Friction and wear characteristics of different Pb-free bearing materials in mixed and boundary lubrication regimes

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Abstract

Traditional bearing materials contain different amounts of lead (Pb) because of its friction reducing properties. However, in view of the negative health and environmental impact of Pb, there is growing emphasis on restricting the usage of Pb in engine bearings. Owing to this, new bearing materials that provide at least comparable tribological performance to that of Pb containing alloys are being developed and some new Pb-free materials are being already used in engine bearing applications. It is, however, still unclear how these new engine bearing materials would perform in mixed and boundary lubricated conditions. In this study, a block-on-ring test setup was employed to investigate the tribological performance of several bimetal and multi-layer Pb-free bearing materials with different compositions of bearing lining and overlay plating. Pb-containing bearing material was also studied as a reference material. Friction and wear properties of these bearing materials were investigated and their wear mechanisms under lubricated conditions have been analysed. Bearing material with overlay of Polyamide-Imide with graphite and MoS₂ exhibited better friction and wear properties than Pb-based and Al-Sn based materials. Pb-containing bearing material shows higher wear resistance and Al-Sn based material has shown higher friction.

Keywords: lead-free; bearing materials; friction and wear

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1. INTRODUCTION

In internal combustion engines, main bearings enable in smooth rotation of the crankshaft and protect the crankshaft from damage. Engine bearings are designed to operate in the hydrodynamic lubrication regime with a thick lubricant film separating the crankshaft and bearing surface [1, 2]. Although they usually operate in the hydrodynamic lubrication regime, but at times other conditions of lubrication, i.e. boundary and mixed lubrication also prevail. Especially during starting and stopping, speed and load changes, the two surfaces may not be fully separated by a lubricant film and bearings may operate in boundary and mixed lubrication regimes. Under these conditions, the contacting material surfaces as well as the engine oils containing additives play an important role in determining the friction and wear [3].

Engine bearings are required to possess desirable tribological properties such as low friction, wear resistance, good embeddability, conformability and seizure resistance [4]. The friction between bearings and crankshaft has to be as low as possible in order to improve efficiency of the engine.

Bearings consist of different layers. Each layer has its own specific function and all together provides the combination of required bearing properties. Commonly the bearing lining, which is a few hundred micrometres in thickness, is applied on a steel backing. An intermediate layer as a diffusion barrier with a thickness of about 1 ~ 4 microns is deposited on top of the lining. Finally, an overlay with a thickness of some tens of microns is electroplated or sputtered on the top. The purpose of the overlay is to improve most of the required tribological properties such as friction, seizure resistance, conformability and embeddability properties [5]. However, in bi-metal bearings where an overlay is absent, tribological performance is determined by the bearing lining itself.

Various materials have been investigated and used as engine bearing. Lead (Pb) containing materials such as Cu-Pb based linings and overlays have been extensively used due to their low friction characteristics and excellent conformability and embeddability behaviour of lead [6]. However, due to environmental issues and its lower strength the use of Pb for manufacturing crankshaft

bearings is being restricted [7, 8]. Various Pb-free bearing materials are suggested by bearing manufacturers. For instance, Al-Sn based overlay materials tested in a ring-on-disk test set up showed better wear resistance compared with Pb-based material [5]. The Tin (Sn) soft phase distributed in the Al-matrix determines friction and wear behaviour [9]. Polymeric overlays such as polyamide-imide containing graphite and MoS₂, has also shown better friction and wear properties than Pb-based overlays and its lower friction is mainly due to the presence of graphite and MoS₂ in the overlay [5].

As is evident that only a very few studies pertaining to Pb-free bearing materials have been conducted so far. Thus the main objective of this study is to compare and understand the friction and wear behaviour of Pb-free bearing materials under mixed and boundary lubrication conditions vis a vis the Pb-containing bearing materials.

2. EXPERIMENTAL

2.1 Materials

Four bearing materials were investigated as listed in Table 1. *A1* was a bi-metal bearing material with no overlay and it has Al-Sn based bearing lining. However, materials designated as *A2*, *A3* and *B1* contain lining, diffusion barrier and an overlay. *A2* has an overlay composed of polyamide-imide (PAI) containing graphite and MoS₂. *A3* has an Al-Sn based overlay material on top of which a material similar to the overlay of *A2* is sputtered. The overlay of *B1* is Pb-based material and studied as a reference.

