LEADED TIN BRONZES: THE EFFECTS OF CASTING METHOD ON DRY SLIDING BEHAVIOUR

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ABSTRACT

In metal-to-metal sliding bearing applications, leaded tin bronzes are widely known as materials with excellent seizure resistance. In conditions of boundary or dry lubrication, lead may smear across the sliding surface, preventing surface contact and catastrophic seizure. The aim of this study was to determine the effects of casting method on the dry sliding behaviour of leaded tin bronzes. Continuous cast, centrifugally cast, and sand cast leaded tin bronze samples with varying lead contents were subjected to pin-on-disk-testing. It was found that casting method has a significant effect on the wear behaviour of leaded tin bronzes in dry sliding conditions. With continuous cast samples, the dominant wear mode was rapid, stable microcracking along copper/lead interfacial boundaries. With centrifugally and sand cast samples, wear occurred more slowly and erratically through the formation of transfer layers. The dominant wear mode was found to be connected to the coarseness of the distribution of lead particles in the copper matrix.

INTRODUCTION

Seizure occurs when two metal surfaces sliding over one another become adhesively linked together to the extent that relative movement is no longer possible. The seizure of bearing components leads to an interruption in production cycles as individual components have to be replaced. At worst, it can cause the complete breakdown of large, complex and expensive machinery. The costs associated with the seizure of bearing components are large enough to make it a phenomenon to be avoided in any circumstances. Usually direct metal-to-metal contact and seizure is prevented by a lubricant layer between the surfaces. In boundary lubrication conditions, such as bearing applications involving high loads and slow sliding speeds, lubricant layers may easily fail, however.

Leaded tin bronzes have excellent tribological properties in boundary lubrication conditions. Lead exists as distinct separate globules in the tin bronze alloy. At times when normal lubrication is absent or impaired, lead facilitates the creation of a layer of solid lubricant. The lead-enriched layer separates the sliding surfaces from one another, preventing direct contact. The leaded tin bronze CuSn10Pb10 is a feasible material for use in bearing applications where lubrication may fail.

The application of lead may be restricted in the European Union in the future because of growing environmental and recyclability concerns, which is why new seizure-resistant materials need to be eventually developed to replace leaded tin bronzes. In order to do this, the mechanisms behind the seizure-resistant qualities of the material need to be understood. Despite numerous studies, these mechanisms remain relatively unclear.

It has been suggested that lead simply smears across the sliding surface as an extremely thin film [1]. The lead enriched surface layer then adheres to the counter surface, forming a transfer layer that prevents direct contact between the bearing surfaces. The effectiveness of smearing depends on a number of factors, such as sliding speed and contact pressure.

More recent studies [2] have also hypothesized that in situations where direct smearing is impossible (such as on roughly finished surfaces), wear particles detached from the leaded tin bronze alloy cause a kind of selective wear to occur. The lead-enriched copper wear particles smear and adhere to the sliding surfaces easily, remaining trapped in the contact area. The lead-enriched wear particles then prevent direct contact between the sliding surfaces.

The incoherent lead globules in the matrix may also have detrimental effects on wear behaviour. Prasad et al. [1, 3] state that high wear rates caused by microcracking along weak copper/lead matrix boundaries are a common occurrence especially at sliding speeds below 0,5 m/s. It is clear that the effect of lead on tribological behaviour is a complex phenomenon that cannot be explained in a simple manner.

The lead globules are supported in a dendritic fcc copper α-matrix containing tin in solid solution. During casting, tin segregates to interdendritic areas and grain boundaries, forming particles of hard and brittle α+δ eutectoid. The amount and distribution of this secondary phase is largely determined by the cooling rate of the solidifying alloy during casting. Faster cooling rates lead to a finer dendritic structure and a greater amount of the hard and brittle eutectoid in the solidified alloy. The distribution and size of the lead globules is similarly affected by casting method [4]. While the effects of the eutectoid and lead phase on the mechanical properties of leaded tin bronze are well known on a general level [5], there is little data available on the effects of the size, distribution and relative amount of each phase on the tribological performance of the alloy.

