A Study on the Shear Strength and Failure Modes of Sn-3.0Ag-0.5Cu Solder Joint Containing Pt

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A Study on the Shear Strength and Failure Modes of Sn-3.0Ag-0.5Cu Solder Joint Containing Pt

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Abstract. A detailed experimental study on the effect of Platinum (Pt) inclusion on the microstructural evolution, shear strength and failure behaviour of SAC solder joint is presented in this paper. Commercial Sn-3.0Ag-0.5Cu (SAC305) lead-free solder paste was mixed with various contents of Pt nanoparticles to form SAC305-xPt (x= 0, 0.10, 0.30 wt.%) composite solder. Single lap shear joint was formed by overlapping two copper plates together at one end. The solder joints were isothermally aged at 150 °C for 500 and 1000 h respectively to study the microstructure evolution and their influences on the solder joint strength. Microstructure studies showed that Pt effectively refined the β-Sn grain and suppressed the growth of intermetallic compound (IMC) during the isothermal aging. Shear strength of the joints increased with increasing Pt contents in the as-reflowed condition. For the isothermally aged specimens, lower degradation rate in shear strength was found in Pt reinforced solder joints as compared to plain SAC solder joints. Fracture behaviour study showed that Pt reinforced SAC305 composite solder joints were more resistive to the ductile to brittle transition as compared to its Pt-free counterparts. In general, Pt incorporation effectively improves the mechanical properties of SAC solder joint by suppressing IMC growth and refining the grain sizes.

Keywords. Platinum, shear strength, fracture behaviour, IMC

1. Introduction

Increasing environmental and health concerns over the toxicity of lead have prompted the electronic packaging industry toward the development and application of lead-free solders. Among the various lead-free solder alloys, SnAgCu (SAC) has been proposed as one of the most promising substitute for lead-containing solders due to its good mechanical properties, solderability and relatively low melting temperature [1-3]. However, limited reliability in high temperature working environment has restrained its usefulness. Compared to traditional Sn37Pb eutectic solder, Sn rich solders like SAC is found to be more susceptible to degradation in mechanical properties due to the fast intermetallic (IMC) layer growth and grain coarsening under service condition [4]. Although a thin layer of IMC is necessary to achieve good bonding between the solder and substrate, excessive growth of brittle IMC layer on solder/substrate interface can deteriorate the mechanical integrity of solder joint, and eventually lead to brittle failure [5].

In order to improve the performance of SAC solder joint, several attempts have been made by researchers in developing new solder material with enhanced properties. This is mainly achieved by two major approaches. One of the approaches is by micro-alloying with additional elements [6-8]. A study by Mahdavifard MH et al. [9], showed that adding small amount of Fe and Bi as alloying elements increased the ultimate tensile strength and yield strength of Sn-1.0Ag-0.5Cu (SAC105) solder. Another approach is by addition of foreign particles of micro and nano-sized [10-12]. Associate with the miniaturization trend in electronic packaging industry, researchers have shown an increased interest in nanoparticle reinforcements that are smaller in size. Extensive research has shown that introducing of nanoparticles like Ni, CNTs, Sb, Co can improve the mechanical strength of solder joint due to solid solution strengthening, grain size refinement and second phase dispersion strengthening [13-15]. Platinum (Pt) that has good resistance to corrosion and oxidation has long been used as the underbump metallization layer to avoid the Cu dissolution [16]. Previous research also found that minor alloying of Pt into SAC solder can result in sluggish IMC growth, refined grain structure and fewer Kirkendall voids formation on the solder substrate interface [17]. Therefore, it is believed that addition of Pt in SAC solder joint will lead to beneficial effect on the mechanical performance.

In this study, effect of Pt additions on the interfacial reaction and solder joint mechanical performance will be assessed by means of single lap joint shear test. Additionally, the fracture surface was observed under SEM to determine the failure mode. The relationship between shear strength, fracture behaviour, and microstructure evolution was then established.

