Embeddability behaviour of tin-based bearing material in dry sliding

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Abstract

In this study, tin-based bearing material has been investigated in dry sliding conditions. The low Sb content (7%) is known as SAE 12 and is Sn–Sb–Cu alloy and is widely used in the automotive industry. Wear and friction characteristics were determined with respect to sliding distance, sliding speed and bearing load, using a Tecquipment HFN type 5 journal bearing test equipment. Scanning electron microscopy (SEM) and energy-disperse X-ray spectrography (EDX) are used to understand the tribological events, especially embeddability.

Thus, the purpose of this study is to investigate the tribological properties of tin-based bearing alloy used especially in heavy industrial service conditions. Tests were carried out in dry sliding conditions, since despite the presence of lubricant film, under heavy service conditions dry sliding may occur from time to time, causing local wear. As a result of local wear, bearing materials and bearing may be out of their tolerance limits in their early lifetime. Embeddability is an important property due to inversely affecting the hardness and the strength of the bearing.

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Keywords: Tribology; Embeddability; Dry sliding

1. Introduction

Friction, wear and lubrication of interacting surface are principal subjects of the wide interdisciplinary science of tribology. As such they have received a great deal of interest by scientists and engineers and a vast quantity of information has been produced showing the complexity of tribological problems. Wear may be defined as the progressive loss of substance from the operating surface of a body occurring as a result of relative motion at the surface. Because of strong irreversible and dissipative interrelations between the components of a system, friction coefficients and wear rates are characteristics of the whole tribosystem and not intrinsic material properties. It is one of the most commonly encountered industrial problems leading to the replacement of components and assemblies in engineering, the others being fatigue and corrosion. Wear is rarely catastrophic but it reduces operating efficiency by increasing the power loss, oil consumption and the rate of component replacement [1].

In dry sliding contacts, some of the materials can be transferred from one sliding surface to the other. Lubricants are used to control friction and minimize wear in a variety of tribological applications. Wear rates in dry contact are about three orders of magnitude higher than those in lubricated contact. Both material and energy losses are reduced by the introduction of a lubricant. Load carrying capacity of bodies increased by low friction coefficient in sliding and rolling contacts [2].

Sliding bearings operate with relative sliding motion of elements that really are separated by a film of lubricant. They include all types of journals or sleeve bearings, which are used to position shafts or moving parts radially; all types of thrust bearings, which in general are used to prevent axial movement of shafts; and bushings used as guides for wear motions of various types. Surface journal bearings completely surround the shafts either as continuous cylinders or as segmented cylinders; others may encompass only an arc of the shaft circumference [3].
When a journal bearing operates in the hydrodynamic regime of lubrication, hydrodynamic film develops. Under these conditions, conformal surfaces are fully separated and a copious flow of lubricant is provided to prevent overheating. In these circumstances of complete separation, mechanical wear does not take place. However, this ideal situation is not always achieved.

The mechanisms by which sliding bearings fail include fatigue, wear, fretting, corrosion, corrosion fatigue and cavitation. Wear of sliding bearings usually occurs during machine break-in. Thereafter, wear continues at a much slower rate because surface roughness has been stabilized and the bearing surface has conformed to the shaft surface. With proper maintenance, only those dirt particles that are too small to be filtered will abrade the bearing surface. Normal wear can be recognized by two conditions. First, in trimmed bearings, some of the Babbitt overlay will have been removed, exposing the nickel dam or the intermediate layer in the primary area of journal dwell. The second sign of normal wear is the presence of minor surface scratches caused by foreign material in the lubricant as it passes through the bearing [4].

2. Bearing materials

The majority of alloys found in this category are still copper-based, both steel-backed and solid; but increasing number of steel backed aluminium alloys are found in automotive applications. Lead- and tin-based white metals are common. Many polymers behave well in lubricated applications, and when the lubrication is sparse, polymer-based bearing materials often outperform metallic bearing alloys.

Plain bearings are most commonly non-ferrous alloys, but may be polymers or polymer-based composites or, rarely, ceramics. Most plain bearings are oil or grease lubricated, and among the major factors determining the choice of bearing materials for a particular application are the type, amount, and quality of the lubricant. The increasingly severe operating conditions, which new designs of engine have imposed on the crankshaft bearings, have led to the virtual disappearance of the once familiar tin-and lead-based Babbitt alloys, and to their replacement by a range of stronger alloys based on aluminium or copper [4].

