MEMI

E-ISSN XXXX-XXXX | P-ISSN XXXX-XXXX
Vol.1, No.1-5, June, 2025, pp. 27-34

TEKNIK MATERIAL DAN METALURGI

IMC LAYER GROWTH IN Cu/Sn-58BI WITH VARYING REACTION TIMES

Amilita Medisa Rizky Dharmayanti [a,1,*], Asri Milanda [a,2], Hizkia Alpha Dewanto [a,3]

[a] Materials and Metalllurgical Engineering Department, Institut Teknologi Kalimantan, Balikpapan 76127, Indonesia
[1] amilita.dharmayanti@lecturer.itk.ac.id*; [2] asrimilanda@gmail.com; [3] hizkia.ad@lecturer.itk.ac.id

ARTICLE INFO

Article history
Received: 2025-05-27
Revised: 2025-06-15
Accepted: 2025-06-21

Keywords
Sn-58bi Solder;
Interfacial Reaction;
Time Reflow;
Intermetallic Compounds;
Printed Circuit Boards.

ABSTRACT

The increasing use of electronic devices has led to a rise in electronic waste, particularly from components such as Printed Circuit Boards (PCBs), which often contain lead-based solder. Lead (Pb) poses significant environmental and health hazards. To address this issue, this study investigates the use of lead-free Sn-58Bi solder as a safer alternative. The research focuses on analysing the interfacial reaction between Sn-58Bi solder and a Cu substrate, particularly the influence of reflow time on the formation of intermetallic compounds (IMCs) and their morphology. The Cu substrates were first cut to the desired dimensions and combined with Sn-58Bi solder balls using the interfacial reaction couple method. Samples were coated with flux and arranged in a solder ball/substrate/solder ball configuration inside a test tube, then subjected to reflow soldering at 220 °C for 15, 30, 45, and 60 minutes. Post-reaction, the specimens were mounted, ground, and examined using Optical Microscopy to observe IMC layer formation. Further characterization was performed using SEM-EDS and XRD to identify the phases and morphologies formed. The results confirmed the formation of Cu_6Sn_5 and Cu_3Sn phases at the solder-substrate interface, with the IMC layer thickness increasing with longer reflow durations.

1. INTRODUCTION

The increasing production in the electronics industry sector has led to higher consumer demand, which consequently generates new types of waste, particularly electronic waste. Among these wastes, printed circuit boards (PCBs) are one of the most prevalent components. In a PCB assembly, a connection system is essential. To establish such connections, solder is used to join two circuit systems (conductors), thus forming an electrical bridge (Yen, Laksono, & Yang, 2019). Solder has long been widely utilized in the electronics industry, with the commonly used solder material being Sn-Pb. Soft solder (Sn-Pb) is found in applications such as devices exposed to sunlight and jewelry manufacturing (Vianco, Kilgo, & Grant, 1995). However, Sn-Pb solder contains lead (Pb), a heavy metal that is hazardous to both human health and the environment. These hazards have raised concerns among researchers about the future implications of continued Pb-containing solder use. This awareness, along with restrictions on hazardous substances (RoHS) in the electronics industry, has promoted the development and use of lead-free solder alternatives. One such alternative is Sn-58Bi solder, which is frequently applied in low-melting-point soldering applications.

Moreover, understanding the kinetics of Intermetallic Compound (IMC) layer growth is vital for ensuring long-term solder joint reliability in modern electronic devices. Excessive or uneven IMC formation can lead to brittleness, thermal fatigue, and ultimately joint failure under cyclic loading or thermal cycling. By systematically studying how reflow time influences the morphology and thickness of Cu_6Sn_5 and Cu_3Sn phases at the Cu/Sn-58Bi interface, this research provides crucial insights for optimizing lead-free soldering processes. These findings will help establish reflow profiles that balance low-temperature processing benefits with mechanical robustness, advancing the adoption of Sn-58Bi solder in high-reliability applications and contributing to sustainable electronics manufacturing.

In soldering processes, wettability is a crucial characteristic for evaluating lead-free soldering technology (A. D. Laksono, Yen, Tanjung, Amatosa, & Harwahyu, 2021). The average thickness of the formed IMC layers increases with higher temperatures and longer dwell times (A. D. Laksono, Shen, Chen, & Yen, 2024). Therefore, to investigate the influence of Sn-58Bi solder and reflow time variation on the interfacial phase and morphology between Cu substrates and Sn-58Bi solder, this study focuses on "IMC Layer Growth in Cu/Sn-58Bi with Varying Reaction Times" This study aims to form IMC layers consisting of Cu_6Sn_5 and Cu_3Sn phases, confirmed through Optical Microscopy (OM), Scanning Electron Microscopy (SEM), and X-ray Diffraction (XRD) analysis.

