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Effect of reflow temperature on intermetallic compound thickness for Sn-58Bi/Cu reaction couple

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Soldering
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ABSTRACT

The technology of electronic connection between the solder and the substrate becomes very important considering that both materials require an electrical bridge. However, the use of conventional solder with lead content is no longer allowed, thus research on lead-free soldering is being developed. This research aims to investigate the effect of reflow temperature on the intermetallic compound (IMC) thickness for Sn-58Bi soldered joints. The interfacial reaction couple between Sn-58Bi solder and Cu sheet is selected. The reflow temperature is set to 61°C, 71°C, 81°C, and 91°C above solder liquidus temperatures for Sn-58Bi. The duration of time above solder liquidus temperature is set to 30 minutes. Scanning electron microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS) are used to investigate the interface morphology and to analyze local composition. In addition, X-ray Diffraction (XRD) measurements are conducted to ensure phase identification on IMC. Statistical analyses are necessary to compare the difference in IMC thickness growth between Sn-58Bi/Cu reaction couple. The result shows the formation of IMC layer of Cu_6Sn_5 and Cu_3Sn in the interface of substrate-solder. The IMC layer thickness increases as a function of temperature.

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1.0 INTRODUCTION

Human life today is inseparable from electronic equipment such as the use of television, computers, laptops, refrigerators, and various other equipment. Along with its development, electronic equipment is becoming more and more light, small, and high-performance, high-density I/O (In/Out) and the miniaturization of interconnection technology adopted between electronic equipment and substrates are becoming increasingly important. The development of new materials with properties such as excellent adhesion and wettability, low friction, and high surface to volume ratio are required to meet the requirements for the advancement of technology such as micro electro mechanicals systems for soldering interconnect applications (Mahayuddin et al., 2020). To connect various circuit systems, solder is needed to connect two circuit systems (conductors) to produce an electrical bridge (Yen et al., 2008). A solder has good properties and easy way to use as a conventional Sn-Pb alloys, thus it is often widely used in the soldering process (Yen et al., 2019). However, according to Waste Electrical and Electronic Equipment (WEEE) and Restriction of Hazardous Substances (RoHS) laws, lead is a dangerous metal, where compounds can be harmful to human health. Where waste from electronic goods containing lead does not have adequate waste treatment so that waste containing lead can pollute groundwater flowing into rivers, hence it is dangerous if these rivers become water sources for the community. The heavy polluting industries from electronic waste contents lead that becomes unfriendly environmental. According to exposure assessments, the hazard quotient values of heavy metal exposure from dust lead were remarkably high, 11.10 that means lead was the most attention pollutant that posed a significant risk. Above 10 percent of children blood lead levels in many countries such as Germany, USA, China were exceeding the limit (Shi & Wang, 2021). To control the amount of lead waste, since July 1, 2007, lead-free solder has almost replaced Sn-Pb solder in the industrial world (Yen et al., 2010). Various studies have shown that 42Sn-58 Bi or Sn-58Bi has the potential to be a substitute for lead solder. This solder has characteristics that can be used in electronic manufacturing processes. It has a low melting point and good connection reliability and high strength, resistance to defects, and fatigue resistance at high temperatures (Hu et al., 2014; Tao et al., 2001; Yen et al., 2010). The mechanical properties and intermetallic compound (IMC) formation of Sn-58Bi were determined in as-reflowed conditions (Lee et al., 2015; Liu et al., 2021).

In the soldering process, the substrate is in contact with the solder and then fused with the melted solder. Chemical potential gradients between different materials can cause interdiffusion of heterogeneous atoms in the solder and substrate boundary layers. When the substrate is in contact with the melted solder, local equilibrium can cause an IMC to form at the solder/substrate interface. The presence of diffusion, IMC, and molten solder are important in the soldering process, where this can affect the mechanical strength and reliability of the solder joint. When the substrate reacts with the solder too fast, electronic devices can short circuit and fail, where the IMC can become thick and the impedance increases, which will affect the electrical conductivity (Glazer, 2012).

