

Development of Piston Surface Treatment for Internal Combustion Engine

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ABSTRACT

Low-friction surface treatment technology that provided high wear resistance was developed for the piston skirt of an internal combustion engine. Conventional low-friction coating materials consist of a solid lubricant, such as molybdenum, and the effectiveness of performance was not expected to be maintained for a long time because lower friction was realized by self-lubrication, wear, and abrasion. The newly developed technology uses a high-strength film, which has an oil adsorption effect, enabling friction to be reduced by about 40% while increasing wear resistance about 5-fold as compared to conventional coating materials.

Concerning productivity, because this technology employs piston spray painting technology, the new film can be applied by simply replacing the material without any need for special production equipment.

1. Introduction

Efficient use of energy resources has been demanded due to social and economic background, such as the necessity of protecting the environment, emissions regulations, and depletion of fossil fuel reserves. Approximately 40% of the total energy generated by gasoline internal combustion engines is lost as mechanical loss⁽¹⁾. The reduction of mechanical loss therefore has a role to play in increasing the fuel efficiency and power of gasoline engines.

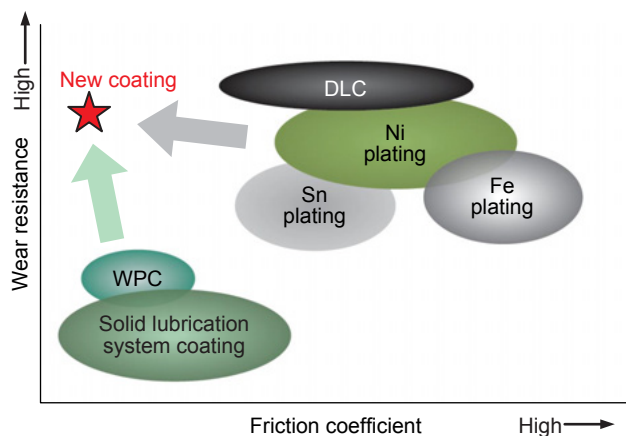


Fig. 1 Piston surface treatment

The sliding resistance of the pistons accounts for approximately 40% of mechanical loss⁽²⁾, and the development of technologies such as lighter components, low-tension piston rings, and piston surface treatments has resulted in increased mechanical efficiency.

The main objectives in the application of surface treatments to pistons are to enhance initial performance, to simplify the break-in run including adaptation to contact faces⁽³⁾, and to increase seizing resistance. The representative piston surface treatments are shown in Fig. 1.

The use of dry film lubricants is one typical piston surface treatment, which employs solid lubricants such as molybdenum disulfide, graphite, and PTFE. Solid lubricants reduce friction by means of cleavage (slipping on the faces of the crystal structure where the van der Waals force is weak) and other forms of self-lubrication, and abrasion is therefore unavoidable. Because of this, the retention of the film over an extended period remains an issue to be addressed.

2. Lubrication State of Piston Skirt

The important factor in piston tribology is that the cylinder bore and piston are able to maintain hydrodynamic lubrication. Figure 2 shows a Stribeck curve⁽⁴⁾, illustrating the state of lubrication and the friction characteristics of the sliding surfaces.

When the sliding speed is low, the surfaces are in a

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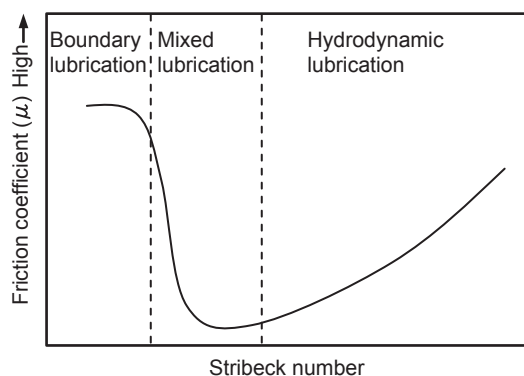


Fig. 2 Stribeck curve

state of boundary lubrication, in which they make contact and slide against each other. Therefore, the coefficient of friction is high. At high speeds the surfaces are in a state of hydrodynamic lubrication with almost no contact between them, and the coefficient of friction is low. At medium speeds, in the transfer zone between boundary and hydrodynamic lubrication, the surfaces are said to exhibit a mixed lubrication state.

