Experimental Studies on Friction and Scuffing Resistance of Ceramics for Cylinder Liner and Piston Ring*

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The present paper refers to the experimental studies on tribological characteristics of lubricated ceramics for cylinder liners and piston rings. The experiments have been carried out under the large sliding velocity condition close to that of practical engines with pin-on-disk-type reciprocative slide test equipment. The major results are that : (i) for the materials, it is desirable that the sliding surface get a moderate running-in under the more elastic contact condition, and that the liner and the ring be superior in thermal diffusibility and in heat resistance, respectively ; (ii) the respective influences of roughness and velocity on the scuffing are so large that the roughness should be kept smaller at the faster slide ; and (iii) the effects of additives in mineral oil on the lubricity and the scuffing resistance disappear, and the contaminated oil has worse influences on both, thus it is necessary to select the proper lubricants.

Key Words : Tribology, Ceramics, Internal Combustion Engine, Cylinder Liner, Piston Ring, Friction, Scuffing Resistance, Surface Roughness, Lubricant

1. Introduction

In recent years, much research and development on the application of ceramics to engine parts were carried out in order to improve the performance and durability of internal combustion engines^{(1)~(4)}. Especially, in case of the application to cylinder liners and piston rings, it becomes necessary to select materials superior in the tribological properties of low friction, antiwear and scuffing resistance, because these sliding surfaces are placed under the severe lubricating conditions of high temperature and gas pressure with reciprocating motion^{(5)~(8)}.

Therefore, many investigations concerned with the tribological characteristics of ceramics were reported, such as the friction and wear at high

temperature^{(9)~(11)}, the compatibility with lubricants^{(12)~(14)}, the influence of surrounding substances⁽¹⁵⁾⁽¹⁶⁾ and the occurrence mechanism of failure^{(17)~(19)}.

However, most of these reports evaluate only the tribological characteristics under the boundary lubrication or dry sliding condition of low speed and high load, which are different from those under the condition of mixed lubrication between piston rings and cylinder liners in actual working engines⁽²⁰⁾. Consequently, they are not sufficient for obtaining proper information regarding the tribological characteristics of ceramics applied to these sliding surfaces in practical engines.

In the present studies, the experiments were carried out under the large sliding velocity condition close to that of practical engines with a pin-on-disk-type reciprocative slide test equipment⁽⁸⁾, as shown in Fig. 1. As a result, the influences of the combinations of materials, the surface roughness, the sliding velocity, the ring profile and the properties of lubricants on the friction and the scuffing resistance of the lubricated ceramics were evaluated.

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Table 1 Properties of test materials

Material	Si ₃ N ₄	SiC	ZrO ₂	TiC	Al ₂ O ₃	Cr ₂ O ₃ Coat	Cr Plate	FC
Bulk Density [g/cm ³]	3.2	3.2	6.0	6.0	3.8	3.3	7.0	7.2
Vickers Hardness [GPa]	14.7	19.6	12.3	16.0	14.7	17.7	8.8	2.3
Fracture Toughness [MN/m ^{3/2}]	8.3	5.6	6.7	8.5	6.0	-	-	-
Young's Modulus [GPa]	294	432	206	441	245	108	88	108
Poisson's Ratio	0.28	0.16	0.31	0.23	0.20	-	-	0.27
Coefficient of Linear Thermal Expansion [1/°C]	2.6	4.4	11.0	7.4	8.0	13.3	9.4	11.5
Thermal Conductivity [W/(m·K)]	20.9	62.8	3.8	16.7	20.9	3.7	67.0	45.2
Specific Heat [kJ/(kg·K)]	0.67	0.63	0.46	0.71	0.92	0.59	0.46	0.54
Melting Point [°C]	1900	2350	2677	-	2050	1610	1850	1200
Thermal Shock Resistance [°C]	600	400	300	350	200	800	-	-

1. Rotary Shaft
2. Liner Specimen Disk
3. Ring Specimen Block
4. Ring Block Holder
5. Load Bellows
6. Compressed Air Tube
7. Oscillatory Arm
8. Horizontal Rod
9. Rod Guide
10. Vertical Support
11. Oscillation Device
12. Balance Weight
13. Load Sensor
14. Adjust Screw

Fig. 1 Schematic diagram of test equipment

2. Experimental Method

2.1 Test equipment

Figure 1 shows the schematic diagram of the test equipment. A downward loaded ring specimen ③ with a width of 7 mm and a length of 23 mm slides with an oscillatory motion on a rotary disk liner specimen ② with a diameter of 190 mm. Accordingly, the sliding velocity and direction of the ring are cyclically varied to be similar to those of the actual engines. The frictional force acting on the ring is measured by a strain gauge type load sensor ⑬. A small amount of test oil is fed to the liner specimen surface. The temperature of the specimens is raised by electric heaters installed below and around the liner specimen, and is measured by an embedded thermocouple in the ring.

