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Microstructural and Reliability Analysis of SAC305/Sn-57Bi-1Ag Composite Solder Joints with Different Printing Aspect Ratios

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Abstract

In semiconductor packaging, solder is a key material that electrically connects between the chip and printed circuit board (PCB) while forming a mechanical joint. Among various solder alloys, Sn-Ag-Cu (SAC) solder is widely used due to its excellent mechanical reliability. However, its high melting point of 217 °C can lead to PCB warpage and reliability issues during a bonding process. To address these concerns, although a Sn-Bi-Ag based Sn-Bi, which has a low melting temperature, has been gained attention due to its improved mechanical properties with comparing to Sn-58Bi der has gained attention, with Sn-Bi-Ag solder being a major research focus due to its improved mechanical properties with comparing to Sn-58Bi, reducing brittle properties of Bi is still limited. Therefore, composite solder joints combining SAC and Sn-Bi solders have been investigated to maximize their advantages while compensating for their drawbacks. , studies comparing the effect of conditions of solder paste printing for SAC/Sn-57Bi-1Ag composite solder joints remain limited. In this study, the influence of the printing conditions induced by aspect ratio (AR) of the solder paste printing on microstructures, mechanical properties, and thermal reliabilities at the composite solder joints of SAC305 and Sn-57Bi-1Ag were reported. The results indicate that, for the Smaller AR condition printed with a larger diameter and lower height, Bi diffusion was more uniform along the Cu₆Sn₅ interface, while for the Larger AR condition paste by a smaller diameter and higher height, Bi coarsening was observed around the intermetallic compound (IMC) interface. For a low-speed shear test after a thermal shock (-40°C to 85 °C, 2,000 cycles), the Smaller AR condition maintained mixed fractures due to uniform Bi diffusion reducing stress concentration at the IMC interface whereas the Larger AR condition showed increasing brittle fracture due to Bi coarsening. From the our results, we suggest the critical role of solder paste printing conditions to control the diffusion, distribution, and coarsening of Bi for using low-temperature composite solder systems. Therefore, we also provides the process guideline with controlling the printing condition during the reflow soldering for forming composite solder joints.

1. Introduction

In semiconductor packaging industries, solder is a key material that electrically connects and mechanically joints between various electronic components and printed circuit boards (PCBs). Until now, Sn-Ag-Cu (SAC) system solders are the most widely used due to its excellent mechanical reliability [1]. However, SAC solders require a high-temperature soldering process due to their high melting point about 217 °C. During this process, PCB warpage may occur, leading to gaps at the solder joint between components and boards, which can result in issues such as open joints [2]. Recently, extensive research has been actively conducted on low-melting point solders which have a melting temperature about 137 °C with being based Sn and Bi. Nevertheless, a

eutectic Sn-Bi solder has lower mechanical ductility and higher brittleness compared to SAC solder, which can make it more prone to be fractured under mechanical stress [3]. To address this, research have been studied to enhance performance by adding trace elements such as Ag, Cu, and Ni. Among these, Sn-Bi-Ag solder, which strengthens solder joints through the addition of Ag, has become a major research focus due to its improvements in brittleness and reliability. In particular, it has gained attention in applications that require high reliabilities such as ball grid array (BGA) packages and chip scale packages (CSPs) [4-5]. Recently, some studies have been performed on composite solder joints combined with SAC and Sn-Bi solders to maximize their advantages and compensate for their drawbacks. There have been previous studies showed that the excellent mechanical