The aim of this study was to find out the effects of the casting method of leaded tin bronzes on wear behaviour in dry sliding conditions. Pin-on-disk testing was used to determine the wear performance of leaded tin bronzes with varying lead contents cast with various casting methods.

It should be remembered that pin-on-disk testing represents a dry sliding contact situation, a condition that is extremely undesirable in bearing applications. It doesn't give direct information about the ability of the material to maintain a lubricant film in boundary lubrication conditions. The most desirable property of leaded tin bronzes is the ability to resist seizure in boundary lubrication conditions, however. In these situations contact between sliding surfaces inevitably happens. It is therefore important to know the mechanisms that leaded tin bronzes exhibit in dry sliding contact, if the seizure-resistant properties are to be developed in other materials.

EXPERIMENTAL PROCEDURE

The pin-on-disk tests were conducted with a cylindrical pin fabricated from leaded tin bronze pressed against a rotating steel counter plate. The test setup is shown schematically in Figure 1.

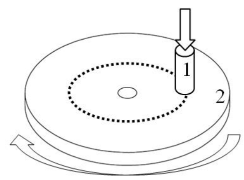

Figure 1. A schematic of the pin-on-disk test setup.

The experiments in this article were conducted on the commercial tribometer UMT-2 manufactured by CETR. The tests were conducted at Tampere Wear Center (TWC) of the Tampere University of Technology.

The normal force and sliding speed in the pin-on-disk tests were 60 N and 0,5 m/s respectively. The 60 N normal force corresponds to a nominal surface pressure of approximately 2 MPa with a 6 mm diameter pin.

The testing of each specimen consisted of five test runs, each 10 minutes in length. After each run, the specimen was weighted to determine wear as mass loss. The normal force and friction force were recorded continuously during test runs with a 2D force sensor. Average friction coefficients could be calculated from this data.

Six leaded bronze materials cast with different casting methods and varying lead content were tested. Three pin specimens were created from each sample material. Table 1 lists the tested materials and casting methods.

The counter plates were machined from 34CrNiMo6 steel with a hardness range of 240-270 HV. The surface roughness (R_a) of the counter plates was in the range of 0,4 - 0,5 μm. Prior to testing, the plates were cleaned with acetone to remove traces of oil and grease. The heads of the pins were ground with P600 silicon carbide paper and similarly cleaned before testing.

Cross-sectional samples were prepared from worn pin specimens and characterized with the Philips XL30 scanning electron microscope (SEM). The SEM was equipped with the EDAX DX-4 energy dispersive spectrometer (EDS).

RESULTS

The results presented in the following are roughly divided into two sections. First the results of the tribological testing are shown. After that the results of the materials characterization of the pin cross-sections will be discussed.

Figure 2 presents the wear results as the average value of the amount of total mass loss in the tests for each sample. The error bars represent the standard deviation of the results.

It was found that continuous cast samples had a significantly higher wear rate compared to sand cast and centrifugally cast samples. Figure 2 shows that the total mass loss of the continuously cast samples was an order of magnitude higher than either the sand cast or centrifugally cast samples. The effect of the lead content on the wear behaviour of the samples was considerably smaller.

The wear of the continuous cast samples was regular and steady, whereas the sand and centrifugally cast samples showed highly irregular wear. The friction coefficients measured during the tests reflect this behaviour: the continuous cast samples had a stable steady-state friction coefficient while the sand cast and centrifugally cast samples had an unsteady, constantly changing friction coefficient. Examples of the evolution of friction coefficients between a sand cast and continuous cast leaded tin bronze are shown in Figure 3.

Figure 3 shows that with the continuously cast sample, the coefficient of friction reaches a steady state almost immediately, whereas the sand cast sample does not reach a steady state at all. The coefficient of friction is also significantly higher for the sand cast alloy. The friction behaviour of the centrifugally cast alloy was similar to the sand cast alloys.

