Impact of Thermal Ageing and Multiple Reflow on Lead Free Composite Solder: A Short Review

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Abstract. This paper reviews the impact of the thermal ageing and multiple reflow to the intermetallic compound (IMC) layer and mechanical performance of lead free solder reinforced with various reinforcements. Based on available literatures it had been proved that, the IMC layer and mechanical properties can be affected with the exposure of different temperatures and time. Besides that, the incorporation of the reinforcement in the matrix of solder alloys could improve the thickness of IMC layer and strength of the solder joints although it had been subjected to thermal ageing and multiple reflow cycles as compared to unreinforced solder. Therefore, the composite solder system could be possibly applied and adapted in current electronic devices even with the exposure of high temperatures.

1 Introduction

Soldering technologies have been prominent electronic interconnections since the early age of electronics and the technology will continually grow further in the future [1]. The performance and the reliability of the solder interconnections in the electronic devices are undeniably crucial in ensuring the longer lifetime of the electronic devices. In addition, current trend in the electronic industry are associated with the high speed, lightweight, miniaturization and multifunction of electronic devices. Therefore, a very robust interconnected materials need to be developed to ensure good performance of the interconnections prior to current trends. As more than 50 years ago, tin lead (Sn-Pb) solder alloys were dominantly used in the electronic industry as one of an outstanding interconnected material [2]. However, the concern regarding the toxicity of lead to the environment led to the emergence of many lead-free solder alloys that were expected to perform equivalently or better than lead solders. Examples of lead free solders were tin-copper (Sn-Cu), tin-copper-silver(SAC) and tin-copper-nickel (Sn-Cu-Ni) [3-5]. To date, researchers also introduced composite solders, solder that intentionally reinforced with

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reinforcements either it was intrinsic or extrinsic reinforcements [6]. The incorporation of the reinforcements in the solder matrix were aimed to improve the service temperature capability, altered and stabilized the fined-grain microstructure as in returns affect the mechanical performance of the solder joints. Reinforcements reportedly used by previous researchers are aluminium (Al) [7], iron (Fe) [8], silicon carbide (SiC) [9], titanium oxide (TiO₂) [6, 10], cerium oxide (Ce₂O) [11] and kaolin geopolymer ceramics [2]. It was reported in terms of microstructures, thermal properties, mechanical properties and solderability were seen with the additions of reinforcements [1, 10, 12-14].

In a semiconductor devices, the solder joints between the die and substrate, and the substrate with the base plate were exposed to the thermal and mechanical stresses either during the processing and also subsequent operations [15]. In additions, during the service of the electronic components, solder joints were extremely exposed to the changes in the cycles of temperatures which in return would induce the thermal fatigue failures. Therefore, it was extremely important to investigate the performance of the new developed composite solders as it will subjected to different thermal conditions, so as to improve the reliability of the solder joints. Moreover, the most important parts that might be affected with different thermal exposure during the operations and services were the growth of intermetallic compound layer (IMC) which then affects the mechanical properties of the solder [16].

Therefore, this paper discussed on the impacts of different thermal treatments to the growth of intermetallic compound layer and mechanical properties of composite solders with the incorporation of various types of reinforcements.

2 Thermal effects in composite solders

Temperature is one of the important factors that lead to changes in the microstructure of the solder and induce internal stress in the solder joints which later promotes to the occurrence of the failure at the solder joints. The effects of temperature to the solder joint investigate as the solder joints were subjected to thermal ageing, thermal cycle and multiple reflow conditions. Thermal ageing is a condition where the solder joints are exposed to the various constant temperatures for some period of time [17]. Table 1 shows some of the temperatures and time that had been used by previous researchers in order to investigates the influence of thermal ageing to the composite solders. While, thermal cycle involves exposing the solder joints to the alternate extremely low and high temperatures at distinct temperature cycles such as from – 40 to 125 °C, - 40 to 150 °C and – 55 to 125 °C [18, 19] . Multiple reflow is a term referring to the process experienced by the solder joints in the electronic assemblies starting from the wafer bumping to the board level assembly [20]. Solder joints are commonly the weakest points as it was subjected to different kind of thermal treatments and it was the most likely part that would initiate the failure in the electronic devices. Therefore, the reliability and performance of the solder joints would dictate the reliability and also overall performance of electronic devices. Moreover, the intermetallic compound (IMC) layer directly linked with the mechanical properties of the solder. Thus, failure at the IMC layer of the solder joints would affects the mechanical performance of the solder. In next section, effects of the thermal ageing and multiple reflow on the intermetallic compound (IMC) layer and mechanical properties of the composite solder.
Table 1: Thermal ageing of different solder compositions at different temperatures and times.

| Solder compositions | Temperatures (°C) | Time (hours) |
|---------------------|-------------------|--------------|
| Sn-3.0Ag-0.5Cu + TiC [21] | 150              | 169, 324, 484 |
| Sn-3.5Ag-0.5Cu + ZnO [22] | 120              | 2.5, 5, 10, 50 |
| Sn-3.5Ag-0.5Cu + TiO\textsubscript{2} [23] | 125              | 168          |
| Sn-58wt.%Bi + multiwalled carbon nanotubes [24] | 85, 95, 105 and 115 | 100, 300, 500 and 1000 |
| Sn-0.7Cu + TiO\textsubscript{2} [25] | 150              | 500, 1000, 1500 and 2000 |
| Sn-Cu-Ni + TiO\textsubscript{2} [25] | 100, 125, 150, 175 | 168          |
| Sn-3.5Ag-0.5Cu+ TiO\textsubscript{2} [26] | 75, 125 and 150 | 120, 240 and 720 |
| Sn-Ag-Cu + Sm\textsubscript{2}O\textsubscript{3} [1] | 125 and 175 | 24 and 240 |
| Sn-Cu-Ni + TiO\textsubscript{2} [27] | 125 and 175 | 24 and 240 |

