Influence of Titanium Oxide on Creep Behavior, Microstructure and Physical Properties of Tin-Antimony and Tin-Aluminum-Antimony Based Bearing Alloys

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Abstract: Influence of adding titanium oxide (TiO₂) nanoparticles on creep behavior, structure, mechanical and thermal properties of tin-antimony-lead and tin-aluminum-antimony alloys has been studied and analyzed. Stress exponent of tin-antimony-lead and tin-aluminum-antimony alloys decreased after adding titanium oxide. Internal friction of tin-antimony-lead and tin-aluminum-antimony alloys increased after adding titanium oxide. Elastic modulus of tin-antimony-lead alloys varied after adding titanium oxide. Microstructure of tin-antimony-lead and tin-aluminum-antimony alloys changed after adding titanium oxide. Strengths of tin-antimony lead and tin-aluminum-antimony alloys increased after adding titanium oxide. Thermal properties of tin-antimony-lead and tin-aluminum-antimony alloys decreased after adding titanium oxide. Increasing Sb content led to better hardness properties such as lowest internal friction, high elastic modulus and higher thermal diffusivity for industrial applications.

Key words: stress exponent, titanium oxide, bearing alloys, internal friction, creep indentation, thermal properties, mechanical properties

1. INTRODUCTION

Bearing is a device to allow constrained relative motion between two or more parts, typically rotation or linear movement. Bearing is a device used to transmit loads between relatively moving surfaces. The tribological properties of tin-based bearing alloys with different compositions, (7% and 20%), have been investigated [1]. Structure, electrical resistivity and elastic modulus of SnSbX (X = 0, Cu, Ag, or Cu and Ag) and Pb₁₅Sn₆₅Sb₁₅Cu₁₅ [x=0 or x≥2.5] alloys have been studied and analyzed [2, 3]. Electrical resistivity, elastic modulus and internal friction of Pb₅Sn₃Sb₃ decreases after adding Cu. Mechanical properties of Sn-Sb bearing alloys have been evaluated [4]. Mechanical properties of Sn-Sb improved after adding 1 wt. % of Cu or Ag. Also the elastic modulus, internal friction and stiffness of Sn-Sb based bearing alloys varied after annealing for 2 and 4 h at 120, 140 and 160 °C. Creep behavior of SnSb₅ alloy and SnPb₄₀Sb₁₅ peritectic alloy were studied by long time Vickers indentation testing at room temperature [5-7]. Increasing Sb content from 7.5% to 20% provided an increase in hardness. Tensile properties of SnSb₅Bi₁₅ and SnSb₅Cu₁₅ alloys have been studied at different strain rates ranging from 5×10⁻⁴ to 1×10⁻² s⁻¹ over the wide temperature range of 298-400 K [8]. Strength and ductility of SnSb₅ improved after adding Bi and Cu. Creep behavior, elastic modulus and internal friction of SnSb₅CuₓX₂ (X = Pb, Ag, Se, Cd and Zn) alloys have been investigated and stress exponents have been determined [9]. The effect of solidification rate, heating and micro additions on microstructure and hardness of tin-based white metals have been studied [10, 11]. Rapid cooling suppresses formation and growth of SbSn cuboids and increases hardness. Structure, hardness, mechanical and electrical transport properties of Sn₆₀₋₉₃Sn₁₀Biₓ (x = 0, or x ≥ 1) alloys have been studied and analyzed [12]. Electrical resistivity and hardness of SnSb₁₀ increased after adding bismuth content. Internal friction, elastic modulus and thermal diffusivity of SnSb₁₀ decreased after adding bismuth content. The effects of small amounts of Ag and Cu on the as-cast microstructure and creep properties of the SnSb₅ alloy have been investigated [13]. Small additions of Ag and Cu elements could effectively change the creep behavior of the SnSb₅ alloy. The friction coefficients of SnSb₅Sn₆₅Pb₁₅Cu₁₅ is lower than that of SnSb₅PbSn₆₅Cu₁₅ under all scratch test conditions [14]. The directionally solidified microstructure of SnSb₅ hyperperitectic alloy has been investigated at various solidification rates using a high-thermal gradient directional solidification apparatus [15]. The volume fraction of the SnSb phase firstly decreased and then increased when the solidification rate increased. The aim of this work was to study and analyze the effects of adding titanium oxide nanoparticles on creep behavior, structure, mechanical and thermal properties of tin-antimony-lead and tin-aluminum-antimony based alloys.

