Ultra Low Friction of DLC Coating with Lubricant

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Abstract. The objective of this study was to find a trigger to make clear a mechanism of the ultra low friction by evaluating the friction property of DLC-DLC combination under lubrication with the simple fluid. The Pin-on-disc reciprocating and rotating sliding tests were conducted to evaluate the friction property. The super low friction property of pure sliding with the ta-C(T) pair coated by the filtered arc deposition process under oleic acid lubrication was found at the mixed lubrication condition. It was thought that the low share strength tribofilm composed of water and acid seemed to be formed on ta-C sliding interface. Additionally, the smooth sliding surface formed on ta-C(T) was seemed to be required to keep this tribofilm. Then, the super low friction was thought to be obtained by this superlubrication condition. Although the accurate and direct experimental data must be required to make clear this super low friction mechanism, the advanced effect obtained by the simple material combination is expected to be applied on the large industrial fields in near future.

1. Introduction
Reduction of the mechanical friction especially for automotive engine has been strongly required in recent years for improving fuel economy. Reducing the friction between the cam and follower is effective in this regard in the low engine speed range. A diamond-like carbon (DLC)-coated cam follower of the bucket type has been applied to the gasoline engines to reduce engine friction[1]. This low friction property is obtained by the hydrogen free DLC, ta-C lubricated with the ester containing oil[2]. The objective of this study was to find a trigger to make clear a mechanism of the ultra low friction by evaluating the friction property of DLC-DLC combination under lubrication with the simple fluid.

2. Test Method
The Pin-on-disc reciprocating and rotating sliding tests were conducted in the following manner. The pins, measuring 9 mm in diameter and 9 mm in length, were made of hardened bearing steel (AISI52100) and polished to a surface roughness below 0.05 micron. The disc measured 33 mm in diameter and 3 mm in thickness and was made of AISI52100 and polished to a surface roughness below Ra 0.05 micron. Three kinds of DLC were coated on those discs and pins. Those were a-C:H coating by Plasma Enhanced CVD with 1micron thickness, ta-C coating by the multi-arc PVD method with 1micron thickness and ta-C(T) coating by the T-Filtered arc PVD method[3] with 0.3 micron thickness. The droplets of the ta-C coating were removed by polishing.

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The pin was secured to prevent it from rotating and was pressed against the reciprocating or rotating disc as shown in Fig.1. Contact at the sliding interfaces was in the shape of line under high Hertzian pressure of 70 MPa. The maximum sliding speed was 0.05m/s and the stroke was 20mm for the reciprocating test. The sliding speed was 0.05m/s for the rotating test. Lubrication with oleic acid and oleyl alcohol was provided by wetting on disc with several droplets (0.01ml) at ambient temperature.

![Diagram](image)

Figure 1. Pin on disc sliding test

3. Results and Discussions
The friction properties of DLC-DLC and the steel-steel pair after sliding for 30 minutes without lubrication (ambient air), with oleic acid lubrication and oleyl alcohol lubrication by the reciprocating test were compared in Fig.2. The friction coefficient of ta-C(T)-ta-C(T) pair under lubrication at 30 minutes was much lower than those of the other pairs, especially for the oleic acid lubrication. Additionally, the much different friction curves were observed for the sliding time from 0 to 30 minutes as shown in Fig.3. The friction coefficient of the steel-steel pair was very low level, 0.02 for 300 seconds and increased gradually to 0.085 finally. That of the a-C:H-a-C:H pair decreased from 0.08 to 0.045 for 1200 seconds, then kept the stable level. That of the ta-C-ta-C pair decreased continuously from high level of 0.09 to 0.045. On the other hand, that of the ta-C(T)-ta-C(T) pair decreased to the super low friction regime below 0.01 in very short time and kept very low level of 0.015 for 1800 seconds. Then, the original friction curves for the a-C:H-a-C:H and the ta-C-ta-C pair were shown in Fig.4. The friction coefficient for the ta-C-ta-C pair decreased to the super low friction in only 30 seconds from the starting point. On the other hand, that of the a-C:H-a-C:H pair did not decrease largely in 45 seconds.

The condition of the oleic acid fluid on the disc was observed as shown in Fig.5. The shape of the oleic acid for the ta-C(T) pair was enlarged in the whole sliding track after the sliding test compared with that of the a-C:H pair. This result suggests that the wettability for the ta-C(T) pair to the fluid must be changed better than that of the a-C:H pair and the tribochemical reaction between ta-C(T) and oleic acid might be generated during sliding.
The friction properties of DLC-DLC under oleic acid lubrication were also evaluated by the rotating sliding test. The friction coefficient for the ta-C(T) pair decreased rapidly to the super low friction regime about 0.005 as shown in Fig.6. Those of the ta-C pair and a-C:H pair decreased gradually to 0.025 level. The shapes of these friction curves except the steel pair were much similar to those for the reciprocating test in Fig.3. On the other hand, that of the steel/steel did not decrease much compared with that for the reciprocating test.