2. METHODS

This research uses the interfacial reaction method. Initially, the substrate was prepared by cutting to specified dimensions, while the solder was cleaned sequentially using acetone, HCl, and ethanol. The substrate and solder were weighed with a mass ratio of 1:3, as established in prior research (A. D. Laksono, Chen, & Yen, 2023). Based on previous studies, the specimens were coated with a small amount of flux on both sides to enhance the wettability of molten solder by removing surface oxides on the sample plates.

The solder/substrate/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 OM, SEM, and XRD.

3. RESULTS AND DISCUSSION

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

3.1 OM

OM was conducted on specimens subjected to interfacial reaction at 220 °C for 15, 30, 45, and 60 minutes using a Zeiss Digital Microscope at the Integrated Laboratory, Institut Teknologi Kalimantan. This analysis aimed to observe the formation of IMC layers at the Cu substrate–Sn-58Bi solder interface.

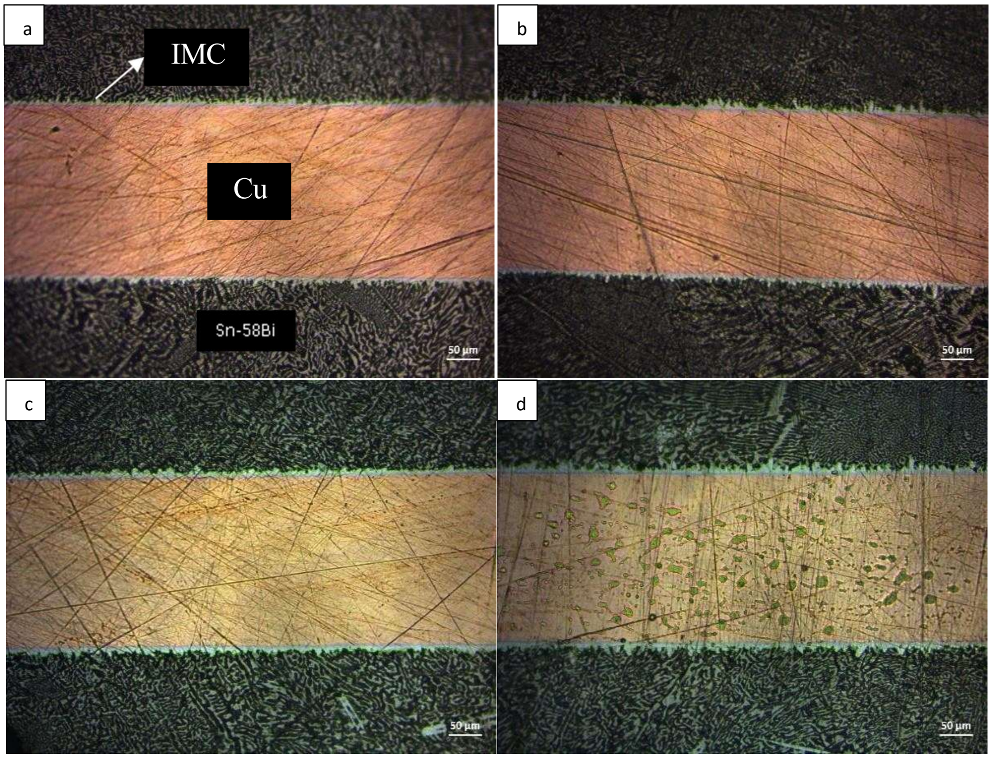


Figure 1. OM Images Results at 50x Magnification with Time Variations: a) 15 min, b) 30 min, c) 45 min, d) 60 min.

Figure 1 shows the formation of thin IMC layers at the Cu/solder interface. The interfacial reaction products may vary depending on the soldering conditions. Differences in IMC thickness were observed across different reflow times. ImageJ software was used to measure and average the IMC thickness for each time variation, as shown in the following table:

Table 1. Average IMC Thickness

Time (minute)	**IMC thickness (µm)**				**Average IMC thickness (µm)**
	side 1	**side 2**	**side 3**	**side 4**	
15	3.8	4.8	4.6	3.9	4.3
30	5.3	4.9	4.8	4.5	4.9
45	7.5	7.4	7.6	6.3	7.2
60	8.5	8.0	8.9	8.6	8.5

As shown from Table 1, that the thinnest IMC layer (4.3 µm) occurred during time reflow at 15 minutes, while the thickest (8.5 µm) was at 60 minutes. This indicates that IMC thickness increases with longer reflow times, in line with Fick's second law, which states that diffusion is time-dependent. This observation is supported by (A. D. Laksono, Tsai, Chung, Chang, & Yen, 2023), who also reported that IMC thickness increases with reaction time and temperature.

