Selective etching and hardness properties of quenched SAC305 solder joints

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Abstract

Purpose – The purpose of this paper is to investigate the morphology of intermetallic (IMC) compounds and the mechanical properties of SAC305 solder alloy under different cooling conditions.

Design/methodology/approach – SAC305 solder joints were prepared under different cooling conditions/rates. The performance of three different etching methods was investigated: simple chemical etching, deep etching based on the Jackson method and selective removal of \( \beta \)-Sn by a standard three-electrode cell method. Phase and structural analyses were conducted by X-ray diffraction (XRD). The morphology of etched solder was examined by a field emission electron microscope. The hardness evaluations of the solder joints were conducted by a Vickers microhardness tester.

Findings – The \( \text{Ag}_3\text{Sn} \) network was significantly refined by the ice-quenching process. Further, the thickness of the \( \text{Cu}_6\text{Sn}_5 \) layer decreased with an increase in the cooling rate. The finer \( \text{Ag}_3\text{Sn} \) network and the thinner \( \text{Cu}_6\text{Sn}_5 \) IMC layer were the results of the reduced solidification time. The ice-quenched solder joints showed the highest hardness values because of the refinement of the \( \text{Ag}_3\text{Sn} \) and \( \text{Cu}_6\text{Sn}_5 \) phases.

Originality/value – The reduction in the XRD peak intensities showed the influence of the cooling condition on the formation of the different phases. The micrographs prepared by electrochemical etching revealed better observations regarding the shape and texture of the IMC phases than those prepared by the conventional etching method. The lower grain orientation sensitivity of the electrochemical etching method (unlike chemical etching) significantly improved the micrographs and enabled accurate observation of IMC phases.

Keywords Quenched soldering, SAC305, IMC, Electrochemical etching, Hardness

Paper type Research paper

1. Introduction

Soft solders are metal alloys that are usually used to join mechanically and connect electrically two or more electrical components of assemblies. Recently, the \( \text{Sn}–\text{Ag}–\text{Cu} \) (SAC) solder family, particularly the \( \text{Sn}–3.0\text{Ag}–0.5\text{Cu} \) (SAC305) alloy, has been the leading lead-free solder alloy used in the electronics industry (Wang et al., 2012). The intermetallic compound (IMC) phases within the solder joints mainly determine the properties of SAC305 solder joints. The fine \( \text{Cu}_6\text{Sn}_5 \) and \( \text{Ag}_3\text{Sn} \) phases in the \( \beta \)-Sn matrix can improve the mechanical properties of the SAC305 solder joints (Garami and Krammer, 2015). However, there are several factors such as phase migration (Chen et al., 2016), thermal aging (Deng et al., 2005; Wang and Nishikawa, 2014), type of substrate (Liu et al., 2015) and solidification rate (Lee et al., 2016) that can facilitate the formation of larger IMC phases. The larger IMC phases impede lower dislocation movement. This disadvantage will result in more unsatisfactory mechanical performance (such as a reduction in the tensile and hardness properties). Among these, the aforementioned factors, the solidification rate is the most significant.

The cooling rate affects the morphologies of the \( \text{Ag}_3\text{Sn} \) and \( \text{Cu}_6\text{Sn}_5 \) phases. Lee et al. found that rapid cooling such as 63.17°C s\(^{-1}\) resulted in the formation of a very fine \( \text{Ag}_3\text{Sn} \) network and suppressed the formation of the \( \text{Cu}_6\text{Sn}_5 \) IMC layer, thereby improving the tensile strength up to 60.8 MPa (Lee and Huang, 2016). Tsao et al. reported that small \( \text{Ag}_3\text{Sn} \)...
precipitates, obtained by water cooling at 102 K s\(^{-1}\), also increased the hardness of the SAC305 alloy from 12.1 to 13.6 HV (Tsao et al., 2016). Previous findings clearly highlighted the strong relationship between IMC microstructure and the cooling conditions. The investigation of the solder joint microstructure is usually applied only on two-dimensional cross-sections to study the size and morphology of the IMC phases. However, different etching technologies can be applied to investigate the three-dimensional morphology of the IMC phases. During etching, the interdendritic elements are removed by an electrochemical reaction to allow excellent observations of the remaining dendritic core of the IMC phases (Hurtony et al., 2013; Yahaya and Mohamad, 2017b; Ahmad et al., 2019; Ahmad and Mohamad, 2019; Yahaya et al., 2020). Wang et al. used a deep etching technique on SAC305 solder joints and found a complex Ag\(_3\)Sn network around large rod-like Cu\(_6\)Sn\(_5\) (Wang et al., 2012). The removal of the β-Sn matrix achieved by selective electrochemical etching also revealed significant differences in the morphologies of the SAC305 prepared by vapor phase soldering and CO\(_2\) laser soldering techniques (Hurtony et al., 2012). As the IMC layer plays an important role in the reliability of the solder joint, it is important to perform detailed observations and analysis on these layers obtained under the different cooling conditions. Mechanical evaluation such as hardness tests is also essential to further correlate the morphological observations with the mechanical properties of SAC305 as part of the reliability of the solder joint on application/operation (Nasir et al., 2019).

