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Effects of PEEK's surface roughness on seizure behaviors of PEEK/steel pairs under oil-lubricated sliding contacts

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Abstract

Effects of surface roughness of polyether ether ketone (PEEK) on the seizure behaviors of PEEK/steel pairs are studied using a block-on-ring wear tester under oil-lubricated conditions. The blocks are made of unfilled PEEK and a PEEK composite filled with carbon fibers of 30 mass%. The block's surface roughness varies between 0.03 to 4.77 $\mu\text{m Ra}$. The ring is made of forged steel (SF540A) and its surface roughness is 0.12 $\mu\text{m Ra}$. The sliding velocity and load are 19 m/s and 883 N respectively. During the test, the ring temperature is measured with an alumel-chromel thermo-couple with a diameter of 0.5 mm, located 1 mm below the frictional surface. Results indicate that the seizure behaviors are strongly dependent on the PEEK material's surface roughness. Seizure occurs in both materials when the surface roughness exceeds a certain value. The critical surface roughness in the PEEK composite is significantly higher than in PEEK. Thus it is concluded that the PEEK composite has an excellent seizure-resistant property at high sliding velocity. Wear scars are observed using a scanning electron microscope. The seizure mechanisms are discussed from the viewpoints of the SEM observation results and the ring temperature.

Key words : PEEK, PEEK composite, Surface roughness, Seizure, Sliding friction and wear, Oil lubrication

1. Introduction

Poly-ether-ether-ketone (PEEK) is one of advanced engineering polymeric materials and has excellent mechanical and chemical properties (the book by Japanese Society of Tribologists, 1991). 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 (Ovaert and Cheng, 1991; Wang et al., 2000). From these studies, PEEK composites show low friction and wear when fillers contribute to form a thin, uniform, and tenacious transfer film on the counterface.

Some researchers have focused on the counterface surface roughness and reported its effects on the tribological behaviors of PEEK and PEEK composites under un-lubricated conditions. Zhang et al. (Zhang et al., 2015), who studied the effects of steel counterface topography on the formation mechanisms of tribofilm, reported that a thin tribofilm formed on counterface with a submicron roughness benefits best the tribological performance of the composite. Elliot et al. (Elliot et al., 1998) reported that PEEK composite filled with carbon fiber has lower friction and wear than PEEK when sliding against polished and ground counterface of stainless steel. Friedrich et al. (Friedrich et al., 1991) reported that effects of steel counterface roughness are more pronounced in the non-reinforced PEEK than in fiber-filled versions.

It has been reported that the testing temperature is also important in the tribological behaviors of PEEK and PEEK composites (Hanchi and Eiss, 1997). Friedrich et al. (Friedrich et al., 1991) reported that an increase in testing temperature results in higher specific wear rates and in lower coefficients of friction for the different materials tested. They also showed that the composition with the highest resistance to wear at elevated temperatures and a low coefficient of friction is a PEEK version containing 15 wt% PTFE particles and 15 wt% graphite lubricant. Chang et al. (Chang et al., 2007)

reported that conventional fillers such as short carbon fiber and graphite flakes can effectively enhance both the wear resistance and the load carrying capacity. They also showed that, with the addition of sub-micro particles of TiO₂ and ZnS, the frictional coefficient and the wear rate of the composites are further reduced especially at elevated temperatures. Pei et al. (Pei and Friedrich, 2012) suggested that the temperature stability of polymers should be highly focused under conditions where friction and wear are critical issues. These reports suggest that the frictional heat generated during the test is important and the specimen's temperature should be monitored.

As previously shown, numerous papers regarding PEEK's tribological properties have been published. These previous works have been conducted under un-lubricated conditions and at low sliding velocities. PEEK composites have recently been applied to various machine elements such as a thrust bearing (Matsueda et al., 2000), a pump bearing (Sugiyama et al, 2001), 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. Within a high sliding velocity environment, 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 in such environment (Akagaki et al., 2002; Akagaki and Kawabata, 2016a). Furthermore, the effects of PEEK's surface roughness on the tribological behavior have not been studied so far. Our previous work showed that PEEK materials transit from hydrodynamic lubrication or mixed lubrication to seizure under severe oil-lubricated conditions such as high sliding velocity and high load (Akagaki and Kawabata, 2010; Akagaki et al., 2016b). 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 sliding conditions.

In this study, the seizure behaviors of PEEK/steel pairs were studied over a wide range of PEEK's surface roughness under oil-lubricated sliding contacts. During the test, the steel'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's temperature, the seizure mechanism was discussed.

2. Experimental apparatus and procedure

Experiments were conducted with blocks on a ring wear tester shown in Fig.1 (Akagaki et al., 2002). The testing materials are listed in Table 1. The ring was made of forged steel (SF540A), with 130 mm diameter and 20 mm thickness; it was shaped by cylindrical grinding. The ring's surface roughness was 0.12 $\mu\text{m Ra}$. The materials used to make the blocks were unfilled PEEK (PEEK for short) and a PEEK composite filled with 30 mass% carbon fiber (PEEK composite). The carbon fiber was 8 μm in diameter and its length ranged from 50 to 200 μm . The blocks were 90 mm long, 10 mm wide, and 10 mm thick. They were finished with an emery paper, and their surface roughness ranged from 0.03 to 4.77 $\mu\text{m Ra}$. Both of these PEEK materials have a glass transition temperature of 143°C and a melting point of 340°C. The experimental conditions are listed in Table 2. The sliding velocity was 19 m/s, and the load was 883 N. During the test, a frictional torque was measured with a torque meter. The ring temperature was measured with an alumel-chromel thermo-couple with a diameter of 0.5 mm, located 1mm below the frictional surface. The test duration was 1800 s. However, when the frictional torque increased suddenly, the tests were ended. When the symptom showing seizure was observed, the tests were continued over 1800 s. The lubricant used was a non-additive turbine oil (ISO VG46). It was supplied to the frictional surface at a flow rate of 1 ml/s with a pump. The oil temperature was kept at $30 \pm 3^\circ\text{C}$ with a controller.