All the tests were carried out by the following method. The contact pressure $\bar{p}$ and the mean sliding velocity $\bar{v}$ were alternatively increased in steps up to the respective predetermined values during the first 55 minutes; subsequently, the temperature alone was raised at a rate of 2°C/min until scuffing occurred.

Table 2 Properties of test lubricants

Lubricant	M30	M30A	S30A
Viscosity 40°C (cSt)	100.5	90.3	81.8
Viscosity 100°C (cSt)	11.1	10.9	12.0
Viscosity Index	96	105	142
TBN (mgKOH/g)	0.0	8.2	9.7

Table 3 Property of contaminated oil

Lubricant		UM30A	
Viscosity (cSt)		40 °C	210.4
		100 °C	35.7
Additives		Insolubles	
TBN(mgKOH/g)	1.5	Soot (Wt%)	7.1
Ca (ppm)	1630	Dust	Si(ppm) 9
Ba	10	Wear Debris	Fe(ppm) 69
Zn	250		Cu 15
P	380		Cr 5

The occurrence of scuffing was judged from both the sudden rise in temperature and the abnormal increase in friction.

2.2 Materials

Table 1 shows the properties of the materials for liner and ring specimens. In this table, Si₃N₄ (silicon nitride), SiC (silicon carbide), ZrO₂ (zirconia) and Al₂O₃ (alumina) are pressureless sintered monolithic ceramics, TiC is a cermet, and Cr₂O₃ Coat is a densified coating of chromium oxide chemically bonded with metal of about 0.1 mm in thickness⁽²¹⁾. On the other hand, Cr Plate (hard chromium plate) and FC (cast iron) are used as reference materials of conventional liners and rings.

2.3 Lubricants

Table 2 shows the properties of the lubricants used for experiments. These lubricants are mineral oil without additives M30, mineral oil with additives M 30 A and synthetic oil (polyalphaolefin) with additives S 30 A. The additives are equivalent to those of the CD-level engine oil. One more lubricant UM 30 A is the contaminated oil of M 30 A used in an actual diesel engine, as shown in Table 3.

3. Test Results and Considerations

3.1 Influences of materials

Figure 2 shows the values of the occurrence temperature of scuffing T_s and the minimum coefficient of friction $\mu_{\min}$ examined on some ring materials with the four liner materials of cast iron, ZrO_2 , Si_3N_4 and the Cr_2O_3 coating. The R_{rms} denotes the surface roughness of the specimen before the experiment and $\mu_{\min}$ is the minimum value of the coefficient of friction μ which changes as the sliding condition becomes severe during the experiment, as shown in Fig. 3, where η is the oil viscosity and $\bar{p}'$ is the load per unit length of the ring.

From these figures, in the case where the liner material is cast iron, more improvement could not be expected in the lubricity and the scuffing resistance such that T_s exceeds 200°C and $\mu_{\min}$ is less than 0.01 by the use of even the ceramic ring material in comparison with the conventional ring materials of cast iron or the Cr plate.

On the other hand, in case of the ceramic liner materials of ZrO_2 , Si_3N_4 and the Cr_2O_3 coating, it is recognized that the values of T_s increase to more than 200°C and the values of $\mu_{\min}$ become about 0.01 with the ring materials of the Cr plate, Si_3N_4 , TiC and the Cr_2O_3 coating. However, the ring materials of both SiC and Al_2O_3 have large values of $\mu_{\min}$ and low values

of T_s , although the values of T_s tend to be higher with the increase in hardness of the liner materials. Also, the T_s values of ZrO_2 ring materials are low in spite of the smaller values of $\mu_{\min}$.

On the basis of these results, the following points can be considered. In the case of the liner material of cast iron, the rings of ceramics with much higher hardness and melting point can hardly achieve running-in, because the plastic deformation or the adhesive wear at the contact areas mainly occurs on the liner. Consequently, the friction is high, and scuffing failure occurs at a lower value of T_s due to the low plastic flow pressure and melting point of cast iron.

On the other hand, in the case of the ceramic liners, each ring material shows a similar tendency of superiority or inferiority in the friction and the scuffing resistance regardless of the liner materials. Namely, the ring materials of SiC or Al_2O_3 have lower values of T_s since the friction is high due to the smaller fracture toughness⁽¹⁹⁾, and the thermal shock resistance is not so large. Also, the ZrO_2 ring inferior in thermal diffusibility shows the lower value of T_s , although the friction is markedly low. As the reason, it is considered that a number of cracks on the sliding surface can easily be created, which are caused by the shortage of thermal strength against the higher tem-