In this work, SAC305 solder joints were prepared under different cooling conditions. Cyclic voltammetry (CV) was used to determine a suitable etching potential. Electrochemical etching was then conducted on the SAC305 solder joints by means of chronoamperometry (CA). Evaluations on the phase, morphology and hardness were subsequently conducted to investigate the effects of the cooling conditions.

2. Experimental

2.1 Sample preparation of SAC305 solder alloy

A SAC305 paste of ALPHA CVP-390 (Alpha Assembly Solutions) was printed onto FR4 substrate (2 × 3 cm) by a custom stencil 5 mm in diameter and 1 mm in thickness. The printed SAC305 were reflowed in a reflow oven (TYR-108C, Madell Technology) in accordance with the programed reflow profile: preheating (160°C-180°C), reflow (213°C-247°C) and cooling (247°C-40°C).

Different cooling conditions were applied after the reflow stage, which is right after achieving the temperature peak of 247°C: normal oven cooling, air cooling (26°C), water quenching (25°C) and ice quenching (0°C). Mechanical cutting by a diamond cutter (MICRACUT, Metcon) was conducted before 800, 1,200 and 2,000 grit silicon carbide grinding and 1.0, 0.5 and 0.03 μm alumina suspension polishing. Electrical connections were prepared by single core copper wire for subsequent CV and electrochemical etching.

2.2 Etching preparation on SAC305 solder alloy

Preliminary CV measurements were carried out in a conventional airtight three-electrode cell containing 1% sulfuric acid (H\(_2\)SO\(_4\)) electrolyte at 25°C with a potentiostat (Autolab PGSTAT 101, Metrohm Autolab). A saturated calomel electrode (SCE) was used as the reference electrode, a carbon rod as the counter electrode and SAC305 as the working electrode. CV curves were recorded at a scanning rate of 1 mV s\(^{-1}\) with a potentiostat operating software, NOVA 11.1.

The polished samples were chemically etched with 0.1 M ferric chloride etchant. The samples were immersed in 0.1 M ferric acid for 10 s before rinsing with distilled water to remove the remaining etchant and to prevent overetching. This process was carried out in a fume cupboard at ambient temperature.

The deep etching process was based on the Jackson method (Lewis et al., 2002). The polished samples were initially etched in a 20% nitric acid solution for 5 h. On rinsing with distilled water, a subsequent etching process in 20% hydrochloric acid solution was conducted for 70 h. The samples were then rinsed with distilled water to remove any remaining etchant from the surface. Both etching processes were carried out in a fume cupboard at ambient temperature.

Selective removal of β-Sn was performed by a standard three-electrode cell connected to the potentiostat in CA mode. The cell consists of an SCE as the reference electrode, a carbon rod as the counter electrode and the SAC305 solder alloy as the working electrode. H\(_2\)SO\(_4\) (80 mL; 1%) was used as the electrolyte. The etching was conducted at a fixed potential bias of –3.5 V with an etching duration of 120 s.

2.3 Characterization of SAC305 solder alloy

Phase and structural analyses were performed by X-ray diffraction (XRD) (Bruker AXS D8 Advance, AXS Inc., Fitchburg, WI) with monochromatized Cu Kα radiation (λ = 1.5406 Å) in the range of 10° < 2θ < 90°. The morphology of etched solder was examined by a field emission scanning electron microscope (FESEM, 35VP, Zeiss SupraTM) equipped with energy-dispersive X-ray spectroscopy. The thickness of the IMC layer was determined using the FESEM images by ImageJ software.