After the test, a profilometer was used to measure the block's wear scar and to determine which of the block's profile was parallel to the sliding direction. A cross-sectional area, A , of the wear scar was measured with a planimeter. The wear volume, V , was derived by multiplying A with the width W , of the block (in this case, $W=10$ mm). Each block's specific rate of wear, W_s , was calculated as $W_s=V/(PS)$, where P is the load and S is the sliding distance. The S used to calculate specific wear rates was calculated from each test's duration.

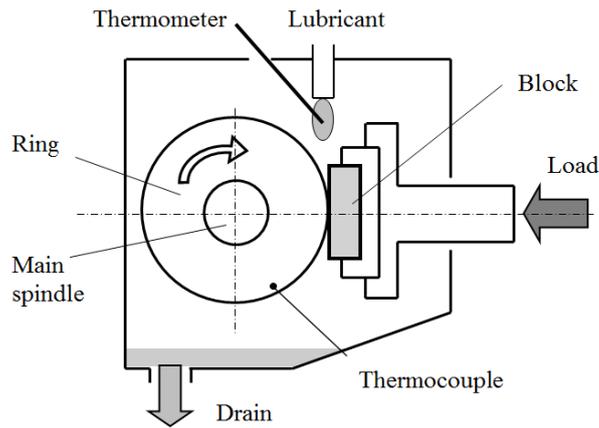


Fig.1 Schematic diagram of experimental apparatus.

Table 1 Properties of testing materials

	Material	Hardness	Surface roughness, Ra (μm)
Ring	Forged steel (SF540A)	HV189	0.12 ± 0.03
Block	Unfilled PEEK	$HD86 \pm 4$	$0.03 - 4.77$
	PEEK Comp. (CF: 30 mass %)	$HD91 \pm 7$	$0.08 - 4.19$
	WJ2	$HV26 \pm 3$	$0.05 - 3.06$

Table 2 Experimental conditions

Sliding velocity (m/s)	19.0
Load (N)	883
Test duration (s)	1800
Lubricant	Non-additive turbine oil (ISO-VG46)
Flow rate (ml/s)	1.1
Oil temp. ($^{\circ}\text{C}$)	30 ± 3

3. Results and discussion

3.1 Friction behavior

Figure 2 illustrates the relationship between the friction coefficient and the run time obtained with PEEK. Figure 3 is the ring temperature curves corresponding to Fig.2. When PEEK is smooth and its roughness is less than $0.05 \mu\text{m Ra}$, the friction coefficient and ring temperature are both low and constant: 0.008 and 105°C , respectively. When PEEK's roughness is in the range of $0.15-0.51 \mu\text{m Ra}$, at first the friction coefficient is low and then increases gradually. Finally it increases rapidly: seizure occurs. Although the ring temperature almost becomes constant, it keeps increasing gradually and increases rapidly up to about 200°C . When PEEK is very rough and its roughness is more than $0.51 \mu\text{m Ra}$, seizure occurs soon after the start of the test. The ring temperature increases at a high increasing rate and reaches 200°C soon.

Thus, it is apparent that seizure behavior is strongly dependent on PEEK's surface roughness. The PEEK composite also shows the similar tendency, as shown in Figs. 4 and 5. The PEEK composite, however, maintains low friction coefficient until larger surface roughness as compared to PEEK. When the ring temperature becomes low and constant, the low friction coefficient is maintained in PEEK and the PEEK composite.

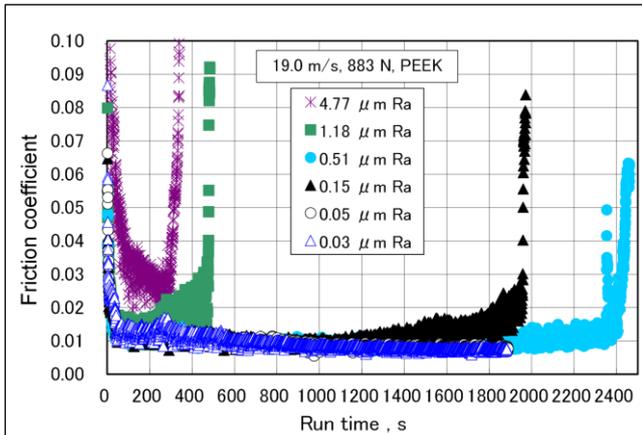


Fig.2 Relationship between friction coefficient and run time obtained with PEEK. Seizure behaviors depend on block's surface roughness.