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properties of SAC solder and the low melting point of Sn-Bi solder help reduce PCB warpages and alleviate thermal stress [6]. Additionally, research have also reported that this approach can mitigate the brittleness issue of Bi. Nonetheless, when compared to studies on SAC or Sn-Bi solder conducted individually, research on composite solder joints is still very inadequate and in early stages. Meanwhile, in the packaging process between components and boards, the joining conditions have been optimized for using one materials such as SAC or Sn-Bi. Therefore, it is necessary to optimize the joining process for forming composite solder joint to ensure joint properties using conventional processes such as the reflow soldering technology. Most previous studies have examined Bi diffusions and microstructural evolutions in SAC/Sn-Bi composite solder joints under varying only soldering temperatures. Some studies also already investigated composite and hybrid solder joints using low-melting temperature solders [7–9]. However, the effects of process parameters, such as the aspect ratio (AR) of the stencil mask for the printing of a solder paste, at an initial stage of the reflow soldering, on joint properties of composite solder has not been sufficiently reported. The AR, which affects solder volume and joint geometry, can significantly influence microstructures, interfacial reactions, intermetallic compounds (IMCs) and fracture behavior under various stress environments. In this study, we focused on the effects of the printing conditions of Sn-57Bi-1Ag solder paste on the diffusion and redistribution of Bi, microstructural evolution, and thermal shock reliability at the SAC/Sn-57Bi-1Ag composite solder joint. The printing conditions were varied based on the AR of dimensions of the printed solder paste and the opened stencil mask, with two conditions: Larger AR and Smaller AR, to evaluate their properties of interfaces and joints. The composite solder joints formed under these two conditions showed differences not only in metallurgical properties but also in mechanical properties. Thus, we suggest the most suitable condition of the printing process for the composite solder joint from these experimental results.

2. Experimental Procedures

2.1. Specimen preparation

In our experiment, Sn-3.0Ag-0.5Cu (SAC305) solder balls with a diameter of 250 μm and a type 4 Sn-57Bi-1Ag solder paste were used. A flame retardant-4 (FR-4)-based PCB with Cu pads was also used and Cu pads with a diameter of 230 μm on the PCB were finished by an organic solderability

preservative (OSP) to form solder joints. Through a surface mount technology (SMT) process, Sn-57Bi-1Ag solder paste was firstly applied on the PCB pads using two printing conditions with two stencil masks. For the consistency of the printed solder paste volume, we calculated the printing volume and the dimensions of the opened stencil mask by using the Eq. 1 and Eq. 2. From the calculation, the printing conditions were determined and classified into Smaller AR and Larger AR. As shown in Fig. 1 and Table 1, Smaller AR was printed with a larger diameter and lower height while Larger AR which has a smaller diameter and higher height.

$$\text{Solder paste volume} = \frac{\pi d^2 h}{4} \quad (\text{Eq. 1})$$

$$\text{Aspect ratio (AR)} = \frac{\text{Height}(\mu\text{m})}{\text{Diameter}(\mu\text{m})} \quad (\text{Eq. 2})$$

Where d is the diameter of the deposited solder paste, and h is its height

After the paste printing with two conditions, SAC305 solder balls were placed on the printed paste, the soldering process was carried out using the reflow process under two different conditions to fabricate composite solder joints. The first condition was a peak temperature of 180 $^{\circ}\text{C}$ (R180), where only the Sn-Bi solder melted, while the peak temperature of the second condition was 270 $^{\circ}\text{C}$ (R270) which can melt the SAC305 solder as well. Although our main focus was on low-temperature soldering with Sn-57Bi-1Ag, the R270 condition with a high process temperature was also performed because joint properties were clearly compared and analysed. This condition is actually used in various package fabrication processes for melting SAC305 solder.