To ensure the reliability of the connection, as well as the effect of reflow temperature on the IMC of the Sn-58 Bi solder joint, it is necessary to conduct research on effect of temperature reflow on IMC thickness for Sn-58Bi/Cu reaction couple. The obtained IMC were analyze using morphological and composition as well as the research about thin film that has been investigated previously (Razak et al., 2020).

2.0 EXPERIMENTAL PROCEDURE

The experiment was divided into two major sections, sample production and sample characterization.

Sample was produced from copper (Cu) substrate and Sn-58Bi solder. Cu substrate was pure copper (99.99% purity) metal sheet, cut into the size of 10 mm × 5 mm × 0.1 mm. Industrial grade Sn-58Bi (99.99% purity) was obtained from Anhui Fitech Materials, Co. Ltd. The liquidus temperature for Sn-58Bi is 139 °C. Experiment steps were based on the previous research (Laksono et al., 2019).

Sn-58Bi solder balls were cleaned by acetone, acid, and alcohol in sequence in order to remove oxide layer and impurities prior to use. After thorough cleaning of sample materials, substrate and solder balls were put inside the test tube in such a way that copper substrate stood upright inside the tube, flanked by solder balls, as indicated in Figure 1. This experiment used reflow temperatures of 61°C, 71°C, 81°C, and 91°C above solder liquidus temperatures as representative of liquid state from Sn-Bi binary phase diagram with 58 wt.% Bi to prove the reaction couple of Sn-58Bi and Cu under ambient pressure. The Sn-58Bi/Cu couples were heated using a box furnace with reflow temperature of 200, 210, 220, and 230 °C and holding time (reflow time) of 1800 s (30 minutes). After heating in the furnace, the samples were cooled by air cooling method.

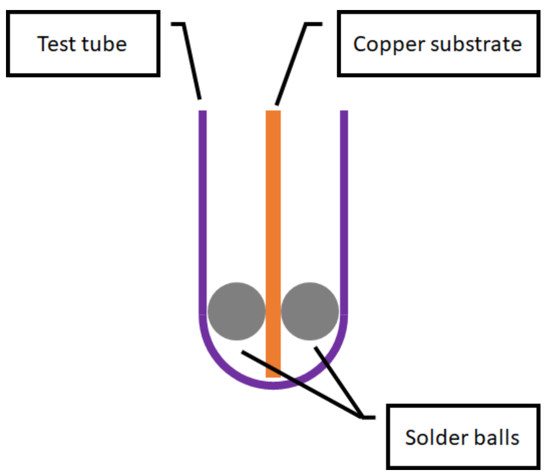

Figure 1: Substrate and solder ball placement inside test tube for sample production.

The second section of the experiment is sample characterization. The main goal of characterization is determination of IMC layer appearance and composition. First, the specimen was cut through its middle-lower section in such a way that the cross section of solder and substrate is clearly seen. Then, the specimen was mounted on resin mounting. After that, the specimen was grinded and polished, so the clear appearance of the cross section was exposed, and presence of IMC could be clearly distinguished.

The characterization itself consisted of 3 separate methods:

(a) Optical microscopy, to observe the presence and measure the thickness of the IMC layer.
(b) Scanning Electron Microscope (SEM) observation, to observe the morphology of the IMC layer and areas surrounding it with detail, assisted by the ImageJ program in the thickness measurement.

(c) X-Ray Diffraction (XRD), to obtain composition of the IMC layer and identify the phase that composed the IMC layer. The composition identification was assisted by utilization of Match! program.

3.0 RESULTS AND DISCUSSION

Observation by optical microscopy showed the thickness of the IMC layer in response to reflow temperature used in a simulated soldering process using a furnace. The magnification level used in observation is 100x.

Optical microscope images showed that the surface of the sample was not quite smooth, which we thought was caused by the option of sandpaper roughness we chose in the grinding process. The presence of the IMC layer was distinctive enough to aid thickness measurement using image analysis software. The image themselves was shown in Figure 2.

