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Tribological Performance and Scuffing Resistance of Cast-Iron Cylinder Liners and Al-Si Alloy Cylinder Liners

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Abstract: In order to better determine the applicable working conditions of Al-Si alloy cylinder liners and cast-iron cylinder liners, their tribological performance and scuffing resistance are discussed in this paper. After wear and scuffing tests, it was found that cast-iron cylinder liners had better wear resistance and better scuffing resistance, but poor friction performance. Al-Si alloy cylinder liners had weaker wear resistance and scuffing resistance, but excellent friction performance. The wear mechanism of cast-iron cylinder liners is slight adhesive wear, and they are suitable for traditional fuel engines and turbocharged engines with high load, high power, and high stability. The wear mechanism of Al-Si alloy cylinder liners was a mixture of adhesive wear and abrasive wear, and they are suitable for engines that are lightweight, efficient, and energy-saving, and operate at high speeds.

Keywords: tribological performance; wear and friction; scuffing resistance; cast-iron cylinder liner; Al-Si alloy cylinder liner

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1. Introduction

Cylinder liners are key components in engines, responsible for high-frequency-wear tasks [1]. From the past to the present, cast-iron cylinder liners are widely used, with higher hardness and better wear resistance. Many scholars have studied the friction behavior and wear process of cast-iron cylinder liners under various working conditions [2,3]. However, their weight is large, their thermal conductivity is poor, and their thermal expansion coefficient is inconsistent with that of the aluminum piston, resulting in a large cylinder clearance. In recent years, aluminum-alloy cylinder liners have begun to emerge, which can compensate for these shortcomings of cast-iron cylinder liners [4]. Aluminum-alloy cylinder liners are only one-third of the weight of cast-iron cylinder liners, which can promote the lightweight of automobiles. If the mass of the entire vehicle is reduced by 10%, fuel consumption can be reduced by 6% to 8%. For every 1 L reduction in fuel usage, CO_2 emissions can be reduced by 2.5 kg, and emissions of nitrogen compounds, sulfides, etc., can also be correspondingly reduced. Aluminum-alloy cylinder liners are lightweight, have excellent thermal conductivity [5], have excellent heat dissipation, stabilize engine temperature, improve fuel economy, and prevent cylinder burnout, engine failure, etc. The lightweight of automobiles not only helps reduce carbon emissions but also reduces fuel consumption and improves the power performance of automobiles. Therefore, replacing traditional cast-iron materials with lightweight aluminum alloys has become an inevitable trend in the development of vehicle components. However, the disadvantage of aluminum alloys is their insufficient wear resistance [6]. In order to improve the tribological and mechanical characteristics of aluminum alloys, various reinforcements are added and appropriate composites are formed [7]. Al-Si alloy cylinder liners with added wear-resistant silicon particles are currently popular in the field of engine components, and scholars are further exploring how to increase their wear resistance [8]. Hekimolu A P et al. [9]

proposed to improve the wear resistance by refining the size of silicon particles. Walker J C et al. [10] expounded the necessity of improving the tribological behavior of Al-Si automotive cylinder liner materials.

Scholars have conducted more research on the tribological performance of cast-iron cylinder liners [11,12], while there is less research on Al-Si cylinder liners. Currently, research on aluminum cylinder liners often focuses on enhancing material hardness and evaluating single wear or friction performance. Baby A K studied the wear behavior of an Al-Si alloy under varying loads and speeds in a severe wear regime [13]. Kim H T added Ca to an aluminum alloy to enhance its tensile strength [14]. Walker J C studied the surface texturing of an Al-Si alloy [15]. The comprehensive and systematic studies on tribological performance and scuffing resistance are lacking. At present, cast-iron cylinder liners are widely used in engines, while aluminum cylinder liners are rarely used. Although aluminum cylinder liners have the obvious advantage of being lightweight, their wear resistance is not as good as that of cast-iron cylinder liners. The application scope of the two should be clear, which requires a clear and comparative explanation of the wear mechanism and scuffing resistance mechanism. In order to better determine the applicable working conditions of Al-Si alloy cylinder liners and cast-iron cylinder liners, and compare their tribological properties, this paper analyzes them from multiple perspectives such as friction coefficient, weight loss, worn surface, and scuffing resistance. The wear mechanism should be obtained and provide guidance for the application of engine cylinder liners.

