

Formation mechanism of pillar-shaped intermetallic compounds dispersed lead-free solder joint

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Abstract. Large area joining between a substrate and a heat sink is desirable for high performance power modules. An intermetallic compounds (IMCs) pillar dispersed solder joint has been developed as a highly durable joint to achieve large area joining. The aim of this study is to clarify the generation and growth mechanism of the IMC pillar during soldering process. The structural characteristic of the IMC pillar was also examined by cross-sectional observation. The area ratio of the IMC pillars in the cross section of the joint increased with increasing the joining temperature. The shape of the IMC pillar became finer when the cooling rate was fast. In addition, the IMC pillar grew along the cooling direction.

1. Introduction

The demand for electric vehicles is expected to increase, and inverters are required to be had high power density for cost reduction and downsizing of them [1]. In a power module that dominates the cost and the size of the inverter, it is possible to further increase the current density by increasing per unit area (cooling performance) to further miniaturize the module [2]. Moreover, to improve heat radiation performance, it is effective to change a direct cooling structure joined with solder from a separate structure filled with heat dissipating grease between the power module and the heat sink [3]. The structure enables miniaturization, weight reduction, and cost reduction of the module. However, in the case of the direct cooling structure, large thermal distortion occurs at the joint portion between the insulating substrate with a small coefficient of thermal expansion (CTE) and the aluminum or copper plate with a large CTE. The authors have developed a pillar shaped intermetallic compounds (IMCs) dispersed lead-free solder joint that can suppress the crack generation in the joint under thermal fatigue conditions and improve durability of the joint. Figure 1 shows cross sectional views of as-soldered joint with Sn-3.0Ag-0.5Cu-5.0In and the joint after thermal cycle test. Cu dissolved from the substrate forms a pillar shaped intermetallic compound (hereinafter referred to as an IMC pillar) in the soldered joint and the IMC pillar can suppress crack growth. On the basis of the quantitative analysis with an electron probe X-ray microanalyzer (EPMA), it was found that the IMC pillar consists of Cu and Sn [4]. The aim of this study is to investigate the formation mechanism of the IMC pillar.



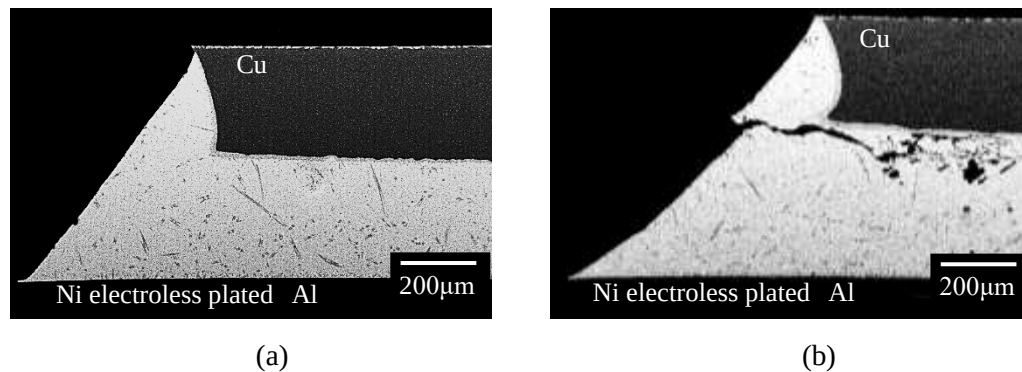


Figure 1. Cross sectional secondary electron images of pillar-shaped IMC dispersed lead-free solder joints.

(a) As-soldered, (b) Crack formed in solder layer after thermal cycle test (500 cycles, -40 - 120°C).

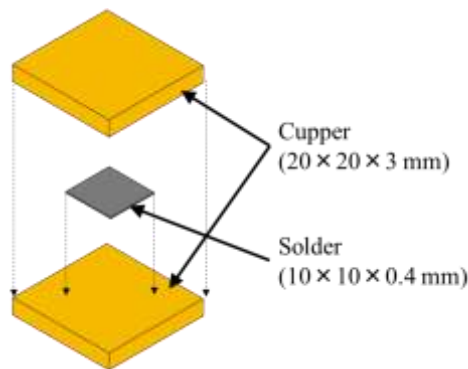


Figure 2. Shape and dimensions of specimen to investigate effect of joining conditions.