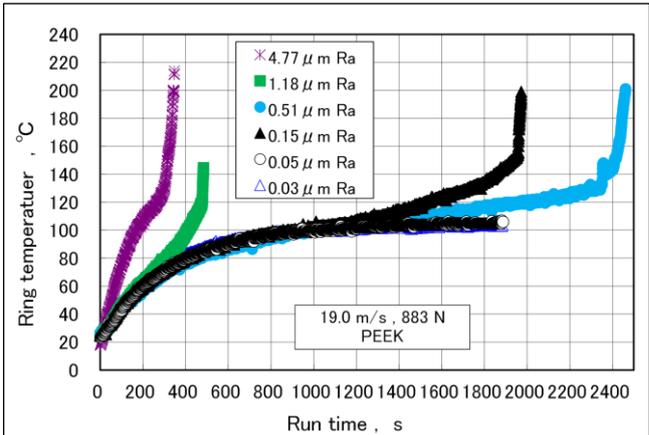


Fig.3 Relationship between ring temperature and run time obtained with PEEK. Seizure is sensitive to ring temperature.

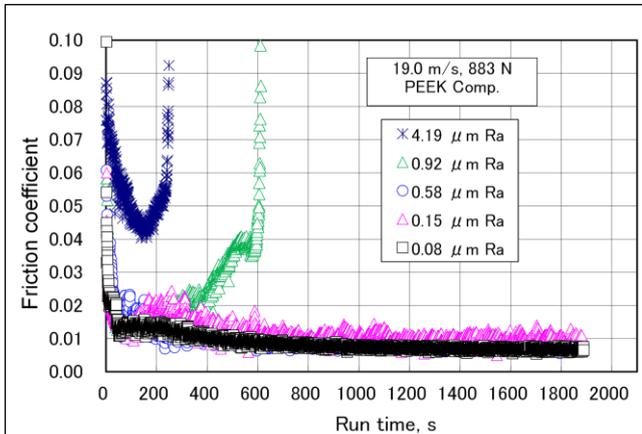


Fig.4 Relationship between friction coefficient and run time obtained with PEEK composite. Results show similar tendency to PEEK.

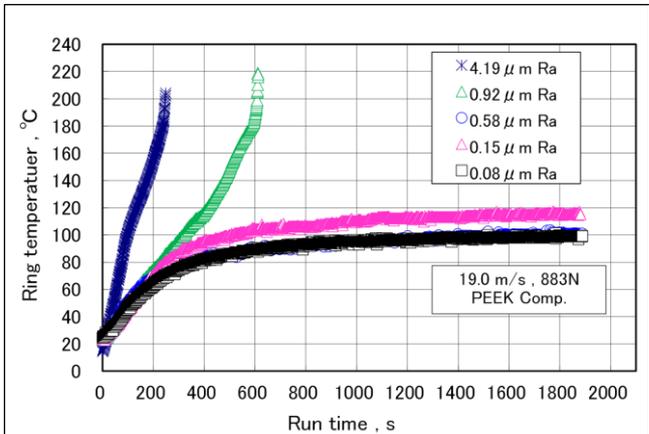


Fig.5 Relationship between ring temperature and run time obtained with PEEK composite. When ring temperature becomes low and constant, low friction is maintained.

Figure 6 illustrates the relationship between the friction coefficient and the block's surface roughness. When seizure occurs, the friction coefficient increases from low values of less than 0.01 to high values of 0.06–0.13. As shown in Fig.6, seizure occurs as the block's surface roughness exceeds a critical value. The critical values are in the range about 0.06–0.1 $\mu\text{m Ra}$ for PEEK and about 0.6–0.9 $\mu\text{m Ra}$ for the PEEK composite. Thus, it is said that the seizure-resistant property of the PEEK composite is superior to that of PEEK.

A lambda ratio (the book by Hutching, 1992) is calculated for discussion of the results. It is defined as $\Lambda = h_{\min} / (Rq_1^2 + Rq_2^2)^{1/2}$, where h_{\min} is the minimum film thickness and Rq_1 and Rq_2 are the root mean square roughness of the ring and block, respectively. The minimum film thickness is calculated using the Dowson-Higginson formula (the book by Yamamoto and Kaneta, 1998). Oil viscosity is calculated at the ring temperatures obtained from each test, and Rq_1 and Rq_2 are calculated from the arithmetic average roughness, Ra, where $Rq = 1.25 Ra$ (the book by Hashimoto, 2006). The numerals in Fig.6 denote the Λ ratio calculated from the initial surface roughness. Parenthetic values in Fig.6 denote the Λ ratio calculated from the block's surface roughness after friction. The block's surface roughness changed significantly, although the ring's surface roughness did not change appreciably after the seizure.

The Λ ratio values are mostly more than 3 when the block's roughness is small, which suggests that hydrodynamic lubrication is predominant and low friction coefficients less than 0.01 are maintained. In contrast, the Λ ratio values are less than 1 when the block's surface roughness is large, which suggests that boundary lubrication is predominant (the book by Hutching, 1992): in this case, direct contact occurs between the ring's surface and the block, resulting in high friction coefficients and high temperatures. When the Λ ratio values are in the range 1–3, mixed lubrication is

predominant. In such a case, if the block's surface roughness becomes rough probably due to wear, and the Λ ratio values decrease and become less than 1, boundary lubrication becomes predominant leading to seizure, as shown in the results of PEEK in Fig.6. If the block's surface roughness becomes smooth probably due to plastic deformation and wear, and the Λ ratio values increase and becomes in the range of 2–3, low friction coefficient can persist, as shown in the results of the PEEK composite in Fig.6. Figure 7 shows the relationship between the friction coefficient and the Λ ratio. The open and the closed marks show the results calculated from the initial surface roughness and from the block's surface roughness after friction, respectively. The red and the blue arrows indicate that the Λ ratios shift depending on the change of the frictional surface. Figure 7 supports the above discussion.