The foregoing considerations show that the choice of an engine bearing alloy is a compromise. Conformability – the ability to conform to a misaligned counterface – is inversely related to hardness, as is dirt embeddability, and to some extent also compatibility, because of the desirability of a soft, low-melting-point phase.

Selection of materials for either fluid-film or rolling element bearings depends on matching material properties with the need for low friction, low wear rate, and long life. While almost all engineering materials have been used at some time in a search for optimum bearing materials, final selection is commonly based on judgment as to the most essential material properties, type of application and cost [5].

2.1. Fatigue strength

It is the prime requirement of the bearing that it should be able to carry loads without suffering damage. The common crankshaft bearing has a steel backing with a thin lining of bearing alloy, and to some extent it is this construction of the bearing which provides its load-carrying capability. However, the strength of the lining alloy is also important, and in choosing an alloy for a particular application the first step is to compute the maximum value of the dynamic pressure generated oil film, and to ensure that the alloy has the strength to survive.

2.2. Surface properties

Dirt entering the bearing clearance with the oil flow is another source of bearing damage. If dirt cannot be fully embedded into the bearing surface, it may score the crankshaft (depending on the relative hardness of the dirt and the crankshaft surface), and the roughened crankshaft may in turn cause wear of the bearings. Embeddability, which is inversely related to hardness and the strength of the bearing, is thus an important property.

When dirt is embedded, particularly a relatively large particle of in-built dirt such as that which may be left in crankshaft drillings, bearing material is displaced around the particle and appears as a ring of alloy protruding from the bearing surface. This ring is rubbed by the crankshaft, but again the presence of a soft, low-melting-point phase prevents the local welding or “pickup” of bearing alloy onto the crankshaft and avoids seizure [4].

Sometimes misalignment, either inherent in the way the machine is assembled or of a transient nature arising from thermal or elastic distortion, may cause metal-metal contact. Moreover, contact may occur at the instant of starting (before the hydrodynamic film has had the opportunity to develop fully), the bearing may be overloaded from time to time and foreign particles may enter the film space. In some applications, internal combustion engines, for example, acids and other corrosive substances, may be formed during combustion and transmitted by the lubricant thus inducing a chemical type of wear. The continuous application and removal of hydrodynamic pressure on the shaft may dislodge loosely held particles. In many cases, however, it is the particles of foreign matter which are responsible for most of the wear in practical situations. Most commonly, the hard particles are trapped between the journal and the bearing. Sometimes the particles are embedded on the surface of the softer material, as in the case of white metal, thereby relieving the situation. However, it is commonplace for the hard particles to be embedded on the bearing surface thus constituting a lapping system, giving rise to rapid on the hard shaft surface. Generally, however, the wear on hydrodynamically lubricated bearings can be regarded as mild and caused by occasional abrasive action. Chromium plating of crankshaft bearings is sometimes successful in combating abrasive and corrosive wear [6].
2.3. Corrosion and erosion

Corrosion resistance and cavitation erosion resistance are another two important properties of crankshaft bearing alloys. Cavitation erosion resistance of bearing alloys is broadly related to alloy hardness, but microstructure is also important. Tin-based white metal has a much higher cavitation erosion resistance than lead-based white metal of approximately the same hardness, probably due to the copper-tin needles in the microstructure.

As a class, the white metals have excellent surface properties: compatibility, conformability, and dirt embeddability. However, their fatigue strength is inadequate for the majority of internal combustion engines, and these alloys survive only as crankshaft bearing linings in slow-speed marine diesel engines. The tin-based alloy mentioned above, often with a 1% cadmium addition for increased strength, is the most popular alloy for marine diesel applications.

2.4. Compatibility

Even bearings that operate with a full oil film can be expected to contact their shaft during initial break-in, while starting and stopping, or during interruptions in lubricant supply. During this direct material contact, the bearing material must avoid being locally welded to the shaft with scoring or galling under the high stress, high strain and elevated temperature at localized areas [5].

