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Effect of Current Stressing on Mixed Solder Joint Resistance and Temperature

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Abstract

This paper aims to investigate the impact of current stress on the electrical performance of mixed solder joints made of SnPb with SnCu and SnPb with SAC305. This information is currently missing and requires further research. The resistance of current-stressed pin-through-hole (PTH) solder joints, namely SnPb, SnCu, SAC305, and mixed solder joints of SnPb/SnCu and SnPb/SAC305, was measured using a micro-Ohm meter based on the Kelvin method. Temperature measurements were conducted by attaching two thermocouple probes to the solder joints. A microstructure examination was performed on the cross-section sample of PTH solder joints and further analyzed using open-source image processing software, ImageJ. It is noteworthy that fully mixing leaded and lead-free solder can reduce the variation of resistance during the application of current. The resistances of SnCu solder joints vary more compared to those of SAC305 joints with increasing applied current. Resistance variation of the SnPb/SnCu mixed solder joint is more dominant towards the SnPb solder joint trend, whereas SnPb/ SAC305 mixed solder joint is more dominant towards the SAC305 solder joint trend. The findings obtained from the ImageJ software analysis can be utilized to examine the evolution of microstructure and its correlation with the electrical properties of mixed solder joints.

1. Introduction

Solder alloys have found widespread use as interconnections in the semiconductor industry. The adoption of lead-free (Pb) solder has become a prevailing trend, primarily driven by health and safety consideration [1]. However, in some industries, namely aerospace and military, the application of lead solder, also known as mixed solder, is still applied due to its higher ductility and reliability performances [2]. Mixed solder is a combination of lead and lead-free solders, and its purpose is to achieve intermediate or enhanced performance compared to pure leaded and lead-free solders [3–5].

The electrical performance, such as resistivity, of mixed solder has not been widely analyzed since most of the studies were based on the individual type of solder, either leaded or lead-free solders. A four-point probe is the most widely used method to characterize the electrical properties of solder. In addition, there are some reports that utilize the micro-Ohm meter based on the Kelvin method to measure the resistivity of the solder joints [6,7]. The micro-Ohm meter offers the advantages of ease of setup and portable. Several studies have found that micro-Ohm meters or Kelvin probes are suitable for evaluating the electrical properties of solder and sensitive to voids and intermetallic compound compounds (IMC) during electromigration (EM) [8].

Microstructure examination is a crucial aspect of understanding the evolution of the internal structure and its relationship to the electrical and mechanical properties of solder joints. This is because any changes in terms of size, volume, and distribution of several elements, as well as intermetallic compound (IMC) and void formation, will influence the electrical performance of solder joints. Yu et al. [6] reported that the formation of IMC is the primary reason for the increasing resistance of solder bumps under high temperature and current stress. Chang et al. [8] studied the void formation due to EM in flip-chip solder joints using Kelvin probes and noted their high sensitivity to void formation and propagation making them valuable for detecting stages of void formation.

The effect of fast current stress on the electrical performance of mixed solder is still lacking and requires further study. For the current analysis, the resistance of current-stressed pin through hole (PTH) solder joints, namely SnPb, SnCu, and SAC305, mixed solder joints of SnPb with SnCu, as well as SnPb with SAC305, were measured using a micro-Ohm meter based on the Kelvin method. The temperature was measured by attaching two probes of a thermocouple to the solder joints. A microstructure examination was performed on the cross-section sample of PTH solder joints and further analyzed using open-source image processing software, ImageJ.

2. Materials and Methods

For this study, four samples of PTH solder joints were made as listed in table 1.

