Microstructural analysis for Sn-Bi-Sb-In alloy prepared by rapid solidification

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Abstract

In the present study, Sn70-x Bi15-x Sb15 In x (x = 0, 2, 4, 6) alloy were prepared by melt spinning technique. Optical microscopy, scanning electron microscopy combined with energy dispersive X-ray analysis (SEM-EDX), X-ray diffraction analysis (XRD), and Vickers microhardness (HV) were used to characterize the phase transformation and the microstructure evolution. The results contribute to the understanding of the microstructure evolution in alloys of the type prepared by melt spinning technique. This work reports on a comparative study of the rapidly solidified, in order to compare the microhardness and microstructural analysis.

Keywords

Rapid Solidification (RS); Lead Free Solder Alloys; Sn-Bi-Sb, X-Ray Diffraction Analysis (XRD), Scanning Electron Microscope; Energy Dispersive X-Ray, Vickers microhardness (HV).

Academic Discipline and Sub-Disciplines

Physics; Solid State Physics

SUBJECT CLASSIFICATION

Solder alloy

TYPE (METHOD/APPROACH)

Experimental

Introduction

In the electronics industry lead-tin (Pb-Sn) solder is a very important material. Due to the harmful effects of Pb the use of the Pb-Sn solder alloys are being avoided and new Pb-free solder alloys are used for electronic applications. Several alternate solder alloys are investigated and their various properties are studied [1-3]. Rapid solidification of metallic alloys results in refined microstructures with reducing microsegregation and improves mechanical properties of the final products as compared to normal castings. The rapidly solidified Sn-based solders by melt spinning have proved to be suitable for soldering at low temperature and short soldering duration [4-6].

The properties and performance of lead-free solder alloys such as fluidity and wettability may be controlled by alloy composition and solidification microstructure. The hardness of the bearing and the inter-relation between resistance to deformation and conformability is the main consideration. High-tin lead free alloys are used in applications where high unit loads and high temperatures are encountered. With heavy fluctuating loads such as that encountered in internal combustion engines, however, experience has shown that the softer alloys are superior in spite of lower fatigue properties. The reason is that they bound up with greater ability to conform to shaft deflection.

This work aims to understand the different intermetallic alloys that are formed in Sn70-x Bi15-x Sb15 In x alloys (where x = 0, 2, 4, and 6 in at. % ). Also, some light are exposed on the homogenous of elements which used in preparing alloys and the intermetallic compound that formed and it's mechanical properties.

Experimental procedures

The materials used in the present work are Sn, Sb, Bi, and In fragments, with purity better than 99.99% produced by a single copper roller (200 mm in diameter) melt-spinning technique which described previously in some details [7-10]. The process parameters such as the ejection temperature, and the linear speed of the wheel were fixed at 873 K and 30.4 ms-1 respectively. X-ray diffraction analysis (XRD) was carried out with a XPERT-PRO X-ray diffractometer, using Cu-Kα radiation (λ = 1.5406 Å). The polished and etched samples were observed using an optical microscope (Olympus Model: PMG 3) with the objective of determining the microstructural evolution. The microstructure analysis was carried out on a scanning electron microscope (SEM) of type (FEI Inspect-S50) operate at 30Kv with high resolution 3nm. Quantx Bruker EDS spectrometer System is a full-featured X-Ray Microanalysis System (EDX/EDS) for SEM result. The elastic moduli of melt-spun ribbons were examined in air atmosphere with a modified dynamic resonance method [11]. The hardness of the melt-spun ribbons was measured using a digital Vickers microhardness tester (model SHIMADZU HMV) [12]. The test carried out at load 98.07mN (10 gram force) with loading time 15 sec.
2- Results and Discussion