2. Material and methods

2.1. Sample preparation

SAC305-xPt (x = 0, 0.10, 0.30 wt.%) composite solder was prepared by mechanical mixing different content of Pt nanoparticles into commercial SAC305 solder paste (RedRing). Single lap joint specimen with dimension as shown in figure 1 was prepared by connecting two copper plates together through reflow soldering process at peak temperature of 240 °C. A special designed jig was used to control the solder joint thickness to 0.20 mm. The overlapping area was 10 x 10 mm^2. One set from each group was set aside as standard while the remaining samples were thermally aged at 150 °C up to 1000 hours.

2.2. Microstructure studies

Metallographic investigation was carried out using a Hitachi S-3400 N scanning electron microscope. The solder joints were cross-sectioned and mounted in acrylic resin. It was then ground with SiC sandpaper down to 2000 grits and polished to mirror flat surface with 1 µm diamond suspension. Lastly, the specimens were etched with a solution of 5% HCl in ethanol. Energy Dispersive X-ray technique was performed for chemical analysis of the phase present.

2.3. Shear Test and fracture behavior studies

The shear strength of solder joint was measured by Instron 5582 Universal Testing Machine with constant strain rate of 1.20 mm/min. For each aging condition, 3 samples were tested and the average value was taken. To understand the fracture mechanism of Pt reinforced nanocomposite solder, broken solder joints after shear test were collected and observed under SEM.

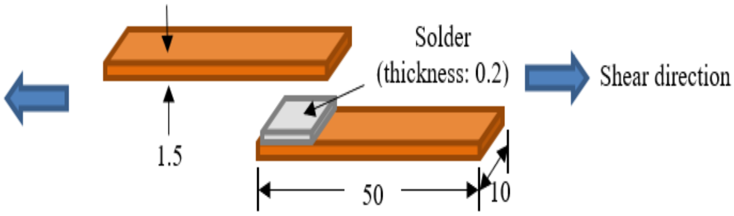

Figure 1. Specification of single lap shear joint. (unit: mm)

3. Result and discussion

3.1. Microstructure and IMC growth

Figure 2 presents the optical microstructure of SAC305 solder with different Pt contents. According to the Cu-Sn phase diagram, the major components presents in SAC305 solder reflowed at 240 °C are β-Sn (bright region) and eutectic Cu_6Sn_5/Sn (dark region) and large Ag_3Sn precipitation. From the figure, it can be seen that microstructure of solder matrix was refined by Pt addition. As shown in figure 2(b)-(c), increase in Pt concentration results in smaller β-Sn dendrite and more uniformly distributed Cu_6Sn_5/Sn eutectic phase. The reason behind could be due to the effect of Pt in controlling the undercooling required for solidification of tin dendrites. Similar observation was reported with Zn addition, where minor addition of Zn into SAC solder was found to reduce the undercooling for β-Sn formation and, subsequently, lead to finer microstructure [18].

Figure 3 reveals the cross-sectional microstructures of as-reflowed SAC-xPt/Cu (x = 0, 0.10, 0.30 wt.%) solder joints. It is seen that an intermetallic compound layer with large and spiky grain structure formed between the SAC305 solder and Cu substrate (figure 3(a)). Based on previous studies, this discontinuous scallop-type IMC layer was identified to be Cu_6Sn_5 [19]. Upon addition of Pt nanoparticle, the morphology of IMC layer become more continuous with smaller scallop-shape grain. The grain refinement is more pronounced when amount of Pt addition increased from 0.10 wt.% to 0.30 wt.%, as in figure 3 (b)-(c). Pt was found to dissolve in solder/Cu interface of Pt containing nanocomposite solder (figure 4). It is believed that Pt can substitute the Cu atom from Cu_6Sn_5 lattice and forming $(Cu,Pt)_6Sn_5$ ternary compound, as in the case of Pt as alloying element [17].