Table 1 *Samples assignment for PTH solder joints*

Sample	PTH Solder Joint
1	With Lead (SnPb)
2	Without Lead (SnCu and SAC305)
3	Mixed SnPb/SnCu
4	Mixed SnPb/SAC305

The hand soldering method was used to join the solders, where the soldering temperature applied for SnPb solder wire was 340 °C, while for lead-free SnCu and SAC305 solder wires it was 400 °C. For the creation of SnPb/SnCu and SnPb/SAC305 mixed solder joints, hand soldering was performed by soldering the SnPb solder wire at 340 °C, followed by SnCu or SAC305 at 400 °C, onto the Cu wire and pad. All the hand soldering procedures were performed for about two seconds. The values of 340 °C and 400 °C were selected because the values are much higher than the melting points of lead-solder (SnPb) and lead-free solder (SnCu and SAC305) joints, respectively. This is to make sure the particle distribution, especially in the Pb-rich phase of mixed solder joints, is even or full-mixing [9,10]. Fig. 1 shows the schematic of the experimental setup to measure the solder joint resistance and temperature.

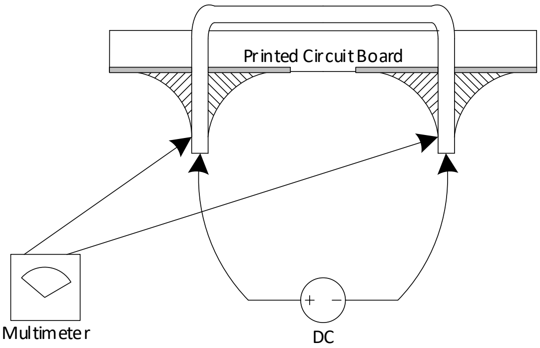


Fig. 1 *Schematic of experimental setup to measure the solder joints resistance and temperature*

The current stressing effect was evaluated by measuring the solder joint resistance and temperature based on the experimental setup in Fig. 1. The applied currents of 1-5 A were used for the current study. Solder joint resistance was measured using a micro-ohm meter that used the Kelvin four-terminal configuration and has the advantage of eliminating errors caused by test lead and contact resistance [11]. The temperature of the solder joints was measured with a multimeter connected to a thermocouple. Eight readings of resistance and temperature were taken for each of SnCu, SAC305, SnPb/SAC305 mixed solder joint, and SnPb/SnCu mixed solder joint. Resistance and temperature readings were recorded for approximately 10 seconds. This duration was chosen because the microstructural changes due to electromigration are least affected when the time duration for the current stress test is less than an hour [12].

The sample preparation was carried out by conducting resin mounting and curing. To expose the cross-sectional area of solders, wet grinding was conducted with 600, 800, and 1200 grits of abrasive papers, followed by polishing with 3 μm, 1 μm, and 0.25 μm diamond suspension silk cloth. The microstructural examination of the cross-sectioned sample was conducted using scanning electron microscopy (SEM). SEM is used to obtain the micrograph image of the samples.

An open-source image processing software, ImageJ, was utilized to determine the size, number, and distribution of lead, Pb particles from the cross-sectioned SEM micrograph. The size and distribution of Pb were selected for the current study because Pb is located at the dendritic or along Sn grain boundaries. Intermetallic compounds (IMC) that could be made, especially from lead-free solder, are also found along Sn grain boundaries. These compounds are Ag_3Sn and Cu_6Sn_5 for SAC305 and SnCu solders, respectively. Therefore, any changes that happen in the Sn-rich phase grain boundaries will directly affect the size and distribution of Pb and IMC precipitates. Additionally, Pb particles can be easily identified in SEM micrographs as they appear as black particles. By using ImageJ, the measurement and calculation of the size and distribution of Pb taken from the SEM micrograph will be based on the pixel value calculated from the black color of Pb particles [13].

3. Results and Discussion

Fig. 2 to Fig. 5 display the variation of resistances towards applied current of SnPb, SnCu, SAC305, and mixed solder joints (SnPb/SnCu and SnPb/SAC305), respectively.

