# Reliability assessment of self-alignment assemblies of chip component after reflow soldering process

A.M. Najib[1], M.Z. Abdullah[2], A.A. Saad[3], F. Che Ani[4] and Z. Samsudin[4]
[1]*Fakulti Kejuruteraan Pembuatan, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia.*
[2]*School of Aerospace Engineering, Universiti Sains Malaysia, Engineering Campus,14300, Nibong Tebal, Penang, Malaysia*
[3]*School of Mechanical Engineering, Universiti Sains Malaysia, Engineering Campus,14300, Nibong Tebal, Penang, Malaysia.*
[4]*Process and Material Research Division, Jabil Circuit Sdn. Bhd., Bayan Lepas Industrial Park, 11900, Penang, Malaysia.*
*najibali@utem.edu.my*

***Abstract* - Reliability of surface mount components and interconnect are significant issues in electronic manufacturing. Although the reliability of devices has been broadly studied, here we are focusing on the reliability of the solder joint after the self-alignment phenomena during reflow soldering. In this study, the quality of the self-alignment assemblies was analyzed relate to the joint shear strength according to the JIS Z3 198-7 standard and the inspection according to IPC-A-610E standard. The results from reliability study indicate that the shear strength of the misalignment component of solder joints indeed depends on the degree of chip component misalignment. For shift mode configuration in the range of 0-300µm, the resulted chip assembly inspection after the reflow process was in line with the IPC-A-610E standard.**

***Keywords* -Lead-Free Solder; Reliability; Shear Stress; Solder Joint.**

## I. INTRODUCTION

The Restriction of Hazardous Substances Directive (RoHS) bans the intentional addition of lead (Pb) to consumer electronic parts produced in countries in the European Union start from 1st July 2006. Hence, lead-free solder has become obligatory in the electronic industry, and in-depth study of behavior is now more important than ever including in the reliability aspects. One of the reliability aspects of solder joints is the mechanical strength. The mechanical strength of solder alloys can be characterized by tensile and shear strength. In case of bulk solder, tensile strength is used for the characterization, while in case of real soldered structures, the shear strength of actual configurations is measured. The reliability studies of electronic components joining were investigated by many researchers in terms of various factors.

Some scholars claim that the thermal and soldering time could have a major effect on the solder joint shear strength [1] [2] [3] [4] [5] [6]. Szendiuch *et al.* [1] focused his study on the solder joints after the thermal cycling effect. He pointed out that the cyclic exposure of solder interconnection to temperature deteriorate solder joint strength partly due to the growth of intermetallic layer after the thermal cycling. The study also claimed that the shear strength of solder joint based on the SAC305 solder compound was higher compare to the solder joint from SN100C solder paste. The reason for the high shear strength was most probably due to the intermetallic composition of Ag3Sn and Cu6Sn5 near copper to the copper pad in the intermetallic region. Choudhury et al. [2] observed that with an increase of the soldering time from 10 minutes to 60 minutes of Sn3.5Ag and copper joint, the IMC thickness in the solder joint was increased. The study found that from the single lap-shear test of joint with 60% of IMC thickness, the shear strength increased compare to the joint with 40% IMC thickness. The shear strength reduces when the joint consist of 80% IMC thickness from the total solder joint. The reason was explained to be the hard and brittle IMC layer resist the shear deformation of the joint. The shear strength deteriorates when the IMC layer thickness further increased due to the thicker and planar layer of Cu-Sn in IMC tend to be fracture easily during shear deformation. A study by Hu *et al.* [3] claimed that the shear strength of solder joints increased with increasing strain rate and the shear strength also increased with the reduction of the IMC layer. It was observed that higher peak reflow temperature (280°C) resulted thicker IMC layer compare to peak reflow temperature at 250°C, thus reducing the shear strength of the joints. The growth of IMC layer during reflow soldering is believed to have resulted primarily in the diffusion of Cu atoms from the substrate during reflow soldering process. According to Fick's first law, the diffusion flux of Cu atoms is proportional to the diffusion temperature. Therefore, at a higher reflow temperature, the diffusion flux is higher, resulting in a thicker interfacial Cu-Sn IMC layer. The study by Lee *et al.* [4] arrived at the similar conclusion where the shear strength of the SAC305 solder joints decreases with aging temperature and time attributed by brittle interface due to the thick IMC layer.Hu *et al.* [5] investigated aging effect at a various temperature on the ultimate shear strength of solder joining of Sn37Pb. His study found that the ultimate shear strength of Sn37Pb solder joint decrease as aging time increased and the shear strength decreased as temperature during aging was also increased. The reduction of the shear strength may be contributed by the increasing thickness of brittle IMC layer through diffusion of copper in Cu-Sn IMC layer which proportional to the aging time and aging temperature. Secondly, it could be contributed by the grain coarsening effect of Pb-rich and Sn-rich in the solder matrix during aging. Kim *et al.* [6] studied the effect of multiple reflow numbers on the shear strength of flip chip solder joints. The study found that the ultimate shear force of Sn37Pb flip chip solder joint decreased as reflow numbers were increased. The shear force of SAC305 flip chip solder joint decrease in slower manner compare the conventional leaded solder joint. The possible explanation of the shear strength reduction after multiple reflows was increasing the IMC thickness causing brittle solder joint.