Thus the Λ ratio values suggest that low friction coefficient tends to persist in the PEEK composite even if the mixed lubrication is predominant. In contrast, PEEK tends to transit from mixed lubrication to seizure. Furthermore, the friction coefficient in the seizure of the PEEK composite seems to be lower than in the PEEK.

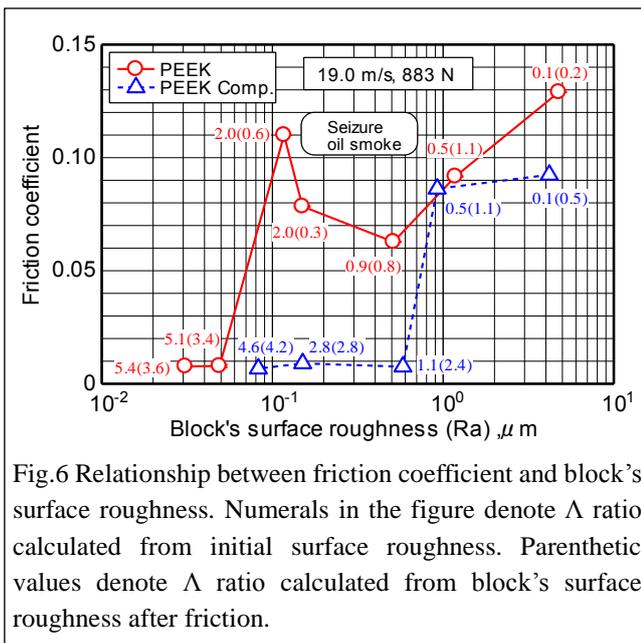


Fig.6 Relationship between friction coefficient and block's surface roughness. Numerals in the figure denote Λ ratio calculated from initial surface roughness. Parenthetic values denote Λ ratio calculated from block's surface roughness after friction.

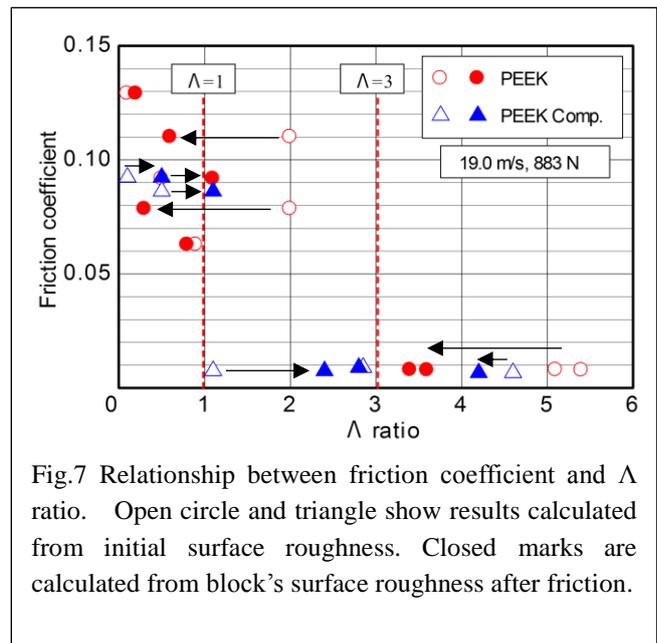


Fig.7 Relationship between friction coefficient and Λ ratio. Open circle and triangle show results calculated from initial surface roughness. Closed marks are calculated from block's surface roughness after friction.

3.2 Block wear

Figure 8 illustrates relationship between the specific wear rate of the block and the block's surface roughness. Similar to the friction behavior shown in Fig.6, the block's wear rate increases rapidly at a certain value as the block's surface roughness increases. This wear behavior corresponds to the transition from hydrodynamic lubrication or mixed lubrication to boundary lubrication leading to seizure. The block's wear rates of PEEK and the PEEK composite increase from low values of the order of 10^{-9} – 10^{-10} to high values of the order of 10^{-8} – 10^{-6} $\text{mm}^3/(\text{N}\cdot\text{m})$. In PEEK, the friction coefficient and the specific wear rate seem to decrease in the range of 0.1–0.5 μm , as shown in Figs. 6 and 8. When the friction coefficient rapidly increased, the tests were stopped immediately. Thus it is apparent that the seizure is not in a steady state; the data measured in the seizure are dependent on a time until the test is stopped. Therefore, it is supposed that these decreases are within the fluctuation of friction and wear data.

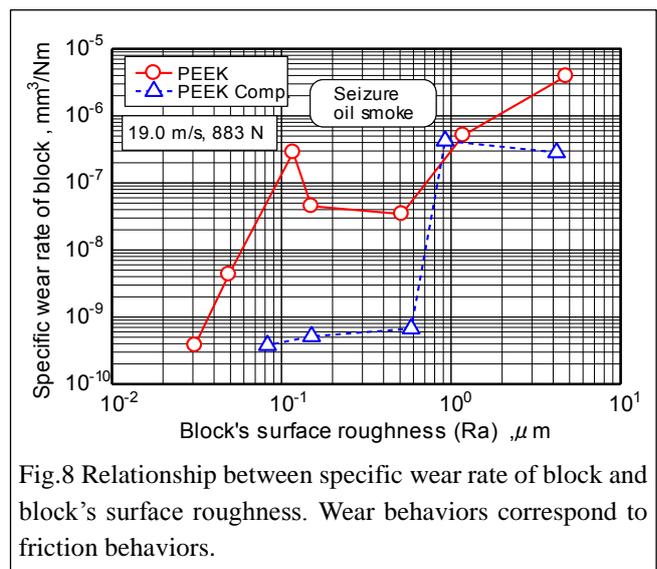


Fig.8 Relationship between specific wear rate of block and block's surface roughness. Wear behaviors correspond to friction behaviors.