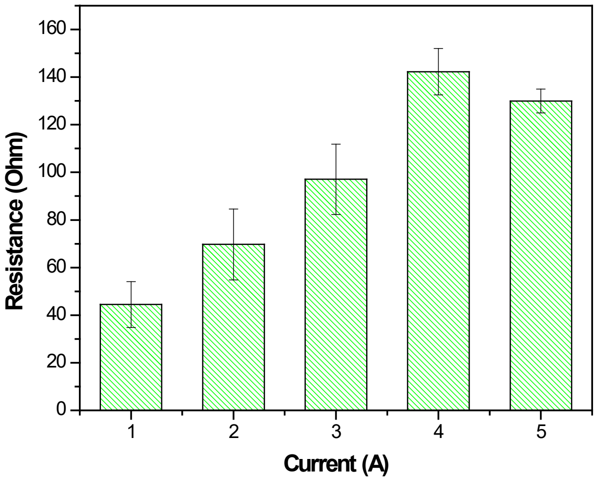


Fig. 2 *Variation of resistances towards applied current on PTH SnPb solder joint*

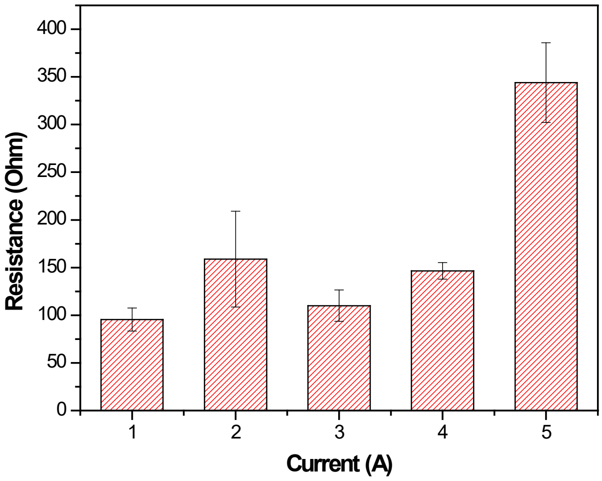


Fig. 3 *Variation of resistances towards applied current of SnCu solder joint*

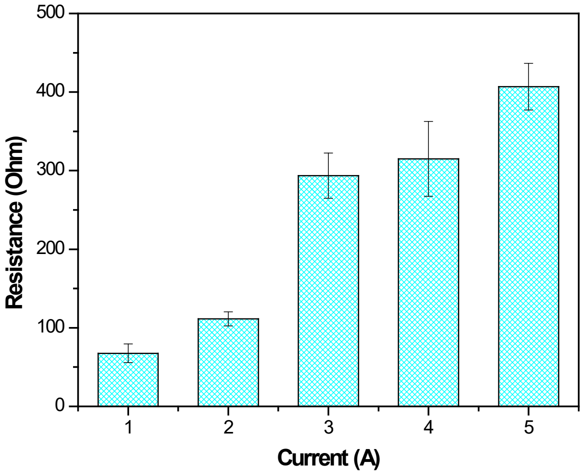
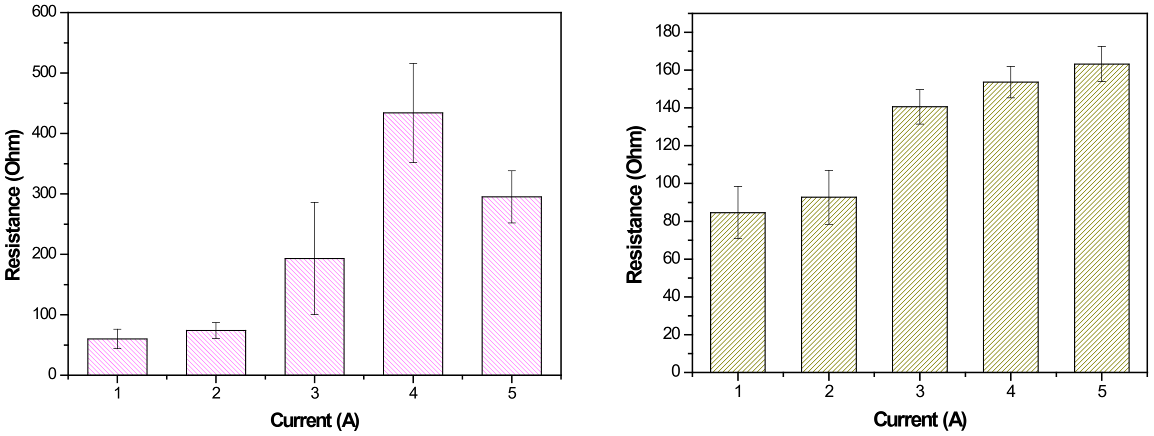