Table 1 shows to characteristics of widely used bearing materials [5].

2.4.1. White metals

Many materials have been tried as bearing components. In 1839 Babbitt patented a Sn–Sb–Cu alloy for use in journal bearings. White metal is now widely used as a material for sliding bearings operating under oil lubrication, for example, bearing for general industrial use, marine use and automotive use. One of the most heavy duty applications of thrust bearings is in hydroelectric power stations for support of the shaft, carrying hydraulic turbine and electric generator. White metal can be fundamentally classified into two types. One has lead as its main component, the other tin. A bearing works in a stabilized manner when a proper film thickness is formed and maintained between the shaft and the bearing. However, under unacceptably high loads and shaft revolution speeds, or improper lubricating conditions, the bearing is often damaged when a sufficient thickness of the oil film is not formed between the shaft and the bearing. Under these conditions, shaft and white metal make partial contact with each other during the sliding wear process. This condition is called boundary lubrication [5–9].

Table 1
Characteristics of widely used bearing materials

<table>
<thead>
<tr>
<th>Physical property</th>
<th>Significance of property in service</th>
<th>Characteristics of widely used materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatigue strength</td>
<td>To sustain imposed dynamic loadings at operating temperature</td>
<td>Adequate for many applications, but falls rapidly with rise of temperature</td>
</tr>
<tr>
<td>Compressive strength</td>
<td>To support uni-directional loading without extrusion or dimensional change</td>
<td>As above</td>
</tr>
<tr>
<td>Embeddability</td>
<td>To tolerate and embed foreign matter in lubricant, so minimising journal wear</td>
<td>Excellent-unequalled by any other bearing materials</td>
</tr>
<tr>
<td>Conformability</td>
<td>To tolerate some misalignment or journal deflection under load</td>
<td></td>
</tr>
<tr>
<td>Compatibility</td>
<td>To tolerate momentary boundary lubrication or metal-to-metal contact without seizure</td>
<td>Tin-based white metals excellent in the absence of sea water. Lead-based white metals attacked by acidic products</td>
</tr>
</tbody>
</table>

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The babbitts are among the most widely used materials for hydrodynamically lubricated bearings. Babbitts are either tin or lead-based alloys having excellent embeddability and conformability characteristics. They are unsurpassed in compatibility and thus prevent shaft scoring [10–14].

The steel-backed white metals used in the journal and thrust bearings of rotating plant are generally tin-based, SnSb8Cu3 being the most commonly used alloy. Higher strength can be obtained from alloys of more complex composition, but at the expense of loss of ductility. Tin-based white metal bushings in mid-range fractional-horsepower (fhp) motors, that is, with shaft diameters from 10 to 16 mm, are used in combination with oil impregnated wick lubrication [4].

Babbitt bearings are quickly run in and assume very smooth surfaces. Application is usually made to a steel back. Thickness of the lining is usually about 0.015 in. Thin Babbitt bearing with linings 0.002–0.005 in. thick are also used and can carry somewhat heavier loads. Babbitt bearings have good conformability, or the property of adjusting themselves to small misalignments or shaft deflections. They also make excellent bearings from the standpoint of embeddability because a reasonable amount of dirt or foreign matter in the lubricant can be absorbed by the soft bearing material and the shaft is thus protected against scoring [15]. Table 2 covers representative physical properties of typical Babbitt compositions (ASTM 1990; SAE 1991) [5].