2.1 Structure

Figure (1) shows the X-ray diffraction pattern for as-quenched melt-spun of Sn$_{70-x}$Bi$_{15}$-Sb$_{15}$-In$_x$ alloys (where $x=0, 2, 4,$ and $6$ in at. %). The experimental observed interplanar spacing's of the first few strong reflections are tabulated in Table (1). The pattern can be indexed in terms of the co-existence of Tetragonal Sn, Rhombohedral Sb and Bi phases, Tetragonal In, and intermediate compounds such as Rhombohedral SnSb and Orthorhombic InSn, Tetragonal Bi$_3$In$_5$, Hexagonal In$_{0.2}$Sn$_{0.8}$. The XRD for Sn$_{70}$-Bi$_{15}$-Sb$_{15}$ alloy is shown in Figure 1(a). Sn, Bi and Sb are precipitated as indicated and SnSb Intermetallic compound is appeared. The unit cell of $\beta$-Sn is body centered tetragonal (S.G.: $I4_1/amd$). The crystal structure of Bi is Rhombohedral-hexagonal (S.G.: R3m), the unit cell of Sb is Rhombohedral (S.G.: R-3m) and the unit cell of SbSn is Rhombohedral (S.G.: R-3m).

Figure 1(b) shows Sn$_{68}$-Bi$_{15}$-Sb$_{15}$-In$_2$ alloy, in which a formation of new Intermetallic compounds and these are, InSb with Orthorhombic crystal structure (S.G.: Pmmn), and Bi$_3$In$_5$ Intermetallic phase with Tetragonal unit cell (S.G.: $I4/mcm$). Also, the Sn, In, Bi, and Sb phases are exist in their positions.

By Increasing In at.% as in Sn$_{66}$-Bi$_{15}$-Sb$_{15}$-In$_4$ alloy (Figure 1(c)) It is quite obvious that, a new phase is formed, In$_2$Sn$_{1.8}$ with Hexagonal crystal structure (S.G.: P6/mmm). SnSb Intermetallic phase returns to appear again in the absence of Sb phase. (Figure 1(d)) is for Sn$_{64}$-Bi$_{15}$-Sb$_{15}$-In$_6$ alloy. In this alloy, all intermediate phases are formed except In$_2$Sn$_{1.8}$. Particle size can be calculated for each present phase using Scherrer’s equation [11]. The detail of XRD analysis is shown in Table 1.

### Table 1. The XRD patterns details for as-quenched melt-spun alloys. Sn$_{70}$-Bi$_{15}$-Sb$_{15}$; Sn$_{68}$-Bi$_{15}$-Sb$_{15}$-In$_2$; Sn$_{66}$-Bi$_{15}$-Sb$_{15}$-In$_4$; and Sn$_{64}$-Bi$_{15}$-Sb$_{15}$-In$_6$.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Phase present</th>
<th>hkl</th>
<th>The lattice parameter for each phase</th>
<th>Particle size (μm)</th>
<th>Crystal structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn$<em>{70}$-Bi$</em>{15}$-Sb$_{15}$</td>
<td>Sn 200</td>
<td>5.8177</td>
<td>3.1697</td>
<td>107.2854</td>
<td>0.5448</td>
</tr>
<tr>
<td></td>
<td>Bi 012</td>
<td>4.6166</td>
<td>11.8450</td>
<td>218.6304</td>
<td>2.5657</td>
</tr>
<tr>
<td></td>
<td>Sb 003</td>
<td>4.4346</td>
<td>11.2270</td>
<td>191.2017</td>
<td>2.5316</td>
</tr>
</tbody>
</table>
2.2 Sample preparation

Specimens were mounted at room temperature using acrylics castable mounting materials (cold resin). Then, the specimens were mechanically ground using emery papers up to 1200 grade. Scratches from the abrasive papers are removed by polishing specimens for several minutes on a wheel covered with a short-nap cloth impregnated with 0.25 μm diamond paste. The samples rinsed and degreased with acetone, and then etched using 5 ml nitric acid + 2 ml HCL in 100 ml methanol for 45s.

2.3 Microstructural characteristics

In the present investigation, rapidly quenched alloys Sn_{10-x}Bi_{15}Sb_{15-In_{x}} (x = 0, 2, 4, and 6 in at. %) were examined by optical microscope, scanning electron microscope and energy dispersive spectroscopy x-ray. Knowledge of the microstructure of a material, which is the number of phases present, their distribution, volume fraction, shape, and size, are essential since many properties are structure sensitive, e.g. mechanical and electrical properties. Thus this section is concerned with the study of the microstructure of the alloys which have been prepared to explain their properties.