Some researchers found that micro-alloy addition to the common SAC solder could enhance the solder shear strength [7][8][9][10][11][12]. Ali *et al.* [7] in his experimental study found that adding Fe and Bi in the SAC105 resulted in higher shear strength value. In the study, the Fe was added to the SAC105 samples at 0.05% whereas Bi was added 1% and 2% to the SAC105 samples, respectively. The researcher reported that Bi and Fe addition reduced the large primary ß-Sn grain in the SAC105 solder and significantly reduced the IMCs size. The study claimed that Fe/Bi is dissolved in the bulk SAC105 alloy and strengthen the solder matrix through suppressing the IMC formation and reduce ß-Sn grain size, thus improve the shear strength performance of the solder joint. Fleshman *et al.* [8] claimed that Ni dopant in the SAC305 improved its shear strength during the solder ball shear test investigations. The possible explanations for the mechanical strength enhancement were attributed to the grain structure modification into smaller grain size and the multiple grains with partially interlaced structure became mechanical barrier from cracks propagation during the shear test. Salleh *et al.* [9] claimed that adding TiO2 in Sn0.7Cu solder alloy resulting shear strength insensitive to the number of reflow cycles compare to the un-reinforced solder alloy. Their possible explanation was TiO2 containing solder suppressed primary and interfacial Cu6Sn5 formation, thus strengthen the interfacial layer. Gain et al. [10] investigated shear force of ZrO2 nanoparticles reinforced SAC305 solder joint. The ZrO2 was found uniformly distributed in the solder matrix which strengthens solder joint. The study claimed that the failure mode change from brittle fracture mode to a more ductile failure characteristics through the addition of the nanoparticles in the SAC305 solder alloy. Liu et al. [11] performed shear test evaluation of Nickel reinforced SAC387 solder joint to test it's joining mechanical reliability. The study stated that Nickel particle addition at certain composition amount in the SAC305 alloy could suppress the growth of Cu-Sn IMC layer and maintained scallop-shape IMC layer, thus decreasing shear strength at slower rate compare to the non-reinforce solder alloy. Secondly, the study stated that the performance of its shear strength could be contributed by refined IMC grain at the interface of the solder joints. Huang et al. [12] investigated the effect of graphene nanosheets addition to SAC305 solder matrix to study the shear strength of solder joints including after aging process. Their study claimed that graphene nanosheets in the solder matrix acted as a diffusion barrier for Sn and Cu, suppressed IMC layer morphology transformation from scallop-type to layer-type, thus enhance the shear strength of SAC305 with graphene nanosheets even after aging process. Sharma *et al.* [13] claimed that adding epoxy-based polymer in the SAC305 solder paste increased shear strength up to 14% when tested on 1608 chip surface mount component. The study stated that a slower growth rate of Cu-Sn IMC layer between the solder and copper bonding interface for the epoxy embedded solder contributed to the higher shear strength value.

Some scholars have also investigated the high-temperature lead-free solder [14], different surface mount devices [15] [16] and alternative shear test technique such as nanoindentation technique [17]. Mahmudi et al. [14] carried out an investigation of high-temperature lead-free solder involving Zn-4Al-3Mg-xSn (X=0.7 wt%,13 wt%) alloy. Their findings indicated that Zn-Al-Mg-Sn alloy possessed high shear strength level up to 115-130 MPa at test temperature range of 25-200°C. However, combining the high-temperature lead-free solder with actual electronic components was unrealistic due to most electronic components defects when reaching 300°C. The solder alloy in their study was melted at 580°C in an electrical furnace. Krammer et al. [15] presented solder joint strength of chip resistor and chip capacitor by considering shear loading force and the amount of solder joined surface. The FE-Model was created to investigate the shear stress of misplaced chip components. The calculation of solder profile for each misplaced direction was conducted using Surface Evolver. The study focuses on solder SAC305 only. Koo et al. [16] investigated the shear strength of solder ball joints of solder Sn37Pb and solder Sn3.5Ag. The study found that the ball shear strength of Sn37Pb solder joint decreased with increasing aging time and increasing shear displacement rate. The shear strength of Sn3.5Ag solder ball joint was better after aging compares to the Sn37Pb. In his study, the fracture joint occurred in the bulk solder for Sn3.5Ag solder joint for all aging time and displacement rate whereas the fracture joint occurred in the brittle IMC layer of the Sn37Pb solder joint. On the contrary, an investigation by Kim et al. [18]) on the SAC305 solder joints resulted maximum shear force increased with increasing shear speed. The shear test on coated flip chip bumps was tested using nanoindentation technique by [17]). A 20μm spherical indenter was used to find the fracture force of 100μm diameter of the flip chip bump. The bump was coated to prevent plastic deformation. In his analysis, the critical force at which the bump fails was around at 234mN.