Further aging to 1000 h causes the IMC layer coarsened to layer-type structure. A darker layer known as Cu_3Sn appeared on the interface between the Cu_6Sn_5 IMC and Cu substrate (figure 5). In SAC305/Cu solder joint, a large amount of kirkendall void was found on the thick Cu_3Sn IMC of plain solder joint (figure 5 (a)). In comparison, thickness of Pt reinforced nanocomposite solder joint remains thinner and no obvious kirkendall void was detected from the micrograph (figure 5 (b)-(c)).

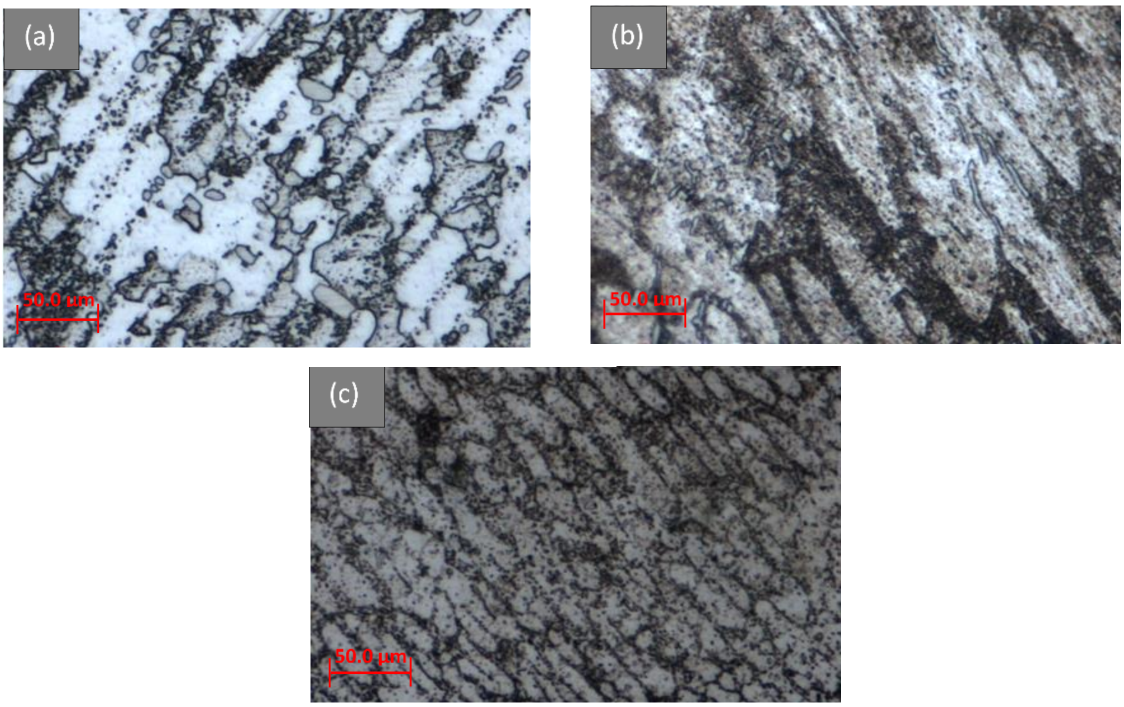

Figure 2. Optical microstructure of SAC-xPt solder: (a) 0 wt.%; (b) 0.10 wt.%; (c) 0.30 wt.%.