3.2 SEM-EDS ANALYSIS

SEM-EDS analysis was conducted using the Phenom ProX at the Integrated Laboratory, Institut Teknologi Kalimantan. SEM was used to examine the IMC morphology, while EDS was used to determine the chemical composition. The results was shown below in Figure 2.

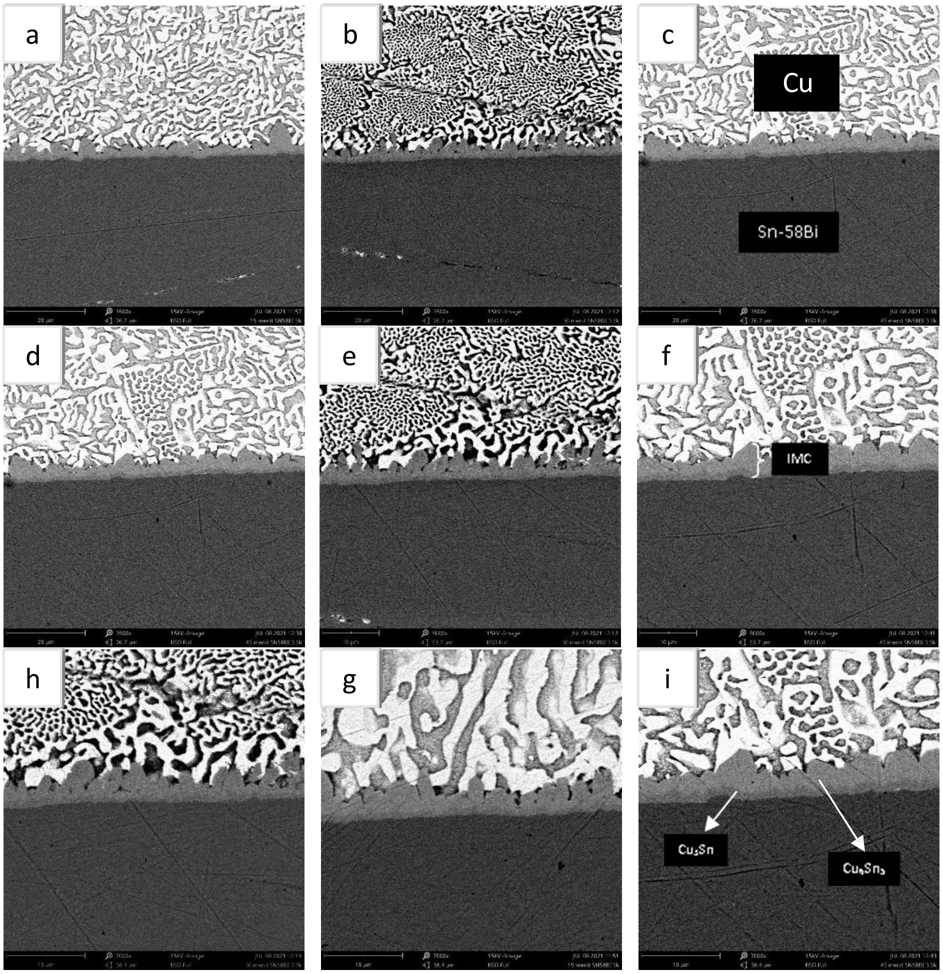


Figure 2: SEM images with reflow time variations of 15, 30, and 45 minutes at magnifications of (a–c) 3500x, (d–f) 5000x, and (g–i) 7000x.

Based on the Figure 2, the SEM results confirmed the formation of IMC layers at the Cu–Sn-58Bi interface, which specifically shows the existence of intermetallic phases of Cu_6Sn_5 and Cu_3Sn phases. According to (Yen et al., 2025), Cu_6Sn_5 forms first due to its easier nucleation and its relatively easy crystal growth in molten Sn, followed by Cu_3Sn phase. Each time variation shows both IMC phases, and the IMC thickness increases with time. As observed in the figure, both Cu_6Sn_5 and Cu_3Sn phases are present at all time variations, and the thickness of the IMC layer increases with longer reflow times. Regarding morphology, a scallop-like structure is observed, which aligns with the findings of (Hu, Li, & Min, 2013), who reported that during the reflow process, the Cu_6Sn_5 IMC layer forms continuously with a scallop-shaped morphology at the substrate interface.