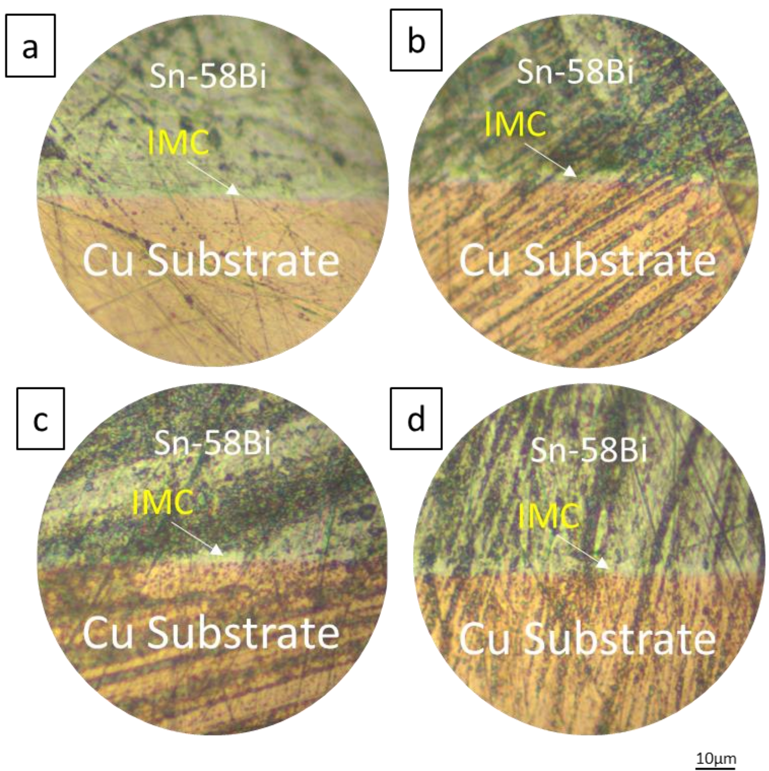

Figure 2: The appearance of the result of the interface reaction between Cu substrate and Sn-58Bi solder, observed by optical microscope with 100x magnification, classified into reflow temperature used: (a) 200 °C, (b) 210 °C, (c) 220 °C, (d) 230 °C. IMC is visible as a light gray border between yellowish (copper) and darker gray (Sn-58Bi solder). Black scale bar is 10μm.

The difference of color itself showed the proof of the formation of an intermetallic compound between solder and substrate, as the compound had different properties to the originating elements, including the color. In Figure 2, between Cu and Sn-58Bi, there was a layer observed with a distinctive light color. This is the IMC layer, which formed due to reaction between substrate and solder material during reflowing process, which indicated good metallurgical bonding between solder and the substrate (Hu et al., 2014; Šimeková et al., 2012).

Using image analyzing software, the thickness of IMC was able to be determined. From the result of IMC layer thickness measurement, as shown in Table 1, it is found that the layer thickness is related to reflow temperature applied to the specimen. The increase in the thickness of the IMC layer along with the increase in temperature variation was caused by the diffusion of Cu atoms during reflowing. The formation of the IMC layer is influenced by chemical reactions that occur while the growth of the IMC layer is influenced by the diffusion flow of Cu atoms (Abdelhadi & Ladani, 2012). The diffusion flow of Cu atoms based on Fick's law will increase with increasing temperature, therefore the thickness of the IMC layer will also increase with increasing temperature. Based on the research of Pan et al., the results of the thickness of the IMC layer can still be said to be ideal, this is because the thickness of the IMC layer up to 4 µm is still acceptable in industrial technology (Pan et al., 2009), but until now the maximum thickness of the IMC layer which will cause failure in solder joints is unknown.

Table 1: The average thickness of the IMC layer at each variation of the reflow temperature.

