Effect of Cobalt Nanoparticles on Mechanical Properties of Sn-58Bi Solder Joint

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Abstract

Brittle phases are responsible for crack formation and propagation in tin-bismuth (Sn-58Bi) solder material. The purpose of this work is to investigate the effects of various cobalt (Co) nanoparticle (NP) concentrations on the tensile properties of the Sn-58Bi solder matrix. Different aging times were studied to find out the effect of Co NP on ultimate tensile strength. Tin-Bismuth solder joints of different Co NP concentrations of 0%, 0.5%, 1% and 2% were prepared. The reflow process was done at 180°C for 1 minute. Scanning Electron Microscopy and Energy Dispersive X-ray spectroscopy were used to analyze the solder joints. The tensile test was carried out for the Sn-58Bi and Sn-58Bi-xCo (x = 0.5, 1 and 2) solder joints. The tensile test was run before and after aging time. The tensile results reveal that the addition of Co NP increased the tensile strength significantly at different concentrations of Co NP. The

Tensile test revealed that ductility was improved as the temperature was increased. As the aging time increased, the ultimate tensile strength of all samples decreased.

Keywords: Tensile Test, Ultimate Tensile Strength, Strain Rate, Ductility.

INTRODUCTION

In microelectronic packaging, solders not only provide electronic connections but also ensure mechanical properties, which is crucial for the operation of electronic devices. However, with the trend toward functional and miniaturized devices, solder joint reliability is becoming more and more concerned [1]. Despite this, high circuit density device chips produced a considerable amount of Joule heat due to their increasing functionality. For bonding, we need solder materials with a lower melting point [2]. Lead-based solders are the best option since they possess a lower melting point [3]. The lead-based solder materials used earlier were highly toxic, so it was found in the 1970s that lead-free materials be used instead of Pb-based solders [4, 5].

Recent research had found several Pb-free solder materials instead of Pb-based solders, and most of them are tin-based alloys [6]. One suggested solder material is a tin-bismuth (Sn-Bi) alloy that has eutectic or near eutectic composition [7]. Sn-Bi solder alloy was considered in place of Sn-Pb alloy because it has the same mechanical properties at a lower temperature and has a melting point that is lower than Sn-Pb solder alloy. It helps reduce thermal damage to the chips during the reflow process [8, 9]. Chips can generate heat during the use of the electronic device, which can damage the solder joints. In solder, atoms diffuse faster as the homologous temperature increases, causing their mechanical properties to decline. As the mechanical properties decrease, deformation issues can arise in a solder joint [10, 11].

Researchers have investigated several techniques for improving the mechanical properties of the Sn-Bi solder matrix, including adding alloying elements [12], adding microparticles [13], adding nanoparticles (NP) [14-20] and adding carbon nanotubes [21]. A number of elements have been added to the Sn-Bi, including Y [22], Ce [23] and Ti [24]. Researchers used Sn-Bi solder matrix with Ag [25], Au [26], and Zn [27] to improve mechanical properties. Ni was also added to the Sn-Bi solder matrix by some researchers [28-30], and they found significant improvements in the mechanical properties of the solder joints. Less attention has been given to the effects of adding cobalt (Co) into Sn-Bi. Co, being one of the possible candidates, could enhance the mechanical properties of the Sn-Bi solder matrix [31]. Previous studies investigated the effect of cobalt on SAC305 solder joint and observed that cobalt improved the microstructural and mechanical properties of the solder joint [32]. To understand the effects of mechanical properties on the Sn-58Bi-Co system, tensile stress, tensile strain, maximum tensile strength, and elongation following Co addition to the system are required. It is necessary to comprehend the effect of Co NP on microstructural and mechanical properties of the Sn-Bi solder joint. As no research has been done on Co NP added to Sn-Bi alloy solders, this study investigated the tensile properties of Sn-58Bi solder alloys with different amounts of Co NP.

The objective of this work is to investigate how Co NP addition affects the tensile properties of the Sn-58Bi solder joint. Changes in microstructure were observed after reflow. Tensile tests were conducted after reflow to study how Co NP affects the Sn-58Bi solder joint. Different aging times were studied to find out the effect of Co NP on ultimate tensile strength.

METHODOLOGY

Solder paste and copper bar preparation are the first steps in the process. One end of the copper bar was cleaned and polished to remove the oxide layer. After grounding, the copper bar was cleaned with distilled water and 20% sulphuric acid (H_2SO_4) to remove any oxide and stain. Tensile samples with different percentages of Co NP of size 28 nm addition into Sn-58Bi solder paste were prepared. Around 1 mm thickness between the two copper bars was created to allow the solder paste to insert into the space created. Solder paste with different Co NP was added between the two copper bars as shown in Figure 1 (a). The aluminum plates were used to fix the position of the copper bars in Fig 1 (b). The plate was then put into the reflow oven at 180°C for 1 minute to undergo a reflow process. The variation of temperature was kept at ±5°C. After the reflow process, the excess solder on the surface was removed manually to prevent the excess solder affect the tensile test result. Figure 1 (c) shows the tensile samples of Sn-58Bi. A tensile test was performed by using the universal tensile machine (UTM). A Strain rate of 6.96×10^{-4} s^{-1} was applied to pull the samples. After the samples fractured, the results were collected and analyzed. Different aging times were used to determine the impact of Co NP on ultimate tensile strength.

