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Influence of piston surface treatment on piston assembly friction in an eco-mileage vehicle engine

ARTICLE INFO

This study investigated the effect on piston assembly friction after treating piston surfaces with a fine particle bombarding process, using a friction measurement apparatus with a floating cylinder liner, similar to an eco-mileage vehicle engine. Friction was measured in four conditions: (1) no treatment (standard piston in a commercially-available engine), (2) micro dimple treatment (45 μm ceramic particles were air-blasted onto the piston surface), (3) molybdenum disulfide (MoS_2) shot treatment (1 μm MoS_2 particles were air-blasted onto the piston surface), and (4) combination of the previous two micro dimple and MoS_2 shot treatments (first 45 μm ceramic particles and then 1 μm MoS_2 were air-blasted onto the piston surface). Results indicated that friction decreased in the following order: no treatment > micro dimple treatment > MoS_2 shot treatment > combination of micro dimple and MoS_2 shot treatments.

1. Introduction

In eco-mileage vehicles, reducing engine friction is an effective means for improving fuel efficiency. Because the piston assembly friction (the friction between the piston, the piston rings, and the cylinder liner) makes a significant contribution to engine friction [1, 3, 4, 6], it is important to reduce this piston assembly friction. The friction between the piston and the cylinder liner accounts for more than 50% of the piston assembly friction, and its ratio increases with increasing engine speed and decreasing engine load [7]. There have been reports on reducing piston assembly friction by applying a surface treatment on the piston skirt [2, 5, 9–11, 13–15]. One approach plates a piston with tin [5]. Tin not only reduces friction, but also simplifies the break-in run. However this tin plating wears out during protracted engine operation, losing the friction reduction effect. Another approach plates a piston with a resin coating in which molybdenum disulfide (MoS_2) and polytetrafluoroethylene (PTFE) are dispersed in a resin binder [2, 5, 15], a resin coating in which fine hard particles are dispersed in a resin binder [14], or a resin coating of two layers in which MoS_2 is dispersed in a resin binder in the upper layer and graphite is dispersed in the lower layers [13]. This rein does not wear out even during protracted engine operation, achieving sustainable friction reduction. But the performance of slide and transfer of solid lubricants such as MoS_2 and PTFE, is suppressed by the resin binder [10]. In addition, the thickness of these resin coatings is approximately 10 μm, so it is necessary to design the piston with advance consideration of the final coating thickness. Yet another approach uses a micro dimple treatment (by air-blasting fine ceramic particles at a high speed) [9, 11] and a MoS_2 shot treatment (by air-blasting fine MoS_2 particles at a high speed) [10, 11] on the piston surface using a fine particle bombarding (FPB) process. This approach reduces friction even during protracted engine operation, and has minimal effect on piston dimension. This process (of micro dimple and MoS_2 shot treatments with FPB) can be easily applied

to the piston in an eco-mileage vehicle engine, where it can be expected to reduce friction even during protracted operation. Our previous study developed a friction measurement apparatus with a floating cylinder liner, by using components of an eco-mileage vehicle engine as much as possible [8]. This study employs that measurement apparatus to quantify the effect on piston assembly friction of piston surface treated with a FPB process.

2. Experimental apparatus and method

Figure 1 shows the apparatus to measure piston assembly friction with the floating liner, as developed in our previous study [8]. This measurement apparatus was designed to be similar as possible to an actual eco-mileage vehicle engine. So it employed a commercially-available, four-stroke, air-cooled, horizontal, single-cylinder, gasoline engine, displacing 49 mL, with a bore diameter of 39 mm and a stroke of 41.4 mm. The crankcase of this engine was cut, and a cover was attached to the cut of the crankcase. The engine was turned from horizontal to vertical. The floating liner was produced by machining the outer periphery of the air-cooled cylinder (aluminum finned cylinder casting cast-iron liner). This floating liner was installed in the aluminum cylinder block. Joint plates were installed in the grooves on the outer periphery of the floating liner at both the thrust and the anti-thrust sides. Then the joint plates, as well as load washers of piezo type, were mounted in the cylinder block, as shown in Fig. 2. To suppress lateral displacement due to piston thrust force, clamping bolts were mounted to the cylinder block at four sides: thrust, anti-thrust, front, and rear. Heaters were installed in the cylinder block at the thrust, anti-thrust, and rear sides, and thermocouples were installed into the clamping bolts at the front and rear sides so that the bore surface temperature of the floating liner could be measured and adjusted. In addition, an oil tank was set outside the engine, and a heater and a thermocouple were installed into the oil tank to adjust the oil temperature to a fixed temperature. The heated oil was

then pumped from the oil tank to a pipe in the upside of the crankcase, and supplied from there to the crankshaft at a flow rate of 600 mL/min.

