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Short Communication

Effects of Molybdenum Trioxide on the Tribological Properties of Aluminum Bronze under High Temperature Conditions

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The effect of molybdenum trioxide (MoO_3) on the friction and wear of aluminum bronze was studied at the temperature up to 973 K. MoO_3 powder supplied to the sliding interface between aluminum bronze and stainless steel reduced friction coefficient and wear of materials at the temperature from 773 to 973 K. Copper-molybdenum oxide was generated by sliding aluminum bronze and stainless steel in presence of MoO_3 powder at high temperature. This oxide is supposed to be $Cu_3Mo_2O_9$ from the results of XRD analysis of the friction track. The authors obtained $Cu_3Mo_2O_9$ powder by heating the mixture of MoO_3 powder and CuO powder in air. The lubricity of $Cu_3Mo_2O_9$ powder was compared with that of MoO_3 powder at the temperature up to 973 K. $Cu_3Mo_2O_9$ powder reduced wear and friction at the temperature from 773 to 973 K while MoO_3 powder could not work as lubricant at the temperature over 873 K.

Keywords: aluminum bronze, molybdenum trioxide, high temperature, $Cu_3Mo_2O_9$, solid lubricant

1. Introduction

Aluminum bronze is one of the conventional bearing materials which can be applied in the high temperature atmosphere more than 573 K because of its excellent fatigue resistance, corrosion resistance and wear resistance. However, it shows high friction coefficient and poor wear resistance due to oxidation and softening of this material at the temperature of over 673 K. In order to improve the wear resistance of the aluminum bronze bush bearing for the butterfly valve used in the exhaust brake system, which is exposed to high temperature of exhausted gas, the wear reduction effect by adding silicon and manganese particles to the aluminum bronze has been studied. The addition of silicon and manganese particles reduced wear of aluminum bronze especially at high temperature[1].

Tribological properties of many kinds of materials under high temperature condition have been studied. Although ceramics is one of the capable materials which can be used at high temperature because of their thermal stability, their lubricity and wear resistance are required to be further improved. Other possible materials used as tribomaterial at high temperature are metal oxides. The lubricity of many kinds of oxide and double oxide at high temperature has been studied and some of them showed good lubricity at high temperature. It was reported that the molybdenum trioxide (MoO_3) showed superior lubricity (friction coefficient of about 0.2) as a lubricant in the sliding between the nickel chrome alloys at about 973 K[2].

It was expected that MoO_3 enhances wear resistance of aluminum bronze at high temperature. In this paper, we report the effect of MoO_3 supplied to the sliding surface on the friction and wear of aluminum bronze under high temperature conditions and the lubricity of generated materials on the friction track.

2. Samples and experiment

2.1. Sample preparation

Aluminum bronze, C6191 (JIS H 3250), was chosen as a material under test. The compositions of C6191 are shown in Table 1. It is copper based alloy which includes about 10% aluminum and a few% iron. Stainless steel, SUS304 (JIS G 4303) was used as a counterpart material for the friction test.

