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Load capacity of lubricated bismuth bronze bimetal bearing under elliptical sliding motion

V.T. Oksanen[a,*], A.J. Lehtovaara[a], M.H. Kallio[b]

[a] Group of Tribology and Machine Elements, Laboratory of Materials Science, Tampere University of Technology, P.O. BOX 598, 33101 Tampere, Finland
[b] Metso Minerals, Inc., P.O. BOX 306, 33101 Tampere, Finland

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ABSTRACT

Leaded tin bronze alloys are widely used in heavy machinery bearings operating in boundary and mixed lubrication regions due to the excellent dry lubrication properties of lead. However, restrictions on the use of lead have created an increasing demand for lead-free or low-lead bearing materials. In the present study, suitability of a novel bismuth bronze bimetal material for possible substitution of leaded tin bronze was studied with a special thrust bearing test device, which simulates the contact conditions in the main thrust bearing of mineral crushers. The oil-lubricated test bearings have a flat-on-flat type contact with oil grooves and a constant eccentric motion against a case hardened steel counter plate under a periodically increased axial pressure. The test was continued until a sudden rise in friction, which indicates bearing failure and risk of an imminent seizure. The bismuth bronze showed a load capacity of the same level with the reference material, continuously cast CuSn10Pb10. Characterization by electron microscopy showed that the dry-lubricating bismuth precipitations had a fine grain size and an even distribution, which explains the good load carrying capacity. It was concluded that the bismuth bronze has potential for substituting the leaded tin bronzes in the studied operating conditions.

1. Introduction

Leaded tin bronze alloys are widely used in heavy machinery bearings operating in boundary and mixed lubrication regions due to the excellent dry lubrication properties of lead. One such application is the thrust bearing supporting the main shaft in mineral crushing machines under harsh operating conditions. The emergency dry-lubrication property of leaded bronze bearings is based on insolubility between lead and copper. Instead of forming solid solution with the copper-rich base, the lead forms precipitations. The lead is soft and has a low melting point, due to which it is easily spread under asperity contacts, during which local flash temperatures sufficiently high for melting the lead occur [1]. The smearing lead tribolayer prevents further asperity contacts between the harder bronze matrix and the counter surface.

Prasad [2] proposed conditional requirements for efficient dry-lubrication in leaded tin bronzes. Dry sliding tests with pin-on-disc test device showed that, at slow sliding rates, wear of the bronze is dominated by microchipping leading to removal of large debris. At higher sliding velocities, frictional heat will promote smearing of the lead on the contact surfaces, and further, inhibits the microchipping. Instead, the bronze surface will deform strongly, forming a strain-hardened layer, and the wear rate decreases [2].

Similarly to lead, bismuth has a low hardness and a low melting point, and furthermore bismuth is not hazardous on environment or health, rendering it a potential alloying element to substitute lead in bronzes. Studies on mechanical and tribological testing of bismuth bronze alloys have been published for example by Sahu [3] and Thomson et al. [4]. Thomson et al. [4] produced bronzes with 5 wt% Bi and 10 wt% Sn, 10 wt% Bi and 10 Wt % Sn, and 10 wt% Pb and 10 wt% Sn. The lead bronze and the bismuth bronze showed somewhat globular morphology of the soft phase, whereas the bismuth precipitations in the alloy with 10% bismuth have a more elongated form. The traditional leaded tin bronze showed better mechanical properties and lower friction force in lubricated block-on-ring tests. The lead precipitations of the reference bronze had micro hardness 11 HV, whereas the bismuth precipitations of the bronzes with 5 wt% and 10 wt% Bi had micro hardnesses of 30–40 HV and 24–25 HV, respectively, which explains the difference in the friction. However, the bismuth tin bronzes had higher wear rates, indicating better conformability, and less fluctuating frictional behaviour [4].

The bismuth tin bronze with 10% Bi showed lower friction force than that with 5% Bi, but also suffered from interconnected shrinkage porosity and bismuth precipitation on the grain boundaries of the

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[*] Corresponding author.
E-mail address: ville.t.oksanen@tut.fi (V.T. Oksanen).

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matrix. The shrinkage porosity had similar morphology to that of the bismuth precipitations, i.e. somewhat elongated. The shrinkage porosity was observed to affect ultimate tensile strength, elongation and fatigue strength adversely [4]. Increasing size and irregularity of the morphology of the pores are known to aggravate these adverse effects. Porosity may, however, also have positive effect on tribological behaviour by functioning as reservoir for a liquid or solid lubricant. Controlled, interconnected porosity is utilized for example in self-lubricating journal Cu-Sn bearings produced by powder metallurgy [5].

Bismuth is known to be prone to form grain boundary phases detrimental to the mechanical properties of copper-bismuth alloys. Plewes and Loiacono [6] found tin to be the best alloying element for preventing the bismuth precipitation on the grain boundaries. In tribological studies by Yin et al. [7], 3.0 wt% was found to be optimal bismuth content for bimetal bronze bearings operating under boundary lubrication.

In addition to bulk materials complex multi-layer solutions for hybrid bearings have been studied. Gebrestadik [8,9] et al. compared tribological performance of various multilayer bearings for automotive engines under mixed and boundary lubrication conditions with a block-on-ring test device. Nilsson and Prakash [10] also describe sliding bearing test device operating under dry contacts and all lubrication regimes.

