Tribofilm Properties of Polyether–Ether–Ketone-Based Coating under Mixed and Boundary Aviation Kerosene-Lubrication Condition

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Abstract: Because of its excellent tribological performance, polyether–ether–ketone (PEEK)-based coatings have been used extensively under mixed and boundary water-lubrication conditions. To verify that the PEEK-based coating is applicable to aviation kerosene, one advanced coating was proposed and two typical metals, namely, alloy steel 38CrMoAlA and tin bronze ZQPb17-4-4, were selected as counterparts. Four sets of experiments that involved a scuffing (step load) and Stribeck curve (step speed), constant load, and strengthened load were carried out, which showed that the counterpart material’s properties, such as its hardness, thermal conductivity, and composition, had an important effect on the tribological performance of the PEEK-based coating. Scuffing experiments showed that the PEEK-based coating against ZQPb17-4-4 exhibited better scuffing performance. Stribeck curve experiments showed that the PEEK-based coating against 38CrMoAlA was under the mixed lubrication condition over a wider range of speeds, and wear experiments (constant load and strengthened load) showed that the PEEK-based coating against 38CrMoAlA exhibited a relatively low coefficient of friction and low wear rate. The formation and appearance of the tribofilm on the surface of the counterparts influenced the wear mechanism of the PEEK-based coating. The PEEK-based coating showed excellent properties, especially when rubbed against 38CrMoAlA.

Keywords: PEEK-based coating; tribofilm; boundary lubrication; mixed lubrication

1. Introduction

During normal operation of mechanical equipment, a friction pair will produce an oil film by the hydrodynamic effect. However, the oil film will be damaged because of a start–stop, overload operation, and manufacturing assembly error, and the friction pair will be under a mixed and boundary lubrication [1]. Direct contact of rough peaks of the friction pair will result in deformation, adhesion, wear, and fatigue. The most critical approach to control friction and reduce wear is to reduce the contact number of rough peak points of a friction pair [2]. One method is to find a soft material that can cover a layer of tribofilm on the hard metal surface under mixed and boundary lubrications, to reduce the contact area between the hard metal and the soft material.

A tribofilm with a good lubrication performance can reduce the material friction coefficient and wear rate and prevent catastrophic equipment failure caused by copper burning and gluing of the friction pair [3]. The tribofilm anti-wear performance is related to the load, speed, temperature of the mating surface, type of lubricant, and material thermal conductivity. To improve the durability and reliability of friction pairs, the friction and wear behaviors of materials under mixed and boundary conditions should be understood.
Because of the self-lubrication characteristics, polymer materials have received extensive attention in the field of tribology, especially polyether–ether–ketone (PEEK). PEEK has a thermoplastic resistance to high temperatures, a superior wear resistance over a wide range of pressures and speeds, corrosion resistance, and hydrolysis resistance.

Under dry-friction condition, researchers have added micro/nanometer materials to pure PEEK to provide it with an excellent friction performance. Three effective approaches can be implemented: (a) incorporation of solid lubricants such as polytetrafluoroethylene (PTFE), graphite, and molybdenum disulfide [4–6]; (b) addition of fiber materials such as carbon fiber, glass fiber, and ceramic particles [7–9]; and (c) incorporation of hard micro- and nanoparticles, such as zirconium dioxide, silicon carbide, and carbon nanotubes [10–12]. Literature indicates that PEEK composites can form a tribofilm with good performance on the counterpart surface during dry-friction condition [4,6,8,10–12]. Some researchers have studied the friction and wear characteristics of pure PEEK/PEEK composites in pure water [13–17], seawater [18], and distilled water [19]. Compared with the performance under dry-friction conditions, PEEK composites exhibit better friction and wear characteristics because the interfacial temperature between the PEEK composite and the hard metal decreases as a result of friction heat that is carried away by the water medium. Literature indicates that a water medium can retain the wear debris of pure PEEK/PEEK composites to form a tribofilm on the counterpart surface [13–15,17–19].