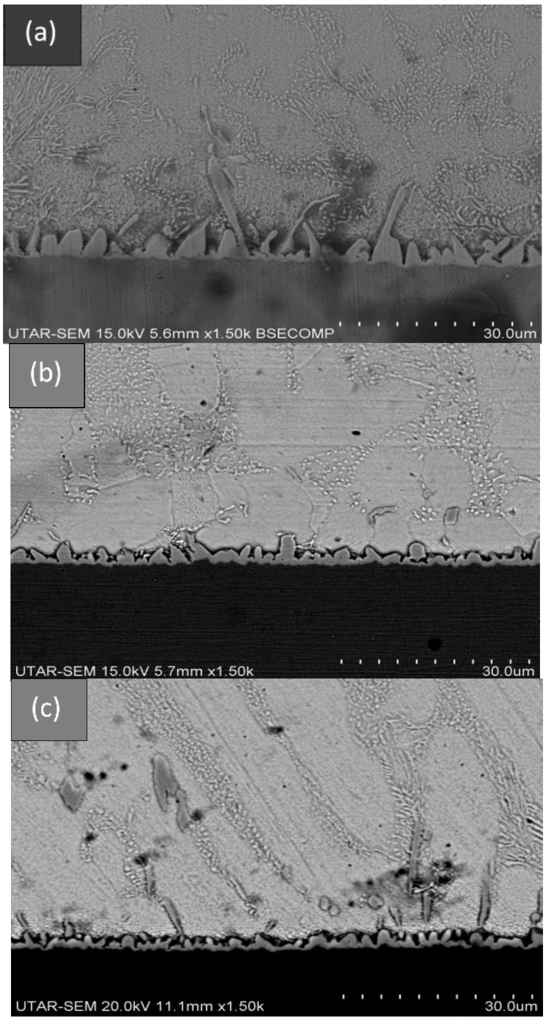

Figure 3. The as-reflowed cross-sectional view of SAC305-xPt/Cu interface: (a) 0 wt.%; (b) 0.10 wt.%; (c) 0.30 wt.%.

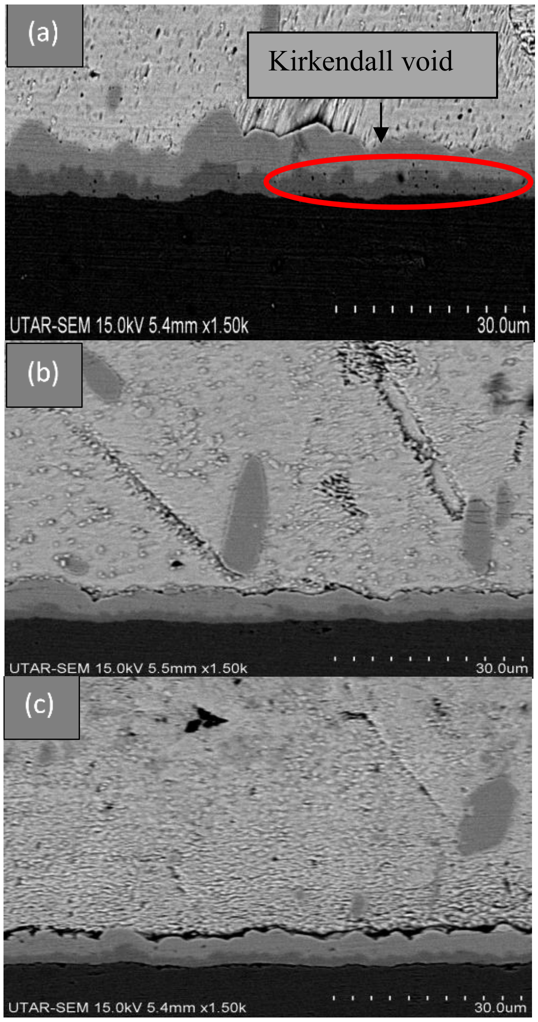

Figure 5. The cross-sectional view of SAC305-xPt/Cu interface being aged at 150 °C for 1000 h: (a) 0 wt.%; (b) 0.10 wt.%; (c) 0.30 wt.%.

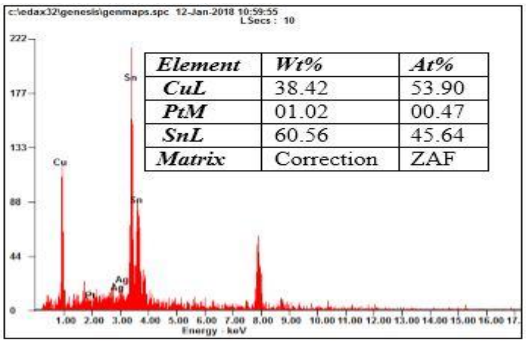

Figure 4. EDX analysis on interfacial IMC layer of Pt reinforced nanocomposite solder.

