SUPER LOW FRICTION PROPERTY OF DLC LUBRICATED WITH ESTER-CONTAINING OIL

--PART 1: FRICTION PROPERTIES EVALUATED IN RIG TESTS--

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This paper presents a material combination that reduces the friction coefficient markedly to a super low friction regime (below 0.01) under boundary lubrication. Friction tests were conducted with a test rig consisting of three pins pressed against a rotating disc, as shown in Fig. 1. The pins were made of bearing steel AISI52100 and the disc was made of carburized steel SCM415, which was coated with a diamond-like-carbon (DLC) film. The test conditions were as follows.

Pins: Fixed, not rotating; DLC: CVD a-C:H, PVD ta-C; Lubricant: 5W-30 API SG Engine oil; Ester-containing oil(PAOES1): Poly alpha-Olefin containing 1 mass% of glycerol mono-oleate; Pressure: 0.7 Gpa; Sliding speed: 0.03 - 1m/s; Oil temperature: 353K (80 deg. Celsius).

The friction coefficients obtained for several material combinations at a constant test speed of 0.03 m/s are shown in Figure 2. In the case of the 5W-30 oil, the friction coefficient of the steel(Pin)/steel(Disc) pair was high at 0.12. That of the steel/ta-C pair decreased substantially to 0.08, although that of the steel/a-C:H pair decreased only a little to 0.1. As the hydrogen content of DLC decreased, the friction coefficient decreased [1].

In the case of the Ester-containing oil PAOES1 oil, the friction coefficient of the steel/ta-C pair showed a surprisingly low level of 0.02. In contrast to that low level, the friction coefficient of the steel/steel or the steel/a-C:H pair displayed a high friction level above 0.08 [2].

Fig. 1 Pins-on-disc test rig & test conditions
Fig. 2 Friction properties at low sliding speed
The friction properties were then evaluated in a pin-on-disc test as a function of the sliding speed for the steel/ta-C pair lubricated with PAOES1 oil and compared with those of the steel/a-C:H pair and with the results found for the roller bearing test lubricated with 5W-30 engine oil. The cylindrical steel roller thrust bearing was set to make rolling contact to the steel disc. The results are shown in Figure 3. The data indicate that the friction coefficients of the steel/ta-C pairs are much lower than those of the steel/a-C:H pairs. The most notable result here is that the steel/ta-C pair lubricated with PAOES1 oil exhibited a super low friction coefficient of 0.006 at sliding speeds over 0.1 m/s (100 rpm), which was comparable to the friction coefficient of the roller bearing (pure rolling). This super low friction performance demonstrates for the first time that the rolling contact friction level of roller bearings can be obtained in sliding contact under a boundary lubrication condition.

After that sliding test, nano-scale friction property of the ta-C disc sample was investigated by nanoscratch measurement for estimating an influence from surface roughness. Figure 4 shows the nano-scale friction distributions relative to depth for the sliding area compared with the non-sliding area under three conditions. The detail experimental conditions are referred to Part 2 of our research (3). The first condition was a non-cleaned surface after the sliding test; the second condition was a cleaned surface subjected to super sonic cleaning in a hexane solvent; and the third condition was a rewetted surface with PAOES1 oil after hexane cleaning. The sliding area displayed a lower friction coefficient than the non-sliding area and exhibited a notable reduction near the surface at a depth of less than 5 nm. There was no large difference of friction in three conditions. Additionally, no significant difference in surface roughness was seen between the sliding and non-sliding areas. These results suggest that a thin tribofilm with low shear strength formed on the sliding surface of the a-C disc lubricated with PAOES1, which resulted in the super low friction phenomenon (4).

The origin of super lubricity in that condition could be attributed to the tribochemical reaction of alcohol groups with the carbon material, resulting in an OH-terminated surface similar to the case of hydrogenated DLC in a dry inert gas atmosphere (5)(6). Such a reduction in sliding friction under lubricated conditions is very important and useful in many industrial applications, especially in automotive powertrain systems for the sake of addressing global environmental issues.

Conclusions:
Material combinations consisting of a DLC coating and friction modifier additive were investigated in sliding tests. The results revealed a material combination that reduced the friction coefficient markedly to a super low regime (below 0.001) under boundary lubrication.
1. The ultra-low friction property was obtained by sliding hardened steel pins on a hydrogen-free diamond-like carbon (ta-C) film lubricated with a poly-alpha-olefin (PAO) oil containing an ester additive at 0.03m/s constant sliding speed.
2. The super-low friction property was confirmed in a pin-on-disc test at higher sliding speeds under a boundary lubrication condition.
3. The super-low friction level is thought to be obtained by the interaction between the ta-C coating and the ester-containing oil and presumably occurred because of the formation of a very thin and low-shear-strength tribofilm on the ta-C sliding surface.

Fig.3 Friction property with increasing speed

Fig.4 Nanoscratch measurements