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INFLUENCE OF REFLOW TIME ON IMC FORMATION AT SAC305 SOLDER AND CU SUBSTRATE INTERFACE

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ABSTRACT

Soldering plays a critical role in electronic packaging by connecting components using metal alloys. In this study, the solder joint is made from lead-free SAC305 solder (96.5 wt% Sn–3 wt% Ag–0.5 wt% Cu) on a Cu substrate, with an intermetallic compound (IMC) layer forming at their interface. The IMC layer, essential for ensuring a strong metallurgical bond, can negatively affect joint reliability if it becomes too thick, as it tends to be brittle. Therefore, this research aims to analyze the effect of reflow time on IMC layer formation at the SAC305/Cu interface. The experimental method includes several steps: preparing the Cu substrate by cutting and cleaning, then assembling specimens using the interfacial reaction couple technique with a 1:3 ratio of Cu substrate to SAC305 solder. Flux is applied to both sides of the substrate, and the setup is placed in a reaction tube, wrapped in aluminium foil, and reflowed in a furnace at 290°C for varying times (10, 30, 50, and 70 minutes). Characterization is performed using optical microscopy, SEM-EDS, and XRD. Results show the formation of Cu_6Sn_5 and Cu_3Sn IMC phases at the interface, with the IMC layer's thickness increasing with longer reflow times, affecting the overall joint quality.

1. INTRODUCTION

In the fabrication of electronic devices, the soldering process plays a crucial role, as it joins components in electronic assemblies using a metallic filler alloy (Tan et al., 2020). The Sn-Pb alloy has traditionally been used as a conventional solder in the electronics industry due to its superior performance. However, since July 2006, the Waste Electrical and

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Electronic Equipment (WEEE) directive and the Restriction of Hazardous Substances (RoHS) regulation have enforced legislation prohibiting the use of lead in electronic devices. As a result, researchers have proposed several lead-free solder alternatives, one of which is the Sn-Ag-Cu (SAC) solder, due to its relatively low melting point, lower cost, good mechanical properties, and excellent solderability. In this study, a SAC305 solder alloy (96.5 wt% Sn – 3 wt% Ag – 0.5 wt% Cu) was used with a Cu substrate.

During the soldering process, interfacial reactions lead to the formation of an Inter Metallic Compound (IMC) layer at the solder joint interface. A thin IMC layer typically indicates good metallurgical bonding at the joint. However, excessive IMC layer growth is undesirable, as the brittle nature of IMCs can negatively impact the mechanical reliability of the joint (Tan et al., 2020). Previous studies have identified that the reflow temperature and time are critical parameters affecting the reliability of solder joints (Pan et al., 2009).

The interfacial reaction between SAC solder and the Cu substrate during soldering commonly results in the formation of IMC layers such as Cu_6Sn_5, Cu_3Sn, and other IMCs. During soldering, Cu from the substrate dissolves into the molten solder and contributes to IMC formation. The scallop-type Cu_6Sn_5 layer typically forms first at the SAC305 solder–substrate interface, followed by the formation of a thin Cu_3Sn layer between the Cu_6Sn_5 and the Cu substrate (Tan et al., 2020). According to the Cu–Sn phase diagram, seven phases can form: γ, β, δ (Cu10Sn3), δ (Cu41Sn11), ε (high-temperature Cu_6Sn_5), ε′ (low-temperature Cu_6Sn_5′), and η (Cu_3Sn). However, among these, only Cu_3Sn, Cu_6Sn_5, and Cu_6Sn_5′ are typically observed at solder joint interfaces during soldering below 350°C (Kattner, 2002).

