The present study describes the tribological properties of a bronze alloy used as a sliding interface for operation under dry conditions. Many industrial slide bearings are made from bronze alloy. To achieve easy running-in and enhanced anti-seizure, solid lubricants are added to the alloys. However, it is difficult to simultaneously achieve easy running-in and anti-seizure with one solid lubricant. Thus, the combined effects of a solid lubricant and a dispersed sulfide layer on reducing and stabilizing the friction coefficient were also examined. The tribological properties of the resulting alloy were evaluated with a 3-ball on disc type testing apparatus under dry conditions and in air atmosphere. The surface state of the solid lubricant and dispersed sulfide layer was evaluated by observation of the morphology and phase states via atomic force microscopy. Distinctive features of a phase comprising mixed stiff and soft regular regions on the micrometer scale were observed. These two regular regions are considered to be formed from graphite and sulfide by burnishing. The effect of the dual phase state leads to achievement of both easy running-in and anti-seizure.

Keywords: bronze, sulfide, sintering, shot peening, burnishing, atomic force microscopy

1. Introduction

The present study describes the tribological properties of a bronze alloy used as a sliding interface for operation under dry conditions, such as that employed in the guide-way of a press machine or the working surface of a valve. For such equipment, achievement of easy running-in and anti-seizure is desirable to extend the lifetime of the products. Surface texturing is one of the key techniques used to enhance the properties of the products. In the texturing field, microgrooves are well-known as bimetal sintering bearings for automotive applications [1]. Specifically, the tops of the ridges between grooves are easily deformed and worn. Because of the high flow rate of the lubricant along the grooves, only a small increase of the bearing temperature occurs. Thick lubricant films are kept towered to the width of the bearings to prevent low side leaks of the lubricants.

As an example, a three-step study was performed in order to understand the effect of the groove pattern of a paper friction plate on its lifetime [2]. In the first step, the effect of the friction surface temperature on the lifetime of the paper friction plate was evaluated. For this test, the pressure and rotational speed were held constant, while durability tests were carried out in which the friction surface temperatures were independently changed by forced heating or cooling. The results showed that a critical value of the surface temperature exists, above which the change in the thickness of the friction paper increases rapidly, and the surface temperature rises, leading to surface damage and decay of the dynamic friction coefficient. In the second step, the friction surface temperatures for three groove patterns were directly measured and differences in the cooling effectiveness based on the groove pattern were observed. In the third step, the lifetime of friction plates with the same three groove patterns used in step two was investigated. That study concluded that a reduction of the friction surface temperature and consequent enhancement of the lifetime of the paper friction plate could be achieved by the design of an appropriate groove pattern.
Another example demonstrated that micro and/or nano scale dimples formed by laser treatment as surface texturing on sintering bimetals with copper linings enhanced the friction properties [3]. A lower friction coefficient and reduced fretting wear were realized by surface texturing the materials in the presence of a lubricant. Moreover, diamond like carbon (DLC) is also a well-known high performance coating. Sintering bimetals with copper linings with a DLC coating have also been prepared after peening with a high-frequency sonic wave [4]. The test pieces exhibited enhanced mechanical properties and better friction properties than DLC-coated bimetals without peening. On the other hand, a bronze specimen containing a micro-sized sulfide layer (called “sulfide bronze”) acting as friction modifier was fabricated by sintering [5,6] and casting. Surface modification based on a plastic deformation process near the surface via micro shot peening and roller burnishing was applied to a sintering bronze surface. This process is a kind of surface texturing. During the roller burnishing process after micro shot peening, graphite penetrated into the surface of the bronze and the sulfide bronze.