A reliability study was an important aspect of electronic component joining. Different researchers characterized the mechanical strength of real solders joints configurations through the shear test. Many reliability studies investigated the effect of micro-alloy addition and thermal effect in common lead-free solder. Self-alignment effect mainly occurred due to the various forces including surface tension force of solder during the reflow soldering [19]. From the literature, the study involving component misalignment effect on the joint mechanical reliability was still limited. Moreover, there is no literature concern on the solder joint reliability study involving different silver content effect for various chip component offset.

## II. METHODOLOGY

Initially, the selected solder alloy was transferred through a stencil on the copper pad positions. Then chip component was deposited before the joint was made permanent through reflow soldering using appropriate reflow soldering process [20]. After that, shear testing was conducted to determine the reliability of the passive resistor component after the reflow process. The shear test is well known Destructive Physical Analysis (DPA) for passive electronic components. The strength of the solder joints is evaluated by pushing the lead component until the solder joint crack. The shear strength assessments are conducted in accordance with the JIS Z3 198-7 standard [21].

The selected SnAg-alloy for the analysis was Sn95.5 Ag4.0 Cu0.5 (SAC405) Sn96.5 Ag3.0 Cu0.5 (SAC305), Sn98.5 Ag1.0 Cu0.5 (SAC105) and Sn99.4 Cu0.6 Ni (SN100C). The percentage composition of the silver in the total substance in SAC405 solder alloy was 4% composition. The percentage composition of silver in the SAC 305, SAC105 and SN100C was 3%, 1%, and 0% composition, respectively.

In the experiment, four type of lead-free solder paste was used. For each type, various chip component offset was set. The investigation of joint shear strength involved the final position of the chip component after reflow soldering. The misalignment offset of the component was measured before the shear test was conducted. In the study, misalignment effect on shear strength was investigated. The misalignment margin of 0-40µm (after reflow) was selected.

The PCB type used was FR-4. PCB size is 2-inch x 2-inch x 0.063 inch, and maximum allowable PCB reflow temperature was 260°C. In the experiment, peak temperature for reflow profile was limited to 250°C and reflow profile according to JEDEC JSTD-020D standard was used.

The shear test was performed using test machine Instron 3367 with load cell maximum measurement capacity up to 50 N. Shear test are done in compression form. In the study, a fixture was designed to hold the test printed circuit board (PCB) vertically. At the lower end of PCB, it was fixed and lock into position during the test. The general setup of the shear test experiment was depicted in Figure 1.

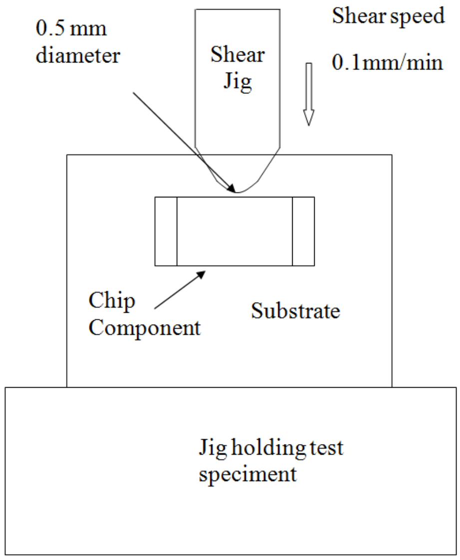



Figure 1: General setup for shear test experiment.

The positioning and alignment of the chip component were done with the aid of USB microscope attached near the side and near the top of the chip component. The enlargement of the component can be viewed using microscope connected to the portable computer. The gap between the shear jig and the substrate was set to be at around 100µm or less. At the start, the shear jig was brought near to the chip component but still not in contact as not to give a shock during measurement. A shear jig which connected with the measurement sensor was move from above at test speed 0.1mm/min and measurement were recorded. Figure 2 illustrates the test machine and the experimental setup used in the study.