For this study, test samples were cut out from the bearing shells using a spark erosion cutting machine. Each test sample was 5.5 mm in width and 12 mm in length. A bearing outer ring made from high grade bearing steel AISI 52100 with diameter of 35mm and polished to a roughness (Ra) of about 0.1 μm was used as a counter surface. A low-SAPS (low-sulphated ash, phosphorous and sulphur), fully formulated engine oil was used. The viscosity of the oil is 0.146 and 0.0149 Pas at 25 °C and 95 °C, respectively.

2.2 Test methods and parameters

For hardness measurements a triboindenter was used and measurements were carried out on cross-sections of lining and overlay of test materials. Measurements were carried out in a displacement controlled manner with indentation depth of 100nm and at 5N load. Surface topography of test materials were investigated using Wyko 1100NT 3D optical surface profiler. Worn surfaces were also investigated using optical microscopy and scanning electron microscopy (SEM) incorporated with EDS.

Table 1: Nominal composition and thickness values of lining, interlayer and overlay of bearing samples.

For the friction and wear studies, a CETR UTM-2 tribometer with a block-on-ring test configuration was used as shown in Fig. 1. The upper carriage consists of a block with dual friction and normal load sensor. A test sample holder carrying on the bearing test sample is mounted on the block. The carriage is lowered for loading the bearing test sample against the steel ring. It can also be moved in x-direction for aligning the test sample with the counter surface. The lower ring drive has a rotating shaft on which the steel ring counter surface specimen is mounted. There is an oil bath in which the lower part of the test ring is immersed for lubrication of the interface. There is a heating cartridge for the oil bath for conducting tests at elevated temperatures.

Figure 1: Schematics of block-on-ring test configuration used for friction measurement.

To investigate how sliding speed influences running-in friction in mixed and boundary lubrication regimes tribological tests were carried out at different rotational speeds of 1, 5, 25, 100, 150 and 250 rpm. The rotation of 1 rpm corresponds to about 0.002 m/s.

These tests were carried out by changing rotational speed from higher to lower speed to minimise the surface damage and wear during the tests. At each step, test duration was 15s to reduce effect of wear on contact area. Tests were carried out at three different loads 30, 50 and 80N at room temperature and 95 °C respectively.

To investigate the steady state-friction behaviour and wear characteristics, tests with relatively longer test duration were also conducted. Test conditions listed in Table 2 were carefully selected so as to ensure operation in mixed/boundary lubrication regimes. Test condition 1 is with relatively higher sliding speed so that mixed lubrication condition is achieved and test condition 2 and 3 were at lower sliding speed to completely avoid the effect of mixed lubrication and ensure operation in boundary lubrication.

Sample	Composition			Thickness (μm)		
	Lining	Interlayer	overlay	Lining	Interlayer	Overlay
A1	AlSn25Cu1.5Mn0.6	n/a	n/a	706	n/a	n/a
A2	CuSn5Zn1	Ni	(PAI, MoS ₂ 45%, graphite 23%)	511	4.2	21.6
A3	CuSn5Zn1	Ni	AlSn20Cu1, (PAI, MoS ₂ 45%, graphite 23%)	508	3.2	19 9.2
B1	CuPb23Sn2	Ni	PbSn10Cu5	270	2.25	15

Table 2: Test conditions

Condition	Load	Speed	Duration	Temperature
1	50N	25 rpm	120s	RT and 95 °C
2	50N	1 rpm	50 min	RT and 95 °C
3	200N	1 rpm	3 hrs	RT and 95 °C

3. RESULTS AND DISCUSSION

3.1 Hardness

Fig. 2 shows hardness values for bearing test materials. The lining of A1 has lower hardness than the other linings. A2 and A3 have identical lining and exhibit higher hardness values. For A3, the overlay beneath the PAI based top overlay is harder than the other overlay materials and has almost similar hardness value as that of A1. The variations shown with the error bar might be because of variations in roughness of indented surface, indentation on grain boundaries, indentation on the soft inclusion or porosity of materials.

Figure 2: Hardness values for linings and overlays of test materials.

3.2 Surface topography of test samples

Test materials exhibit different surface features as shown in Fig. 3. For instance, A1 has machining marks on the lining. A2 and A3 show no machining marks as the top overlays are prepared by sputtering technique. B1 has distinctive microgroove patterns which are intended to improve lubrication [10]. Roughness values of original surfaces are shown in Table 3.

Figure 3: Surface topography of test materials.

