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Short Communication

Frictional Properties of DLC films in Plane Contact due to Reciprocal Micro-Sliding

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The objective of this research is to investigate the frictional behavior of a-C:H coating in plane contact by using reciprocating micro-sliding test under controlled relative humidity. The friction tests were conducted at various relative humidities (RH) between 5% and 90% without lubrication at room temperature under the following conditions: normal load of 1 N, sliding stroke of 2 μm, sliding speed of 10 μm/s, and up to 80000 cycles. The friction coefficient of the DLC coatings first increased and then decreased with increasing relative humidity when the number of sliding cycles was below 30000. Critical relative humidity was noticed, which corresponded to the highest coefficient of friction. At a relative humidity of 80%, the friction coefficient became almost constant over the whole number of sliding cycles.

Keywords: DLC, plane contact, micro-sliding, humidity, nitrogen, reciprocal sliding

1. Introduction

Diamond-like carbon (DLC) films have attracted a great deal of interest in recent years mainly because of their low friction and wear properties[1-11]. It has been demonstrated that test conditions and environments can also play major roles in their friction and wear performance. For example, previous studies have shown that the presence of water molecules in the test environment is very helpful to the frictional behavior of hydrogen-free DLC films. For hydrogenated DLC, water molecules show an adverse effect[1,3,4,6-9]. However, there have been few studies of the effects of relative humidity on the friction coefficients in a nitrogen environment. In this paper, we will limit our attention to the hydrogenated DLC film and investigate the frictional behavior of a-C:H coating in plane contact by using reciprocating micro-sliding tests under conditions of controlled relative humidity. The frictional tests were conducted in dry and wet nitrogen environments.

2. Experimental details

The friction tests were conducted in block-on-plate type reciprocal sliding. The block and plate specimens used are shown in Fig. 1. There block specimens had a square protrusion measuring 4 × 4 mm in the center, which came into plane contact with the plate specimen 0.1 mm thick. The material of the block specimen was stainless steel SUS410, while that of the plate specimen was SUS631. Both the block and plate specimens were coated with DLC after their surfaces were ground. With the ion beam vapor deposition method, benzene gas was used as the raw material. The ionized benzene ions were accelerated and irradiated onto the substrate to precipitate an amorphous carbon film. The thickness of DLC coating was about 1 μm. There was an interlayer of Si between the DLC film and the base metal, which had a comparatively stable adhesion with respect to amorphous carbon films. The surface roughness Ra of the specimens after DLC coating was 0.2 μm. The apparent contact area between the block and plate specimens was 4 × 4 mm^2.

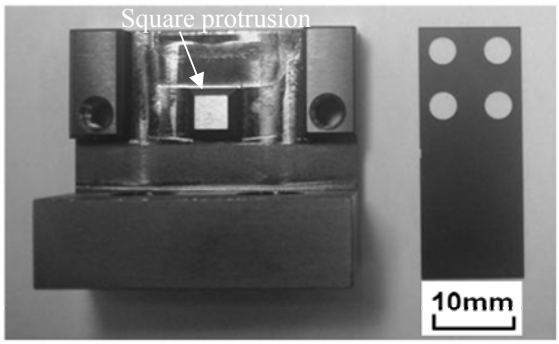

Fig. 1 Photograph of specimens used (block and plate)

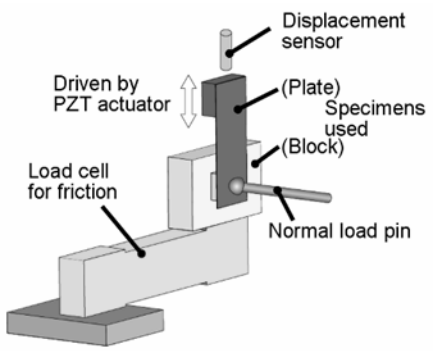

Fig. 2 Schematic drawing of experimental apparatus

Figure 2 shows a schematic diagram of the experimental apparatus. The block specimen was attached to a load cell for friction force and the plate specimen was driven by a PZT actuator. Displacements of the block specimen as a function of friction force were measured beforehand. The compliance of the load cell was 61.76 μm/N. Displacements of the plate specimen were measured using a capacitance measurement system during the friction experiments. Relative displacements between the block and plate specimens were used to describe the test results. A stainless steel enclosure was used to create and maintain the dry and wet nitrogen environments. To prevent the uneven contact between the block and plate specimens, the relative tilt angle of the block specimen to the plate specimen was adjusted within 10 s using a laser autocollimator.

A normal force of 1 N was applied to the normal load pin of tip radius 2 mm, which pressed the plate specimen. The amount of displacement and speed of movement applied to the plate specimen had to be adjusted occasionally so that the relative displacement of 2 μm between the block and plate specimens as well as the sliding speed of 10 μm/s were kept constant during the friction test. It took 20 s to calculate the amount of displacement and the speed of movement applied to the plate specimen. During the calculation, the friction test was interrupted.