Generally speaking, oxide powders are difficult to

Table 1 Compositions of aluminum bronze C6191

Content	Cu	Al	Fe	Mn	Ni
Dens., %	81-88	8.5-11	3-5	0.5-2	0.5-2

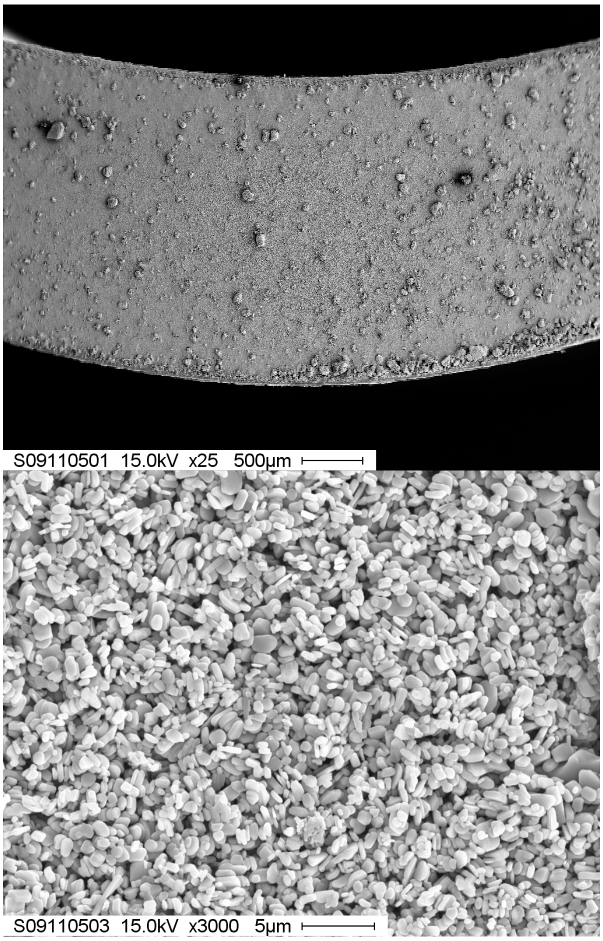

Fig.1 SEM images of the powder coated surface of ring specimens in two different magnifications

adhere to metal surface. Therefore, in this sample preparation, oxide powder was coated on the surface of stainless steel specimen by the following method. The sliding surface of specimen was polished and then slightly sandblasted. Its surface roughness was around 1.0 μm (*Ra*). It was put in the acetone in which a certain amount of oxide powder was mixed. After dispersing oxide powder in acetone by ultrasonic vibration, it was warmed up to 318 K to evaporate acetone. Finally, the oxide powder was uniformly accumulated on the sliding surface of the stainless steel specimen and this specimen was used as a powder coated specimen. The quantity of accumulated oxide powder on the specimen was estimated by measuring the weight of specimen before and after coating treatment, and was controlled to be between 5 and 6 mg. The SEM images of the coated surface of ring specimen in two different magnifications are shown in Fig. 1. As shown in these images, the surface of ring specimen was fully covered with the powders.

MoO_3 (purity 99.5%) powder was coated on the stainless steel specimen as metal oxide powder in the friction test of aluminum bronze. The reported Mohs hardness of MoO_3 is 2.55[3)]. Besides MoO_3 powder, the heated mixture of CuO and MoO_3 powders was coated in the additional friction test for verification, which is described later in results and discussion. This mixed powder can be obtained by heating the well mixed powder which consists of equivalent mass of CuO (purity 95%, ash color) and MoO_3 (white) in air at 973 K for 1 h. It is dark brown colored fine powder. The mean particle sizes of MoO_3 powder, CuO powder and heated mixture of CuO and MoO_3 powders were measured from the SEM images of them and they were 1.56 μm, 1.94 μm and 5.05 μm, respectively.

2.2. Friction test

The friction test was conducted with the ring-on-disk tribometer with a furnace in which the ring and disk specimens were mounted. Stainless steel was used as a ring specimen and some of them were coated with the oxide powder as mentioned previously. The outer and inner diameter of the ring specimen was 20 and 15 mm, respectively. Aluminum bronze or stainless steel was used as a disk specimen. The thickness of disk specimen was 5 mm. The applied load was 61.8 N which corresponds to the contact pressure of 0.46 MPa. The rotating speed of the ring specimen was 60 rpm which corresponds to the sliding speed of 55 mm/s. The sliding distance was about 200 m. The temperature in the furnace was controlled to be from the room temperature (R.T.) to 973 K. The wear amount of the specimen was obtained as a weight loss by measuring the weight of the specimen before and after friction test. Preliminary to the friction test, it was confirmed that the weight increase of heated specimen by oxidation was negligibly small comparing with the value of wear amount.

3. Results and discussion

3.1. Effect of MoO_3 on the friction of aluminum bronze and stainless steel

Figure 2 shows the results of friction test for the pair of aluminum bronze disk and uncoated / MoO_3 coated stainless steel ring. Figure 2(a) shows the averaged value of the friction coefficient for the latter half of sliding periods. The negative value in Fig. 2(c) means that the weight of ring specimen increased after friction test because the material of disk specimen adhered on the ring specimen.

The friction coefficient for the uncoated specimen increased from 0.27 to 0.72 with increase of temperature from R.T. to 873 K. The friction test was aborted at 973 K because friction force exceeded the upper limit of this tribometer in a moment. On the other hand, the friction coefficient of MoO_3 coated specimen increased from 0.19 to 0.56 with increase of the temperature from R.T. to 673 K, and then it decreased to 0.44 with increase of the temperature up to 873 K. Although the friction coefficient increased again to 0.57 by increasing temperature to 973 K, it was small enough comparing with that of uncoated specimen and friction test was accomplished at this temperature.

