LUBRICATED WEAR OF PEEK AND ITS COMPOSITE

T. AKAGAKI
Hachinohe Nat. Coll. of Tech., Hachinohe, Aomori 039-1192, JAPAN; e-mail: akagaki-m@hachinohe-ct.ac.jp

K. KATO
Tohoku University, Sendai, Miyagi 980-8579, JAPAN; e-mail: koji@cc.mech.tohoku.ac.jp

M. KAWABATA
Tribotex Incorporation, Obu, Aichi 474-0052, JAPAN; e-mail: kawabata@tribo.co.jp

SUMMARY
Friction and wear characteristics of PEEK and its composite sliding against smooth and rough steel rings were studied under oil lubricated conditions. Three kinds of block materials were tested: unfilled PEEK, PEEK composite filled with 30 wt.% of carbon fibers and WJ2. The load was varied in the range 196 to 1192N and the sliding velocity was 10.2 m/s. The experiment was conducted with a block on ring wear tester. It was found that the friction and wear characteristics of the PEEK composite were superior to those of the unfilled PEEK and WJ2. When slid against rough ring at 588N and 10.2 m/s, the PEEK composite had the lowest friction coefficient of 0.04-0.06 and the lowest specific wear rate of $10^{-7}$ mm$^3$/Nm, although the wear loss of the rough ring was the highest. Those of the unfilled PEEK and WJ2 were $0.07-0.09$ and $(4 - 8) \times 10^{-6}$ mm$^3$/Nm respectively. It also found that the temperature increases of ring slid against PEEK materials were larger than that slid against WJ2. Sliding against the rough ring, severe ploughing in the PEEK and WJ2 and cracking and separation of matrix layers in the PEEK composite were predominant.

Keywords: PEEK, PEEK Composite, Lubricated Wear, Wear Mechanism, SOAP

1 INTRODUCTION
Poly-ether-ether-ketone (PEEK) is a high performance thermoplastic polymer. PEEK has some excellent properties such as high strength, high toughness, heat resistance, thermal stability, easy processing and chemical inertness [1]. PEEK has also superior tribological properties along with PTFE. Recently, PEEK composites, containing various kinds of fillers, have been developed and used in practice [1 - 2]. Most of the studies on the friction and wear behaviour of PEEK materials have been conducted under un lubricated condition [3 - 5]. In most practical situations, machine elements operate at high sliding velocity. At high sliding velocity, lubrication is indispensable for maintaining low friction and wear for a long time. In order to enlarge the application field of PEEK materials in practice, therefore, it is essential to study the friction and wear behaviour of PEEK materials at high sliding velocity under oil lubricated condition. In this study, the friction and wear properties of unfilled PEEK and its composite sliding against smooth and rough steel rings at high sliding velocity were evaluated under oil lubricated condition.

2 EXPERIMENTAL APPARATUS AND PROCEDURE
Experiments were carried out with a block on ring wear tester. The schematic diagram is shown in Fig.1. The properties of testing materials are summarized in Table1. The ring was a forging steel (SF55) of diameter 128 mm and length 20 mm. Two kinds of ring having different surface roughness were used. By turning and further cylindrical grinding, the rings were finished to the roughness of 1.42 and 0.11 µm Ra respectively. The block materials were unfilled PEEK (PEEK for short), its composite filled with 30 wt.% of carbon fiber (PEEK composite) and white metal (WJ2). The block had a length of 90 mm and a width of 10 mm. The block surfaces were finished with an emery paper. The experimental conditions are summarized in Table 2. The sliding velocity was 10.2 m/s and the load was varied in the range of 196 to 1192 N. The oil was supplied to the frictional surface at a flow rate of 23 cc/min with a pump. The oil temperature was kept at 30 °C with a controller.

![Fig. 1 Schematic diagram of experimental apparatus.](image-url)

During the test, the frictional torque was measured with a torque meter. The ring temperature was measured with an almel-chromel thermo-couple of diameter 0.5 mm, which was located at 1mm below the frictional surface. The block temperature was also measured at 2 mm below the frictional surface. The wear scar of the block was measured with a profilometer after the test to obtain the profile parallel to the sliding direction. The cross-sectional area of the wear scar “A” was measured with a...
The wear volume “V” was derived from the multiplication of the cross-sectional area “A” and the width of the block “W” (W = 10 mm). The specific wear rate of the block “Ws” was calculated by the following expression: Ws = V/(PL), where “P” is the load and “S” is the sliding distance. For wear debris analysis, the oil was collected from the drain. The oil was analysed using spectrometric oil analysis program (SOAP). Wear scars and wear debris were observed with a scanning electron microscope (SEM) and analysed with an energy-dispersive X-ray spectroscopy (EDS).