Table 1. The casting methods of the studied materials.

	Sand casting	**Continuous casting**	**Centrifugal casting**
CuSn10Pb4	X	X	
CuSn10Pb10	X	X	X
CuSn10Pb15	X		

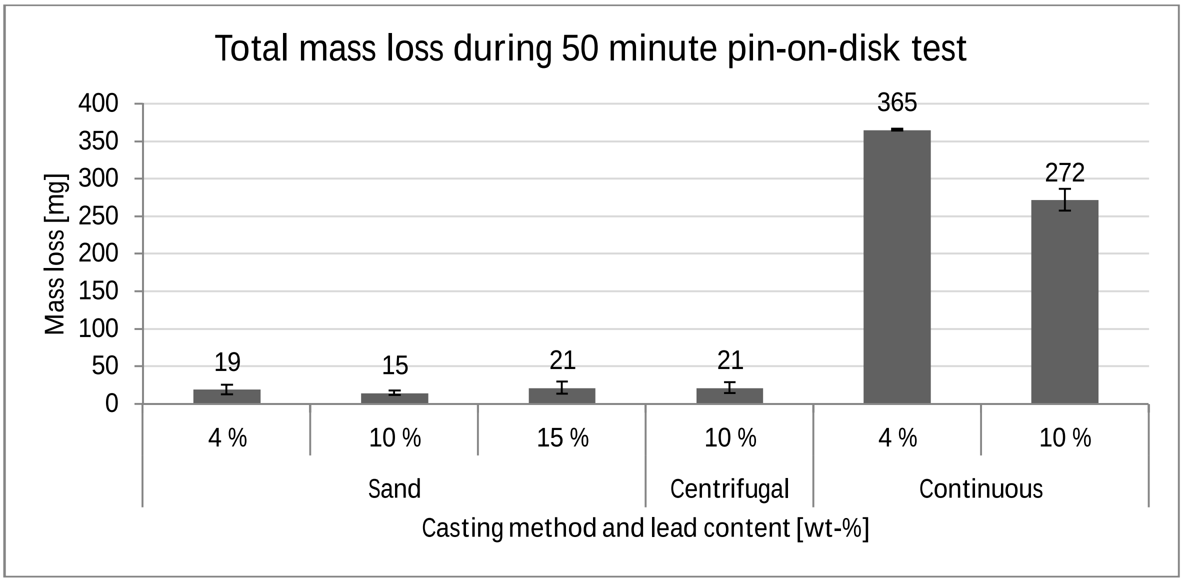

Figure 2. Total mass loss in the pin-on-disk tests.

