Met. Mater. Int., Vol. 15, No. 6 (2009), pp. 903~908
doi: 10.1007/s12540-009-0903-0 Published 26 December 2009

Effect of Hardness of the Piston Ring Coating on the Wear Characteristics of Rubbing Surfaces

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(received date: 30 March 2009 / accepted date: 18 November 2009)

In marine engines, the wear between the piston-ring face and the cylinder liner is an extremely unpredictable and hard-to-reproduce phenomenon that significantly decreases engine performance. This study investigates the characteristics of wear arising between both hard and soft piston-ring coatings and the running surface of the cylinder liner. A detailed tribological analysis using a Pin-on-Disk (POD) testing machine compares the wear rate and the friction coefficient between piston-ring coatings and the cylinder liner for various test parameters, such as test temperature, roughness of the liner, and lubrication. The experimental results show that the wear rate and the friction coefficient of soft coatings were higher than those of hard coatings. The wear rate and the friction coefficient were also found to be influenced by test temperature, due to the lubrication effect of the wear-protective oxidized layers that developed at elevated temperatures. The surface roughness of the cylinder liner on the wear rate strongly influenced the soft coating but was much less apparent for the hard coating. The morphological features of the scuffed cylinder liner revealed that a harder piston-ring coating enhances scuffing of the cylinder liner.

Keywords: sliding wear, wear testing, hardness, surface analysis, scuffing

1. INTRODUCTION

The tribological properties of cylinder liners and piston rings have attracted much attention due to their strong influence on engine performance and lifespan [1-11]. Depending upon engine operating conditions, various materials have been applied to the surface of the piston ring that is in contact with the cylinder liner [2-4].

As the contact phenomenon is a complex function of sliding speed, force, plastic deformation, and roughness of the interface, the wear between the piston-ring face and the cylinder liner is an extremely unpredictable and hard-to-reproduce issue. In engineering applications of tribology, the characteristics of the surface topography and roughness are also important factors in describing the wear and damage to surfaces. Surface roughness, in particular, is known to play an important role in scuffing under conditions of contact that are starved of lubrication [4-7].

Scuffing is a complicated phenomenon. It involves mechanical, physical, chemical, and thermal interactions among the contacting surfaces, the environment, the lubricant, and other entities at a sliding interface. To understand the scuffing mechanisms of the piston-ring/cylinder-liner contact in engines and to investigate the use of coatings to prevent scuffing, material pairs have to be studied in a motional environment similar to that of a real engine [8].

This study investigates the characteristics of wear between hard and soft piston ring coatings with the running surface of the cylinder liner. Scuffing analysis through a Pin-on-Disk (POD) testing machine will also be conducted to examine the relationship of the wear rate and the friction coefficient, between piston ring coatings and the cylinder liner, to various test parameters, such as test temperature, roughness of the liner, and lubrication.

2. EXPERIMENTAL PROCEDURE

2.1. Materials

Two different feedstock coating layers of piston rings were used. The soft coating layer shown in Fig. 1(a) consisted mainly of Cu-Al (Cu 74 %, Al 17 %, etc.) alloy; the coating layer was about 0.25 mm to 0.35 mm thick and the average Vickers hardness was 143.7HV. The hard coating shown in Fig. 1(b) consisted mainly of chrome-aluminum oxide; the coating layer was about 0.3 mm to 0.4 mm thick and the average Vickers hardness was 719.6 HV. The material used for the cylinder liner was gray cast iron with a coarse-flake

