Improvement of the Low-Speed Friction Characteristics of a Hydraulic Piston Pump by PVD-Coating of TiN

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The hydraulic pump of an Electro-hydrostatic Actuator should be able to quickly feed large volume of oil into hydraulic cylinder in order to reduce the response time. On the other hand, it should be also able to precisely dispense small amount of oil through low-speed operation so that the steady state position control error of the actuator can be accurately compensated. Within the scope of axial piston type hydraulic pumps, this paper is focused on the investigation how the surface treatment of their cylinder barrel with TiN plasma coating can contribute to the reduction of the friction and wear rate of valve plate in the low-speed range with mixed lubrication. The results showed that the friction torque of the valve plate mated with a TiN-coated cylinder barrel could be reduced to 22% of that with an uncoated original one when load pressure was 300 bar and rotational speed 100 rpm. It means that the torque efficiency of the test pump was expected to increase more than 1.3% under the same working condition. At the same time, the wear rate of the valve plate could be reduced to 40～50%.

Key Words : Low-Speed Friction Characteristics, Hydraulic Piston Pump, Plasma Coating, TiN-Layer, Cylinder Barrel

Nomenclature

A_b : Effective area of cylinder barrel (mm^2)
A_p : Cross-sectional area of piston (mm^2)
β : Balance coefficient
F_p : Normal force acting on valve plate (N)
μ_v : Friction coefficient of valve plate
p_i : Pressure of each cylinder chamber (bar)
r_c : Moment arm of normal force on valve plate w.r.t. pump shaft (mm)
θ_s : Rotation angle of pump shaft (°)
T_b : Friction torque on shaft bearings (Nm)
T_f : Friction torque acting on cylinder barrel (Nm)
T_i : Ideal input torque of pump (Nm)
ω_s : Rotational speed of pump shaft (rpm)

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1. Introduction

In order to save the energy loss of valve-controlled electro-hydraulic actuators, caused by the

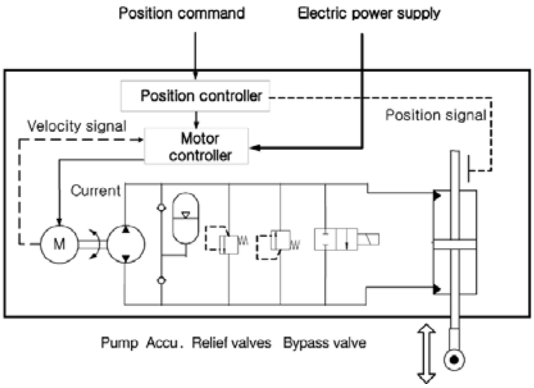


Fig. 1 Basic configuration of electro-hydrostatic actuator

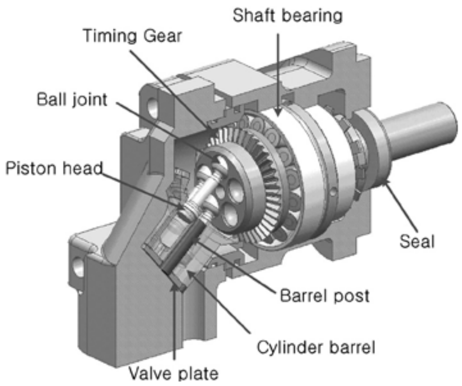


Fig. 2 Schematic diagram of bent-axis type hydraulic piston pump with timing gears

flow restriction in control valves and pipe lines, the so-called electro-hydrostatic actuators have been developed and recently activated their application to the aircrafts.

The electro-hydrostatic actuators (abbreviated as EHA in the following) operate in closed circuit, comprising a constant displacement pump and a hydraulic cylinder, as shown in Figure 1. The pump is driven by an electrical servomotor whose angular velocity is controlled to position the hydraulic cylinder.

As for the pump of the EHAs, its operation is almost unsteady because it has to continuously compensate the position control error. For example, if a sinusoidal command signal is input to the position controller, the pump speed changes in the form of a cosine function. Therefore, the lubrication condition of the pump is much worse than that of conventional pumps running at a constant speed in open circuit.

In particular, the low speed friction characteristics of internal pump parts come into serious question as they are influenced by the mixed lubrication condition which augments friction loss and wear rate to a great extent.