When the conditions of sliding and state of lubrication of a piston skirt is represented as a Stribeck curve, at close to top dead center in the cylinder bore, the piston skirt surface is in a state of boundary or mixed lubrication. From the center to bottom dead center, it is in a state of hydrodynamic lubrication⁽⁵⁾.

Slight differences also occur in the state of lubrication of the piston in response to engine speed. In particular, boundary lubrication predominates at low engine speeds, and this surface state has an effect on sliding loss in the piston skirt⁽⁶⁾.

While the situation differs depending on conditions, the fact that the pistons display a state of boundary lubrication makes it challenging to reduce friction.

3. Material Design

The technology discussed here reduces sliding loss by forming a film on the piston skirt that ensures adsorption and retention of oil, thus extending the range of hydrodynamic lubrication to low-speed sliding, which had previously been characterized by boundary lubrication. In addition, the strength of the film was enhanced to increase abrasion resistance, which has conventionally been a challenging issue.

The following issues of manufacturability and practicality were considered in the design of the materials:

- (1) The material should not need special production facilities.
- (2) The material should not use environmentally harmful substances.
- (3) The material should be produced at low cost.

Dry film lubricants were focused on as materials satisfying the above requirements. The adhesive force of

the bonding resins used in dry film lubricants enables solid lubricants such as molybdenum disulfide, graphite, and PTFE to adhere to the sliding surfaces⁽⁷⁾. The coating is applied at the adequate thickness, after which it is dried or heat strengthened, which produces a lubricant film.

In general, when the strength of the film is increased its toughness declines, and the degree of adhesion is reduced. In other words, there is a trade-off between the strength of the film and its adhesive strength. In order to maximize each of these contradictory properties, the following three parameters were optimized in the development of the material:

- (1) Selection of added particles
- (2) Amount of added particles
- (3) Selection of resin and baking temperature (degree of crosslinking)

4. Tests of Materials

The dynamic friction abrasion testing machine shown in Fig. 3 was employed to simulate the reciprocal motion of the pistons in tests.

Surface treatments were applied to the disks used as a test piece. A pin was used to apply a vertical load to the disk, and the disk was subjected to right-left reciprocating motion under specific conditions of lubrication.

Performance measurements and durability tests in an actual engine were also conducted to evaluate the adhesion of the surface treatment and its performance in an actual engine.

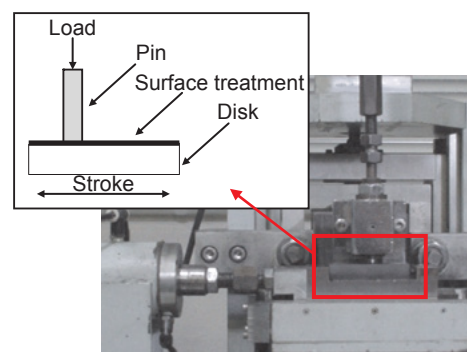


Fig. 3 Dynamic friction abrasion testing machine

5. Test Results

5.1. Oil Adsorption and Abrasion Resistance

Resin materials generally display low wettability and lipophilia⁽⁸⁾, and this was also true of the binding resin employed in this project. Because this research was attempting to use the oil-retaining properties of the film to extend the range of the state of hydrodynamic

lubrication of the piston skirt, it was necessary to increase lipophilia.

In order to increase lipophilia, the properties of the surface were modified by mixing microscopic hard particles in the binding resin that was used as the base of the surface treatment agent. The size of the used particles would affect the ratio of the surface area of the piston occupied by the particles and the binding resin, and would thus change the properties of the piston surface with respect to abrasion. Figure 4 (a) shows the degree of abrasion when the size of the grains is changed for a fixed amount of additive particles to the binding resin.

The graph shows that the degree of abrasion on the treated section of the surface decreases as the size of the grains diminishes. It can be considered that the increase in the specific surface area of the particles in the resin surface had an effect in modifying the abrasion properties of the piston surface, and thereby increasing oil lubrication performance. Larger additive particles were found to reduce the specific surface area of the piston surface. The particles were found to not have an effect in modifying the properties of the surface, but would instead increase the degree of abrasion by themselves causing abrasive wear.

