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DLC Coating Technology Applied to Sliding Parts of Automotive Engine

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In this paper, the author presents several recent applications of diamond-like carbon (DLC) coating to sliding parts in an automotive engine with superior wear resistance and tribological properties. The author focuses on the technology of applying a hydrogen-free DLC, tetrahedral amorphous carbon (ta-C) coating to an engine valve lifter to reduce engine friction. This application is based on the superlow friction generated by a ta-C coating lubricated with various lubricants that contain a hydroxyl group. This material combination reduces the coefficient of friction significantly to a superlow friction coefficient regime (below 0.01) under boundary lubrication, as indicated by the results of pin-on-disc toric sliding tests and reciprocating sliding tests (SRV). This superlubricity was obtained by sliding hardened steel pins on a ta-C disc lubricated with polyalpha-olefin (PAO) oil containing an ester additive and a ta-C/ta-C pair with pure glycerol. This superlubricity is thought to be generated by the formation of a very thin and weak share-strength tribofilm made of a hydroxyl group. Significant reductions in both friction and wear under boundary lubricated conditions are crucial for applications in many industrial fields. Moreover, the outstanding performance of the ta-C friction pair lubricated by glycerol, whose elements are only carbon, oxygen and hydrogen, suggests very promising future applications in medical science, food and in the field of nanotechnology.

1. Introduction

Recently, the increase in the number of environmental problems and petroleum depletion rate have appeared to accelerate becoming severer each year. Therefore, the reduction in automotive power-train friction has become necessary in recent years for improving fuel economy.

Diamond-like carbon (DLC) is a promising coating material for improving fuel economy because of its superior wear resistance and friction properties.(1,2) Therefore, several types of DLC have been applied to the sliding parts of automotive devices.

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Table 1 shows some recent applications of DLC. A few types of hydrogenated DLC, a-C:H have been applied to the sliding parts in the differential gear and the torque-controlled electromagnetic clutch coupling of a sports utility vehicle, and to a diesel engine fuel pump (plunger, bearing pin, washer, bush, needle valve). For the differential gear, the superior wear resistance of DLC to pitting and scoring has been exploited. For the electromagnetic clutch application, the superior friction properties with the high friction coefficient, the flat friction coefficient to changing sliding velocity and the high wear resistance have been used in the compact clutch system. For the diesel fuel pump, the superior wear resistance to scuffing in severe diesel fuel lubrication has been used. Additionally, one type of a-C:H has been applied to the engine piston top and oil piston rings of a motorcycle engine, for which the high scuffing wear resistance to the sliding on the aluminum alloy cylinder liner has been used.

Although these types of hydrogenated DLC can be enlarged to be applied to severe sliding parts, they are mainly used for their advantage of high wear resistance. The friction coefficient of the hydrogenated DLC, a-C:H formed by chemical vapor deposition (CVD), is comparable to other hard coatings, such as TiN and CrN formed by physical vapor deposition (PVD) under the boundary lubrication condition lubricated with standard gasoline engine oil.(3,4)

On the other hand, hydrogen-free tetrahedral DLC, ta-C reduces friction substantially by 40% when lubricated with standard engine oil compared with hardened steel, and lubrication with the ester containing polyalpha olefin (PAO) oil reduces friction drastically by 80%.(5–7) Additionally, the material combination of ta-C/ta-C lubricated with pure glycerol has a superlow friction coefficient of below 0.01.(8) These experimental results obtained by rig tests are shown in detail in this paper.

Reducing the friction between the cam and the follower is effective in the low-engine-speed range and can reduce fuel consumption effectively during this most frequent condition. The ta-C-coated cam follower of the bucket type has been applied to gasoline engines to reduce engine friction. Additionally, low friction is obtained using ta-C lubricated with ester-containing PAO oil. This low friction technology of the ta-C coated cam follower with a new formulated gasoline engine oil, which contains an ester, will be applied to mass-produced gasoline engines from autumn 2006 for the first time in the world.