Apart from the lubrication performance in the low speed range, the bent-axis type piston pumps with timing gears shown in Fig. 2, seem to most advantageously meet the functional requirements of the EHAs. They allow rapid change of the rotational speed and high operation pressure with low leakage loss, while their pistons are kept almost free from lateral forces.

Hong (2004) analyzed the friction loss of a bent-axis type hydraulic piston pump based on the experimentally identified friction models for shaft bearings, piston heads, spherical joints and valve plate. This study was mainly focused on the high speed friction characteristics of the object pump to show that, in the high speed range over 5,000 rpm, the friction torque is produced significantly by the viscous friction acting on the shaft bearings and the valves plate.

On the contrary, this paper is dealing with the low speed friction characteristic of the valve plate under the mixed lubrication condition. The valve plate usually made of bronze is the softest part of the pump. Therefore, its wear rate is significantly dependent on the lubrication condition. In order to improve the tribological interaction between the valve plate and its mating cylinder barrel, the PVD-coating process was employed in this study. To be more specific, the surface of the cylinder barrel contacting with the valve plate was coated with TiN in the form of a thin layer which was expected to enhance the tribological property even under the mixed friction condition.

The researches carried out by Nevoigt (2000) or Bebber (2002) aimed at the improvement of the tribological property of hydraulic pumps handling environment-friendly fluids by the PVD-coating technology. There were tried and tested various kinds of materials including ZrC which is characterized by good lubricity and affordability.

TiN was proposed in this study because its PVD coating had been widely applied to machine tools to improve their anti-wear property (Lee, 2005). Based on this motivation, the following two questions were raised and examined, as reported below: i.e. 1) how much the friction coefficient and wear rate of a valve plate can be reduced by the TiN-layer coated on its mating cylinder barrel and 2) how much the torque efficiency of a pump can be improved by this friction coefficient reduction, when common petroleum-based hydraulic oil is used.

2. Important Factors of Friction Torque Acting on Valve Plate

The cylinder barrel and valve plate of the bent-axis type hydraulic piston pump investigated in this study are depicted in Fig. 3. In general, the friction torque between them can be expressed by Equation (1):

$$T_f=\mu_v r_c(1-\beta)\sum_{i=1}^{N} A_p p_i=\mu_v r_c(1-\beta)F_p \quad (1)$$

where

μ_v = friction coefficient,

$F_p=\sum_{i=1}^{N} A_p p_i$ = normal force acting on valve plate by cylinder chamber pressure [N],

A_p = working area of piston [mm^2],

N = total number of pistons,

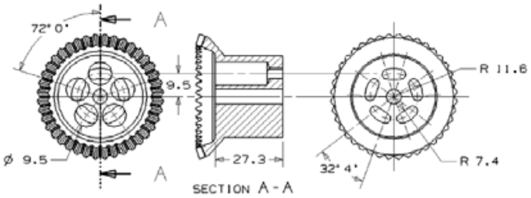
p_i = pressure of each cylinder chamber [bar],

β = balance coefficient and

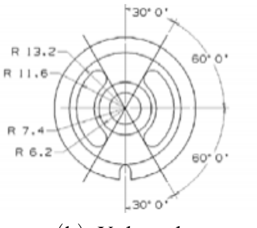
r_c = moment arm of F_p w.r.t. pump shaft [mm].

It is to be noted that A_p, r_c and β are determined by the geometry of the cylinder barrel and the valve plate. β denotes the ratio of the cylinder barrel lifting force, generated by the pressure acting on its bottom surface, to the cylinder barrel pressing force, F_p. It should be smaller than 1 to prevent oil from excessively leaking through the gap between the cylinder barrel and the valve plate. β and r_c, illustrated in Fig. 4, were computed from the geometrical data given in Fig. 3.

p_i changes periodically between suction and discharge pressure, while its waveform is dependent on the valve plate geometry, shaft speed and discharge pressure. It can be directly measured or