3.3 Relation between friction coefficient and ring temperature

Figures 9 and 10 illustrate the relationship between the friction coefficient and the ring temperature in PEEK and the PEEK composite, respectively. When the block's surface roughness is less than $1 \mu\text{m Ra}$, there are good correlations between the friction coefficient and the ring temperature in both PEEK and the PEEK composite. As the ring temperature increases, the friction coefficient is small and constant until about 110°C for PEEK and about 120°C for the PEEK composite. Then it increases gradually until each critical temperature and finally seizure occurs. Thus the transition process to seizure can be roughly divided into three regimes strongly depending on the ring temperature: hydrodynamic lubrication, mixed lubrication, and boundary lubrication leading to seizure. The temperature readings transiting from mixed lubrication to seizure are about 150°C for PEEK and about 180°C for the PEEK composite. These temperatures are higher than the PEEK's glass transition temperature of 143°C . This suggests that the higher temperature more than the glass transition temperature is required to cause severe plastic deformation and flow extensively in the seizure of the PEEK materials (Akagaki et al., 2016b). Thus the PEEK composite has a high transition temperature for resisting to the seizure. This is probably because many carbon fibers are evenly distributed in the PEEK composite, thus improving the resistance to severe plastic deformation and flow at high temperature.

When the block's roughness is more than $4 \mu\text{m Ra}$, the temperature curve does not agree with other curves, although the tendency is similar. In this case, the Λ ratio value is 0.1, as shown in Fig.6, which suggests that boundary lubrication is predominant and direct contact between the ring's surfaces and the block occurs from the start of the testing. It is considered that the direct contact causes high friction coefficient and further high temperature because of high sliding velocity. It has been supposed high temperatures have two contrary effects on the friction behavior of the PEEK materials (Chang et al., 2007). One is the friction coefficient decreases because the shear strength decreases. The other is that the coefficient friction increases because the contact area between the PEEK materials and the steel increases. In the result of this study, it is considered that the seizure process which the friction coefficient increases is due to the latter reason. The decreasing process of the friction coefficient in boundary lubrication might be due to the former reason.

3.4 Surface profiles of wear scars and SEM observations

Figure 11 illustrates the cross-sectional profiles of wear scars of the ring and block. When the friction coefficient is small value less than 0.01, and the ring temperature becomes constant at 100°C or so, each cross-sectional profile of PEEK and the PEEK composite does not agree with each ring's profile, as shown in Figs.11 (a) and (b). This means that the elastic contact is predominates. In contrast, when the friction coefficient is high value more than 0.06, and the ring temperature rises to a high value more than the glass transition temperature: in seizure, the plastic contact is predominant due to the softening of the PEEK materials as both the profiles agree well each other, as shown in Figs.11 (c) and (d).

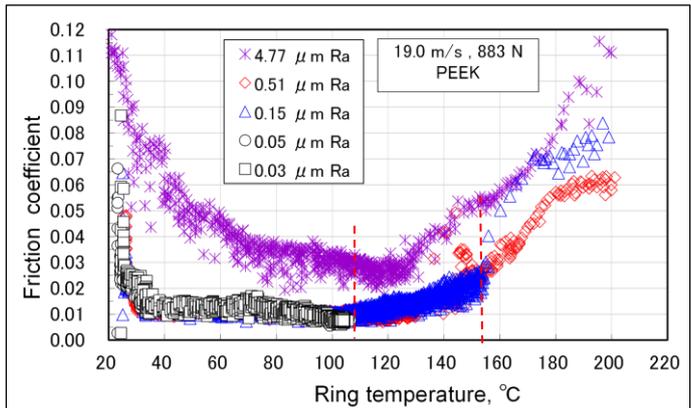


Fig.9 Relationship between friction coefficient and ring temperature in PEEK. Transition process to seizure can be roughly divided into three regimes.

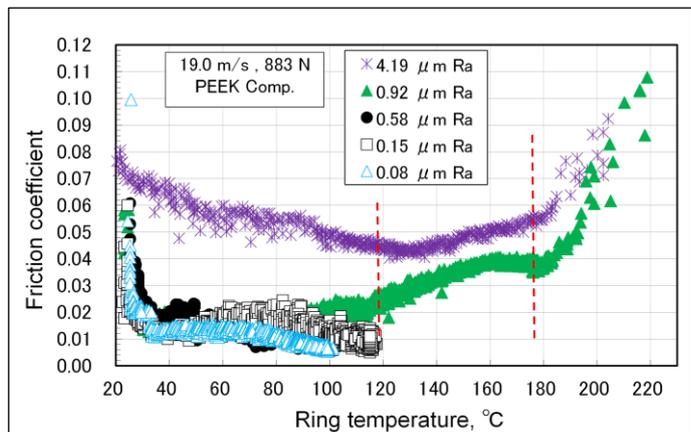


Fig.10 Relationship between friction coefficient and ring temperature in PEEK composite. PEEK composite has higher transition temperature as compared to PEEK.