Table 1
DLC coating technology applied to sliding parts in automotive device.

Applied parts	DLC coating	DLC property
Motorcycle engine piston ring	CVD a-C:H	High scuffing resistance to aluminum alloy of cylinder
SUV differential gear	CVD a-C:H	High pitting wear resistance
SUV 4WD torque-controlled coupling clutch	CVD a-C:H-Si	High friction coefficient and wear resistance
Diesel fuel pump (plunger, washer, bush, needle valve)	CVD a-C:H	High scuffing resistance to diesel fuel lubrication
Automotive engine valve lifter, piston ring, piston pin	PVD ta-C	Ultralow friction and high wear resistance

Additionally, the total effect of reducing friction by applying the gasoline engine oil to a ta-C-coated piston top ring, a piston pin and a valve lifter is measured to be more than 20%, which is estimated to reduce fuel consumption by about 2%.

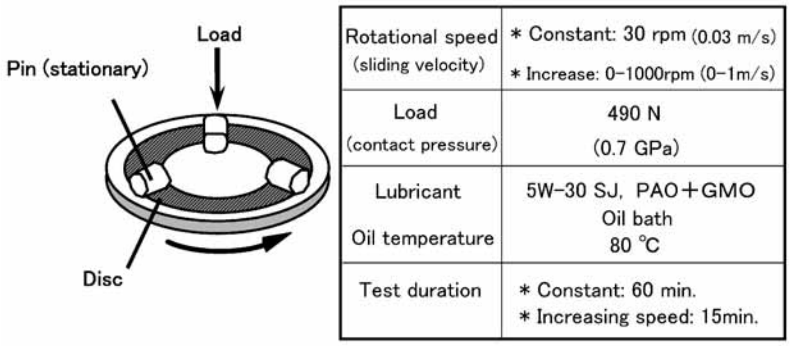
2. Superlow Friction

2.1 *Test method*

Pin-on-disc sliding tests were conducted in the following manner. The pins, measuring 5 mm in diameter and 5 mm in length, were made of hardened bearing steel and polished to a surface roughness of Ra 0.05 μm. The disc measured 35 mm in diameter and 2.5 mm in thickness and was made of carburized steel. DLC was coated on the disc and pins. The three pins were secured to prevent them from rotating and were pressed against the toric sliding surface of the rotating disc 20 mm from the center of the disc, as shown in Fig. 1.

Contact at the sliding interfaces was in the shape of lines under a high Hertzian pressure of 700 MPa. Lubrication was provided by an oil bath heated to 353 K. Two types of DLC were prepared. The first type was a-C:H coated by CVD that contained about 20 atomic% hydrogen, and the other was ta-C coated by PVD. The two types of lubricant used were standard engine oil and simply blended oil. The engine oil was 5W-30 API SG oil. The blended oil was an ester-containing oil named PAO+GMO, which consisted of polyalpha-olefin containing 1 mass% of glycerol mono-oleate (GMO). The kinematic viscosity of PAO+GMO was the same as that of 5W-30 oil at 80°C. Two conditions for the sliding tests were used. The first was a constant speed of 0.03 m/s for 60 min, and the second was an increasing speed from 0 to 1 m/s.

Reciprocating sliding (SRV) tests were performed using a reciprocating pin-on-disc tribometer that was lubricated before the test by wetting with several droplets (5 cc) of the test oil heated to 353 K. The pins, measuring 18 mm in diameter and 22 mm in length, were made of hardened steel and polished to a surface roughness of Ra 0.05 μm. The disc measured 24 mm in diameter and 7.9 mm in thickness and was made of carburized steel. The reciprocating pins were pressed against the stationary disc by a force of 400 N that generated 270 MPa of pressure, as shown in Fig. 2. The length of the track was 3.0 mm and the reciprocating time was 15 min at 50 Hz.