RESULTS AND DISCUSSIONS:

Tensile test result analysis:

Figure 2 shows SEM images of Sn-58Bi and Sn-58Bi-xCo after reflow. There were two distinct phases in the microstructure: the darker phase was Sn-rich, while the brighter phase was Bi-rich. The structure of tin and bismuth were broken down and grain size was refined when Co NP was added to Sn-58Bi as shown in Figure 2 (b), (c), and (d). A similar result was also found when Ni was added inti Sn-58Bi [29]. Researchers have also found similar alterations in the structure of the Sn-58Bi solder matrix after the addition of a third element [28, 33]. From Fig 2, it was observed that as the concentration of Co was increased, the grain size become smaller. As fine grain size was obtained, the tensile strength of the solder matrix was increased to a distinct value.

In previous studies, Co NP was added to Sn-based solder and it was found that the intermetallic compound formed by Co was thermodynamically more stable [31]. Co reduced the grain size and refined the interfacial IMC layers as well [31, 32]. In the current study, it was also observed in SEM images that the grain size inside the solder matrix significantly reduced which enhanced the mechanical properties. The thermodynamic stability of IMC can promote equilibrium in structure [34] which significantly enhanced the mechanical properties.

The tensile test was performed on the prepared samples, and the results were summarized in Table 1. The tensile test result showed that the cobalt addition significantly increased the maximum stress of reflowed sample (Fig 3 a-d). After aging, it was observed that the maximum stress was decreased for all the samples, but the cobalt addition into the Sn-58Bi solder joint controlled the reduction of maximum stress significantly (Fig 3 a-d). The maximum stress values for all the samples are given in Table 1. The range of the tensile strain of the samples was observed between 3.58 mm to 6.57 mm. The stress-strain graph of Sn-58Bi with and without Co NP revealed that Co addition improved the stress and strain values. Co also controlled the reduction of maximum stress after the aging process. The Sn-58Bi-2Co has the highest strain value, the possible reason that improved the stress and strain of Sn-58Bi solder might be due to the refined grain structure [Fig 2 (b-d)]. The refined grain structure was also observed when Ni was added into Sn-58Bi [29, 35].

According to American Elements, the theoretical maximum tensile stress of the Sn-58Bi is between 51.5MPa and 55.4MPa [36]. However, the tensile strength obtained in this research work was higher than the theoretical value (71.25 MPa). Various temperatures and strain rates were studied by Chen et al. for the Sn-58Bi solder matrix [33]. The authors reported that when the strain rate was increased, the tensile strength also increased and the tensile strain was decreased. This indicates that the Sn-58Bi solder matrix was sensitive to the strain rate. The deformation mechanism of the Sn-58Bi was changed to gliding when a high strain rate is applied.

Fig. 4 shows the ultimate tensile strength versus aging time variation. From this, we concluded that when the Co concentration increased, the ultimate tensile strength was also increased. As the aging time increased, the ultimate tensile strength was decreased for all samples. The results were summarized in Table 2. Sn-58 Bi had a tensile strength of 71.25 MPa, while Sn-58Bi-2Co had a tensile strength of 90.02 MPa. Based on these findings, the ultimate tensile strength of the Sn-58Bi was lower than the Sn-58Bi-2Co. Yang et al. studied the mechanical properties of Sn-58Bi and found that the ultimate tensile strength increased with increasing Ni concentration and reduced with increasing aging time [29]. This means that the concentration of the third element determined the ultimate tensile strength of the solder matrix [24]. It was significant that the Co concentration and aging time affect ductility substantially.

CONCLUSION:

The effect of Co NP on the mechanical properties of Sn-58Bi was investigated. The tensile test was carried out to determine the effect of the Co NP on the tensile properties of the Sn-58Bi solder matrix at various aging times:

1. With the increase of Co NP concentration, the tensile strength was substantially increased to a significant value. The tensile test revealed that ductility was improved as the temperature was increased.
2. The tensile strength of Sn-58Bi (71.25 MPa) was lower than the Sn-58Bi-0.5Co (79.45 MPa), Sn-58Bi-1Co (84.63 MPa) and Sn-58Bi-2Co (90.02 MPa).
3. As the aging time increased, the ultimate tensile strength was decreased for all samples.

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Compliance with Ethical Standards:

The authors followed the ethical standards during the experiments as well as during the preparation of the manuscript.

Author contribution:

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The authors have no relevant financial interests to disclose.

Research Data Policy and Data Availability:

The current study is based on experimental data. In the manuscript, the experimental data were correlated and discussed with existing studies done by other researchers (given in the references). The experimental data of the current study is unpublished and will be provided for the evidences and for review.

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