

Effects of Material Combinations on Friction and Wear of PEEK/Steel Pairs under Oil-Lubricated Sliding Contacts

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Abstract. The effects of material combinations on the friction and wear of PEEK/steel pairs are studied using blocks on a ring wear tester under oil-lubricated conditions. The rings are made of forged steel (SF540A) and a PEEK composite filled with 30 wt% carbon fibre. The surface roughness is 0.15 and 0.32 $\mu\text{m Ra}$, respectively. The blocks are also made of the same materials as the rings: the forged steel and the PEEK composite. Finished with an emery paper of #600, the surface roughness is 0.06 and 0.23 $\mu\text{m Ra}$, respectively. Sliding tests for 4 combinations of two materials are conducted. The load is increased up to 1177 N at 1 N s⁻¹. The sliding velocity is varied in the range of 10 to 19 m s⁻¹. In some cases, the ring temperature is measured with a thermocouple with a diameter of 0.5 mm, located 1 mm below the frictional surface. Results indicate that the forged steel's ring and the PEEK composite's block is the best combination among 4 combinations, because seizure does not occur under the increasing load up to 1177 N at the sliding velocity of 10–19 m s⁻¹. In contrast, seizure occurs at 15 and 19 m s⁻¹ in the other three combinations. However, the PEEK composite's ring shows a lower friction coefficient as compared to the forged steel's ring, when seizure does not occur. Wear scars are observed with a scanning electron microscope (SEM). The seizure mechanisms are then discussed.

1. Introduction

Poly-ether-ether-ketone (PEEK) is one of advanced engineering polymeric materials and has excellent mechanical and chemical properties [1]. It also has been well known that PEEK has superior tribological properties. To further improve PEEK's tribological behaviors, PEEK composites filled with various fillers and solid lubricants have been developed and studied [2-5]. Although numerous papers regarding PEEK's tribological properties have been published, most of them have been conducted under unlubricated conditions and at low sliding velocities.

PEEK composites have recently been applied to various machine elements such as a thrust bearing [6], a pump bearing [7], a seal ring, and a retainer for a rolling bearing. These PEEK composites must operate under severe conditions such as high sliding velocities and high temperatures. At a high sliding velocity, lubricants are indispensable for maintaining PEEK's low friction and low wear for a long time.



However, there has been little work regarding the lubricated friction and wear of PEEK materials at a high sliding velocity [8, 9]. Furthermore, the effects of the mating materials sliding against PEEK materials on the tribological behavior have not been studied so far. Our previous works showed that PEEK materials transit from hydrodynamic lubrication or mixed lubrication to seizure under severe oil-lubricated conditions such as high sliding velocities and high loads [10, 11]. In order to increase PEEK applications in practice and establish maintenance guidelines for PEEK sliding bearings, it is important to study PEEK's friction and wear behaviors under various experimental conditions.

In this study, the friction and wear behaviors of PEEK/steel pairs were studied from the viewpoint of material combinations under oil-lubricated sliding contacts. During the test, the steel ring's temperature was measured. Wear scars were observed using a scanning electron microscope (SEM). Based on the SEM observation results and the measurement results of steel ring's temperature, the seizure mechanisms were discussed.

2. Experimental Apparatus and Procedure

Experiments were conducted with blocks on the ring wear tester shown in figure 1 [10]. The testing materials are listed in table 1. The rings were made of forged steel (SF540A) and a PEEK composite filled with 30 wt% carbon fiber, with 130 mm diameter and 20 mm thickness; it was shaped by turning and further finished by cylindrical grinding or grinding with an emery paper. The carbon fiber was 8 μm in diameter and its length ranged from 50 to 200 μm . The ring's surface roughness was 0.15 and 0.32 $\mu\text{m Ra}$, respectively. The blocks were also made of the same materials as the rings. The blocks were 90 mm long, 10 mm wide, and 10 mm thick. They were finished with an emery paper of #600, and their surface roughness was 0.06 for the steels' block and 0.23 $\mu\text{m Ra}$ for the PEEK composite's block. The experiments were conducted for four combinations of two materials at each sliding velocity. In this paper, the expression of "SF540A/PEEK composite" stands for the combination of the SF540A ring and the PEEK composite's block. The experimental conditions are listed in table 2. The sliding velocity ranged from 10.2 to 19 m s^{-1} , and the load was increased at a rate of 1 N s^{-1} up to 1177 N. During the test, a frictional torque was measured with a torque meter. The steel's ring temperature was measured with an alumel-chromel thermo-couple with a diameter of 0.5 mm, located 1mm below the frictional surface. The maximum testing load was 1177 N. However, when the frictional torque increased suddenly, the tests were ended. The lubricant used was a non-additive turbine oil (ISO VG46). It was supplied to the frictional surface at a flow rate of 1.1 ml s^{-1} with a pump. The oil temperature was kept at $30 \pm 3^\circ\text{C}$ with a controller.