In addition to the water medium, Zhang et al. [20] studied the friction characteristics of pure PEEK, PEEK composite, and s50-2 paired with 100Cr6 when immersed in engine oil. Although PEEK composites have many advantages, they cannot guarantee the size stability because of their thermal-expansion characteristics where the shape and position tolerance should be maintained with a high accuracy. In this case, PEEK composites can be sprayed on the metal surface, e.g., using electrostatic spray deposition (ESD) method [21,22] or thermal spraying [23]. However, only a small amount of work has been done to study the friction properties of PEEK thin coatings (thickness <50 µm) under mixed and boundary oil-lubrication conditions. Lan et al. [21,22] have shown that PEEK-based coating (1704 PEEK/PTFEs) debris can form tribofilm on 4130 alloy steel for ISO 46 grade mineral oil boundary lubrication, to improve its anti-scruff and anti-wear performance. Yeo et al. [23] performed a series of tests on a PEEK-based coating using a specialized high-pressure friction meter under oil-free oscillation and unidirectional test conditions. It indicated that the effect of polymer coating wear debris was shown to be more dominant in determining the overall wear behavior of polymeric coatings than the mechanical properties of the polymer coating itself. Minimal studies have been conducted on the friction and wear characteristics of PEEK-based coatings under mixed and boundary aviation kerosene-lubrication conditions. A PEEK-based coating and two kinds of common piston pump friction pair materials were selected to evaluate the friction and wear performance of PEEK-based coatings in aviation kerosene medium under different loads and speeds through a series of tests. The goal of this work was to contribute to the application of PEEK-based coatings in fuel–pump friction pairs.

2. Experiments

2.1. Material Preparation

Spheroidal cast iron QT600-3 was used as the disc substrate, and high-quality nitrided steel 38CrMoAlA and lead bronze ZQPb17-4-4 were used as the counterparts. VICOTE™ 816 (Victrex, Thornton Cleveleys, UK) dispersion was used for the coating. VICOTE™ 816 dispersion is produced with VICTREX PEEK polymeric material, and its wear resistance, high temperature resistance, and chemical resistance are enhanced. Before spraying, the substrate material should be cleaned and degreased thoroughly, and the roughness value of the spraying surface should be increased to 3–4 µm using silicon dioxide. During coating preparation, a high-flow low-pressure spray gun was used to spray the thoroughly mixed 816 dispersion liquid onto the surface of the substrate evenly. The coating was kept at ambient temperature for 5 min before baking in an oven at 120 °C for 5 min. The oven temperature was increased to 390 °C. The coating was heated for a further 5–10 min
before being removed from the oven and cooled to room temperature. The microstructural features of the coating were investigated by a scanning electron microscope (Merlin Compact, Carl Zeiss, Oberkochen, Germany) equipped with an electron dispersive spectrometer (Quantax 800, Bruker, Karlsruhe, Germany), as shown in Figure 1.

Photographs of the substrate, PEEK-based coating and counterparts are shown in Figure 2. The main dimensions of the interface are shown in Figure 2a,c. The nominal contact diameter was 46 mm and the contact area of the interface was 289 mm$^2$. To obtain the coating thickness, a PEEK coating was cut, as shown in Figure 3a. The SEM image of the cross-section of the rectangular box in Figure 3a is shown in Figure 3b. The measured thicknesses of the other coatings were similar in the range of 40–45 µm.

![Figure 1](image1.png)

**Figure 1.** The microstructural features of the polyether–ether–ketone (PEEK)-based coating.

![Figure 2](image2.png)

**Figure 2.** The photos of the materials: (a) the photo of the substrate QT 600-3; (b) the photo of the PEEK-based coating; (c) the photo of the counterpart 38CrMoAlA; (d) the photo of the counterpart ZQPb17-4-4.
Figure 3. (a) The photo of the PEEK-based coating on QT600-3 substrate and cut area; (b) SEM image of the PEEK-based coating cross-section for observing the thickness of the coating.