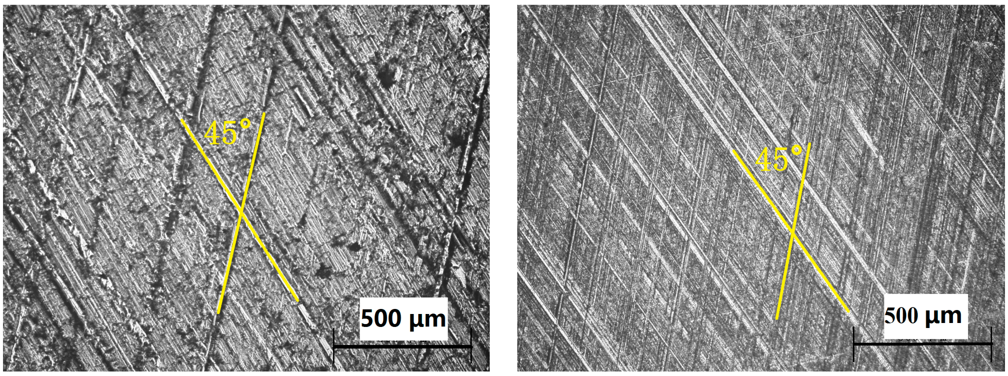
2. Materials and Experimental Section

The inner diameter of both the cast-iron and the Al-Si alloy cylinder liner is 110 mm; the main chemical composition of the latter is shown in Table 1. The test samples were cut from the liners along the circumference every 9° with a 42 mm length using WEDM machine. The size of the cylinder liner samples after cutting was approximately 42 mm × 8 mm × 6 mm. Figure 1 shows the honing roads on the surface of the cylinder liners. The honing roads on the surface of the two types of cylinders liners are clear, with high densities. The honing roads are evenly distributed, and the transition between the stripes and the platform is smooth. The honing line angle of both types of cylinder liners is 45°, which meets the design requirements [16]. The matrix structure of the cylinder liner samples after polishing is shown in Figure 2. The graphite appears as a black, wormlike dispersion on the polished surface of the cast-iron cylinder liner. A pearlite structure can be seen on the polished surface of the cast-iron cylinder liner after being corroded with a 4% nitric acid alcohol solution. The hard phase is dispersed in blocks and embedded in the pearlite (Figure 2a). Many small blocks can be observed dispersed on the polished surface of the Al-Si alloy cylinder liner, which are silicon particles with a size smaller than 5 μm (Figure 2b). The hardness of the cast-iron cylinder liner is 597 $HV_{0.3}$, and the hardness of the Al-Si alloy cylinder liner is 428 $HV_{0.3}$.

Conventional wear experiments are usually carried out using universal pin–disc or ball–disc testing machines, which are used to characterize the wear performance of materials [17,18]. However, for the cylinder liner and piston ring, the true motion of this friction pair is reciprocating, and there is lubricating oil between the two. In order to better simulate actual working conditions and intensify wear, an independently designed reciprocating-wear testing machine was used. The wear tests and scuffing tests were conducted using this testing machine under lubrication. Figure 3 shows the schematic diagram of the reciprocating-wear tests.

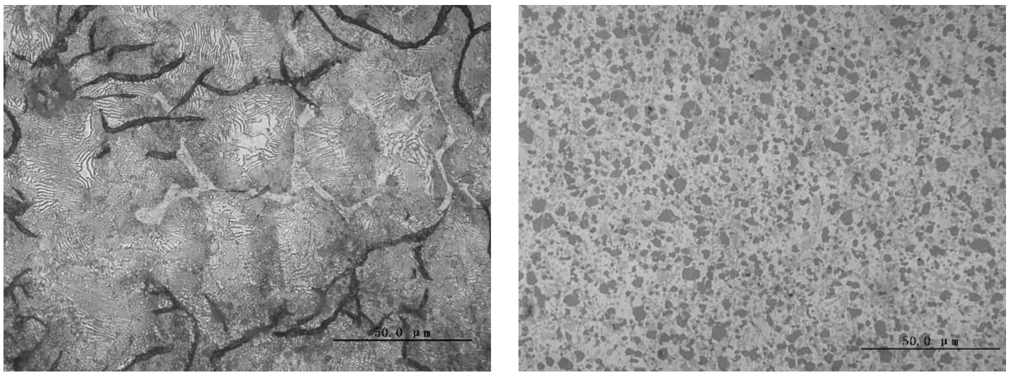
Table 1. The main chemical composition of the Al-Si alloy cylinder liner.