After the test, wear scars were observed with a scanning electron microscope (SEM).

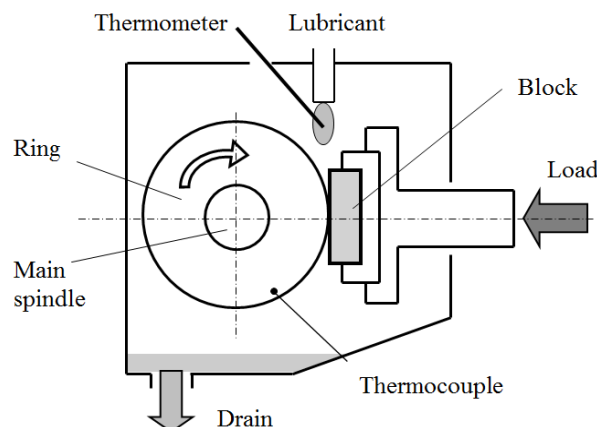


Figure 1. Schematic diagram of experimental apparatus.

Table 1. Properties of testing materials.

	Material	Hardness	Surface roughness, Ra (μm)
Ring	Forged steel (SF540A)	HV189 \pm 8	0.15 \pm 0.04
	PEEK composite	HRR124	0.32 \pm 0.03
Block	Forged steel (SF540A)	HV189 \pm 8	0.06 \pm 0.02
	PEEK composite	HRR124	0.23 \pm 0.04

Table 2. Experimental conditions.

Sliding velocity (m s^{-1})	10.2, 15.0, 19.0
Load (N)	Up to 1177 N at increasing rate of 1 N s^{-1}
Lubricant	Non-additive turbine oil (ISO-VG46)
Flow rate (ml s^{-1})	1.1
Oil temp. ($^{\circ}\text{C}$)	30 \pm 3

3. Results and Discussion

3.1. Friction property

Figure 2 illustrates the relationship between the friction coefficient and the load at 10.2 m s^{-1} . Figure 3 illustrates the relationship between the steel's ring temperature and the load, corresponding to figure 2. The friction coefficient decreases with the increase of the load and becomes almost constant and low values for all the material combinations. The steel's ring temperature increases linearly with the increase of the load, and reaches about 60°C at the end of testing. It does not become constant. However, the friction coefficients at the steady state become constant, and its values depend on the material combinations. Their values are 0.0109 ± 0.0022 for SF540A/SF540A, 0.007 ± 0.002 for SF540A/PEEK composite, 0.0055 ± 0.0023 for PEEK composite/SF540A, and 0.0043 ± 0.0015 for PEEK composite/PEEK composite. The PEEK composite's ring shows the lower friction coefficient than the steel's ring. Among four combinations, PEEK composite/PEEK composite shows the lowest value.

A lambda ratio [12] is calculated for discussion of the results. It is defined as $\Lambda = h_{\min} / (R_{q1}^2 + R_{q2}^2)^{1/2}$, where h_{\min} is the minimum film thickness and R_{q1} and R_{q2} are the root mean square roughnesses of the ring and block, respectively. The minimum film thickness is calculated using the Dowson-Higginson formula [13]. Oil viscosity is calculated at the ring temperatures obtained from each test, and R_{q1} and R_{q2} are calculated from the arithmetic average roughness, R_a , where $R_q = 1.25 R_a$ [14]. The lambda ratio is calculated from the initial surface roughness. Their values for all the material combinations are mostly more than 3 in the temperature ranges shown in figure 3, which suggests that hydrodynamic lubrication is predominant and low friction coefficients are maintained. The minimum film thickness calculated in both rings of the steel and the PEEK composite was almost the same values of about $1.0 \mu\text{m}$ under the conditions of 10.2 m s^{-1} , 1177N, and the oil temperature of 60°C . Thus the minimum oil thickness calculated cannot explain the reason why the PEEK composite's ring gives lower friction coefficients. As the width of the PEEK composite's ring is wider than that of the block, it is supposed that the ring's surface might deform elastically and could easily hold the oil between two surfaces. This result is very important, and further works are the next subject in future.

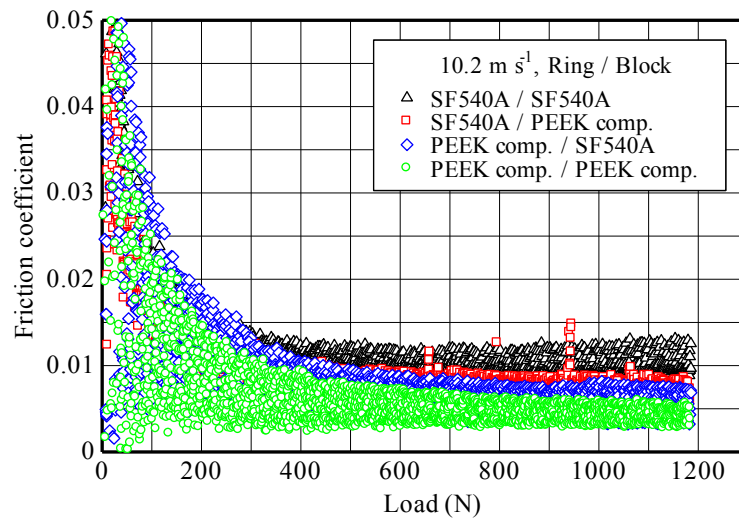


Figure 2. Relationship between friction coefficient and load at 10.2 m s^{-1} .