Rotational speed (sliding velocity)	* Constant: 30 rpm (0.03 m/s) * Increase: 0–1000rpm (0–1m/s)
Load (contact pressure)	490 N (0.7 GPa)
Lubricant Oil temperature	5W-30 SJ, PAO+GMO Oil bath 80 °C
Test duration	* Constant: 60 min. * Increasing speed: 15min.

Fig. 1. Pin-on-disc sliding test and test conditions.

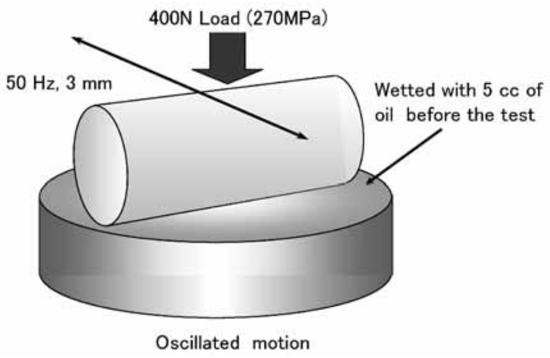


Fig. 2. SRV oscillated-motion sliding test.

2.2 *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 are shown in Fig. 3. 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 slightly to 0.1. As the hydrogen content of the DLC coating decreased, the friction coefficient decreased.(4) In the case of PAO+GMO oil, the friction coefficient of the steel pin/ta-C disc pair was surprisingly low at 0.02. In contrast to that, the friction coefficient of the steel pin/a-C:H disc pair was high, above 0.08.

The friction properties were then evaluated by a pin-on-disc test as a function of the sliding speed for the steel pin/ta-C disc pair lubricated with PAO+GMO oil. The results were compared with those for the steel pin/a-C:H disc pair and those 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 PAO+GMO oil exhibited a superlow friction coefficient of 0.006, which was comparable to the friction coefficient of the roller bearing (pure rolling) at sliding speeds of over 0.1 m/s (10 rpm). This superlow 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.

Second, using the more severe SRV friction test, to confirm this ultralow friction (below 0.1) property, the ta-C/steel friction pair lubricated with PAO+GMO was evaluated using the SRV test machine, which is commonly used to evaluate the boundary lubrication properties of engine oil. The ta-C/steel couple showed a friction coefficient of 0.04, as shown in Fig. 5, compared with the value of 0.02 measured in the pin-on-disc test. The reason for this discrepancy is that SRV was averaged with values measured during reciprocating motion, including the high values at the reciprocating points. Nevertheless, the friction coefficient of ta-C/steel was much lower than the friction coefficients exhibited by the a-C:H/steel couple and the steel/steel couple, both of which showed a higher friction coefficient than that from the pin-on-disc test results. Thus, the ultralow friction property of the ta-C/steel couple lubricated with PAO+GMO was observed in two different testing machines.

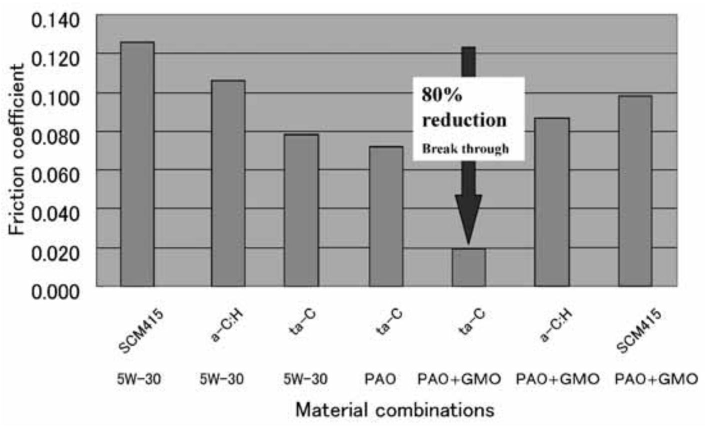


Fig. 3. Ultralow friction of ta-C/steel lubricated with ester-containing oil.

