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Effects of Indium Content on the Tensile Properties of Sn-Bi-In Solder[†]

MOKHTARI Omid *, NISHIKAWA Hiroshi **

Abstract

A comparative analysis between the microstructure and the tensile properties of eutectic Sn-Bi, (Sn-Bi)-0.5In, and (Sn-Bi)-1In solder alloys was conducted. Tensile tests were performed on bulk solder alloys, followed by post-test fracture surface analysis. The results of the tensile tests indicated that the addition of In is highly effective in improving the ductility of the Sn-Bi solder alloy. Moreover, on increasing the In content from 0.5 to 1 wt.%, the elongation of the Sn-Bi solder alloy exhibited a significant increase. In addition, the dimple-like structure on the fracture surfaces of the tensile tested In-bearing solder alloys indicated the ductile properties of the alloys.

KEY WORDS: (Sn-Bi), (tensile test), (lead-free solder), (elongation)

1. Introduction

Because of the continual miniaturization and densification of electronic products, it is necessary to establish a low-temperature process that exerts a low thermal load on the packaging components. Low-temperature soldering reduces the thermal damage to the device and enables the fabrication of inexpensive printed circuit boards without high temperature resistance. Sn-Bi is one of the most promising lead-free solders for low-temperature applications [1-3]. This is due to its low melting point (138 °C [4]) and superior tensile strength compared to the eutectic Pb-Sn solder [5].

Sn-Bi solder alloys also have disadvantages, such as the coarsening of the microstructure during thermal aging [6]. This coarsening becomes a concern in the case of Bi-rich phases, which are generally brittle in nature, as it can result in poor mechanical properties of the solder [7-9]. Moreover, thermal aging can cause further Bi coarsening by inducing the precipitation of over-saturated Bi. It has been reported that the Bi-rich phases grow by the attachment of previously formed and precipitated Bi-rich phases via thermally activated diffusion during thermal aging which leads to Ostwald ripening as the large Bi particles grow at the expense of the small ones [10].

An investigation of the microstructure of Sn-Bi solder joints with 1 and 0.5 wt% In additions has previously been reported [11-13], and the microstructure of the solder/substrate interface as well as the solder bulk after

reflow and thermal aging were explained. In other prior studies, Bi coarsening was not observed in the microstructure of In-bearing solder joints. Authors of this study also reported that the addition of 0.5wt.% In improved the ductility of the Sn-Bi solder [14]. To perform a detailed study, we focus here on the influence of In content on the tensile properties of Sn-Bi solder. The motives of this paper is to clarify the microstructure and mechanical properties of (Sn-Bi)-0.5In and (Sn-Bi)-1In solder joints. A comparative analysis of the microstructure and tensile properties of the aforementioned solder alloys was conducted in this study.

2. Experimental

2.1 Solder-alloy preparation

The basic eutectic Sn-58Bi solder used in this research was a commercially available Sn-Bi solder rod. Alloyed solders with 0.5 and 1 wt% of In (99.99%), herein referred to as (Sn-Bi)-0.5In and (Sn-Bi)-1In, respectively, were fabricated in-house by dissolving the corresponding metallic powders and wires at 700 °C for 5 h. A balance with a 0.0001-g precision was used to weigh the elements. The alloying process was performed in air, and the molten solder was frequently mechanically stirred to ensure a homogenous alloy. After the alloying procedure, the compositions of the respective alloys were examined using inductively coupled plasma optical emission spectroscopy, as detailed in a previous study

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[11].

2.2 Tensile test

The alloys were remelted at 250 °C for 1 h in a crucible, cast into bar-shaped steel molds, and machined into a dumbbell shape for tensile testing. The long-term aim of this study is to perform an in situ investigation of the fracture by scanning electron microscopy (SEM). The fracture at the middle of the samples for the SEM-equipped tensile machine requires three wide regions. Hence, the dimensions of the gauge section of the tensile test specimen were 1.0 mm thick \times 2.0 mm wide \times 10 mm long, as shown in Fig. 1. Tensile tests were performed at room temperature on a Shimadzu Autograph AG-X machine at a strain rate of $5 \times 10^{-4} \text{ s}^{-1}$ to obtain data on the tensile properties, i.e., the ultimate tensile strength (UTS) and elongation. An SEM (JEOL JSM-6500F) was then used to examine the microstructures and post-test fracture surfaces of the tensile samples.