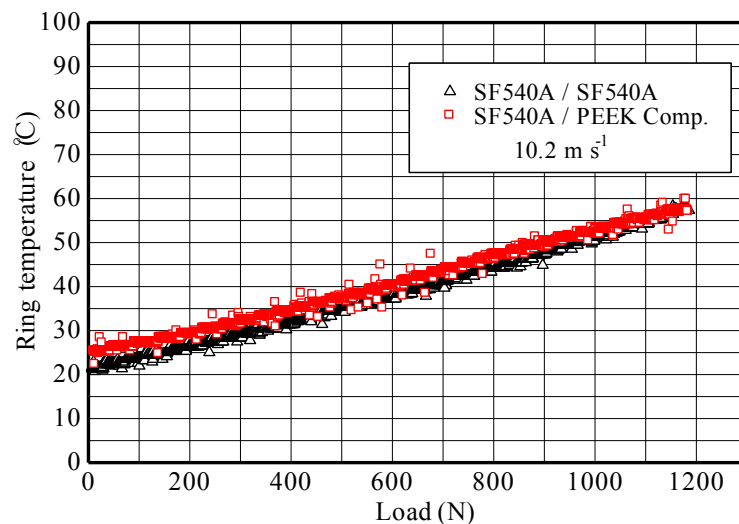


Figure 3. Relationship between ring temperature and load at 10.2 m s^{-1}

Figure 4 illustrates the relationship between the friction coefficient and the load at 19.0 m s^{-1} . It is apparent that the friction behaviors are strongly dependent on the material combinations. Except for SF540A/PEEK composite, the seizure occurs in other three material combinations as the load exceeds a certain value. The critical load is defined as the seizure load. In SF540A/SF540A, the friction coefficient rapidly increases from 0.015–0.02 to 0.27 at 270 N. In PEEK composite/SF540A and PEEK composite/PEEK composite, its values rapidly increase from 0.005–0.008 to 0.023 at 500 N and from 0.005–0.01 to 0.026 at 290 N, respectively. The friction coefficients, when the seizure occurs in the PEEK composite's ring, are significant lower values as compared to SF540A/SF540A. When the seizure occurred in the PEEK composite's ring, however, oily smokes together with noise were generated. It has been confirmed that the oily smoke is generated at the ring temperature of $140\text{--}160^\circ\text{C}$ [12]. Thus it is said that the seizure in the PEEK composite's ring has much to do with the high temperature.

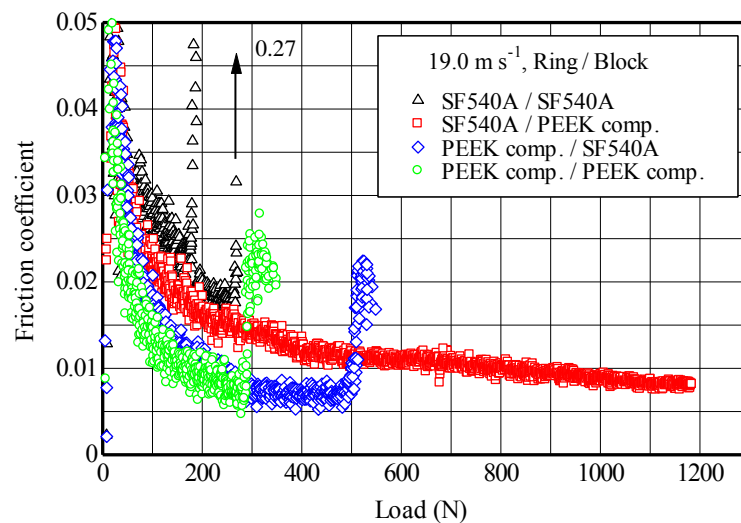


Figure 4. Relationship between friction coefficient and load at 19.0 m s^{-1} .

3.2. Comparison of seizure load

Figure 5 shows the seizure load obtained at each sliding velocity for all the material combinations. At 10.2 m s^{-1} , the seizure does not occur for all the material combinations. However, as the sliding velocity increases over 15.0 m s^{-1} , except for SF540A/PEEK composite, the seizure occurs for other three combinations. Their seizure loads decrease as the sliding velocity increases. With higher sliding velocity, there are clear differences in the seizure loads between the material combinations. The order of the seizure load at 19.0 m s^{-1} is as follows: SF540A/PEEK composite \gg PEEK composite/SF540A $>$ PEEK composite/PEEK composite, SF540A/SF540A.