<table>
<thead>
<tr>
<th>Materials</th>
<th>Hardness</th>
<th>Roughness Ra, µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring</td>
<td>SF55</td>
<td>0.11±0.04</td>
</tr>
<tr>
<td></td>
<td>HV189</td>
<td>1.42±0.10</td>
</tr>
<tr>
<td>Block</td>
<td>PEEK</td>
<td>0.23±0.03</td>
</tr>
<tr>
<td></td>
<td>HRR120</td>
<td>0.22±0.05</td>
</tr>
<tr>
<td></td>
<td>Comp.</td>
<td>0.24±0.05</td>
</tr>
<tr>
<td></td>
<td>WJ2</td>
<td>0.11±0.04</td>
</tr>
</tbody>
</table>

Table 1: Properties of testing materials.

<table>
<thead>
<tr>
<th>Sliding velocity (m/s)</th>
<th>10.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load (N)</td>
<td>196 ~ 1176</td>
</tr>
<tr>
<td>Test duration (min)</td>
<td>~ 30</td>
</tr>
<tr>
<td>Lubricant</td>
<td>Non-additive turbine oil (ISO VG46), 23 cc/min</td>
</tr>
</tbody>
</table>

Table 2: Experimental conditions.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Friction property

Fig.2 shows the friction and temperature curves of the PEEK composite sliding against the steel ring at 588 N. When sliding against the smooth ring, the friction coefficient is small and becomes constant at ~0.01. The temperatures of ring and block become constant at ~50 °C. When sliding against the rough ring, the friction coefficient initially increases and then decreases gradually. It becomes constant at higher value of 0.04 and does not fluctuate. The temperatures of ring and block raise to 160 and 120 °C respectively. The test was interrupted for the safety, as oil smoke was produced.

All friction data, obtained from the friction curves, were plotted together in relation to the load. The result is shown in Fig.3. The friction coefficient decreases with the increase in the load. When the ring is smooth, the friction coefficient is low and of the order of 10⁻³. The value does not depend on the block material. It is expected that the sufficient oil film is formed and the fluid lubrication is predominant. When the ring is rough, the friction coefficient becomes high and lies in the range of 0.04 to 0.15. The value is strongly dependent on the block materials. Among them, the friction coefficient of the PEEK composite is the lowest. As the surface roughness of ring is larger than the thickness of oil film, the oil does not contribute the reduction of friction due to oil film formation. Consequently the surface temperature of ring raises to 160 °C, as shown in Fig.2. Under such a severe condition, the PEEK composite has a high capacity to maintain low friction coefficient. The friction coefficients of the PEEK and WJ2 are about two times as high as that of the PEEK composite.

3.2 Wear property of block

Fig.4 shows the relationship between the specific wear rate of the block and the load. The specific wear rate of the block is strongly dependent on the mating surface roughness and the block material. When sliding against the smooth ring, the specific wear rates are low. The values are ~5×10⁻⁶ mm³/Nm for WJ2 and ~10⁻⁵ for the PEEK. That of the PEEK composite is the lowest and less than ~2×10⁻¹⁰. Thus the specific wear rates of polymers are smaller than that of metal, although the friction coefficients are the same. It is probably because
the contact between polymer and metal is often predominantly elastic and so EHL film is easily formed. When sliding against the rough ring, the specific wear rates of the blocks become very high.

The values of the PEEK and WJ2 lie in the range \((2 \times 10^{-6} \sim 3 \times 10^{-5})\) mm\(^3\)/Nm. That of the PEEK composite is \((1 \sim 2) \times 10^{-7}\) mm\(^3\)/Nm. Thus the rough ring causes high friction and high specific wear rate of block. This is because severe ploughing occurs when the harder asperities of the ring penetrate into the block. On the surface of the PEEK composite, much carbon fillers are evenly distributed. They may prevent the harder asperities from penetrating into the composite. Therefore the friction coefficient and the specific wear rate of the PEEK composite are the lowest. In contrast, those of the PEEK and WJ2 become the highest, because severe ploughing occurs in these block materials. The SEM observation results showed that severe ploughing was predominant in these blocks. Further, they also showed that severe adhesion and separation, that is, seizure occurred in WJ2. However, any evidences showing seizure were not observed in the PEEK composite. Thus the PEEK composite has excellent wear resistance under such a severe sliding conditions.

The relationship between specific wear rate of block and load is shown in Fig. 4. The specific wear rates of PEEK and WJ2 are lower than that of the composite. The specific wear rate of the composite is the lowest, which is about one order of magnitude lower than that of PEEK and WJ2. This is because the carbon fillers in the composite act as a lubricant, reducing the friction and wear.

