

Original Research

CHARACTERIZATION OF THE Sn78Bi22 ALLOY AS AN ENVIRONMENTALLY FRIENDLY LEAD-FREE SOLDER

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Abstract

The development of reliable lead-free solder alloys remains essential for applications in the electronics industry. This paper investigates the mechanical, electrical, and microstructural properties of a Sn78Bi22 solder alloy. The alloy was prepared by melting and casting, followed by a homogenization heat treatment. Tensile testing, Vickers microhardness measurements, electrical conductivity testing, and SEM/EDS microstructural analysis were performed at room temperature. The investigated alloy exhibited enhanced ultimate tensile strength (~93 MPa) and microhardness (45.5 HV0.05) compared with pure Sn, while electrical conductivity decreased to 5.4 MS/m. These changes were attributed to solid-solution strengthening, grain refinement, and the formation of a Bi-rich secondary phase, which also promoted brittle fracture during tensile testing. Microstructural observations revealed a Sn matrix with finely distributed Bi-rich phases, particularly along grain boundaries. The results contribute additional experimental data on the mechanical, electrical, and microstructural characteristics of non-eutectic Sn–Bi solder alloys.

Keywords: Sn78Bi22 alloy, mechanical properties, electrical conductivity, microstructure.

INTRODUCTION

Sn–Pb solders have been extensively used in the electronics industry for decades due to their excellent solderability, low melting temperature, low cost, and favourable mechanical properties. However, lead is unequivocally harmful to human health and the environment, necessitating the gradual elimination of lead-containing materials from electronic products. With the implementation of the Waste Electrical and Electronic Equipment (WEEE) and Restriction of Hazardous Substances (RoHS) directives, the European Union mandated the use of lead-free solder alloys in electronic assemblies [1,2].

In response to these regulations, numerous lead-free solder systems have been investigated over the past two decades, including Sn–Cu, Sn–In, Sn–Zn, Sn–Ag–Cu, and Sn–Bi alloys [2]. Among these candidates, the Sn–Bi system has attracted considerable attention due to its relatively low melting temperature and good wettability. In particular, the eutectic Sn58Bi

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alloy has been extensively studied and reported in the literature, as summarized by Kamaruzzaman *et al.* [3]. Despite its industrial applicability, the high bismuth content in eutectic Sn–Bi alloys leads to pronounced brittleness, which represents a significant drawback in terms of mechanical reliability and susceptibility to brittle fracture in solder joints.

To address these limitations, recent research efforts have increasingly focused on non-eutectic Sn–Bi alloys with lower bismuth contents (typically up to ~20 wt.% Bi), aiming to achieve a balance between mechanical strength, ductility, and functional properties. Shen investigated the mechanical strength and thermal behaviour of Sn–2.5Bi and Sn–5Bi alloys [4]. Yang *et al.* examined the effects of graphene nanosheets (GNS) on the microstructure and properties of Sn–20Bi solder alloys [2]. Lai *et al.* focused on non-eutectic Sn–Bi alloys, with particular emphasis on microstructural evolution and fracture behaviour [5].

Furthermore, Wang *et al.* reviewed recent progress in the development of low-temperature Sn–Bi solders and concluded that the intrinsic brittleness of bismuth remains a critical challenge, especially under mechanical shock loading in electronic devices. In addition, segregation of Bi-rich phases and excessive growth of the intermetallic compound (IMC) layer were identified as major reliability concerns that can compromise the long-term performance of solder joints [6].

Although substantial research has been devoted to the mechanical, microstructural, and physical properties of non-eutectic Sn–Bi solder alloys, further systematic investigations are still required to fully understand the structure–property relationships in this alloy system. In this context, the present study contributes additional experimental data and analysis to the existing body of knowledge on non-eutectic Sn–Bi solder alloys.

MATERIALS AND METHODS

Alloy preparation

Commercially pure tin (99.9 wt.%) and bismuth (99.9 wt.%) were used to prepare the Sn78Bi22 alloy. The metallic granules were placed in a graphite crucible and melted in a muffle furnace at 350 °C. During melting, the crucible was covered with a carbon piece to minimize oxidation. After complete melting, the alloy was mechanically stirred using a pure graphite stirrer to ensure chemical homogeneity.