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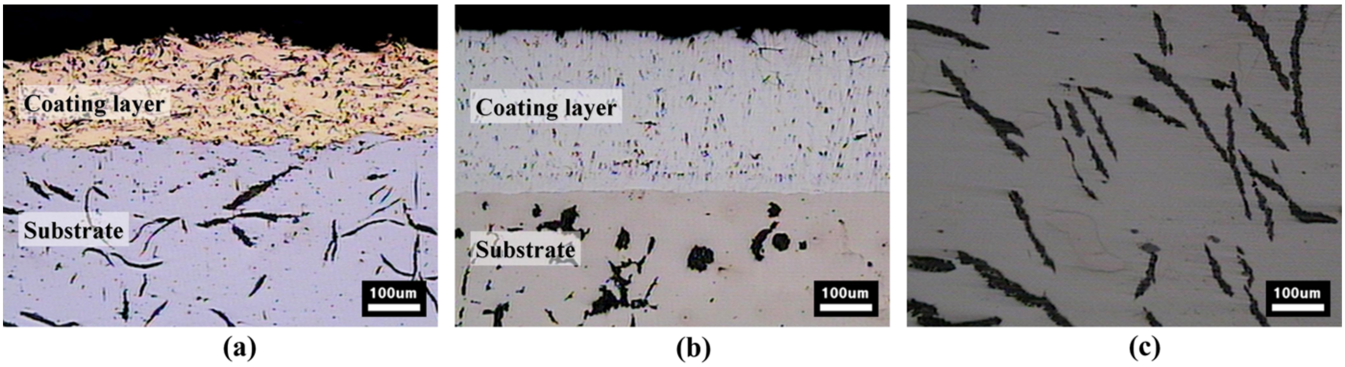

Fig. 1. Microstructures of piston ring and cylinder liner: (a) soft coated piston ring, (b) hard coated piston ring and (c) cylinder liner.

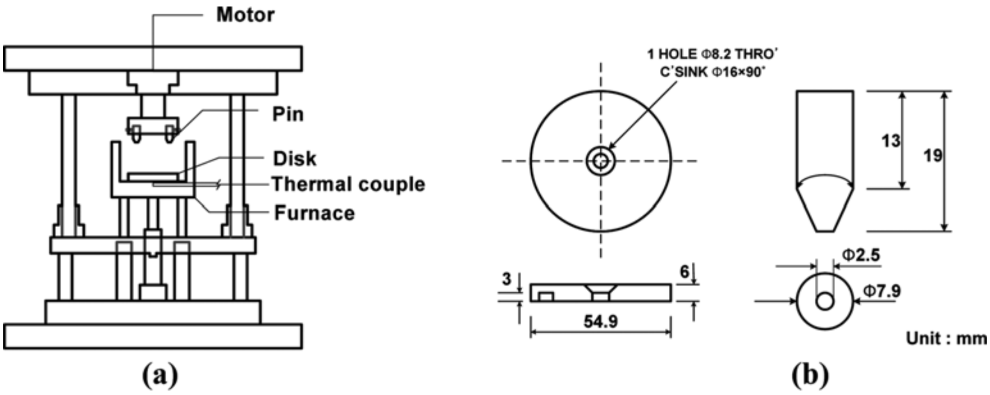

Fig. 2. Pin-on-disk test: (a) test system and (b) dimensions of the disk and the pin.

graphite structure as shown in Fig. 1(c); the hardness was measured to be an average of 300 HV.

2.2. Experimental procedures

The experiments were conducted on a pin-on-disk (POD) test apparatus. The material used for the piston ring was machined into the pin and that of the cylinder liner was machined into the disk. Figure 2(a) shows a schematic drawing of the test system. During testing, a data logging system continuously recorded the test time (sliding distance), the friction coefficient, the temperature, the torque, and the normal force. The data were written to a file for further processing. The dimensions of the pin and disk are shown in Fig. 2(b). The disks had a diameter of 54.9mm and a height of 6 mm. The pin was shaped so that the disks could be firmly mounted, and the disks had a circular contact area with a 2.5 mm diameter.

