gradient during solidification and the possible growth preference in certain lattice orientations for this alloy, the deposition process of Sn atoms is not homogeneous even if the concentration of Sn and Ag is the same for the entire interface. This breaks the homogenous growth, leading to branch-like Sn dendrites. As mentioned above, since $\beta$-Sn is difficult to nucleate, SnAgCu grains can grow large.

In all the specimens, the small joints contain fewer grains than the large ones at the same cooling rate. Obviously, the account for 3D reduction of a joint size would only strengthen this conclusion. In fact, the range between the two studied cooling rates covers most of cooling conditions that electronic industry uses to assemble package. Therefore the shift from polycrystalline to single crystals and the corresponding shift for the mechanical behaviour may be unavoidable for SnAgCu micro-joints in electronics. Traditionally, creep is the most concerned inelastic behaviour since the stresses are unable to exceed the yield point in most cases. However, when a joint is close to a single crystal, this may be no longer applicable. For instance, there may be no clear yield point due to the decrease of the grain boundary. In this case, both the thermally activated and non-thermally activated inelastic behaviour becomes important. While this paper demonstrates that the latter one is lattice-based, part of the former behaviour (lattice-diffusion) is expected to be grain orientation-dependent. This lattice-based behaviour causes a high concern since the reliability of solder joints can be determined not only by the structural features. This can result

Fig. 13 Optical image of a small joint ($b = 108 \, \mu m$) formed at high cooling rate (4.5°K/s). (a) Bright field image for the whole joint. (b) Local image. (c) Polarized light image.

Fig. 14 Bright-field image of a loaded small joint (corresponding to Fig. 13); $\lambda = 60\%$.

Grian 1 Grian 2 Grian 3 Grian 4
in the varying life due to different grain features even in a similar structural position in a package.

**Conclusions**

In the present paper, a shearing test specimen is designed to study grain features of Sn3.8Ag0.7Cu solder joints and the corresponding inelastic behaviour. The result shows that:

1. The decrease of the joint thickness from 1000 µm to 100 µm results in diminishment of the number of grains.
2. The increase in the cooling rate causes a finer microstructure in grain of the solder joint. However, the size of grain is not significantly sensitive to the cooling rate in the range of 0.13°K/s and 4.5°K/s.
3. The non-thermally activated inelastic behaviour of Sn3.8Ag0.7Cu grains in a micro-joint is considerably lattice-dependent.

**Acknowledgments**

The work is financially support by the Engineering and Physical Sciences Research Council’s Innovative Manufacturing and Construction Research Centre at Loughborough University under GR/R64483/01P.

The technical support from A. Sandaver and the workshop in the Wolfson School, Loughborough University in sample preparation is gratefully acknowledged.

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