Table 3: Roughness of original bearing surfaces

Sample	A1	A2	A3	B1
Ra (μm)	0.36	0.80	0.78	0.65
Rq (μm)	0.46	1.03	0.99	0.84

Fig. 4 shows SEM micrographs of original surfaces of test materials. For A1, the surface of the lining material shows the distribution of Sn soft phase (bright) in the Al matrix. On the other hand, overlays of A2 and A3 have similar features and their surfaces are uneven. For B2 the soft overlay has typical features of an electroplated surface.

Figure 4: SEM micrographs of the original surfaces of test materials: (a) A1 (b) A2 (c) A3 and (d) B1

3.3 Effect of sliding speed on friction

Effect of sliding speed on friction for different test materials is shown in Fig. 5. Coefficient of friction (COF) values are average values from each test step for the duration of 15s [11]. At both room temperature and

95 °C, COF decreases for all test materials when the sliding speed increases. At higher sliding speed, COF values for all materials become close to each other as they enter the full film lubrication regime where friction is determined by the bulk property of oil [12].

Figure 5: Effect of sliding speed on friction behaviour at RT: a) 30N, b) 50N, c) 80N & at 95 °: d) 30N, e) 50N, f) 80N.

At lower speed, A1 shows higher friction value. At room temperature and lower speeds, COF values for A2, A3 and B1 were close to each other and lower than that of A1. However, at 95 °C and lower speed and load, friction values for A2 and A3 were found to be lower than that of B1. At room temperature and 95 °C, for the metallic materials A1 and B1, the decrease in COF is sharp when sliding speed increases. For A2, the decrease in COF as sliding speed increases are significantly different at room temperature and 95 °C. At 95 °C, the decrease in COF as a function of sliding speed is slow and this might be related with decrease in lubricant viscosity and higher roughness of A2 [13].

for A2 and A3 can be attributed to the exposure of more MoS₂ in the contact surface.

Figure 6: Friction behaviour at test condition 1: 50N, 25 rpm and 120s (a) RT and (b) 95 °C

3.4 Steady-state friction behaviour

Steady-state friction behaviour of test the materials were investigated under three different test conditions. Sliding speeds for each test conditions were selected based on results presented in section 3.3.

Test condition 1: Tests were carried out at 50N, 25 rpm and 120s on each test materials. Friction behaviours are shown in Fig. 6. It can be seen that in the mixed lubrication regime, A1 has higher COF compared with the other test materials. B1 exhibits lower COF. However, A2 and A3 have similar friction behaviour as the top overlay has similar PAI based overlay containing graphite and MoS₂.

Test condition 2: Fig. 7 shows the friction behaviour of test materials in boundary lubrication regime (50N, 1 rpm and 50 min). A1 shows higher friction values. In contrast to the mixed lubrication condition, B2 has higher friction value than A2 and A3. The lower friction values

Figure 7: Friction behaviour at test condition 2: 50 N, 1 rpm and 50min (a) RT and (b) 95 °C

Test Condition 3: Tests at higher load and longer test duration were also carried out (200N, 1rpm, and 3hrs). Higher load was chosen so that for some of the test samples (especially A3) the thin top overlay is worn and the second overlay is exposed. As shown in Fig. 8 A1 has higher COF. At room temperature, stick-slip phenomenon occurs on the Al-Sn based lining. However, at 95 °C, stick-slip was observed only at early stage of the

test. Tin has lower hardness than Aluminium and it becomes softer as temperature increases [14]. Softer Sn can easily be squeezed out of the Al matrix and modifies the layer.

However, A2 possesses the lowest COF which might be attributed to the MoS₂ particles which are exposed under the applied load. MoS₂ is well known for its lubricity [15]. For A3, an increase in friction shows that after some time the PAI based overlay is worn out. Once the PAI based top overlay is worn, COF becomes similar to that of A1 which is also an Al-Sn based bearing alloy. At room temperature, stick-slip phenomenon occurs once the Al-Sn overlay of A3 is exposed. B1 exhibits intermediate friction behaviour.

Figure 8: Friction behaviours at test condition 3: 200N, 1rpm and 3hrs (a) RT and (b) 95 °C

3.5 Wear behaviour

Wear of the test samples was quantified in terms of wear scar width and the results are shown in Fig. 9. B1 which has a Pb-based overlay exhibited the highest wear among the tested samples. Wear resistance the Pb-based overlay is associated with its lower hardness. Compared with B1, Al-Sn based overlay materials of A1 and A3 with higher hardness show better wear resistance. However, A2 which has a PAI overlay containing graphite and MoS₂ has better wear resistance than the other test materials.