Liner	Ring	R_{rms} (μm)	T_s (°C)			$\mu_{\min}$
			100	200	300	
FC ($R_{rms} = 0.11 \sim 0.19 \mu m$)	FC	0.31				0.038
	Si_3N_4	0.04				0.023
	Cr	0.10				0.012
	ZrO_2	0.03				0.013
	TiC	0.05				0.039
	SiC	0.08				0.034
	Cr_2O_3	0.04				0.013
	SiC	0.04				0.026
ZrO_2 ($R_{rms} = 0.04 \sim 0.07 \mu m$)	ZrO_2	0.05				0.012
	Cr	0.14				0.006
	Si_3N_4	0.08				0.012
	TiC	0.06				0.012
	Cr_2O_3	0.04				0.006
	SiC	0.04				0.006
Si_3N_4 ($R_{rms} = 0.11 \sim 0.14 \mu m$)	Al_2O_3	0.13				0.046
	SiC	0.07				0.022
	ZrO_2	0.04				0.005
	Cr	0.13				0.010
	Si_3N_4	0.05				0.010
	TiC	0.03				0.009
Cr_2O_3 ($R_{rms} = 0.04 \sim 0.07 \mu m$)	Al_2O_3	0.13				0.028
	SiC	0.08				0.037
	Cr	0.17				0.008
	TiC	0.03				0.013
	Si_3N_4	0.05				0.007
	Cr_2O_3	0.05				0.007

Fig. 2 Influence of combinations of materials
($\bar{p} = 3 \text{ MPa}$, $\bar{v} = 15 \text{ m/s}$, M30 oil)

Fig. 3 Changes of friction coefficient with bearing modulus

perature rise at the real contact areas⁽⁷⁾. However, in the case of the ring materials of Si_3N_4 , TiC and the Cr_2O_3 coating, T_s is high and $\mu_{\min}$ is small, because these materials have comparatively high hardnesses, fracture toughnesses, melting points and thermal shock resistances.

In particular, it is noteworthy that the ring of the Cr_2O_3 coating is the most superior in scuffing resistance among all ring materials, although the thermal diffusibility is as small as that of ZrO_2 .

This superior scuffing resistance is probably due to the properties of the Cr_2O_3 coating that the solid contact condition between the sliding surfaces becomes more elastic. This is because the ratio of Young's modulus to hardness giving the plasticity index⁽²²⁾ of the Cr_2O_3 coating is the smallest of all the test materials; for instance, the ratio is 47 to cast iron, 17-28 to the monolithic ceramics, 10 to the Cr plate and 6 to the Cr_2O_3 coating. Namely, the decrease in the ratio causes the plastic deformation and the brittle fracture at the real contact areas to be small in scale⁽²³⁾. Consequently, it is considered that the running-in on the sliding surface is promoted and it becomes difficult for scuffing to occur.

As for the liner materials, it can be said that the liner of Si_3N_4 , as well as the Cr_2O_3 coating, is low in friction and superior in scuffing resistance, but the ZrO_2 liner is somewhat inferior in scuffing resistance.

Consequently, from the viewpoints of both low friction and scuffing resistance, it is desirable that the liner materials have hardnesses which allow the ring surface to achieve moderate running-in, and that the materials for liner and ring be superior in thermal diffusibility and in heat resistance, respectively.

3.2 Influences of surface roughness and sliding velocity

Figure 4 shows the influence of the surface roughness on the values of T_s and $\mu_{\min}$ for several combinations of materials, and Fig. 5 shows the changes of the relationship between T_s and $\bar{v}$ with the surface roughness of the Cr_2O_3 coating liner.

Ring Liner	Rrms (μm)		T_s ($^{\circ}\text{C}$)			$\mu_{\min}$
	Liner	Ring	100	200	300	
Al_2O_3 Si_3N_4	0.15	0.75				0.011
	0.24	0.14				0.011
	0.14	0.13				0.046
ZrO_2 Si_3N_4	0.16	0.31				0.008
	0.14	0.04				0.013
Si_3N_4 ZrO_2	0.28	0.06				0.014
	0.07	0.08				0.012
Si_3N_4 Si_3N_4	0.32	0.04				0.006
	0.12	0.05				0.010

Fig. 4 Influence of surface roughness
($\bar{p}=3\text{ MPa}$, $\bar{v}=15\text{ m/s}$, M30 oil)

From these figures, it is found that scuffing occurs more easily with the increase in the surface roughness of the liner or the ring. Such a large reduction in T_s values with the surface roughness is a characteristic peculiar to ceramics which are short of running-in property due to its large hardness, unlike that of the conventional material of cast iron⁽⁸⁾. However, it is noteworthy that the decreasing tendency of friction with the increase in the surface roughness is observed, as shown in Fig. 6.

On the other hand, from Fig. 5 and Fig. 7, it is recognized that the value of T_s decreases considerably and the value of $\mu_{\min}$ increases with the increase in

Fig. 5 Changes of the relationship between T_s and $\bar{v}$ with surface roughness

Fig. 6 Changes of the relationship between μ and $\eta\bar{v}/\bar{p}$ with surface roughness

sliding velocity $\bar{v}$ since the temperature rise at the real contact area is promoted by the increase in the sliding velocity⁽²⁴⁾.