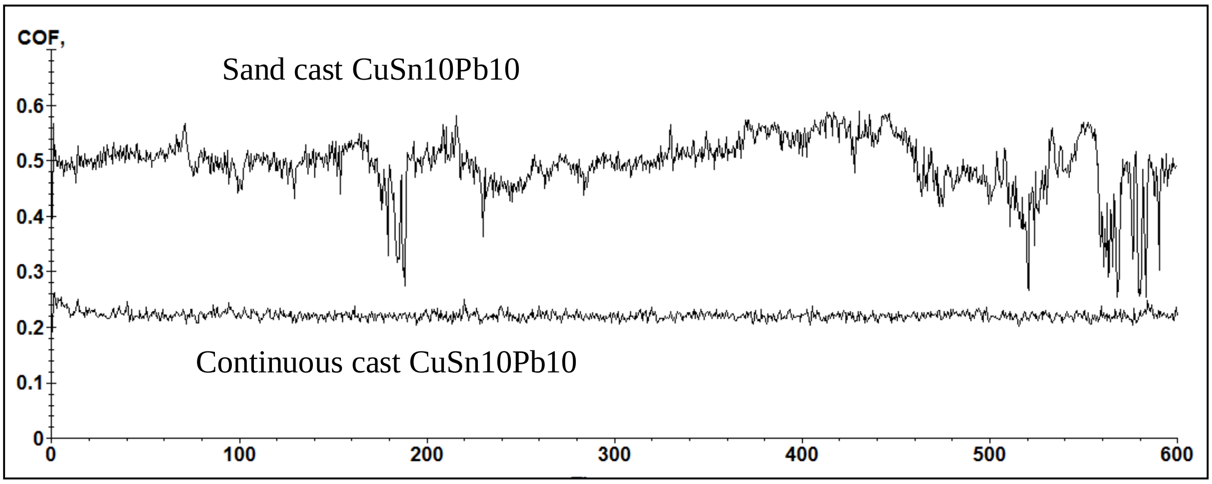

Figure 3. The evolution of the coefficient of friction for sand cast and continuous cast CuSn10Pb10 during a single test run.

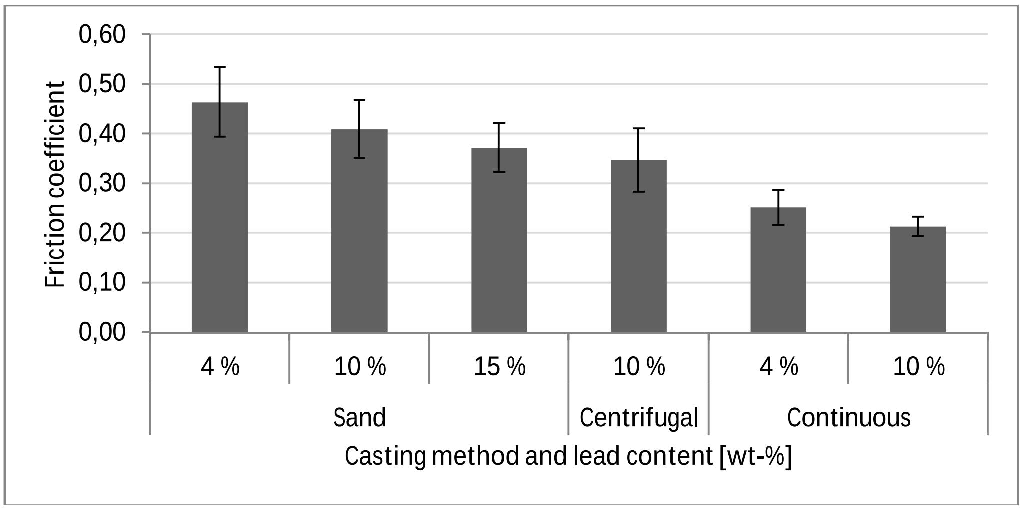

Figure 4. The averages of the friction coefficients in the tests.

The average values of the friction coefficients in the tests are shown in Figure 4. It should be remembered that in the case of sand cast and centrifugally cast alloys, the average value of the coefficient of friction does not give an accurate picture of the friction behaviour of the material. This is reflected by the large standard deviation in the results, shown as error bars in Figure 4.

The results of the pin-on-disk tests were clearly divided into two categories. The sand cast and centrifugally cast samples exhibited slow wear rates associated with a high, irregular friction coefficient. No steady state behaviour of friction or wear was achieved. The continuous cast samples, on the other hand, reached a steady state of wear and friction almost immediately. The steady state was associated with very high wear rates and a low, steady friction coefficient.

Cross-sectional samples were manufactured from the pin specimens and examined with a scanning electron microscope to determine the possible wear mechanisms.

Figure 5 shows examples of surface structures found in the sand cast samples. The sliding direction is from right to left in the images. Distinct surface layers can be detected on the surface of all samples in the images. In the images, the lead phase shows as white globules, the hard eutectoid phase as light gray areas, and the fcc copper matrix as darker gray areas.

It was found in an EDS spot analysis that the layers in the images in Figure 5 contain elements from both the bronze pin and the steel counter plate. In addition to copper, tin and lead, traces of iron and oxygen were found in all of the layers. The layers in Figure 5 can therefore be characterized as transfer layers.