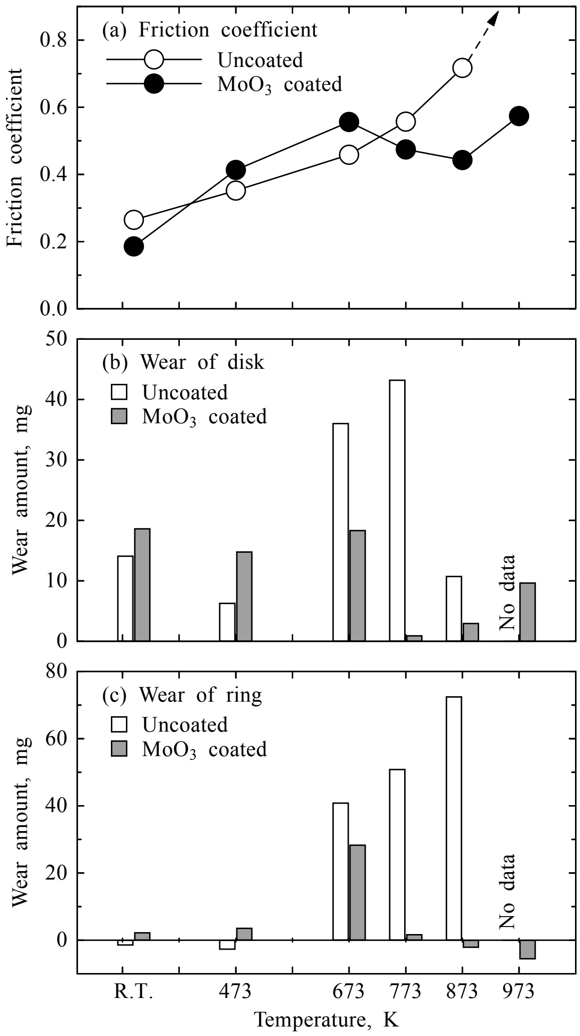

Fig.2 Results of the friction test for the pair of aluminum bronze disk and uncoated / MoO_3 coated stainless steel ring, (a) friction coefficient, (b) wear amount of disk specimen and (c) that of ring specimen

The wear amount of uncoated specimen was smaller than that of MoO_3 coated specimen tested at R.T. and 473 K for both of the disk and ring. At the temperature of over 673 K, the wear amount of uncoated specimen was larger than that of MoO_3 coated specimen. Though the wear amount of the uncoated specimen at 973 K cannot be directly compared with the results for other temperatures, it is obvious that the wear amount of the specimen at 973 K is larger than that for the temperature less than 873 K. MoO_3 coating showed remarkable wear reducing effect especially at the temperature from 773 to 973 K.

The results of XRD (X-ray diffraction) analysis of the friction track on the aluminum bronze disk specimen, which was slid against MoO_3 coated stainless steel ring, are shown in Fig. 3. The diffraction peaks obtained from MoO_3 powder and CuO powder are also shown in Fig. 3

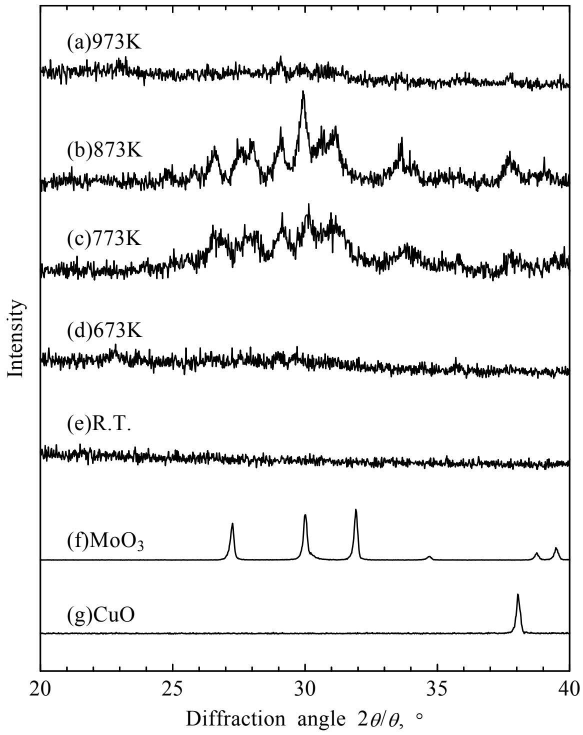

Fig.3 XRD spectra obtained from (a)-(e) the friction track of the aluminum bronze slid against MoO_3 coated stainless steel ring, (f) MoO_3 powder and (g) CuO powder