2. EXPERIMENTAL WORK

Two groups of alloys, Sn₆₀₋₉₃Sn₁₀Pb₅(TiO₂)ₓ (x = 0.5, 1 and 1.5 wt.%) and Sn₆₀₋₉₃Al₂₀Sn₁₀Pb₅(TiO₂)ₓ (x = 0.5, 1 and 1.5 wt. %), were molten in the muffle furnace. Using elements tin, antimony, lead, aluminum and titanium oxide have a high purity, more than 99.95%. The resulting ingots were turned and re-melted several times to increase the homogeneity of the ingots. From these ingots, long ribbons of about 3-5 mm width and ~ 70 μm thickness were prepared as the test samples by directing a stream of molten alloy onto the outer surface of rapidly revolving copper roller with surface velocity 31 m/s giving a cooling rate of 3.7 × 10⁴ K/s. The samples then cut into convenient shape for the measurements using double knife cutter. Structure of used alloys was performed using an Shimadzu x-ray diffractometer (DX-30, Japan) of Cu–Kα radiation with λ = 1.54056 Å at 45 kV and 35 mA and Ni–filter in the angular range 20 ranging from 0 to 100° in continuous mode with a scan speed 5 deg/min. Scanning electron microscope JEOL JSM-6510LV, Japan was used to study microstructure of used samples. The melting endotherms of used alloys were obtained using a SDT Q600 V20.9 Build 20 instrument.
A digital Vickers micro-hardness tester, (Model-FM-7- Japan), was used to measure Vickers hardness values of used alloys. Internal friction $Q^1$ and the elastic constants of used alloys were determined using the dynamic resonance method [16-18].

3. RESULTS AND DISCUSSIONS

Structure
X-ray diffraction patterns of Sn$_{80-x}$Sb$_x$Pb$_1$(TiO$_2$)$_x$ (x= 0.5, 1 and 1.5 wt.%) rapidly solidified alloys have lines corresponding to β-Sn, Pb, Sb and SbSn intermetallic phases as shown in Figure 1. X-ray analysis of Sn$_{98}$Sb$_{12}$Pb$_3$ show that, formed phases (intensity, peak broadness, miller indices, position (2$\theta$), and area under peaks) changed after adding of (TiO$_2$)$_x$. That is because TiO$_2$ disappeared, dissolved in the matrix of alloy. Also crystal particle size of β-Sn in Sn$_{98}$Sb$_{12}$Pb$_3$ alloy increased after adding TiO$_2$ as seen in Table 1.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Particle size Å</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn$<em>{98}$Sb$</em>{12}$Pb$_3$</td>
<td>317.25</td>
</tr>
<tr>
<td>Sn$_{78}$Sb$_1$Pb$_3$(TiO$<em>2$)$</em>{0.5}$</td>
<td>395.12</td>
</tr>
<tr>
<td>Sn$_{78}$Sb$_1$Pb$_3$(TiO$_2$)$_1$</td>
<td>448.06</td>
</tr>
<tr>
<td>Sn$_{78}$Sb$_1$Pb$_3$(TiO$<em>2$)$</em>{1.5}$</td>
<td>415.38</td>
</tr>
</tbody>
</table>

Table 1: crystal particle size of β- Sn in Sn$_{80-x}$Sb$_x$Pb$_3$(TiO$_2$)$_x$ alloys

Scanning electron micrographs, SEM, of Sn$_{80-x}$Sb$_x$Pb$_3$(TiO$_2$)$_x$ alloys show heterogeneous structure as shown in Figure 2 and that agreed with x-ray analysis. Adding TiO$_2$ caused change in microstructure of Sn$_{98}$Sb$_{12}$Pb$_3$ alloy.

X-ray diffraction patterns of Sn$_{60-x}$Al$_{20}$Sb$_x$Pb$_3$(TiO$_2$)$_x$ (x= 0.5, 1 and 1.5 wt.%) rapidly solidified alloys have lines corresponding to β-Sn, Pb, Sb and SbSn intermetallic phases as shown in Figure 3. X-ray analysis of Sn$_{60}$Al$_{20}$Sb$_1$Pb$_3$ show that, formed phases (intensity, peak broadness, miller indices, position (2$\theta$), and area under peaks) changed after adding of (TiO$_2$)$_x$. That is because Al and TiO$_2$ disappeared or not detected, dissolved in the matrix of alloy. Also crystal particle size of β-Sn in Sn$_{60}$Al$_{20}$Sb$_1$Pb$_3$ alloy increased after adding TiO$_2$ as seen in Table 2.
Mechanical properties

The elastic constants are directly related to atomic bonding and structure. Elastic moduli of Sn_{60-x}Sb_{15}Pb_{x}(TiO_{2})_{x} alloys are listed in Table 3. Elastic modulus of Sn_{60}Sb_{15}Pb_{5} alloy increased after adding TiO_{2} nanoparticles.