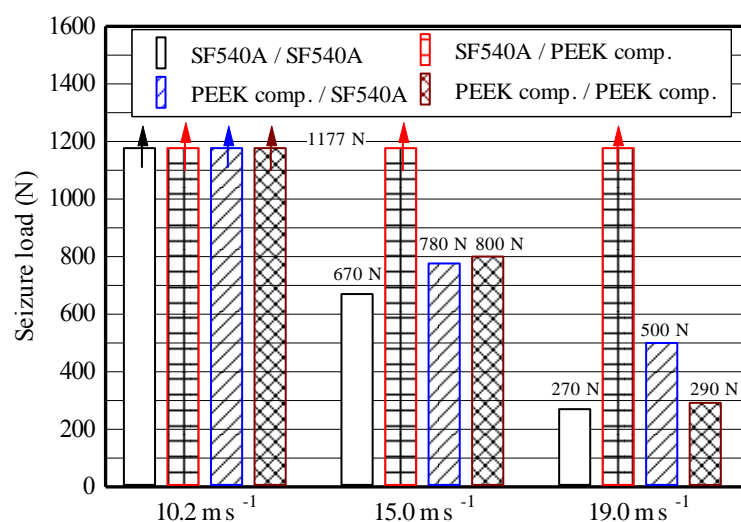


Figure 5. Seizure load at each sliding velocity for all material combinations.

In SF540A/PEEK composite, the seizure does not occur within the tested load range at 10.2–19.0 m s⁻¹. Figure 6 illustrates the relationship between the friction coefficients, the steel ring's temperature, the lambda ratio, and the load at 19 m s⁻¹ for SF540A/PEEK composite. Similar to the results of 10 m s⁻¹, although the friction coefficient becomes a small and constant value of less than 0.01, the ring temperature increases linearly up to about 90°C and does not become constant. The lambda ratio is mostly more than 3, which suggests that the hydrodynamic lubrication is predominant, resulting in a low friction coefficient. Thus it is said that this pair has a high ability to maintain the hydrodynamic lubrication, leading to a superior seizure-resistant property.

The self-mated pair of SF540A has the lowest seizure load at 15.0 and 19.0 m s⁻¹, as shown in figure 5. They are about 670 and 270 N, respectively. Figure 7 illustrates the relationship between the friction coefficient, the ring temperature, the lambda ratio, and the load at 19.0 m s⁻¹ in SF540A/SF540A. Although the friction coefficient increases instantaneously up to 0.1 at 30°C, eventually the seizure occurs at 40°C, and the friction coefficient rapidly increases from 0.02 to 0.27. The lambda ratio calculated at 40°C, which is the ring temperature for transiting to seizure, is much higher than 3. This value does not agree with the result at all. Considered the surface roughness after seizure, it becomes less than 1 when the ring temperature is 40°C or so. As the Hertz contact pressure between metals is higher than polymers, it is supposed that the surface roughness might become rough due to wear during a running-in process. If so, it is also expected that wear particles might be generated and remain on the surface. Even when the seizure does not occur, it has been confirmed that oil sample collected from the drain became a little dark because it contained small wear particles. Based on this idea, even if the lambda ratio calculated is high, wear particles and rough surface probably promote adhesion between metals at high sliding velocity, leading to the seizure.

When the seizure occurs in the PEEK composite's ring, oily smokes and loud noise were generated. This fact is the evidence that the surface temperature reaches or exceeds 140–160°C. The PEEK composite has a glass transition point of 143°C, above which it becomes soft. Therefore the friction coefficient increases because the contact areas between the PEEK composite's pair or the PEEK composite and the steel increases. This high temperature causes severe plastic deformation and flow of the PEEK composite, leading to severe tearing fracture [11, 12]. The seizure load at 19.0 m s⁻¹ in PEEK composite/SF540A is higher than in the self-mated pair of the PEEK composite. This is probably because the mated steel block has a higher heat conductivity than the PEEK composite's block, and the increasing rate of the surface temperature is relatively low.