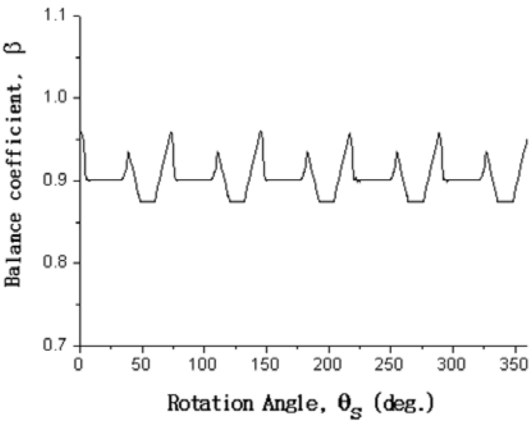


(a) Cylinder barrel

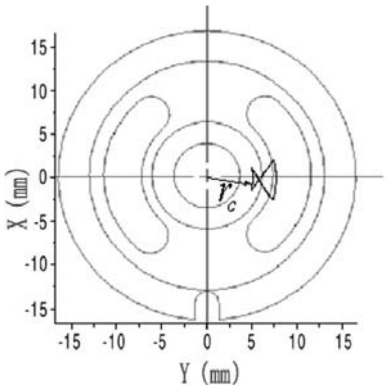


(b) Valve plate

Fig. 3 Dimensions of cylinder barrel and valve plate



(a) Balance coefficient, β



(b) Acting point trajectory of F_p

Fig. 4 Balance coefficient and acting point trajectory of normal force on valve plate theoretically computed with acceptable accuracy. However, in concern with μ_v, it has to be only experimentally identified, if the valve plate is subject to the mixed lubrication condition in the low speed range.

The valve plates are usually made of bronze so that their surface hardness is lower than that of the steel cylinder barrel. On the contrary, the contact surface of the cylinder barrel is treated by nitrogen hardening to enhance its anti-wear property. The nitrification layer is usually 20 μm thick and as hard as 600 to 700 Hv. Therefore, in the low speed range with mixed lubrication, the wear tends to occur on the valve plate surface. And the friction coefficient between the two components is higher than that in the high-speed range because of partial solid contact.

Nowadays the PVD-coating process is widely applied to change the tribological property of metal surface such as lubricity and anti-wear characteristics. In this study, TiN was coated on the sliding surface of a cylinder barrel and its influence on the wear of the mating valve plate surface was investigated. Since the PVD-coated surface of cylinder barrel is as hard as 2200 Hv, an additional test was made to find out whether the wear rate of the valve plate reduces when it is made of harder material such as steel.

3. Experimental Comparison of Friction Coefficient and Wear Rate

3.1 Experimental apparatus

Figure 5 depicts the so-called tribometer for measuring friction coefficients and for testing anti-wear performance. This apparatus was built up

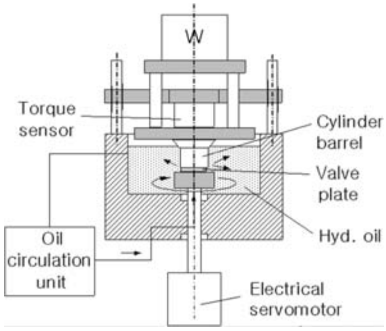


Fig. 5 Configuration of tribometer

to simulate the tribological contact between the cylinder barrel and the valve plate. In order to generate their relative motion, the valve plate was rotated by an electrical servomotor. Instead, the cylinder barrel was hold stationary by the reaction torque sensor which was constrained to the vertical movement by guide bars. The dead weights were used to bring up the normal force, $(1-\beta)\cdot F_p$ on the contact surfaces between the cylinder barrel and the valve plate. The torque signal then corresponds to the friction torque, $T_f=\mu_v r_c(1-\beta)F_p$ with fixed r_c.

The cylinder barrel and valve plates were submerged in the oil reservoir. The petroleum-based oil (ISO-VG6 type) was circulated through the drive shaft with its temperature regulated at 40℃ and supplied to the contact surfaces between the specimens to flush away wear particles.

3.2 Surface conditions of cylinder barrel and measured results of friction coefficient

Table 1 shows three test conditions to investigate the influence of cylinder barrel surface conditions on the friction coefficient and the wear

Table 1 Experiment conditions

Test conditions		I	II	III
Cylinder barrel	Material & surface treatment	AISI 4340, nitrided	AISI 4340, nitrided & TiN-coated	AISI 4340, nitrided & TiN-coated
	Hv	614.5	2200	2200
	R_a (μm) before test	0.269	0.174	0.174
Valve plate	Material	bronze	bronze	AISI 4340
	Hv	123.5	123.5	224.7
	R_a (μm) before test	0.165	0.165	0.184

rate of valve plate. The hardness of the TiN layer coated on the nitrided surface was as high as 2200 Hv, approximately 4 times as high as that of the uncoated surface of AISI 4340 steel. At the same time, the surface roughness of the cylinder barrel became better through the TiN coating.