To measure the wear rate and friction, the wear test was carried out for 60 min using a POD testing system under varying temperatures (25 °C, 100 °C, 170 °C and 230 °C). The initial levels of roughness of the pins were maintained the same as those of feedstock materials, i.e., Ra 0.28 μm to 0.35 μm for hard coatings and Ra 7.5 μm to 8.0 μm for soft coatings, respectively. The disk was formed by turning followed by grinding of the contacting surfaces, giving the disk an initial roughness of Ra 0.2 μm to 0.5 μm. Prior to the test, the pin and the disk were cleaned by an ultrasonic cleaner. Following the test run, the pin and the disk were removed from the test apparatus and again cleaned as per the initial cleaning procedure. Then, the weight of the pin was measured by an electronic balance with a resolution of 0.1 mg. For the wear test, 100 N of load was applied under a sliding speed of 2.75 m/s in a motional environment similar to that of a real, marine diesel engine [9]. The speed was easily realized by the software control package. Once an appropriate maximum sliding distance and/or maximum friction coefficient was set, the test began, and a continuous log of the friction coefficient vs. the sliding distance was written to a computer file.

To investigate the effect of the surface roughness of the cylinder liner, the test was carried out for three different values of liner roughness: Ra 0.2 μm to 0.5 μm, Ra 0.7 μm to 1.0 μm, and Ra 1.2 μm to 1.5 μm. To obtain a more sensitive roughness effect, 50N of load was applied under a sliding speed of 0.916 m/s. Further, to examine the effect of lubricant, a POD test with lubricant was also conducted. To accelerate the wear rate under lubrication, 400N of load was applied under a sliding speed of 2.75 m/s.

To investigate scuffing behaviors, worn surfaces obtained from the POD test were analyzed by an optical microscope.

To observe the gradual initiation and propagation of surface scars with the sliding distance, the worn surface was periodically observed during the test. For this test, 50N of load was applied under a sliding speed of 1.83 m/s.

3. RESULTS AND DISCUSSION

3.1. Wear characteristics of coated layers

The wear rate was calculated using the wear volume and the sliding distance. The variations in the wear rate as a function of the sliding distance and the average friction coefficient of the stable sliding region at temperatures of 25 °C, 100 °C, 170 °C, and 230 °C are shown in Fig. 3. Here, wear was expressed as the sum of the wear volumes of the pin. As shown in Fig. 3, the wear rates at higher temperatures were considerably greater than those at 25 °C. The decreased deformation resistance and the increased friction coefficient at higher temperatures were responsible for the accelerated wear rate. The decreasing wear rate and friction coefficient at even higher temperatures of 170 °C and 230 °C can be explained by the lubrication effect of the wear-protective oxidized layers.

Figure 4 shows the variations in the friction coefficient (μ) with sliding distance at a normal pressure of 100N and sliding speed of 2.748 m/s. The graphs clearly show two distinct regions of interest: running-in and stable sliding. Running-in took place during the first part of the run during which μ was unstable, usually rising from low values to approximately 0.45. Then stable sliding prevailed for a distance [9]. The friction coefficient was calculated by measuring the torque on the pins and the radius of the wear track using the following equation:

$$\mu = \frac{T}{F_N \cdot r} \tag{1}$$

Where μ is the friction coefficient, T is the torque, F_N is the applied load, and r is the radius of the wear track.

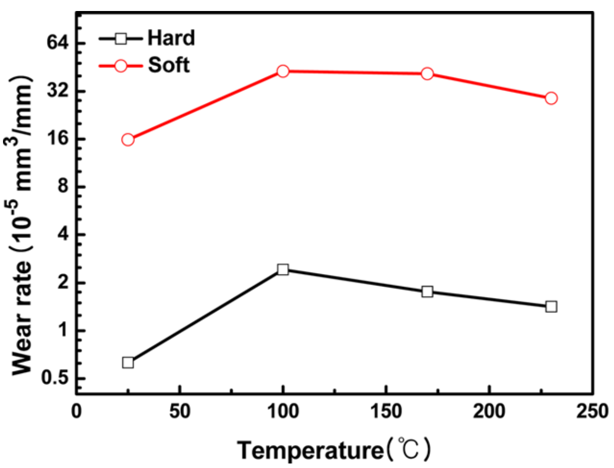

Fig. 3. Wear rates of pin at various temperatures.