In figure 6, the thickness of each individual IMC layer is plotted with respect to aging time. From the plot, a lower IMC growth rate was observed from Pt containing solder joint. This finding could be attributed to the formation of thermodynamically stable $(Cu,Pt)_6Sn_5$ that is harder to decompose to form Cu_3Sn [20]. Similar result was reported in Pt as alloying element of SAC solder joint [17]. Therefore, Pt nanoparticle might exert its effect on the IMC growth through partially alloying effect.

3.2. Shear test and fracture behaviour

Solder joints are constantly subjected to mechanical loading during manufacturing, transportation and application. To better understanding the mechanical performance of Pt reinforced composite solder joint under actual service conditions, single lap shear test was conducted. Figure 7 shows the shear strength of monolithic SAC305 and Pt reinforced solder joint after reflowing and isothermal aging at 150 °C for duration up to 1000 h. For the as-reflowed samples, the shear strength of solder joint is seen to increase with increasing Pt content, as shown in figure 7, the shear strength of SAC305/Cu solder joint was increased from 28.5 MPa to 30.8 MPa and 34.4 MPa, respectively with addition of 0.10 wt.% and 0.30 wt.% Pt. This discrepancy in strength could be explained by the microstructure of the solder joint. According to Hall-Petch strengthening mechanism, materials with smaller grain size will have higher mechanical strength since they possess greater amount of grain boundaries that can resist dislocation movement [21]. In addition, similar result was reported with Ni addition, where dispersion of smaller $(Cu,Ni)_6Sn_5$ IMCs grain size in bulk solder is found to contribute to higher shear strength [22]. Therefore, it is believed that higher shear strength of nanocomposite solder joint is due to the finer grain structure as well as thinner IMC layer resulted by Pt addition as in figure 2 and 3.

After isothermal aging at 150 °C, shear strengths of both monolithic and nanocomposite solders are seen to decrease with increasing aging time, but the deterioration in shear strength of solder joint without Pt is more prominent. Upon aging for 1000 h, SAC305/Cu experiences a tremendous drop in shear strength of about 34%, however, there is only a 26% and 21% drop in shear strength for composite solder with Pt contents of 0.10 wt.% and 0.30 wt.% respectively. These discrepancies suggested that inclusion of Pt nanoparticle in SAC solder can lead to better reliability in high temperature working environment. Previous studies also showed that excessive growth of IMC layer could result in thermal fatigue failure due to its intrinsic brittleness [23]. Therefore, the reason behind the higher shear strength of aged Pt reinforced solder joint could be accounted for the effectiveness of Pt in controlling the interfacial growth and grain ripening during the solid state diffusion. Besides that, absence of Kirkendall voids on the aged composite solders joint could result in stronger mechanical attachment between solder and substrates. Hence, better mechanical properties were achieved by Pt addition.

In order to investigate the fracture mechanism of the solder joints aged for different duration, the fracture morphologies of the solder joints were examined with SEM. Figure 8(a) shows the fracture surface of as-reflowed solder joint. Evidence of elongated solder along the loading direction and parabolic-shaped dimple indicated that the solder joint undergoes a ductile failure.

With further increase of aging duration to 1000 h, the fractured morphology of plain solder was majorly covered by IMCs and some residual solder, as shown in figure 8(b). The IMC layer was identified to be Cu_3Sn through EDX analysis (figure 9). The result shows that delamination of Cu_6Sn_5/Cu_3Sn was the primary failure mechanism. It could be resulted from the Kirkendall void formed due to the imbalance diffusion flux between the Cu_6Sn_5/Cu_3Sn interface. Previous researches also showed that Kirkendal voids could reduce the effective area of solder joint in resisting the shear loading and allow the crack initiation to happen [24].