Fig. 4 *Variation of resistances towards applied current on SAC305 solder joint*



(a) **(b)**

Fig. 5 *Variation of resistances towards applied current for mixed solder joints of (a) SnPb/SnCu; and (b) SnPb/SAC305*

In Fig. 2 to Fig. 5, it is noted that the resistance variation towards the applied current is different for each type of solder joint. Each of the solder joints has a different standard error range that represents the variation of the data. The SnPb, SnCu, SAC305, SnPb/SnCu mixed solder joint, and SnPb/ SAC305 mixed solder joint have a standard error range of 13.1–92.8, 8.8–50.3, 8.9–47.6, 4.9–14.9, and 8.2–14.3, respectively. It is noted that SnPb solder joints have the highest standard error range, followed by SnCu, SAC305, SnPb/SAC305 mixed solder joint, and lastly SnPb/SnCu mixed solder joint. It is noted that the mixed solder joints of SnPb/ SnCu and SnPb/ SAC305 have the least resistance standard error range or variation, and thus the act of fully mixing the lead free (SnCu and SAC305) and leaded (SnPb) solders can reduce the variation of resistance of solder joints with increasing applied current. Wang et al. [9] reported that the full mixing act for the creation of mixed solder can depress the EM performance.

According to Su et al. [14] SnPb solder is less sensitive to current stress or EM phenomena. However, lead-free solders are quite sensitive to EM. SAC305 solder has a higher sensitivity towards EM compared to SnCu due to the particulate network of Ag_3Sn IMC [15]. Furthermore, the distribution and size of IMC and Pb particles play a role in varying the resistivity of the solder joints. The Pb-rich phase of SnPb solder is known to not create any IMC due to neutral diluent behavior and is located at the dendritic end of the grain boundary of the Sn-rich phase. Thus, the distribution of the Pb-rich phase has a direct relationship with the resistivity of SnPb solder [16]. While the lead-free solders SnCu and SAC305 are mostly influenced by the size and distribution of IMC to determine their relationship with resistivity. According to [17], the as-soldered SAC305 has a small particulate and uniformly distributed Ag_3Sn IMC. Whereas as-soldered SnCu forms large hollow hexagonal plates with poorly distributed Cu_6Sn_5 IMC. Therefore, Fig. 3 and Fig. 4 illustrate that the resistances of SnCu solder joints vary more compared to those of SAC305 joints with increasing applied current due to less well distributed Cu_6Sn_5 IMC.

In Fig. 5, It is observed that both mixed solder joints of SnPb/SnCu and SnPb/SAC305 exhibits different trends of resistance variation towards applied current. The resistance variation of the SnPb/SnCu mixed solder joint is increased during 1 A until it plateaus at 4 A before being reduced during 4 A and 5 A of applied current, where the trend has similarity with Fig. 2 for the SnPb solder joint. In contrast, the resistance variation of SnPb/ SAC305 mixed solder joint increases from 1 A to 5 A of applied current and closely following the trend shown in Fig. 4 for the case of SAC305 solder joint. Therefore, the resistance variation of the SnPb/SnCu mixed solder joint is more dominant towards the SnPb solder joint trend, whereas the SnPb/SAC305 mixed solder joint is more dominant towards the SAC305 solder joint trend.

Fig. 6 to Fig. 8 show the variation of temperature concerning the applied current for SnPb, SnCu, SAC305, and mixed solder joints (SnPb/SnCu and SnPb/SAC305), respectively. In Fig. 7 to Fig. 8 the temperature trend of SAC305 and mixed solder joints (SnPb/SnCu and SnPb/SAC305) exhibit a gradual increment. In contrast, Fig. 6 illustrates the temperature trend for SnCu solder joints has a different trend, with the temperature increasing from 1 A until a plateau at 4 A before being reduced during 4 A and 5 A of applied current. The primary mechanism for the increment of temperature with the increase of the applied current is the Joule heating phenomenon [18].