Element	Al	Si	Fe	Cu	Mg	Zn
Content/%	71	21	0.9	5	0.6	1.0



(**a**) (**b**)

Figure 1. Honing roads on the surface of cylinder liners. (**a**) Cast-iron cylinder liner. (**b**) Al-Si alloy cylinder liner.



(**a**) (**b**)

Figure 2. Polished surface of cylinder liners. (**a**) Cast-iron cylinder liner. (**b**) Al-Si alloy cylinder liner.

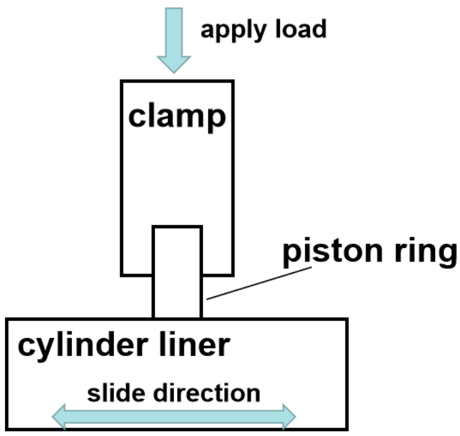


Figure 3. Schematic diagram of reciprocating-wear tests.

The counterface samples were cut from a CKS (Chrom–Keramik–Schicht) piston ring. The rotating speed of the wear test rig was 200 r/min. The tests used 4652D oil (10W-40 CF-4) to provide lubrication with a speed of 0.1 mL/min. There are many reported methods for tribological tests [19,20]. The tribo-test was carried out by adjusting parameters to make the friction state more severe than the actual working condition in this paper, and with a short-distance reciprocating motion, the lubrication state of the friction pair was maintained as boundary lubrication. Thus, accelerated wear was achieved, and the weight loss was easily measured, demonstrating the differences between the two types of cylinder liners. Under normal circumstances, the load on the cylinder liner and piston ring is below 10 MPa.

In order to obtain comparable and achievable weight losses, the test load was increased to 20 MPa. The first piston ring of the engine is close to the combustion chamber, and its maximum operating temperature is 150–200 °C with lubrication. During the low-load running-in period, a lower temperature can promote the formation of a stable lubricating oil film. At high loads, the temperature can be increased without damaging the oil film and exacerbating wear. All the wear tests were investigated at 120 °C for 1 h at 5 MPa, 10 MPa, and 15 MPa, respectively, and then at 260 °C for 21 h at 20 MPa. All the scuffing tests were conducted at 120 °C for 20 min at 5 MPa, 10 MPa, and 15 MPa, respectively, and then at 200 °C for 120 min at 20 MPa. Then, the oil supply was stopped, and the wear behavior continued until severe wear occurred on the surface of the cylinder liner and a sharp sound occurred. The time from oil cut-off to severe adhesion was recorded to characterize the scuffing resistance of the cylinder liner. Figure 4 presents the trend in the friction force variation in the scuffing test. Scuffing tests generally consist of three stages: low-load running-in stage, high-load running-in stage, and oil cut-off friction stage. The low-load running-in period is usually short in order to form a stable lubricating oil film between the cylinder liner and the piston ring. Gradient loading can be adopted during the low-load running-in period, and this method was adopted in the tests for this paper. When loading at high loads, the loading speed should be slow to avoid damaging the oil film. After cutting off the oil, the friction force is usually higher than that with lubrication. When scuffing occurs, the friction force suddenly increases sharply, presenting a vertical line on the curve. These tests were repeated least 4 times. The weight losses were obtained by calculating the difference in weight before and after wear. The polished surfaces of the cylinder liners were observed using optical microscopy (OM). The surface morphologies were observed through scanning electron microscopy (SEM).