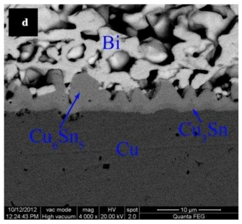
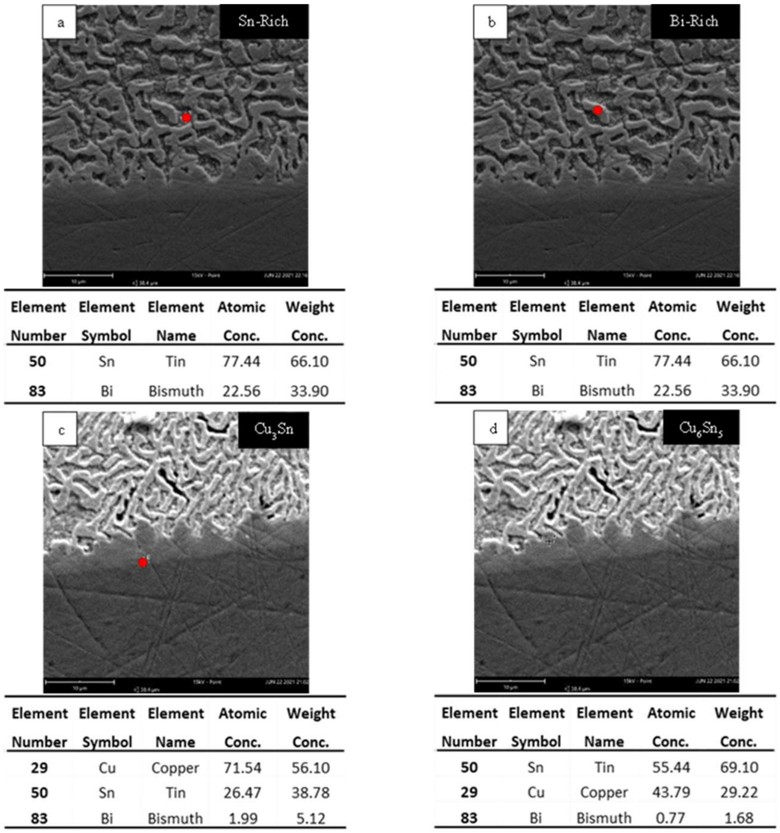


Figure 3. IMC Layer Morphology (Hu et al., 2013).

According to Hu (2013), Bi phase appears as white regions, while Cu phase shown as dark areas, Cu_6Sn_5 as bright IMC areas, and Cu_3Sn as darker IMC areas. These identifications were supported by atomic and weight percentage analysis through EDS, correlated with the Cu-Sn binary phase diagram.



Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
50	Sn	Tin	77.44	66.10
83	Bi	Bismuth	22.56	33.90

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83	Bi	Bismuth	22.56	33.90

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
29	Cu	Copper	71.54	56.10
50	Sn	Tin	26.47	38.78
83	Bi	Bismuth	1.99	5.12

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
50	Sn	Tin	55.44	69.10
29	Cu	Copper	43.79	29.22
83	Bi	Bismuth	0.77	1.68

Figure 4. SEM-EDS results (a-b) 45 min reflow, (c-d) 30 min reflow.

EDS results revealed Bi at points 3 and 4 as shown as Figure 4. Based on classical diffusion control theory (Ismail, Laksono, Dewanto, Putri, & Yen, 2022; A. Laksono, Chou, & Yen, 2024), Bi tends to precipitate because its solubility in Cu_3Sn is lower than in Cu_6Sn_5. As Cu_6Sn_5 transforms into Cu_3Sn during IMC growth, Bi accumulates and migrates to the Cu_3Sn/Cu interface under the Kirkendall effect, potentially forming nanoscale Bi precipitates. Since Bi does not react with Cu, this can deteriorate the IMC layer with prolonged reflow time.

3.3 XRD ANALYSIS

XRD analysis was conducted using a Bruker instrument at the Integrated Laboratory, Institut Teknologi Kalimantan. The objective was to identify, analyze, and confirm the phases formed at the interfacial layer between the Cu substrate and Sn-58Bi solder after being reacted for varying durations of 15 minutes, 30 minutes, 45 minutes, and 60 minutes. Data were processed using Diffrac.EVA and plotted in Origin, following established literature methodologies (A. D. Laksono, Al-Audhah, Chen, Ho, & Yen, 2023; A. D. Laksono & Yen, 2023).