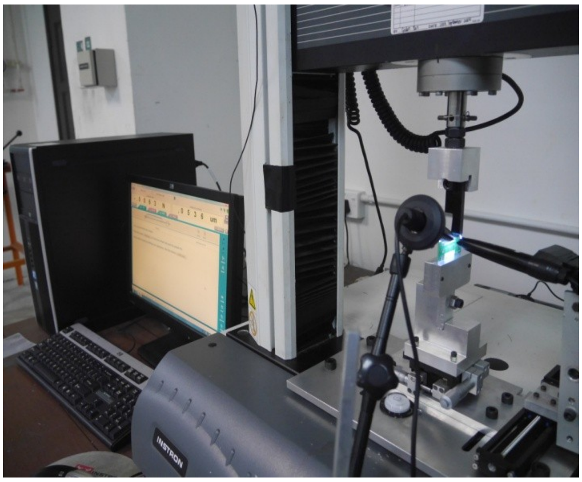


Figure 2: Test machine Instron 3367 with load cell maximum up to 50 N.

Each row of the test board content five chip components. In the shear test, half of the lower part of PCB was used for clamping. Each test piece consists of a passive component, which was soldered to the substrate using selected reflow profile. The peak shear strength of solder joint was recorded, and the results were analyzed.

## III. RESULTS

After the chip component went through self-alignment during the reflow process, two types of reliability study were conducted. Firstly, the chip was inspected according to IPC-A-610E. Secondly, the shear strength assessments are conducted in accordance with the JIS Z3 198-7 standard. To determine the fracture mode, SEM analysis with EDS was conducted.

Taking IPC-A-610E [22] as a reference, visual inspection of joint quality were investigated for all the self-aligned chip resistors in the study. Figure 1 shows an example of visual inspection and measurement of chip resistor 0603 with an initial offset of 200µm in the y-direction and final misalignment of 58µm after reflow soldering. Infinite Focus machine enabled measurement of the 3D solder joint geometrical data. For 200µm initial offset, the post-reflow inspection resulted end joint solder width (W) was of the same magnitude with component termination width (C) and was within the width of land (P).

(a) (b)

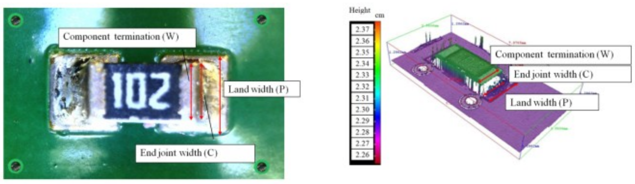



Figure 1: An example of visual inspection (a) using USB microscope camera and (b) precision machine Infinite Focus, ALICORNA

Figure 2 lists the standard features used for joint inspection after the reflow soldering. Three common features used for the inspection of joining in the study were side overhang, end overhang, and end joint width. These features were general standard for rectangular end chip component with side terminations in surface mount assemblies according to IPC standard.

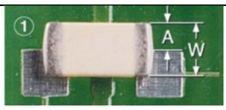
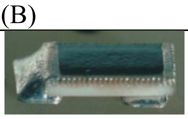
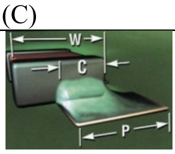
| Side Overhang (A) | End Overhang (B) | End Joint Width (C) |
|---|---|---|
|  |  |  |

Figure 2: Illustration of standard criteria of rectangular end chip components according to IPC-A-610E [22].

The inspection results show that there was no side overhang (A) are detected. Most all of the resistors side joints are within the width (W) of component termination area and width of the land after reflow soldering. All self-aligned resistor type 0805 and type 0603 achieved "Target" condition. In case of 300µm offset, the side overhang was observed in all chip resistor before reflow soldering. At 300µm lateral offset, 149µm chip side was observed overhang for chip resistor type 1206, 200µm side overhang in case of chip resistor type 0805 and 192µm side overhang in case of chip resistor 0603 before the reflow soldering. The ratio of average travelled distance to the offset value in width direction was 0.4 (type 1206), 0.7 (type 0805) and 0.9 (type 0603). Due to the self-alignment effect, the average distance traveled in the width direction was the least in case of chip resistor 1206 with average distance traveled of 139µm. Base on the average value, the average distance for side overhang was 10µm in case of 300µm offset for chip resistor 1206. It was only 0.7% of the total width of component termination and acceptable according to the IPC standard. Other positional offset 0-250µm achieved the target condition.