3 Effects of thermal ageing and multiple reflow to the intermetallic compound layer of composite solders

Solder joints in the electronic devices were often exposed to the elevated temperature at a longer period of time. Thus, this condition could affect the reliability of the solder joints since the intermetallic compound (IMC) layer and mechanical performance could be affected with the temperature. According to Chen et al [21], the addition of titanium carbide (TiC) in the matrix of Sn-3.0Ag-0.5Cu could change the morphology of the interfacial layer of Cu\textsubscript{6}Sn\textsubscript{5} from circular granular to short rod like with the rate of growth of the interfacial layer were suppressed. Fig. 1 shows the morphology of the interfacial layer which subjected to isothermal ageing at 150 °C for 169 h, 324h and 484 h. He also reported that, Cu\textsubscript{3}Sn interfacial layer was significantly suppressed with the incorporation of TiC which could be attributed by the adsorption of reinforcement particles on the surface of interfacial layer that hindered the diffusion of copper to the solder matrix [21]. The formation of Kirkendal voids were associated with the thermal ageing time and temperature. It was interestingly proved that, the formation of Kirkendal voids at the interfacial layer of Cu\textsubscript{3}Sn were reduced in the composite solders of Sn-3.0Ag-0.5Cu/TiO\textsubscript{2} as compared to pure Sn-3.0Ag-0.5Cu [25].

During multiple reflow, the thickness of interfacial IMC layer were decreased with the addition of titanium oxide (TiO\textsubscript{2}) with the maximum thickness of interfacial IMC layer for the composite solder Sn-3.0Ag-0.5Cu/ TiO\textsubscript{2} with multiple reflow cycle was 8 µm [25]. However, in pure Sn-3.0Ag-0.5Cu the thickness of interfacial IMC would grow until 13 µm. In addition, the morphology of Ag\textsubscript{3}Sn in the composite solders of 96.4Sn-3.6Ag/Al\textsubscript{2}O\textsubscript{3} transformed from the coarser to finer spheroidal shape with multiple reflow cycles [28]. Therefore, the reinforcements particles added shows the ability to suppressed the formation of thicker IMC layer although it was subjected to different ageing time and temperature and also multiple reflow cycles [29-30].
4 Effects of thermal ageing and multiple reflow to the mechanical properties of composite solders

In previous sections, it was proved that the thickness and morphology of interfacial IMC changed with the exposure of different temperature at different times. Thus, the strength of the solder joint could also affect which would dictates the subsequent mechanical performance of the solder. Fig. 2 shows the graph of stress strain curve for Sn-3.5Ag-0.5Cu (SAC355) composite solders. As reported by [22], the tensile strength of SAC355 lead free solder and SAC355/ZnO were affected with the increasing in the ageing temperature. According to stress strain curve in Fig.2, the stress strain curves were shifted to the lower stress level as compared to the lower ageing temperature. Moreover, the ultimate tensile stress, yield stress and fracture stress were reduced with an increase in the ageing temperature for SAC355 with ZnO and SAC355 without addition of ZnO. However, the reduction in the ultimate tensile stress, yield stress and fracture stress in the SAC355 with ZnO was not as higher as in SAC355 without ZnO, which proved the effectiveness of
the ZnO as the reinforcement particles. The reason in the improvement of solder strength in SAC355/ZnO was due to the formation of finely dispersed IMCs and β-Sn dendrite size which help in suppressing the plastic deformation.

![Stress strain curve](image)

**Fig. 2.** Stress strain curve of (a) SAC355 (b) SAC355/ZnO subjected to thermal ageing at 2.5 hours for different temperatures [22].

Besides that, addition of strontium titanate (SrTiO₃), to Sn-Ag-Cu reduced the shear strength of the solder joints with increasing in ageing times. Although the shear strength was reduced with respected to ageing time, but the strength in Sn-Ag-Cu reinforced with SrTiO₃ were still higher than pure Sn-Ag-Cu.
In terms of multiple reflow, the strength of the solder joint was decreased with the increasing of reflow cycle. Tikale et. al [28], reported that the strength of Sn-Ag-Cu solder was gradually decreased start after the second reflow. The decrement in the strength of the solder alloys was due to the formation of thick Cu6Sn5 and the formation of Cu3Sn layer at the interfacial IMC. Formation of Cu3Sn IMC could lead to the mismatch of thermal coefficient of thermal expansion between IMCs. Thus, promotes the existence of micro-cracks along the IMC layer as it was subjected to multiple reflow cycle.

5 Summary

This reviews had documented the changes in the intermetallic compound layer and mechanical properties of solder under thermal ageing and multiple reflow cycle. It can be concluded that the addition of reinforcement particles into existing lead free solder alloy could enhanced the properties of the solder even though it was subjected to thermal ageing and multiple reflow cycle. The strength of the solder were reduced with ageing time and temperatures, but the value still higher than the solder alloys without the addition of reinforcement particles. Therefore, in developing new solder composite, the effects of different temperatures exposure to the intermetallic layer and mechanical properties should of composite solder should be carefully examined in order to integrate and applied composite solder so as to adapt with the modern electronic devices.

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