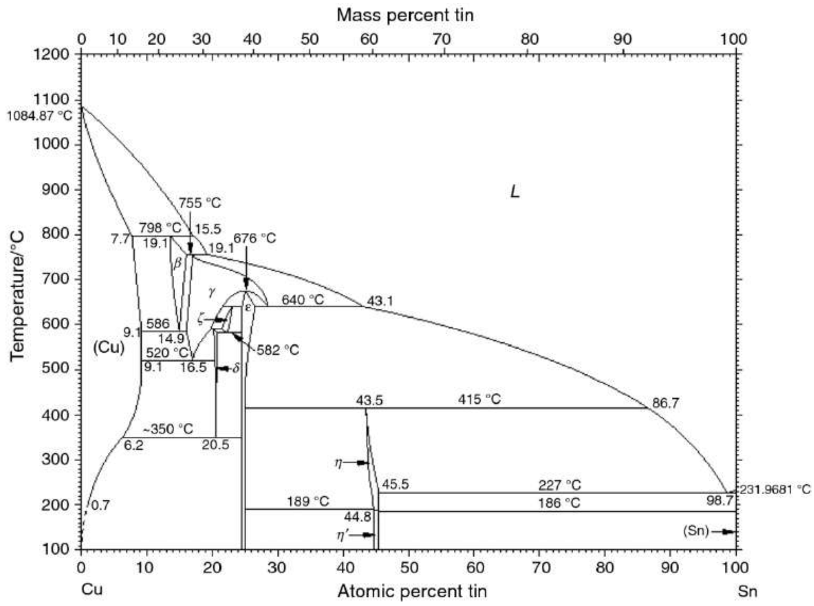

Figure 1. Phase diagram of Cu-Sn (Ting Tan *et al*, 2015)

In a study conducted by Xu et al. (2017), Sn-3Ag-0.5Cu (wt%) solder and a Cu substrate were used, with a reflow temperature of 280°C for 10 minutes, followed by aging treatment for up to 360 hours at varying temperatures of 120°C, 180°C, and 200°C. The study observed the formation of a Cu_6Sn_5 IMC layer immediately after soldering, and the subsequent formation of a Cu_3Sn layer after the aging process. Additionally, the total IMC thickness was found to increase with longer aging durations.

The present study aims to investigate the morphology and phases formed as a result of interfacial reactions between SAC305 solder and a Cu substrate, as well as the growth of the IMC layer thickness at the solder–substrate interface. Soldering was performed at a temperature of 290°C with reflow durations of 10, 30, 50, and 70 minutes. Several characterization techniques were employed: optical microscopy was used for initial observation of the solder joint interface, scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM-EDS) was conducted to analyze the detailed morphology and elemental composition of the formed IMC layers, and X-ray diffraction (XRD) analysis was performed to confirm the interfacial reaction phases.

2. METHODS

2.1 Tools and Materials

The equipment used in this study included a muffle furnace, test tubes, beakers, stopwatch, petri dishes, tweezers, ruler, optical microscope, SEM-EDS machine, and XRD machine. The materials used in this research included copper (Cu) sheets as substrates, SAC305 solder balls, flux, hydrochloric acid (HCl), acetone, alcohol, methanol, distilled water, abrasive paper (sandpaper), aluminum oxide (Al_2O_3), aluminum foil, resin, and catalyst.

2.2 Research Procedure

2.2.1. Preparation

Copper sheet plates were cut to dimensions of 15 mm × 7.5 mm × 0.1 mm and subsequently cleaned using alcohol. The SAC305 solder balls were cleaned using acetone, hydrochloric acid (HCl), and alcohol.

2.2.2. Specimen Fabrication

The Cu substrate and SAC305 solder balls were weighed in a 1:3 ratio (Laksono et al., 2019). A small amount of flux was applied to both sides of the Cu substrate to improve solder wettability by removing oxide layers from the Cu surface. The Cu substrate and SAC305 solder balls were then arranged in the order of solder–substrate–solder and placed inside a test tube. The test tube was tightly sealed with aluminum foil. Subsequently, the test tube containing the specimen was placed on a test tube rack and inserted into a heating furnace set at 290°C with varied reflow times of 10, 30, 50, and 70 minutes. After the reflow process, the test tube was slowly cooled and cleaned with acetone to remove any residual flux. Selected specimens were then mounted for further testing.

2.2.3. Testing

The reflowed specimens were subjected to several testing methods. Optical microscopy was used as an initial observation to confirm the presence or absence of the intermetallic compound (IMC) layer at the solder-substrate interface. SEM-EDS analysis was conducted to observe the detailed morphology and IMC layer growth on the microstructure cross-section, as well as to determine the elemental composition of the IMC formed at the SAC305 solder and Cu substrate interface. X-ray diffraction (XRD) testing was performed to identify the reaction phases of the IMC layer formed at the solder-substrate interface. The solder/waste sample/solder stack was placed in a quartz tube and subjected to reflow treatment at 220°C to induce a solid–liquid interfacial reaction. To assess phase growth and transformation at the interface, reflow times were varied at 15, 30, 45, and 60 minutes. After reflowing, the tubes were slowly cooled, and the specimens were analyzed using Optical Microscopy, SEM, and XRD.