The Vickers hardness of the PEEK-based coating and counterparts was measured by a digital microhardness tester (HXD-1000TM/LCD, Shanghai Optical Instrument Factory, Shanghai, China). During the test, the loading was 50 gf for 15 s. Ten measuring points were selected from each test piece, and the hardness was taken as the test average. A Nexview™ 3D optical surface profiler (Zygo, AMETEK Taiwan Corp., Taiwan) was used to measure the PEEK-based coating-layer roughness. Five measuring surfaces were selected from each test piece, and the roughness was taken as the test average. Important performance values for the PEEK-based coatings and counterparts are summarized in Table 1.

| Material          | Hardness | Thickness (µm) | Roughness, Rq (µm) |
|-------------------|----------|----------------|--------------------|
| QT600-3           | 600 HV   | -              | 0.52               |
| PEEK-based coating| 160 HV   | 43             | 2.8                |
| 38CrMoAlA         | 720 HV   | -              | 0.36               |
| ZQPb17-4-4        | 310 HV   | -              | 0.36               |

2.2. Friction Test

The tribological properties of a PEEK-based coating sliding against 38CrMoAlA and ZQPb17-4-4 immersed in aviation kerosene (Rocket propellant 3, Sinopec Group, Beijing, China) were studied with disc-on-ring (DOR) tests using a self-developed high-pressure and high-speed tribosystem (HPHST). A photograph of the HPHST is shown in Figure 4a. Photographs of the specific components of the HPHST are shown in Figure 4b,c. The DOR sliding pair was immersed in aviation kerosene in the oil cup shown in Figure 4b. The plate–ring sliding pair was used to simulate the valve plate/cylinder block friction pair of the axial piston pump, and the section view and wear scar schematic diagram are shown in Figure 4d. HPHST has the following characteristics: a closed-loop normal load up to 10,000 N with a precision ±1%, a continuously adjustable speed from 100 to 3000 r/min, a closed-loop temperature from 10 to 110 °C with a precision of ±0.5%. The load and speed direction are shown in Figure 4b. The friction force of the sliding pair was obtained from the force-measuring element in Figure 4c. The normal wear displacement was monitored and collected online using a linear variable differential transformer sensor (LVDT, Soway, Shenzhen, China) with a linear precision of ±0.05%. Because the hardness of 38CrMoAlA and ZQPb17-4-4 is higher than that of the PEEK-based coating, and because the wear loss of 38CrMoAlA and ZQPb17-4-4 is negligible compared with the PEEK-based coating, it is believed that the data that were collected by the LVDT sensor are the wear depth of the PEEK-based coating. After the test, the wear scar of the PEEK-based coating were measured by the Nexview™ 3D optical surface profiler, and the surface morphology of the PEEK-based coating...
and counterparts were measured and analyzed by scanning electron microscopy (Merlin Compact, Carl Zeiss, Oberkochen, Germany).

Figure 4. The details of the disc-on-ring (DOR) test: (a) the photo of the high-pressure and high-speed tribosystem (HPHST) test rig; (b,c) close view of the HPHST; (d) the schematic diagram of DOR sliding pair and wear scar (black).

As shown in Table 2, four tests were performed: the scuffing test, Stribeck curve test, constant load test, and strengthened load test. During the test, sliding pairs were immersed in aviation kerosene, and the oil temperature in the oil cup was maintained at 70 ± 0.5 °C.