2.3.1 Optical microscopy

A more detailed view of the alloys surfaces is shown in figure (2) where optical microscopy images show that the surfaces have different structures for each prepared alloy.

2.3.2 SEM and EDS

Figure (3) shows the SEM image of alloy Sn_{70}Bi_{15}Sb_{15}. EDS Spectra of the points 1 and 6 of EDS spot analysis and EDS map analysis of the alloying elements shows a homogenous distributions of the alloying elements in alloy Sn_{70}Bi_{15}Sb_{15}. Figures (3a1, 3a2) shows the formation of the soft phase (Sn) nearly continuous network in the Sn_{70}Bi_{15}Sb_{15} alloy. The grains in the middle of ribbon, which looks like a rod in shape, are extended along the length direction (the direction of the linear momentum of the wheel). The number of grains per μm^2 was found to be 418, total projected area is 79 μm^2, mean grain area is 190*10^{-15} m^2, mean grain size is 0.42 μm, total grain volume is 42*10^{-21} m^3.
Fig. 2 Optical Microscopy images for (a) Sn$_{70}$-Bi$_{15}$-Sb$_{15}$; (b) Sn$_{68}$-Bi$_{15}$-Sb$_{15}$-In$_2$; (c) Sn$_{66}$-Bi$_{15}$-Sb$_{15}$-In$_4$; and (d) Sn$_{64}$-Bi$_{15}$-Sb$_{15}$-In$_6$. 
Figures (4a1, 4a2) show the SEM image for alloy Sn$_{68}$Bi$_{15}$Sb$_{15}$In$_2$. Figures (4b1, 4b2) are shown EDS Spectra of the points 1 and 6 of EDS spot analysis and figure 4c is the EDS map analysis of the alloying elements.

Figures (5a1, 5a2) show the SEM image for alloy Sn$_{66}$Bi$_{15}$Sb$_{15}$In$_4$. EDS Spectra of the points 1 and 6 of EDS spot analysis shown in figures (5b1, 5b2) and EDS map analysis of the alloying elements showing the homogenous distributions of the alloying elements for alloy Sn$_{66}$Bi$_{15}$Sb$_{15}$In$_4$ shown in figure 5c.

Figures (6a1, 6a2) show the SEM image for alloy Sn$_{66}$Bi$_{15}$Sb$_{15}$In$_4$. Figures (6b1, 6b2) show EDS Spectra of the points 1 and 6 of EDS spot analysis. Figure 6c show EDS map analysis of the alloying elements showing the homogenous distributions of the alloying elements for alloy Sn$_{66}$Bi$_{15}$Sb$_{15}$In$_4$.

Table (2) EDS spot analysis of the points 1, 2, 3, 4, 5 and 6 in the SEM images for all alloys. Table (3) shows the variation of number of grains and the grain size for different alloys. Crystallite and grain are both single crystals; a crystallite is a single crystal in powder form but a grain is a single crystal within a bulk/thin film.