In case of lengthwise positional offset from 0-300µm, none of the chip resistors has end overhang after the reflow soldering. After the reflow soldering process, the solder joint was formed on the solder land. The ratio of average traveled distance to the offset value in lengthwise direction was 0.3 (type 1206), 0.6 (type 0805) and 0.8 (type 0603). Extra land on the end side of the chip component still can be assessed, and the solder was formed on the land. For example, in case of 300µm lengthwise direction offset, type 1206 resistor resulted in extra land size at least side on average of 498µm, type 0805 resistor resulted in extra land size at least side on average of 350µm and type 0603 resistor resulted in extra land size at least side on average of 282µm.

All end joint width (C) of type 0603 and type 0805 is equal to the width (W) of the component termination and within the width (P) of land in case of 0-300µm lateral offset. All the self-aligned resistor achieve "Target." For chip resistor type 1206, the average distance for end joint width was 1489 µm in case of 300µm offset for chip resistor 1206. It was 99% of the total width of component termination and acceptable according to the IPC standard.

The inspection was conducted for all chip resistor component after reflow condition, and the results show that all the chip was in line with the IPC standard after the self-alignment study. However, the inspection according to the IPC-A-610E alone unable to ensure the complete reliability of the electronic assemblies during operation. Therefore, a shear test was conducted additionally for assessing the solder joint reliability in case of solder joining involving self-alignment during the micro assembly.

The solder shear strength after reflow soldering was analyzed and presented in this section. Figure 3 shows an example of shear strength measurement for chip component with a certain offset. The offset position resulted from an original position offset of 50µm before reflow soldering. Due to self-alignment effect, the final position was measured as 21.5µm from the center position. The peak shear strength represents maximum force acting on the contact region between solder and chip component before failure mode occurred. The peak shear strength value was 23.4 N/mm². The graph shows that the shear strength increases rapidly to the peak shear value before decreasing steadily. The decreasing region in the graph was not significant for the study as the chip already break off from the solder joint. The amount of shear strength reduced drastically as the force needed to move the breaking chip component at designated shear test speed was also decrease significantly. Moreover, the contact area of solder was different after break-off point, and therefore the shear strength value after the peak value will not be considered for the analysis.

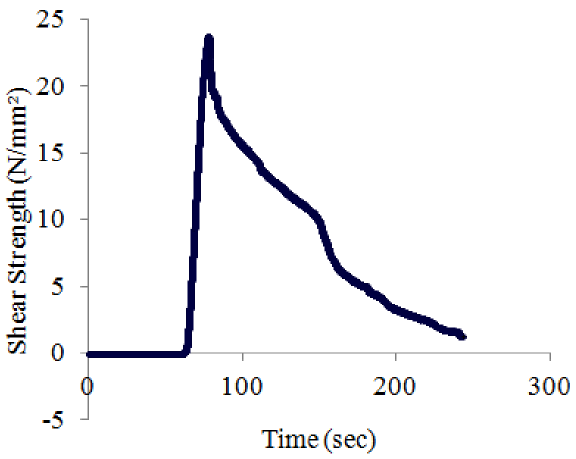



Figure 3: Shear strength of an offset of solder joint during the shear test after the reflow soldering process

The shear strength of solder joint in the function of misalignment was illustrated in Figure 4 until Figure 7. The effect of solder type variation on the shear strength was studied. The relative wetted area used was 0.825 mm². The degree of misalignment was different before and after reflow soldering due to the chip component self-alignment. The y-axis values illustrated in the graph represent peak shear strength value during shear experiment over a range of misalignment. For evaluation of the shear strength results, the group was created based on the degree of misalignment. The group was based on the misalignment value after reflow soldering. To evaluate the results base on the different lead-free solder and different range of misalignment, ANOVA test was conducted. The statistical approach was used to test the significance of the results. ANOVA single factor test was used to test each factor. ANOVA single factor test reveals that the difference between groups of misalignment was indeed significant for all investigated lead-free solder. In case of SAC405 (P-value, 0.005<0.05;F-value, 9.42>Fcritical(4.06)), in case of SAC305 (P-value, 0.03<0.05;F-value, 4.51>Fcritical(4.06)), in case of SAC105 (P-value, 0.001<0.05;F-value, 13.19>Fcritical(4.06)) and in case of SN100C (P-value, 0.002<0.05;F-value, 12.43>Fcritical(4.06)). As shown in the graph, there were decreasing trends in shear strength value as misalignment offset increases. Hence, it indicated that the shear strength of solder joints of misalignment components depends on the degree of that misalignment. The probable cause of this phenomenon was that in case of misalignment components, the shape and contour of the joint was imbalance and therefore distribute the load unevenly compare to the correctly placed components. FEM study by Oliver [15] was coherence with the results of the study, where displaced components resulted in higher shear stress value at the solder joint, and it correlates with joint maximum shear strength. At higher shear stress region, the fracture could occur more easily compare to the lower stress region.