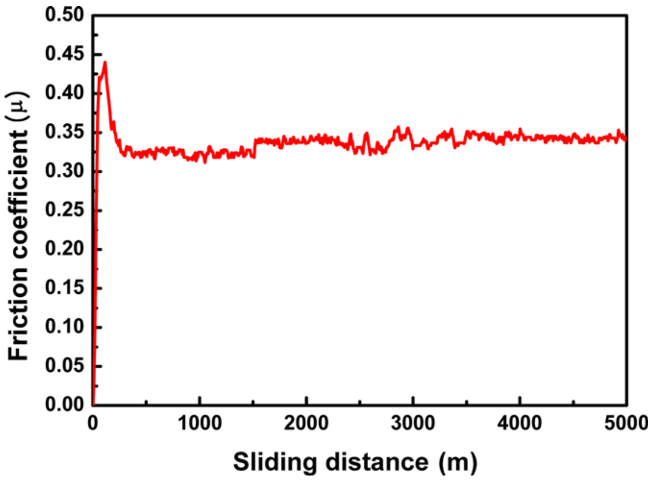

Fig. 4. Representative runs showing the variation of friction coefficient of hard coating at 25 °C.

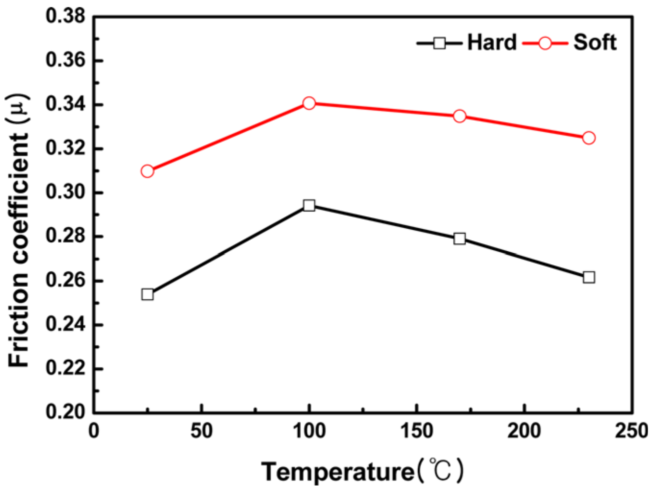

Fig. 5. Friction coefficients at various temperatures.

Figure 6 shows the disk surface tested at various temperatures. The colors of the disk surface varied with test temperatures; (a) 25°C - dark gray, (b) 100°C - light brown, (c) 170°C - reddish brown and (d) 230°C - purple. This means that oxide films were formed by surface oxidation and the friction coefficient was influenced by the oxide films on the rubbing surfaces.

Figure 7 compares the worn disk surfaces at 100°C and 230°C. At 100°C, smearing, pits, and tearing of the local surfaces were observed, while smoother surfaces appeared on the rubbing surfaces at 230°C. These smooth surfaces with lower friction coefficient are supposed to originate from the lubrication effect of the wear protective oxidized layers developed at 230°C [1,9].

Figure 8 compares the wear rates obtained at various roughness levels of the surface of the disk. The findings show that the influence of surface roughness on the wear rate

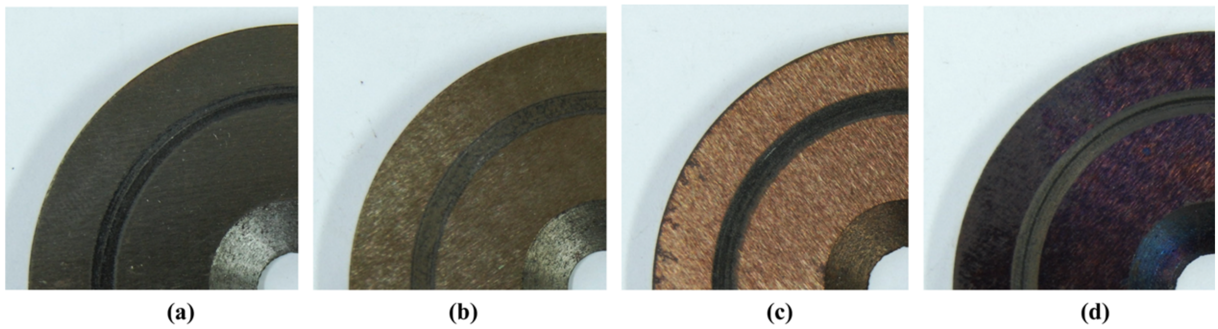

Fig. 6. Disk surface color at various temperatures and worn surface: (a) 25 °C-dark gray, (b) 100 °C-light brown, (c) 170 °C-reddish brown, and (d) 230 °C-purple.