The friction tests were conducted at various relative humidities (RH) between 5% and 90% without lubrication at room temperature under the following conditions: normal load of 1 N, sliding stroke of 2 μm, sliding speed of 10 μm/s and up to 80000 cycles. To cause sliding between the plate and block specimens, linear displacement given to the plate specimen was greater than 2 μm as the load cell for friction force was also deformed. If no sliding occurred, the amount of displacement applied to the plate specimens was increased.

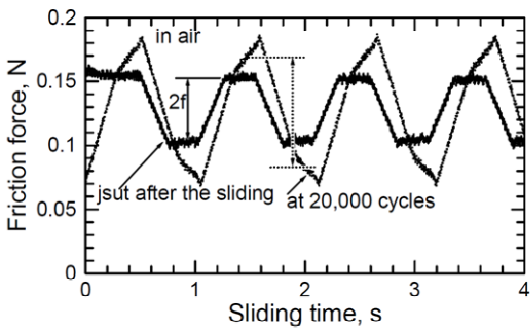

Fig. 3 Friction forces as a function of time

3. Experimental results

The variation of friction force just after the friction test in air at a relative humidity of 30% is shown in Fig. 3. At both ends of the sliding strokes, relative sliding between the specimens occurred and the friction force became almost constant as a function of time. Friction coefficient is defined as the friction force divided by the normal load. In this case, the difference, 2f, between the forces at both stroke ends is equal to a twofold friction force. At a sliding stroke of 20000, the friction force increased and was not constant during sliding. In this case, the friction force was defined as the average force when the relative sliding occurred.

Figure 4 shows the changes in friction coefficients just after the sliding test. In air, the variation of the friction coefficients was large until 60 sliding cycles. Therefore, the amount of displacement and the speed of movement applied to the plate specimen were recalculated every 10 sliding cycles. After 60 sliding cycles, the recalculation was performed every 100 strokes. The calculation time was 20 s. During the calculation, the friction test was interrupted. At 160 sliding cycles, there was a small gap in the friction coefficient. After interruption, the friction coefficient showed a slightly higher value compared to before. However, the friction coefficient then gradually decreased with sliding cycles. This gap tended to become greater as the interruption time became longer.

In dry nitrogen, the friction coefficient also decreased with number of sliding cycles. At 150 sliding cycles, the friction coefficient dropped slightly just after

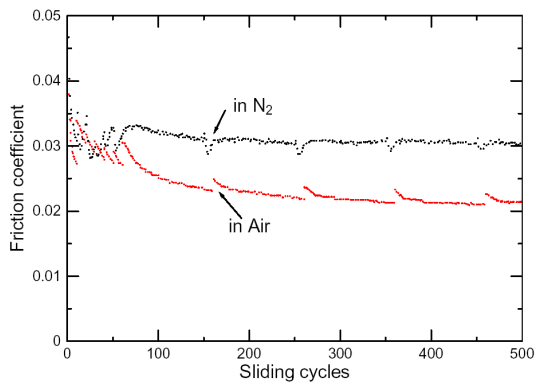

Fig. 4 Friction coefficients a function of sliding cycles

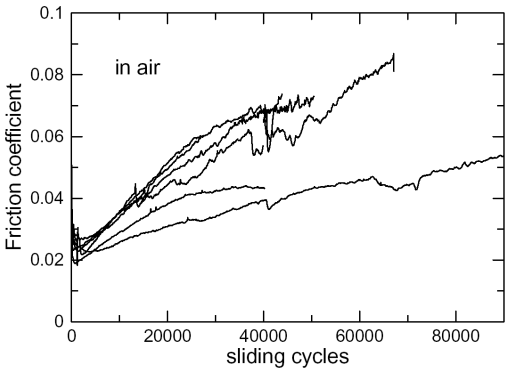

Fig. 5 Friction coefficients as a function of sliding cycles, in air

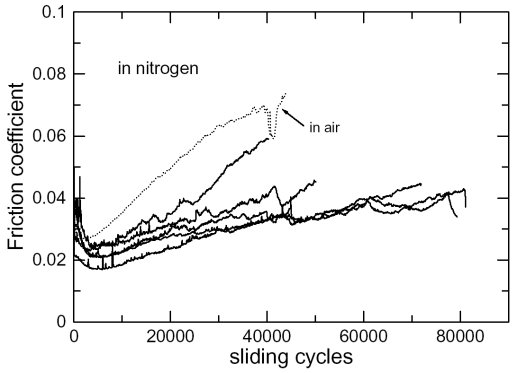

Fig. 6 Friction coefficients as a function of sliding cycles, in dry nitrogen

the interruption. These observations were in contrast to those in an air environment. The absorption of oxygen or nitrogen during the interruption may affect the frictional properties[11].