Hardness evaluations were conducted with a Vickers microhardness tester (LM-248AT, Leco Corporation) at a maximum load of 10 g and a dwell time of 15 s. To ensure the correct acquisition of the hardness value across the entire SAC305 solder surface cross-section, 10 indentations were performed on a particular design pattern (Figure 1).

3. Results and discussion

3.1 Effect of cooling methods on phases of SAC305 solder alloy

XRD analyses of the different samples were carried out. In the SAC305 solder joints, the following phases are expected: β-Sn (ICSD-98-009-1748), Ag\(_3\)Sn (ICSD-98-000-1559) and Cu\(_6\)Sn\(_5\) (ICSD-98-010-9332). The oven-cooled samples displayed the highest peak intensities of the Cu\(_6\)Sn\(_5\) phase at 46° and of the Ag\(_3\)Sn phase at 52.5° [Figure 2(a)]. The air-cooled SAC305 showed a lower peak intensity for the Cu\(_6\)Sn\(_5\) phase but higher peak intensities for the β-Sn and Ag\(_3\)Sn phases than the oven-cooled samples [Figure 2(b)]. It was observed that on further increasing the cooling rate with water quenching, the peak intensities of the β-Sn, Ag\(_3\)Sn and Cu\(_6\)Sn\(_5\) phases significantly reduced [Figure 2(c)], and all the peaks almost disappeared in the case of ice-quenched cooling.
cooling was because of the allotropic transition of the α-Sn phase in the case of ice-quenched cooling. [Figure 2(d)]. Interestingly, α-Sn (ICSD-98-009-1898) was also detected in the case of ice-quenched cooling.

The relatively higher peaks of the Ag₃Sn and Cu₆Sn₅ phases in the cases of oven and air-cooling conditions might be attributed to the favorable growth of these phases because of the relatively longer solidification period (Mu et al., 2012). The longer cooling time provided by these two conditions allowed the Ag₃Sn and Cu₆Sn₅ phases to coalesce into larger grains, which contribute to the higher peak intensities, as observed from the XRD results. This effect could also explain the significant reduction in the peak intensities of the Ag₃Sn and Cu₆Sn₅ phases obtained under the water and ice-quenched cooling conditions. The faster solidification reduced the growth rate of all the phases (both IMC and β-Sn), resulting in smaller grains with varying orientations. This made them less detectable during XRD analysis (lower intensities). The appearance of the α-Sn phase in the case of ice-quenched cooling was because of the allotropic transition of β-Sn below 13.2°C (Lee et al., 2015). Previous results clearly showed the influence of the cooling condition on the formation of the different phases in the SAC305 solder joints.

3.2 Potential-bias determination and selective electrochemical etching

The potential-bias (CV) curves were determined to find a suitable potential for selective β-Sn removal. The CV curves at different cycles show the different reaction peaks for SAC305 solder alloy, especially along the oxidation region, which is the most significant for the potential selection of electrochemical etching (Figure 3). An oxidation peak appeared at −0.29 V during the anodic period in the first cycle [Figure 3(a)]. Then, the second cycle produced two oxidation peaks at −0.49 and −0.33 V [Figure 3(b)]. During the third cycle, both peaks shifted slightly to −0.47 and −0.35 V [Figure 3(c)].

The single peak of the first cycle is attributed to the dissolution of the β-Sn and IMC phases (Zhang et al., 2009). It was quite hard to obtain the separate dissolution of the IMC phases during the first cycle because most of the defects from the surface of the cross-sections were removed (mainly because of the grinding and polishing processes). On the second cycle, the appearance of individual peaks for the β-Sn and IMC phases could be caused by the deposited IMC phases during the first cycle and the dissolution of the IMC phases during the second cycle from the agitated surface. Considering the stabilization of the method, −0.35 V (from the third cycle) was selected as a suitable potential for the selective removal of β-Sn during electrochemical etching.

The subsequent electrochemical etching conducted at −0.35 V resulted in a consistent CA plot for all the cooling conditions [Figure 3(d)]. Generally, the cooling conditions did not have any significant influence on the electrochemical etching process. The initial rapid increase in the current was a good indicator of the instantaneous removal of β-Sn (Hurtony et al., 2012). The higher current in the case of ice-quenched samples was caused by the finer grain structure of the IMC phases as a result of the fast solidification. Thus, it led to more grain boundaries and a more intense dissolution of β-Sn (Wang et al., 2017).