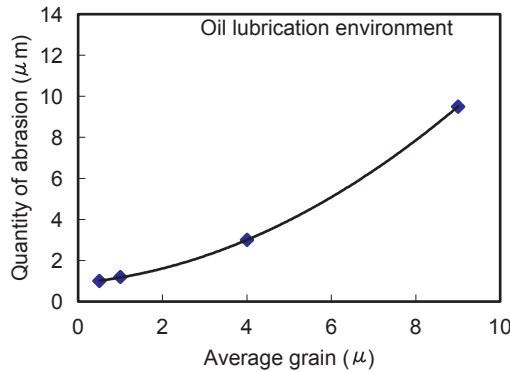
Figure 4 (b) shows the change in the degree of abrasion with respect to the quantity of added particles when the specific surface area of added particles in the resin surface is increased by dispersion of particles of 1 μm and below in size. Figure 4 (c) shows the oil adsorption and oil maintenance effects under the same conditions.

$$\text{Effect} = 1 - \frac{\delta A_{\text{oil}}}{\delta A_{\text{dry}}} \times 100(\%)$$

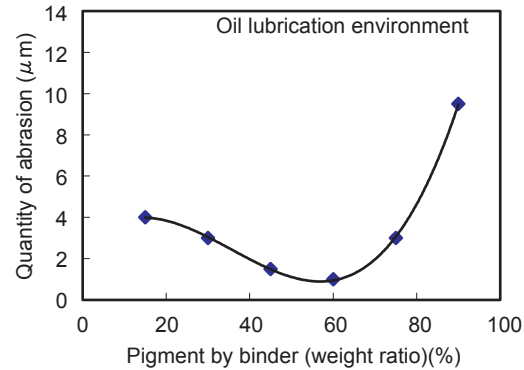
Here, the ratio between the degree of abrasion when oil is employed, δA_{oil} , and the degree of abrasion when no lubrication is employed, δA_{dry} , is used as an index of the oil adsorption and retention effect.

The graph indicates that the degree of abrasion can be controlled by increasing the amount of added particles to the material when oil is used. However, abrasion increases when the ratio of the particles exceeds 60%. This is because when the amount of additive particles exceeds the allowable limit, the binding resin cannot retain the particles and becomes brittle.

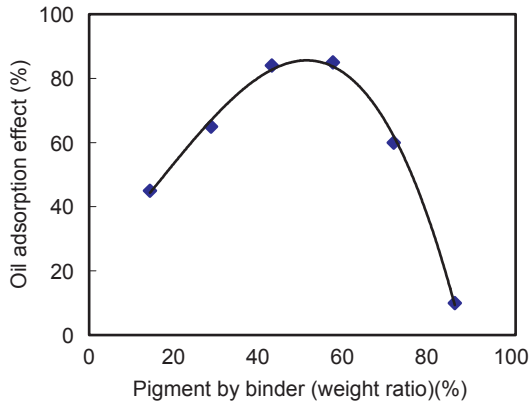
Figure 4 (d) shows a comparison on the oil adsorption and retention of the new coating with current mainstream coatings such as dry film lubrication, electro-less nickel



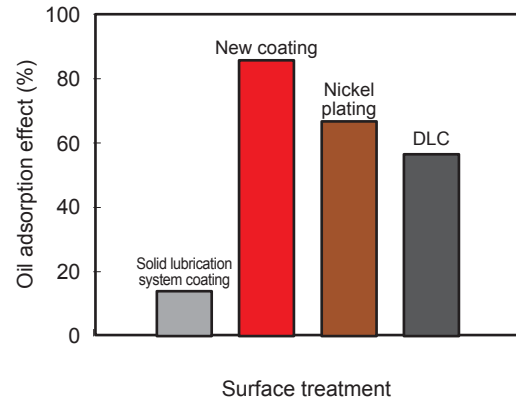
(a) Quantity of abrasion according to mixture particle size



(b) Quantity of abrasion according to particle mixture



(c) Oil maintenance effect according to mixture particle size



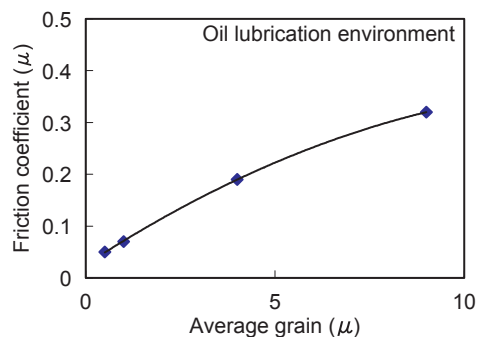
(d) Oil maintenance effect of each surface treatment