### Table 2
Physical properties of babbitte alloys (tin-based white metals)

<table>
<thead>
<tr>
<th>Designation</th>
<th>Tin-based</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM B23</td>
<td>2 3</td>
</tr>
<tr>
<td>SAE</td>
<td>11 12</td>
</tr>
<tr>
<td>Nominal composition (%)</td>
<td></td>
</tr>
<tr>
<td>Tin</td>
<td>87 89 84</td>
</tr>
<tr>
<td>Lead</td>
<td>7 7 8 8</td>
</tr>
<tr>
<td>Antimony</td>
<td>6 3 8</td>
</tr>
<tr>
<td>Copper</td>
<td>3,5</td>
</tr>
<tr>
<td>Arsenic</td>
<td></td>
</tr>
<tr>
<td>Specific gravity</td>
<td>7,4 7,39 7,45</td>
</tr>
<tr>
<td>Melting point (°C)</td>
<td>240 241 240</td>
</tr>
<tr>
<td>Complete liquefaction (°C)</td>
<td>400 354 422</td>
</tr>
<tr>
<td>Hardness (HB)</td>
<td>26 24 27</td>
</tr>
<tr>
<td>Ultimate tensile strength (MPa)</td>
<td>90 77</td>
</tr>
<tr>
<td>Compressive yield strength (MPa)</td>
<td>45 42</td>
</tr>
<tr>
<td>Approximate strength retained at 100 °C</td>
<td>49 52 52</td>
</tr>
<tr>
<td>150 °C</td>
<td>23 24 24</td>
</tr>
<tr>
<td>200 °C</td>
<td>5 7 7</td>
</tr>
</tbody>
</table>

The lead- and tin-based white metals, or Babbitts, are alloys of lead, antimony, and tin, or tin, antimony, and copper. The most popular lead-based alloys are PbSb10Sn6 and PbSb15Sn1As1; the most popular tin-based alloy is SnSb8Cu3. (Formulae of this type are used in this article to indicate compositions as recommended by the International Standards Organization: SnSb8Cu3 = Sn–8%Sb–3%Cu.) The former consist of cuboids of antimony–tin compound SbSn in a pseudoeutectic of lead–antimony–tin. The latter consist of needles of copper–tin compound Cu6Sn5 in a tin–antimony solid solution.

Tin babbitt alloys commonly contain about 3–8% copper and 5–8% antimony. Within a soft solution matrix antimony in tin, small, hard Cu6Sn5 copper–tin intermetallic particles are dispersed. Increasing copper increases the proportion of Cu6Sn5 needles or stars in the microstructure. An increase in antimony above 7.5% results in antimony–tin cubes. Hardness and tensile strength increase with greater copper and antimony content, while ductility decreases. Low antimony (3–7%) and low copper content (2–4%) provide maximum resistance to fatigue cracking. Since these low-alloy compositions are relatively soft and weak, a compromise is often made with fatigue resistance and compressive strength [5,7].

### 3. Experimental

#### 3.1. Materials and experimental conditions

In the experimental set-up used, shaft was made of AISI 440C stainless steel and bearing was made of tin-based white metal. The chemical analysis of bearing material is given in Table 3. Hardness of specimen is represented in Table 4 [16].

#### 3.2. Results of the experiments

In Fig. 1, variation of friction torque with sliding distance is presented for the tin-based bearing alloy used in the experiments. For high sliding distances (above 50,000 m), friction torque appears to be almost constant for WM-2.

The amount of wear was determined using the weight loss measured by a Scaltec balance. Fig. 2 shows which wear increases linearly with sliding distance.

Fig. 3 shows the relationship between friction coefficient and sliding distance for tin-based bearing alloy. It can be seen from the figure that friction coefficient is approximately constant for sliding distances over 50,000 m.

### Table 3
Chemical compositions of specimens

<table>
<thead>
<tr>
<th></th>
<th>Sb</th>
<th>Pb</th>
<th>Cu</th>
<th>Bi</th>
<th>Cd</th>
<th>Zn</th>
<th>Fe</th>
<th>In</th>
<th>Tl</th>
<th>Te</th>
<th>Ni</th>
<th>Sn</th>
</tr>
</thead>
<tbody>
<tr>
<td>WM-2</td>
<td>7.2305</td>
<td>.4024</td>
<td>3.0320</td>
<td>.0033</td>
<td>.0027</td>
<td>.0100</td>
<td>.0162</td>
<td>.0048</td>
<td>.0224</td>
<td>.0022</td>
<td>.0072</td>
<td>89.264</td>
</tr>
</tbody>
</table>

### Table 4
Hardness and wear in dry sliding of tested material

<table>
<thead>
<tr>
<th>Material</th>
<th>Hardness (HB)</th>
<th>Wear in dry friction (gr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WM-2</td>
<td>40.5</td>
<td>10.18</td>
</tr>
</tbody>
</table>
Fig. 4 illustrates the relationship between friction coefficient and shaft speed. The friction coefficient remains constant up to 1400 rpm and then sharply decreases at this speed. This result indicates that this material can be used at high shaft speeds for a long time without a significant wear and change in bearing tolerances. This is an important property for engines used in automotive and hydro-electric industry.