Figure 9: Wear scar width for tests at (a) RT and (b) 95 °C. Wear scar of test sample B1 is shown in Fig. 10 (a). It is characterised by a pattern of dark patches. The appearance of microgrooves and non-uniform wear

becomes visible after the soft overlay is worn. There is pile up of mechanically deformed material in the sliding direction as shown in Fig. 10 (b). This pile up of displaced material is attributed to the lower hardness of the Pb-based overlay. There is also material removal in the vicinity of the highly loaded area. Some flaked materials and surface damage can also be seen in Fig. 10 (c) and (d).

Figure 10: SEM images of sample B1 (a) full wear scar (b) pile ups on the edge of wear scars (c) and (d) materials removed due to fatigue damage.

Backscattered images of the worn surface show that the composition of the dark patches is different from that of the original surface as shown in Fig. 11 (a) and (b). EDS analysis of the dark areas has shown that the composition of the dark compound layer is mainly Ni, Cu and Sn. Similar type of compound layers were also reported earlier by other researchers [16]. The formation of a dark compound layer initiates at the highly loaded peaks of the microgrooves.

Figure 11: SEM images of B1: a) dark material in highly loaded peaks of microgrooves and b) higher magnification of dark materials.

SEM images of worn surfaces of test sample A1 are shown in Fig. 12 (a), (b) and (c). The distribution of Sn on the worn surface is different from that on the original surface. The surface is modified and a mixed layer is formed. This occurs because the Sn soft phase can be mechanically squeezed out and sheared at higher load [9]. EDS analysis at different points on the worn surface shows that there is considerable amount of Sn mixed with the Al matrix all over the worn surface. There is also

material removal from the worn surface as shown in the SEM images in Fig. 12 (d). This usually occurs when Al based materials slide against steel. However, the extent of material transfer is reduced due to the mixing of Al with the soft Sn. There was no trace of transferred Fe from the counter surface.

Figure 12: SEM images of sample A1 (a) full wear scar (b) boundary between the original and worn surfaces (c) middle of worn surface and (d) material removed on worn surface.

For A2, the boundary between the original and worn surfaces is not as obvious as the other test samples. However, the worn surface is a bit brighter than the original surface as shown in Fig. 13 (a). As shown in Fig. 13 (b), on the worn surface, the MoS₂ particles are exposed. There are no signs of detached material on the worn surface. There is damage on the MoS₂ particles in the form of cracking as shown in Fig. 13 (c). Unlike the other metallic materials, the worn surface consists of coarse feature and granular structures. These surface features can act as oil reservoir and improve lubrication.

Figure 13: SEM images of A2 (a) full wear scar (b) exposed MoS₂ particles on worn surface (c) cracks on MoS₂ particle.

For sample A3, SEM images in Fig. 14 (a) and (b) show that the top overlay is worn and the intermediate overlay is exposed. This resulted in an increase in friction as

shown previously in Fig. 8. The initial friction coefficient value of 0.7 was observed when the original PAI-based overlay was intact. However, when this overlay is worn the intermediate Al-Sn based overlay is exposed and leads to an increase in friction. This increase in friction is not sharp. Even though the Al-Sn overlay is exposed, the counter surface is in contact with both the Al-Sn based overlay and the top PAI-based overlay since test samples are curved.

Once the Al-Sn overlay is exposed there is a mechanically modified surface which resulted in mixed layer formation as shown in Fig. 14 (c). The soft Sn phase is not separately seen as it is smeared over the surface. EDS analysis at different points on worn surface of A3 confirmed that there is mixing of Al and Sn and there was no material transferred from the counter surface.

Figure 14: SEM images of sample A3 (a) full wear scar (b) boundary between the original and worn surfaces (c) middle of worn surfaces showing mixed layer formation.

4. CONCLUSIONS

- At both RT and 95 °C, for Al-Sn based lining (A1) and Pb-based overlay materials (B1), the decrease in COF is sharp as sliding speed increases. For PAI based overlay (A2), the decrease in COF as sliding speed increases is slow and are significantly different at RT and 95 °C.
- Al-Sn based lining (A1) with no overlay has higher friction but better wear resistance than Pb-containing bearing material (B1). Similar friction behaviour was also observed for Al-Sn based overlay (A3) after the top PAI based material is worn.
- At higher load, friction behaviour of Al-Sn based lining (A1) and intermediate overlay (A3) is affected by temperature. The degree of stick-slip is higher at RT compared to 95 °C.
- At lower sliding speed, PAI based overlay containing MoS₂ and graphite shows lowest friction and has better wear resistance than Pb-based and Al-Sn based materials.

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