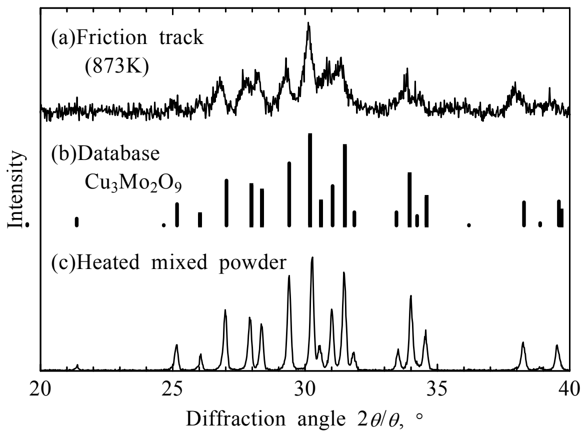

Fig.4 (a) XRD spectra obtained from the friction track of the aluminum bronze slid against MoO_3 coated stainless steel ring at 873 K, (b) reference data of $Cu_3Mo_2O_9$ in the database and (c) XRD spectra obtained from the heated mixed powders of MoO_3 and CuO

as reference. These data were obtained by using cobalt target X-ray source because aluminum bronze contains a few% iron as shown in Table 1. In this range of diffraction angle, aluminum bronze shows no peak. Several peaks with certain intensity were observed from the specimens tested at 773 and 873 K. The similar peaks are obtained also from the specimens tested at 973 K, though the diffraction intensity is small. The obvious diffraction peaks were not observed from the specimens tested at R. T. and 673 K because most of the MoO_3 powder was eliminated from the friction track. The elimination of MoO_3 powder was confirmed by EPMA analysis of the friction track. By comparing with the diffraction peaks obtained from MoO_3 and CuO powder, it can be concluded that the peaks obtained from the friction track on the aluminum bronze are not from MoO_3 or CuO.

As a result of peak identification with the diffraction peak intensity in the database, it is considered that the material observed from the friction track is "$Cu_3Mo_2O_9$". This material was generated by rubbing aluminum bronze whose major ingredient is copper in the presence of MoO_3 powder under high temperature condition. It is probable that this oxide worked as a high temperature lubricant and reduced friction and wear of specimens.

3.2. Lubricity of copper - molybdenum oxides under high temperature conditions

In order to confirm the lubricity of the material generated on the friction track on the aluminum bronze, the friction test was conducted for the pair of stainless steel disk and ring specimens under the same conditions as previous friction test. MoO_3 powder and heated mixture of CuO and MoO_3 powders were tested as coating on the stainless steel ring specimen. The result of XRD analysis obtained from this heated mixed powder is shown in Fig. 4. For comparison, the XRD spectra obtained from the friction track of aluminum bronze slid against MoO_3 coated ring at 873 K and the diffraction peak intensity of $Cu_3Mo_2O_9$ in the database (JCPDS 01-070-1495) are also shown in Fig. 4. Taking into account the difference between the wavelength of X-ray from cobalt target and that from copper target, the diffraction angles for $Cu_3Mo_2O_9$ in the database were shifted in this figure. It can be considered that the heated mixed powder is also $Cu_3Mo_2O_9$ because the diffraction peak position and intensity of database are in good agreement with that of heated mixed powder.

Figure 5 shows the result of friction test for the pair of stainless steel disk and uncoated / MoO_3 coated / $Cu_3Mo_2O_9$ coated stainless steel ring. Figure 5(a) shows the averaged value of the friction coefficient for the latter half of sliding periods. The friction coefficient of the uncoated specimen was around 0.55 at the temperature from R.T. to 873 K, but increased to 0.66 at 973 K. MoO_3 and $Cu_3Mo_2O_9$ coated specimens showed high friction coefficient of around 0.8 at R.T. The friction coefficient of MoO_3 coated specimen was slightly increased from 0.58 to 0.64 with increase of the temperature from 673 to 973 K. On the other hand, the friction coefficient of $Cu_3Mo_2O_9$ coated specimen was decreased with increase of the temperature. It showed friction coefficient of 0.36 at 973 K.