Fig. 5 represents the relationship between friction coefficient and bearing load. As expected, friction coefficient increased with increasing bearing load.

The microstructure of the alloy used in the experimental study was investigated by scanning electron microscopy (SEM) to understand the tribological behavior better. The alloy was prepared by metallographical techniques and etched with Nital after polishing. The micrographs shown in Fig. 6 belong to the alloy WM-2.

As seen in Fig. 6, the Cu₆Sn₅ intermetallics are distributed in the Sn matrix and have characteristic large star shapes that can be easily identified [5]. The SbSn intermetallics are small white precipitates, dispersed in the solid solution [16].

Fig. 7 represents the image of the white metal bearing alloy that is used in the wear test and the image of wear surface after test. When the image that is shown in Fig. 7b is examined, it is obvious that there are some embedded particles (Fe) that are found on the wear surface. Fe particles come out from the worn shaft because of dry sliding. The soft bearing
materials reduce the abrasive wears that is a kind of serious wear, since these kinds of materials have good embeddability properties for the worn particles.

A kind of metal-oxide structure forms in shaft materials that has a great hardness compared to the bearing materials due to impurities, that have a metallic characteristic, and that have rapidly been oxidized. In this case, it is possible that undesired wears occur on the bearing materials and shaft materials.

These kinds of undesired wears commonly cause the earlier deformation and exceed the tolerances of the tight fit parts. These impurities cannot be removed from the interface and therefore most of them are embedded, thus the damages of these kinds of impurities can be reduced. This situation shows that Sn-based bearing alloys have a high embeddability feature.

When Figs. 8 and 9 are examined, it is obvious that the particle has a degree of oxidation.

As seen in Fig. 10, the black coloured particles appear from the surface of the sub-matrix in the regions that have intensive wears.

When we focused on Fig. 11 that represents an example of energy-dispersed X-ray spectrography (EDX) spectrum for the particle, it is obvious that these kinds of black coloured particles indicate Pb (vide Table 1). Lead (Pb), which is found with a low scale in the alloy, acts as a lubricant with tin (Sn) in the metal–metal interfaces. This case gives a positive addition to tribological properties of Sn-based bearing alloys.

Fig. 6. An optical microscope image of Sn-based bearing alloy that is tribologically examined (etched, 200×).

Fig. 7. (a) An example of SEM image of the bearing materials that is used in the wear test and (b) image of the bearing surface after test.

Fig. 8. An example of a SEM image with a high magnification of the particle that is shown in Fig. 7b (400×).

Fig. 9. An example of EDX spectrum for the particle that is shown in Fig. 7b.

Fig. 10. The black coloured particles appear from the surface of the sub-matrix in the regions that have intensive wears.

Fig. 11. An example of energy-dispersed X-ray spectrography (EDX) spectrum for the particle.
4. Conclusion

1. WM-2 alloy can be used in dry sliding conditions. As shown in Fig. 4, for this alloy friction coefficient sharply decreases after a shaft speed of 1400 rpm. So both of these materials can be used at high shaft speeds and suitable material automotive industry.

2. This result indicates lower metal–metal friction for bearing and shaft materials and thus lower thermal effects in the bearing. In the literature, seizure failure type of Tin Babbitt bearings is Babbitt failure at critical temperatures [17]. Thus, the materials having lower friction coefficient are preferred.

3. Babbitt bearings have good conformability, or the property of adjusting themselves to small misalignments or shaft deflections. They also make excellent bearings from the standpoint of embeddability because a reasonable amount of dirt or foreign matter in the lubricant can be absorbed by the soft bearing material and the shaft is thus protected against scoring [15]. As shown in Figs. 8–11, WM-2 has a good embeddability performance; thus both shaft and bearing materials can be protected against abrasive wears.

4. WM group alloys are not new materials. These materials are known since 1800s. These bearing materials, that are basically Sb–Sn–Cu alloys, can be safely used in a large variety of industrial applications, by adding different alloying elements and providing the microstructural characterization.

References