3.3 Morphological evaluation of the intermetallic phases attained by different etching methods

Differences in the shape and size of the IMC phases and the IMC layer were observed on the cross-sections after the application of the chemical etching technique (Figure 4). Generally, the morphologies of the IMC phases were similar for the oven-cooled and air-cooled SAC305 solder joints. The rod-like Cu₆Sn₅ and the thread-like Ag₃Sn were located at the central matrix [Figures 4(a) and 4(b)]. A scallop-like Cu₆Sn₅ IMC layer dominated at the solder–substrate interface. However, the IMC layer in the case of air cooling was thinner than in the case of oven cooling. The microstructure changed considerably in the case of rapid cooling methods (water quenching and ice quenching). In the case of water quenching, the thickness of the scallop-like type Cu₆Sn₅ IMC layer reduced significantly and the thread-like Ag₃Sn was refined [Figure 4(c)]. The Ag₃Sn phase was further refined [Figure 4(d)], and rod-like Cu₆Sn₅ IMC phases were not found in the matrix after the ice-quenching process.

The deep etching method provides more information about the morphological differences of the IMC phases under different cooling conditions (Figure 5). This etching method showed how the thread-like Ag₃Sn network surrounds the Cu₆Sn₅ phases [Figures 5(a) and 5(b)]. The scallops in the Cu₆Sn₅ IMC layer were less elongated for both cooling conditions in comparison to the micrographs revealed by...
Figure 3 CV curves of SAC305 solder joints for three cycles

- (a) First cycle; (b) second cycle; (c) third cycle at scan rate 1 mV/s; (d) CA curves of the SAC305 with the different cooling condition at 120 s at -350 mV/s

Notes:
- (a) First cycle; (b) second cycle; (c) third cycle at scan rate 1 mV/s; (d) CA curves of the SAC305 with the different cooling condition at 120 s at -350 mV/s

Figure 4 Microstructures of SAC305 solder joints by different cooling methods

- (a) Oven cooling; (b) air cooling; (c) water quenching; (d) ice quenching investigated by chemical etching

Notes:
- (a) Oven cooling; (b) air cooling; (c) water quenching; (d) ice quenching investigated by chemical etching
Figure 5  Microstructures of SAC305 solder joints by different cooling methods

Notes: (a) Oven cooling; (b) air cooling; (c) water quenching; (d) ice quenching investigated by chemical etching

Figure 6  Microstructures of SAC305 solder joints by different cooling methods

Notes: (a) Oven cooling; (b) air cooling; (c) water quenching; (d) ice quenching investigated by chemical etching
chemical etching. Smaller rod-like Cu$_6$Sn$_5$ was obtained by water-quenched SAC305 [Figure 5(c)]. A combination of scallop-like and planar Cu$_6$Sn$_5$ IMC layers also differentiated the morphologies of water-quenched SAC305. Thread-like Ag$_3$Sn was significantly refined, with a better distribution throughout the central matrix for the ice-quenching condition [Figure 5(d)]. The transition from a scallop-like to a planar Cu$_6$Sn$_5$ IMC layer was also more prominent.

Significant differences in the micrographs were obtained between the chemical and deep etching as a higher volume of the $\beta$-Sn phase was removed. During solidification, the scallop-type Cu$_6$Sn$_5$ IMC layer was found to be favorably grown as IMC. This was caused by the rapid diffusion of Cu into molten solder (Lee et al., 2003; Gagliano and Fine, 2003). This enabled Cu$_6$Sn$_5$ to grow further toward the central matrix of the SAC305 solder joints. The acquisition of a planar Cu$_6$Sn$_5$ IMC layer, especially for the ice-quenched SAC305, was possible because of the shorter solidification duration for Cu diffusion. The rapid cooling rate in the case of the water-quenched and ice-quenched solder joints resulted in a decrease in the interfacial energy, which caused the refinement of the Ag$_3$Sn and Cu$_6$Sn$_5$ phases and limited the growth of the Cu$_6$Sn$_5$ IMC layer (Chuang et al., 2012). This contributed to the instantaneous solidification of the Cu$_6$Sn$_5$ and Ag$_3$Sn precipitates, which inhibited further growth (He et al., 2004).