The uncoated specimen showed larger wear amount

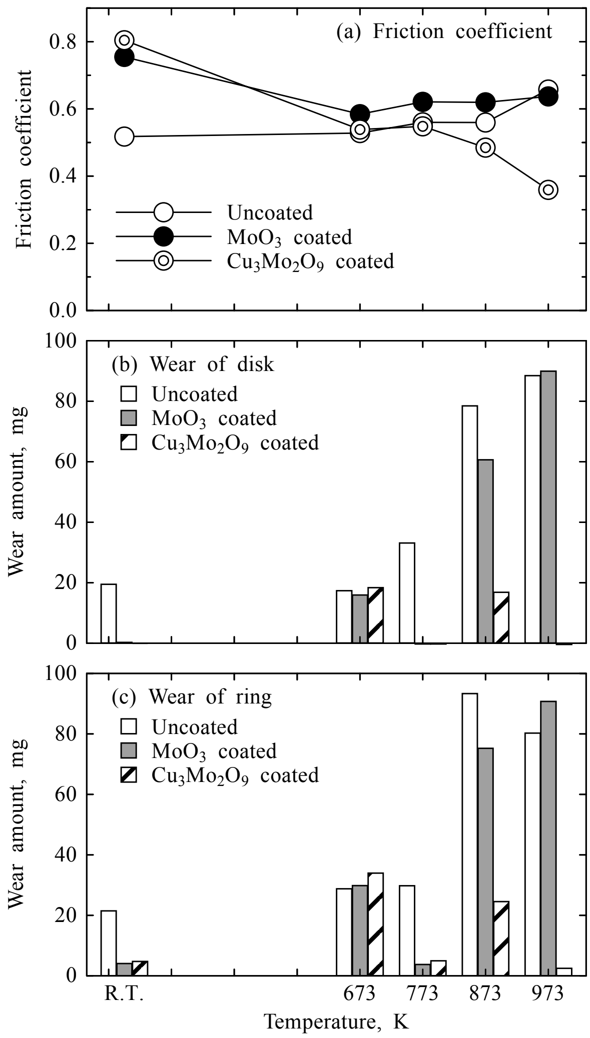

Fig.5 Results of the friction test for the pair of stainless steel disk and uncoated / MoO_3 coated / $Cu_3Mo_2O_9$ coated stainless steel ring, (a) friction coefficient, (b) wear amount of disk specimen and (c) that of ring specimen

comparing with that of coated specimens at R.T. Three kinds of specimens showed no difference in wear amount at 673 K. The wear amounts of uncoated and MoO_3 coated specimen were increased with increase of the temperature from 673 to 973 K, except that of MoO_3 coated specimen at 773 K. Though the superior lubricity of MoO_3 at about 973 K was reported[2), MoO_3 powders coated on the sliding surface was not effective at 973 K in our experiment. One reason might be poor adhesiveness of MoO_3 powder to the metal surfaces in our sample preparation method. On the other hand, the $Cu_3Mo_2O_9$ coated specimen kept low wear amount at the temperature over 773 K. The wear reducing effect of $Cu_3Mo_2O_9$ was maintained up to 973 K while MoO_3 cannot reduce the wear at 873 and 973 K.

In the case of friction between aluminum bronze and stainless steel, it can be considered that MoO_3 didn't work directly as a lubricant at high temperature but it reduced friction and wear by changing into $Cu_3Mo_2O_9$. Copper contained in the aluminum bronze is easily oxidized especially at the surface by heating in air. $Cu_3Mo_2O_9$ was generated during sliding at high temperature under high pressure by the reaction of MoO_3 powder and copper oxide. Wahl et al. reported that the ion-beam deposited amorphous Cu-Mo coating on alumina substrates showed low friction coefficient at 803 and 923 K[4). They suggested that the amorphous Cu-Mo coating changed to crystalline oxide $CuMoO_4$ and that the softened oxides worked as high temperature lubricant.

Though $Cu_3Mo_2O_9$ has different crystal structure from $CuMoO_4$, it is possible that $Cu_3Mo_2O_9$ which has similar ingredient with $CuMoO_4$ is softened and shows superior lubricity at high temperature. The temperature dependence of mechanical properties such as ductile of $Cu_3Mo_2O_9$ and the crystal structure of $Cu_3Mo_2O_9$ are needed to be studied further.

4. Conclusions

Molybdenum trioxide powder supplied to the sliding interface between aluminum bronze and stainless steel reduced friction coefficient and wear of both materials at high temperature. Copper-molybdenum oxide, which was supposed to be $Cu_3Mo_2O_9$, was generated by sliding aluminum bronze and stainless steel in presence of MoO_3 powder. The heated mixed powder of MoO_3 and CuO, which is also supposed to be $Cu_3Mo_2O_9$, showed good lubricity and wear reducing effect at high temperature from 773 to 973 K.

5. Acknowledgement

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6. References

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