Figure 3 shows the four experimental pistons and the surface shapes on the piston skirts. The piston without surface treatment (1) is standard part of a commercially-available engine, and has a streaked sliding surface (Ra 2.4 μm) and three grooves in the skirt. In the micro dimple treatment (2) ceramic particles with a diameter of 45 μm were air-blasted on the standard piston surface. In the MoS_2 shot treatment (3) MoS_2 particles with a diameter of 1 μm were air-blasted on the standard piston surface. In the combination of micro dimple and MoS_2 shot treatments (4) first ceramic particles with a diameter of 45 μm were air-blasted on the standard piston surface, and then MoS_2 particles with a diameter of 1 μm were air-blasted onto it. There was no difference in the outer diameter, measured with a micrometer, at each position of the pistons with and without surface treatments.
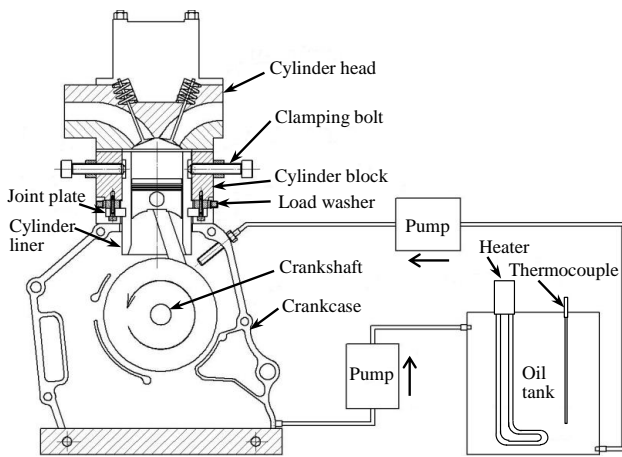

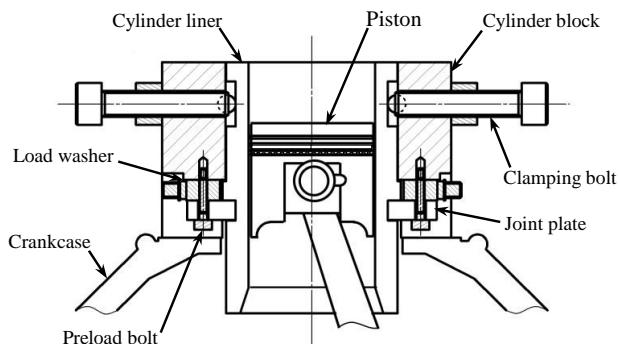Fig. 1. Measurement apparatus of piston assembly friction

Fig. 2. Measurement unit of piston assembly friction with floating liner

Table 1 shows the experimental rings, which are standard parts of a commercially-available engine. These rings had been fully run earlier [8].

The floating liner had been also fully operated earlier [8]. The roughness of the sliding surface on the liner bore was Rz_{JIS} 1.22~1.34 μm (Ra 0.20~0.22 μm).

