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Super low friction of DLC applied to engine cam follower lubricated with ester-containing oil

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Abstract

This paper presents a material combination that reduces the friction coefficient markedly to a superlow friction regime (below 0.01) under boundary lubrication. A state approaching superlubricity was obtained by sliding hardened steel pins on a hydrogen-free diamond-like carbon (DLC) film (ta-C) lubricated with a poly-alpha-olefin (PAO) oil containing 1 mass% of an ester additive. This ta-C/steel material combination showed a superlow friction coefficient of 0.006 at a sliding speed of 0.1 m/s. A hydrogencontaining DLC coating/steel combination also showed a lower friction coefficient in air than a steel/steel combination, 0.1 vs. 0.8, but no large reduction was observed when the sliding surfaces were lubricated with ordinary 5W-30 engine oil and the PAO oil containing an ester additive. The friction coefficient of the hydrogen containing DLC/steel combination lubricated with the PAO containing an ester additive was above 0.05. On the other hand, the superlow friction performance demonstrates that the rolling contact friction level of needle roller bearings can be obtained in sliding contact under a boundary lubrication condition. It is planned to apply this advanced DLC coating technology to valve lifters lubricated with a newly formulated engine oil in actual mass-produced gasoline engines. A larger friction reduction of more than 45% is expected to be obtained at an engine speed of 2000 rpm.

Keywords: Diamond like carbon; Super low friction coefficient; Ester containing oil

1. Introduction

Fuel-saving technologies have become more important recently, especially for automobiles, in order to avoid global environmental destruction and resource depletion. Technologies for reducing friction are direct ways of improving vehicle fuel economy.

The cam follower accounts for about 20–30% of automotive engine friction under the conditions of ordinary use at engine speeds below 2000 rpm. In the last 10 years, various techniques have been developed for reducing the surface roughness of the camshaft and cam follower. To keep the surface roughness low, a hard coating such as chromium nitride (CrN) or titanium nitride (TiN) is now applied to the cam follower of the valve lifter type. A cam follower coated with a diamond-like carbon (DLC) has also been developed to reduce engine friction [1].

2. Test method

A friction test was conducted by sliding three pins on 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 DLC. Although the friction coefficient of three bearing steel pins slid on a DLC-coated disc in air was reduced from 0.8 to 0.1, the effect of the DLC coating on reducing the friction coefficient was very small in engine oil [2]. In the present study, we observed for the first time anywhere in the world that DLC lubricated with an ester-containing oil displayed super low friction properties.

The test condition is shown in the table of Fig. 1. The slow sliding speed was ranging from 0.03 to 1 m/s and the high contact pressure of 700 Mpa was comparable to the actual cam follower contact pressure.

Two kinds of DLC were prepared. First one was the a-C:H coated by CVD process which contained about 20 atomic % hydrogen and the other was the ta-C coated by

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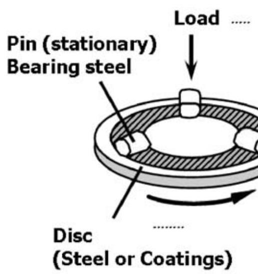

	Lubricated condition
Rotational speed (sliding velocity)	30 rpm – 1000rpm (0.03 m/s - 1m/s)
Load (contact pressure)	490 N (0.7 GPa)
Circumstance	Oil bath
Temperature	80 .
Test duration	60 min.

Fig. 1. Pin on disc test rig and test conditions.

PVD process. Two kinds of main lubricants were the standard engine oil and the simply blended oil. The engine oil was 5W-30 API SG Oil. The blended oil was the ester-containing oil named as PAOES1 which was Poly alpha-olefin containing 1 mass% of glycerol mono-oleate. The kinematic viscosity of PAOES1 was same as that of 5W-30 oil at 80 °C.

3. Results and discussion

The friction coefficients for several-material combinations at a constant test speed of 0.03 m/s after sliding for 60 min s are shown in Fig. 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 pin/ta-C disc pair decreased substantially to 0.08, although that of the steel pin/a-C:H disc pair decreased only a little to 0.1. As the hydrogen content of the DLC coating decreased, the friction coefficient decreased, as shown in Fig. 3 [3].

In the case of PAO containing glycerol mono-oleate (PAOES1 oil), the friction coefficient of the steel pin/ta-C disc pair showed a surprisingly low level of 0.02. In contrast to that low level, the friction coefficient of the steel or a-C:H disc pair displayed a high friction level above 0.08 [4].