Temperature (^oC)	**IMC layer average thickness (µm)**
200	1.075 ± 0.142
210	1.265 ± 0.108
220	1.418 ± 0.132
230	2.150 ± 0.309

After testing the optical microscope, it was continued with SEM-EDX testing which was carried out on the reaction specimens at a temperature of 220 ^oC with a reflow time of 30 minutes (Figure 3) which had passed the optical microscope testing. The SEM test was carried out to determine the morphology of the IMC layer while the EDX test was carried out to determine the chemical composition contained in the IMC.

In Figure 4, the results of SEM-EDX on the reaction specimen of the Cu substrate and Sn-58Bi solder, point 2 which are indicated to form Cu_3Sn phase and dominated by Cu while pointing 3 which are indicated to form Cu_6Sn_5 phase and dominated by Sn. Cu atom is the dominant part for diffusion, and it slowly diffuses through the Cu_3Sn layer and reacts with Cu_6Sn_5 (Zhao et al., 2018). The solubility of Bi in Cu_3Sn is higher than in Cu_6Sn_5. When Cu dispersed in the Sn melt, the phase formation was Cu_6Sn_5 due to easily growth and followed by Cu_3Sn phase. The reaction should be

$$Cu_6Sn_5 + 9Cu \rightarrow 5Cu_3Sn.$$

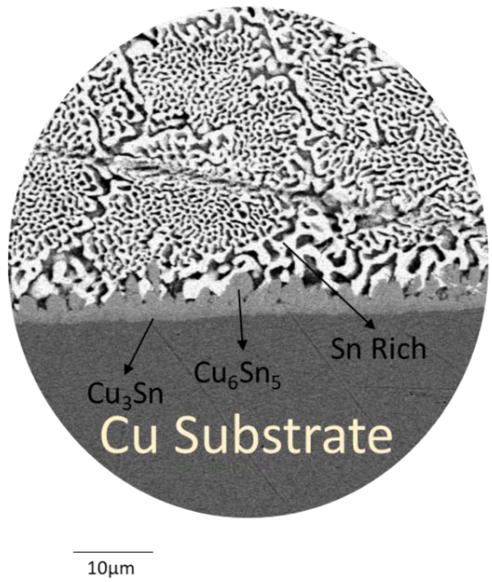

Figure 3: SEM from the Sn-58Bi/Cu sample after the reflow temperature of 220 °C for 30 minutes, showing Cu_6Sn_5 scallop-type interface.

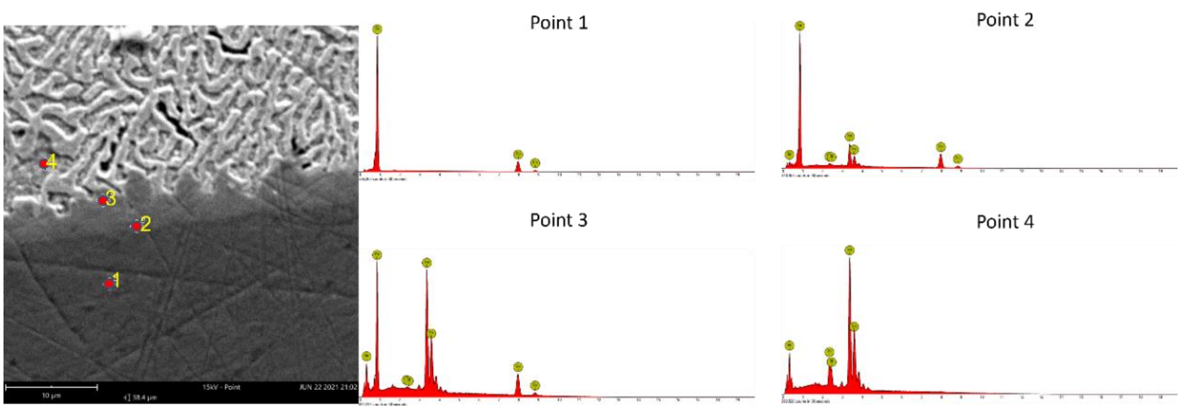

Figure 4: BEI image and EDS results of Sn-58Bi/Cu at reflow 220 °C for 30 minutes.