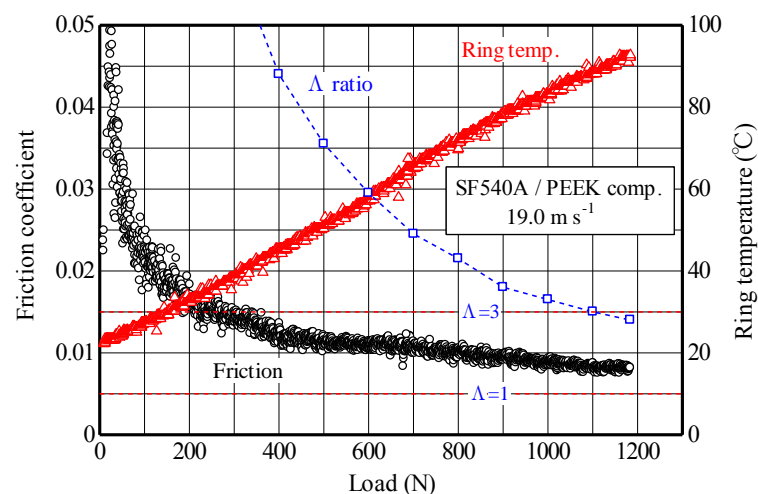


Figure 6. Relationships between friction coefficient, ring temperature, lambda ratio, and load at 19.0 m s⁻¹ for SF540A/PEEK composite.

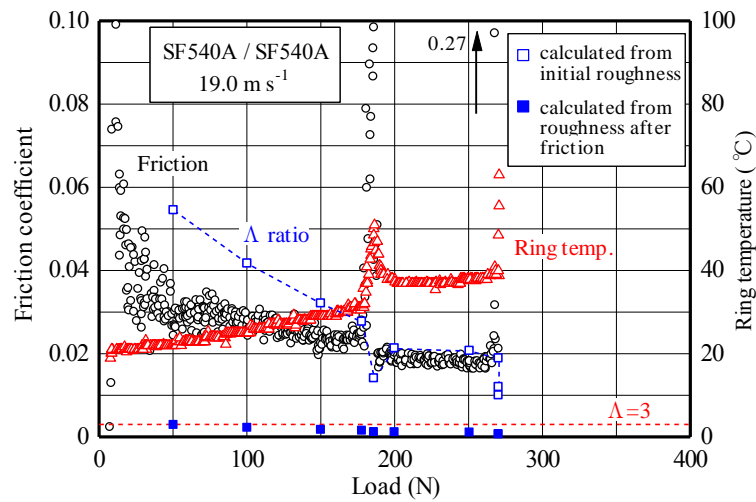


Figure 7. Relationships between friction coefficient, ring temperature, lambda ratio, and load at 19 m s^{-1} for SF540A/SF540A.

3.3. SEM observations of wear scars

Figure 8 shows the SEM micrographs of the ring and block's wear scars generated when the seizure occurs at 19.0 m s^{-1} in SF540A/SF540A. It is apparent that both the ring and block's surfaces suffer severe damages. The surface layers, probably formed due to the plastic flow and the transfer of materials, separate as plates less than 100 μm or so in size, as shown in figures 8 (a) and (b). It is well known that these plate-like wear particles are commonly generated in a seizure of steels [15]. Replaced the block material of SF540A with the PEEK composite in SF540A/SF540A, the low friction coefficient of less than 0.01 was maintained as shown in figures 4 and 6. Figure 9 shows the optical microscope and SEM micrographs of the wear scars in SF540A/PEEK composite. The ring's wear surface does not change appreciably and the original grinding marks remain, as shown in figure 9 (a). The block's wear scar has evidences showing slight contacts as small ripple marks are commonly observed, as shown in figures 9 (b) and (c). The original grinding grooves and carbon fiber fillers do not change and remain on the surface. These ripple marks are probably formed during the plastic flow process due to the mild plowing actions of the ring's surface asperities during the running-in period.

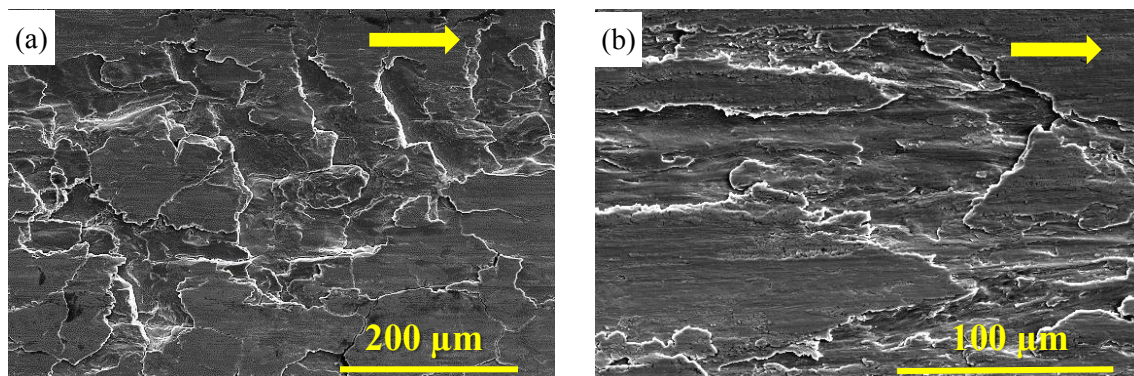


Figure 8. SEM micrographs of wear scars of ring and block generated in seizure of SF540A/SF540A at 19.0 m s^{-1} . (a) Ring; (b) Block. The arrow indicates the relative direction of motion of the counterface.