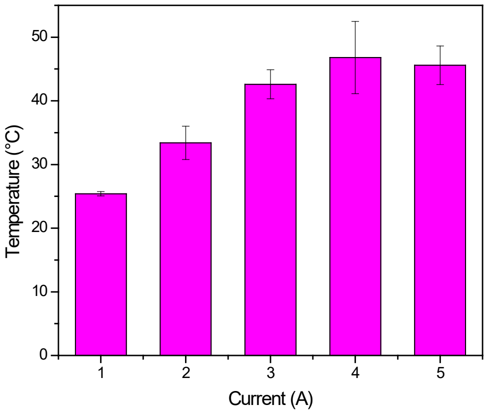


Fig. 6 *Variation of temperature towards applied current on SnCu solder joint*

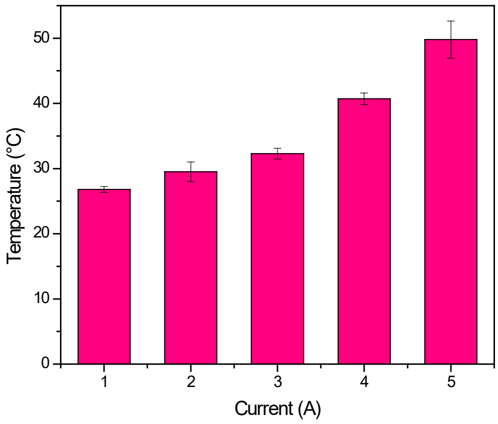
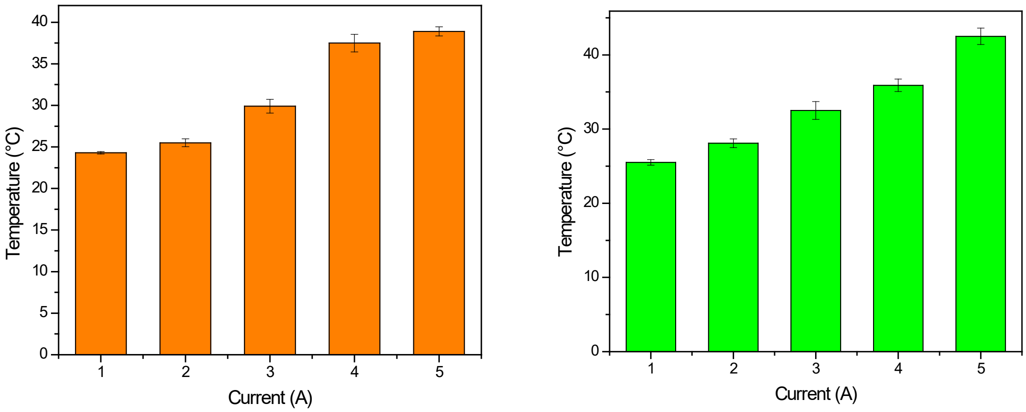


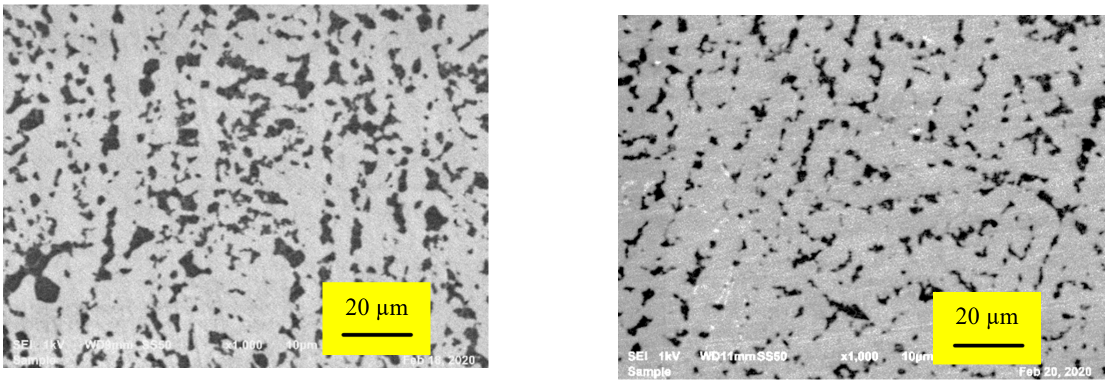
Fig. 7 *Variation of temperature towards applied current on SAC305 solder joint*



