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Effects of water environment on tribological properties of DLC rubbed against brass

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ABSTRACT

The effects of the water environment, such as temperature, dissolved ions, and dissolved oxygen, on the tribological properties of diamond-like carbon (DLC) against brass were studied as part of the development of water-lubricated hydraulics, valves and cylinders based on metals (Fe alloys, Cu alloys, etc.). A ball-on-disk type tribotester was used to examine the above various factors. DLC was deposited on stainless steel disks using an unbalanced magnetron sputtering system. Pure water and quasi-tap water, which imitate typical tap water sampled in Tokyo, were used to study the effects of dissolved ions. The water temperature was elevated from 20 °C to 80 °C. The results show that temperature as well as the dissolved ions has a major impact on friction and wear. More specifically, the coefficient of friction was increased at elevated temperatures. Also, in pure water, abrasive wear of DLC was observed due to aluminum condensation on the brass surface, whereas it was prevented in quasi-tap water since aluminum was removed from the contact region due to the dissolved ions. EPMA, XPS and AES indicated that the tribo-layer on the metal surfaces, which consists of carbon and the base metal as well as some elements from water, plays an important role.

1. Introduction

The development of water hydraulic systems using metal-based materials has been carried out as a national research project in Japan. Although water hydraulic systems made primarily from ceramics and plastics are commercially available at present, their use is limited because of high cost and inferior fracture toughness. The use of metal-based materials could improve and eliminate such difficulties.

The water to be used in these systems is tap water with no additives, for ease of use and drainage. In addition, the operating conditions of the water, such as the water temperature, water pressure, dissolved oxygen and dissolved ions, will vary depending on the machinery, plant, system, region, etc. Thus, the developed system must be robust in a water environment.

Combinations of diamond-like carbon (DLC) vs. stainless steel and DLC vs. brass are expected to achieve low friction and wear under water lubricated conditions, for excellent tribological performance [1–4]. Researchers have studied the effects of the water environment on wear and friction of DLC rubbed against AISI 630 stainless steel, and they have shown that the water temperature and the dissolved ions have a significant impact on the phenomena [5]. Specifically, wear and friction increased at elevated temperatures especially in tap water environment. It was also found that that the tribo-layer on the steel surface, which is affected by the temperature and dissolved ions, plays an important role in inhibiting direct contact and subsequent wear by a degraded DLC top-layer and the wear debris [5]. The importance of the tribo-layer on the DLC counter surface has also been demonstrated in previous work [4,6–9].

With regards to DLC vs. brass in a water-based environment, investigations by Ohana et al. and Yamamoto et al. have shown larger wear of the brass and higher friction than those of DLC vs. steel [3,4]. Also, these studies have shown that the wear of brass and friction are strongly affected by the hardness and surface roughness of the DLC. However, most studies related to water lubrication with DLC were conducted in pure water, and there are no previous reports on the tribological aspects of DLC vs. brass focusing on the temperature, dissolved ions, etc. in a tap water environment, which is more realistic from an application point of view.

This study therefore is aimed at clarifying the effects of the water environment on the tribological properties of DLC rubbed against brass.

2. Experimental

A ball-on-disk type rotating tribotester in an autoclave, which can be operated under a controlled water environment in terms

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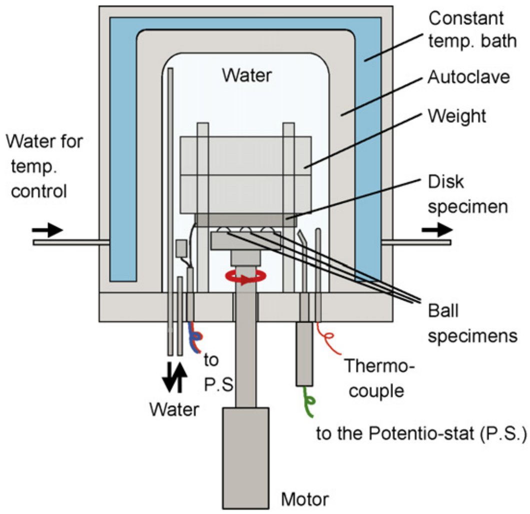

Fig. 1. Schematic diagram of the tribotester used in this study.

of temperature (20–80 °C), water pressure (0.1–20 MPa) and dissolved oxygen (0.01–8 ppm), was used in this research (Fig. 1) [5]. The water temperature was controlled using a constant temperature bath as shown in Fig. 1. The water pressure and the amount of dissolved oxygen were controlled with a high pressure pump and N_2 and $N_2 + O_2$ gas aeration, respectively.