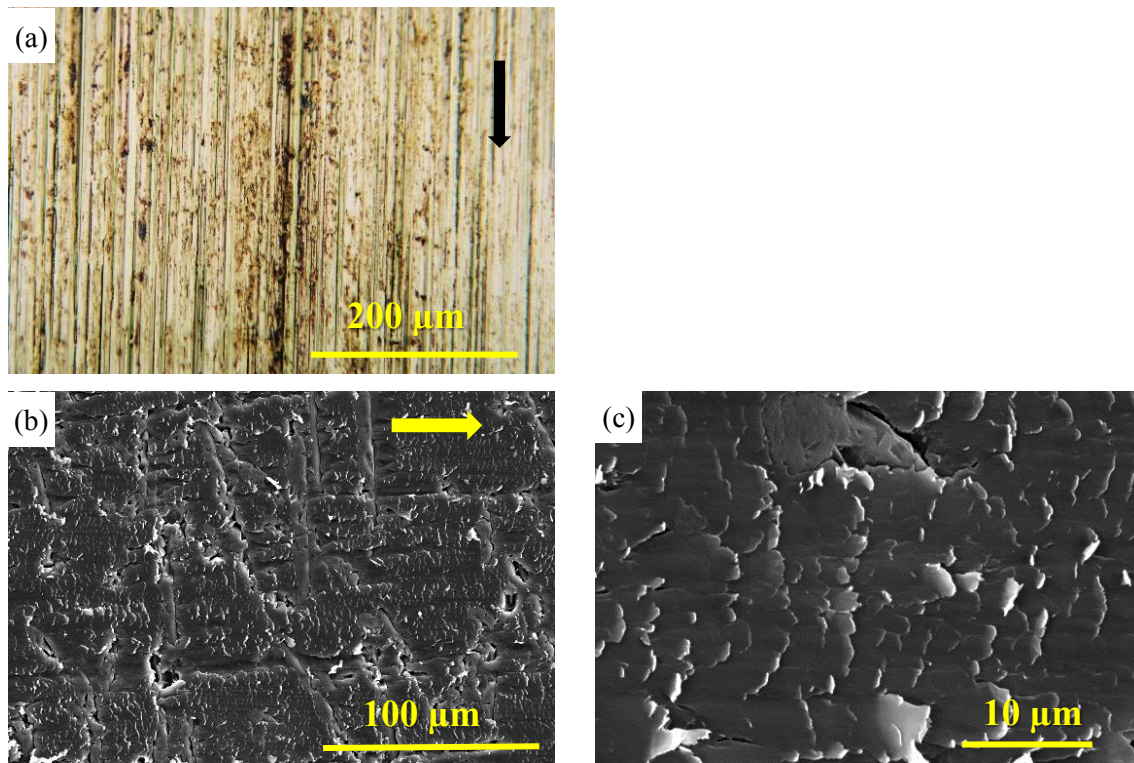


Figure 9. Optical microscope and SEM micrographs of wear scars of ring and block when low friction coefficient is maintained in SF540A/PEEK composite at 19.0 m s^{-1} . (a) Ring; (b)–(c) Block. The arrow indicates the relative direction of motion of the counterface.

Figure 10 shows the optical microscope and SEM micrographs of the ring and block's wear scars generated in the seizure of PEEK composite/SF540A at 19.0 m s^{-1} . Only the ring surface suffers the severe damages in the seizure, as shown in figures 10 (a) and (b). Regions look white in (a) are the original surface of the PEEK composite's ring. There is only a few original surface left. The severe damages are over a wide range and the worn surface looks very rough. In contrast, the block surface of SF540A does not suffer severe damages although slight and regular grooves are observed, as shown in figures 10 (c) and (d).

Figure 11 shows the optical microscope and SEM micrographs of the ring and block's wear scars generated in the seizure of PEEK composite/PEEK composite at 19.0 m s^{-1} . Both the ring and block's surfaces suffer severe damages. The ring's worn surface is very rough, and it seems like the original surface mostly disappears and the ring surface's fracture occurs, as shown in figures 11 (a) and (b). The block's surface is also rough, and severe damages are observed over a wide range, as shown in figure 11 (c). The separations of the large plate-like fragments and the exposure of carbon fibers are common features, as shown in figures 11 (c) and (d). Figures 11 (e) and (f) are the scars after the large fragments separate from the surface. Many elongated strings which are typical features of tearing fracture are commonly observed, as shown in figure 11 (e). Porous structures which is probably formed in semi-melting or melting states are observed, as shown in figure 11 (f). These observation results show that the surface temperature of the PEEK composite rises to the high value of more than the glass transition point of 143°C .