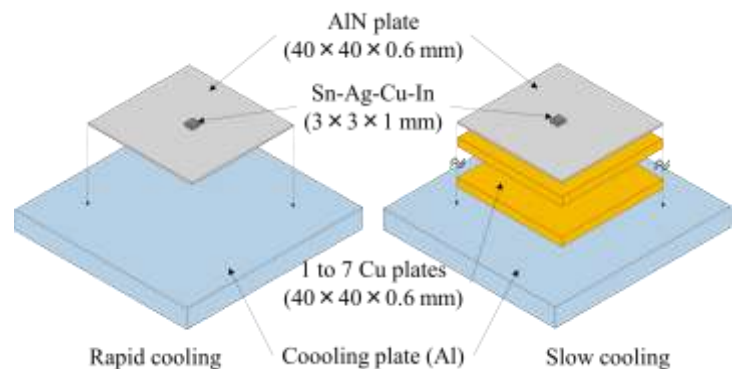


Figure 3. Schematic of specimen preparation to investigate effect of unidirectional cooling

2. Experimental Procedure

To elucidate the formation mechanism of the IMC pillar, the effects of joining conditions and cooling conditions in solidification on the shape of the IMC pillar were investigated.

2.1. Investigation of the effect of joining conditions on the shape of the IMC pillar

Figure 2 shows a specimen to investigate the effect of joining conditions on the shape of the IMC pillar. The specimen was prepared by sandwiching a Sn-3.0Ag-0.5Cu-5.0In (mass%) alloy with 10×10×0.4 mm size between two Cu plates with 20×20×3 mm size. Joining was conducted in a vacuum below 1 kPa. In this study, heating and cooling system are located under the specimen. Joining temperature and joining time were 270, 300 and 330 °C and 10, 20 and 30 min, respectively. The cooling rate in solidification was 5 °C/sec. After joining, each specimen was filled with an epoxy resin and the cross section of it was cut out with a cutter. The cross section was polished with emery papers from #320 to #1000, and buffing was carried out with diamond suspension of 15 to 1 µm. Thereafter, the cross-sectional observation was carried out using a scanning electron microscope (SEM). In SEM observation, the working distance and the acceleration voltage were 8 mm and 20 kV, respectively. Back-scattered electron (BSE) images were observed. For the obtained image of the microstructure of the joint, binarization processing was performed with an image processing software (WinROOF), and the area ratio of the IMC pillar in the joint was measured. In order to confirm the effect of the joining

conditions on the dissolution amount of Cu, the abundance ratio of Cu in the cross section of the solder layer was semi-quantitatively analyzed using energy dispersive X-ray spectroscopy (EDS). In EDS analysis, the working distance and the take-off angle of X-ray were 10 mm and 35 degrees, respectively.

2.2. Investigation of the effect of cooling conditions in solidification on the shape of the IMC pillar

2.2.1. Investigation of the effect of cooling rate. In order to eliminate the effect of dissolution of Cu in the molten solder and confirm the effect of only the cooling rate in solidification, an alloy in which Cu was added in advance to the Sn-3.0Ag-0.5Cu-5.0In alloy was prepared. Figure 3 shows the schematic of the specimens. The Sn-3.0Ag-0.5Cu-5.0In alloy of 3×3×1 mm in size was completely melted at 500 °C that is higher than the melting point of Cu₆Sn₅ on a ceramic (AlN) plate and then cooled. The specimen with the Sn-3.0Ag-0.5Cu-5.0In alloy and the ceramic plate was heated to 500 °C and the ceramic plate with the molten alloy was placed on a cooling plate. The cooling rate was varied by stacking 1 to 7 Cu plates between the solder material and the cooling plate. In this study, the average cooling rate from 500 °C to 200 °C in the vicinity of the solidus temperature of solder was defined as cooling rate.