In the experiment, the intake and exhaust valves were not activated (no cylinder pressure was applied) while the engine was operated by motoring. Using the same rings and floating liner, each experimental piston was installed in the engine. Before measuring piston assembly friction, the engine was run in for 20 hours, at an engine speed of 1600 rpm, with temperatures of the liner bore and lubricant of 80°C. Then the piston assembly friction was measured at temperatures of 40°C, 60°C and 80°C, and at engine speeds from 800 rpm to 1600 rpm every 200 rpm. Table 2 shows the kinematic viscosities of the experimental lubricant (Honda genuine Ultra Green) at each temperature, measured with the Redwood viscometer.
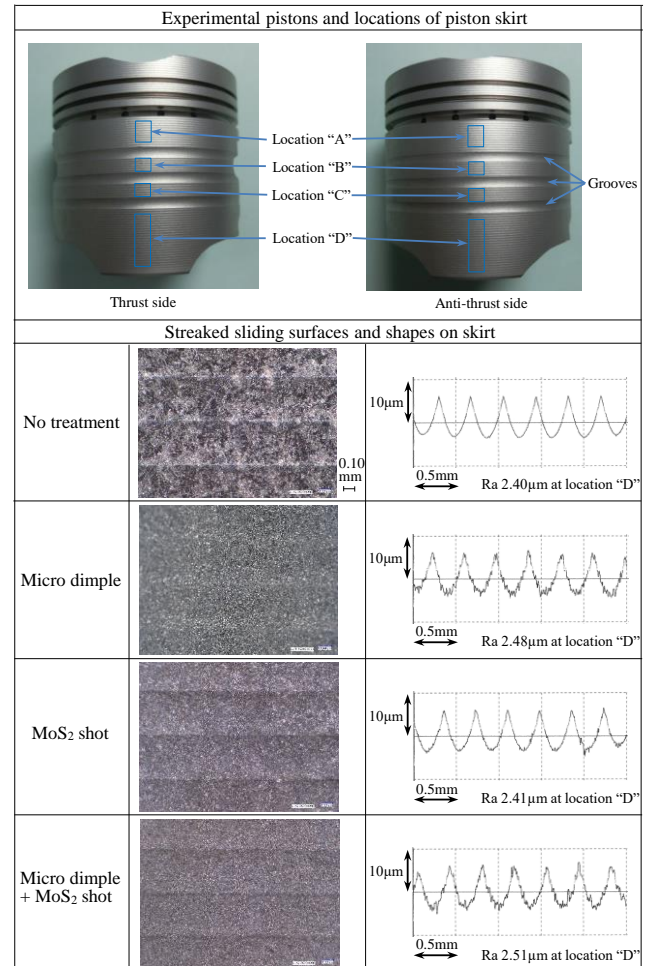

Fig. 3. Experimental pistons and the surface shapes on the piston skirts

Table 1. Experimental piston rings

[mm]

Top ring	Second ring	Oil ring
1.7 / 0.78	1.7 / 0.78 / 1°46′	1.04 / 0.3 / 0.3
End clearance 0.08 mm	End clearance 0.15 mm	End clearance 0.52 mm
Tension 3.2 N	Tension 4.4 N	Tension 11.2 N
Chrome plating	Phosphate	Chrome plating

Table 2. Kinematic viscosities of experimental lubricant

Temperature	Kinematic viscosity
40°C	30.3 mm²/s
60°C	15.8 mm²/s
80°C	10.4 mm²/s

3. Results and discussion

Figures 4 to 6 show the measurement results of the piston assembly friction at an engine speed of 1000 rpm and at temperatures of 40°C, 60°C and 80°C, respectively. In Figs 4 to 6, crank angles of 0º and 360º represent engine top dead center (TDC), and 180º bottom dead center (BDC). Since the intake and exhaust valves were not activated, only two strokes of the piston (downward stroke and upward stroke) are indicated. At each temperature, not only near TDC and BDC but also near the center of the stroke, friction decreased in the following order: no treatment > micro dimple treatment > MoS$_2$ shot treatment > combination of micro dimple and MoS$_2$ shot treatments. As the temperature increased, the friction reduction ratio of each surface treatment (compared to no treatment) decreased, especially near TDC and BDC.

