The effect of multiple reflow on intermetallic layer of Sn-4.0AgCu/Cu by using microwave and reflow soldering

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Abstract. Soldering method is a general trend in demand that can be used to analyse different process parameter and their relationship in faster and easier way. Different soldering methods will influence the growth of intermetallic layer. This study investigates the effect of multiple reflow on intermetallic layer of Sn-4.0Ag-0.5Cu with diameter 700 µm solder size and Cu substrate by using microwave soldering. As comparison, reflow soldering was conducted. The material characteristic was characterised by using optical microscope, emission scanning (SEM) and energy dispersive X-ray analysis (EDX). The results revealed that only Cu6Sn5 intermetallic compound (IMC) was formed on solder joint. Meanwhile, Cu3Sn layer was detected after second and third reflow. The results also indicated that the soldering method could influence the IMC growth, where the microwave soldering produced a thinner IMC layer than reflow soldering. Besides, the morphology of IMC was observed as smaller circle bumps and scallop shapes. Moreover, the grain sizes of IMC for reflow soldering presented a larger, denser and rounder compared to microwave soldering.

1. Introduction
The formation of intermetallic compound (IMC) layer between lead-free solders and substrate is necessary for solder joint. The solder joint between the electronic device and substrate is a main interconnection for the performance and reliability of an electronic system. The IMC formation take place when there is a metallurgical reaction between a molten solder and metallization on the substrate [5, 13]. Basically, two types of IMCs which are Ag3Sn and Cu6Sn5 can be formed at interface. Large and excessive IMCs layer are quite brittle, where it can reduce the reliability of solder joint. Jen et al (2011) reported that, the brittleness of IMC caused the strong stress concentration effect during thermal cycle, and the crack propagation could easily occur near the IMC layers [6]. Subsequently, the growth of IMC could be influenced by type and size of solder, surface finish, bonding temperature and time, as well as soldering method.

Soldering is one of the important processes to melt the metals for the permanent joining of materials. The understanding of soldering process is necessary to achieve good performance of printed circuit board (PCB) manufacturing process. In electronic industrial processes, soldering method is a common trend demand that can be used to analyze difference process parameters. One of the soldering methods is using conventional furnaces such as blast furnace, induction furnace, electric arc furnace and crucible furnace [1, 12]. However, the conventional method consumes a large amount of energy and also material and energy losses [12]. In order to surpass the disadvantages of conventional furnaces, microwave processing was introduced because of their advantages such as high heating rate, shorter processing time, and low power consumption and less environmental hazard. According to
Moon et al (2005), the growth of IMC can be affected by the peak temperature and holding time in the reflow process, where a faster heating and shorter holding time can reduce the thickness of IMC layer as well as its grain size [11].

Furthermore, microwave processing also produces large amount of heat, where it can generate losses material via the volumetric. Compared to conventional furnaces, the material is melted or heated throughout external heat source as well as radiative transfer [7]. During microwave heating, it can cause sparking of metallic materials and most metals are known to reflect microwave. In this process, susceptor or cladding is used as microwave absorbing materials, where it can develop heat energy to the bulk material as well as relatively lower heating efficiency [1, 2]. Several absorbing materials such as charcoal, silicon carbide, graphite and iron powder are used in microwave soldering [1, 2, 10, 15, 16]. This paper presents the results of an experimental investigation to the effect of multiple reflow on intermetallic layer in term of thickness, type and morphology of Sn-4.0Ag-0.5Cu/Cu by using microwave soldering and reflow soldering.

2. Experimental Procedure

2.1. Material selection
In this study, the double type copper with polymer (FR-4) was selected as the substrate for joining with dimension of 40 mm x 50 mm x 1.2 mm. Solder alloy of Sn-4.0Ag-0.5Cu (SAC405) with a diameter of 700 µm was prepared for soldering. Prior to soldering, a thin layer no-clean flux was applied. Then, the solder balls were manually arranged in several rows onto the Cu substrate. The no-clean flux worked to avoid oxidation from the Cu substrate and improve the wetting of solder ball during soldering process.

2.2. Joining process
In this study, microwave is used as a soldering technique and reflow soldering for comparison. By using microwave soldering, the samples were put in the crucible alumina boat which contained iron powder, where it acted as an absorber material. Besides that, the usage of crucible could improve heating efficiency, where it can generate microwaves heat very well. The crucible that contained the samples was closed with the lid/top cover to prevent the microwave energy reflection to the Cu substrate and sent into a microwave with frequency of 2.45GHz and 800W for 60 seconds. For reflow soldering, the conventional oven was used at the reflowing temperatures of 230°C for 20 minutes to form a joint at the SAC405/Cu interface. After first reflow, the samples were exposed to second and third reflow (multiple reflow) and cooled under room temperature before they were cleaned with acetone and dried for both soldering method.

2.3. Characterization methods
Two methods of the cross-sectional and top surface were prepared for metallographic characterization. The characterizations of IMC layer on the thickness and morphology were examined using the scanning electron microscope (SEM) and image analyzer (IA). Energy dispersive x-ray (EDX) was used to identify the element of IMC composition.