A DLC coating with 1 μm thickness was applied on H900 hardened AISI 630 stainless steel disks (Fe–17Cr–4Ni–4Cu) by an unbalanced magnetron sputtering system [4]. The measured nanoindentation hardness of the DLC coating was 16 GPa. More details on the coating can be found in Refs. [4,5]. The balls were made of type P31CHL high tensile brass (Cu–26Zn–3Al–2Ni) 9.5 mm in diameter. The hardness of the ball material was HV 500 (4.9 GPa). The surface roughness of both specimens was 0.03 μm in Ra.

Quasi-tap water, imitating typical tap water sampled in Tokyo, was prepared and used for the experiment. The properties of the quasi-tap water are listed in Table 1. Pure water de-ionized with an ion-exchange resin was also used for comparison.

Experiments were carried out in two steps. The screening of environmental factors was conducted first using an L9 orthogonal table as shown in Table 2. The normal load was also varied as indicated in Table 2. In this L9 experiment, the number of repetition is one. Then, a detailed examination of varying the temperature and the dissolved ions, which were found to be significant for wear in the L9 experiment, was conducted according to the experimental conditions shown in Table 3. The experiment was conducted twice at each condition.

The wear volume of the DLC disk was calculated from wear scar profiles obtained with a stylus profilometer. An optical microscope was employed to estimate the wear volume of the ball specimen under the assumption that the wear scar is flat. Scanning electron microscopy (SEM), electron probe microanalysis (EPMA), Auger electron spectroscopy (AES) and X-ray photoelectron spectroscopy (XPS) were employed for surface characterization of the specimens.

Table 1
Details of typical tap water in Tokyo and quasi-tap water in Tokyo.

	Tap water sampled in Tokyo	Quasi-tap water
Dissolved ions (mg/l)		
Cl^-	30	31
NO_3^-	12	13
SO_4^{2-}	36	37
Na^+	22	24
K^+	2.8	2.5
Mg^{2+}	5.0	5.3
Ca^{2+}	22	23
Electrical conductivity (mS/m)	28.9	29.4
pH	7.2–7.8	7.4–7.9

Table 2
L9 orthogonal table for examination of environmental factors and load.

Exp. no.	Load (N)	Temperature (°C)	Dissolved oxygen (ppm)	Water pressure (MPa)
1	10	20	0.01	0.1
2	10	50	0.1	1.0
3	10	80	7	19
4	30	20	0.1	19
5	30	50	7	0.1
6	30	80	0.01	1.0
7	57	20	7	1.0
8	57	50	0.01	19
9	57	80	0.1	0.1

Table 3
Experimental conditions for detailed examination of temperature and dissolved ions.

Turning speed	0.4 m/s
Load (on three balls)	11, 31, 58 N
Number of revolutions	36,000 (approx)
Water pressure	0.1 MPa
Dissolved oxygen	7–8 ppm
Water temperature	(20, 50, 80) ± 2 °C
Water	Pure water, quasi-tap water

3. Results

Fig. 2 shows the results of the L9 experiment. It can be seen that the temperature strongly affects the wear of the DLC. In addition, the wear rate of the brass ball decreased with an increase in the load probably due to topographical change of the ball specimens, i.e., the actual contact pressure decreases with flattening of the balls [4]. It can also be observed that the wear of the brass ball is much smaller in a pure water environment.

Fig. 3 shows the specific wear rate of the DLC disks at various water temperatures and load conditions, as shown in Table 3. The average of coefficients of variation in pure water and quasi-tap water at each condition were 30% and 20%, respectively. It can be seen that the wear of the DLC increased with increasing temperature. In addition, the wear of the DLC is larger in a pure water environment compared to that in quasi-tap water. These results are consistent with those of the L9 experiment.

Changes in the coefficient of friction as a function of time in various water environments are shown in Fig. 4. At first, the friction decreased as a function of the sliding distance for all cases. However, at 80 °C, the friction increased after a sliding distance of 200 m, different from that of the case at 20 °C.

Figs. 5 and 6 compare the morphologies of the DLC wear scars in different water environments. As can be seen, the wear scar in pure water shows deep and severe scratches, whereas the scar in the quasi-tap water shows a wide and shallow profile with a smaller number of scratches. Since the depth of the scratches (~600 nm) is less than the coating thickness (1 μm), contact between the brass and stainless steel substrate has not occurred.

Fig. 7 shows SEM images and the corresponding EPMA images of the brass wear scars in the two environments. In pure water, as shown in Fig. 7(a), condensation of aluminum is seen on the wear scar, whereas in the quasi-tap water, aluminum accumulates on the backside of the wear scar, as shown in Fig. 7(b)-region A. Oxygen and a small amount of carbon are also found on the wear scars for both tribo-surfaces. AES depth profiles of the brass wear scars shown in Fig. 8 also demonstrate condensation of aluminum