

Development of Piston Surface Treatment for Internal Combustion Engine

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ABSTRACT

Low-friction surface treatment technology and machined piston surface 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 low friction were realized by self-lubrication, wear and abrasion; therefore it was not possible to expect the effectiveness of performance to be maintained. The newly developed technology uses a high-strength film which has an oil adsorption effect, enabling friction to be reduced by about 40% while improving wear resistance about 5-fold compared to conventional coating materials. Conventional piston surface have a streak in wave shape for oil maintenance. The top of the streak has sharp edges causing an increase of partial aspect pressure, long term of break-in run and early coating abrasion. Developed piston surface for coating has the suitable trapezoid shape that causes low-friction and high wear resistance. The newly developed surface treatment and machining technology improves 30% of wear resistance and 4% of maximum engine output. Since this technology employs piston spray coating technology and processing techniques, the new film can be applied by simply replacing the material and the machined tool without any need for special production equipment.

INTRODUCTION

Efficient use of energy resources is expected due to social and economic demands, such as environmental protection, 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 much to contribute to improve the fuel efficiency and power of gasoline engines.

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 have resulted in increased mechanical efficiency.

Because the piston skirt is one of the main factors of mechanical loss, accurate machining has been required to control dimensions and forms. The streaks which are the traces of tool bit that remain on the piston surface. These form grooves which have oil retention. However, in terms of shape, the streak has wave-shaped sharp edges which cause abrasion at the initial running and scuffing wear from wear particles.

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

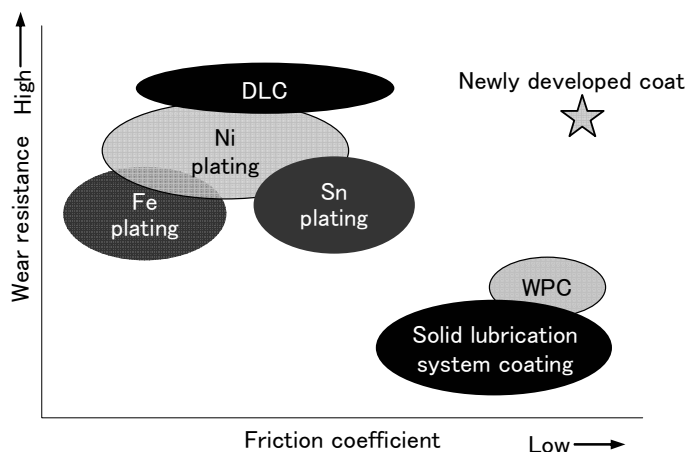


Fig. 1 Piston surface treatment

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, therefore abrasion is unavoidable. Because of this, the maintenance of the film over an extended period remains an issue to be addressed.

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 abrasion characteristics of the sliding surfaces.

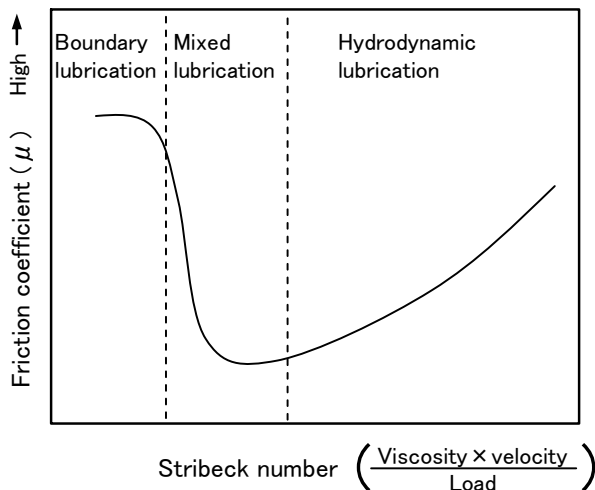


Fig. 2 Stribeck curve

When the sliding speed is low, the surfaces are in a state of boundary lubrication, in which they make contact and slide against each other. Therefore, the coefficient of abrasion is high. At high speeds, by contrast, because the surfaces are in a state of hydrodynamic lubrication, there is almost no contact between them, and the coefficient of abrasion 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 the state of boundary lubrication makes it difficult to reduce friction.

MATERIAL DESIGN

The technology discussed here reduces sliding loss by forming a film on the piston skirt that ensures adsorption and maintenance 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.

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 [8]. 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)

EXPERIMENTAL APPARATUS

The dynamic friction abrasion testing machine shown in Figure 5 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. Table 1 shows the test conditions.

Performance measurements and durability tests were also conducted to evaluate the adhesion of the surface treatment, streak shape effect and its power output in an actual engine.

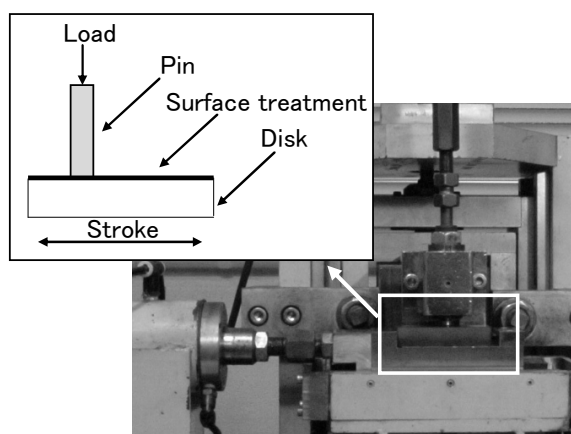


Fig. 5 Dynamic friction abrasion testing machine

Table 1 Test conditions

Stroke	50 mm
Speed	600 cycle/min
Load	980 N
Pin	ϕ 8 mm
Temperature	25 °C
Oil	PAO4
Oil feed rate	0.3 ml

TEST RESULTS

OIL ADSORPTION AND ABRASION RESISTANCE

Resin materials generally display low wettability and lipophilia [9], 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 6 (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 6 (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 6 (c) shows the oil adsorption and oil maintenance effects under the same conditions. Appearing below is a relatively simple expression for oil adsorption effect.

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

Where δA_{oil} is the degree of abrasion when oil is employed and δA_{dry} is the degree of abrasion when no lubrication is employed.

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. And it was found that 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 6 (d) shows a comparison on the oil adsorption and maintenance effect of the new coating with current major coatings such as dry film lubrication, electro-less nickel 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.