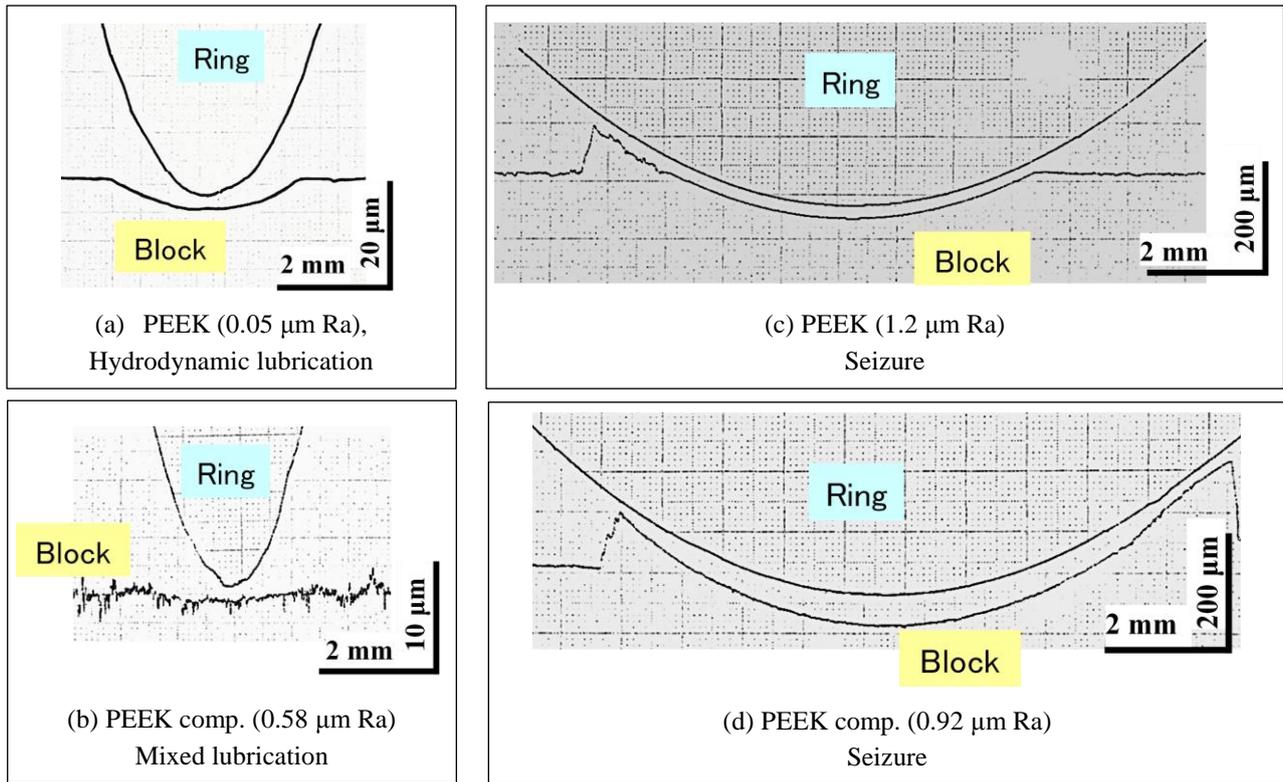
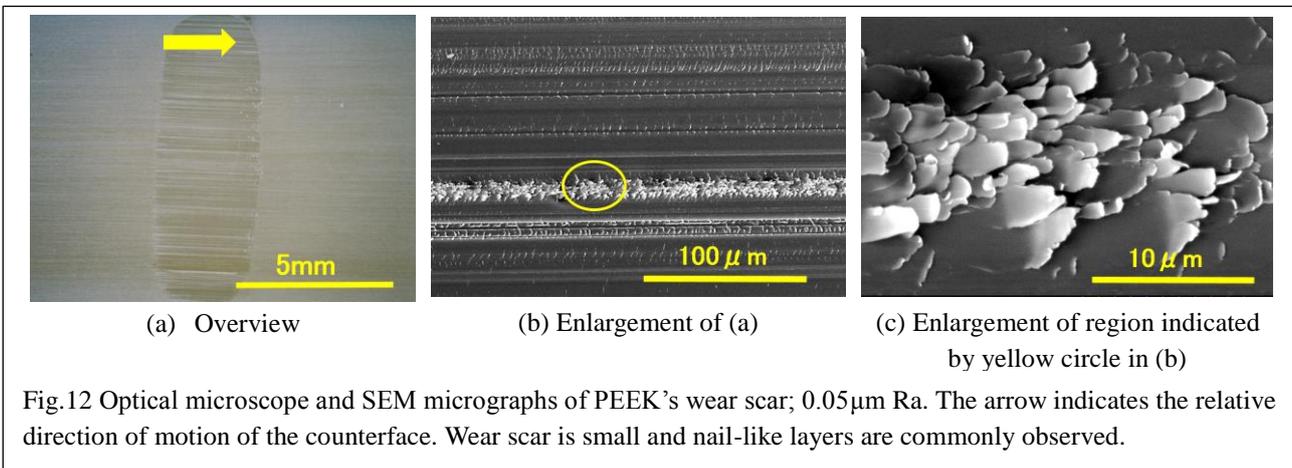
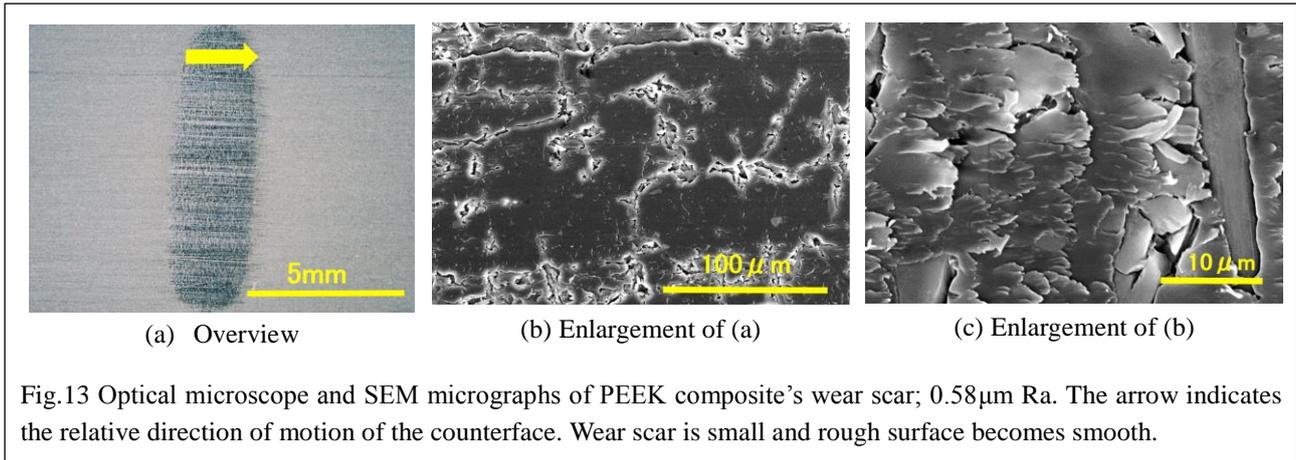