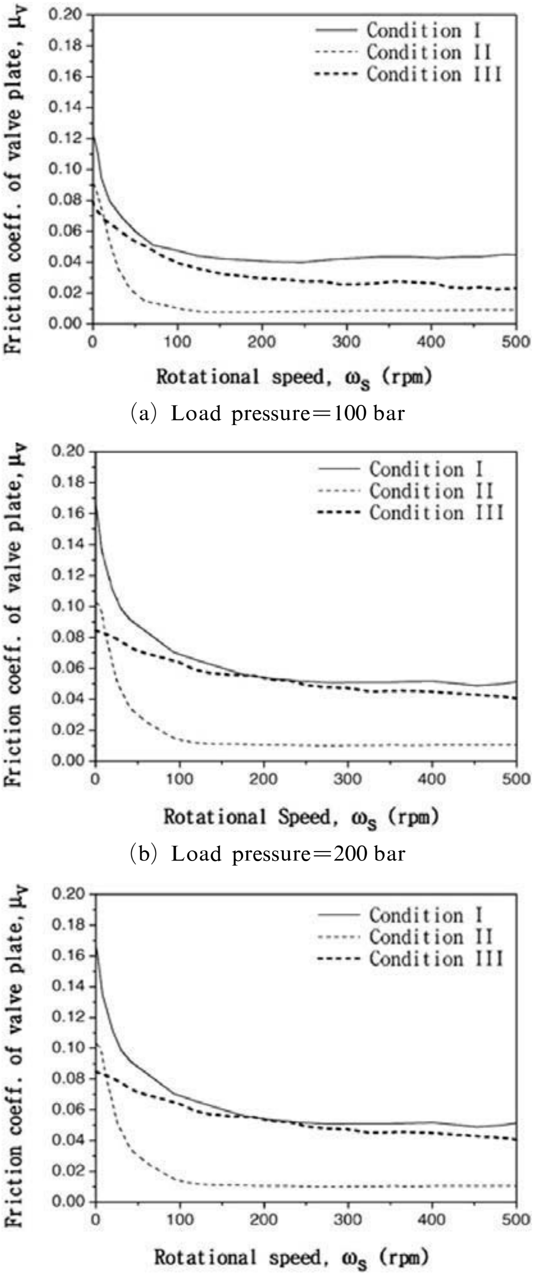
Since the TiN-coated surface was very hard, a steel type valve plate was extra tested. In this case, significant wear reduction of valve plate was expected because the steel valve plate was two times as hard as the bronze type.

It is to be pointed out that much effort was devoted to make the initial surface roughness of specimens as identical as possible, in order to exclude its influence on test results.

The friction coefficients, obtained for above three test conditions using the tribometer in Fig. 5, are depicted in Fig. 6. The weight applied to the specimens corresponded to the mean value of the normal load, $(1-\beta)\cdot F_p$ when the pump discharge pressure was assumed to be 100, 200 and 300 bar, respectively. Under these conditions the contact surface pressure of the specimens became approximately 1.1, 2.2 and 3.3 N/mm^2, respectively.

It is to be noted that the friction coefficient of the condition-II was little influenced by the load pressure, in contrast to those of other conditions. As a result, it turned out to be less than 20% of that measured for the condition-I, when the load pressure was 300 bar and the rotational speed higher than 150 rpm. This can be explained by the fact that the TiN-coated specimen had not only smoother surface but also better lubricity than the simply nitrided one.

However, the condition-III with steel-type valve plate indicated 3 to 4 times higher friction coefficient than the condition-II. The reason can be found from different wear mechanisms. In case of the soft bronze type valve plate, it was abrasively worn out by the harder cylinder barrel, while the wear particles were continuously flushed away from the contact surfaces. But the steel type valve plate was apparently subjected to adhesive wear, where the wear particles stuck on the contact surface again. These phenomena could be confirmed by microscopic observation as shown in the following.



