Study on Hardness and Shear Strength with Microstructure Properties of Sn52Bi/Cu + 1% Al2O3 Nanoparticles

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Abstract. The Sn-58Bi (SB) lead-free solder was added with 1% nanoparticles (NP) of aluminium oxide (Al2O3) to investigate the shear strength based on microstructure and joint properties. The microstructures of the SB added with 1% Al2O3 NP containing Bi precipitation and β-Sn grains. The spacing between the lamellar structures of a SB solder alloy was narrower. Proper arrangement of the microstructure of β-Sn, Bi and with the presence of Al2O3 as discrete particles (dispersion strengthening) contributes to the increase on the shear strength and hardness value. The shear strength of the SB added with 1% Al2O3 NP solder joint was enhanced by 50% compared to the bare SB solder joint while there was a 33% increase in the microhardness as well. The shear test was conducted based on ASTM D1002 specification of single lap joint method. The presence of Al2O3 NP along the interface (Hall-Petch effect) contributes to the improvement in the shear strength by reducing the thickness of the IMC layer and retarding the growth of the Cu6Sn5 IMC layer. This study provides evident results for the enhancement of the mechanical properties of the 1% Al2O3 NP added SB solder.

1. Introduction/Literature

The electronic packaging industry vastly developed in current era creates more importance to the solder as it plays a crucial role in providing integrity electronic assemblies. Unfortunately, the common Sn-Pb solder is harmful to the environment and human due to lead (Pb) [1,9]. To replace this solder, the alternative solder alloys should be competing with the credible mechanical property of the lead solder alloy, especially in the shear strength. The SnPb solder alloy provides a thin IMC layer between the solder and the copper substrate in the printed circuit board, which contributes to the shear strength increment. Therefore, replacing this solder requires the alternative solder alloys to be practically compatible with the traditional solder. Numerous lead free solder alloys such as SnCu [1], SnAg [2], SnZn [3], SnBi [4], SnAgZn [5], SnAgCu [6] and the research materials are vastly available. On the other hand, some major drawbacks are found upon testing these solder alloys, for example poor wettability (SnZn) [7], thick intermetallic (IMC) layers (SnCu, SnAg) [8], low shear strength (SnAgZn, SnAg) [9], disposed to corrosion (SnZnAg, SnZn) [10] and many more. Another key aspect is to provide a low-temperature solder alloy and in that context, the SnBi solder is a potential candidate. Based on the phase diagram, a eutectic composition of SnBi solder provides melting temperature of, TM=139ºC which is lower than the most used SnPb, TM=183ºC [11] and SnAgCu, TM=227ºC [12]. At the same time, the electronic products are currently minimized, making the mass and density to be a vital aspect to select...
a solder alloy. As commonly practised, adding a new element to the mother solder alloy usually increases the shear strength, but then the mass increases as well making the electric components to be heavy. Such a problem should be resolved and the current researches lean to enhance the properties of a solder alloy with additions of nanoparticles. These nanoparticles can influence by affecting the solubility of the solder alloy and being discrete particles to the mechanical strength. It is crucial to provide and understand the influences of these nanoparticles to a solder alloy [13].

2. Methodology
The preparation of bare Sn58Bi (SB) solder alloys was based on the weight percentage of 42% Tin (Sn) and 58% Bismuth (Bi). An overall weight of 20g of SB chosen to replicate the usage of small consumption of solder paste used in the electronic industries. The Al2O3 NP (size < 50nm,) of 0.6 gram (1%) was weighed and melted together in the SB solder alloy using an induction furnace for an hour and thirty minutes hour at a constant temperature of 600°C to ensure a homogeneous mixture. To ensure all nanoparticles are properly mixed, the SB added with the Al2O3 was re-melted using a hot plate at 250°C with stirring for 30 minutes. The SB + 1% Al2O3 solder alloy was formed into billets of 5mm × 1mm for experiment purposes. The SB + 1% Al2O3 billet undertakes the standard metallographic sample preparation to produce clean and mirror-like surface finish. The Vickers micro hardness test with 1kgf load were induced to the solder billets to discover the hardness value. The shear strength were evaluated based on the ASTM D1002 (single shear lap) as the billets were soldered onto the Copper (Cu) substrate with a dimension of 30×10×1.5mm at a soldering temperature of 250°C for 30 seconds. The Zinc Chloride (ZnCl) flux applied during soldering to avoid oxidation.