3. RESULTS AND DISCUSSION

The results and discussion cover findings obtained from Optical Microscopy, SEM, and XRD analyses. In this results and discussion section, the reaction outcomes obtained during the research process are presented obtained from Optical Microscopy Observation, SEM, and XRD analyses.

3.1 Optical Microscopy

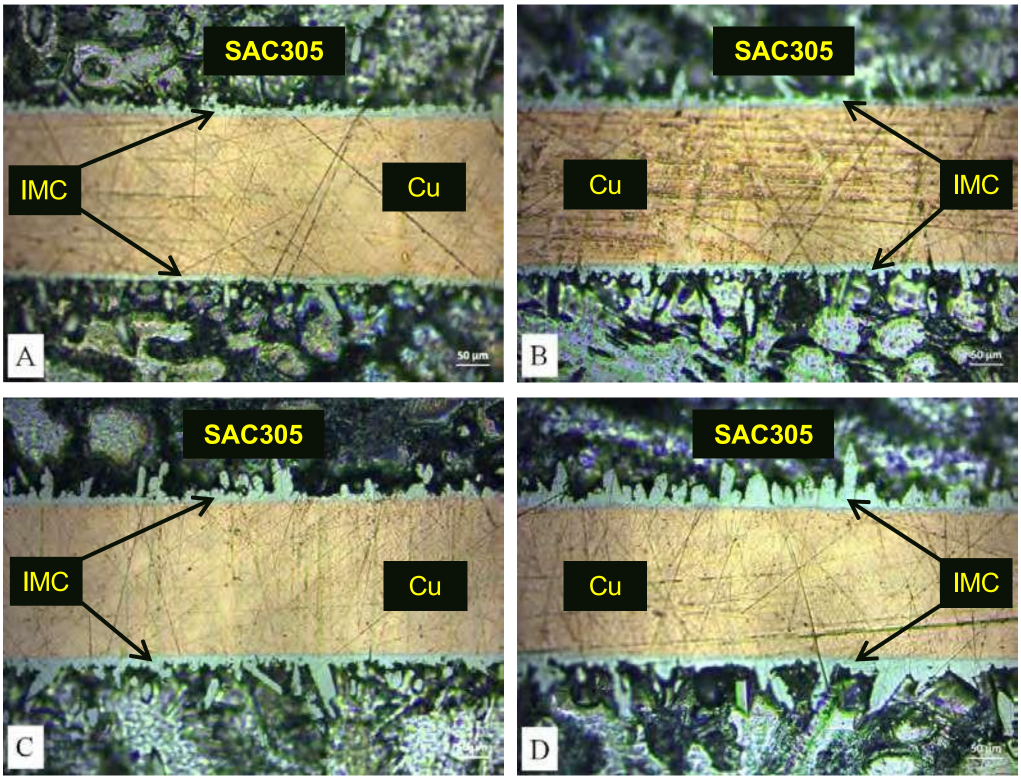

Figure 2. Optical microscope images of the SAC305/Cu interface at 50x magnification with various reflow times: (a) 10 minutes; (b) 30 minutes; (c) 50 minutes; and (d) 70 minutes.

From Figure 2, it is observed that an intermetallic compound (IMC) layer formed at the SAC305/Cu solder joint interface for each reflow time variation at a temperature of 290°C. These results are consistent with the findings of Tan et al. (2020) and Hu et al. (2016), who stated that during the reflow soldering process, an IMC layer forms at the solder joint interface, indicating the formation of a good metallurgical bond. It is also evident from the observation that the thickness of the IMC layer differs with each reflow time. Therefore, the IMC layer thickness was measured using ImageJ software. The resulting data of the IMC layer thickness for each reflow time variation is presented in the following Table 1:

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Table 1. IMC Layer Thickness at the SAC305/Cu Solder Joint Interface for Each Reflow Time Variation

Temperature	***Reflow* time**	**IMC interface thickness (μm)**				**Average IMC interface thickness (μm)**
		1	2	3	4	
290°C	10 **minutes**	11.837	10.490	10.725	-	10.738
	30 **minutes**	17.085	14.029	14.467	-	15.453
	50 **minutes**	20.543	19.068	19.202	-	19.907
	70 **minutes**	24.891	20.581	23.408	25.628	23.628