Figures 7 to 10 show the Stribeck diagrams (at 1000 rpm with crank angles of 3° to 177° and 183° to 357°) for each piston corresponding to the friction measurement results in Figs 4 to 6. Here the friction coefficient was obtained by dividing the absolute value of friction by the sum of the thrust force of the piston (which was obtained by multiplying the inertial force of the piston by the tangent of the tilt angle of the connecting rod) and the normal force of the rings (which was obtained by multiplying the ring surface pressures by the outer peripheral surface areas of the rings). The lubrication parameter was also obtained by multiplying the lubricant viscosity, μ, by the piston speed, U, and dividing by W, the sum of the surface pressures of the piston skirt (one skirt side) and the rings. In Figs 7 to 10, fluid lubrication was dominant at lower temperatures, but mixed lubrication was dominant at higher temperatures. In all lubrication regions, friction coefficient again tended to decrease in the following order: no treatment > micro dimple treatment > MoS$_2$ shot treatment > combination of micro dimple and MoS$_2$ shot treatments.
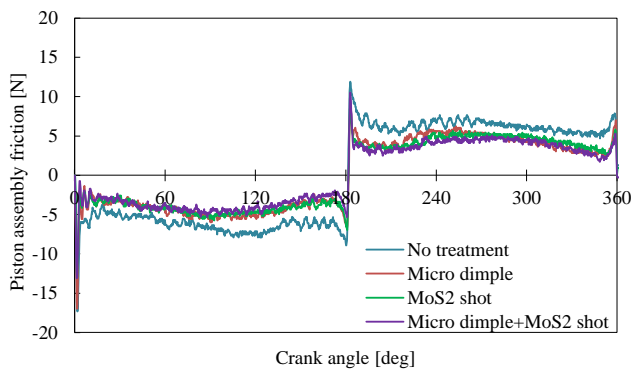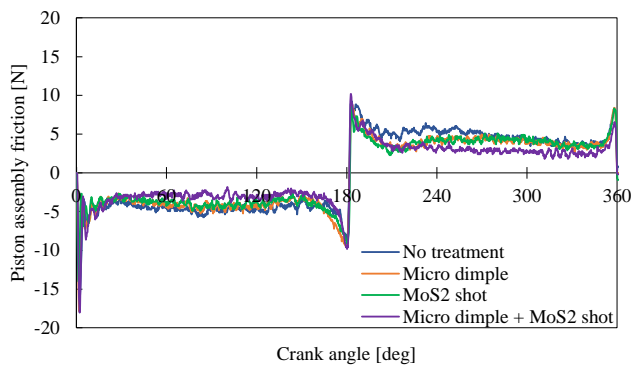

Fig. 4. Piston assembly friction at 40°C (1000 rpm)

Fig. 5. Piston assembly friction at 60°C (1000 rpm)

Fig. 6. Piston assembly friction at 80°C (1000 rpm)
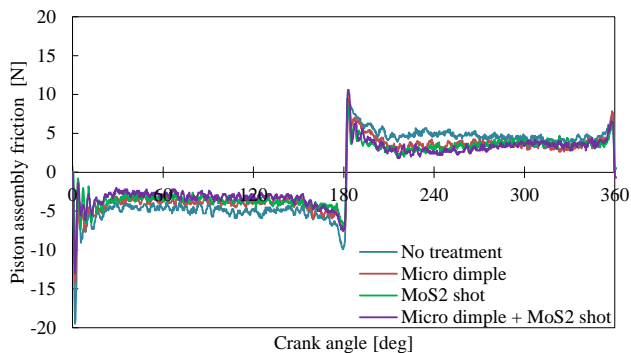

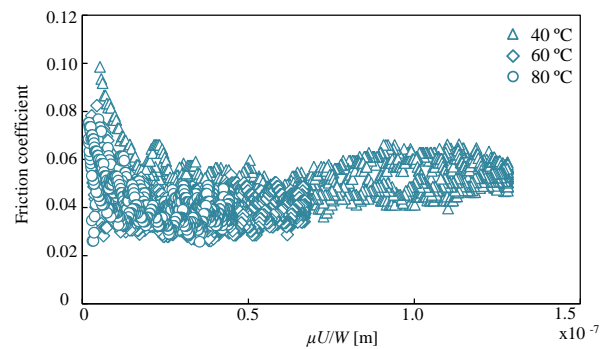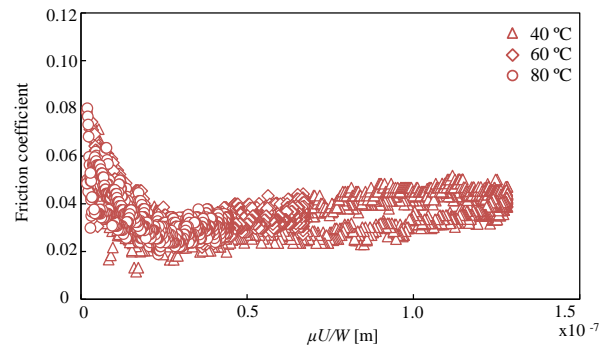
Fig. 7. Stribeck diagram in no treatment (1000 rpm)