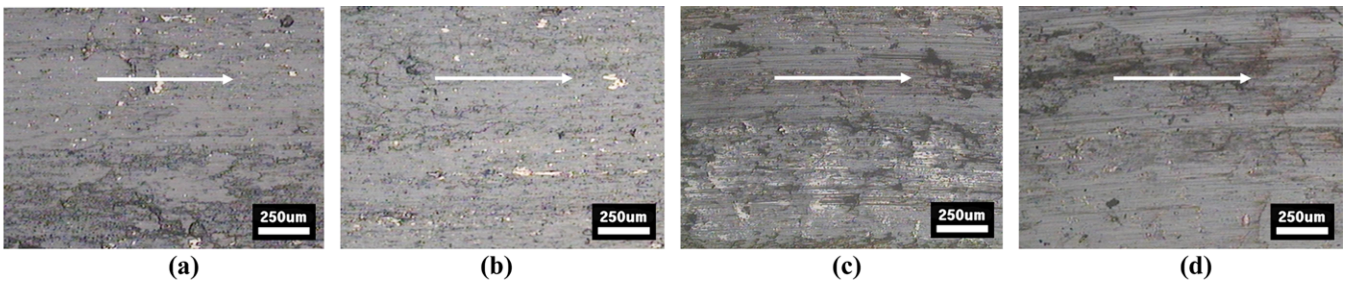

Fig. 7. Worn disk surface (the arrow indicates the apparent sliding direction): (a) soft coating-100 °C, (b) soft coating-230 °C, (c) hard coating-100 °C, and (d) hard coating-230 °C.

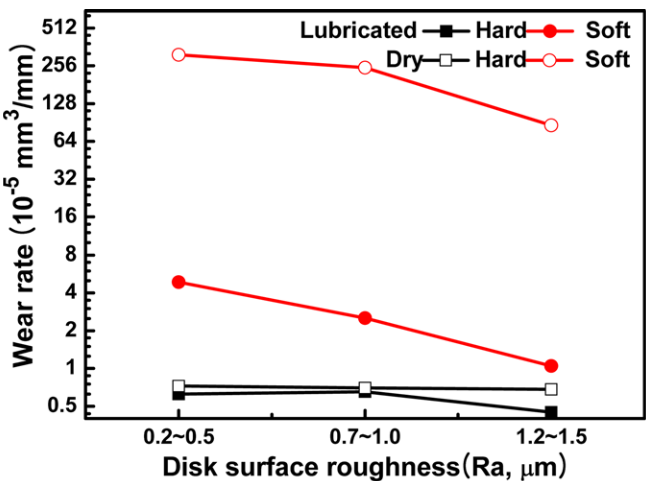

Fig. 8. Wear rates at various disk surface roughnesses.

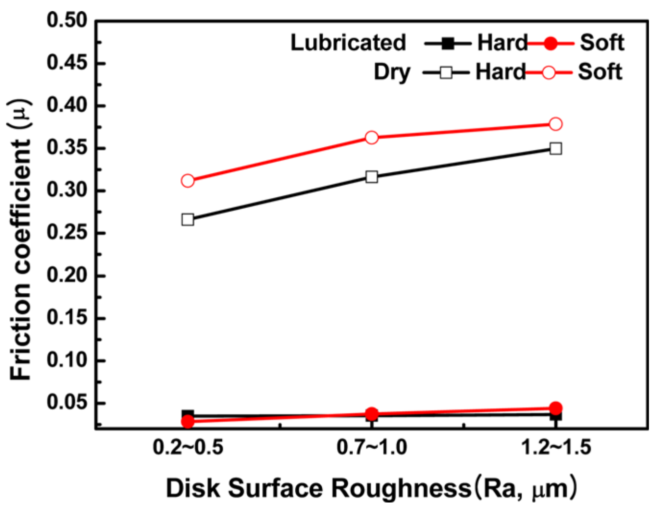

Fig. 9. Friction coefficients at various disk surface roughnesses.