The IMC phases were most distinguishable after the application of the selective electrochemical etching method (Figure 6). Micrographs of the oven-cooled SAC305 solder joint showed that it contained large-sized Cu$_6$Sn$_5$ rods, which extended from the interface to the center of the matrix [Figure 6(a)]. Height and thickness differences of the scallop-like Cu$_6$Sn$_5$ IMC layer were clearly observed at the interface (the line over Cu$_6$Sn$_5$ lips). Even a slightly faster cooling rate of the air-cooling method reduced the size of the Cu$_6$Sn$_5$ rods [Figure 6(b)]. However, the Ag$_3$Sn in the high-density refined branch network was still distributed mostly around Cu$_6$Sn$_5$ [Figures 6(c) and 6(d)]. The distribution of both IMC phases was greatly improved, especially at the central matrix. Such an alteration in the trend continued further in the case of faster cooling provided by the ice-quenching method.

The actual shape of large rod-like Cu$_6$Sn$_5$ was attributed only after the complete removal of the $\beta$-Sn phase. The longer solidification period in the case of oven cooling allowed Cu$_6$Sn$_5$ to grow in the preferred orientation of the rods (Mu et al., 2012). The extension from Cu$_6$Sn$_5$ at the interface further indicated such a favorable growth. Because Cu$_6$Sn$_5$ acts as a nucleation site for the Ag$_3$Sn precipitates, the dominant position of Ag$_3$Sn was near Cu$_6$Sn$_5$ (Kim et al., 2003). Faster solidification (in the case of water- and ice-quenching) inhibited the enlargement of the Cu$_6$Sn$_5$ and Ag$_3$Sn precipitates. The previous effects resulted in two main outcomes on the morphology of the SAC305 solder joints: finer and more homogeneous grain structure. The small Ag$_3$Sn precipitates could also suppress the growth of the Cu$_6$Sn$_5$ IMC layer (Liu et al., 2010).

The average thicknesses of the Cu$_6$Sn$_5$ IMC layer, measured on the chemically etched micrographs, were 4.6 $\mu$m (oven cooling), 3.8 $\mu$m (air cooling), 1.8 $\mu$m (water quenching) and 1.4 $\mu$m (ice quenching) (Table 1). It was observed that the

| Table 1 Thickness of the Cu$_6$Sn$_5$ IMC layer of the SAC305 with different cooling conditions |
|---|---|---|---|
| Cooling condition | Chemical | Deep | Electrochemical |
| Oven cooled | 4.676 | 3.944 | 3.676 |
| Air cooled | 3.849 | 3.501 | 3.411 |
| Water quenched | 2.541 | 2.113 | 1.734 |
| Ice quenched | 1.922 | 1.451 | 1.342 |

Figure 7 Vickers hardness evaluation on the SAC305 solder joints by different cooling conditions
measured IMC thickness decreased with an increase in the removed amount of $\beta$-Sn. Sufficient removal was found in the case of electrochemical etching, which probably enabled the most accurate observations of the scallop-like Cu$_6$Sn$_5$ IMC layer (Hurtony et al., 2013). The results clearly indicated that the growth of the Cu$_6$Sn$_5$ IMC layer depended highly on the cooling conditions as it affected the reaction time for the dissolution of Cu to form Cu$_6$Sn$_5$ at the solder–substrate interface and the interfacial energy involved (Lee et al., 2001).

3.4 Hardness properties of SAC305 solder joints under different cooling conditions
The different cooling rates resulted in differences in the hardness properties as well (Figure 7). It was observed that the hardness increased with the cooling rate. The lowest hardness value of 13.99 HV was measured on the oven-cooled solder joints. The hardness increased slightly to 14.09 HV when air cooling was applied. The hardness of the water-quenched solder joints increased by 10.36%, up to 15.44 HV. The highest hardness value of 16.05 HV (a 14.65% increase compared with the oven-cooled samples) was measured on the ice-quenched solder joints.

The increase in the hardness value with the increase in the cooling rate was mainly because of the strengthening of the grain boundaries by the IMC phases (Chuang et al., 2012). The size reduction of the Ag$_3$Sn and Cu$_6$Sn$_5$ IMC phases, because of the higher cooling rate, resulted in more grain boundaries within the matrix of the solder joints. The grain boundaries act as barriers to dislocation movements during the application of a load, thereby providing higher mechanical resistance of the solder joints against deformation (Bieler et al., 2012; Yahaya and Mohamad, 2017a). The homogeneous distribution of the fine Ag$_3$Sn and Cu$_6$Sn$_5$ IMC phases also hindered the propagation of forces within the matrix (Yahaya et al., 2016).