Fig. 8. Stribeck diagram in micro dimple treatment (1000 rpm)
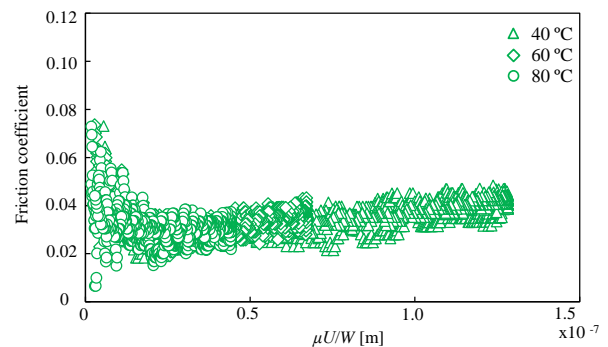

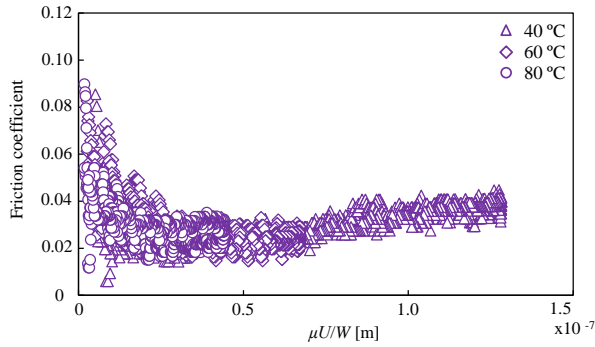Fig. 9. Stribeck diagram in MoS$_2$ shot treatment (1000 rpm)

Fig. 10. Stribeck diagram in combination of micro dimple and MoS$_2$ shot treatments (1000 rpm)

Figures 11 to 13 show the friction mean effective pressure (FMEP) at 40°C, 60°C and 80°C, respectively. Here the FMEP was obtained by integrating the absolute value of friction at crank angles of 0° to 360° and dividing by the stroke volume. At each temperature and engine speed, the FMEP also tended to decrease in the following order: no treatment > micro dimple treatment > MoS$_2$ shot treatment > combination of micro dimple and MoS$_2$ shot treatments. At a lower temperature, as the engine speed increased, fluid lubrication became dominant, so the FMEP increased in each piston. At a higher temperature, when the engine speed increased from 800 rpm to 1200 rpm, boundary contact decreased, and the FMEP decreased in each piston. But when the engine speed further increased from 1200 rpm to 1600 rpm, fluid lubrication became dominant, and the FMEP tended to increase in each piston. Here, the FMEP was reduced by 31% to 45% for the combination of micro dimple and MoS$_2$ shot treatments, compared to no treatment.
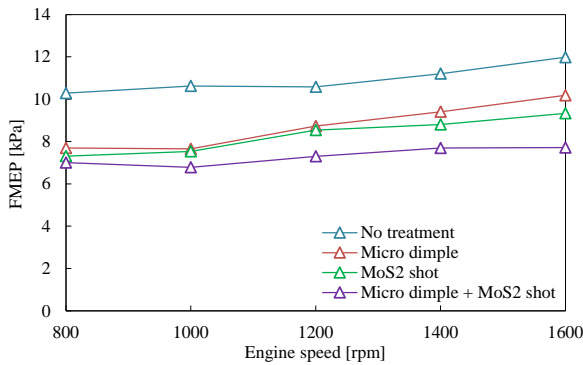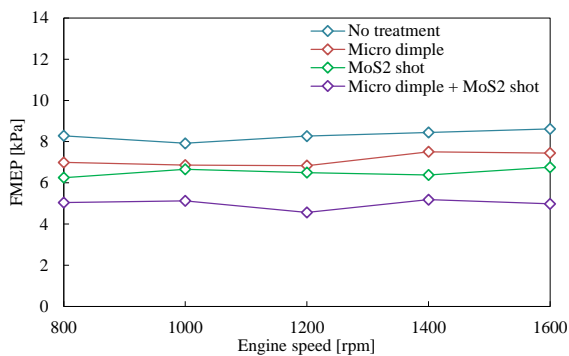