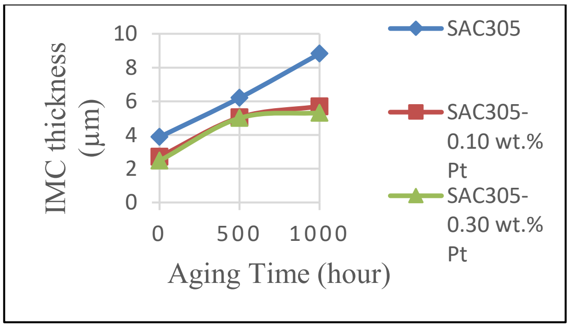

Figure 6. IMC thickness after various thermal aging duration.

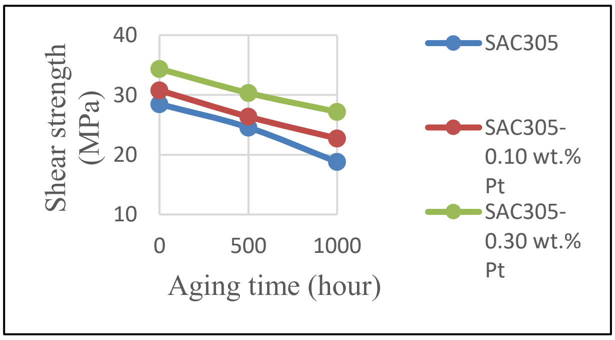

Figure 7. Shear strength after thermally aged for various duration.

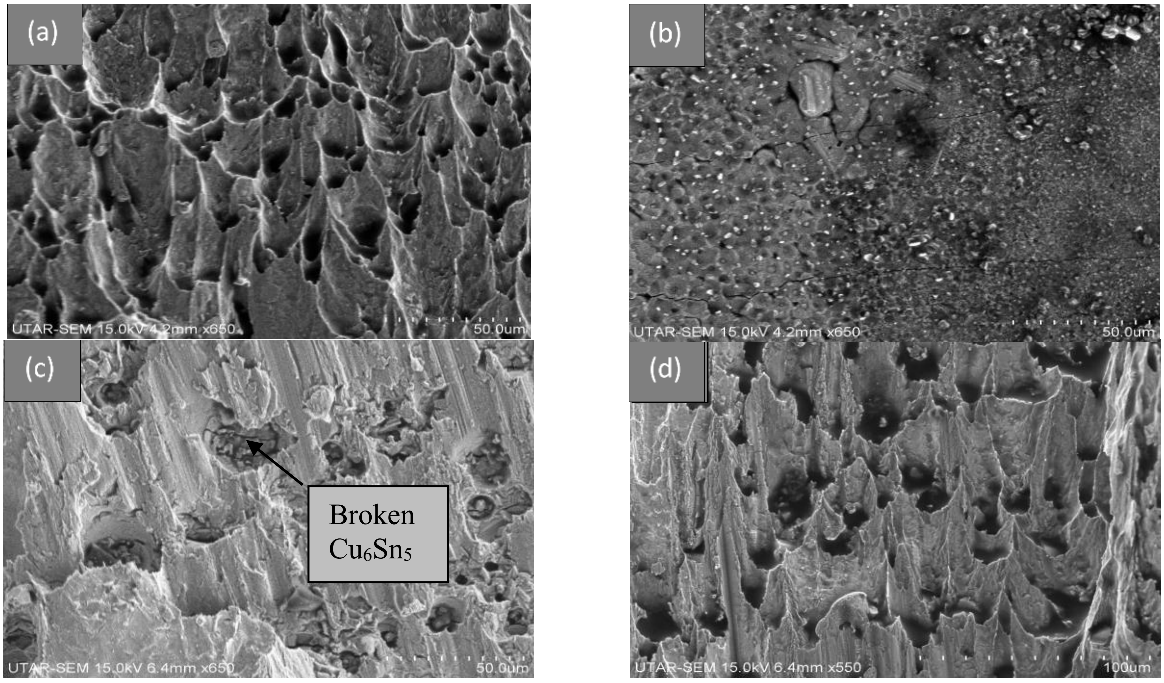

Figure 8. Fracture surface of SAC305-xPt/Cu solder joint: (a) as-reflowed; (b) 0 wt.%; (c) 0.10 wt.%; (d) 0.30 wt.% after thermal aging at 150 °C for 1000 h.