(a) **(b)**

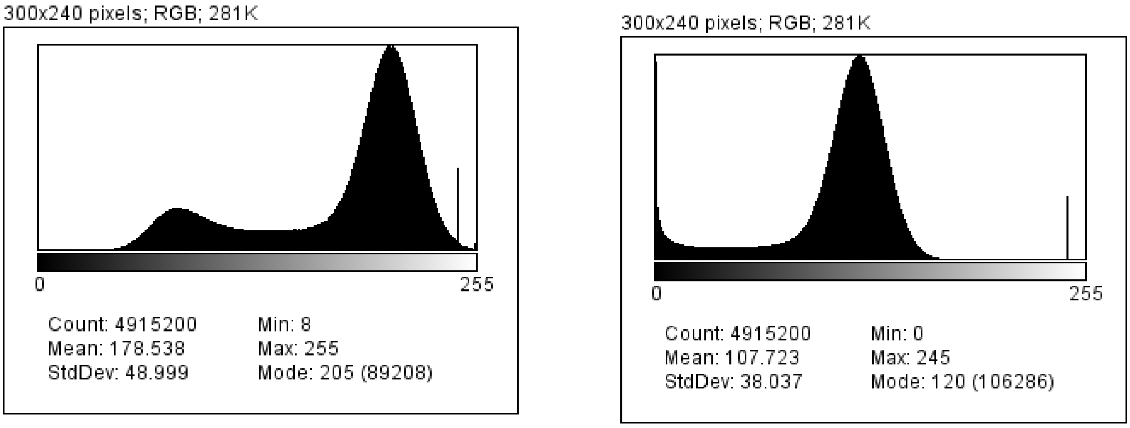
Fig. 8 *Variation of temperature towards applied current on PTH mixed solder joints of (a) SnPb with SnCu; and (b) SnPb with SAC305*

Fig. 9 displays the SEM micrographs of mixed solder joints of SnPb/SnCu and SnPb/SAC305. Fig. 10 presents the histogram of pixel distribution obtained from ImageJ for mixed solder joints of SnPb/SnCu and SnPb/SAC305. Figure 11 shows how the number of particles changes, and Figure 12 shows the average particle size for SnPb/SnCu and SnPb/SAC305 mixed solder joints, both of which were taken from ImageJ. From Fig. 10, the SnPb/SnCu mixed solder joint has a higher standard deviation of 49 compared to the SnPb/SAC305 mixed solder joint, which has a standard deviation of 38. In Fig. 10, it is evident that the pixel distribution of the SnPb/SnCu mixed solder joint is skewed to the right, while the SnPb/SAC395 mixed solder joint is distributed in a normal distribution. In Fig. 11 and Fig. 12, it is noted that the SnPb/SnCu mixed solder joint has the highest number of particles (406) and an average particle size of 0.003 μm compared to the SnPb/SAC305 mixed solder joint. All these features of higher variation (standard deviation and histogram of pixels distribution), number of particles, and average particle size justify the higher variation trend or sensitivity of resistance towards applied current possessed by SnPb/SnCu mixed solder joint (Fig. 5(a)) as compared to that of SnPb/SAC305 mixed solder joint (Fig. 5(b)) [10,16,19]. Hence, the higher number and variation of Pb-rich particles can be correlated with the higher variation of IMC created in the solder joint, leading to a higher variation trend or sensitivity of resistance towards applied current.