Fig. 4 Oil adsorption effect and anti-abrasivity

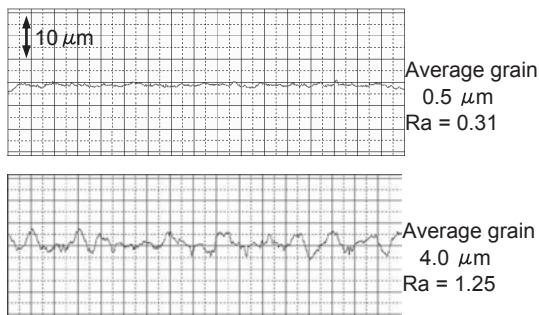
plating of anti-abrasion piston surface, and diamond-like carbon (DLC) which is a high strength film. The graph shows that the film developed in this project has the higher oil adsorption effect.

5.2. Oil Adsorption Effect and Low Sliding Friction Performance

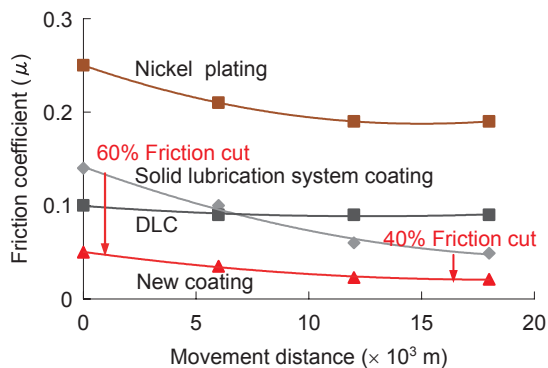
Modifying surface properties by means of the addition of microscopic hard particles not only affects abrasion resistance characteristics, but also affects sliding friction performance. The relationship between the average size of the added grains and the coefficient of kinetic friction when the amount of added particles to the binding resin is held constant is shown in Fig. 5 (a). The graph shows that sliding friction becomes lower as the average size of



(a) Relationship between friction and average grain



(b) Surface coarseness according to grain size



(c) Friction of each surface treatment according to movement distance

Fig. 5 Oil adsorption effect and friction

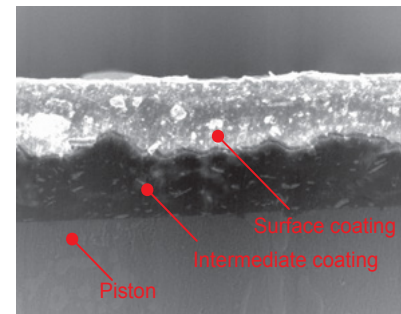
the grains decreases. Figure 5 (b) shows surface coarseness when two types of films with different average grain sizes are compared. The reduction of surface coarseness may be considered to reduce surface pressure by increasing the surface area of the sliding parts making actual contact, thus reducing the coefficient of kinetic friction.

Figure 5 (c) compares the new coating and other surface treatments in terms of the change in the sliding friction characteristic over the entire sliding distance. Due to the effect of adaptation to the contact faces, each treatment is saturated over a total sliding distance of approximately 10 000 m. The surface treatment developed in this project reduces sliding friction by 60% in the initial stage and 40% in a saturated state compared to a conventional dry film lubricant.

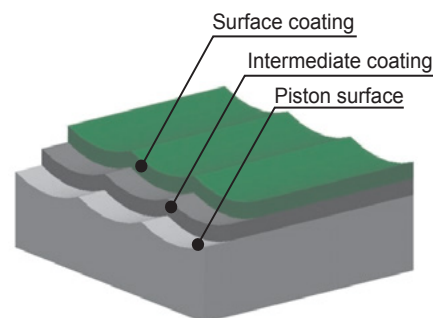
5.3. Surface Treatment Adhesion and Anti-abrasion Performance

Binding resins are chain polymers, and are baked to increase their strength by forming a bridged structure⁽⁹⁾.