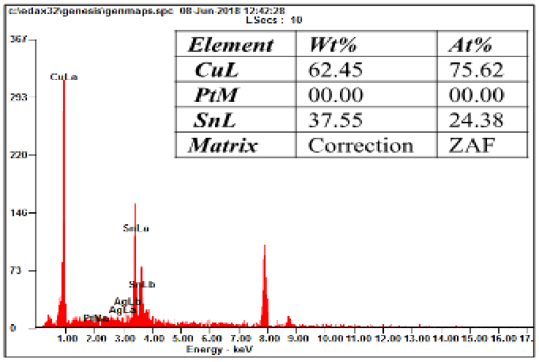

Figure 9. EDX analysis of figure 5(b).

4. Conclusion

The effect of Pt particles addition on microstructure evolution, shear strength and fracture behaviour of SAC solder have been studied in this work. The main conclusions obtained are as follows:

1) Compared to plain SAC solder, Pt containing composite solder was found to exhibit slower growth rate under thermal aging. This might be attributed to the effect of Pt inclusion. It was found that Pt dissolved into Cu_6Sn_5 IMC layer forming the thermodynamically stable $(Cu,Pt)_6Sn_5$ which slows down the overall growth of the IMC layer.

2) The shear strength of both monolithic and Pt containing composite solder joints were observed to decrease with increasing aging time. However, lower degradation rate in shear strength was found with Pt addition.

3) Pt additions slow down the ductile to brittle transition of SAC305 solder joint resulted from isothermal aging. This was attributed to the effect of Pt in suppression of interfacial layer growth and grain coarsening process.

In conclusion, all of these findings proved that a more reliable solder joint was obtained by Pt inclusion.

5. References

[1] Ma H, Suhling JC. A review of mechanical properties of lead-free solders for electronic packaging. Journal of materials science. 2009 Mar 1;44(5):1141-58.

[2] Zhang L, He CW, Guo YH, Han JG, Zhang YW, Wang XY. Development of SnAg-based lead free solders in electronics packaging. Microelectronics Reliability. 2012 Mar 1;52(3):559-78.

[3] Sun L, Zhang L. Properties and microstructures of Sn-Ag-Cu-X lead-free solder joints in electronic packaging. Advances in Materials Science and Engineering. 2015;2015.

[4] Che FX, Pang JH. Characterization of IMC layer and its effect on thermomechanical fatigue life of Sn–3.8 Ag–0.7 Cu solder joints. Journal of Alloys and Compounds. 2012 Nov 15;541:6-13.

[5] Sona M, Prabhu KN. Review on microstructure evolution in Sn–Ag–Cu solders and its effect on mechanical integrity of solder joints. Journal of Materials Science: Materials in Electronics. 2013 Sep 1;24(9):3149-69.

[6] Gao L, Xue S, Zhang L, Sheng Z, Ji F, Dai W, Yu SL, Zeng G. Effect of alloying elements on properties and microstructures of SnAgCu solders. Microelectronic Engineering. 2010 Nov 1;87(11):2025-34.

[7] Lin TC, Kung HY, Lee SH, Chen MH, Chiu YT, Lin KL. The failure mode of Bi and Ni-doped Sn-Ag-Cu solder joint under electromigration tests. InElectronics Packaging and iMAPS All Asia Conference (ICEP-IAAC), 2018 International Conference on 2018 Apr 17 (pp. 226-229). IEEE.

[8] Syed A, Kim TS, Cho YM, Kim CW, Yoo M. Alloying effect of Ni, Co, and Sb in SAC solder for improved drop performance of chip scale packages with Cu OSP pad finish. InElectronics Packaging Technology Conference, 2006. EPTC'06. 8th 2006 Dec 6 (pp. 404-411). IEEE.

[9] Mahdavifard MH, Sabri MF, Shnawah DA, Said SM, Badruddin IA, Rozali S. The effect of iron and bismuth addition on the microstructural, mechanical, and thermal properties of Sn–1Ag–0.5 Cu solder alloy. Microelectronics Reliability. 2015 Aug 1;55(9-10):1886-90.