3. Results and Properties Discussion.

3.1 Microstructure Properties
The microstructure of the SB + 1% Al2O3 NP was investigated using the high-resolution optical microscope as shown in Figure 1. This investigation provides an initial sight on the morphology of the SB + 1% Al2O3 NP that can be related to the mechanical properties especially the hardness of the solder. Figure 2 shows the microstructure of SB + 1% Al2O3 NP with a clear presence of lamellar type structure observed relating to the common structure of a Sn-Bi solder alloy system [14], which was also investigated as a purpose if comparison. Adding 1%, Al2O3 NP shows light phases (Bi) as well dark phase (Sn) and nearer lamellar gap structure compared to the bare SB solder alloy in Figure 2 (a). This confirms that the presence of Al2O3 NP is the main factor that influences the different configuration of the microstructure. The Al2O3 NP will be avoiding a self-diffusion process with the SB solder matrix due to its high melting temperature, Tm=2072°C. This consequently enables the nanoparticles to accumulate at the grain boundaries of the solder alloy [15]. Literally, this is a typical characteristic of any nanoparticles as they will accumulate at the high-energy site of in a molten solder (at grain boundary), as reported by [16]. The presence of the nanoparticles along the grain boundary will stimulate nucleation site for primary Sn matrices and produces smaller and finer Sn matrices by limiting the growth velocity of the plane. This phenomenon can be explained using the surface absorption theory as researched by [9] which defines that the plane with the maximum surface tension grows fastest (acting as the nucleation site) with an increasing adsorption element (Al2O3). An EDX analysis proved the presence of the Al2O3 in the SB solder alloy as in Figure 2 (e).

3.2 Mechanical Properties (Hardness and Shear Strength)
The addition of 1% Al2O3 NP produces average micro hardness value of 16.3HV taken from five readings. Comparing to the other common solders (Figure 2), the increment in hardness was evident with the presence of Al2O3 NP. These increments are purely due to the presence of the nanoparticles, which acts as an obstacle for the motion of dislocations. The physical property of these Al2O3 NP, which, which does not take part in any diffusion process, acts as discrete particles, which segregate at the grain does not take part in any diffusion process, acts as discrete particles, which segregate at the grain boundary and impedes the dislocation. These characteristics are the key to the increment in hardness [17]. Furthermore, the uniform microstructure with fine Sn-matrices with the wider eutectic area (Figure...
is another factor that increases the hardness in the Al$_2$O$_3$ NP reinforced SB solder alloy. Theoretically, a larger surface area of the nanoparticles per unit volume in the solder alloy can increase the hardness of a material [18].

The shear strength result of the 1% Al$_2$O$_3$ NP added SB solder alloy was 63.45MPa which was 35% higher compared to the bare SB solder alloy. The shear strength results of the bare SB, SB + 1% Al$_2$O$_3$ from this work and few other compiled results are shown in Table 1. The presence of these Al$_2$O$_3$ NP in the solder alloy contributes to increase in the strength of the solder joint as a dispersion strengthening mechanism [15, 19]. Obeying the theory of dispersion, these Al$_2$O$_3$ NP will not take part in any activity and exist as a discrete particle that increases the strength of the solder alloy by pinning along the grain boundary [11, 16]. As more dislocations are pinned at the solder joint, the stress has to bend over these dislocations or penetrate through these high dense dislocations [8]. Such was the findings and explanation in this research too.

| Solder                  | Shear Strength (MPa) | References |
|------------------------|----------------------|------------|
| SB+1% Al$_2$O$_3$      | 63.45                | This work  |
| SB                     | 41.08                |            |
| Sn3.8Ag0.7Cu           | 44.68                | [12]       |
| Sn3.5Ag0.5Cu + 1Ti NP  | 57.6                 | [20]       |
| Sn98.5Ag1Cu0.5/Fe + 30Ni | 53.98              | [5]        |
| Sn9Zn+1% Al$_2$O$_3$   | 39.00                | [19]       |
4. Conclusion
The aims of this research is to provide the hardness and shear strength properties of the SB + 1% Al2O3 NP. High hardness value (16.3Hv) and shear strength value (63.45MPa) in the SB + 1% Al2O3 NP were produced compared to the unreinforced SB. This increment obviously proven by the microstructure morphology of the SB solder alloy, which was altered by the Al2O3 NP. The SB + 1% Al2O3 NP can be operated by the desired soldering temperature in the electronics industry (250°C) as this was the temperature used for soldering purpose in this project. In general, the SB + 1% Al2O3 NP solder in this study shows positive outcome in terms of the mechanical properties and further investigation could be potential to produce an alternative solder alloy to accommodate current miniaturization electronics.

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