The seizure of SF540A/SF540A shows a significant higher friction coefficient as compared to that of the seizure in the PEEK composite's ring, as shown in figure 4. Based on these observations, it is probably because the resistance due to the adhesion between two metals is significantly higher than that due to the tearing fracture of the PEEK composites at high temperature.

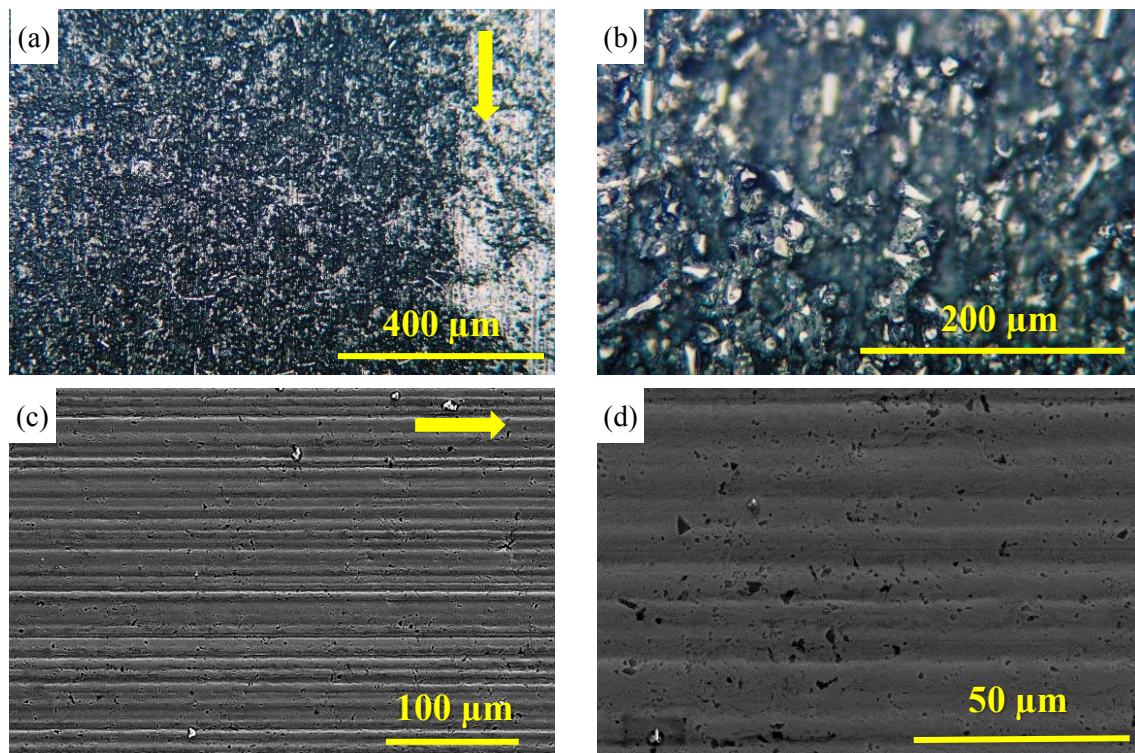
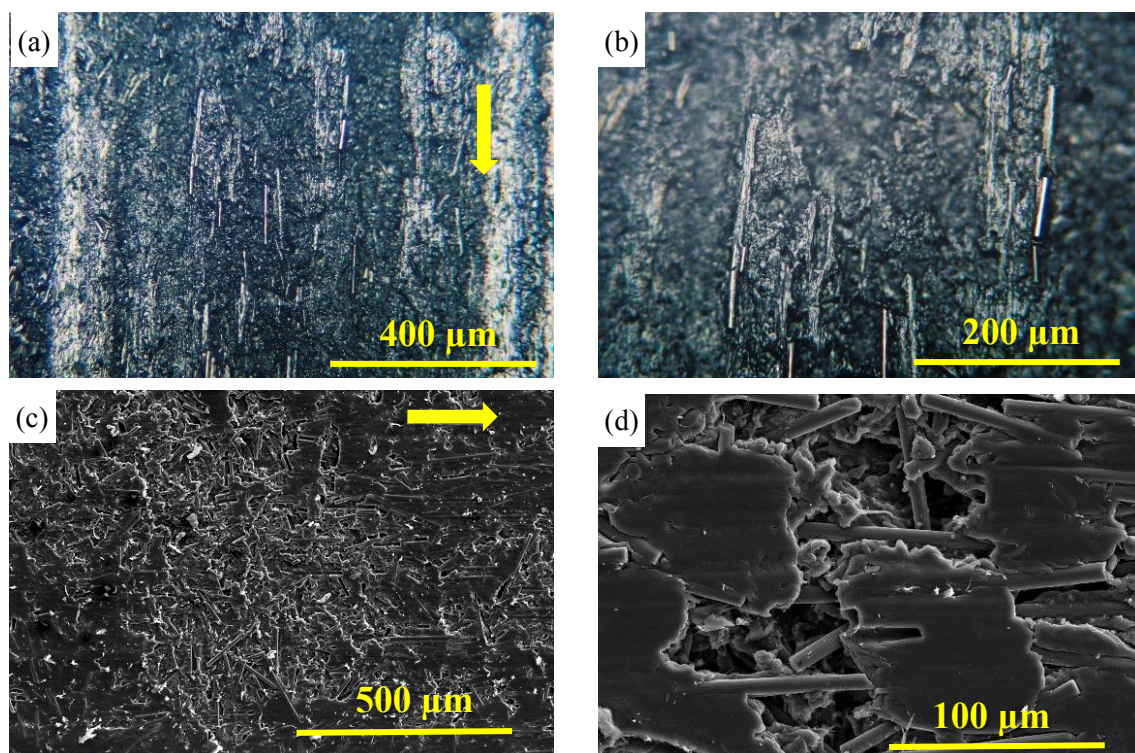