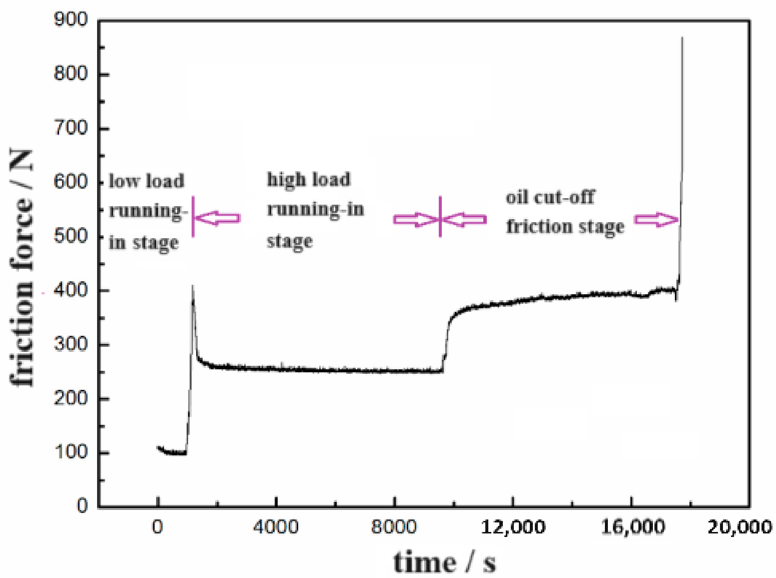


Figure 4. Trend in friction force variation in scuffing test.

3. Results and Discussion

3.1. Tribological Performance and Worn Surface

The average friction coefficient of the cast-iron cylinder liner was 0.142, and that of the Al-Si alloy cylinder liner was 0.134. The friction coefficient of the Al-Si cylinder liner was lower than that of the cast-iron cylinder liner, accounting for 94% of that of the cast-iron cylinder liner (Figure 5). Figure 6 shows the weight losses of the cylinder liner and the piston ring. The average weight loss of the cast-iron cylinder liner was 0.1 mg, and that of the Al-Si alloy cylinder liner was 2.4 mg. The average weight loss of the CKS piston rings against the cast-iron cylinder liner was 0.5 mg, and that against the Al-Si alloy cylinder liner was 0.5 mg. The weight loss of the cast-iron cylinder liner was relatively small, while the weight loss of the Al-Si alloy cylinder liner was relatively large. This is because the surface hardness of the cast-iron cylinder liner is higher than that of the aluminum-alloy cylinder liner, and its wear resistance is better. Therefore, when worn against the same type of piston ring, the weight loss of the cast-iron cylinder liner is relatively small. The weight losses of the piston rings which wore against both types of cylinder liners were similar.

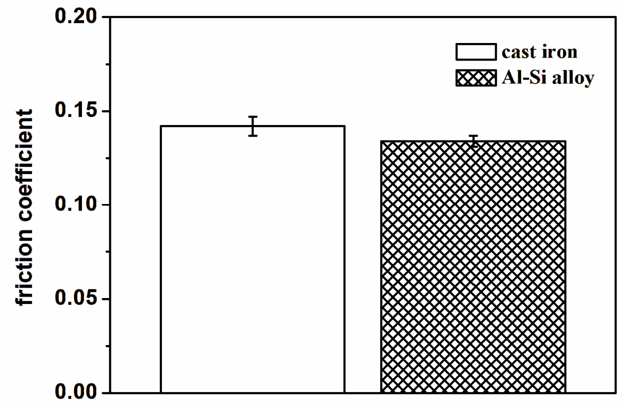


Figure 5. Friction coefficient of two matched pairs.

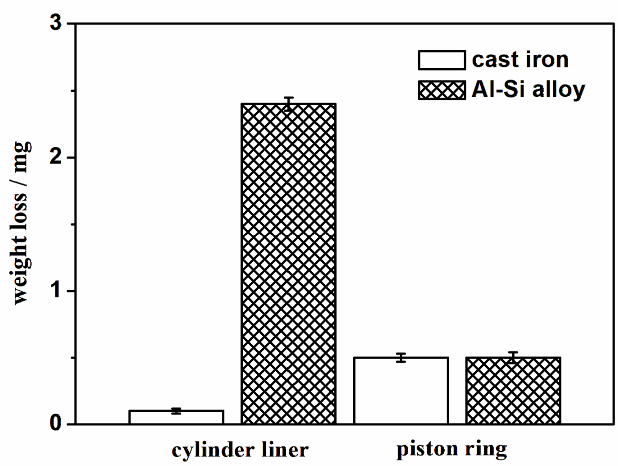
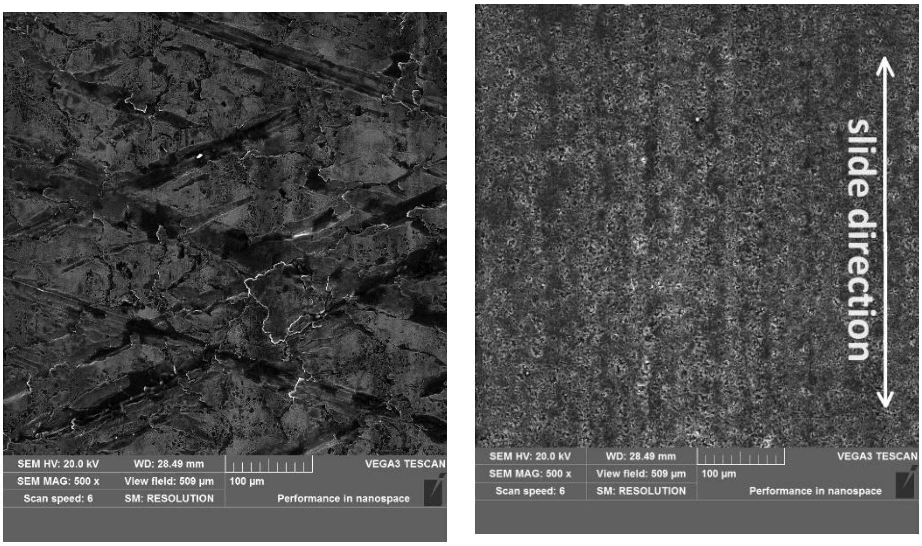