A particle is also thought of as an agglomerate, small enough in size to not consider it as a bulk or thin film, but composed of 2 or more individual crystallites. From the figures, it shows that the microstructures were composed of elongated grains, a few microns in width and several microns in length. Also evident in the micrographs was a highly density of extinction contours which indicated that considerable internal strain was introduced in the material as a result of melt spinning.
Fig. 4 (a) SEM images (b) EDS spectra of the points 1 and 6 and (c) EDS map analysis for Sn$_{68}$Bi$_{15}$Sb$_{15}$In$_2$ alloy.
Fig. 5 (a) SEM images (b) EDS spectra of the points 1 and 6 and (c) EDS map analysis for Sn$_{66}$Bi$_{15}$Sb$_{15}$In$_4$ alloy.
Fig. 6 (a) SEM images (b) EDS spectra of the points 1 and 6 and (c) EDS map analysis for Sn$_{64}$Bi$_{15}$Sb$_{15}$In$_6$ alloy.
Table 2. EDS spot analysis of the points 1, 2, 3, 4, 5 and 6 in the SEM images for all prepared alloys.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Element</th>
<th>Wt.%</th>
<th>Point 1</th>
<th>Point 2</th>
<th>Point 3</th>
<th>Point 4</th>
<th>Point 5</th>
<th>Point 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn70Bi15Sb15</td>
<td>Sn</td>
<td>70.07</td>
<td>81.99</td>
<td>91.02</td>
<td>90.60</td>
<td>64.98</td>
<td>79.71</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sb</td>
<td>14.42</td>
<td>5.57</td>
<td>0.0</td>
<td>0.0</td>
<td>16.10</td>
<td>6.84</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bi</td>
<td>4.49</td>
<td>5.18</td>
<td>6.53</td>
<td>7.46</td>
<td>3.42</td>
<td>6.57</td>
<td></td>
</tr>
<tr>
<td>Sn68Bi15Sb15</td>
<td>Sn</td>
<td>59.85</td>
<td>65.17</td>
<td>36.55</td>
<td>86.51</td>
<td>75.64</td>
<td>65.95</td>
<td></td>
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<tr>
<td></td>
<td>Sb</td>
<td>19.67</td>
<td>18.77</td>
<td>34.68</td>
<td>5.01</td>
<td>11.85</td>
<td>15.87</td>
<td></td>
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<tr>
<td></td>
<td>Bi</td>
<td>1.46</td>
<td>3.20</td>
<td>1.28</td>
<td>3.54</td>
<td>4.52</td>
<td>2.23</td>
<td></td>
</tr>
<tr>
<td>Sn66Bi15Sb15</td>
<td>Sn</td>
<td>40.53</td>
<td>43.29</td>
<td>43.81</td>
<td>34.33</td>
<td>45.46</td>
<td>43.83</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sb</td>
<td>36.46</td>
<td>33.87</td>
<td>33.10</td>
<td>46.8</td>
<td>30.72</td>
<td>35.28</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bi</td>
<td>2.87</td>
<td>11.13</td>
<td>4.13</td>
<td>7.34</td>
<td>13.95</td>
<td>10.34</td>
<td></td>
</tr>
<tr>
<td>Sn64Bi15Sb15</td>
<td>Sn</td>
<td>38.37</td>
<td>50.59</td>
<td>46.93</td>
<td>63.65</td>
<td>9.87</td>
<td>10.56</td>
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<tr>
<td></td>
<td>Sb</td>
<td>32.06</td>
<td>22.03</td>
<td>27.51</td>
<td>14.27</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bi</td>
<td>5.08</td>
<td>11.05</td>
<td>2.71</td>
<td>3.51</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Grain details for all prepared alloys.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Number of grains</th>
<th>Total projected area (μm²)</th>
<th>Mean grain area (10⁻¹⁵ m²)</th>
<th>Mean grain size (μm)</th>
<th>Total grain volume (10⁻²¹ m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn70Bi15Sb15</td>
<td>418</td>
<td>79</td>
<td>190</td>
<td>0.42</td>
<td>42</td>
</tr>
<tr>
<td>Sn68Bi15Sb15In2</td>
<td>958</td>
<td>78</td>
<td>81</td>
<td>0.27</td>
<td>57</td>
</tr>
<tr>
<td>Sn66Bi15Sb15In4</td>
<td>878</td>
<td>223</td>
<td>254</td>
<td>0.42</td>
<td>167</td>
</tr>
<tr>
<td>Sn64Bi15Sb15In6</td>
<td>1154</td>
<td>118</td>
<td>102</td>
<td>0.30</td>
<td>81</td>
</tr>
</tbody>
</table>

2.3.3 Mechanical Properties

Firstly, we study Vickers microhardness analysis. The indentations were made in two directions along the width of the ribbon (X-direction) and along the length of the ribbon (Y-direction which is the direction of the linear momentum of the wheel). The test carried out using SHIMADZU Model, at load 98.07mN (10 gram force) and loading time is 15 sec. The hardness test involves indenting a material by a process of plastic deformation which approximately 8 % strain of the material. Thus the hardness is a function of the yield stress (σₚ). It was found that [14] σₚ is given by;

$$\sigma_p = \frac{VHN}{1.8} \text{ GPa}$$  \hspace{1cm} (1)