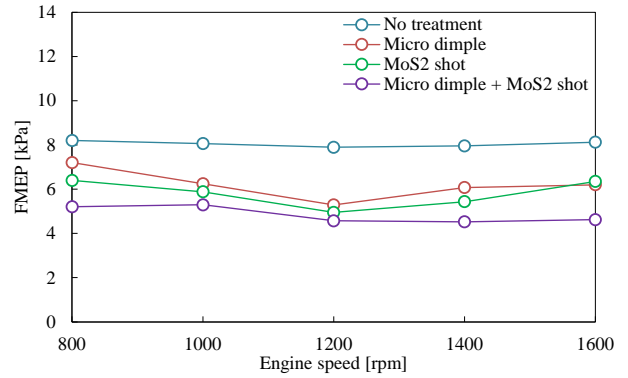Fig. 11. FMEP at 40°C

Fig. 12. FMEP at 60°C

Fig. 13. FMEP at 80°C

Figure 14 shows the maximum amount of wear on the streaked sliding surface at location "C" of each piston skirt after the friction measurement. All pistons had the maximum amount of wear on the streaked sliding surface at the piston skirt "C" at both the thrust and the anti-thrust sides. In Fig. 14, except for the micro dimple treatment, there was no significant difference in the maximum amount of wear on each piston skirt. Except for the micro dimple treatment, the maximum amount of wear at the anti-thrust side was larger than that at the thrust side. At the thrust side, the maximum amount of wear with the micro dimple treatment was greater than that of all other treatments, including no treatment. It was considered that the outer diameter of the streaked surface became larger due to the micro dimple treatment. Figure 15 shows the observation results of the streaked surface at the piston skirt "C" on the anti-thrust side. In Fig. 15, the micro dimples remained even on the worn surface of the streak, with both the micro dimple treatment and the combination of the micro dimple and the MoS$_2$ shot treatments. In all pistons, the amount of wear on the streaked sliding surface at locations (skirt "A," "B" and "D") other than skirt "C" was 0~1 μm, and there was no significant difference in the amount of wear.
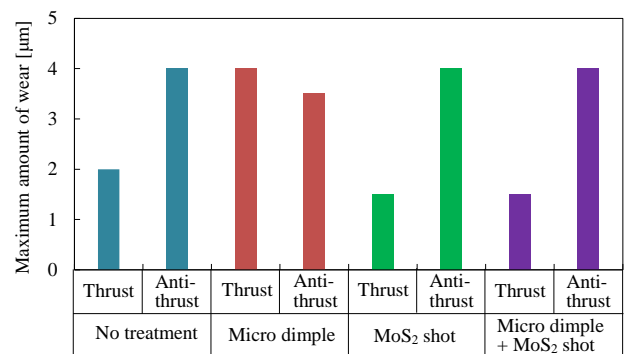
Fig. 14. Maximum amount of wear on streaked sliding surface at part of "C" after friction measurement

The micro dimple treatment reduced friction compared to no treatment. The micro dimples also remained on the worn surface of the streak with the micro dimple treatment. It is thought that, in the mixed lubrication region, the lubricant in the valley between streaks circulated through micro dimples as a passage, covering not only the actual sliding

surfaces but also those micro dimples there, reducing friction [9]. It is also considered that, in the fluid lubrication region, the shear force of the lubricant between the sliding surfaces became smaller due to the formation of a vortex inside each micro dimple, reducing friction [12].
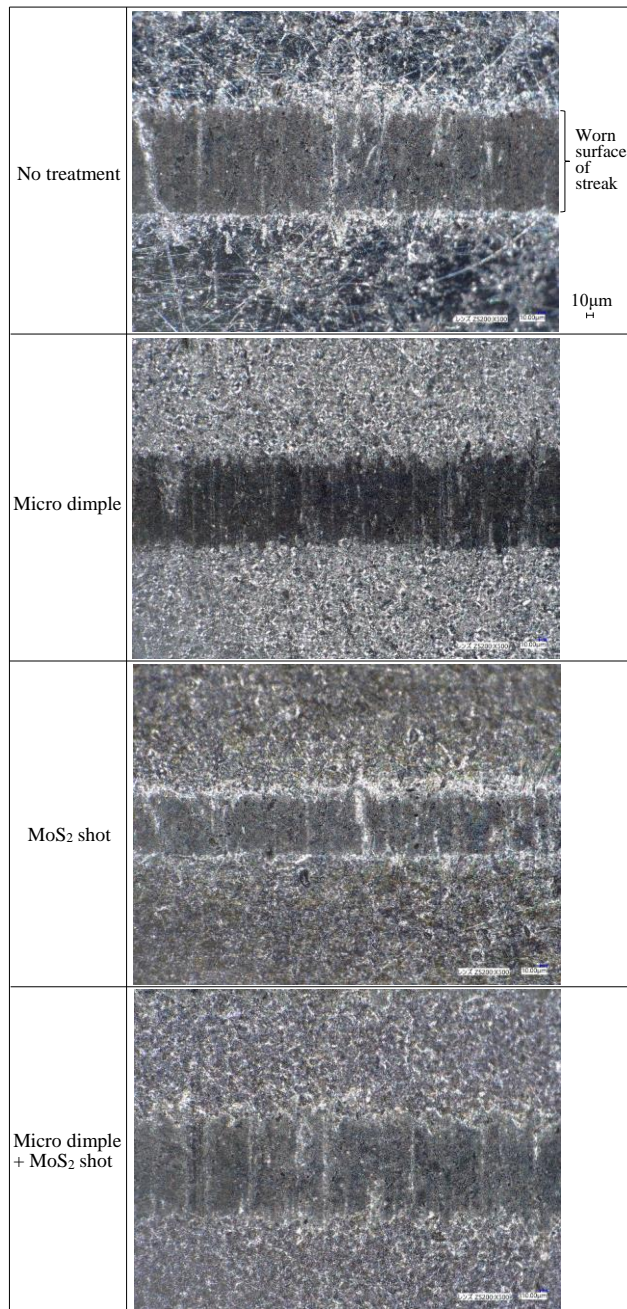