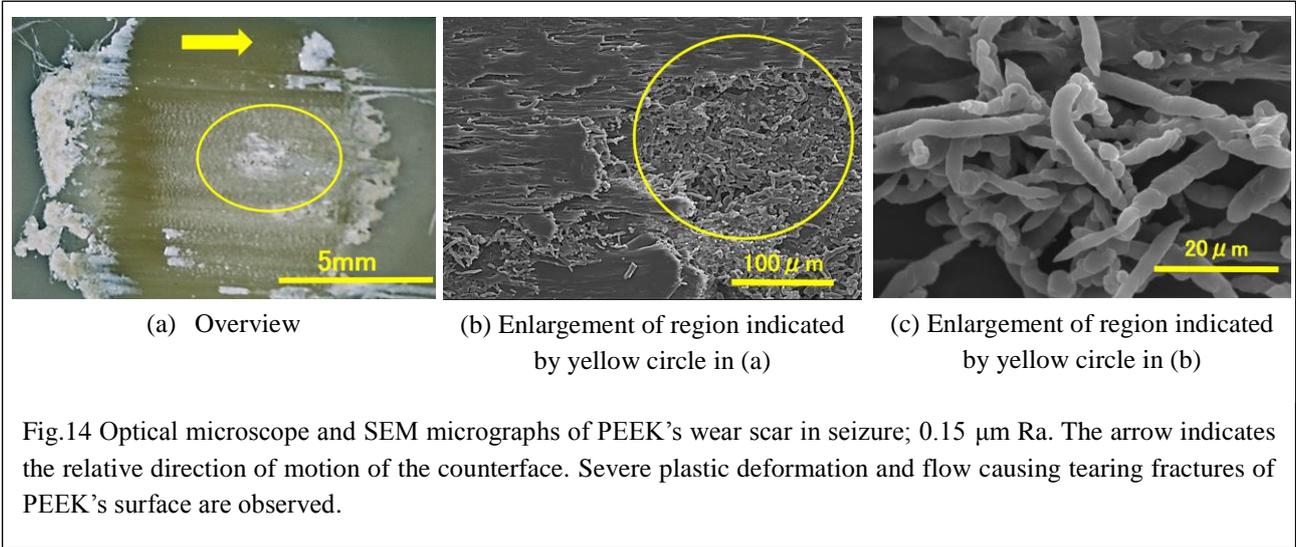
Fig.11 Cross-sectional profiles of ring and block: (a)–(c) PEEK block; (b)–(d) PEEK composite’s block. Figures (a)-(b) and (c)-(d) show that elastic deformation and plastic deformation are predominant, respectively.

Figure 12 shows the optical and SEM micrographs of the PEEK’s wear scar that caused when the smooth PEEK slides against steel ring. In this case, low friction and wear are maintained because of hydrodynamic lubrication. Although the wear scar is small, some micro grooves are commonly observed, as shown in Figs.12 (a) and (b). Nail-like layers less than mostly a few microns in size are observed in the grooves, as shown in Fig.12 (c). These layers are probably formed during the plastic flow process due to mild plowing action of the ring’s asperities during the running-in period. Figure 13 shows the optical and SEM micrographs of PEEK composite’s wear scar that caused when the relatively rough PEEK composite slides against the steel ring. In this case, low friction and wear are maintained because the Λ ratio value increases from 1.1 to 2.4 and mixed lubrication persists. The wear scar is small and the rough surface becomes smooth probably due to the plastic deformation and flow, as shown in Figs.13 (a) and (b). Indeed, the block’s roughness decreased from 0.58 to 0.25 $\mu\text{m Ra}$. Many nail-like layers similar to PEEK’s wear scar are commonly observed on the wear scar, as shown in Fig.13 (c). These layers also might be formed during the plastic flow process due to the plowing action of the ring’s asperities.