The resonance curves of Sn_{60-x}Sb_{15}Pb_{x}(TiO_{2})_{x} alloys are shown in Figure 5. Calculated internal friction and thermal diffusivity of Sn_{60-x}Sb_{15}Pb_{x}(TiO_{2})_{x} alloys are listed in Table 3. Internal friction of Sn_{60}Sb_{15}Pb_{5} alloy varied after adding TiO_{2} nanoparticles. The Sn_{60}Sb_{15}Pb_{5}(TiO_{2})_{0.5} alloy has better bearing properties such as lowest internal friction, high elastic modulus and higher thermal diffusivity for industrial applications.

Table 3:- elastic moduli, internal friction and thermal diffusivity of Sn_{60-x}Sb_{15}Pb_{x}(TiO_{2})_{x} alloys

<table>
<thead>
<tr>
<th>Samples</th>
<th>E GPa</th>
<th>µ GPa</th>
<th>B GPa</th>
<th>Q^1</th>
<th>D_θ x10^{-8} m² sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn_{60}Al_{20}Sb_{15}Pb_{5}</td>
<td>24.28</td>
<td>8.93</td>
<td>28.80</td>
<td>0.034</td>
<td>21.12</td>
</tr>
<tr>
<td>Sn_{60.5}Al_{20}Sb_{15}Pb_{5}Pb_{0.5}</td>
<td>32.96</td>
<td>12.18</td>
<td>37.49</td>
<td>0.036</td>
<td>17.7</td>
</tr>
<tr>
<td>Sn_{60}Al_{20}Sb_{15}Pb_{3}(TiO_{2})_{1}</td>
<td>38.25</td>
<td>14.08</td>
<td>45.09</td>
<td>0.029</td>
<td>34.5</td>
</tr>
<tr>
<td>Sn_{60}Sb_{15}Pb_{5}(TiO_{2})_{1.5}</td>
<td>42.67</td>
<td>15.71</td>
<td>50.12</td>
<td>0.041</td>
<td>12.3</td>
</tr>
</tbody>
</table>

Scanning electron micrographs, SEM, of Sn_{60-x}Al_{20}Sb_{15}Pb_{x}(TiO_{2})_{x} alloys show heterogeneous structure as shown in Figure 4 and that agreed with x-ray analysis.

Figure 5:- resonance curves of Sn_{60-x}Sb_{15}Pb_{x}(TiO_{2})_{x} alloys

Figure 4:- SEM of Sn_{60-x}Al_{20}Sb_{15}Pb_{x}(TiO_{2})_{x} alloys
The Sn95 Al50Sb15Pb5(TiO2) alloy has better bearing properties such as adequate internal friction, high elastic modulus and higher thermal diffusivity for industrial applications.

Table 4: - elastic moduli, internal friction and thermal diffusivity of Sn60-8Al20Sb15Pb5(TiO2)2 alloys

<table>
<thead>
<tr>
<th>Samples</th>
<th>E</th>
<th>μ</th>
<th>B</th>
<th>Q−1</th>
<th>Dth x 10⁻⁸</th>
<th>m²/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn60 Al20Sb15Pb5</td>
<td>38.95</td>
<td>14.35</td>
<td>45.56</td>
<td>0.031</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sn59.5 Al20Sb15Pb5(TiO2)0.5</td>
<td>36.99</td>
<td>13.63</td>
<td>43.11</td>
<td>0.033</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sn59 Al20Sb15Pb5(TiO2)1</td>
<td>42.22</td>
<td>15.56</td>
<td>49.07</td>
<td>0.036</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sn58.5 Al20Sb15Pb5(TiO2)1.5</td>
<td>37.55</td>
<td>13.85</td>
<td>43.49</td>
<td>0.030</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Resonance curves of Sn60-8Al20Sb15Pb5(TiO2)2 alloys](image)

Figure 6: - resonance curves of Sn60-8Al20Sb15Pb5(TiO2)2 alloys

**Thermal properties**

Thermal analysis is often used to study solid state transformations as well as solid-liquid reactions. Figure 7 shows DSC thermographs for Sn60-8Al20Sb15Pb5(TiO2)2 alloys. Variation occurred in exothermal peak of Sn60Sb10Pb5 alloy. The melting temperature and other thermal properties of Sn60Sb10Pb5 alloys are listed in Table 5. Melting temperature of Sn60Sb10Pb5 alloy decreased after adding TiO2 nanoparticles.

Specific heat, enthalpy and thermal conductivity of Sn60Sb10Pb5 alloy varied after adding TiO2 nanoparticles. That is because TiO2 nanoparticles due change in matrix microstructure of Sn60Sb10Pb5 alloy.