Based on Table 1, the average IMC layer thickness at 10 minutes was 10.738 μm, at 30 minutes was 15.453 μm, at 50 minutes was 19.907 μm, and at 70 minutes was 23.628 μm. These thickness values were then used to generate a graph illustrating the relationship between IMC thickness and reflow time, as shown below:

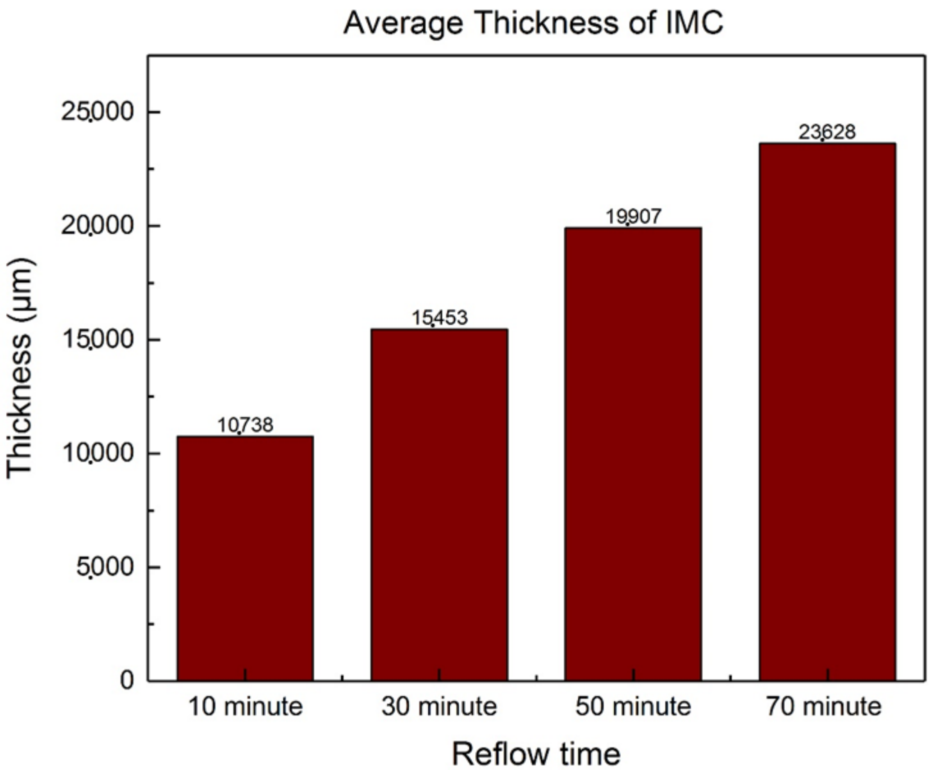

Figure 3. Graph of the Average Thickness of the IMC Layer at the SAC305/Cu Solder Joint Interface for Each Reflow Time Variation

From Figure 3, the thickness of the IMC layer at the solder joint interface increases with longer reflow times during the soldering process. This increase is attributed to the growth of the IMC layer caused by the diffusion of Cu atoms. With a longer reflow time, more Cu atoms are able to diffuse, resulting in a thicker IMC layer. This observation is in agreement with the statement by Kong et al. (2015), which states that the growth of the IMC layer is time-dependent and is governed by a diffusion-controlled mechanism.

3.2 SEM-EDS Analysis

SEM analysis was conducted using a Phenom ProX instrument with several magnifications on specimens reflowed for 10, 30, 50, and 70 minutes at a temperature of 290°C. The SEM observation was carried out on the cross-sectional area of the specimen using the BSE (Backscatter Electron) detector, which distinguishes the different phases in the specimen based on the contrast in brightness.