Figure 6. Weight loss of two matched pairs.

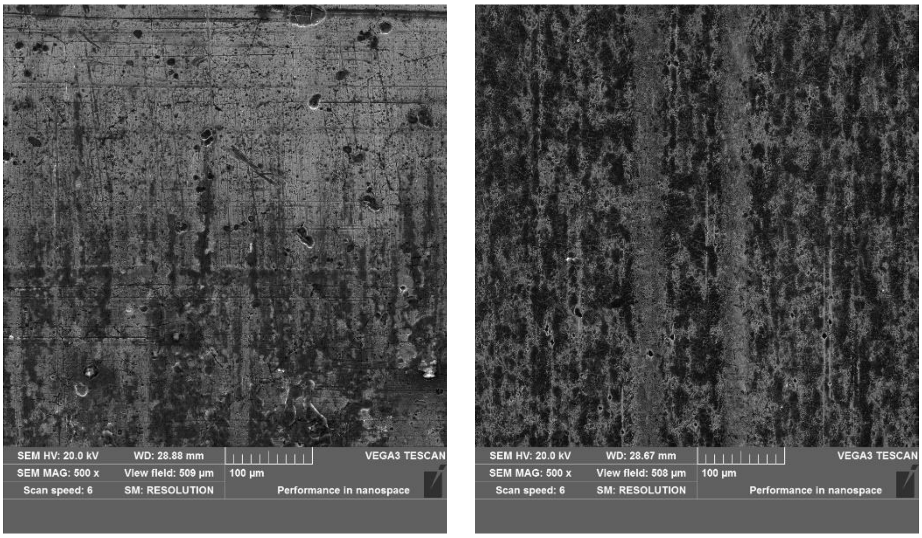
Figure 7 shows the worn surface morphology of the cylinder liners. The worn surface of the cast-iron cylinder liner was still observed to have honing roads, and there were traces of crushing at the edges of the honing roads (Figure 7a). The honing roads on the worn surface of the Al-Si alloy cylinder liner disappeared (Figure 7b). Wear marks along the vertical sliding direction were observed on the surface, with many pits left by the detachment of silicon particles.

Figure 8 shows the worn surface morphology of the CKS piston ring. When worn against the cast-iron cylinder liner, the original transverse machining marks could still be observed on the worn surface of the CKS piston ring (Figure 8a). When worn against the Al-Si alloy cylinder liner, the worn surface was relatively severe (Figure 8b). The original transverse machining marks on the surface had been worn off, with obvious wear marks along the vertical sliding direction.



(a) **(b)**

Figure 7. Worn surface morphology of cylinder liners: (**a**) cast-iron cylinder liner; (**b**) Al-Si alloy cylinder liner.



(**a**) (**b**)

Figure 8. Worn surface morphology of CKS piston ring (SEM): (**a**) CKS piston ring worn against cast-iron cylinder liner; (**b**) CKS piston ring worn against Al-Si alloy cylinder liner.