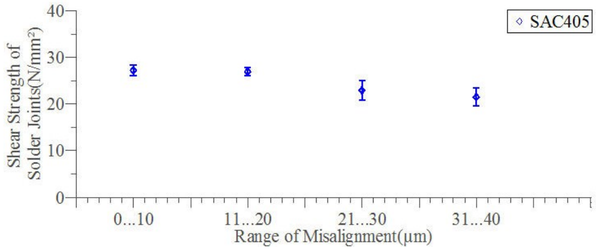



Figure 4: Shear strength of solder joints in the function of y-direction misalignment for SAC405.

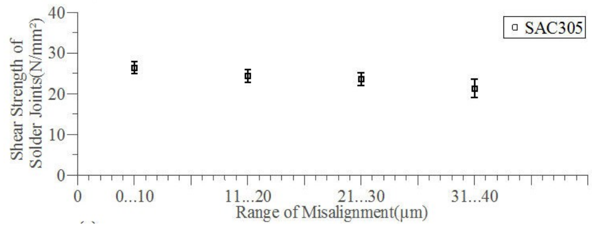



Figure 5: Shear strength of solder joints in the function of y-direction misalignment for SAC305.

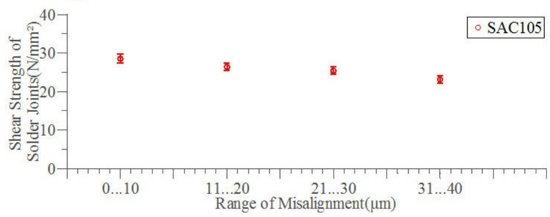



Figure 6: Shear strength of solder joints in the function of y-direction misalignment for SAC105.


Figure 7: Shear strength of solder joints in the function of y-direction misalignment for SN100C.

The average shear strength at lower misalignment group of SAC405, SAC305, SAC105, and SN100C was 27.3N/mm², 26.4N/mm², 28.5N/mm² and 28.0 N/mm² respectively. The shear strength value was slightly different most probably due to the interfacial IMCs formed between solder and Cu substrate was also different depends on the solder type.

The significant of the solder variation to the shear strength value was further investigated through ANOVA analysis. Each misalignment group was selected, and the significant of solder variation on the shear strength was investigated using ANOVA single factor. Misalignment group range of 0-10µm shows that the variation was not significant. The statistical analysis shows that the F-ratio was smaller than the critical value ($F(3,8)$ 1.36 < 4.06). The following misalignment groups resulted $F(3,8)$ 3.03 < 4.06 for 11-20µm offset, $F(3,8)$ 1.46 <4.06 for 21-30µm offset and finally $F(3,8)$ 0.80 < 4.06 for 31-40µm offset. The ANOVA analysis of all offset groups shows that the variation of solder type was insignificant to the shear strength of the chip component.

This behavior could be explained through investigation of the fracture mode of the shear test component. To explain the fracture mode of a shear test of the leadless component, an optical microscope and SEM analysis was used. For a selected sample, elemental mapping at the microstructural level by scanning electron microscope (SEM) with energy dispersive X-ray spectrometry (EDS) was conducted. Element maps are used to display element distribution and quantify element composition of the predefined area. Each point in the selected area is scanned. Based on energy window of each element, the element is quantified to build up element map. Figure 8 illustrates the fracture occurred during the shear test, SEM image of one selected area and an elemental map of SEM.

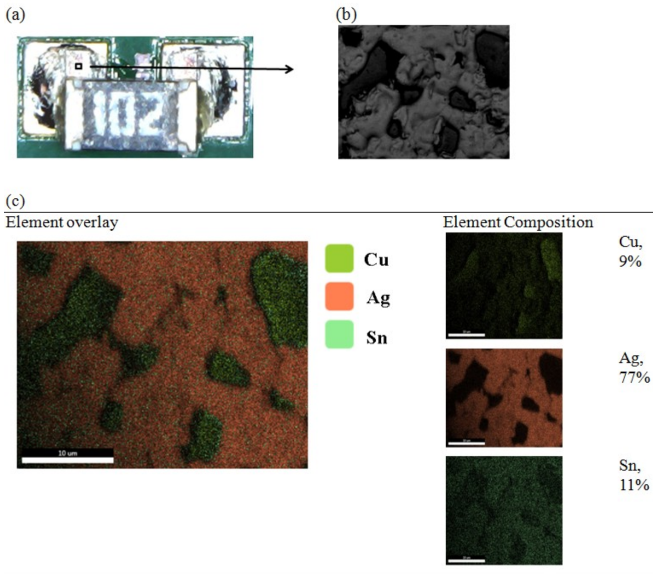



Figure 8: (a) Sample of fracture image occurred during the shear test. (b) SEM image of one selected area and (c) Elemental map of SEM with energy dispersive X-ray spectrometry (EDS).