The friction properties were then evaluated in a pin-on-disc test as a function of the sliding speed for the steel pin/ta-C disc pair lubricated with PAOES1 oil. The results were compared with those for the steel pin/a-C:H disc pair and with the results found for a roller bearing lubricated with 5W-30 engine oil. The results are shown in Fig. 4. The data indicate that the friction coefficients of the steel pin/ta-C disc pairs are much lower than those of the steel pin/a-C:H disc pairs. The most notable result here is that the steel pin/ta-C disc 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). During this test, the surface roughness of the steel pin decreased from 0.033 to 0.011 μm Ra and that of ta-C disc decreased from 0.014 to 0.013 μm Ra. The composite surface roughness of the steel pin and ta-C disc which was defined as the root mean square deviation of roughness profile decreased from 0.049 to 0.024 μm Rq. The calculated minimum oil film thickness, Hmin was increased from 0.0033 μm at 30 rpm (0.03 m/s) to 0.039 μm at 1000 rpm (1 m/s). Then, the film parameter which was calculated by $H_{\min}/\mathrm{Rq}$ was increased from 0.14 to 1.58. Judging from these values, this test was estimated to be conducted under a boundary lubrication condition. This super low friction performance demonstrates for the first time that the rolling contact friction

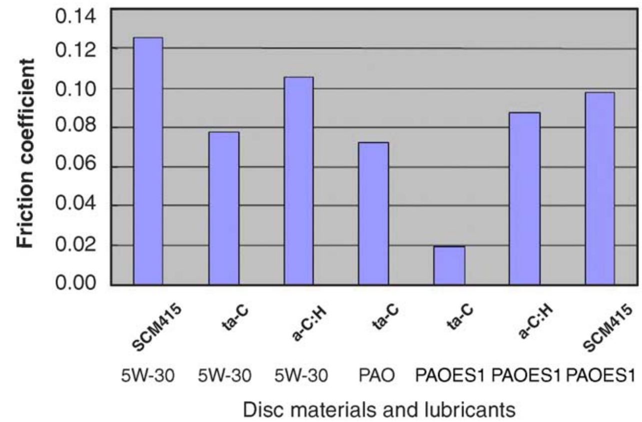

Fig. 2. Friction properties at low sliding speed.

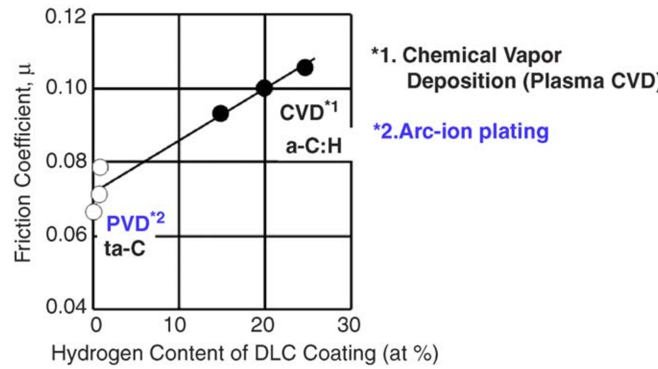

Fig. 3. Effect of hydrogen content in DLC on friction coefficient.

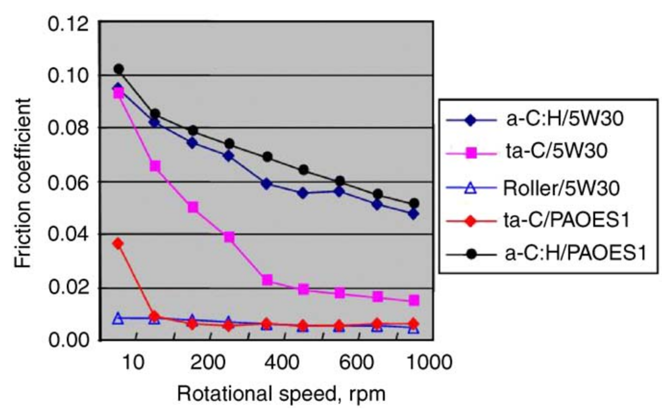

Fig. 4. Friction property with increasing speed.

level of roller bearings can be obtained in sliding contact under a boundary lubrication condition.

The valvetrain is a significant source of mechanical friction loss in an automobile engine, especially at low speeds where fuel economy is most important. Friction at the sliding interfaces between the cam and follower accounts for about 80% of all valvetrain system friction and 20% of the total engine friction. Therefore, the DLC coating for obtaining a super low friction level was first applied to the engine cam follower lubricated with standard 5W-30 engine oil.

A cam and follower pair was tested, with the test cam made of chilled cast iron fitted to a shaft driven by a variable speed DC motor while the follower was pressed against the cam by a load spring, as shown in Fig. 5. Friction torque was measured with a torque sensor. The measured results for the friction torque at the cam/follower interface are shown in Fig. 6 as a function of the cam/follower composite surface roughness after the test. The results indicate that friction torque decreased as the composite surface roughness was reduced. The ta-C coating is below a line drawn in relation to the composite roughness. This result reaffirmed the finding of the preliminary pin-on-disc tests.