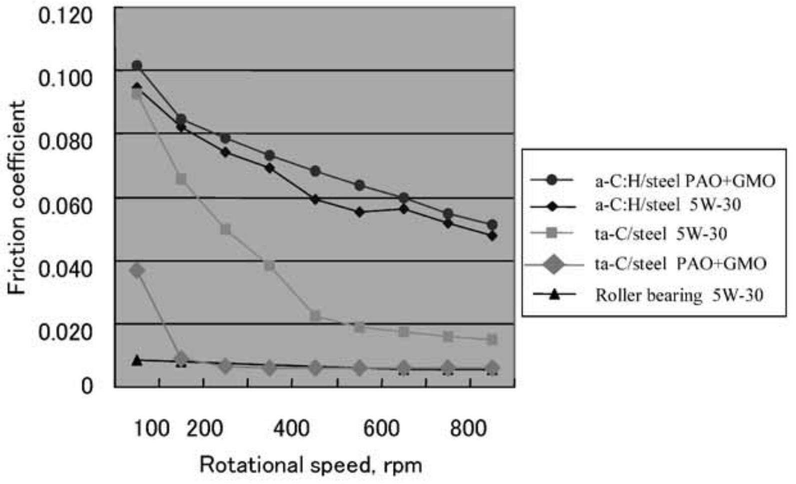


Fig. 4. Superlow friction comparable to roller bearing.

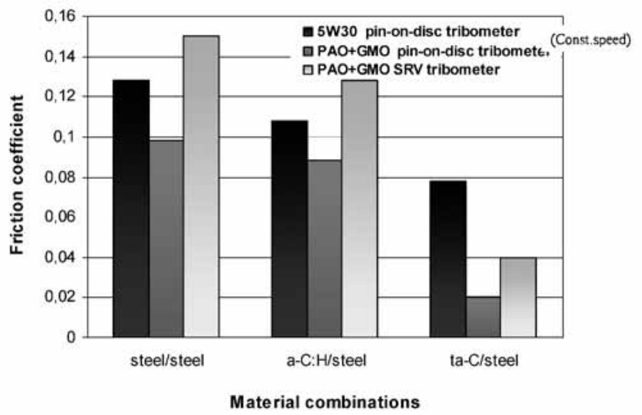


Fig. 5. Ultralow friction property evaluated by pin-on-disc and SRV tests.

The friction properties of DLC couples lubricated with PAO+GMO were also evaluated by the SRV test to clarify the reason for the ultralow friction. Figure 6 shows the friction coefficients of different material combinations lubricated with PAO+GMO and pure glycerol. Extremely impressive results were obtained for the ta-C/ta-C combination. The friction coefficients of the ta-C couples were substantially lower than those of the a-C:H couples and that of the ta-C/steel combination (see Fig. 5). These results strongly suggest that ultralow friction is obtained by the interaction between the ta-C coating and the ester-containing oil and is definitely due to the formation of a very thin low-shear-strength tribofilm on the ta-C sliding surface. Moreover, outstanding superlow friction and zero-wear behaviour were obtained for the ta-C/ta-C combination lubricated with pure glycerin at 80°C. As shown in Fig. 6, the friction coefficient was below 0.01 and was not actually measurable with the equipment at hand. Moreover, the wear scar was not visible by optical microscopy. This result suggests that the superlubricity is related to the alcohol chemical function (OH), which is common to both GMO and glycerol molecules.

The origin of superlubricity under these conditions has been investigated by ToF-SIMS (time of flight secondary ion mass spectrometry) analysis of worn surfaces. Results are in agreement with the formation of an OH-terminated carbon surface. This new surface chemistry is formed by the tribochemical reaction of alcohol functional groups with the friction-activated ta-C atoms. The origin of superlubricity could be due to the very low energy of interaction between OH-terminated surfaces. Such a marked reduction in both friction and wear under boundary-lubricated conditions will be crucial for many industrial applications. Moreover, the outstandingly low friction of the ta-C pair lubricated by glycerol, whose elements are only carbon, oxygen and hydrogen, suggests very promising future applications in medical science and in the field of nanotechnology.