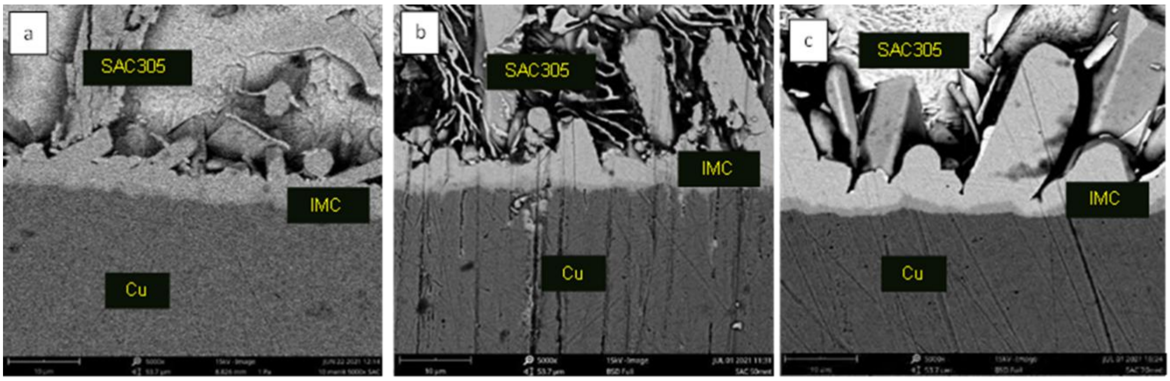

Figure 4. SEM results of the SAC305/Cu solder joint interface at 5000x magnification for various reflow times: (a) 10 minutes, (b) 50 minutes, and (c) 70 minutes

From Figure 4, it is evident that there are two distinct IMC layers with different brightness levels and morphologies. The brighter layer exhibits a scallop-like morphology, whereas the darker layer displays a planar morphology. According to Tan et al. (2020), the IMC phases typically formed at the interface between SnAgCu solder and Cu substrate are Cu_6Sn_5 and Cu_3Sn. During the soldering process, the scallop-shaped Cu_6Sn_5 layer forms first and grows rapidly, followed by the formation of a thin Cu_3Sn layer between the Cu_6Sn_5 layer and the Cu substrate.

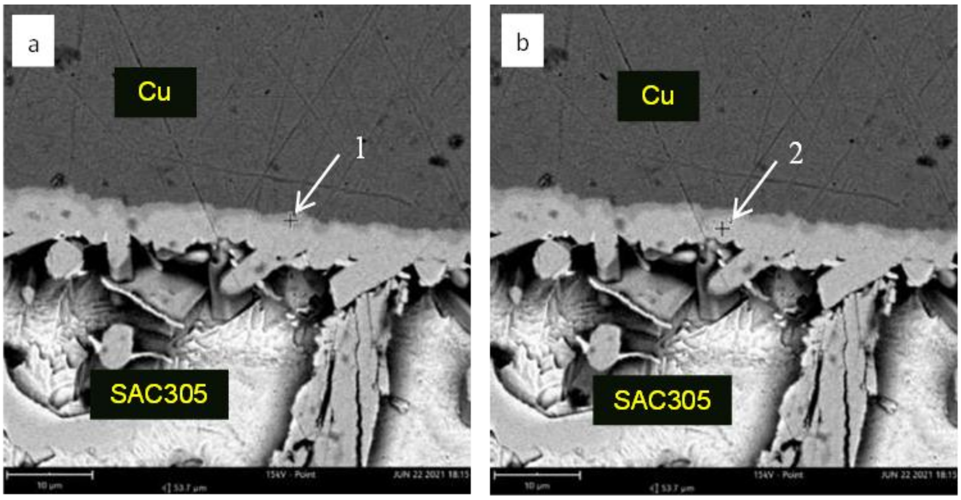

Figure 5. EDS Analysis Results of the IMC Layer at the SAC305/Cu Solder Joint Interface with a Reflow Time Variation of 10 Minutes: (a) Spot 1 and (b) Spot 2

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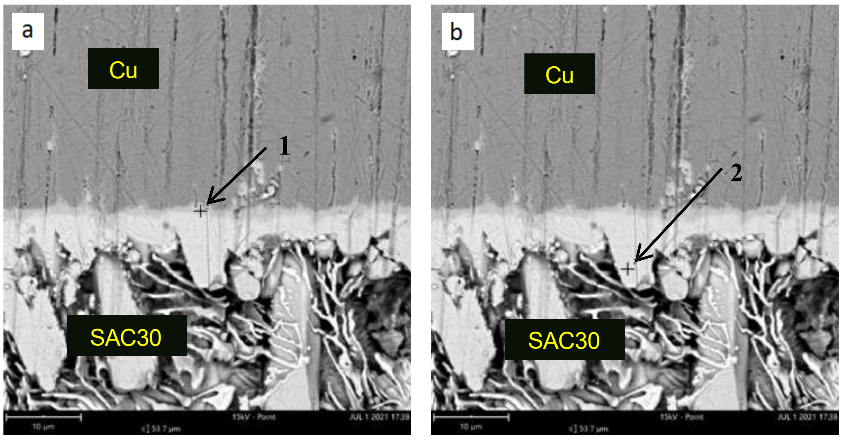