Herein, the tribological properties of bronze and sulfide bronze are evaluated with a 3-ball on disc type testing apparatus under dry conditions and in air atmosphere. A lower and stable friction coefficient and a larger critical load for seizure occurrence are demonstrated for the solid lubricant-penetrated surface. Particularly, the combined effects of the solid lubricant and dispersed sulfide layer on the reduction and stabilization of the friction coefficient are also examined. To investigate the surface state of the solid lubricant and dispersed sulfide layer, the morphology and phase states are observed by atomic force microscopy (AFM) under certain conditions where it is difficult to use an optical microscope or a scanning electronic microscope (SEM) or its optional function as an energy dispersive X-ray spectrometer (EDS). AFM analysis is major way to investigate the surface state, such as configurations, phases, etc., on the micro and nano scale. Pandey et al. found that AFM phase imaging provides a distinct contrast between graphene oxide (GO) and the underlying highly oriented pyrolytic graphite (HOPG) [7].

Phase images acquired by scanning force microscopy (SFM) also revealed substantial nanoscale morphological detail of poly-films such as polyethylene terephthalate, as demonstrated by Beake et al. [8].

These AFM studies mainly treated the surfaces of polymers. Certain studies applied the tribological approach to polymers or solid lubricants. For example, the nanostructures and mechanical properties of the surface of two kinds of tribofilm were determined by Ye et al. via AFM [9]. These two kinds of tribofilm were formed from zinc dialkyldithiophosphate (ZDDP) and molybdenum dithiocarbamate (MoDTC). Under certain sliding conditions in the pin-on-disk test, nanostrps oriented in the sliding direction were observed via phase imaging by AFM. These nanostrps acted as a solid lubricant to reduce the boundary friction coefficient of the tribofilm. As other examples, wear phenomena were observed by AFM, as reported by Samyn et al. [10] and Sikora and coworkers [11]. Sintered polyimide and graphite composite cylinders were worn in a macroscale line-on-plate test at different temperatures. The relation between the coefficients of friction and surface morphology was most adequately quantified based on evolution of the roughness parameters determined from AFM scans [10]. AFM studies of polyanazomethine with thioephene rings and ester groups were conducted and non-homogeneities in the local energy dissipation were revealed by use of phase imaging mode [11,12]. Phase contrast imaging by AFM showed promise as an effective tool for better understanding the micromechanical properties of worn surfaces [13]. This approach may provide insight into the formation of surface films and the influence of the microstructure on the friction and wear process. Bagul et al. observed the surfaces of Cu,S (x = 1.0, 1.76, and 2.0) to estimate the roughness of sulfide thin films fabricated by a solution growth technique. However, phase images were not acquired in that study [14]. Unfortunately, there are very few examples of evaluation of the surfaces after burnishing or of surfaces combining both graphite and sulfide. Thus, it is interesting to observe such surfaces by AFM, as performed in this study.

Herein, the distinctive features of a phase comprising mixed stiff and soft regions on the micrometer scale are demonstrated. These two regions are considered to be formed from graphite and sulfide by burnishing. The dual phase state leads to achievement of easy running-in and anti-seizure.

2. Experimental methods

2.1. Materials

A sintered copper-based alloy containing a sulfide phase was used as the test specimen. SEM and EDS images of the alloy are presented in Fig. 1. The specimen has pores and a micro-sized sulfide phase at the boundary region. The alloy was sintered on a steel surface. After sintering, the specimen was machined into a disc shape (44/20 mm outer/inner diameter and 8 mm in thickness). Figure 2 shows the specimen surfaces before the plastic
deformation processes. Both surfaces were polished by a rapping process. Lower roughness was observed before the plastic deformation process. Almost 4 mass% of sulfides is contained in the sulfide bronze alloy; the sulfides were well dispersed in the alloy as shown in Fig. 2(b). Surface modification based on a plastic deformation process near the surface, consisting of micro shot peening and roller burnishing, was applied to the bronze surface; the former and latter processes were used to fabricate micro dimples and to truncate, respectively.

Shot peening treatment was applied to fabricate the surface texture consisting of micro dimples. Figure 3 shows a schematic of the developed shot peening apparatus. The impact media was enclosed with rubber balls for crushing cohesive fine particles in the storage tank, and was then introduced into the inner part of the double-walled nozzle with pressurized air. The impact media mixed with air was further accelerated with more highly pressurized air from the outer part at the tip of the nozzle. Accordingly, it was possible to control the flow rate and the impact velocity of the media by adjusting the air pressure of the outer/inner nozzle individually (flow pressure: 0.5 MPa, impact pressure: 0.6 MPa). Glass beads (90 µm in mean diameter) were used as the impact media.