Figure 5 shows the friction coefficients as a function of the sliding cycles in an air environment at a relative humidity of 30%. The friction tests were conducted 7 times. After an initial rapid drop in the friction coefficients to minimum values of 0.02 at the initial stage of 2000 to 3000 cycles, the friction coefficients rose again with increasing number of sliding cycles and then reached values of 0.05 to 0.08. A slightly larger variation in the friction coefficients sometimes occurred because the reciprocating micro-sliding machine stopped when the displacement of the plate specimen exceeded the limited value.

In dry nitrogen, the friction coefficient also decreased with the number of sliding cycles down to a minimum value of 0.02 (Fig. 6). The friction tests were conducted 6 times. However, it took about 5000 sliding cycles longer than in the air environment. The friction coefficient in air tended to be larger than that in dry nitrogen.

Figure 7 shows the friction coefficient as a function of the number of sliding cycles in wet nitrogen. At a

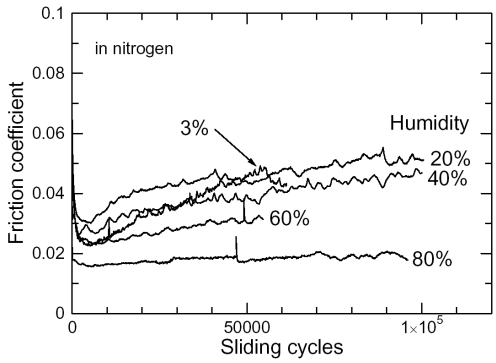

Fig. 7 Friction coefficients as a function of sliding cycles, in wet nitrogen

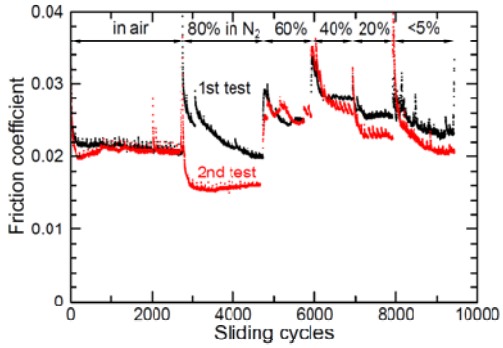

Fig. 8 Friction coefficients as a function of sliding cycles, in various wet nitrogen

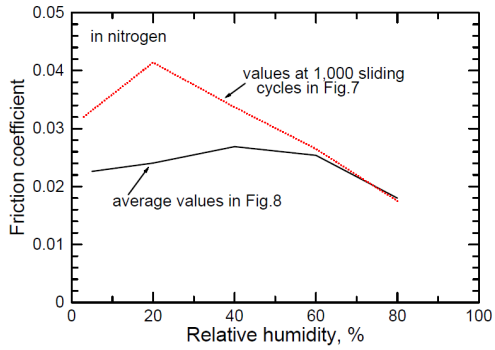

Fig. 9 Friction coefficient and relative humidity

relative humidity of 3%, the rate of increase of the friction coefficient was relatively large after reaching the minimum value of 0.02. As the relative humidity increased, the rate of increase of the friction coefficient decreased. At a relative humidity of 80%, the friction coefficient became almost constant over the whole range of sliding cycles.

Figure 8 shows the results of friction test in which the specimens were rubbed with each other until 3000 sliding cycles in air for the running-in process and then the atmosphere within the chamber was replaced with

nitrogen and the relative humidity was changed in steps from 80% to below 5%. At the end of the first 3000 sliding cycles in air, the friction coefficient settled down to a low and steady value of 0.02. Subsequently, the friction coefficient reached the lowest value at a relative humidity of 80% and highest value at 40%. The friction coefficient decreased slightly with further decreases in relative humidity.

Figure 9 shows the average friction coefficients at 1000 sliding cycles for each relative humidity shown in Fig. 8. The friction coefficient increased until a relative humidity of 40% beyond which it decreased. There appears to be a critical relative humidity (RHc) at which the highest coefficient of friction can be found. In addition, the friction coefficients at 1000 sliding cycles for each relative humidity were re-plotted from Fig. 7. In this case the critical relative humidity was 20%. This tendency of the critical relative humidity was similar to that in a previous study [2].

After the friction tests the specimen surfaces were observed through an optical microscope and any wear debris was not noticed. However, the contact zones appeared to be polished on the asperity tips during the friction tests. 3-D surface height profiles of the specimens did not show any amount of wear. Thus it can be thought that only a fraction of the asperity tip in contact would be gradually worn out during the friction test.

4. Conclusions

The frictional behaviors of a-C:H coating in plane contact were investigated by using reciprocating micro-sliding tests under conditions of an ambient air circumstance and controlled relative humidity in nitrogen.

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