3. Application of Superlow Friction

The valve train is a significant source of energy loss due to mechanical friction in automobile engines, particularly at low engine speeds, where fuel economy is most important. Friction at the sliding interfaces between the cam and the follower accounts for

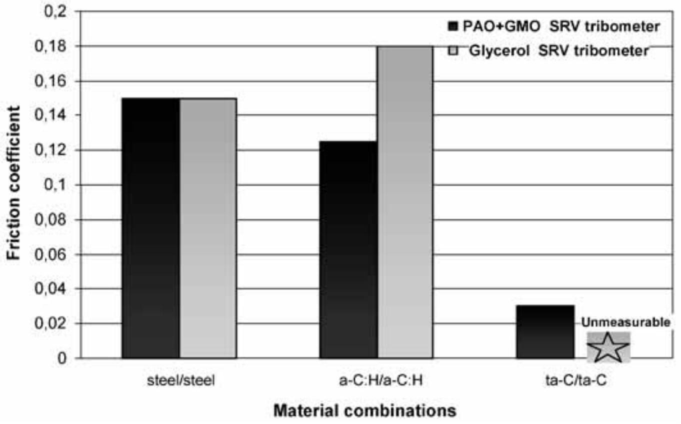


Fig. 6. Superlow friction obtained by ta-C/ta-C lubricated with glycerol.

about 80% of all the valve train system friction and 20% of the total engine friction. Therefore, the ta-C coating was first applied to the engine's cam and follower lubricated with standard 5W-30 engine oil to obtain a low friction level, as shown in Fig. 7.

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. 8. Friction torque was measured using a torque sensor. The measured results for the friction torque at the cam/follower interface are shown in Fig. 9 as a function of the cam/follower composite surface roughness after the test. The results indicate that friction torque decreased as composite surface roughness was reduced. The results for the ta-C coating are below the line drawn in relation to the composite roughness. This result reaffirmed the finding of the preliminary pin-on-disc tests.

Finally, bench tests were conducted with an actual engine to examine the effect of the ta-C coating on reducing energy loss from friction. 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. 10.

Figure 11 shows the effect of various coatings on valve train friction torque as a function of engine speed. The ta-C coating reduced friction torque by 45% compared with a conventional phosphate coating at an engine speed of 2000 rpm. A durability test was then

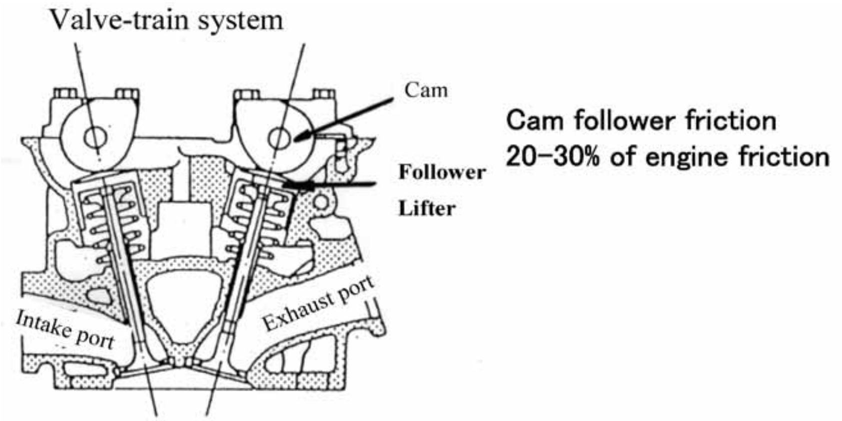


Fig. 7. Valve train system.