Figure 6. EDS Analysis Results of the IMC Layer at the SAC305/Cu Solder Joint Interface with a Reflow Time Variation of 50 Minutes: (a) Spot 1 and (b) Spot 2

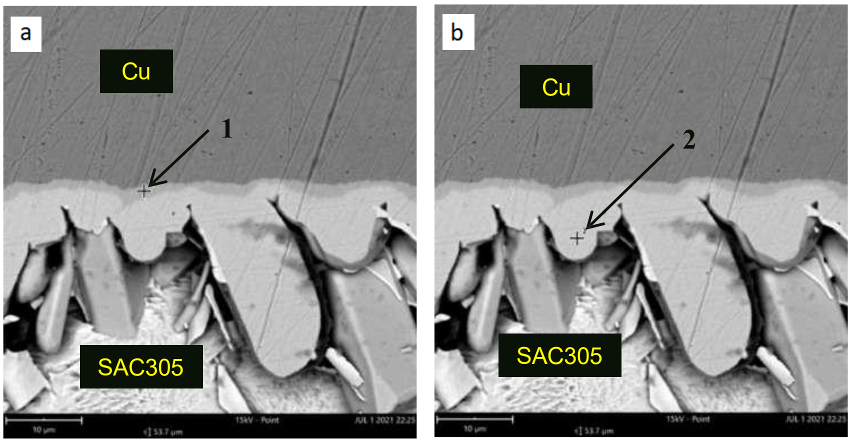

Figure 7. EDS Analysis Results of the IMC Layer at the SAC305/Cu Solder Joint Interface with a Reflow Time Variation of 70 Minutes: (a) Spot 1 and (b) Spot 2

Table 2. Elemental Composition of the IMC Layer at the SAC305/Cu Solder Joint Interface for Each Reflow Time Variation

Reflow time	Element number	Element symbol	Element	Atomic Conc.	Weight Conc.
10 menit	29	Cu	Copper	66.28	51.27
	50	Sn	Tin	33.72	48.73
	50	Sn	Tin	53.80	68.51
	29	Cu	Copper	46.20	31.49
50 menit	29	Cu	Copper	65.24	50.25
	50	Sn	Tin	32.79	47.18
	50	Sn	Tin	51.53	65.69
	29	Cu	Copper	45.87	31.30
70 menit	29	Cu	Copper	65.68	50.71
	50	Sn	Tin	32.59	47.02
	50	Sn	Tin	51.01	65.41
	29	Cu	Copper	46.98	32.24

Following the EDS analysis, it was observed that the brighter IMC layer with a scallop-type morphology—shown in Figure 5(b)—had a composition of 46.20 at% Cu and 53.80 at% Sn. Similarly, in Figure 6(b), the composition was 45.87 at% Cu and 51.53 at% Sn, while in Figure 7(b), it was 46.98 at% Cu and 51.01 at% Sn. Across all reflow time variations, the spot 2 regions exhibited Cu contents above 45% and Sn contents above 50%, indicating the formation of the Cu_6Sn_5 phase based on the Cu–Sn phase diagram. According to Ting Tan et al. (2015), the Cu_6Sn_5 phase forms when Sn-based solder melts and either dissolves the Cu substrate or facilitates rapid Cu atom diffusion at the interface between molten solder and solid Cu substrate.

In contrast, the thinner, darker, planar-type IMC layer—seen in Figure 5(a)—had a composition of 66.28 at% Cu and 33.72 at% Sn. The corresponding compositions for Figures 6(a) and 7(a) were 65.24 at% Cu and 32.79 at% Sn, and 65.68 at% Cu and 32.59 at% Sn, respectively. For all reflow time variations, the spot 1 regions exhibited Cu contents above 60% and Sn contents above 30%, suggesting the presence of the Cu_3Sn phase. According to Lee et al. (2013), the Cu_3Sn layer forms subsequent to the Cu_6Sn_5 phase, as it requires longer Cu diffusion times into the molten solder. This phase typically develops between the Cu_6Sn_5 layer and the Cu substrate. Although the Cu_3Sn layer thickness increased with reflow time, its growth was not significant and remained as a thin interfacial layer.