is strong for the soft coating but much less apparent for the hard coating. In the case of the soft coating, the wear rate was directly influenced by the actual contact area of the surface of the disk. The decreased contact area at rougher surfaces was presumed to be the main reason for the decreased wear rate for the soft coating. In the case of the hard coating, the wear rate was not significantly influenced by the roughness of the disk because the disk was softer than the pin coating. The friction coefficients obtained at various roughness levels of the surface of the disk are shown in Fig. 9. It is evident from Fig. 9 that surface roughness does exert an influence on the average friction coefficient, with smoother surfaces generally yielding lower friction coefficients [12,13]. This considerable difference indicates that a smooth surface (lower surface roughness) is beneficial in reducing friction, especially under boundary lubrication.

3.2. Scuffing behavior

Figure 10 shows the optical micrograph of a cylinder liner that has been scuffed.

In the case of the soft coating as shown in Fig. 10(a), the

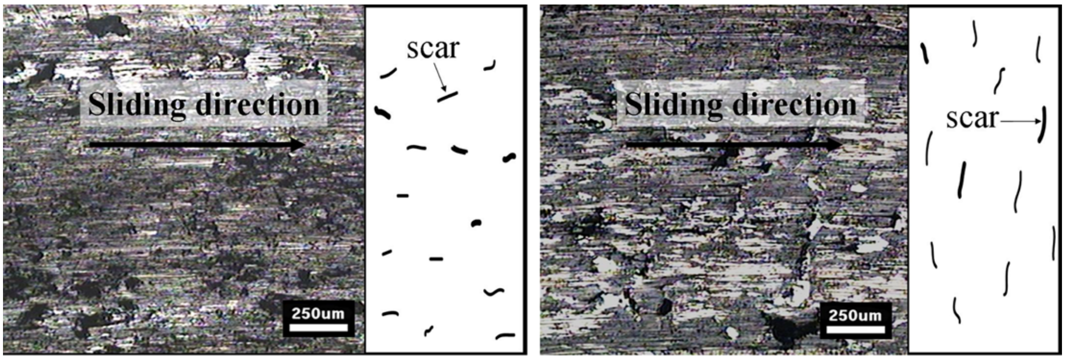

Fig. 10. Optical micrograph of real cylinder liner that has scuffed: (a) disk surface against soft coating and (b) disk surface against hard coating.

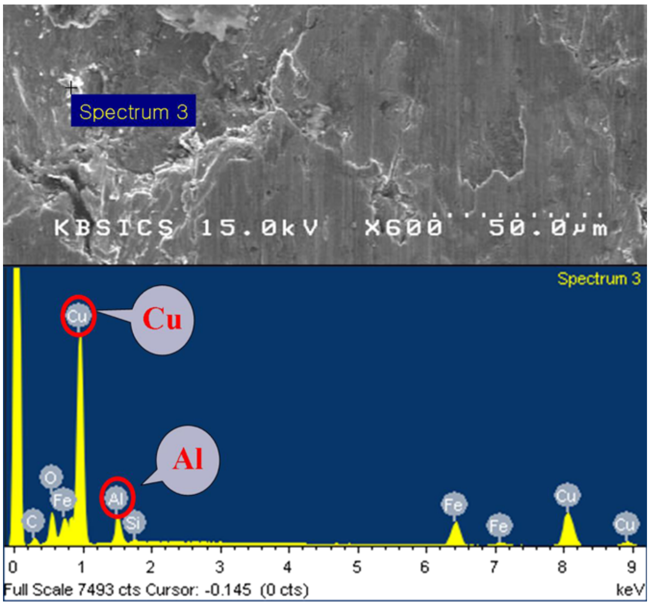

Fig. 11. Chemical analysis of spectrum 3 using an EDX analyzer.