2.2.2. Investigation of the effect of cooling direction. As shown in figure 1, it was suggested that the IMC pillar is formed along the cooling direction. Therefore, the structure of the IMC pillar was also investigated when giving directionality to the direction of heat flow during solidification. The experiment was conducted in the same manner as shown in figure 3. The heating temperature was set to 500 °C, and for the cooling rate, a rapid cooling and a slow cooling were examined. In the rapid cooling, the solder material was melted on the ceramic plate and then cooled on a cooling plate. In the slow cooling, seven Cu plates were added between the ceramics plate and the cooling plate. The cooling of the specimen was conducted approximately uniformly. In the rapid cooling, a billet of Sn-3.0Ag-0.5Cu-5.0In alloy with 91×15.5×24 mm size was melted and then cooled in water, cooling rate was 50 °C/s. In the slow cooling, Sn-3.0Ag-0.5Cu-5.0In alloy of 3×3×1 mm in size was melted in a muffle furnace and then furnace cooled, cooling rate was 10 °C/s.

3. Results and Discussion

3.1. Effect of joining conditions on the shape of the IMC pillar

Figure 4 shows the measurement results of the area ratio of IMC pillars in the solder joints under several conditions. Figure 5 shows back-scattered electron images of the cross sections of the joints at 270, 300 and 330 °C for 30 min. In the case of the same joining temperature, the area ratio of IMC pillars does not change even if the joining time increases. On the other hand, the effect of the joining temperature on the area ratio of IMC pillars is remarkable. Figure 6 shows the semi-quantitative analysis result of Cu in the solder layer by EDS plotted on the Sn-Cu phase diagram with the liquidus line. The abundance ratio of Cu in the solder layer increases with increasing the liquidus temperature and changes along the liquidus line. When the joining temperature rises, the solubility limit of Cu dissolved in the molten solder also increases. Since the dissolved Cu crystallizes as Cu₆Sn₅ during cooling from the peak temperature of reflow soldering, the area ratio of IMC pillars increases with increasing the joining temperature.

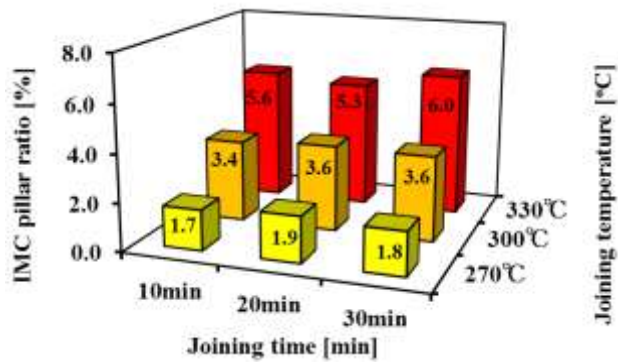


Figure 4. Effect of joining conditions on rate of IMC pillar.

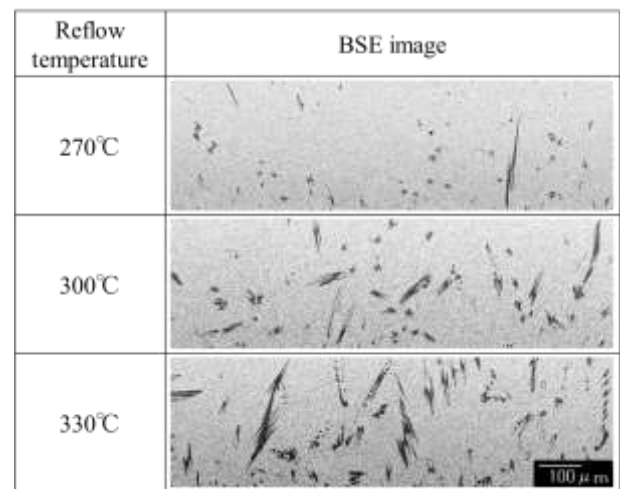


Figure 5. Back-scattered electron (BSE) images of sections of joints (joining time: 30 min).

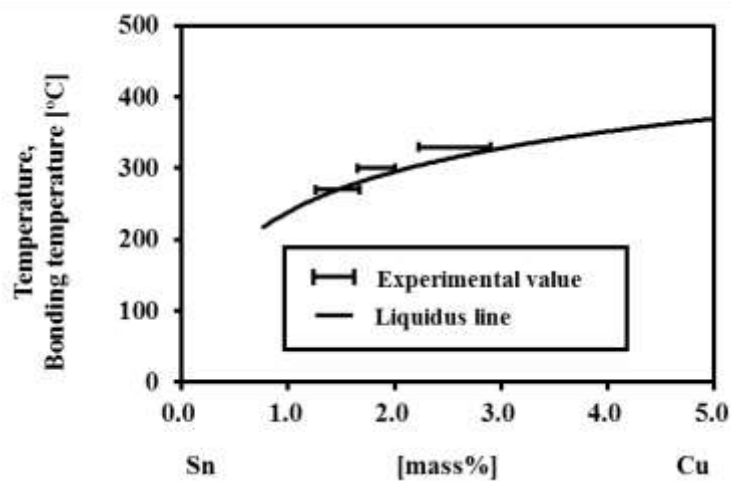


Figure 6. Cu dissolution rate in joint layer to solubility limit of Cu.