3. Results and Discussion

Fig. 2 shows the microstructure of gauge sections between the shoulders of the Sn-Bi, (Sn-Bi)-0.5In, and (Sn-Bi)-1In samples. The bright and dark regions represent Bi and Sn, respectively, which appear as interlocked lamellar structures. As was reported elsewhere [11], In was detected in the Sn phase, and Ni appeared to be included in the Bi phase. As shown in Fig. 2, the eutectic Sn-Bi and In-bearing samples both reveal primary Sn dendrites and eutectic phases. To verify the consistency of this observation, a quantitative image analysis was conducted on five different SEM images of all three examined alloys and the volume fraction of Sn dendrites for Sn-Bi, (Sn-Bi)-0.5In, (Sn-Bi)-1In alloys were 13.7, 21.8, and 33.2%, respectively.

Fig. 3 illustrates the fractured specimens obtained from the tensile tests. As can be seen, the Sn-Bi solder with 1 wt.% addition of In exhibits the highest elongation amongst all solder alloys investigated in this study.

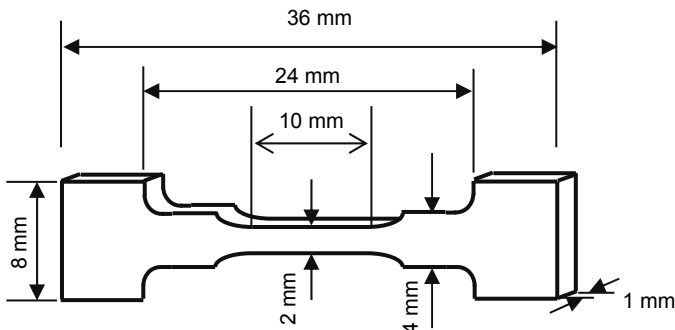


Fig. 1 The schematic illustration of the tensile samples.

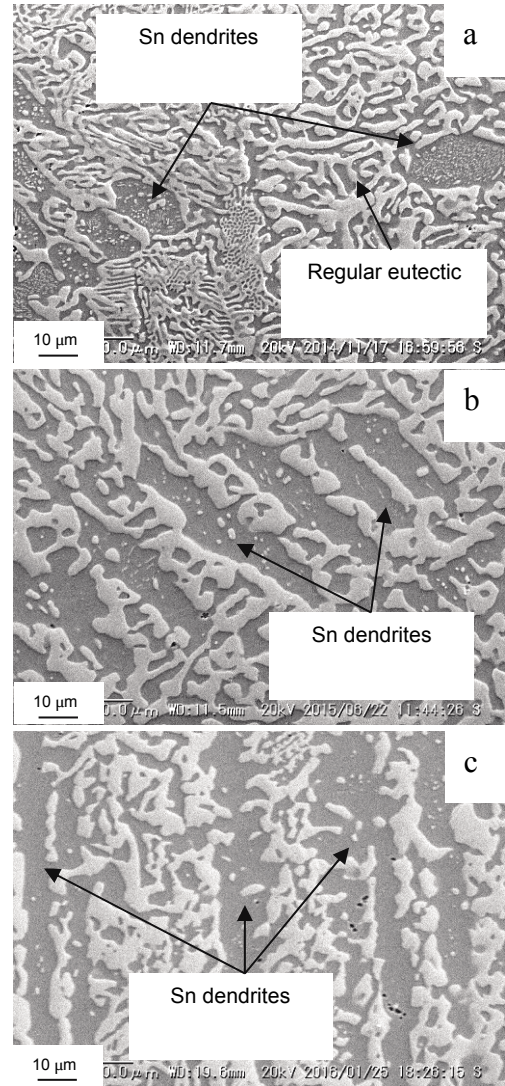


Fig. 2 Microstructure of tensile samples: (a) eutectic Sn-Bi, (b) (Sn-Bi)-0.5In, and (c) (Sn-Bi)-1In.