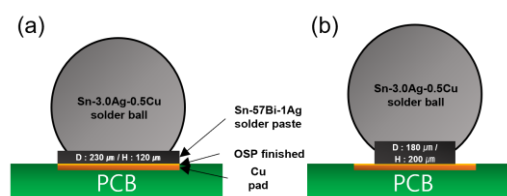


Fig. 1. Solder paste printing conditions based on AR (a) Smaller AR and (b) Larger AR

Table 1
Conditions of solder paste printing

Printing condition	Smaller AR	Larger AR
Diameter (μm)	230	180
Height (μm)	120	200
AR	0.52	1.10

2.2. Observation of microstructure and mechanical properties

The SAC305/Sn-57Bi-1Ag composite solder joint was observed using scanning electron microscopy and an energy dispersive X-ray spectroscopy (SEM-EDS, Inspect F, FEI Co., USA). The interface between the Cu pads and the composite solder joint, as well as the fracture surface, were analysed to compare the microstructural differences between two printing conditions. To evaluate the shear strength of joints with two AR printing conditions were evaluated by a shear tester (Dage 4000, Nordson Co., UK) used following the JEDEC standard JESD22-B117A. A low-speed shear test was conducted with a shear speed of 200 $\mu\text{m/s}$ a shear height of 50 μm , while for a high-speed shear test, a shear height of 50 μm and a shear speed of 1 m/s were applied.

2.3. Thermal shock reliability test

To evaluate the reliability of the SAC305/Sn-57Bi-1Ag composite solder joint, a thermal shock test was also conducted from -40 to 85 $^{\circ}\text{C}$ with a dwell time of 20 minutes during one cycle. Two shear tests and cross-sectional analysis were performed at intervals of 500 cycles until 2,000 cycles.

3. Results

3.1. Microstructure of composite solder joints

Figure 2 shows cross-sectional backscattered electron (BSE) images of solder joints under the Smaller AR condition (a) and the Larger AR condition (b). In the Smaller AR condition for R180, Bi atoms gradually were diffused toward the upper region and sides of the SAC305 solder as thermal shock cycles progressed. Bi gradually also diffused toward the upper region and sides of the SAC305 solder. In contrast, in the Larger AR condition for R180, Bi diffusion was more suppressed though thermal shock test was performed.

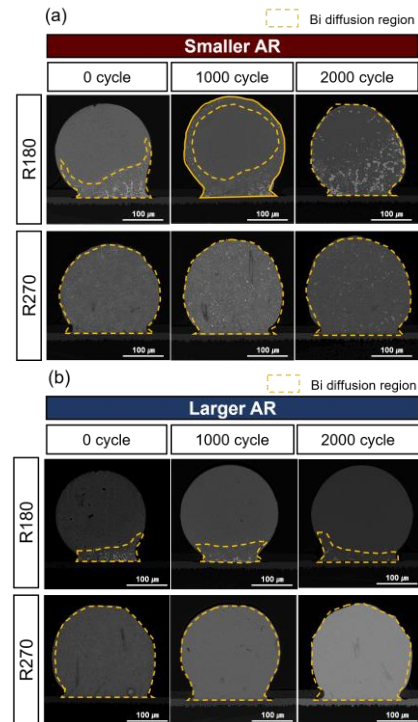


Fig. 2. Cross-section of composite solder joint with AR conditions: (a) Smaller AR and (b) Larger AR

3.2. Intermetallic compound and microstructure at joint interface

The IMCs and microstructures under the Smaller AR condition was shown in Fig. 3(a). Cu_6Sn_5 IMC was formed at the PCB interface, while Ag_3Sn was observed inside the solder. In R180 process, due to the relatively low processing temperature, Bi diffusion was not sufficiently activated, which induced the presence of coarsened Bi at the Cu_6Sn_5 interface. Fig. 3(b) shows the IMCs and microstructures under the Larger AR condition were shown in Fig. 3(b). Compared to the Smaller AR condition, Ag_3Sn and Cu_6Sn_5 were more uniformly distributed at the PCB interface and Bi particles were evenly dispersed throughout the solder. Additionally, as thermal shock test was progressed, Bi coarsening was observed. However, compared to the Smaller AR condition, the Bi particles remained smaller and more uniformly distributed.