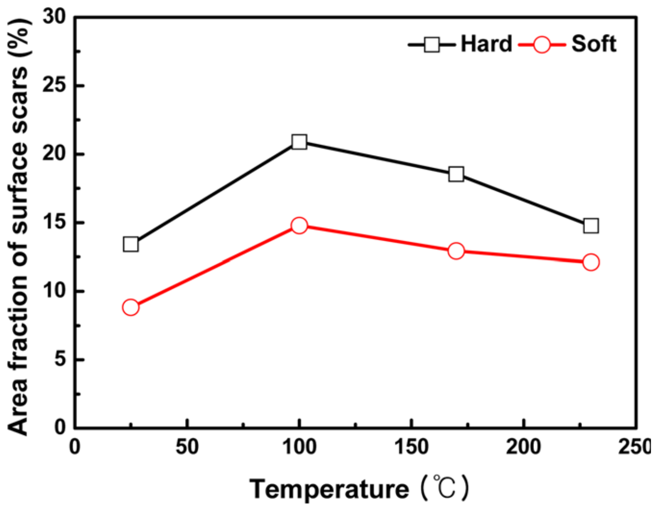

Fig. 12. Area fraction of surface scars at various temperatures.

surface scars were mainly aligned with the sliding direction. Furthermore, particles of the soft coating material partially adhered to the surface of the disk at the initial stage. This can be confirmed through the topography of the disk surface using a SEM and through the chemical composition of spectrum 3 shown in Fig. 11.

The EDX analyses indicate significant levels of Cu and Al, revealing that particles of the coating layer adhered to the surface of the disk. This adherence promotes the resistance of the soft coating to scuffing. In the case of the hard coating shown in Fig. 10(b), the surface scars were mainly aligned perpendicular to the sliding direction because the hard coating layer caused a separating force in the direction of the sliding; further, particles of the coating layer did not adhere to the surface of the disk. Figure 12 shows the area fraction of surface scars at various temperatures after a scuffing test for 20 min. Owing to the rigidity of the coating layer, more scars formed on the disk surface and the resultant scuffing was accelerated for the hard coating [14]. The volume of surface scars at 100 °C was greater than that at 25 °C. The decreasing volume of surface scars at even higher temperatures of 170 °C and 230 °C can also be consistently explained by the lubrication effect of the wear-protective oxidized layers that develop above 100 °C.

4. CONCLUSION

(1) The soft coating helps prevent scuffing that tends to occur early during engine operation and promotes stability of contact with the liner at the initial stage. The hard coating can be used to improve the lifespan of the piston ring through its outstanding resistance to wear.

(2) The wear rate of soft coatings is greater than that of hard coatings, and the friction coefficient decreases with increasing hardness of the coating of the piston ring.

(3) The wear rate, the friction coefficient, and the surface scarring at 100 °C were greater than those at 25 °C. At even

higher temperatures above 100 °C, these values decrease due to the lubrication effect of the wear-protective oxidized layers that develop above 100 °C.

(4) The influence of surface roughness on the wear rate is strong for the soft coating but much less apparent for the hard coating.

(5) In the case of the soft coating, the surface scars were mainly aligned with the sliding direction, while on the other hand, in the case of the hard coating, the surface scars were mainly aligned perpendicularly to the sliding direction because the hard coating layer induces a separating force in the direction of sliding.

(6) The adherence of soft coating materials to the surface of the disk promotes the resistance of the soft coating to scuffing. In the case of the hard coating, more scars were formed on the disk surface and the resultant scuffing was accelerated due to the rigidity of the coating layer.

ACKNOWLEDGMENT

This work was partially supported by grants-in-aid for the National Core Research Center Program from MOST/KOSEF.

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