Ruusila et al. [11] studied the effect of lead content and the microstructure of tin bronzes on tribological properties in dry and boundary lubricated sliding contacts. Copper alloys with different lead contents (0–20 wt%) and produced by different casting methods were studied. In dry-sliding pin-on-disc tests, continuously cast leaded tin bronzes with fine microstructure had the lowest coefficients of friction but also the highest wear rates, due to wear mechanism dominated by microcrack initiation on the phase boundaries between lead and the copper matrix. In the pin-on disc test, the material removal rate was too high for efficient dry-lubrication. As an optional method for testing the dry-sliding conditions, ball-on-disc tests were carried out. In the ball-on-disc tests, the continuously cast leaded bronze showed a low wear rate and a low friction in comparison to lead-free tin bronze CuSn12. The authors concluded that in contrast to the pin-on-disc tests, the dry-lubrication was effectively present in the ball-on-disc tests [11].

Liu et al. [12] present tribological study on graphite containing leaded tin bronze bimetal under reciprocal ball-on-disc sliding test. CuSn10Pb10 bimetal layers with various graphite mass fraction from 1 wt% to 8 wt% were manufactured on steel substrate by powder metallurgy. 3 wt% graphite produced the lowest wear rate of the bearing material and the lowest fluctuation in the coefficient of friction during the test. The minimum of the average coefficient of friction was achieved at 2 wt% carbon, and further additions of carbon did not affect it. The authors concluded that increasing amount of graphite in the bronze decreases the surface hardness, and consequently the bearing surface cannot support the tribofilm, leading to further asperity contacts [12].

Although some research on the bismuth bronzes has been reported, information on their bearing test performance is scarce. Furthermore, extensive tribotesting with block-on-ring, pin-on-disc and ball-on-disc set-ups has been reported, but component level testing for thrust bearings and other bearings operating under severe conditions has not been published on large scale. Previously, the test device utilized in the present study, has been used for evaluating potential thrust bearing materials by Ruusila et al. [11,13], and Kallio et al. [14].

In continuation to the pin-on-disc and ball-on-disc presented above [11], Ruusila et al. [11] carried out thrust bearing test for copper alloys with various lead contents and microstructures. Minimum of 4 wt% of evenly distributed lead in the tin bronzes was considered to provide a good bearing performance. According to the authors, the tendency for crack initiation at the lead/matrix phase boundary was beneficial in the boundary-lubricated conditions. Coarse-structured, sandcast low-lead alloy CuSn10Pb4 showed slightly inferior performance to that of the same alloy with fine microstructure formed by continuous casting. Increased amounts of lead improved the load capacity of the bearings only slightly, as did the casting method in the case on high-lead alloys. According to the authors, above certain level of composition, the increased lead content affects mostly the precipitation size of lead while the amount of precipitations stays almost constant. The amount of the lead precipitations, and consequently the probability for an asperity contact to cause crack initiation at the lead/matrix interface, is the dominant feature affecting the ability of the material to enable local dry-lubrication. The lead-free alloys CuSn12 and CuSn10Zn2 showed inferior performance to all the leaded tin bronzes, which emphasises the importance of the presence of a dry-lubricating phase in the boundary lubricated conditions [11].

Kallio et al. [14] reported performance of bismuth bronzes CuSn10-Bi4 and CuSn6Bi6 in the thrust bearing tests. The bismuth bronzes showed very similar microstructures to those of the reference materials used, leaded tin bronzes CuSn10Pb10 and CuSn10Pb4, but with bismuth precipitations instead of lead. In both leaded and bismuth tin bronzes, the surfaces experienced similar dry-lubrication mechanism through strong deformation and initiation of crack at the phase boundaries between the matrix and the lead precipitations, through which the dry-lubricating phases could spread onto the contact surfaces. However, the studied bismuth bronzes showed poor bearing performance, having both low load capacity and high coefficient of friction. The authors concluded that bismuth was not as good dry-lubricant as lead in the tested alloys [14].

In addition to bulk bronzes, thrust bearing performance of lead-free braze claddings with dry-lubricating graphite inclusions have been studied [13,14]. Some braze cladding types have shown good potential in the thrust bearing test.

In this study, the suitability of an experimental bismuth bronze bimetal for thrust bearing applications was evaluated by the test device presented in the previous work [11–15]. In addition, material characterization and studies of the wear mechanism were carried out. The material test performance and the characterization findings were compared with those of continuously cast CuSn10Pb10.

2. Materials and methods

2.1. Thrust bearing test device

The thrust bearing test device has been described in previous work by Pasanen et al. [15] and Ruusila et al. [11,13]. For clarity, an overview of the test device is given here. The device simulates the main shaft thrust bearing operation in boundary and mixed lubrication conditions in mineral crushing machines. Fig. 1 presents the test chamber. In the test, a planar thrust bearing and a steel counter plate slide against each other on an elliptical trajectory under an axial pressure in oil lubricated conditions. Pure rotation of the test bearing and the counter plate are prevented by fixing bolts and slot presented in Fig. 1. The wear marks on the counter plate surface in Fig. 2b illustrate the elliptical sliding motion at the test interface caused by the eccentric motion of the test bearing. The loading pressure is produced by pressing the counter plate hydraulically against the test thrust bearing. The support sleeve of the counter plate is pivoted to the top of the hydraulic cylinder resulting in a parallel test interface.

During the test, the electric motor used for power transmission was run at 1592 rpm and the eccentricity throw i.e. amplitude was 3 mm, resulting in a sliding velocity of 0.5 m/s. Lubrication was carried out with gear oil ISO VG 150 with EP additives and it was held at a flow rate of 1.00 ± 0.05 l/min, including the lubrication for the test bearing contact and for the support bearings. The oil inlet pressure was kept below 0.08 MPa to prevent hydrostatic lubrication condition. In addition to the above-mentioned parameters, torque loss of the test system and temperature of the counter plate were measured. The coefficient of friction for the test contact cannot be determined directly because