The fracture mode of all test specimens has a similar pattern. The elemental image of the selected sample shows present of Ag, Cu and Sn element. The analysis of elemental map of SEM for element off all selected solder fracture joint indicates a high trace of silver content. As shown in Figure 8, a predefined area scan of selected sample SAC305 fracture joint shows silver composition up to 77%.

## IV. CONCLUSION

After went through the reflow process, the end chip terminations of the chip resistor were examined according to the IPC-A-610E. The acceptance criteria that was observed during the inspection included side overhang, end overhang, and end joint width. Based on the selected criteria, all the joint meet the desired condition according to the IPC standard. However, the inspection takes into account on the dimensional criteria only and may not be necessary ensuring the reliability of the joint assembly in its service environment.

The statistical analysis has been conducted to determine the shear strength of the misalignment components. Two conclusions can be drawn from the study. Firstly, it has been proved by the experimental investigations, that the shear strength of the misalignment component of solder joints truly depends on the degree of chip component misalignment after reflow soldering. In the case of misalignment components, the final shape and contour of the left solder joint and right solder joint were imbalanced. Therefore, during the shear test, the applied load exerted unbalance shear stress on the unbalance solder joint and fracture occurred more easily on solder joint with higher stress region compare to the solder joint with lower stress region. The study reveals that as the misalignment offset of solder joint after reflow soldering increases, the shear strength value of the joint decreases. Secondly, the experimental study shows that the solder type selected in the investigation may not influence the shear strength of the solder joint. The statistical analysis shows that the solder type variation was insignificant to the shear strength of the chip resistor. The study concluded that the fracture occurred partially in the termination metallization at the lower part of chip resistor. The copper content of the joint on that area shows that the crack occurred in the solder joint, and high silver content on the selected zone indicate the fracture happened partially in the termination structure as the termination structure of lead-free chip resistor consists inner layer of silver and an outer layer of tin.

The SEM investigation indicated that the fracture occurred partially in the bulk solder joints and as well as in the termination metallization. It may be the reason why different silver content in the lead-free solder joint have minimal impact in the shear test investigation as the fracture occurred mostly in the termination layer of the lead-free component. The current study is expected to provide valuable guidelines and references for the engineers and IC designers during the reflow soldering process in the microelectronics industry.

ACKNOWLEDGMENT

We would like to express gratitude to Universiti Teknikal Malaysia Melaka for the appreciation of the work through the awarded grant. This work was partially funded under PJP/2018/FKP(5A)9/S01585.

REFERENCES

[1] I. Szendiuch, J. Jankovsky, M. Bursik, and E. Hejatkova, "New facts from lead-free solders reliability investigation," *3rd Electron. Syst. Integr. Technol. Conf. ESTC*, pp. 1–5, Sep. 2010.

[2] S. F. Choudhury and L. Ladani, "Local shear stress-strain response of Sn-3.5Ag/Cu solder joint with high fraction of intermetallic compounds: Experimental analysis," *J. Alloys Compd.*, vol. 680, pp. 665–676, 2016.

[3] X. Hu, T. Xu, L. M. Keer, Y. L. A, and X. Jiang, "Shear strength and fracture behavior of reflowed Sn3.0Ag0.5Cu-Cu solder joints under various strain rates," *J. Alloys Compd.*, vol. 690, pp. 720–729, 2017.

[4] B.-S. Lee, Y.-H. Ko, J.-H. Bang, C.-W. Lee, S. Yoo, J.-K. Kim, and J.-W. Yoon, "Interfacial reactions and mechanical strength of Sn-3.0Ag-0.5Cu/Ni/Cu and Au-20Sn/Ni/Cu solder joints for power electronics applications," *Microelectron. Reliab.*, vol. 71, pp. 119–125, 2017.

[5] X. Hu, Y. Li, Y. Liu, Y. Liu, and Z. Min, "Microstructure and shear strength of Sn37Pb / Cu solder joints subjected to isothermal aging," *Microelectron. Reliab.*, vol. 54, no. 8, pp. 1575–1582, 2014.

