Short Communication

Running-in Behavior in the Combination of Diamond-Like Carbon Film and AC8A Aluminum Alloy

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Abstract

The running-in process affects the friction and wear properties of sliding materials in machines. If it is not done correctly, serious problems such as machine seizure may occur. Diamond-like carbon (DLC) films are used in various fields as an excellent tribo-material because of their low friction coefficient and high wear resistance. However, their running-in behavior has not been clarified quantitatively in detail. In addition, previous studies have not adequately investigated changes in wear particles during the running-in process. In the present work, we investigated the correlation between the friction coefficient and the number of wear particles during the running-in process using an online particle counter. Then, we compared the sliding distance at the completion of running-in judged using the particle counter with that judged using the friction coefficient. As a result, the running-in behavior in the combination of a DLC film and AC8A Al alloy is well clarified. In the case of a DLC/AC8A sliding pair, the DLC surface showed no significant changes after wear tests. The AC8A surface became smooth by abrasion and plastic deformation during running-in, and the ratio of silicon occupying the surface area increased slightly.

Keywords

running-in, diamond-like carbon, AC8A aluminum alloy, particle counter, friction coefficient

1 Introduction

The running-in process for sliding parts in machines has long been known to be important because it affects the friction and wear properties of the sliding materials. Running-in procedures are often empirically determined, as there is little prior knowledge of how the sliding surface will actually respond to running-in [1, 2]. If running-in is not done correctly, serious problems such as machine seizure may occur. However, running-in behavior is not well clarified quantitatively because the running-in process is complex and involves various factors. For instance, the formation of oxidation films on the wear surface, decrease in the plasticity index, an increase in surface hardness, and improvement of wear and seizure resistance by a tribo-layer must be considered [3, 4]. In addition, previous studies have not adequately investigated changes in the wear particles during running-in. The characteristics of wear particles carried in the flow of circulating oil represent the lubricant

conditions at rubbing surfaces [5]. In a previous study, the authors have developed a new technique that can estimate the wear amount quantitatively under lubricated conditions using the on-line particle counter. The authors reported the possibility of a quantitative diagnosis of rubbing surface failure [6].

Recently, diamond-like carbon (DLC) films have been applied in various fields as an excellent tribo-material because of their low friction coefficient, high wear resistance, and chemical inertness. AC8A Al alloy is expected to apply to the engine for automobiles because of their low density and good wear resistance from the viewpoints of reducing fuel consumption.

In this study, wear tests were performed by rubbing the annular surface of a ring (AC8A) against a fixed plate (DLC) under lubrication. The number of wear particles was measured using an online particle counter and a correlation with the friction coefficient was found. We discuss the running-in behavior in the combination of the DLC film and AC8A aluminum alloy.

2 Experimental

2.1 Test materials

Table 1 shows the material properties of both specimens. Not only the roughness but also the waviness will affect to the fluid pressure generation under lubrication and the distribution of the real contact area. But, it does not take into consideration in this paper. The surface was finished as flatly as possible using lapping machine. The DLC films, namely the amorphous hydrogenated carbon coating, a-C:H, were deposited on a bearing material JIS SUJ2 substrate by plasma chemical vapor deposition (CVD). Hydrogen content is 16%, and ID/IG ratio is 0.51. The thickness of the DLC film, which was measured using a ball crater method, was approximately 2 μm . Its hardness, which was measured using a nano-indentation tester, was 23.5 GPa. The indentation hardness was measured at seven randomly distributed points under a load of 4.9 mN. The indentation depth doesn't exceed 0.2 μm . The hardness is the mean value of five points except the maximum value and minimum value. The nano-indentation tester has the trigonal diamond indenter with a vertical angle of 115° .

The ring was an aluminum-silicon alloy. This material is designated as AC8A in the Japan Industrial Standard. The silicon had eutectic structure and was present at 12 mass%. The Vickers hardness was measured at seven randomly distributed points under a load of 0.98 N. It is the mean value of five points except the maximum value and minimum value. The Vickers hardness tester has the pyramidal diamond indenter with a vertical angle of 136° .

2.2 Test apparatus and procedure

The experiments were performed with a ring-on-plate test rig. Figure 1 shows a schematic view of the test apparatus. Two particle counters (designated as IN PC and OUT PC, respectively) were set along the pipe in which the lubricating oil circulated from an oil purifier to the test apparatus and from the test apparatus to an external tank. Flow rate of sample fluid

is 300 ml/min. So, after generating the wear particles, we can measure the size and distribution of them at once. And, we can estimate the wear amount quantitatively [6]. Wear tests were performed by rubbing the annular surface of a ring (AC8A) against a fixed plate (DLC) at applied loads of 200 N, 800 N, and 1400 N and a sliding velocity of 2.0 m/s. The sliding distance was 10 km.

Wear tests were performed under lubrication. The sliding surface was immersed in an oil bath filled with lubricating oil at a temperature of about $60 \pm 1^\circ\text{C}$. The lubricating oil is non-additive paraffinic mineral oil of group II for industrial use. The oil viscosity at 60°C was $14.8 \text{ mm}^2/\text{s}$. The lubrication mode was the mixed lubrication. The friction torque of the rotating table on which the plate specimen was mounted was interrupted by a load cell attached to the rigid body. Its friction torque was measured, and then the friction coefficient was calculated.

2.3 Particle counter

The outline is described here because details concerning the structure and the measurement accuracy of the particle counter have been reported in the references [5] and [6]. Figure 2 shows a schematic view of the particle counter. Selfoc lenses of 0.25 P (pitch) and 0.5 P are set in front of a laser diode (LD) and a photodetector (PD), respectively, to guide the laser beam to the sensor zone. The laser beam is detected by the PD through a small square slit ($50 \mu\text{m} \times 50 \mu\text{m}$).