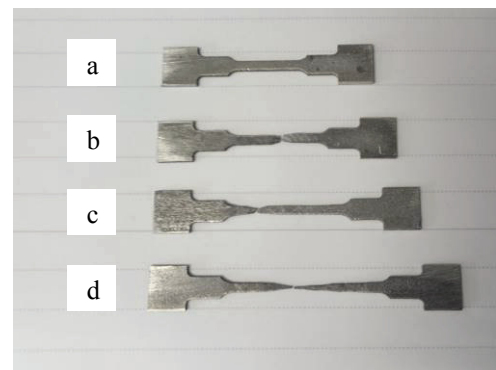


Fig. 3 Fracture of specimens due to tensile test: a) original tensile sample, b) Sn-Bi, c) (Sn-Bi)-0.5In, and d) (Sn-Bi)-1In.

The effects of added elements on the tensile properties of the Sn-Bi solder were investigated, and the representative stress-strain curves obtained from the resulting tensile tests are shown in Fig. 4. The UTS σ_u

(MPa) and elongation δ (%) for Sn-Bi, (Sn-Bi)-0.5In, and (Sn-Bi)-1In after three tests for each alloy, are shown in Fig. 5. The bar charts in Fig. 5 indicate the mean values, and the black dots represent three values for each result.

As shown in Figs. 5 and 6, the addition of 0.5 and 1 wt% In did not significantly impact the UTS of the solders. Although both 0.5 and 1 wt.% In addition improved the ductility of the Sn-Bi solder, 1 wt.% addition of In showed a much larger impact, by manner of exhibiting superplasticity behavior. As mentioned earlier, the In-bearing samples exhibited a larger volume fraction of primary Sn dendrites than the eutectic Sn-Bi, whereas upon increasing the content of In the volume fraction of the primary Sn dendrites increased even further. According to the analysis presented by Kurz and Fisher [15], these ductile dendrites increased the fracture energy, yielding a greater elongation of the In-bearing tensile sample. Additionally, as was reported by Chen et al. [16], Bi as a strong solid solution element in the Sn

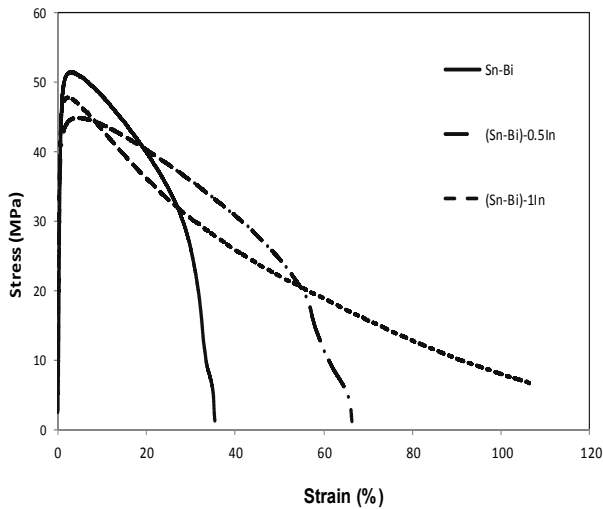


Fig. 4 Tensile test results: eutectic Sn-Bi, (Sn-Bi)-0.5In, and (Sn-Bi)-1In.