The molten alloy was subsequently cast into a steel mold with a diameter of 13 mm. The as-cast samples were then homogenized in an electric furnace at 150 °C for 20 h to promote a more uniform distribution of Bi within the Sn matrix, followed by air cooling to room temperature.

After homogenization, the samples were sectioned for further characterization using a Struers Mesotom metallographic cutting machine.

Tensile strength measurements

To determine the tensile strength, a 5 mm diameter wire of the Sn78Bi22 alloy was prepared. The homogenized cast rod (initial diameter 13 mm) was gradually reduced to 5 mm using a calibrated Joliot rolling mill. The reduction process involved cold rolling with intermediate annealing steps to prevent excessive strain accumulation and cracking.

After reaching the final diameter, the wire was subjected to a final annealing treatment to eliminate residual deformation and ensure that the mechanical properties were representative of the homogenized state. Tensile testing was performed using a Mohr–Federhaff–Losenhausen universal testing machine.

Microhardness measurements

Microhardness measurements were carried out using a PMT-3 microhardness tester employing the Vickers method, in accordance with ASTM E384 [7]. A load of 0.5 N and a dwell time of 15 s were applied. Prior to testing, the sample surface was polished to a mirror finish. Five indentations were made at different locations on the sample surface, and the reported microhardness value represents the average of these measurements.

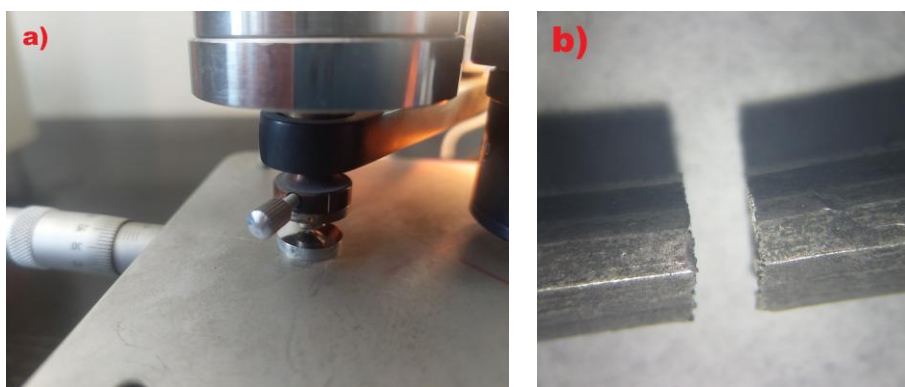


Figure 1 Different measurements performed on the Sn78Bi22 alloy: (a) Vickers microhardness indentation on a polished surface; (b) fractured wire specimen after tensile testing, indicating brittle fracture behaviour

Electrical conductivity measurements

Electrical conductivity was measured using a Foerster Sigmatest 2.063 conductivity tester. Three measurements were performed on each sample, and the average value was reported.

Microstructural characterization

Samples for microstructural analysis were prepared using standard metallographic procedures. Wet grinding was performed using SiC papers with grit sizes of #400, #600, #800, #1000, #2000, and #3000, followed by polishing with Al₂O₃ suspensions of 0.3 µm and 0.05 µm particle size.

The microstructure was revealed by chemical etching for 15 s using a solution composed of 2 ml HCl, 2 ml HNO₃, and 96 ml C₂H₅OH. Scanning electron microscopy (SEM) and energy-dispersive spectroscopy (EDS) analyses were conducted using a Tescan Vega 3 LMU scanning electron microscope equipped with an Oxford Instruments X-act EDS detector.

RESULTS AND DISCUSSION

Tensile strength is one of the most critical mechanical properties in solder materials, as it directly determines the ability of solder joints to withstand deformation and various types of mechanical loading during service. Figure 2 presents the engineering stress–strain curve of

the investigated Sn78Bi22 alloy. Pure β -tin is known to exhibit very low tensile strength at ambient conditions; reported ultimate tensile strength (UTS) values of approximately 16 MPa have been obtained from quasi-static tensile testing of bulk polycrystalline Sn, as reported by Zhou *et al.* [8].