[10] Billah MM, Shorowordi KM, Sharif A. Effect of micron size Ni particle addition in Sn–8Zn–3Bi lead-free solder alloy on the microstructure, thermal and mechanical properties. Journal of Alloys and Compounds. 2014 Feb 5;585:32-9.

[11] Chellvarajoo S, Abdullah MZ, Khor CY. Effects of diamond nanoparticles reinforcement into lead-free Sn–3.0 Ag–0.5 Cu solder pastes on microstructure and mechanical properties after reflow soldering process. Materials & Design. 2015 Oct 5;82:206-15.

[12] El-Daly AA, Desoky WM, Elmosalami TA, El-Shaarawy MG, Abdraboh AM. Microstructural modifications and properties of SiC nanoparticles-reinforced Sn–3.0 Ag–0.5 Cu solder alloy. Materials & Design (1980-2015). 2015 Jan 1;65:1196-204.

[13] Sujan GK, Haseeb AS, Nishikawa H, Amalina MA. Interfacial reaction, ball shear strength and fracture surface analysis of lead-free solder joints prepared using cobalt nanoparticle doped flux. Journal of Alloys and Compounds. 2017 Feb 25;695:981-90.

[14] Chen G, Wu F, Liu C, Silberschmidt VV, Chan YC. Microstructures and properties of new Sn–Ag–Cu lead-free solder reinforced with Ni-coated graphene nanosheets. Journal of Alloys and Compounds. 2016 Jan 25;656:500-9.

[15] Tao QB, Benabou L, Vivet L, Le VN, Ouezdou FB. Effect of Ni and Sb additions and testing conditions on the mechanical properties and microstructures of lead-free solder joints. Materials Science and Engineering: A. 2016 Jul 4;669:403-16.

[16] Wang SJ, Liu CY. Coupling effect in Pt/Sn/Cu sandwich solder joint structures. Acta materialia. 2007 Jun 1;55(10):3327-35.

[17] Wong KM, Tian YK. Effect of trace platinum additions on the interfacial morphology of Sn–3.8 Ag–0.7 Cu alloy aged for long hours. Microelectronics Reliability. 2014 Nov 1;54(11):2536-41.

[18] Kang SK, Leonard D, Shih DY, Gignac L, Henderson DW, Cho S, Yu J. Interfacial reactions of Sn-Ag-Cu solders modified by minor Zn alloying addition. Journal of Electronic Materials. 2006 Mar 1;35(3):479-85.

[19] Zeng G, Xue S, Zhang L, Gao L, Dai W, Luo J. A review on the interfacial intermetallic compounds between Sn–Ag–Cu based solders and substrates. Journal of Materials Science: Materials in Electronics. 2010 May 1;21(5):421-40.

[20] Tan AT, Tan AW, Yusof F. Influence of nanoparticle addition on the formation and growth of intermetallic compounds (IMCs) in Cu/Sn–Ag–Cu/Cu solder joint during different thermal conditions. Science and technology of advanced materials. 2015 May 20;16(3):033505.

[21] Abtew M, Selvaduray G. Lead-free solders in microelectronics. Materials Science and Engineering: R: Reports. 2000;27(5):95-141.

[22] Lee YH, Lee HT. Shear strength and interfacial microstructure of Sn–Ag–xNi/Cu single shear lap solder joints. Materials Science and Engineering: A. 2007 Jan 25;444(1-2):75-83.

[23] Mustafa M, Suhling JC, Lall P. Experimental determination of fatigue behavior of lead free solder joints in microelectronic packaging subjected to isothermal aging. Microelectronics Reliability. 2016 Jan 1;56:136-47.

[24] Hu X, Xu T, Keer LM, Li Y, Jiang X. Microstructure evolution and shear fracture behavior of aged Sn3Ag0. 5Cu/Cu solder joints. Materials Science and Engineering: A. 2016 Sep 15;673:167-77.