3.3 Temperature increase of specimen

Fig. 5 and Fig. 6 show the relationship between the temperature increases of specimens and the frictional work \(\mu PV\), where \(\mu\), \(P\) and \(V\) are the friction coefficient, the load (N) and the sliding velocity (m/s) respectively. To construct Figs. 5 and 6, the data only when the block slid against the smooth ring were used. The temperature increases are found to be directly proportional to the frictional work \(\mu PV\). When sliding against the PEEK and the PEEK composite, the empirical formula can be expressed as \(\Delta T = 0.65 \mu PV\) for the ring and \(\Delta T = 0.35 \mu PV\) for the block, as shown in Fig. 5. Thus the temperature increase of the ring is higher than that of the block. This may result from the difference in thermal conductivity between polymer and metal. When sliding against WJ2, it can be expressed as \(\Delta T = 0.5 \mu PV\) for the ring and the block, as shown in Fig. 6. The temperature increases of the ring and the block are almost the same. Thus the temperature increase increases of ring sliding against the PEEK materials are larger than that sliding against WJ2, even if the calorific power at the frictional interface is the same. This result suggests that the oil degradation may be accelerated in new PEEK composite bearing.

Fig. 5 Relationship between temperature increase and frictional work when SF55 slid against PEEK materials.

Fig. 6 Relationship between temperature increase and frictional work when SF55 slid against WJ2.
3.4 SOAP analysis

Table 3 shows the iron element concentration in oil samples collected at initial stage of friction. The analysis result corresponds to the wear loss of the ring. When the ring is smooth, the wear loss of the ring is not detected. When the ring is rough, the wear loss of the ring is strongly dependent on the block material. Sliding against the PEEK, the wear loss of the ring is negligible. In this case, however, only the blocks such as the PEEK and WJ2 suffer from severe damage. Sliding against the PEEK composite, the wear loss of the ring is higher, although that of the block is the lowest. The iron element concentration of 5.1 ppm corresponds to the specific wear rate of $4 \times 10^{-8}$ mm$^3$/Nm. This is because hard carbon fibers abrade the ring surface. This result suggests that the iron element may be useful for detecting the changes of lubrication mode and wear rate in new PEEK composite bearing.

<table>
<thead>
<tr>
<th>Block material</th>
<th>Surface roughness of ring</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.11 µm Ra</td>
</tr>
<tr>
<td>PEEK</td>
<td>0</td>
</tr>
<tr>
<td>Comp.</td>
<td>0</td>
</tr>
<tr>
<td>WJ2</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3: Iron element concentration (10.2 m/s, 588 N).

3.5 SEM observations of wear scars

Figs. 7 and 8 show the SEM micrographs of wear scars of the PEEK and the PEEK composite sliding against the rough ring. Many ploughing grooves are formed on the wear scar of the PEEK. In the ploughing process, many film-like, chip-like and plate-like layers are formed, as shown in Fig.7. It is expected that these layers and ridges of grooves separate and loose wear debris less than several tens µm in size are mainly generated. The collected oil became clouded because abundant wear debris was generated from the PEEK block. In contrast, on the wear scar of the PEEK composite, clear evidences showing brittle cracking and separations of matrix layers at near regions of carbon fibers are observed, as shown in Fig. 8. It is expected that thin wear debris less than 10 µm are generated from the PEEK composite.

4 CONCLUSIONS

(1) When the PEEK composite slid against the rough ring (1.42 µm Ra) at 588 N and 10.2 m/s under oil-lubrication, the friction coefficient lay in the range of 0.04 ~ 0.06 and its value was the lowest among three kinds of block materials. Those of the PEEK and WJ2 lay in the range of 0.07 - 0.09 and fluctuated.

(2) The specific wear rate of the PEEK composite was also the lowest value of $(1 \sim 2) \times 10^{-7}$ mm$^3$/Nm. Those of the PEEK and WJ2 were $(4 \sim 8) \times 10^{-6}$ mm$^3$/Nm.

(3) The temperature increases of the ring slid against the PEEK and the PEEK composite were larger than that slid against WJ2. The difference was ~10 °C when the calorific power was 75 Nm/s.

(4) When the rough ring slid against the PEEK composite, the wear loss of the ring at the initial period of friction was the highest.

(5) Sliding against the rough ring, severe ploughing was predominant on wear scar of the PEEK. Cracking and separations of matrix layers at near regions of carbon fibers were observed on the wear scar of the PEEK composite.

5 REFERENCES