(a) Load pressure=100 bar

(b) Load pressure=200 bar

(c) Load pressure=300 bar

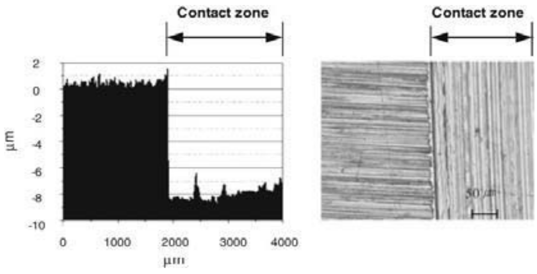
Fig. 6 Measured friction coefficients at different normal loads

3.3 Results of wear rate test

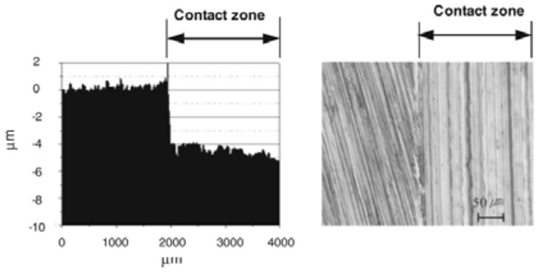
In order to compare the wear property of the valve plates according to the test conditions in

Table 1, the specimens were rotated 2 hours long at 100 rpm, while the normal load applied to the tribometer was equivalent to the load pressure of 300 bar. This test condition was selected so that the wear could be accelerated under mixed lubrication condition. After the tests, the cross section profile of each valve plate and their surfaces were registered as shown in Fig. 7. They show two regions distinguished by wear marks. The contact zone denotes the area where the bottom edge of cylinder barrel made milling contact with valve plate.

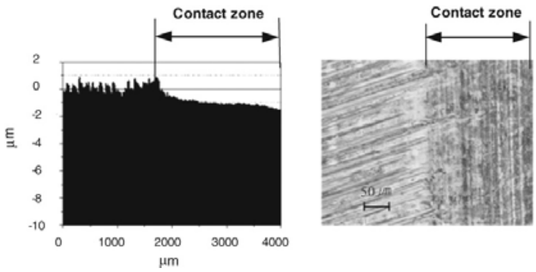
The specimen of the condition-I was worn out about 8 μm deep and showed distinct wear traces with considerable roughness. In contrast to that, the test condition-II proved that the wear volume of the specimen could be remarkably reduced by the TiN-layer : in this case, up to 40～50%. And the surface roughness of the contact zone was also improved because the cylinder barrel has initially better surface roughness with much higher hardness.



(a) Condition I



(b) Condition II



(c) Condition III

Fig. 7 Cross section profile and wear marks of specimens

As expected, the test condition-III registered the least wear depth which corresponded about 13% of that for the test condition-I. It was to be noted that the surface roughness of the contract zone became much better, which was to be explained by the adhesive wear mechanism. Since the steel type specimen was two times as hard as the bronze type of the condition-II, its anti-wear property must be also stronger. Therefore, the grooves of its contact surface must have been filled out by the wear particles, while the peaks were slightly worn out. The microscopic picture indicates that the initial peaks remained distinguishable, whereas the grooves were flattened along the slide contact traces.

4. Effect of PVD-Coating on Friction Torque

In order to compute the friction torque between the cylinder barrel and valve plate, based on Eq. (1) and the experimentally identified friction coefficient, the cylinder chamber pressure, p_i was additionally measured. Fig. 8 shows the wave-

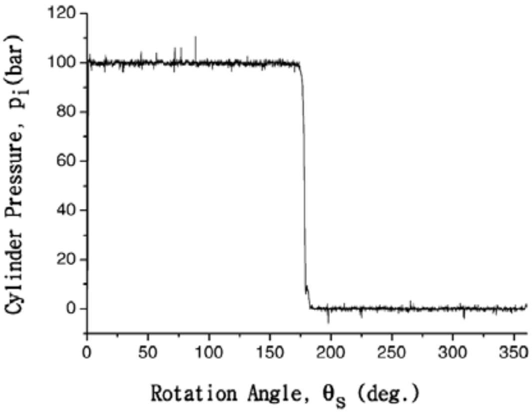


Fig. 8 Change of cylinder chamber pressure as function of shaft rotation angle (load pressure=100 bar, ω_s=50 rpm)

form of p_i as function of shaft rotation angle, when the outlet pressure was 100 bar and the rotational speed 50 rpm.