Figure 3 shows a schematic of the signal treatment. When a particle crosses the sensor zone, the output voltage of the PD drops in proportion to the projected area of the particle as shown in Fig. 3(a). The pulse goes through a high-pass filter and

Fig. 2 Schematic of the particle counter

Material	Plate	Ring
	DLC	AC8A
Vickers hardness	—	89.9
Indentation hardness, GPa	23.5	—
Surface roughness R_a , μm	0.02	0.11

Fig. 1 Schematic of the wear test apparatus

Fig. 3 Schematic of the signal treatment

is then inverted as shown in Fig. 3(b). The peak of the pulse is detected by an A/D converter and counted by a signal processor. The pulse height is converted into the diameter of an equivalent circle for the projected area [5]. The specifications of the particle counter are as follows. Minimum detectable diameter of particles is $5\text{ }\mu\text{m}$, maximum concentration of particles is 100,000 counts/ml, the color is ASTM-8 grade, temperature of sample fluid is $0\text{--}80^\circ\text{C}$, and number of particles are counted with an interval of $1\text{ }\mu\text{m}$.

3 Results and discussion

3.1 Variations in the friction coefficient and the number of wear particles

Figure 4 shows the friction coefficient and the number of wear particles at various applied loads. Both of these values decreased rapidly in the initial stage and then gradually decreased to a steady-state value. The initial friction coefficient was around 0.3; it rapidly decreased to 0.02 - 0.03. The friction coefficient decreased slightly as the applied load increased. The number of wear particles was around 100 - 200 initially and then decreased to 50. The number of wear particles increased with the applied load. In terms of the characteristic changes in the friction coefficient and the number of wear particles as a function of sliding distance, both values showed the similar tendency. They gradually decreased with the sliding distance, and then they became constant.

3.2 Comparison of the running-in completion distance

Figure 5 illustrates how the running-in completion distance is defined. The variations in the friction coefficient and the number of wear particles as a function of sliding distance are approximated by the ninth function using the least square method. When the gradient of friction coefficient vs. sliding distance is less than 10^{-1} and that of the number of wear particles vs. the sliding distance is less than 10^{-3} , we defined the distance as the running-in completion distance. The distances defined by both parameters are almost constant and stable.

The two values are denoted by d_p (running-in completion distance judged by the number of wear particles) and d_μ (that judged by the friction coefficient). Figure 6 compares the two running-in completion distances. The results show good correlation between d_p and d_μ in the running-in process. The results of the number of wear particles using the particle counter apprehend the running-in process well.

Fig. 4 Variations in friction coefficient and number of wear particles at various contact loads
(a) Friction coefficient, (b) Number of wear particles

3.3 Wear surface

After wear tests, the worn surfaces of the plate and ring specimens were observed using an optical microscope and a scanning electron microscope. In addition, the worn surfaces were analyzed using an energy dispersive X-ray spectrometry (EDX). Figure 7 shows optical microscope images and cross-sectional profiles of both specimens. The worn surface of the DLC plate showed no significant differences at sliding distances of 80 m, 130 m, and 10 km. Figure 8 shows the EDX analysis of the worn DLC surface at various sliding distances. The EDX chemical analysis shows that aluminum is slightly transferred from the ring to the plate at sliding distance of 80 m, 130 m and 10 km.

The worn surface of the AC8A ring became smooth by wear and plastic deformation. In the combination of diamond-like carbon film and AC8A aluminum alloy, the aluminum matrix is worn by a small-scale adhesive wear as priority and a lot of Si distributes on the sliding surface. So, surface strength increases and wear decreases. Then the running-in is finished. We observed the wear particles in the sliding distance of 80 m. All wear particles in the scale of 5-10 μm were observed as shown in Fig. 9.

The surface profiles indicate that smoothing during running-in is more significant in the ring than in the plate. In the process of smoothing, the surface layer becomes harder than

Fig. 5 Definition of running-in distance

that of the as-received material [7]. The presence of a highly deformed surface layer may explain why rough surfaces are generally believed to run in more successfully [8]. Again, the surface profile changed within the first minutes of sliding. We guessed that the contact between asperities on the sliding surface decreased and the contact pressure decreased as the

Fig. 6 Comparison of the running-in completion distances

Fig. 7 Optical microscope images and cross-sectional profiles of the specimens
(a) Plate specimen: DLC, (b) Ring specimen: AC8A

Fig. 8 EDX analysis of the worn surface of DLC films at various sliding distances

Fig. 9 SE image and EDX images of wear particles at a sliding distance of 80 m

worn surface of AC8A became smooth, that an oil film was gradually created at the interface.

Figure 10 shows EDX images of the AC8A surface at various sliding distances. The ratio of silicon occupying the surface area increased slightly at 80 m (d_{in}), as well as at 150 m and 10 km. From these results, we expect that wear of the AC8A was limited.

4 Conclusion

- (1) A particle counter may be able to use to determine the running-in completion distance from the results of the correlation between the friction coefficient and the number of wear particles during running-in.
- (2) In the case of a DLC/AC8A sliding pair, the DLC surface showed no significant changes after wear testing. The AC8A surface became smooth by abrasion and plastic deformation during running-in, and the ratio of silicon occupying the surface area increased slightly.
- (3) The friction coefficient decreased slightly and the number of wear particles increased with an increase of applied load.

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Fig. 10 EDX images of AC8A (ring) at various sliding distances. White area means the existence of Si

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