3.2. Scuffing Resistance and Surface Morphologies

Figure 9 shows the friction force during the friction process. Comparing Figures 9a and 9b, it can be seen that the friction force of the cast-iron cylinder liner was higher than that of the Al-Si alloy cylinder liner during the stable wear stage. Evidently, the time from normal wear to the failure of the cast-iron cylinder liner after the oil cut-off was longer than that of the Al-Si alloy cylinder liner. After repeating at least 4 scuffing tests, it was found that the scuffing time of the cast-iron cylinder liner was much longer than that of the Al-Si alloy cylinder liner; about 16 times longer (Figure 10). The scuffing time of the cast-iron cylinder liner was 489 min, and that of the Al-Si alloy cylinder liner was 25 min. The scuffing time of the cast-iron cylinder liner was 20 times that of the Al-Si alloy cylinder liner.

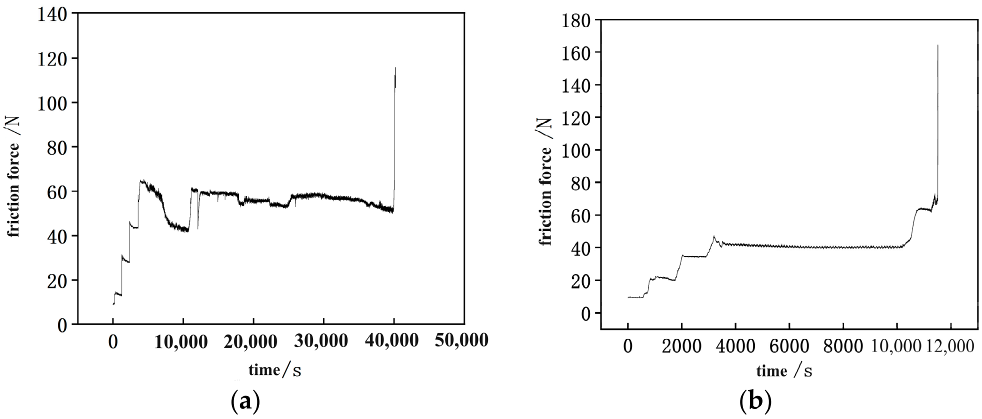


Figure 9. Friction force changes over time. (**a**) Cast-iron cylinder liner. (**b**) Al-Si alloy cylinder liner.

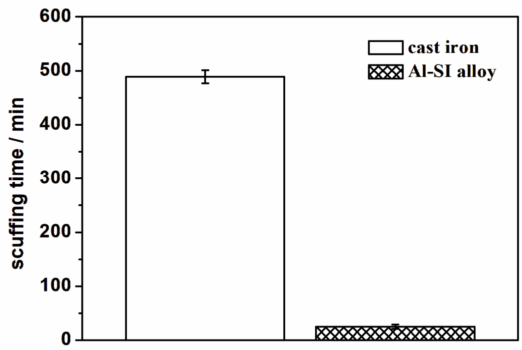


Figure 10. Scuffing time of two matched pairs.

In order to compare and observe the scuffing surface morphology of the cylinders more intuitively, the boundary between the scuffing and the unscuffing area was selected for observation, as shown in Figure 11. In Figure 11a, there are obvious honing roads in the unscuffing area of the cast-iron cylinder liner, while the honing roads in the scuffing area appear to have become shallow. The junction between the scuffing and the unscuffing area is very clear. In Figure 11b, honing roads can be observed in the unscuffing area of the Al-Si alloy cylinder liner. But due to the severe adhesive wear in the scuffing area, the honing roads have been worn off, accompanied by obvious vertical stripe marks along the sliding direction.

Figure 12 shows the scuffing surface morphology of the piston ring. When the CKS ring was worn against the cast-iron cylinder liner, there were detached pits on the scuffing surface (Figure 12a). When the CKS ring was worn against the Al-Si alloy cylinder liner, there are fewer surface pits and obvious traces of material adhesion (Figure 12b). Aluminum has a low hardness and was prone to sticking to the surface of the piston ring due to severe adhesive wear during scuffing. Under the rolling of the reciprocating motion, aluminum adhered to the surface of the piston ring and continued to expand. Aluminum filled the pits that were previously normally worn, resulting in a smoother surface. A similar situation was also reported by Xinyan Bian [21].