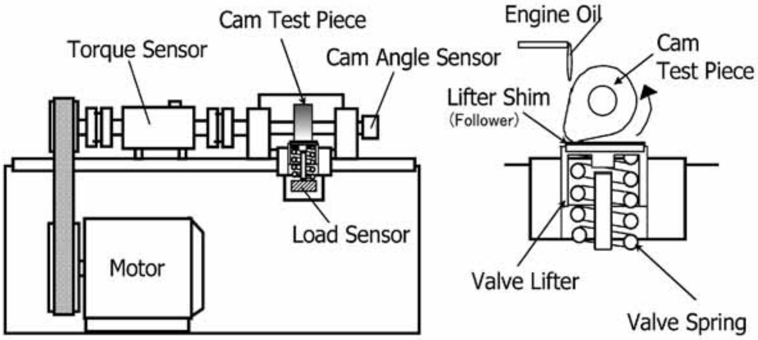


Fig. 8. Single cam and follower sliding test rig.

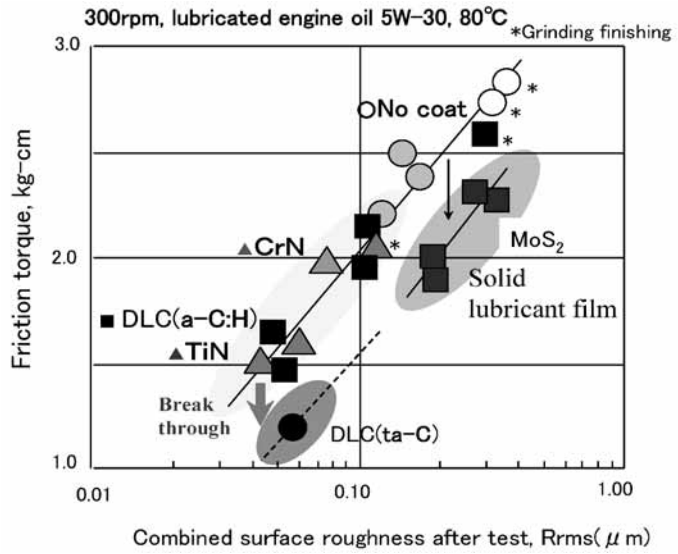


Fig. 9. Friction reduction by ta-C valve lifter (single cam and follower test).

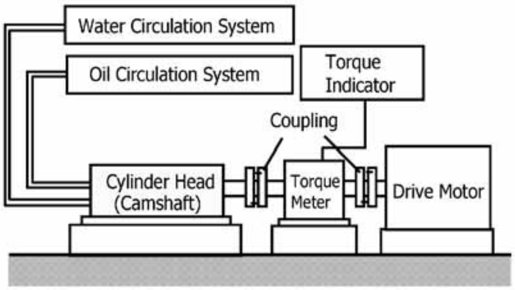


Fig. 10. Friction test using actual engine cam/follower.

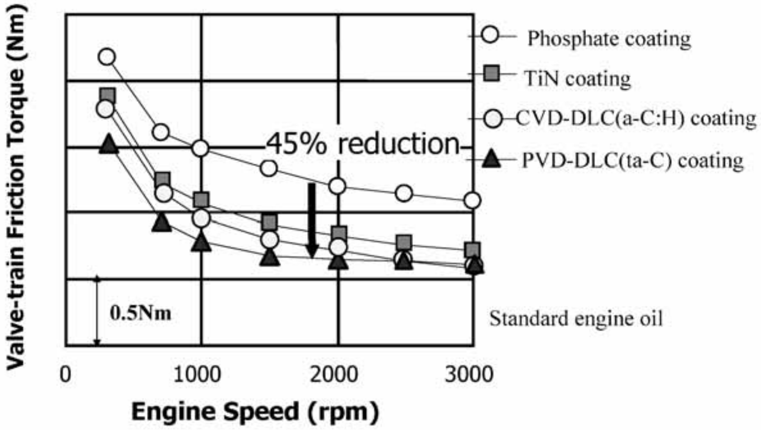


Fig. 11. Friction reduction by ta-C valve lifter (engine motoring test).