3.5 Mechanism of intermetallic formation under different cooling conditions
The growth of the Cu$_6$Sn$_5$ IMC layer is mainly determined by the diffusion of Cu atoms (from the substrate) into the molten

Notes: (a) Oven cooled; (b) air-cooled; (c) water quenched; (d) ice quenched solder joints
solder. Different concentration gradients of Cu at the interface encourage the diffusion of Cu (Chen et al., 2012). The longer cooling time (at the oven- and air-cooled solder joints) caused prolonged diffusion of the Cu, which induced the growth of the Cu$_6$Sn$_5$ IMC layer [Figures 8(a) and 8(b)]. This resulted in a slightly thicker Cu$_6$Sn$_5$ IMC layer in the oven- and air-cooled solder joints because of the extended solidification period. Accordingly, IMC growth was much slower in the case of faster cooling conditions such as water- and ice-quenching. Owing to the rapid drop in the temperature by the quenching process, the migration of Cu$_6$Sn$_5$ was stopped by the prompt solidification. Therefore, the growth of the Cu$_6$Sn$_5$ IMC layer was significantly decreased, resulting in a thinner IMC layer [Figures 8(c) and 8(d)]. It is also possible that the formation of the Cu$_6$Sn$_5$ IMC layer in the quenched solder joints occurred only during the reflow process (because Cu still diffused into the solder alloy) (Hu et al., 2016).

The formation of the central matrix in the solder joints can be described by a similar phenomenon. In the oven- and air-cooled solder joints, the IMC phases have higher interfacial energy because of the slower cooling rate. This was responsible for the formation of the larger-sized Cu$_6$Sn$_5$ and Ag$_3$Sn phases. Furthermore, the slow cooling rate enabled Cu diffusion from the substrate into the central matrix and supported the formation of Cu$_6$Sn$_5$ phases in the central matrix (this explains the occurrence of the long Cu$_6$Sn$_5$ rods near the solder–substrate interface) (Gong et al., 2009).

In the SAC system, the faster cooling condition leads to the nucleation of small Ag$_3$Sn precipitates. The structure and size of the Ag$_3$Sn phases depend on three factors, namely, Ag content, cooling rate and Cu content (Kang et al., 2003). In this case, only the cooling rate changed because the Ag and Cu contents were constant in the SAC305 solder alloy. The faster cooling rate (at the water- and ice-quenching) slowed down the growth of the Ag$_3$Sn phase; thus, a very fine and homogeneous Ag$_3$Sn network formed. During the reflow process, IMC can form in the melting and solidification stages (Yang and Zhang, 2015). At the water- and ice-quenched solder joints, the solidification stage was considerably shortened, which resulted in IMC formation occurring almost only during the melting stage. This effect also blocked effective Cu diffusion into the central matrix and prevented the formation of the rod-like Cu$_6$Sn$_5$ IMC phase, as observed in the case of the oven- and air-cooled solder joints.

4. Conclusion

The influence of the cooling condition on the formation of IMC phases was investigated by different etching methods. A preliminary electrochemical analysis from the CV measurement determined the potential bias for the electrochemical etching. The current recorded from the CA showed similar current responses under all cooling conditions. XRD analysis indicated that the peak intensities reduce as the cooling rate increases, which means the suppression of grain growth into the preferred orientation because of the rapid solidification. All etching conditions exhibited effective removal of the β-Sn phase. The micrographs prepared by electrochemical etching revealed better observations regarding the shape and texture of the IMC phases than the conventional etching method. Lower grain orientation sensitivity of the electrochemical etching method (unlike chemical etching) significantly improved the micrographs and enabled accurate observation of the IMC phases. It was found that the Ag$_3$Sn network was significantly refined with the ice-quenching process. Moreover, the thickness of the Cu$_6$Sn$_5$ layer decreased with an increase in the cooling rate. The finer Ag$_3$Sn network and the thinner Cu$_6$Sn$_5$ IMC layer were the results of the reduced solidification time. The ice-quenched solder joints showed the highest hardness values because of the refinement of the Ag$_3$Sn and Cu$_6$Sn$_5$ phases. Consequently, further research is necessary to determine the optimal cooling rate during the reflow soldering process and the effect of cooling on mechanical properties such as tensile properties. As the effect of the cooling rate will affect the reliability of the solder joint, investigation on the microstructure analysis and hardness properties of SAC305 solders alone on IMCs is insufficient.

References


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