Consequently, as both the surface roughness and the sliding velocity considerably influence the occurrence of scuffing, in the case of the application of ceramics to cylinder liners and piston rings in the advanced high-speed engines, it becomes most important to make the surface roughness as small as possible.

3.3 Influence of the ring face profile

Figure 8 shows the influence of the barrel height H_b on the friction and the scuffing resistance for the ring with a barrel-faced profile. From this figure, it is found that in the case of the ring with the barrel height of 5 μm , the value of $\mu_{\min}$ decreases, the value of T_s increases extremely and the transition value of the

Fig. 7 Change of the relationship between μ and $\eta\bar{v}/\bar{p}'$ with sliding velocity

Fig. 8 Influence of ring face profile

bearing modulus $\eta\bar{v}/\bar{p}'$ from the fluid film lubrication to the boundary lubrication is reduced to a minimum. From this result, it becomes clear that the ring with an optimized barrel-faced profile is effective for the reduction of friction and the improvement in the scuffing resistance.

3.4 Influences of lubricant properties

Figure 9 shows the influences of the types of oil used, the additives and the contaminations with four test lubricants. From this figure, it is recognized that the additives in the mineral oil M 30 A are useful for reducing the friction and improving the scuffing resistance in the case of the combinations of the conventional materials, that is, cast iron or the Cr plate. However, in the case of the combinations of ceramic materials, it is found that the occurrences of scuffing tend to be promoted due to the additives. Namely, the improvement in the tribological properties of ceramics cannot always be expected with the additives in oils which are effective for the conventional materials, since both materials result in the different mechanochemical reactions between the oils and the sliding surfaces⁽¹⁴⁾.

By the use of the contaminated oil UM 30 A instead of the M 30 A oil, the values of T_s examined for the conventional materials become higher, but the values of T_s for the ceramic materials become lower than those values obtained with the M 30 A oil. It is thought that in the case of soft materials such as cast iron or the Cr plate, the running-in on the sliding surface is promoted due to the increased abrasive wear by the oil contaminations, and it becomes difficult for scuffing to occur. On the other hand, in the

Ring Liner	Test Oil	T_s (°C)				$\mu_{\min}$
		100	200	300	400	
FC FC	M30					0.038
	M30A					0.032
	UM30A					0.021
	S30A					0.038
Cr FC	M30					0.013
	M30A					0.002
	UM30A					0.005
	S30A					0.005
SiC Si ₃ N ₄	M30					0.022
	M30A					0.024
	UM30A					0.025
	S30A					0.034
Si ₃ N ₄ Cr ₂ O ₃	M30					0.007
	M30A					0.011
	UM30A					0.030
	S30A					0.016
Cr ₂ O ₃ Si ₃ N ₄	M30					0.009
	M30A					0.005
	UM30A					0.004
	S30A					0.009

Fig. 9 Influence of test lubricants
($\bar{p}=3\text{ MPa}$, $\bar{v}=15\text{ m/s}$)

case of hard ceramic materials, the running-in process is hardly affected by the contaminations due to the excellent antiwear property of ceramics, and the inferior lubricity of the used oil lowers the values of T_s .

In the case of the synthetic oil S 30 A, it is shown that the values of T_s increase markedly, although the values of $\mu_{\min}$ become somewhat large with all combinations of materials. However, it is observed that there is a significant difference in the increment of T_s values between the SiC ring and the Cr_2O_3 coating ring. This result shows that the compatibility of ceramics with lubricants considerably influences the tribological characteristics⁽¹⁴⁾.

Consequently, it becomes clear that the proper selection of lubricants is most important for applying the ceramics as materials for the cylinder liners and piston rings.

4. Conclusions

From the experiments on the friction and the scuffing resistance of the lubricated ceramics for the cylinder liners and piston rings under the large sliding velocity condition, the following conclusions are obtained.

(1) As for the material, it is desired that its sliding surface achieve a moderate running-in under the more elastic contact condition, and that the liner and the ring be superior in thermal diffusibility and heat resistance, respectively.

(2) Since both the surface roughness and the sliding velocity considerably influence the occurrence of scuffing, it is important to make the roughness as small as possible under the large sliding velocity condition.

(3) The ring with an optimized barrel-faced profile is effective for the reduction of friction and the improvement in the scuffing resistance.

(4) Since the additives of the CD-level engine oil are not always useful for the improvement in the tribological characteristics, the contaminated oil promotes the occurrence of scuffing, and the compatibility of ceramics with the synthetic oil influences the scuffing resistance considerably, it becomes necessary to select proper lubricants as well as combinations of materials.

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