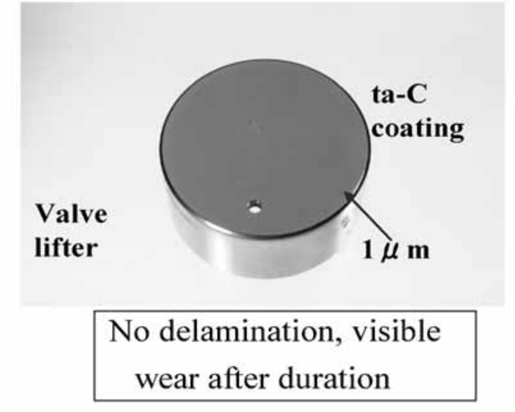
conducted at an engine speed of 4000 rpm for about 300 h, and none of the cam/follower interfaces showed any adhesive or abrasive wear or noticeable peeling of the coating.

From autumn 2006, the ta-C coated valve lifter as shown in Fig. 12, with the new gasoline engine oil, which contains GMO without the MoDTC additive, will be applied to new V6 gasoline engines for mass-produced engines. This new material technology could decrease fuel consumption by about 2%.

4. Technical Issues for DLC Coating Technology

Although DLC coating technology applied to the sliding members is being accelerated for use in actual mass-produced automotive sliding parts, there are several technical issues, as shown in Table 2.

For performance, the superlow friction that was obtained by the rig-sliding test using a simple lubricant, as mentioned before, has not yet been applied to actual mechanical sliding parts. To obtain this performance, the development of lubricants and the optimization of additives and surface finishing are necessary.



No delamination, visible wear after duration

Fig. 12. ta-C coating applied to gasoline engine valve lifter.

Table 2
Technical issues of DLC coating technology.

Performance	Reducing friction in B.L.	Optimizing lubricants and surface finishing
	Increasing wear resistance	Thicker coating layer Wear mechanism and evaluation method
	Increasing adhesive strength	Interlayer for soft substrate material such as aluminum alloy
Productivity	Reducing cost	Coating process breakthrough such as coating by atmosphere plasma
	Size limitation	Coating process breakthrough such as coating by atmosphere plasma
Mechanism	Superlow friction	Analysis method for thin tribofilm

For productivity, the limitation of the coating size and difficulty in coating inner walls uniformly result in increasing cost and limiting application. One promising process will be developed to coat DLC by an atmosphere plasma method.

For the mechanism of superlow friction, it is very difficult to analyze a very thin tribofilm that contains only carbon, oxygen and hydrogen, which are the same elements as in the lubricant and substrate.

5. Summary

A superlow friction coefficient of 0.006 was obtained by the material combination of a steel pin/ta-C disc pair lubricated with an ester-containing PAO oil under the boundary lubrication condition. This value is comparable to the friction coefficient of a roller bearing (pure rolling).

This advanced DLC coating technology has been applied to valve lifters lubricated with an engine oil containing the newly formulated ester for actual mass-produced gasoline engines. Improving fuel economy by a few percent is expected to be obtained at an engine speed of 2000 rpm by combining DLC and the ester-containing oil.

The origin of superlubricity under these conditions was investigated by ToF-SIMS analysis on worn surfaces. Results are in agreement with the formation of an OH-terminated carbon surface. This new surface chemistry is formed by the tribochemical reaction of alcohol functional groups with the friction-activated ta-C atoms. The origin of superlubricity could be due to the very-low-energy interaction between OH-terminated surfaces. Such a marked reduction in both friction and wear under boundary-lubricated conditions is crucial in many industrial applications. Moreover, the outstanding superlow friction performance of the ta-C friction pair lubricated using glycerol suggests very promising future applications in medical science and in the field of nanotechnology.

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