Figure 10. Optical microscope and SEM micrographs of wear scars of ring and block generated in seizure of PEEK composite/SF540A at 19.0 m s^{-1} . (a)–(b) Ring; (c)–(d) Block. The arrow indicates the relative direction of motion of the counterface.



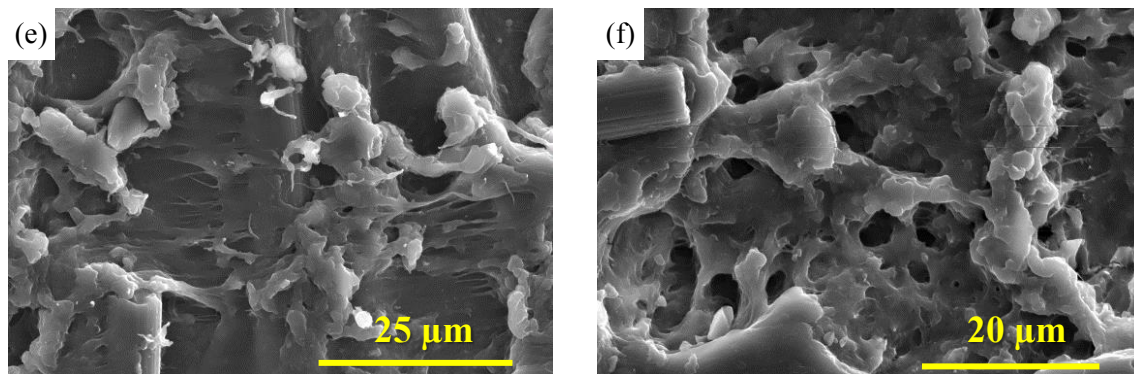


Figure 11. Optical microscope and SEM micrographs of wear scars of ring and block generated in seizure of PEEK composite/PEEK composite at 19.0 m s^{-1} . (a)–(b) Ring; (c)–(e) Block. The arrow indicates the relative direction of motion of the counterface.

In the combination of SF540A and the PEEK composite, there are clear differences in the seizure behaviors when the materials of the ring and the block are exchanged, as shown in figures 4, 5, 9, and 10. The seizure-resistant property of SF540A/PEEK composite is much better than that of PEEK composite/SF540A. The heat conductivity of SF540A is much higher than that of PEEK composite. The ring's surface area is larger than the block's one. As the heat conduction and the heat radiation performances of SF540A's ring are better than those of the PEEK composite's ring, low surface temperature seems to be maintained in SF540A/PEEK composite, leading to low friction and wear, as shown in figures 4 and 6. In PEEK composite/SF540A, the PEEK composite's ring temperature increases gradually, and the ring surface becomes soft when its temperature exceeds the glass transition point. The high temperature has been confirmed by the generation of oily smokes. As SF540A's block is harder than the PEEK composite's ring, it might be considered that SF540A's block bites into the PEEK composite's ring surface at the high temperature. As the result, the seizure occurs, and only the PEEK composite's ring suffers severe damages due to the tearing fracture, as shown in figure 10. These results indicate that the surface temperature plays an important role in the seizure behaviors of the PEEK composite.

4. Conclusions

The effects of material combinations on the friction and wear behaviors of PEEK/steel pairs were studied under oil-lubricated sliding contacts. The following conclusions were obtained.

- (1) The combination of SF540A/PEEK composite (ring/block) showed the best seizure-resistant property among four combinations.
- (2) The seizure load was dependent on the material combination. The combination of SF540A/SF540A was the worst.
- (3) When the seizure did not occur, the PEEK composite's ring showed lower friction coefficients of less than 0.01 as compared to the forged steel's ring.
- (4) The seizure, when PEEK composite's ring was used, was characterized by the ring's severe damages due to the tearing fracture of the surface layers.

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