Table 2: Results of the chemical analyses with numbers indicating positions in Figure 3.

Point	at.%			wt.%			Phase
	Cu	Sn	Bi	Cu	Sn	Bi	
1	100	0	0	100	0	0	Cu
2	71.54	26.47	1.99	56.1	38.78	5.12	Cu_3Sn
3	43.79	55.44	0.77	29.22	69.1	1.68	Cu_6Sn_5
4	0	84.64	15.36	0	75.79	24.21	Sn Rich

Figure 5 demonstrates the X-ray Diffraction (XRD) pattern of specimen. The XRD shows the appearance of Cu_3Sn and Cu_6Sn_5 confirming the SEM-EDX result. In addition, the diffractogram also shows Bi-rich, Sn-rich phase and Cu peak which are expected due to the X-Ray beam size that is overlap with the intermetallic layer thickness.

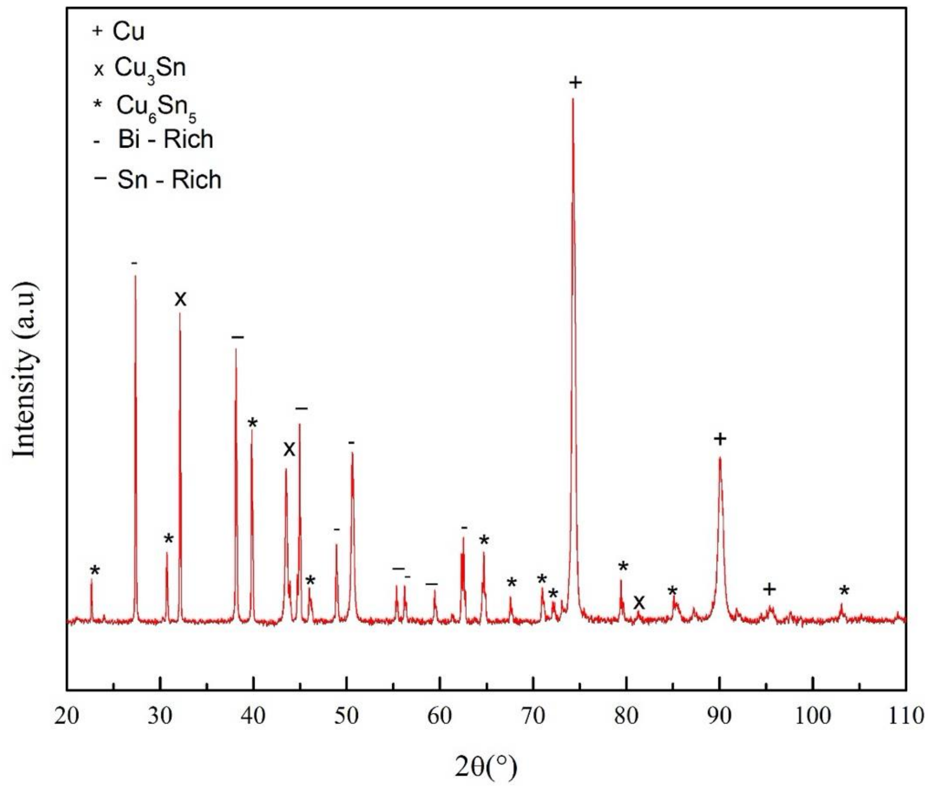

Figure 5: XRD pattern of reaction couple sample showing intermetallic compound.

CONCLUSION

This study investigated the interfacial reactions between the lead-free Sn-58Bi solder and Cu using liquid/solid. The OM, SEM-EDS, and XRD results indicate that the IMC can be identified as Cu_6Sn_5 and Cu_3Sn at 200-230 ^{o}C for 30 minutes. When the reaction temperature was increased, the IMC thickness was increased. The thickness of the IMCs layer in this study may ideal and acceptable for industrial technology.

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