![Fig. 3 Schematic of micro shot peening apparatus](image)

Figure 4 (a,c) shows a comparison of the bronze surfaces before and after micro shot peening. The micro shot peening process induced formation of micro-dimples and resulted in increased roughness. After shot peening, a roller burnishing process using a lathe was applied for truncation. The details of the burnishing roller and the conditions used for burnishing are summarized in Table (1,2). The hardened alloy steel roller (1700 HV) with a diameter of 36 mm and a tip radius of 4 mm was pressed onto the specimen surface at a load of 600 N and at a contact angle of 90° under lubricated conditions and was then moved to the radial direction at a rate of 0.044 mm/rev.

A solid lubricant such as graphite was also supplied to the surface and penetrated into the dimples during the roller burnishing process. The resulting surface...
morphology comprised a patched surface composed of the penetrated lubricant in micro-size regions and the matrix bronze with a flat surface profile, as shown in Fig. 4(b,d). The density of the penetrated solid lubricant was high enough to evaluate the indentation hardness.

As shown in Fig. 4, graphite penetration occurred during peening and/or burnishing, resulting in these samples having similar surface profiles, where these samples are labeled SP in the figure (symbol: Shot Peening) and SP + B (symbol: Burnishing). The surface roughness decreased after the graphite penetration process. Most of the penetrated graphite was entrapped in the dimples and did not project from the surface. Considering the nominal surfaces (NP (symbol: no plastic deformation process) and NP + B) and the shot peened surfaces (SP and SP + B), plastic deformation seemed to occur at the surface region during burnishing.

2.2. Testing apparatus

The tribological properties of the sample were evaluated with a 3-ball on disc type testing apparatus under dry conditions and in air atmosphere, as shown in Fig. 5(a). The mated 3-balls had a mirror flat surface with a diameter of 1.5 mm, finished with polishing, and were installed at equal intervals (120°) on the same circumference (Fig. 5(b)). The applied load was gradually increased (10, 20, 30, 40, and 50 N every 1,000 m sliding distance) to evaluate the critical load for seizure occurrence. Duplicate measurements were conducted for each specimen (sulfide bronze and bronze).

3. Results and discussion

The results of the sliding tests are shown in Fig. 6. At the beginning of the test, the friction coefficient determined from duplicate analyses was between 0.3 and 0.4 for the bronze specimen. Subsequently, the friction coefficient appeared to become stable. However, seizure of the specimen occurred at 20 N in duplicate tests. It seems that graphite is effective for achieving easy running-in at lower loading. On the other hand, seizure did not occur for the sulfide bronze sample in duplicate tests. A lower and stable friction coefficient and a larger critical load for seizure occurrence were found. Herein, duplicate results are presented and the repeatability was estimated.

Figure 7 shows the surfaces of the specimens after the sliding test. Both the bronze and the sulfide bronze disc show ball tracks. However, a metal region is observed in a part of the bronze specimen, which indicates that the plastic deformed surface disappeared due to seizure. As shown in Fig. 7(c), it seems that a seizure region exists (dark gray region) for the bronze tip on the ball surface. On the other hand, although the sulfide bronze sample was plastic deformed, ball tracks were observed on the surface, as shown in Fig. 7(d). Moreover, the surface of the ball that made contact with the sulfide bronze sample had no seizure region after the test. On the surface, dark gray films were observed that might be graphite or sulfide. Thus, the sulfide bronze sample did not undergo seizure because of the complex effects of the graphite and sulfide.