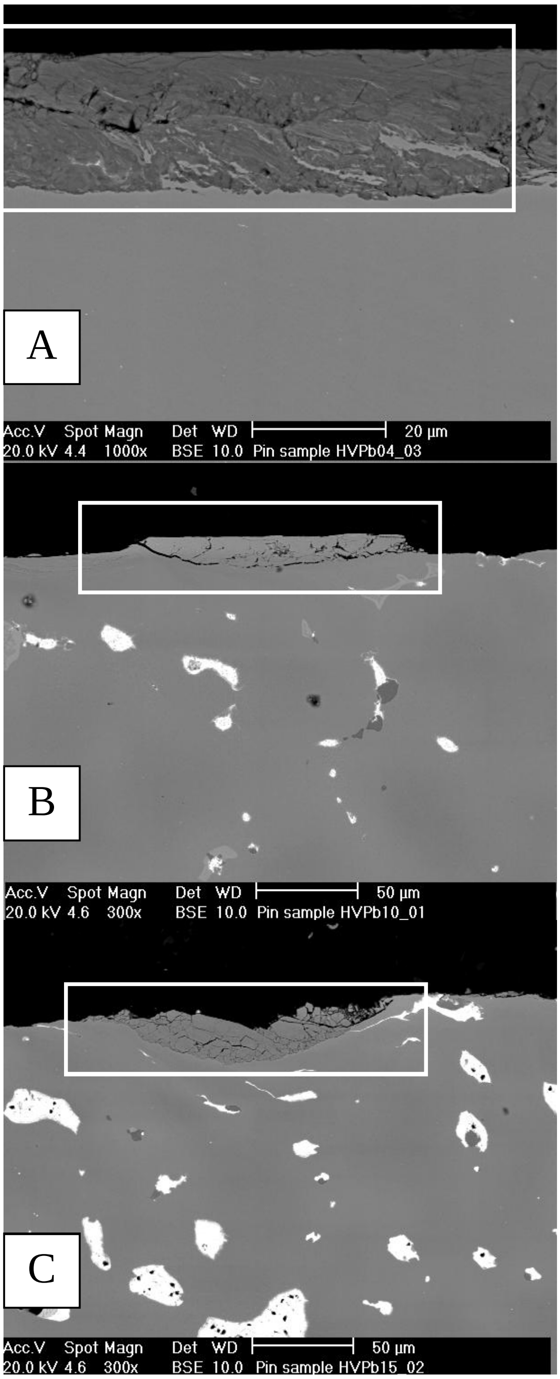

Figure 5. SEM BSE images of distinct layers found on the sand cast samples. A: CuSn10Pb4 B: CuSn10Pb10 C: CuSn10Pb15

The centrifugally cast sample CuSn10Pb10 also had several distinct films on its sliding surface. An example of such a film is shown in Figure 6. An EDS spot analysis showed that the films in the centrifugally cast sample contained oxygen but no elements from the steel counter plate.

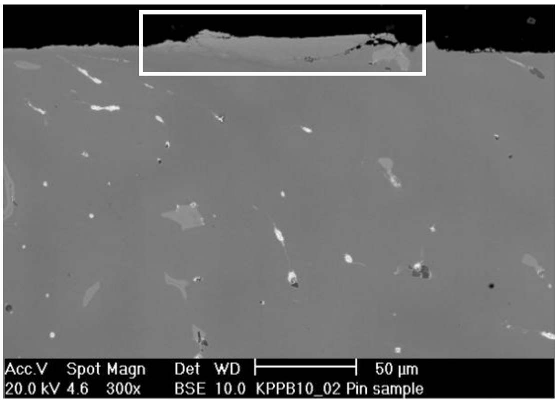

Figure 6. A SEM BSE image of a surface film on the centrifugally cast sample CuSn10Pb10.

It can also be seen from Figure 6 that the centrifugally cast sample exhibited somewhat heavier deformation of the immediate surface area. This can be seen from the clearly distorted lead globules near the surface.