[6] D. Kim, J. Kim, S. Ha, B. Noh, J. Koo, D. Park, M. Ko, and S. Jung, "Effect of reflow numbers on the interfacial reaction and shear strength of flip chip solder joints," *J. Alloys Compd.*, vol. 458, pp. 253–260, 2008.

[7] B. Ali, M. F. M. Sabri, I. Jauhari, and N. L. Sukiman, "Impact toughness, hardness and shear strength of Fe and Bi added Sn-1Ag-0.5Cu lead-free solders," *Microelectron. Reliab.*, vol. 63, pp. 224–230, 2016.

[8] C. Fleshman, W.-Y. Chen, T.-T. Chou, J.-H. Huang, and J.-G. Duh, "The variation of grain structure and the enhancement of shear strength in SAC305-0.1NiOSP Cu solder joint," *Mater. Chem. Phys.*, vol. 189, pp. 76–79, 2017.

[9] M. A. A. M. Salleh, S. D. Mcdonald, C. M. Gourlay, H. Yasuda, and K. Nogita, "Suppression of Cu 6 Sn 5 in TiO 2 reinforced solder joints after multiple reflow cycles," *Mater. Des.*, vol. 108, pp. 418–428, 2016.

[10] A. K. Gain, Y. C. Chan, and W. K. C. Yung, "Effect of additions of ZrO2 nano-particles on the microstructure and shear strength of Sn–Ag–Cu solder on AuNi metallized Cu pads," *Microelectron. Reliab.*, vol. 51, pp. 2306–2313, 2011.

[11] P. Liua, P. Yaoa, and J. Liub, "Evolutions of the interface and shear strength between SnAgCu–xNi solder and Cu substrate during isothermal aging at 150 ◦C," *J. Alloys Compd.*, vol. 486, pp. 474–479, 2009.

[12] Y. Huang, Z. Xiu, G. Wu, Y. Tian, P. He, X. Gu, and W. Long, "Improving shear strength of Sn-3.0Ag-0.5Cu/Cu joints and suppressing intermetallic compounds layer growth by adding graphene nanosheets.pdf," *Mater. Lett.*, vol. 169, pp. 262–264, 2016.

[13] A. Sharma, Y.-J. Jang, J. B. Kim, and J. P. Jung, "Thermal cycling, shear and insulating characteristics of epoxy embedded Sn-3.0Ag-0.5Cu (SAC305) solder paste for automotive applications," *J. Alloys Compd.*, vol. 704, pp. 795–803, 2017.

[14] R. Mahmudi and D. Farasheh, "Microstructure and elevated-temperature shear strength of Zn – 4Al – 3Mg – x Sn high-temperature lead-free solders," *Microelectron. Reliab.*, vol. 54, no. 8, pp. 1592–1597, 2014.

[15] O. Krammer and B. Sinkovics, "Improved method for determining the shear strength of chip component solder joints," *Microelectron. Reliab.*, vol. 50, no. 2, pp. 235–241, 2010.

[16] J.-M. Koo and S.-B. Jung, "Effect of displacement rate on ball shear properties for Sn–37Pb and Sn–3.5Ag BGA solder joints during isothermal aging," *Microelectron. Reliab.*, vol. 47, pp. 2169–2178, 2007.

[17] S. Raghavan and S. K. Sitaraman, "Shear test on hard coated flip-chip bumps to measure back end of the line stack reliability," *Eng. Fract. Mech.*, vol. 178, pp. 1–13, 2017.

[18] J. Kim, M. Jeong, S. Yoo, C. Lee, and Y. Park, "Microelectronic Engineering Effects of surface finishes and loading speeds on shear strength of Sn – 3 . 0Ag – 0 . 5Cu solder joints," *Microelectron. Eng.*, vol. 89, pp. 55–57, 2012.

[19] A. M. Najib, M. Z. Abdullah, A. A. Saad, Z. Samsudin, and F. Che Ani, "Numerical simulation of self-alignment of chip resistor components for different silver content during reflow soldering," *Microelectron. Reliab.*, vol. 79, no. October, pp. 69–78, 2017.

[20] A. M. Najib, M. Z. Abdullah, C. Y. Khor, and A. A. Saad, "Experimental and numerical investigation of 3D gas flow temperature field in infrared heating reflow oven with circulating fan," *Int. J. Heat Mass Transf.*, vol. 87, pp. 49–58, 2015.

[21] Japanese Industrial Standard, "JIS Z 3198-7:2003. Test methods for lead-free solders- Part 7 : Methods for shear strength of solder joints on chip components," 2003.

[22] IPC, "IPC-A-610E," *Accept. Electron. Assem.*, pp. 219–237, 2010.