3. Results and Discussion
The SEM micrographs in Figure 1 and Figure 2 show the IMC growth morphologies of SAC405/Cu after multiple reflow for both reflow soldering and microwave soldering, respectively. During reflow process, the solder ball of SAC405 melted into contact with Cu substrate and then Sn in the molten solder reacted with Cu to form IMC layer at interface. As-reflowed joint, the IMC morphology of Cu6Sn5 was formed at the SAC405/Cu interface as shown in Figure 1 (a) and Figure 2(a). The formation of Cu6Sn5 occurred because of the Cu dissolution, followed by a chemical reaction. Chemical reaction occurred between solder and conductor metal such as Cu substrate and IMC nucleate, and IMC grew at the solder/substrate interfaces [8, 19]. In the case of the second and third reflow, two types of IMCs which were Cu6Sn5 and Cu3Sn appeared at interface. When the molten
solder was exposed long enough with temperature or time, a new layer of Cu$_3$Sn was formed between Cu and Cu$_6$Sn$_5$. Tu et al (2017) and Hua et al (2014) reported that, Cu$_3$Sn was formed by diffusion reaction between Cu atom and Sn atom from the solder [4, 18]. These morphologies can be classified into two majors; scallop and circle bump shapes. It is obviously seen that the grain sizes of IMC become bigger and denser with increasing number of reflow cycles. Meanwhile, the grain size of microwave soldering technique is smaller than reflow soldering as presented in Figure 1 and Figure 2.

![Figure 1](image1.png)

*Figure 1. Top surface images of SAC405/Cu with solder size Ø700 µm by using reflow soldering: (a) first reflow, (b) second reflow and (c) third reflow.*

![Figure 2](image2.png)

*Figure 2. Top surface images of SAC405/Cu with solder size Ø700 µm by using microwave soldering: (a) first reflow, (b) second reflow and (c) third reflow.*

The cross-sectional morphology of SAC405/Cu solder joints with different soldering method was presented in Figure 3 and Figure 4. The results showed that, Cu$_6$Sn$_5$ grew as scallop grains with rough interfacial morphology between Cu substrate and the solder. Whereas, a thin layer of Cu$_3$Sn was found between Cu$_6$Sn$_5$ and Cu substrate. From the cross-sectional images, it is clearly seen that the IMC thickness is greater with the reflow times. This phenomenon might happen because of the Cu concentration in solder balls. When the reflow process exposed to third reflow, Cu concentration in solder was increased and thick IMC layer was produced. If the IMC layer became thicker, it could reduce the reliability of solder joint because the behavior of IMC is brittle [14, 17]. The thickness of IMC layers corresponding to first reflow, second reflow and third reflow were 3.77 µm, 5.73 µm and 6.07 µm for reflow soldering, respectively. The thickness of IMC by using microwave soldering for first reflow, second reflow and third reflow were 2.18 µm, 3.79 µm and 5.35 µm, respectively. These results proved that the thickness of IMC layer can influence the solder joint reliability after multiple reflow cycle.

Comparing the two results of IMC in term of thickness and grain sizes by using the reflow soldering and microwave soldering after multiple reflow process, it was clearly seen that the growth of IMC morphologies by using microwave soldering was thinner and smaller than the IMC results of reflow soldering. Based on the results, it was reasonable to mention the IMC formation on SAC405/Cu grew faster by using reflow soldering. This situation might happen because of the longer reaction time during reflow process and make it accelerates of the IMC growth. As compared to IMC formation by using microwave soldering, the IMC grew is slower and produced a thin and small grain sizes at interface because of shorter processing time during reflow process. These results are supported by Srinath et al (2011) and Moon et al (2005) [11, 15]. These results are reasonable to suggest that by
using the microwave as reflow process, it can reduce the growth of IMC formation at interface and enhance the reliability of solder joint.

Moreover, the IMCs of Cu$_6$Sn$_5$ and Cu$_3$Sn were not only detected at interface, but Ag$_3$Sn was also found in the solder matrix of solder joint as shown in Figure 3 and Figure 4. Besides, Ag$_3$Sn was observed at the SAC405 bulk solder. Figure 5 show the top surface view of the morphology with deep etching process. From the figures, the IMC of Ag$_3$Sn was formed as long and needle like as well as plate-like, as seen in Figure 5(a) and Figure 5(b). Chung and Tai (2004) mentioned that large Ag$_3$Sn was initially existed in the solder bulk and could be observed at the interface onto or next to the Cu$_6$Sn$_5$ IMC [3]. Furthermore, many small particles or nanoparticles of Ag$_3$Sn were observed on the Cu$_6$Sn$_5$ grains with white sports as shown in Figure 1 and Figure 2. This happened during solidification process, where the Ag$_3$Sn nanoparticles could reduce the interfacial energy and retard the growth of the IMC layer. Similar observation was discovered by Liu et al (2010) [9]. However, the size of this IMC would not change or grow with increasing number of reflow time. Subsequently, large Ag$_3$Sn can be affected the reliability of solder joint where it can lead to crack initiation and propagation. Furthermore, large Ag$_3$Sn also caused solid dissolution and precipitation hardening. As a result, the solder joint became weak [8].

![Figure 3](image1.png)

**Figure 3.** Optical microscope images of cross-sectional view for SAC405/Cu with solder size Ø700 µm by using reflow soldering: (a) first reflow, (b) second reflow and (c) third reflow.

![Figure 4](image2.png)

**Figure 4.** Optical microscope images of cross-sectional view for SAC405/Cu with solder size Ø700 µm by using microwave soldering: (a) first reflow, (b) second reflow and (c) third reflow.
4. Conclusion
The lead-free solders of SAC405/Cu that were joined with Cu substrate to form IMC layer by using microwave and reflow soldering was studied. The major conclusions of the study can be summarized as:

i. For both soldering method, only Cu₆Sn₅ IMC was observed at interface as scallop and circle bump shapes. After exposed to second and third reflow, new layer IMC of Cu₃Sn was formed between Cu₆Sn₅ and Cu substrate. Ag₃Sn was also formed as long or needle like and plate-like.

ii. The IMC thickness and grain sizes became thicker, larger and denser with increasing number of reflow cycle, for both soldering method.

iii. Microwave soldering method represented thinner IMC layer and smaller grain sizes compared to reflow soldering.

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