The continuous cast samples had a significantly different surface structure from the sand and centrifugally cast samples. Figure 7 shows typical surface structures encountered in the continuous cast samples.

Heavy deformation can be detected immediately under the sliding surface as the free lead globules have clearly been distorted under strain. Several microcracks can also be detected propagating along the lead / copper matrix interfacial boundaries. Lead can clearly be seen to have squeezed along the propagating fracture, coating both fracture surfaces. Similar microcracking can also be seen in Figure 6, although it is considerably more limited compared to the continuous cast samples.

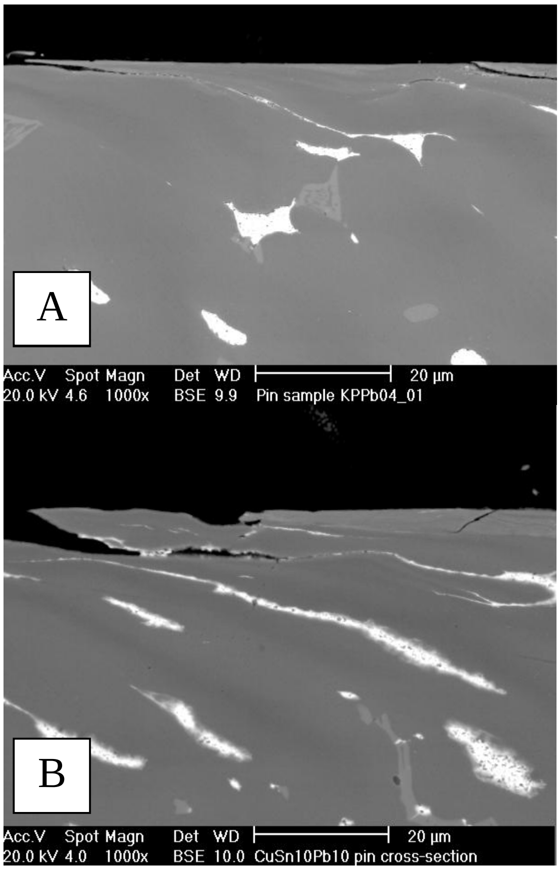

Figure 7. A SEM BSE image of microcracks in the continuous cast samples. A: CuSn10Pb4 B: CuSn10Pb10

Image analysis was used to determine the lead particle population densities and average particle sizes in all sample materials. The results of the analysis are shown in Figure 8. The Figure shows that the continuous cast materials have noticeably higher amounts of separate lead globules than either the sand or centrifugally cast materials.