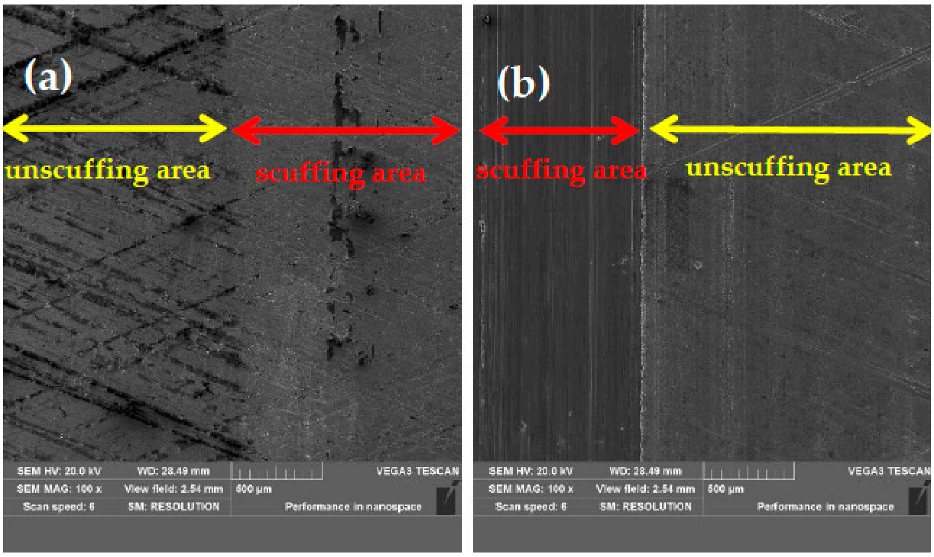
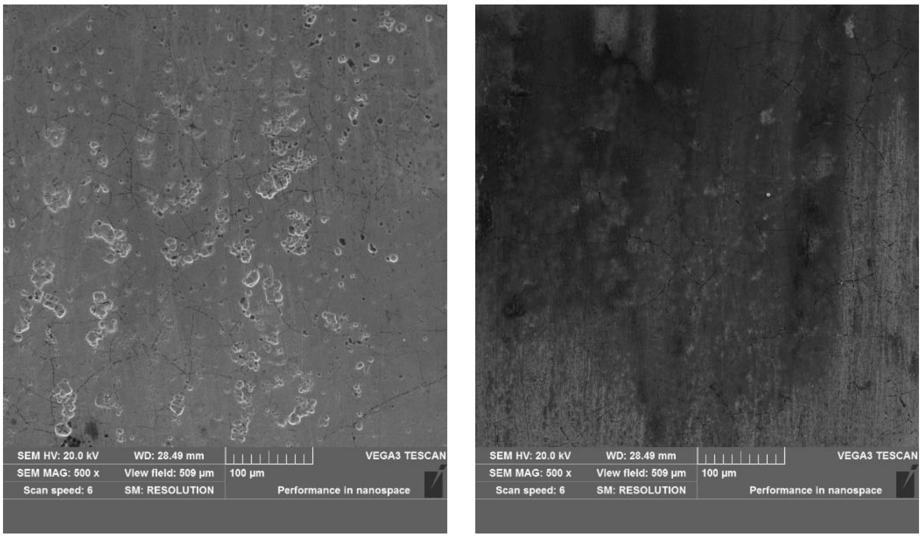


Figure 11. Scuffing surface morphology of cylinder liners: (**a**) cast-iron cylinder liner; (**b**) Al-Si alloy cylinder liner.



(**a**) (**b**)

Figure 12. Scuffing surface morphology of piston ring (SEM): (**a**) CKS piston ring worn against cast-iron cylinder liner; (**b**) CKS piston ring worn against Al-Si alloy cylinder liner.

3.3. Wear Mechanism

Figure 13 is a schematic diagram of the cylinder liner wear process. The cast-iron cylinder liner had higher hardness, less weight loss, and better wear resistance. Therefore, after wearing, the honing roads on the surface still existed, and the wear was relatively mild. In the tests, it was found that the cast-iron cylinder liner could be loaded smoothly and had a strong ability to withstand high loads. The graphite phase on the surface provided a certain lubrication effect [2], allowing it to maintain a stable wear state for a long time after oil cut-off until scuffing. Although cast-iron cylinder liners have a longer scuffing time and better scuffing resistance, they have a higher friction force during the stable wear stage and a higher friction coefficient, resulting in poor friction performance. The wear mechanism of cast-iron cylinder liners is slight adhesive wear.

