Optimization for Industrial Applications by Mechanical Properties and Reducing Static/Dynamic Friction Coefficient of DLC Coatings

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DLC (Diamond-Like-Carbon) providing a useful low friction coefficient, is especially suitable for various drive-line applications including automobile parts, but the value of this friction coefficient is often determined under a constant speed sliding environment. However, many of the sliding parts do not always operate at constant speed, it is necessary to consider motion from a stationary state. In this study, the effects of mechanical properties (Hardness) obtained by adjusting each film structure on static/dynamic friction coefficients were evaluated for DLC deposited by plasma-CVD and arc-PVD. A thrust cylinder type friction wear tester was used to measure each friction coefficient. The maximum friction force at the initial stage of rotation was calculated to the static friction coefficient, and the friction coefficient at a constant peripheral speed was defined as the dynamic friction force. From the result, satisfactory low coefficients of friction and a reduction in static friction force proved that DLC coating is useful for treatment of sliding parts in drive mechanisms. Furthermore, the film structure and mechanical properties of DLC have a large effect on static/dynamic frictional forces, and the study indicates the need to select the optimum DLC according to the application and expected sliding environment.

Keywords: *dry coating, Diamond-Like-Carbon, low friction coefficient, static/dynamic friction*

1. Introduction

In recent years, various efforts to improve the environment have placed emphasis on increasing social responsibility of manufacturing industry, including the need to be carbon-neutral. Surface modification technology by dry coating can contribute to sustainability since it imparts mechanical properties such as high hardness and low friction coefficient to thin films, and thus extends part life by improving wear resistance and reducing frictional energy loss.

Among the dry coatings, DLC (Diamond-Like-Carbon) consists of a mixture of diamond and graphite structure, and is widely used because it is a high-performance amorphous thin film with properties intermediate between those structures. Moreover, hydrogen may be partially included. DLC coating, providing a useful low friction coefficient, is especially suitable for various drive-line applications including automobile parts, but the value of this friction coefficient is often determined under a constant speed sliding environment. However, many of the sliding parts do not always operate at constant speed, pressure, and direction, such as repetitive motion of pistons and forward/reverse rotation of gears. Even if it is momentary, it is important to evaluate the static friction coefficient in addition to the dynamic friction coefficient in the development of DLC coatings because the sliding friction force is maximized when motion is started from the stationary state.

In this study, the effects of mechanical properties obtained by adjusting each film structure on static/dynamic friction coefficients were evaluated for hydrogen-containing DLC deposited by plasma-CVD and hydrogen-free DLC deposited by arc-PVD. DLC was coated on the flat test piece side. The maximum friction force at the initial stage of rotation was calculated to the static friction coefficient, and the friction coefficient at a constant peripheral speed was defined as the dynamic friction force.

2. Experiment

2.1 Deposition method

In this study, a disk made of SUJ2 material (30 mm square, 6 mm thick) was used as the deposition substrate. Using a vacuum deposition system (Hauzer Techno Coating B.V., Flexicoat1200), we deposited hydrogenated DLC (a-C:H) by plasma CVD and hydrogen-free DLC (ta-C) by arc PVD. Acetylene gas (C2H2) was used for a-C:H, and solid carbon was used for ta-C as the main raw materials of DLC. In the DLC treatment, the substrate surface was cleaned by argon plasma etching and the base treatment mainly composed of chromium was performed for adhesion of the film.

2.2 Surface roughness measurement

The DLC droplets (micro-particles) generated during film formation were removed using diamond paper before being evaluated. The surface roughness after polishing was measured using a laser microscope (OLYMPUS, OLS4100). The measurement length was set to 6 mm.

2.3 Film hardness measurement

A DLC film has a mixture of a diamond structure (SP^3 hybrid orbitals) and a graphite structure (SP^2 hybrid orbitals), and the film tends to be harder as it contains more SP^3 hybrid orbitals. DLC can adjust the film hardness, which is known to be 15-25GPa for a-C:H and 30-60GPa for ta-C. In this study, four types of samples were prepared for evaluation by providing high hardness and low hardness patterns for each of the two DLC deposition methods. The hardness of the film was measured using a nano-indentation hardness tester (SHIMADZU, DUH-211) with an indentation depth of 30 nm.

2.4 Friction coefficient measurement

A thrust cylinder type friction wear tester (Orientec, EFM-3-1010) was used to evaluate the sliding properties of each DLC. For the test load, specify the surface pressure in the range of 100 to 1300 MPa, and start rotating when the set load is reached. Rotation accelerates from a stationary state to 100 rpm in 10 seconds and maintains 100 rpm for 5 seconds. After the constant speed section, it will decelerate and stop in 10 seconds. The maximum friction coefficient at the initial stage of rotation was defined as static friction force, and the friction coefficient at constant peripheral speed was defined as dynamic friction force. The test was repeated 30 times for each level, and the average static/friction coefficient values obtained were evaluated. After sliding, the disk test piece was observed for wear marks using a laser microscope (OLYMPUS, OLS4100), and the amount of wear was calculated from the obtained profile data.