![DSC of Sn67.5Sb10Pb12.5TiO2 alloys](image)

Figure 7: - DSC of Sn67.5Sb10Pb12.5TiO2 alloys

Table 5: - melting point and other thermal properties of Sn60-8Al20Sb15Pb5(TiO2)2 alloys

<table>
<thead>
<tr>
<th>Samples</th>
<th>Melting point °C</th>
<th>C_p</th>
<th>J/g, °C</th>
<th>ΔS</th>
<th>J/g, °C</th>
<th>K</th>
<th>W/m².K⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn60Sb10Pb5</td>
<td>231.23</td>
<td>0.12</td>
<td></td>
<td>1.57</td>
<td></td>
<td>1.65</td>
<td></td>
</tr>
<tr>
<td>Sn60.5Sb15Pb5(TiO2)0.5</td>
<td>228.03</td>
<td>3.41</td>
<td>0.189</td>
<td></td>
<td></td>
<td>1.86</td>
<td></td>
</tr>
<tr>
<td>Sn60Sb15Pb5(TiO2)1</td>
<td>225.61</td>
<td>2.53</td>
<td>0.185</td>
<td></td>
<td></td>
<td>1.46</td>
<td></td>
</tr>
<tr>
<td>Sn60Sb15Pb5(TiO2)1.5</td>
<td>227.45</td>
<td>3.35</td>
<td>0.215</td>
<td></td>
<td></td>
<td>2.77</td>
<td></td>
</tr>
</tbody>
</table>

![DSC thermographs for Sn60-8Al20Sb15Pb5(TiO2)2 alloys](image)

Figure 8 shows DSC thermographs for Sn60-8Al20Sb15Pb5(TiO2)2 alloys. Variation occurred in exothermal peak of Sn60Al20Sb15Pb5 alloy. The melting temperature and other thermal properties of Sn60-8Al20Sb15Pb5(TiO2)2 alloys are listed in Table 7. Melting temperature of Sn60 Al20Sb15Pb5 alloy varied after adding TiO2 nanoparticles. Specific heat, enthalpy and thermal conductivity of Sn60Sb10Pb5 alloy varied after adding TiO2 nanoparticles. That is because TiO2 nanoparticles due change in matrix microstructure of Sn60 Al20Sb15Pb5 alloy.

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Figure 8: DSC of Sn$_{60-x}$Al$_{20}$Sb$_{51}$Pb$_1$(TiO$_2$)$_x$ alloys

Table 6: Melting point and other thermal properties of Sn$_{60-x}$Al$_{20}$Sb$_{51}$Pb$_1$(TiO$_2$)$_x$ alloys

<table>
<thead>
<tr>
<th>Samples</th>
<th>Melting point °C</th>
<th>C$_p$ J/g °C</th>
<th>$\Delta$S J/g °C</th>
<th>K W.m$^{-1}$.K$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn$<em>{60}$Al$</em>{20}$Sb$_{51}$Pb$_1$</td>
<td>229</td>
<td>1.6</td>
<td>0.11</td>
<td>2.08</td>
</tr>
<tr>
<td>Sn$<em>{60.9}$Al$</em>{20}$Sb$_{51}$Pb$_1$(TiO$<em>2$)$</em>{0.5}$</td>
<td>231.27</td>
<td>2.46</td>
<td>0.18</td>
<td>2.28</td>
</tr>
<tr>
<td>Sn$<em>{60}$Al$</em>{20}$Sb$_{51}$Pb$_1$(TiO$<em>2$)$</em>{0.5}$</td>
<td>224.16</td>
<td>1.48</td>
<td>0.14</td>
<td>2.03</td>
</tr>
<tr>
<td>Si$<em>{60.5}$Al$</em>{20}$Sb$_{51}$Pb$_1$(TiO$<em>2$)$</em>{1.5}$</td>
<td>230.94</td>
<td>1.97</td>
<td>0.14</td>
<td>1.62</td>
</tr>
</tbody>
</table>

Creep behavior

Creep behavior of Sn$_{60-x}$Sb$_{50}$Pb$_1$(TiO$_2$)$_x$ and Sn$_{60-x}$Al$_{20}$Sb$_{51}$Pb$_1$(TiO$_2$)$_x$ alloys were investigated by indentation method.
5. CONCLUSIONS
Microstructure of tin-antimony-lead and tin-aluminum-antimony-lead alloys changed after adding titanium oxide. Stress exponent of tin-antimony-lead and tin-aluminum-antimony-lead alloys decreased after adding titanium oxide. Strengths of tin-antimony-lead and tin-aluminum-antimony-lead alloys increased after adding titanium oxide. Internal fiction and thermal parameters of tin-antimony-lead and tin-aluminum-antimony-lead alloys varied after adding titanium oxide. The Sn₁₉Sb₁₃Pb₁(TiO₂)₁ and Sn₅₉Al₂₀Sb₁₃Pb₁(TiO₂)₁ alloys have better bearing properties for industrial applications.

6. REFERENCES