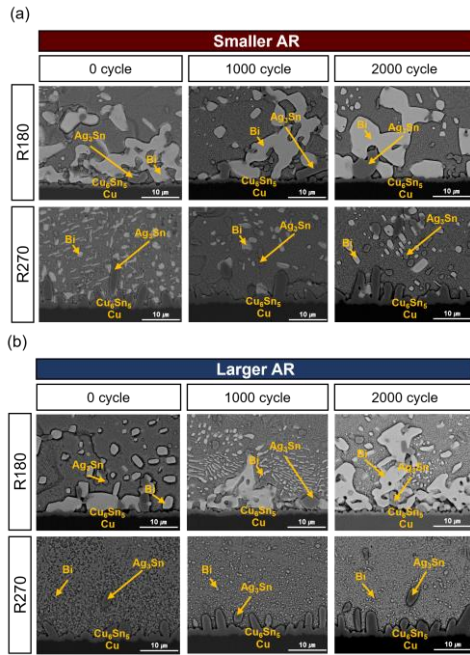


Fig. 3. IMCs and microstructures at joint interfaces of composite solder joints with AR conditions: (a) Smaller AR and (b) Larger AR

3.3. Analysis of shear strength after thermal shock

The shear strength of solder joints evaluated under the low- and high-speed shear test after the thermal shock test was shown in Fig. 4. Regardless of the printing and joining conditions, the strength gradually decreased as the thermal shock cycles were increased. As shown in Fig. 4 (a) and (b), the strength of joints for Smaller AR were higher than that for Larger AR. Furthermore, the strength of Smaller AR joints was also higher and that of Larger AR joints formed under R180 condition was markedly decreased.

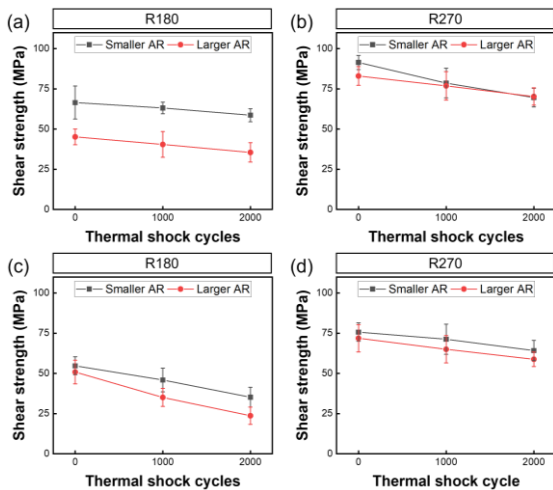


Fig. 4. Shear strength of solder joints with AR condition

after thermal shock test: (a) R180 and (b) R270 under low-speed test, (c) R180 and (d) R270 under high-speed test.

3.4. Analysis of fracture surface after shear test

The fracture surfaces after the low-speed shear test with the printing condition were shown in Fig. 5. In the Fig. 5 (a), fracture occurred at the Cu_6Sn_5 IMC region both R180 and R270 and the brittle fracture tendency was increased as the thermal shock cycle was increased. For Larger AR joints shown in Fig. 5 (b), under R180 condition, ductile fracture was observed within the bulk solder after the reflow soldering while brittle fracture at the Cu_6Sn_5 IMC layer was dominant during the thermal shock test. Meanwhile, in the case of the R270 process, ductile fracture was also observed before the thermal shock test. However, as the number of thermal shock cycles increased, fracture at the Cu_6Sn_5 IMC interface became more prominent and eventually mixed fracture mode was observed. Figure 6 shows the fracture surfaces for the high-speed shear test. In both the Smaller AR (a) and Larger AR (b) conditions, interfacial fracture at the Cu_6Sn_5 region became more predominant with increasing the thermal shock cycle. Compared to the low-speed shear test, brittle fracture behavior was significantly more pronounced under the high-speed shear test, for especially the Larger AR and R180 conditions. Meanwhile, under the R270 condition, mixed fractures were maintained for both Smaller AR and Larger AR during 2000 cycles. Schematic diagrams of the fracture modes occurred at the composite solder joints by the shear tests after the thermal shock test were shown in Fig. 7.