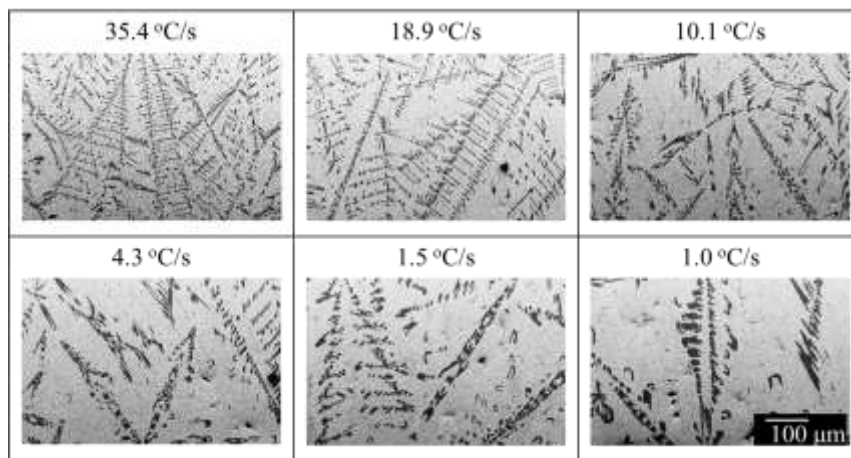


Figure 7. Effect of cooling rate on morphology of IMC (BSE images).

3.2. Effect of cooling conditions on the shape of the IMC pillar

3.2.1. Effect of cooling rate. Figure 7 shows morphology of IMCs in solder at each cooling rate. The IMC becomes fine when the cooling rate increases and it becomes coarse when the cooling rate is slow. The morphology of IMCs is dendritic. This means that the formation mechanism of the IMC pillar is the same as the crystallization mechanism of dendrite. When the cooling rate is high, extrusion of Cu from molten solder in the cooling process becomes fast so that the IMC grows fast. Since the cooling time from the peak temperature to the solidus temperature is short, the joint is cooled without sufficient growth of IMC pillars. Thus the IMC has a fine shape. On the contrary, IMC grows in a thick columnar shape when the cooling rate is slow [5]. In the case of the slow cooling rate, the dendritic growth of the IMC is slow and it coarsens.

3.2.2. Effect of cooling direction. Figure 8 shows BSE images of the cross sections of solder which were cooled under various cooling conditions. In the case of uniform cooling, IMCs grew randomly. On the other hand, directionality was seen in the growth direction of IMC in the case of unidirectional cooling. As shown in figure 3, the cooling plate was placed under the specimen and solder was cooled from below. In figure 8, the heat flow direction is vertical direction. Therefore, it was confirmed that most IMCs form along the cooling direction. This tendency was observed in both rapid and slow cooling conditions. Cu_6Sn_5 crystallizes and it grows toward the liquid phase because the phase transformation from the cooling side to the solid-liquid coexisting phase easily occurs when solder is cooled from one direction. In the specimen shown in figure 3, the phase transformation occurred from the portion below the liquidus line of solder to the solid-liquid coexisting phase by cooling molten solder from the bottom. Extrusion of Cu from molten solder in the cooling process can nucleate Cu_6Sn_5 IMC. Therefore, IMC easily forms along the cooling direction because IMC grows to a high-temperature side where the liquid phase amount is high [6].