Since the number of the pistons is 5, the pressure waveform of each cylinder chamber shifts sequentially with a phase angle of 72°, as the pump shaft rotates. Therefore, the friction torque described by Eq. (1) also changes with the period of 72°. The friction torques computed by Eq. (1) using the data in Fig. 8 are depicted in Fig. 9. The mean value of the friction torque amounts 0.102 Nm for the condition-I and 0.034 Nm for the condition-II, while the ideal input torque to the pump is 7.71 Nm at load pressure = 100 bar.

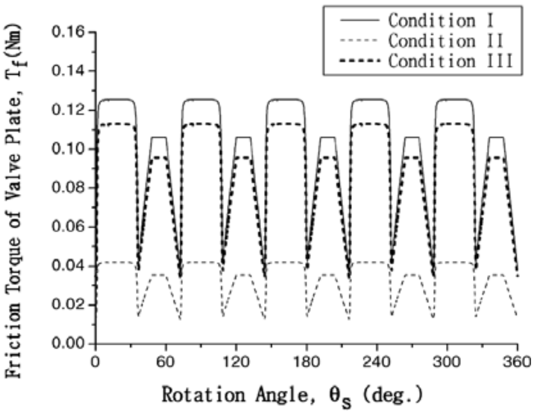


Fig. 9 Computed friction torque of valve plate (load pressure = 100 bar, ω_s = 50 rpm)

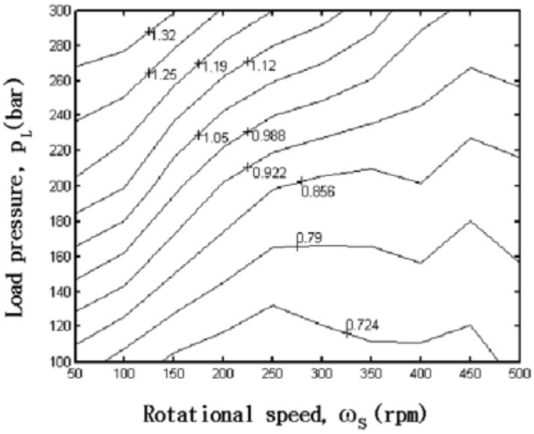


Fig. 10 Increased torque efficiency by TiN coating

If the improvement effect of torque efficiency by the TiN coating is defined as

$$\Delta\eta_t = \left(\frac{100\,T_i}{T_i + T_b + T_f}\right)_{coated} - \left(\frac{100\,T_i}{T_i + T_b + T_f}\right)_{uncoated} \tag{2}$$

where T_i and T_b denote ideal torque and friction torque of bearings, respectively, it can be graphically expressed as shown in Fig. 10. Here the load pressure and the shaft rotational speed were changed from 100 to 300 bar and from 50 to 500 rpm, respectively. It was also assumed that the friction torque caused by the pistons were negligibly small, while the friction torque of shaft bearings for the pump was quoted from the experimental data obtained by Hong (2004). The improvement effect appeared stronger as the load pressure increased and the rotational speed decreased. For example, when the load pressure was 280 bar and the rotational speed 100 rpm, the torque efficiency was expected to increase by an amount of more than 1.3%.

Therefore, it can be said that the PVD coating of TiN can improve not only the durability but also the operation efficiency of an axial piston type hydraulic pump, especially under the low-speed high-pressure working condition. Since this feature is one of most important performance criteria for the pumps to be applied to the EHAs, the application of the PVD coating technology in this study turned out to be very useful and promising.

5. Conclusions

When the bottom surface of a cylinder barrel contacting with bronze type valve plate was coated with TiN in the form of a thin layer, the friction coefficient at load pressure = 300 bar could be reduced to about 20% of the value reached by an uncoated surface, in the rotational speed range of mixed lubrication between 100 and 500 rpm. If this effect is quantified by the torque efficiency, it corresponds to an increase of more than 1.3% at load pressure = 300 bar and rotational speed = 100 rpm.

As for the wear property, the TiN-coated cylinder barrel showed also positive effect on the wear protection of valve plate. The wear rate of the bronze type valve plate could be reduced to 40～50% of the intensity registered by uncoated specimen at load pressure＝300 bar and rotational speed＝100 rpm. Although the steel type valve plate showed better wear resistance, the friction coefficient was rather 3 to 4 times higher than the bronze type.

In conclusion, the wear and the friction coefficient of valve plate could be simultaneously reduced by the plasma coating of the cylinder barrel surface with TiN, as far as the wear mechanism was not changed by using other valve plate material than bronze.

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