3. Results

3.1 Surface roughness of each DLC

Table 1 shows the surface roughness after polishing measured with a laser microscope. Droplets generated during film formation have been removed, and there is no significant difference in surface roughness. The surface roughness of each test piece has little effect on the sliding evaluation, so it is excluded from consideration of the results in this study.

Table 1 Surface roughness Rpk, substrate and each DLC film

	Surface roughness Rpk μm
Substrate	0.040
Low a-C:H	0.048
High a-C:H	0.052
Low ta-C	0.060
High ta-C	0.056

3.2 Film hardness of each DLC

The film hardness of each DLC was measured with a nano-indentation hardness tester. Among the four types of DLC films, a-C:H(Low) is the lowest at 20.4GPa. Next, a-C:H(High) was 27.0GPa, ta-C(Low) was 30.1GPa, and ta-C(High) was 60.3GPa. It can be inferred that one of the factors for the difference in hardness is the adjustment of the film structure of the SP3 hybrid orbital carbon bond.

3.3 Friction coefficient of each DLC

The coefficient of friction was measured with a thrust cylinder type friction wear tester. Figure 1 shows the measurement results at a surface pressure of 100 MPa. In the substrate, the friction coefficient was clearly high at the start and stop of driving from the stationary state, and the friction coefficient was stably low in the constant speed section where the maximum speed was maintained. From this result, the maximum friction coefficient near 0 rpm was defined as the static friction force, and the friction coefficient at a constant speed section of 100 rpm was defined as the dynamic friction force. On the other hand, DLC shows a reduction in the coefficient of friction. In particular, the effect on the reduction of static friction force was large, showing a value equivalent to dynamic friction force. As for the test surface pressure, each static friction coefficient was compared in figure 2. The coefficient of static friction varied depending on the film hardness of DLC as the surface pressure increased. At 500GPa or more for a-C:H and 1100MPa or more for ta-C, the static friction force increased and measurement became impossible due to wear.

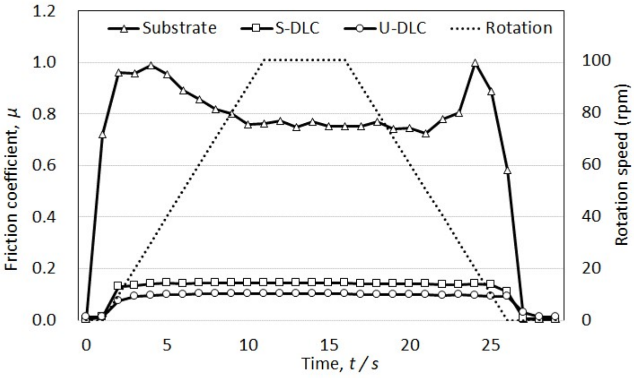

Figure 1 Friction coefficient at surface pressure of 100MPa

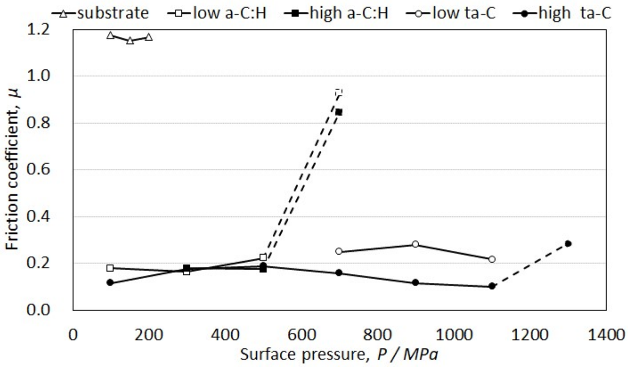

Figure 2 Static friction coefficient at each surface pressure

4. Discussion

In this study, the effects on the static/dynamic friction coefficient were investigated using DLC with different film formation methods and mechanical properties. By applying DLC, a good low coefficient of friction was exhibited, and a decrease in the static friction force was clearly seen. In addition, the coefficient of static friction tends to increase on the high surface pressure side, which is thought to affect the wear of DLC. It is inferred that the film structure (SP3 hybrid orbital) has a close relationship with the tribological properties of DLC because the higher the film hardness, the higher the surface pressure resistance of the static friction coefficient. It suggests the need to fully consider the static friction coefficient in addition to the general dynamic friction coefficient when adopting DLC for sliding parts.

5. Summary

DLC offers a high number of options because it can provide a range of mechanical properties intermediate between those of diamond and graphite depending on the film formation method and conditions, however productivity will also be affected. The purpose of this paper is to propose optimization of DLC for various sliding environments, because it is also important to consider the balance between the function and cost of DLC with respect to obtaining suitable low static friction coefficients for each application.