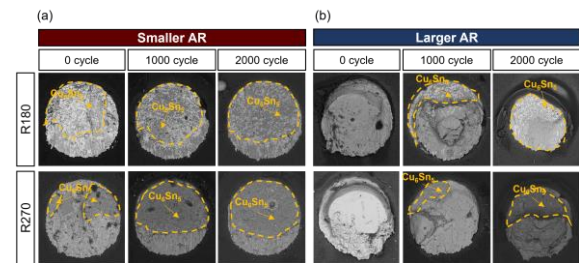


Fig. 5. Fracture surfaces after the low-speed shear test: (a) Smaller AR and (b) Larger AR condition

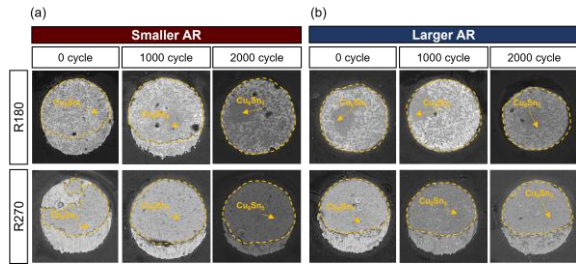


Fig. 6. Fracture surfaces after the high-speed shear test:(a) Smaller AR and (b) Larger AR condition

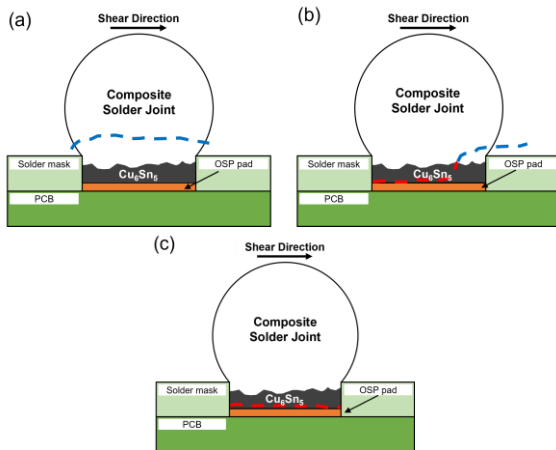


Fig. 7. Fracture modes occurred at the composite solder joints: (a) ductile mode, (b) mixed mode, and (c) brittle mode

4. Discussion

The Bi diffusion was uniformly observed after the reflow soldering for the R270 condition whereas for the R180 condition, the diffusion was gradually progressed as the thermal shock was performed. This indicated that the higher process temperature and more uniform heat distribution of the R270 condition could promote the actively diffusion of Bi and the more stable development of joint microstructures. Under the Smaller AR condition for the R180, the enhancement of wetting and wicking behavior of Sn-57Bi-1Ag solder paste encapsulated around the SAC solder balls was observed and these improved interfacial contact between the solder ball and the solder paste. This flux-assisted spreading reduced surface energy and facilitated actively Bi diffusion during the joining process of joint formation. Therefore, the diffusion and penetration of Bi into the SAC solder ball was deeply occurred, which led to improved interfacial reactions and metallurgical joining properties. Thus, although localized coarsening due to Bi accumulation was observed in some regions, the overall mechanical reliability of the joint was enhanced. In contrast, for the Larger AR condition, the diffusion and distribution of Bi particles

were uniformly observed around the edge of solder balls with being relatively less coarsened. We assumed that this phenomenon could limit interfacial reaction between the ball and the paste. This insufficient diffusion may also adversely affect the joint strength and resistance to thermal or mechanical stress. Moreover, Bi coarsening observed near the Cu_6Sn_5 interface for the Larger AR condition could induce local embrittlement and potential crack. Furthermore, fracture analysis shown in Fig. 5 and 6 supported these observations and assumption. The joint fracture of the Smaller AR condition consistently exhibited mixed fractures after thermal shock test to 2,000 cycle whereas that of the Larger AR condition showed increasing tendency of brittle fracture features. These results indicate that deeper and more active Bi diffusion under the Smaller AR condition mitigates stress concentration at the IMC interface and contributes to improved joint reliability. Conversely, the relatively shallow and narrow coarsened Bi distribution of joint for the Larger AR condition could degrade mechanical integrity.