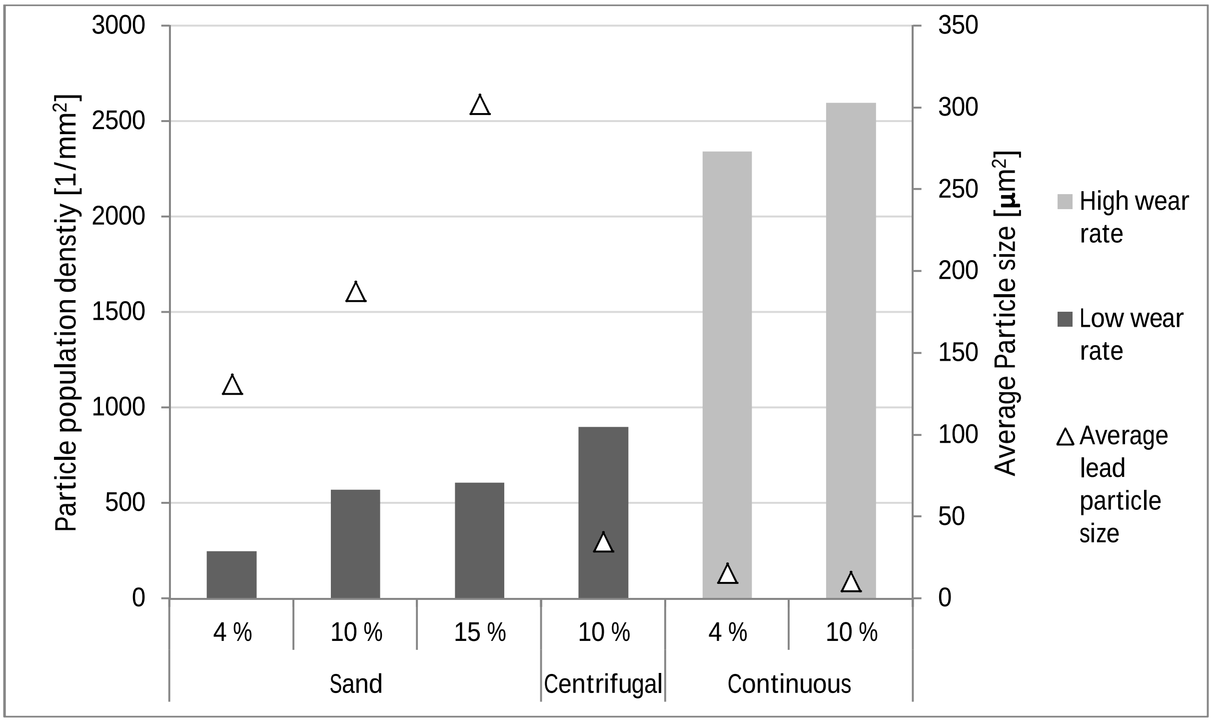

Figure 8. Lead particle population densities of the tested alloys.

DISCUSSION

Pin-on-disk testing has given new insight into the contact mechanisms of leaded tin bronzes. It appears that there is a competition between at least two contact mechanisms in dry sliding conditions: transfer layer formation and rapid wear through microcracking.

The microcracking tendency dominates when the distribution of lead in the alloy is very fine and the lead particle size is small. This is the case with continuous cast alloys. The fine lead particles have two effects on the sliding contact situation. Firstly, the lead particles cause discontinuities in the copper matrix of the alloy, limiting the movement of dislocations and therefore causing limited deformation in a small volume near the sliding surface. Secondly, the weakness of the interfacial boundary between lead and the surrounding copper matrix promotes the nucleation of microcracks at these boundaries. The high deformation near the surface causes the microcracks to rapidly propagate, leading to microfracture and the release of small wear particles. This type of wear behaviour has been observed in numerous studies by Prasad et al [1, 3].

Both the released particles and the fracture surface are covered by a thin layer of lead, limiting contact and the amount of adhesion between the sliding surfaces. This is in accordance with the theories of Equey et al. [2], who state that the wear particles of leaded tin bronzes may have a role in preventing seizure.

The sand cast and centrifugally cast alloys exhibit a distinctly different dominant wear mechanism. Alloys cast with these methods have a considerably coarser distribution of lead. The movement of dislocations is therefore less inhibited and so the deformation of the sliding surface occurs at a larger area. The large size and small number of the lead globules means that there is less lead/copper interface boundary area and therefore less chance for microcrack nucleation. The tendency to microcracking and rapid wear particle generation is then suppressed in favour of transfer layer formation. Small particles are released from both surfaces as the result of adhesion and are mechanically mixed together to form a new layer between the surfaces. The temperature of the forming transfer layer is high, resulting in oxidation.

The two mechanisms may be active simultaneously. The centrifugally cast alloys exhibited both types of wear mechanisms. The size and distribution of the particles in the centrifugally cast alloy were in between the sand and continuous cast alloys.

CONCLUSIONS

The casting method of leaded tin bronze alloys has a significant effect on wear behaviour in dry sliding contact. Continuous casting produces a fine lead distribution that promotes microcracking and rapid, stable wear with low friction, while sand casting produces a coarse microstructure that promotes the formation of transfer layers. Wear is slower in this case, but the value of the friction coefficient is considerably higher.

Increasing the lead content of the alloy appears to decrease the friction coefficient. In the case of continuous cast alloys, increasing the amount of lead also appears to lower the wear rate of the alloy.

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