Table 4. Microhardness (Hv) and yield stress (σₚ) of melt quenched ribbons.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Average of hardness readings (Hv)_{98.07mN} (Gpa)</th>
<th>Yield stress (σₚ) (Gpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn70Bi15Sb15</td>
<td>32.16</td>
<td>10.05</td>
</tr>
<tr>
<td>Sn68Bi15Sb15In2</td>
<td>39.64</td>
<td>12.3875</td>
</tr>
<tr>
<td>Sn66Bi15Sb15In4</td>
<td>52.28</td>
<td>16.3375</td>
</tr>
<tr>
<td>Sn64Bi15Sb15In6</td>
<td>36.42</td>
<td>11.38125</td>
</tr>
</tbody>
</table>
Where VHN is in GPa. The details for Vickers micro hardness yield stress summarized in table for all prepared alloys are summarized in table (4).

From the table, it can be investigated that the maximum value of microhardness was for Sn66Bi15Sb15In4 prepared alloy and the least value for Sn70Bi15Sb15 prepared alloy.

Elastic modulus (E), Shear modulus (G), Bulk modulus (B) and Poisson's ratio (υ) are calculated by dynamic resonance method for Sn70-xSb15-xBi15-In, alloys, x=0, 2, 4, and 6 at. %) [15,16]. It is investigated that (E) increases gradually with increasing the amount of In up to 33.6915 GPa to Sn64Sb15Bi15In4 alloy. It has been found that the additions of In in SnSbBiln as melt-quenched ribbons improve the elastic moduli and it is attributed to the substantial refinement of the solidification microstructure. The mechanical results are shown in Table (5).

Table 5. Young’s modulus (E), Shear modulus (G), Bulk modulus (B) and Poisson’s ratio (υ) for all prepared alloys.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>E (GPa)</th>
<th>B (GPa)</th>
<th>G (GPa)</th>
<th>υ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn70Bi15Sb15</td>
<td>22.21295</td>
<td>25.35725</td>
<td>8.202716</td>
<td>0.354</td>
</tr>
<tr>
<td>Sn66Bi15Sb15In2</td>
<td>26.10022</td>
<td>19.91319</td>
<td>10.18307</td>
<td>0.281</td>
</tr>
<tr>
<td>Sn66Bi15Sb15In4</td>
<td>30.1586</td>
<td>22.28424</td>
<td>11.8321</td>
<td>0.274</td>
</tr>
<tr>
<td>Sn66Bi15Sb15In6</td>
<td>33.69156</td>
<td>24.13401</td>
<td>13.29234</td>
<td>0.267</td>
</tr>
</tbody>
</table>

3. Conclusion

- It’s found that, there are homogenous distributions of the alloying elements for all prepared alloys by melt spinning technique.
- Intermetallics such as BiIn3 and InSb could be formed in the Sn-Bi-Sb melt-spun alloys. Structures of intermetallic SnSb and In2Sb0.8 form in Sn66Bi15Sb15In4 alloy.
- Number of grain increase by increasing indium content.
- The change in micro-hardness depend the formation of intermetallic phase. From XRD result, it shown that In2Sb1.8 intermetallic compound exist only in Sn66Bi15Sb15In4 alloy which showing the maximum value in microhardness.
- It is evident that in this work, the alloy which offers the best properties required for bearing applications is the rapidly solidified as-quenched melt-spun Sn66Bi15Sb15In4 alloy. Since it has higher Young's modulus (30.15 GPa), higher hardness (52.28 Gpa) and higher yield stress (16.33 GPa).

<table>
<thead>
<tr>
<th>Alloy (at.%)</th>
<th>E (GPa)</th>
<th>Hv (GPa)</th>
<th>σy (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn66Bi15Sb15In4</td>
<td>30.15</td>
<td>52.28</td>
<td>16.33</td>
</tr>
</tbody>
</table>

4. References


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