<table>
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<th>Table 1 Burnishing roller</th>
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<td>material</td>
</tr>
<tr>
<td>Hardness HV</td>
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<tr>
<td>Diameter mm</td>
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<td>Curvature radius mm</td>
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<th>Table 2 Burnishing conditions</th>
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<td>Revolutions rpm</td>
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<tr>
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To investigate the surface state of the solid lubricant and dispersed sulfide layer, the morphology and phase states were observed by atomic force microscopy. Figure 8 shows the typical surface state of the bronze sample before and after the test; tapping mode was used for the observation. Comparison of the configuration image of a 2 µm × 2 µm area before and after the test shows that the highest point of the area became lower; being almost half the original height. It appears that the roughness was reduced by the sliding balls. The phase image presented in Fig. 8(b) shows bright and dark regions. The brighter regions indicate a relatively soft surface. Despite the elastic deformation processes, some areas of the surfaces were relatively soft. This might reflect the effect of graphite on the top of the surface. On the other hand, the soft surfaces were expanded by friction. This is because graphite is only effective for achieving easy running-in. However, seizure appeared to occur due to the softer surfaces.

Figure 9 shows the typical surface state of the sulfide bronze sample before and after the test. Comparison of the configuration image of a 2 µm × 2 µm area before and after the test shows that the highest point of the area became lower, as observed for the bronze specimen. Moreover, the height of the highest point is half that before the test (Fig. 9(a,c)), as observed for the bronze specimen. Nevertheless, the sliding distance was almost 2.5 times that of the bronze sample, indicating that the damage to the sulfide bronze sample was reduced. The roughness appeared to become lower because of the
sliding balls. On the other hand, peculiar phase images were observed for the surface of the sulfide bronze sample, which is thought to be due to the complex effect of graphite and sulfide, as shown in Fig. 9(b). After the elastic deformation processes, both surfaces had relatively soft and high viscosity regular regions. The two regions were well dispersed in nano-sized zones. This may be mixed graphite and sulfide resulting from the elastic deformation process. After the test, the phase image changed, as shown in Fig. 9(d). The brightness indicates that the expanse of the relatively softer region decreased and the harder region increased. It appears that seizure was prevented by the relatively hard surface after the running-in process.

As confirmation that the plastic deformation process formed soft and high viscosity regular regions, two phase images of sulfide bronze (as-sintered: Su, and with graphite: Su + C) were observed, as shown in Fig. 10. The as-sintered surface (Fig. 10(a): 1 µm x 1 µm region) showed almost single viscosity and had the same configuration as the surface of sulfide bronze after the test, which was plastic deformed before the ball on disk test, as shown in Fig. 9(d). From these results, the harder region and its configurations in the phase image shown in Fig. 9(d) were oriented relative to sulfide. Moreover, graphite was penetrated in an irregular direction on the as-sintered sulfide bronze surface. The plastic deformation process was not used here, which means that the micro shot peening and burnishing were not adjusted. Figure 10(b) shows a surface phase image of as-sintered sulfide bronze with graphite. The difference in the viscosity was relatively small, but an irregular difference in the viscosity was found. These changes relative to the as-sintered surface appear to be due to graphite penetration. However, the pressure for penetration of graphite into the sulfide bronze sample was much smaller than that of burnishing, which reached 600 N, and the direction of contact was irregular. Thus, the phase and viscosity changes were smaller and the difference in the phase became irregular relative to the plastic deformed surface, as shown in Fig. 9(b).
Thus, distinctive features of a phase comprising mixed stiff and soft regions on the micrometer scale were observed. These two regions are considered to be formed from graphite and sulfide by burnishing. The dual phase state leads to achievement of both easy running-in and anti-seizure given that the nanostrips act as solid lubricants, similar to the results presented by Ye and coworkers [9].
4. Conclusions

The present study describes the tribological properties of bronze and sulfide bronze. Surface modification based on a plastic deformation process near the sample surface, consisting of micro shot peening and roller burnishing, was applied to the surfaces.

- The elastic deformation process results in regular mixing of graphite and sulfide in the minute dispersed region.
- A lower and stable friction coefficient and a larger critical load for the seizure occurrence were observed for the solid lubricant penetrated surface.
- The combined effects of the solid lubricant and dispersed sulfide layer on reducing and stabilizing the friction coefficient was demonstrated.

References