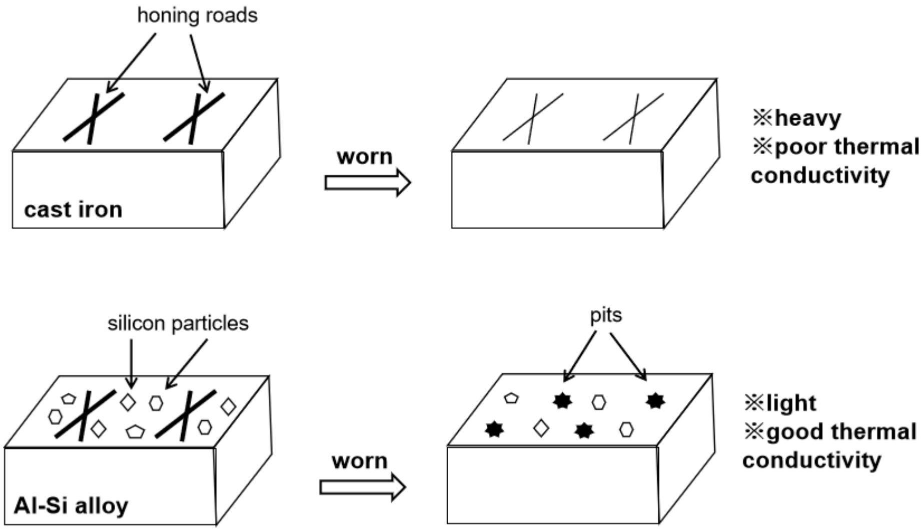


Figure 13. Schematic diagram of the cylinder liner wear process.

The Al-Si alloy cylinder liner had low hardness and significant wear, and its wear resistance was not as good as that of the cast-iron cylinder liner. The honing roads on the worn surface disappeared, and pits left by the detachment of silicon particles could be seen. In the tests, it was found that the Al-Si alloy cylinder liner needed to be loaded slowly, and the rapid increase in load could easily lead to the detachment of surface silicon particles and cause abrasive wear. After cutting off the oil, due to the continuous thinning of the oil film, aluminum was prone to adhere to the piston ring. In addition, small-sized silicon particles were also prone to falling off due to the action of frictional shear force, which accelerates wear, resulting in a shorter scuffing time. The scuffing resistance of the Al-Si alloy cylinder liner was weaker than that of the cast-iron cylinder liner, but its friction force and coefficient of friction were low, and it had excellent friction performance. The wear mechanism of Al-Si alloy cylinder liners is a mixture of adhesive wear and abrasive wear.

In summary, although cast-iron cylinder liners have excellent wear resistance and scuffing resistance, they have poor friction performance, heavy weight, and poor thermal conductivity, resulting in higher fuel consumption. Therefore, cast-iron cylinder liners are suitable for traditional fuel engines and turbocharged engines with high load, high power, and high stability. On the other hand, although Al-Si alloy cylinder liners have weaker wear resistance and scuffing resistance than cast-iron cylinder liners, they have good friction performance, lightweight, and good thermal conductivity, resulting in lower fuel consumption. The good friction performance of Al-Si alloy cylinders liner aids lubrication, saves more oil under low loads, and improves engine efficiency [22]. Therefore, Al-Si alloy cylinder liners are suitable for engines that are lightweight, efficient, and energy-saving.

4. Conclusions

This paper concentrates on the tribological performance and scuffing resistance of cast-iron and Al-Si alloy cylinder liners. The main conclusions arising from this paper are as follows:

(1) The cast-iron cylinder liner had higher hardness, less weight loss, and better wear resistance. Although the cast-iron cylinder liner had a longer scuffing time (20 times that of the Al-Si alloy cylinder liner) and better scuffing resistance, it had a higher friction force during the stable wear stage and a higher friction coefficient, resulting in poor friction performance.

(2) The Al-Si alloy cylinder liner had low hardness and significant wear, and its wear resistance was not as good as that of the cast-iron cylinder liner. The honing roads on the worn surface disappeared, and pits left by the detachment of silicon particles could be seen. The scuffing resistance of the Al-Si alloy cylinder liner was weaker

than that of the cast-iron cylinder liner, but its friction force and coefficient of friction were low (94% of that of the cast-iron cylinder liner), and it had excellent friction performance.

(3) The wear mechanism of the cast-iron cylinder liner was slight adhesive wear. The wear mechanism of the Al-Si alloy cylinder liner was a mixture of adhesive wear and abrasive wear.

(4) In a future context, cast-iron cylinder liners are suitable for traditional fuel engines and turbocharged engines with high load, high power, and high stability. Al-Si alloy cylinder liners are suitable for engines that are lightweight, efficient, and energy-saving and operate at high speeds. From the perspective of future applications, cast-iron cylinder liners are suitable for trucks, while aluminum cylinder liners are suitable for small cars.

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