The addition of bismuth leads to a pronounced improvement in tensile strength, as clearly evidenced in Figure 2. In the present study, the Sn78Bi22 alloy exhibited an ultimate tensile strength of approximately 93 MPa. This substantial increase in UTS is primarily attributed to the incorporation of 22 wt.% Bi, which promotes grain refinement of the Sn-rich matrix, solid-solution strengthening due to partial Bi solubility in Sn, and dispersion strengthening associated with the formation of finely distributed Bi-rich phases. These Bi-induced microstructural and compositional features act as effective obstacles to dislocation motion, thereby significantly enhancing the tensile strength of the alloy [5]. Similar trends have been reported in the literature: Yang *et al.* [2] observed slightly lower UTS values for Sn80Bi20 solder alloys, whereas Lai *et al.* [5] reported UTS values close to 95 MPa, which is in good agreement with the results obtained in the present work.

However, the supersaturation of the Sn matrix with the brittle Bi phase, while beneficial for strength enhancement, also promotes brittle fracture behaviour, as reported by Zhou *et al.* [9] and as observed on the fractured tensile specimen shown in Figure 1b.

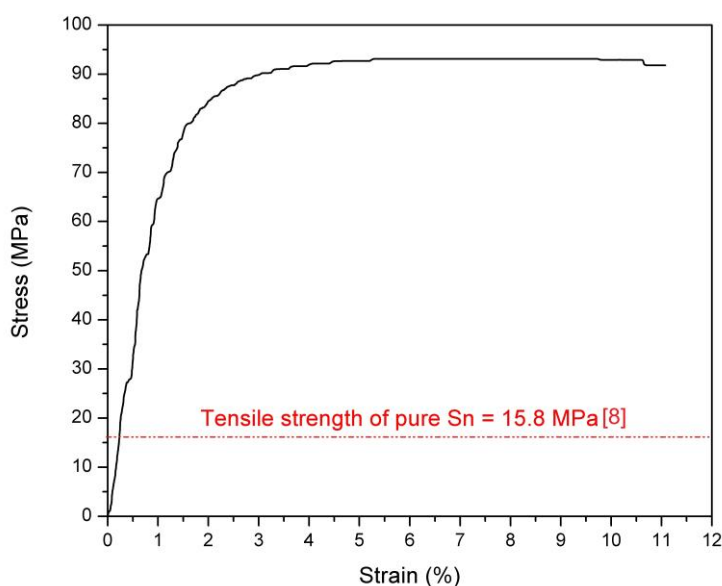


Figure 2 Stress-strain curve of the investigated Sn78Bi22 alloy

The microhardness results are consistent with the tensile strength measurements. Pure β -Sn exhibits very low hardness, with reported values in the range of 8–10 HV, as documented in the literature [4,10]. In the present study, the Sn78Bi22 alloy exhibited a significantly higher microhardness of 45.5 HV_{0.05}.

This pronounced increase in hardness is attributed to the same strengthening mechanisms identified in the tensile investigation, namely grain refinement, solid-solution strengthening, and dispersion strengthening induced by Bi addition. For comparison, Shen *et al.* [4] reported

a hardness of approximately 20 HV for Sn95Bi5, while Thongchai *et al.* [10] reported values of around 17 HV for Sn96Bi4 alloys. Considering both the literature data and the approximately sixfold increase in ultimate tensile strength relative to pure Sn (Figure 2), the observed rise in microhardness is in good agreement with the enhanced mechanical performance of the Sn78Bi22 alloy.

Electrical conductivity is a critical property in solder technology, as solder joints are required to efficiently transmit electrical power and signals between electronic components. Pure tin exhibits relatively low electrical conductivity compared to copper, with reported values of approximately 15–16% IACS, corresponding to ~8–9 MS/m at room temperature, depending on purity and microstructural condition. In contrast, bismuth possesses a significantly lower electrical conductivity, reported to be approximately 0.77 MS/m [11].

In the present study, the Sn78Bi22 alloy exhibited an electrical conductivity of 5.4 MS/m, which lies between the conductivity values of pure Sn and pure Bi. The observed reduction in electrical conductivity relative to pure Sn is expected and can be attributed to several alloying- and microstructure-related factors. First, the substantial atomic size mismatch between Sn and Bi introduces lattice distortion, which enhances electron scattering. Second, the addition of Bi leads to the formation of a supersaturated solid solution of Bi in the Sn matrix, further increasing scattering of conduction electrons. Third, the presence of Bi-rich phases within the microstructure introduces additional phase boundaries that act as electron scattering centres. Finally, Bi-induced grain refinement increases the total grain boundary area, which also contributes to increased resistivity.