Figures 14 and 15 show the wear scars of PEEK and the PEEK composite in seizure, respectively. In PEEK's seizure, plate-like and wire-like extrusions are commonly observed at the outlet position of the wear scar. Some large transfer fragments are observed at the inlet position, as shown in Fig.14 (a). This observation result indicates that the plate-like extrusion formed during severe plastic deformation and flow detach from the outlet position and then adhere to the inlet position. Severe plastic deformation and flow causing tearing fractures of PEEK's surface are observed, as shown in Fig.14 (b). After the separation of plate-like fragments due to tearing fracture, abundant twisted and cylindrical wear particles are observed, as shown in Fig.14 (c). When large detached fragments are forced out from the wear scar, it is assumed that they slide and generate wear particles between the bottom of fragments and PEEK's surfaces. In this process, thin layers which detach from both surfaces might be rolled up and become twisted and cylindrical particles. Thus it is considered that high temperature in seizure plays an important role in severe plastic deformation and flow, tearing fracture and formation of twisted and cylindrical particle, because high temperature of about 200 °C significantly decreases the shear strength of the PEEK materials.



In seizure of the PEEK composite, abundant and long wire-like and ribbon-like extrusions mostly less than 10–20 mm in length are observed at the outlet position, as shown in Fig.15 (a). As carbon fibers strengthen the mechanical properties such as shear strength and deformation resistance, abundant wire-like extrusions seem to be generated from the PEEK matrices. Many carbon fibers are observed on the wear scar, as shown in Fig.15 (b). They gather densely probably due to creep phenomena caused by high temperature and pressure and seem to arrange in the direction of plastic deformation and flow. As shown in Fig.15 (c), cracking of carbon fibers and abundant crashed fine particles less than 1–2 μ m in size are commonly observed. These fine particles might be formed in the crushing process due to the relative motion between carbon fibers and carbonization of carbon fibers and PEEK matrices under high shear stress, high contact pressure and high temperature.

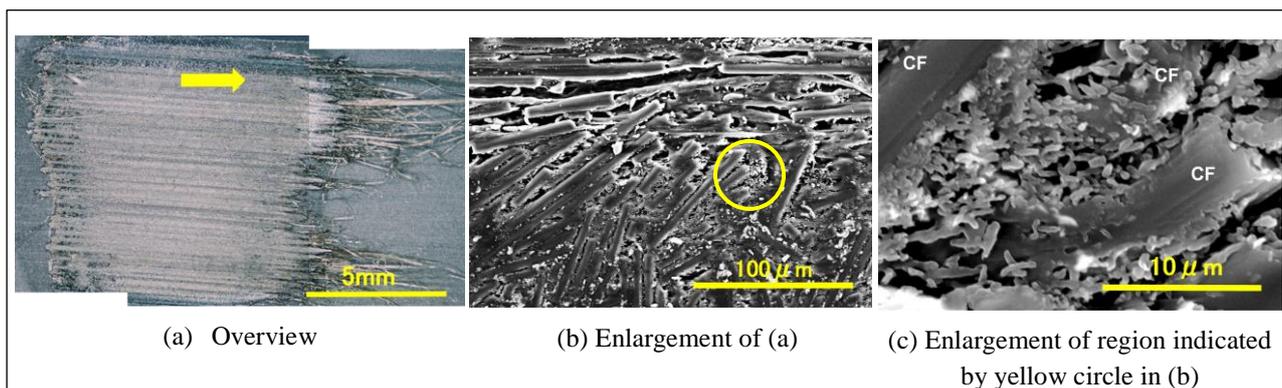


Fig.15 Optical microscope and SEM micrographs of PEEK composite's wear scar in seizure; 0.92 μm Ra. The arrow indicates the relative direction of motion of the counterface. Abundant and long wire-like and ribbon-like extrusions due to plastic deformation and flow are commonly observed.

As discussed in the chapter of 3.3, the temperature plays an important role in the seizure of the PEEK materials. The block's temperature is very important, because the seizure results from the severe plastic deformation and flow of the block materials. In this study, the ring temperature was measured at the position of 1 mm below the ring surface. In general, the thermal conductivity of carbon steel is much higher than PEEK and the PEEK composite. Therefore it is expected that the block's surface temperature is higher than the ring's one measured in this study. The PEEK composite has a higher thermal conductivity as compared to PEEK, as carbon fibers are distributed in the matrix. It is supposed that the carbon fibers might contribute to reduce the surface temperature as well as improving the strength of the matrix. Thus it is assumed that the PEEK composite has the superior seizure-resistant property.

4. Conclusions

(1) The seizure behavior was strongly dependent on the PEEK material's surface roughness. Both the friction coefficient and each block's wear rate increased rapidly when the PEEK material's surface roughness exceeded a certain value. The critical value in the PEEK composite was significantly higher than in PEEK.

(2) The seizure process could be roughly divided into three regimes depending on the ring temperature: hydrodynamic lubrication, mixed lubrication, and seizure. The ring temperatures when transiting to seizure were dependent on the materials, and they were about 150 °C for PEEK and about 180 °C for the PEEK composite.

(3) The elastic contact was predominant in hydrodynamic and mixed lubrication. In contrast, the plastic contact was predominant in seizure.

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