Fig. 15. Observation results of streaked surface at piston skirt "C" at anti-thrust side after friction measurement

The MoS_2 shot treatment further reduced friction, more than both no treatment and the micro dimple treatment. The MoS_2 has a hexagonal layered crystal structure, and in each layer a plane of molybdenum (Mo) atoms is sandwiched by planes of sulfur (S) atoms. The covalent bonds between the Mo and S atoms within layers are relatively strong, while the van der Waals forces cohering S and S atoms between layers are considerably weaker. Therefore the shear force acts between these layers, so interlayer sliding occurs, reducing friction. However, as shown in Fig. 14, the streaked surface at the piston skirt "C" had a maximum wear of 4 μm, which corresponded to approximately the depth of the treatment of MoS_2 shots. Here, Ogihara [10, 11] examined the worn part of the streaked MoS_2 treated piston skirt, after engine motoring, using Field Emission Scanning Electron Microscopy/Energy Dispersive X-ray Spectroscopy (FE-SEM/EDX), and confirmed the remaining presence of MoS_2 both on the worn surface and deep inside the surface. This is because the MoS_2 particles are repeatedly cleaved and transferred to other areas. As in Ogihara [10, 11], this study considered that the cleaved MoS_2 particles were transferred to the worn surface. In the mixed lubrication region, the sliding force acted between MoS_2 layers, facilitating interlayer sliding and reducing friction. It seems that, in the fluid lubrication region, the cleaved MoS_2 particles decreased the shear force of the lubricant, reducing friction.

The combination of the micro dimple and the MoS_2 shot treatments further reduced friction in all regions. It was thought that, in the mixed lubrication region, not only the MoS_2 interlayer sliding occurred (by the sliding force acting between layers) but also lubricant was supplied to the sliding surface through micro dimples, further reducing friction. In the fluid lubrication region, the shear force of the lubricant between the sliding surfaces decreased, due to both the cleaved MoS_2 particles and the vortices generated inside the micro dimples, further reducing friction.

4. Conclusions

Using a friction measurement apparatus with a floating cylinder liner, similar to an eco-mileage vehicle engine, the effect of piston surface treatment with the FPB process on piston assembly friction was investigated. Results indicated that, the micro dimple and the MoS_2 shot treatments reduced friction. The MoS_2 shot treatment reduced friction more than the micro dimple treatment. Finally, the combination of both the micro dimple and the MoS_2 shot treatments further reduced friction. This combination of micro dimple and MoS_2 shot treatments reduced friction from 31% to 45%, compared to no treatment.

Nomenclature

BDC	bottom dead center
FE-SEM/EDX	Field Emission Scanning Electron Microscopy/Energy Dispersive X-ray Spectroscopy
FMEP	friction mean effective pressure
FPB	fine particle bombarding
Mo	molybdenum

MoS_2	molybdenum disulfide
Ra	calculated average roughness
Rz_{JIS}	10-point average roughness
S	sulfur
TDC	top dead center

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