(a) **(b)**

Fig. 9 *SEM micrographs of mixed solder joints of (a) SnPb/SnCu; and (b) SnPb/SAC305*



```
Count: 4915200      Min: 8
Mean: 178.538       Max: 255
StdDev: 48.999      Mode: 205 (89208)
```

```
Count: 4915200      Min: 0
Mean: 107.723       Max: 245
StdDev: 38.037      Mode: 120 (106286)
```

(a) **(b)**

Fig. 10 *Histogram of pixel distribution obtained from ImageJ for mixed solder joints of (a) SnPb/SnCu; and (b) SnPb/SAC305*

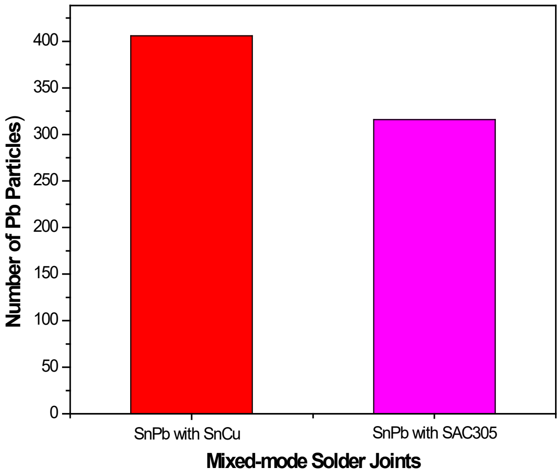


Fig. 11 *Variation of number of Pb particle for mixed solder joints of SnPb/SnCu and SnPb/SAC305*

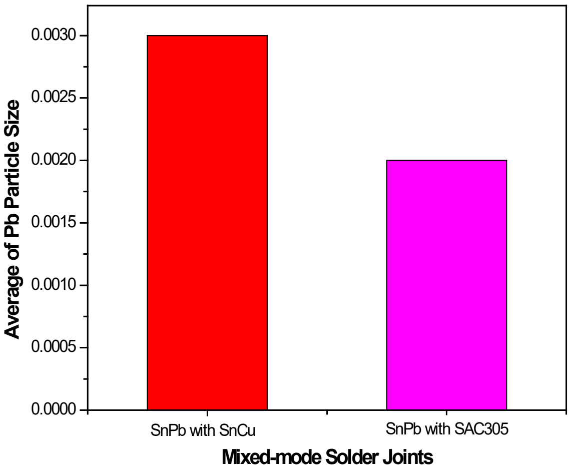


Fig. 12 *Average of Pb particle size for mixed solder joints of SnPb/SnCu and SnPb/SAC305*

4. Conclusion

Resistance and temperature measurements using a micro-ohm meter as well as microstructure examination using ImageJ software were performed on solder joints (SnPb, SnCu, and SAC305) as well as mixed solder joints (SnPb/SnCu and SnPb/SAC305). Mixed solder joints have the least resistance standard error range or variation, and thus the act of fully mixing the lead free (SnCu and SAC305) and leaded (SnPb) solders can reduce the variation of resistance of solder joints with increasing applied current. The resistances of SnCu solder joints vary more compared to those of SAC305 joints with increasing applied current. Resistance variation of the SnPb/SnCu mixed solder joint is more dominant towards the SnPb solder joint trend, whereas the SnPb/SAC305 mixed solder joint is more dominant towards the SAC305 solder joint trend. The main mechanism for the increment of temperature with the increase of the applied current is the Joule heating phenomenon. Results from ImageJ such as higher variation (standard deviation and histogram of pixel distribution), more particles, and a larger average particle size support the higher variation trend or sensitivity of resistance to applied current that the SnPb/SnCu mixed solder joint possesses in comparison to the SnPb/SAC305 mixed solder joint. Hence, the higher number and variation of Pb-rich particles can be correlated with the higher variation of IMC created in the solder joint, leading to a higher variation trend or sensitivity of resistance towards applied current.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***methodology, project administration, supervision, formal analysis, writing-original draft, writing-review & editing:*** *Muhammad Nubli Zulkifli;* ***data collection and investigation:*** *Izhan Abdullah, Muhammad Fatullah Ahmad Azam;* ***funding acquisition:*** *Nurul Hanis Azhan, Afaq Ahmed;* ***conceptualization:*** *Azman Jalar. All authors reviewed the results and approved the final version of the manuscript.*

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