In order to balance the contradictory characteristics of film strength and adhesiveness which are normally in a trade-off relationship, the project discussed here used an intermediate coating that is able to act as a buffer because of its toughness. The high-strength film adheres to the intermediate coating, and the intermediate coating adheres to the piston skirt. Figures 6 (a) shows an electron micrograph of a cross-section and Fig. 6 (b) shows an



(a) SEM image of piston surface



(b) Cut image of piston surface

Fig. 6 Image of piston surface

Table 1-(a) Engine specifications

Type	Air-cooled 4-stroke OHC single cylinder
Cylinder	Aluminum cylinder
Bore x stroke	64 x 50 mm
Displacement	160 cm ³
Compression ratio	8.5:1
Lubrication system	Forced splash

Table 1-(b) Test condition

Engine speed	3600 rpm
Throttle	Wide open throttle
Fuel	Regular (Density 0.7304 g/cm ³)
Oil	API SJ SAE 10W-30
Oil maintenance	Upper to lower

Table 2 Engine durability test result

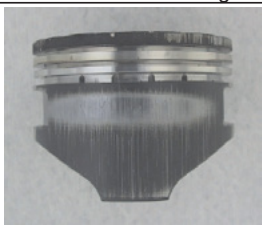
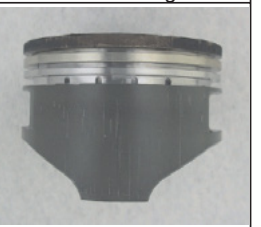
	Conventional coating	New coating	New coating
Piston surface (Thrust side)			
Operation time	20 h	20 h	150 h
Quantity of abrasion	Worn out (Coat 15 μm)	4 μm	6 μm

image of the piston surface.

Tests were conducted in an actual engine to evaluate the degree of adhesion. Table 1 (a) shows the specifications of the test engine and Table 1 (b) shows the test conditions.

This project assumed severe conditions for piston sliding motion, and used a general purpose engine with an aluminum sleeve in tests.

Table 2 shows closeup photographs of the pistons and indicates the degree of abrasion following the tests. In contrast to the pistons employing conventional dry film lubricants, the metal substrate of the piston skirts employing the film developed in this project was not visible following the tests for 20 hours, indicating enhanced anti-abrasion performance. This is considered to be a clear indication of the fact that the method developed in this project achieves lower friction by means of oil retention rather than self-lubrication as conventional dry film lubricants do. Tests were conducted for 150 hrs, and

results showed that the abrasion of the film was steady wear of 2 μm , indicating that the film maintained its performance over a long period.

In addition, the use of the intermediate coating enhanced the adhesion of the high-strength film, and no peeling of the surface coating was observed.

5.4. Results of Engine Performance Tests

Using the same test engine and replacing only the pistons, the power of the engine for each surface treatment was measured. Figure 7 shows the measurement results for power curves with a wide-open throttle.

The measurement data indicates the following effects at 3600 rpm under full load:

- (1) The use of the new surface treatment generates a 4.9% increase in power compared to that with no surface treatment.
- (2) The use of a conventional dry film lubricant generates a 2.4% increase in power compared to that with no surface treatment.
- (3) The use of the new surface treatment generates a 2.4% increase in power compared to that of a conventional dry film lubricant.

6. Conclusion

- (1) A high-strength film was developed by changing the characteristics of the piston surface with enhanced adsorption and retention of oil, enabling the achievement of a balance between low friction and anti-abrasion performance.
- (2) The results of abrasion and friction tests indicated the new surface treatment increased anti-abrasion performance by approximately five times and reduced friction by approximately 40% compared to those of a

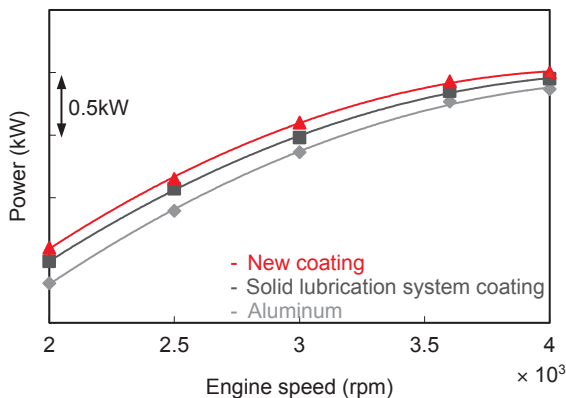


Fig. 7 Power curve

conventional dry film lubricant.

- (3) Power measurements conducted using an actual engine at wide-open throttle indicated that the use of the new surface treatment increases engine power by approximately 4.9%.

7. Afterword

New developments and modifications in relationship to the internal combustion engine are being conducted to respond to social and environmental requirements. The pistons are a key component of the internal combustion engine. Ensuring their continuing high performance and long life will have socioeconomic benefits and play an important role in responding to the depletion of fossil fuels and environmental issues. It is the hope of the author that the research discussed in this paper shall contribute to the achievement of these developmental goals.

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