Collectively, these effects result in an increase in electrical resistivity in accordance with Matthiessen's rule, whereby different scattering mechanisms contribute additively to the total resistivity of the alloy [12]. Similar reductions in electrical conductivity with increasing Bi content in Sn–Bi solder alloys have also been reported by other authors, confirming the trends observed in the present work [13,14].

Microstructural analysis further supports the previously discussed mechanical and electrical property trends. Figure 3 presents the SEM–EDS characterization of the Sn78Bi22 alloy. The microstructure consists of a supersaturated Sn-rich matrix with relatively fine grains, within which a Bi-rich phase is distributed throughout the structure, preferentially along grain boundaries. In backscattered electron (BSE) images, the Bi-rich phase appears brighter due to its higher atomic number and is identified by EDS spectra 1 and 3, whereas the β -Sn matrix corresponds to spectrum 2, as confirmed by the EDS analysis summarized in Table 1.

Such a microstructural configuration, characterized by a Sn-rich matrix reinforced by Bi-rich regions at grain boundaries and within the matrix, is consistent with observations reported in the literature for hypoeutectic Sn–Bi solder alloys [2,4,5,9,10].

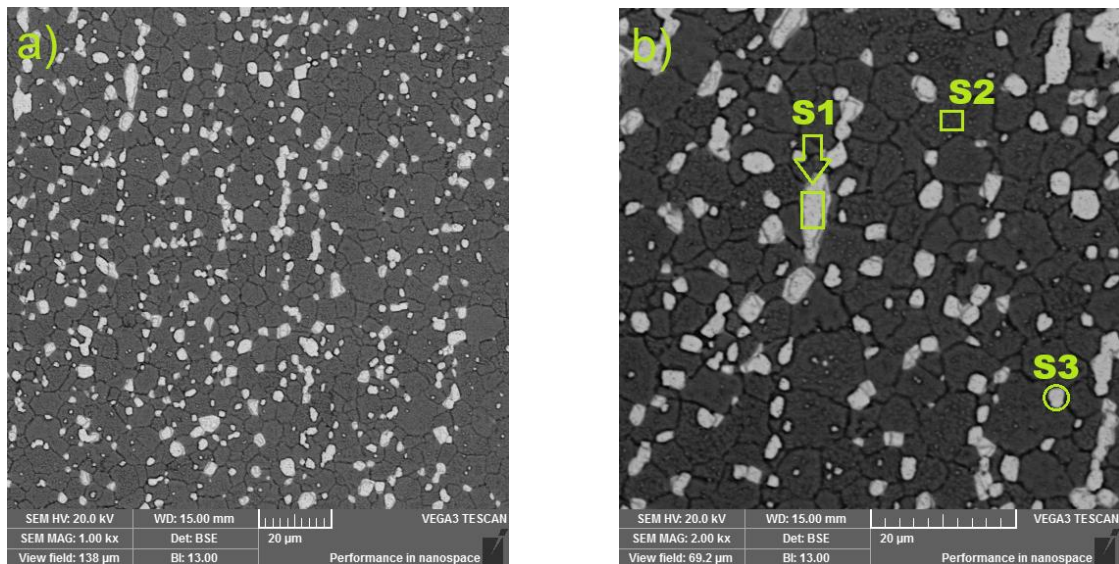


Figure 3 SEM–EDS analysis of Sn78Bi22 alloy: a) x1000 magnification; b) x2000 magnification

Table 1 EDS analysis of the Sn78Bi22 sample

<i>Spectrum</i>	<i>Bi</i>	<i>Sn</i>
Spectrum 1	95.31	4.69
Spectrum 2	2.95	97.05
Spectrum 3	84.6	15.4

CONCLUSIONS

In this study, the Sn78Bi22 solder alloy was systematically investigated with respect to its mechanical, electrical, and microstructural properties. The addition of bismuth resulted in a pronounced increase in ultimate tensile strength and microhardness, accompanied by a reduction in electrical conductivity when compared to pure tin. These changes in properties are attributed to several Bi-induced strengthening mechanisms, including solid-solution strengthening of the Sn-rich matrix, the formation of a Bi-rich secondary phase, and grain refinement effects.

Microstructural analysis confirmed the presence of a supersaturated Sn-rich matrix with Bi-rich phases distributed throughout the microstructure, particularly along grain boundaries, providing microstructural evidence that supports the observed mechanical strengthening and electrical conductivity trends.

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