5. Conclusions

This study reported that the effects and influences of the printing conditions with opened stencil masks on metallurgical and mechanical properties of SAC305/Sn-57Bi-1Ag composite solder joints. For the Smaller AR condition, enhanced wetting and wicking facilitated deeply diffusion of Bi into the bulk solder and led to improve joint properties. Meanwhile, for the joint under the Larger AR condition, shallower and narrower Bi diffusion and coarsening around the Cu_6Sn_5 IMC interfaces induced increasing brittle fractures after the thermal shock test. From these results, we suggest the critical role of solder paste printing conditions to control the diffusion, distribution, and coarsening of Bi for using low-temperature composite solder systems. To optimize the printing AR conditions of the solder paste to ensure sufficient and uniform Bi diffusion is essential for enhancing joint reliability under various thermal and mechanical loading conditions. Therefore, our study provides the process guideline with controlling the printing condition during the reflow soldering for SAC305/Sn-57Bi-1Ag composite solder applications.

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References

- [1] Aamir, M., Tolouei-Rad, M., Din, I. U., Giasin, K., & Vafadar, A. "Performance of SAC305 and SAC305-0.4La lead-free electronic solders at high temperature." *Solder. Surf. Mt. Technol.*, 31(4), 250-260, Apr. 2019.
- [2] Huang, C.-M., Raj, A., Osterman, M., & Pecht, M. "Assembly Options and Challenges for Electronic Products With Lead-Free Exemption." *IEEE Access*, PP(99), 1-1, Jul. 2020.
- [3] Zhou, S., Mokhtari, O., Rafique, M. G., Shunmugasamy, V. C., Mansoor, B., & Nishikawa, H. "Improvement in the mechanical properties of eutectic Sn58Bi alloy by 0.5 and 1 wt% Zn addition before and after thermal aging." *J. Alloys Compd.*, 765, 1243-1252, 2018.
- [4] Ren, G., & Collins, M. N. "Improved Reliability and Mechanical Performance of Ag Microalloyed Sn58Bi Solder Alloys." *Metals*, 9(4), 491, Apr. 2019.
- [5] Sun, L., Chen, M.-H., Zhang, L., & Xie, L.-S. "Effect of addition of CuZnAl particle on the properties of Sn solder joint." *J. Mater. Process. Technol.*, 278, 116507, 2020.
- [6] Liu, Y., Liu, L., Xu, R., Sun, F., Zhu, D., & Xu, H. "Microstructure, hardness, and shear behavior of Sn3.0Ag0.5Cu–Sn58Bi composite solder joint." *Mater. Res. Express*, 6(11), 116328, Nov. 2019.
- [7] Said, R. M., et al. "Mixed Assembly of Lead-free Solder Joint: A Short Review." *J. Phys.: Conf. Ser.*, 2169, 012039, 2022.
- [8] Zhang, S., Jing, X., Chen, J., Paik, K.-W., He, P., & Zhang, S. "Preparation, characterization and mechanical properties analysis of SAC305-SnBi-Co hybrid solder joints for package-on-package technology." *Mater. Charact.*, 208, 113624, 2024.
- [9] Sahasrabudche, S., Mokler, S., Renavikar, M., Sane, S., Byrd, K., Bbrigham, E., Jin, O., Goonetilleke, P., Badwe, N., & Parupalli, S. "Low Temperature Solder – A Breakthrough Technology for Surface Mounted Devices." *Proc. Electron. Compon. Technol. Conf. (ECTC)*, 2018.