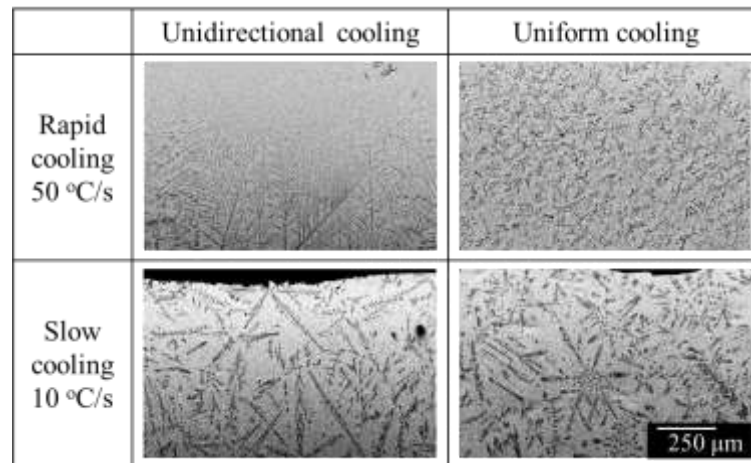


Figure 8. Effect of heat flow direction on morphology of IMC (BSE images).

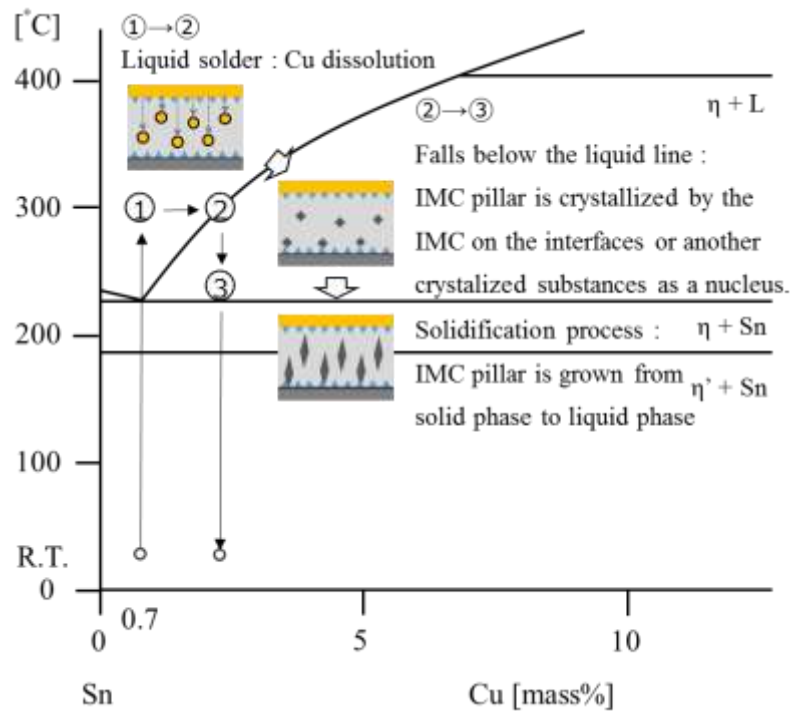


Figure 9. Formation mechanism of IMC pillar shown in Sn-Cu phase diagram.

3.3. IMC pillar formation mechanism

Figure 9 shows the formation mechanism of the IMC pillar with the Sn-Cu phase diagram. Formation of the IMC pillar is considered as follows.

- ① to ②: Cu dissolves in molten solder until the solubility limit of Cu in solder at the joining temperature [7, 8].
- ② to ③: When the temperature of solder reduces below the liquidus line, crystallization of Cu_6Sn_5 IMCs starts. In the nucleation stage, the joint interface, additive metals other than Cu and oxides originally present can be nucleation sites. IMCs grow during the cooling process from liquidus temperature to solidus temperature and thus IMC pillars form in solder. IMC pillars easily grow along the cooling direction [9, 10].

4. Conclusions

In this study, the formation mechanism of the IMC pillar which remarkably improves thermal fatigue life was investigated. The following results were obtained from the experimental results under various joining and cooling conditions.

- (1) The area ratio of the IMC pillars increases with increasing the joining temperature. This is caused that the solid solution limit of Cu dissolved in molten solder increases with increasing the joining temperature.
- (2) The shape of the IMC pillar becomes fine when the cooling rate is fast. The morphology of IMCs is dendritic. The formation mechanism of the IMC pillar seems to be the same as the crystallization mechanism of dendrite.
- (3) The growth direction of the IMC pillar becomes from the low temperature side toward the high temperature side in the heat flow direction during cooling.

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