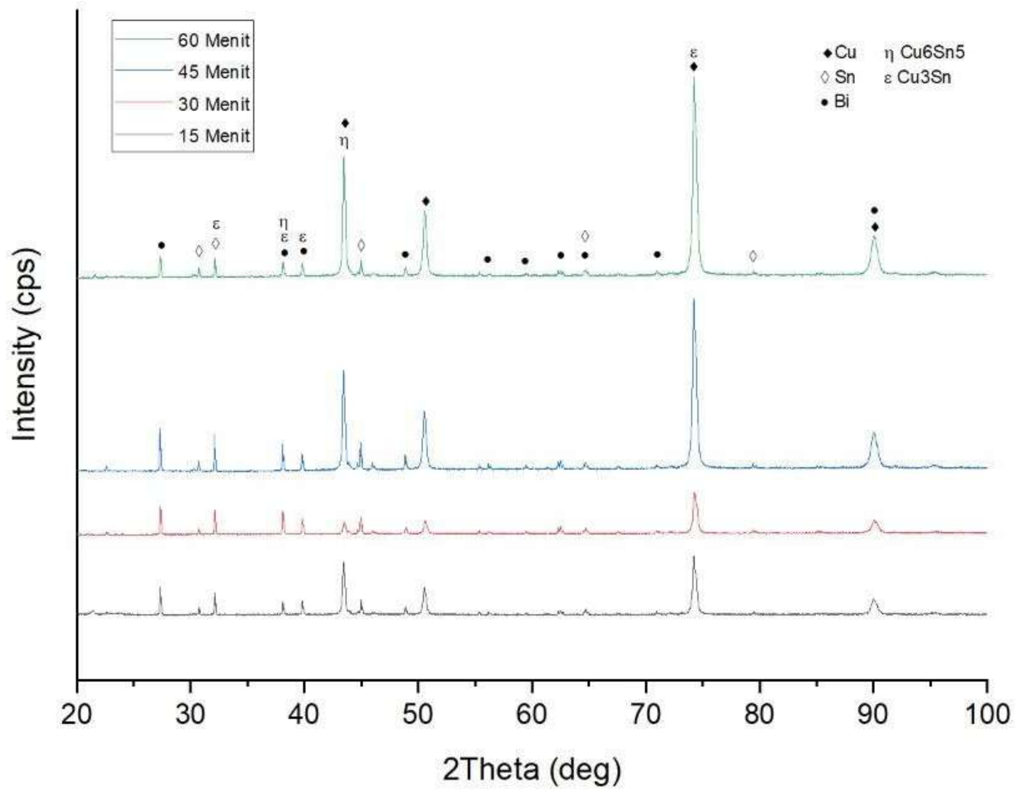

Figure 5. XRD Result Graph.

The XRD data revealed peaks corresponding to Cu, Sn, Bi, Cu_6Sn_5, and Cu_3Sn. According to the PDF-4+ database, Cu_6Sn_5 is indicated by peaks at 38°, 43.4°, while Cu_3Sn appears at 32°, 38°, 39.8°, and 74.2°. Additional peaks were observed for Cu (43.4°, 50.5°, 74.2°, 90°), Sn (30.7°, 32°, 45°, 64.5°), and Bi (27.3°, 38°, 39.8°, 90°), along with minor peaks.

The XRD results show that the peaks are similar across different reaction time variations, but the wave intensity increases as the reaction time increases. The graph in Figure 4 shows variations in the diffraction patterns for each time interval. The diffraction patterns, as represented by the peaks, are similar across the variations, and the detected phases include Cu, Sn, Bi, Cu_6Sn_5, and Cu_3Sn.

4. CONCLUSION

Based on the analysis and discussion, the study concludes that the interfacial reaction between Cu substrates and Sn-58Bi solder produces IMC layers consisting of Cu_6Sn_5 and Cu_3Sn with scallop-like morphology. The average IMC thickness increases with reflow time. With prolonged reflow, the IMC morphology shifts from scallop to planar. The increased IMC thickness enhances shear strength, improving mechanical integrity. The most optimal IMC characteristics were obtained at 45 minutes of reflow time.

ACKNOWLEDGMENTS

All praise and gratitude we offer to God Almighty for His blessings and grace, which have enabled us to complete this research. We would also like to express our deepest thanks to all individuals who contributed to the completion of this research, whose names cannot be mentioned one by one.

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