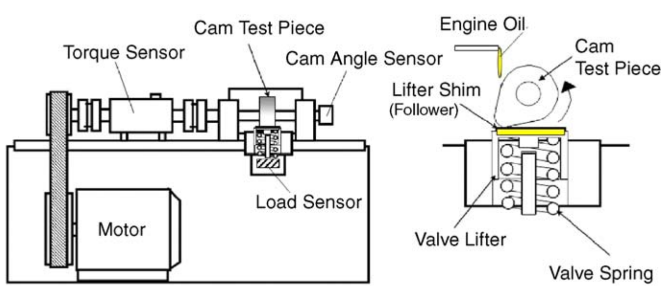

Fig. 5. Single cam and follower test rig.

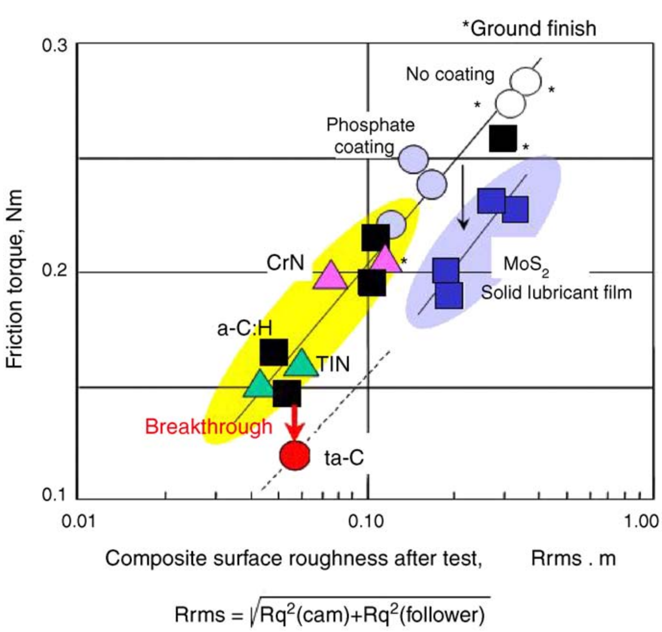

Fig. 6. Reduction in cam/follower friction torque.

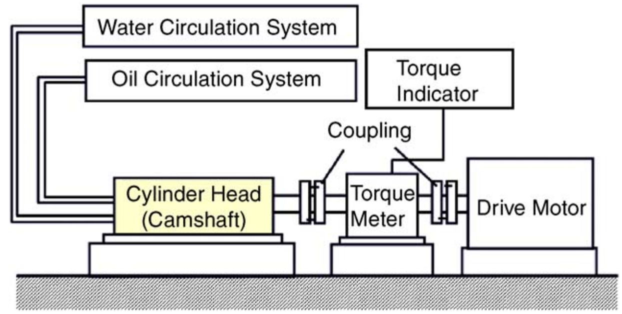

Fig. 7. Engine valvetrain motoring test.

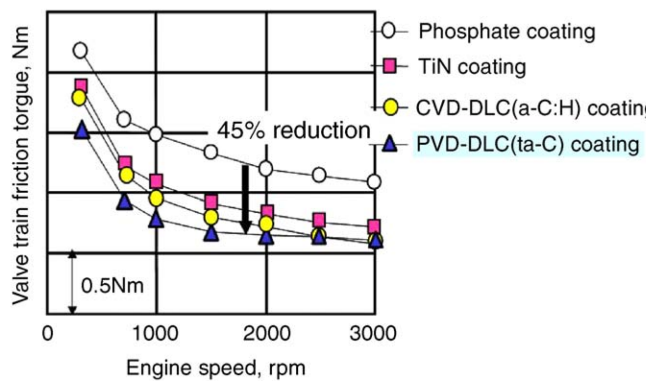

Fig. 8. Reduction in valvetrain friction torque.

Based on the results of the preliminary experiments, bench tests were then conducted with an actual engine to examine the effect of the ta-C coating on reducing friction losses. The cylinder head was mounted on a test stand, and the camshaft made of chilled cast iron was driven directly by a drive motor via a torque meter, as shown in Fig. 7. Fig. 8 shows the effect of various coatings on valvetrain friction torque as a function of engine speed. The ta-C coating reduced friction torque by 45% compared with the result for a conventional phosphate coating at an engine speed of 2000 rpm. A durability test was then conducted at an engine speed of 4000 rpm for about 300 h, and none of the cam/follower interfaces showed any adhesive or abrasive wear or noticeable peeling of the coating.

4. Conclusions

The super low friction coefficient of 0.006 was obtained by the material combination of the steel pin/ta-C disc pair lubricated with the ester containing PAO oil at the boundary lubrication condition. This value was comparable to the friction coefficient of the roller bearing (pure rolling).

It is planned to apply this advanced DLC coating technology to valve lifters lubricated with a newly formulated ester containing engine oil in actual mass-produced gasoline engines. A larger friction reduction of more than 45% is expected to be obtained at an engine speed of 2000 rpm by using the ester containing oil.

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