Figure 2. Friction coefficient of DLC-DLC pair

Figure 3. Different friction curves for DLCs
The wear condition on the sliding track was observed by the scanning electron microscopy. Although a few numbers of shallow and circular grooves without the clear delamination were observed on the discs, more numbers of deep and linear grooves were observed on the pin. The pin wear seemed to be severer than that of the disc because the contact area of the pin was always same during the test. The wear conditions on the pin for the a-C:H and ta-C(T) pin were shown in Fig.7. The dark gray colored area was the un-sliding area, the light gray area was the sliding scar and the white colored lines were deep grooves in the upper photograph (low magnification). The deep grooves were formed in the middle of the wear track. Judging from the high magnification photograph, the DLC layer seemed to be delaminated partially for the ta-C(T) pin but the surface roughness around the
grooves kept very smooth. Additionally, the wear debris for the a-C:H and the ta-C(T) seemed to be very fine with submicron size and the granular shape. Therefore, it seemed to keep very smooth sliding surface around the grooves and keep low friction coefficient even if the shallow grooves were formed partially.

**Figure 6.** Friction coefficient of rotating sliding test

**Figure 7.** Wear on a-C:H and ta-C(T) pin after rotating test
For the ta-C which had rougher surface roughness with the droplets generated at the deposition process, the friction coefficient of the reciprocating test decreased from very high level, 0.09 to 0.05 continuously for 1800 seconds in Fig.3 and that of the rotating test decreased from 0.09 to 0.03 in Fig.6. Those friction coefficients seemed to be decreased more. Then, the reciprocating sliding test for longer time (2hours) lubricated with oleic acid was conducted for the ta-C pair and the ta-C(T) pair, as shown in Fig.8. Although the friction coefficient for the ta-C pair reached to lower level of 0.03 at 2 hour, the ta-C film on the pin had deep grooves and the substrate was appeared. Therefore, the friction coefficient might decrease more if the ta-C film would remain uniformly. The performance of reducing friction of ta-C seemed to be almost same as the ta-C(T). This ultra-low friction is thought to be generated by forming very thin and weak tribofilm.

Then the relation between the friction coefficient and the combined surface roughness after the sliding tests was shown in Fig.9. As the combined surface roughness decreased, the friction coefficient decreased lineally except the steel pair. The initial surface roughness numbers for the steel pair, a-C:H pair and ta-C(T) pair were almost same low level, therefore the reason of this super low friction below 0.01 for the ta-C(T) was not thought that the sliding condition entered initially in the simple hydrodynamic lubrication. This ultra-low friction is thought to be generated by forming very thin and weak tribofilm at the mixed lubrication condition.

The friction curves of the DLC pair and the steel pair under oleyl alcohol lubrication by the reciprocating sliding test were shown in Fig.10. The friction coefficient for the ta-C pair and ta-C(T) pair did not decrease largely compared with those of the oleic acid lubrication in Fig.3. That for the a-C:H pair seemed to be almost same level as that for the oleic acid. Although that for the steel pair decreased to 0.03 level and kept low level, the tendency of increasing friction coefficient was observed. It seemed that the reducing friction performance for ta-C and ta-C(T) with oleyl alcohol was lower than that of oleic acid.
Figure 9. Relation between roughness and friction

Figure 10. Friction curves for oleyl alcohol lubrication
J.M. Martin et al. proposed the possible mechanism of the super low friction was the forming water layer by the tribochemical reaction between ta-C and glycerol[4]. In this paper, the formation of water and acid was indicated as one possible chemical reaction for glycerol, as shown in Fig.11. For the oleic acid test, the water can be supplied from the ambient air. Therefore, the super low friction obtained by the ta-C(T) lubricated with oleic acid seemed to form the similar low shear strength tribofilm at the sliding interface. Additionally, it was found that the surface roughness was required to be kept very smooth to maintain this tribofilm. Then, the super low friction was thought to be obtained by this superlubrication condition.

![Dissociation of glycerol (P, T)](image)

Although the accurate and direct experimental data must be required to make clear this super low friction mechanism, the advanced effect obtained by the simple material combination is expected to be applied on the large industrial fields in near future.

### 4. Conclusions

The super low friction property of pure sliding with the ta-C(T) pair coated by the filtered arc deposition process under oleic acid lubrication was found at the mixed lubrication condition. It was thought that the low shear strength tribofilm composed of water and acid seemed to be formed on ta-C sliding interface. Additionally, the smooth sliding surface formed on ta-C(T) was seemed to be required to keep this tribofilm. Then, the super low friction was thought to be obtained by this superlubrication condition.

### 5. References

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