3.3 XRD Analysis

XRD analysis was performed using a Bruker diffractometer on each specimen with reflow time variations of 10, 30, 50, and 70 minutes at a temperature of 290°C. The diffraction data obtained were then processed using Diffract EVA and Origin software.

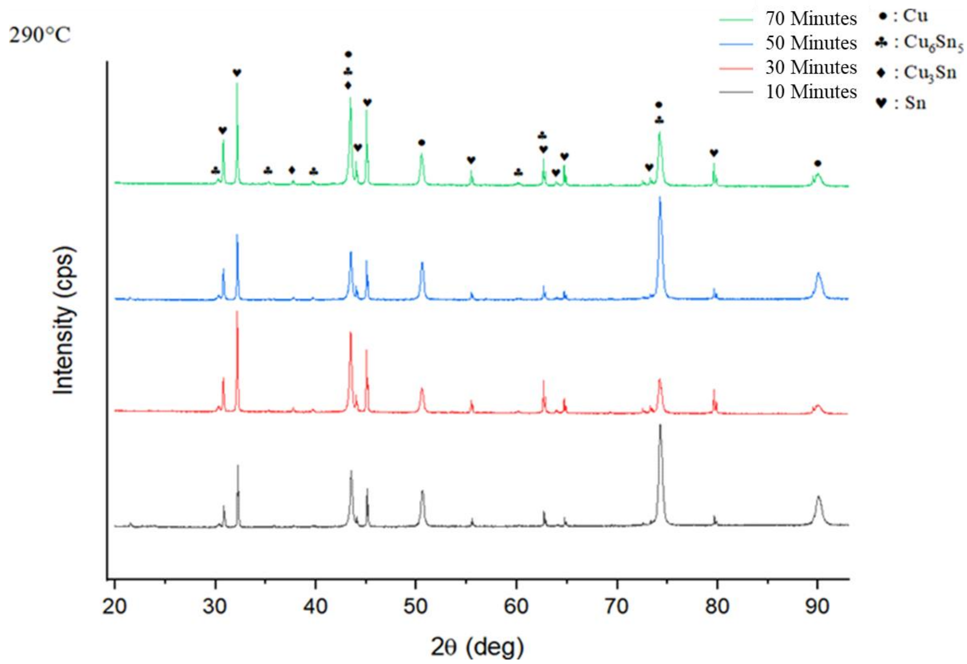

Figure 8. XRD Analysis Results of the IMC Layer at the SAC305/Cu Solder Joint Interface for Each Reflow Time Variation

Figure 8 shows the XRD diffraction patterns of the intermetallic compound (IMC) layers formed at the SAC305/Cu solder joint interface for each specimen reflowed at 290°C for 10, 30, 50, and 70 minutes. The diffraction patterns confirm the presence of several IMC phases formed at the solder interface, namely Cu_6Sn_5 and Cu_3Sn. In addition, elemental Cu and Sn were also detected. Peaks observed at 30.42°, 30.81°, 35.82°, 43.45°, 45.15°, 60.17°, 62.77°, and 74.30° were identified as Cu_6Sn_5 phases, while peaks at 37.75° and 43.45° correspond to Cu_3Sn. These identifications were made by matching the diffraction data with the PDF-4+ database using Diffrac.EVA software.

From the diffraction patterns in Figure 8, the Cu_6Sn_5 phase appears more prominently than Cu_3Sn. This is attributed to the fact that Cu_6Sn_5 forms earlier at the SAC305/Cu solder interface, followed by the formation of the thinner Cu_3Sn layer, which requires a longer diffusion time to grow (Lee et al., 2013). The presence of both Cu_6Sn_5 and Cu_3Sn phases contributes to strong metallurgical bonding at the solder joint. According to Bernasko (2012), these IMC phases' exhibit superior mechanical properties compared to the solder alloy and the Cu substrate themselves.

4. CONCLUSION

The formation of intermetallic compound (IMC) layers at the SAC305/Cu solder joint interface was achieved using the interfacial reaction couple method. The resulting IMC layers consisted of the Cu_6Sn_5 phase with a scallop-like morphology and the Cu_3Sn phase with a planar morphology. The average thickness of the IMC layers increased progressively with longer reflow times. Specifically, the average IMC thicknesses for reflow durations of 10, 30, 50, and 70 minutes were 10.738 µm, 15.453 µm, 19.907 µm, and 23.628 µm, respectively.

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