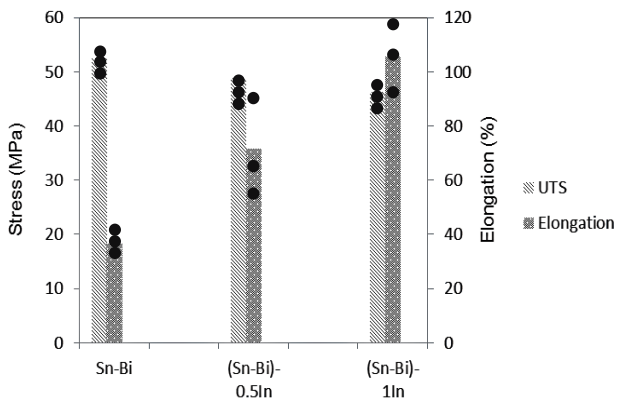


Fig. 5 Corresponding results of the tensile tests: UTS and Elongation.

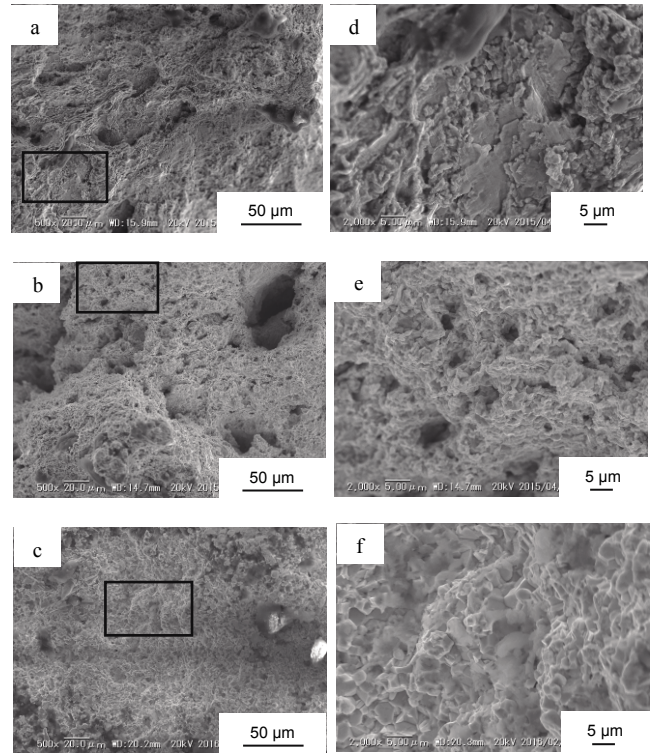


Fig. 6 Fracture surfaces after tensile tests: (a) eutectic Sn-Bi, (b) (Sn-Bi)-0.5In, and (Sn-Bi)-1In, (d), (e), and (f) are magnified black boxes in (a), (b), and (c).

matrix counteracted the strengthening effect of the Bi solution, and consequently softened the Sn matrix. As a result, the UTS barely changed but the ductility improved significantly [16]. Therefore, the increase of In content not only promotes the formation of primary Sn dendrites but also enhances the softening of the Sn matrix.

To further verify the variation in the tensile properties, the fracture surfaces of the tensile samples were examined, as shown in Fig. 6. Both In-bearing samples exhibited a dimple-type structure on the fracture surface, indicating a ductile property. The eutectic Sn-Bi sample however, revealed a brittle structure.

4. Conclusion

The tensile properties of eutectic Sn-Bi, (Sn-Bi)-0.5In, and (Sn-Bi)-1In solder alloys were investigated in this study. To determine the causes of different mechanical properties, the microstructure of the samples were investigated before the tests. In addition, the fracture surfaces of the samples after the tensile tests were examined. The results are summarized as follows:

- The addition of 0.5 and 1 wt% In did not significantly impact the UTS of the solders.
- The In-bearing solder alloys exhibited a larger volume fraction of the primary Sn dendrites than the eutectic Sn-Bi solder whereas increasing the content of In increased the formation of primary Sn dendrites even further.
- Although both 0.5 and 1 wt.% In addition improved the ductility of the Sn-Bi solder, 1 wt.% addition of In

showed a much larger impact by exhibiting superplasticity behavior.

· The significant effect of higher In content on increasing the elongation of the Sn-Bi solder was attributed to both an increase in occurrence of primary Sn dendrites and a counteracting effect of the added In, strengthening the effect of the Bi solution within the Sn matrix.

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