Table 2. The test conditions.

| Test Type                  | Load (N) | Speed (r/min) | Length of Time (min)                      |
|----------------------------|----------|---------------|-------------------------------------------|
| Scuffing                   | Step load 100 N/min | 2000          | Until the end of the test 60              |
| Stribeck curve             | 300      | Step speed 400 r/10 min | Short test for 20 min; long test against 38CrMoAlA for 210 min, against ZQPb17-4-4 for 180 min |
| Constant load              | 1000     | 2200          | No more than 180 min                     |
| Strengthened load          | 1300     | 2200          |                                           |

The scuffing test was used to evaluate the limit \( pv \) of the PEEK-based coating. When scuff occurred, the oil film between the mating surfaces was destroyed, the friction coefficient increased suddenly and the interfacial temperature increased sharply. Because the interfacial temperature tends to be difficult to collect, the friction coefficient is often taken as the standard. In the scuffing test, the constant speed was 2000 r/min, and the nominal linear velocity (the linear velocity of particles on the nominal diameter
The load started at 500 N, that is, a nominal contact stress of 1.73 MPa (load divided by nominal mating area) and increased by 100 N (0.35 MPa) per minute. When the friction coefficient increased suddenly, the scuffing test was terminated.

The Stribeck curve test was used to determine how the lubrication state of the PEEK-based coating sliding against the counterparts varied with load and speed. When the Stribeck curve test was performed, the load was 300 N (1.05 MPa) and the speed increased gradually at 500 r/min (1.2 m/s), 900 r/min (2.2 m/s), 1300 r/min (3.1 m/s), 1700 r/min (4.1 m/s), 2100 r/min (5.0 m/s), and 2500 r/min (6.0 m/s). The test was conducted for 10 min at each speed, and the total test time was 60 min.

The constant load test was conducted to investigate the relationship between the wear resistance and wear mechanism of the PEEK-based coating and the tribofilm on the counterface. The load was 1000 N (3.46 MPa) at 2200 r/min (5.3 m/s). The test was divided into a short test of 20 min with a PEEK-based coating against 38CrMoAlA and ZQPb17-4-4, a long test of 210 min with a PEEK-based coating against 38CrMoAlA, and a long test of 180 min with a PEEK-based coating against ZQPb17-4-4. The special wear rate was calculated with Equation (1) [24]:

$$w_s = \frac{\Delta m}{\rho F_N L},$$

where $w_s$, $\Delta m$, $\rho$, $F_N$, and $L$ represent the special wear rate, the mass loss, the density of the PEEK-based coating, the normal load, and the sliding distance during the test, respectively. The time-related (depth) wear rate was calculated with Equation (2) [24]:

$$w_t = \frac{\Delta h}{t},$$

where $w_t$, $\Delta h$, $t$, represent the time-related wear rate, the depth loss, and the sliding time during the test, respectively. The relationship between $w_s$ and $w_t$ can be expressed with Equation (3) [24]:

$$w_t = w_s p v,$$

where $p$ and $v$ represent the pressure and the velocity during the test, respectively.

The strengthened load test was conducted to evaluate which counterpart material had better friction performance under a higher load of 1300 N (4.50 MPa) at 2200 r/min (5.3 m/s).

3. Results and Discussions

3.1. Scuffing Test

Figure 5 shows the typical evolution of friction coefficient with time and load during PEEK-based coating sliding against 38CrMoAlA and ZQPb17-4-4. The friction coefficient decreased with an increase in load for the PEEK-based coating against 38CrMoAlA and ZQPb17-4-4. With the increase in load, the PEEK-based coating surface was smoother because of the increase in grinding effect. In addition, the PEEK-based coating as a third-body, solid lubricant helped to reduce friction [22]. The friction coefficient of the PEEK-based coating against the 38CrMoAlA dropped faster, had a smaller fluctuation range, and the scuff curve was smoother. When the friction coefficient of the PEEK-based coating against 38CrMoAlA changed suddenly, the test time was ~15.2 min, the sliding displacement was ~4377 m and the load was 2000 N (6.92 MPa). When the friction coefficient of the PEEK-based coating against ZQPb17-4-4 changed suddenly, the test time was ~18.1 min, the sliding displacement was ~5212 m and the load was 2400 N (8.30 MPa). At the end of the test, the PEEK-based coating was examined, and exposed substrate material was found, because the wear mechanism changed from slight to excessive wear as the load increased. Therefore, the sudden change of friction coefficient was caused by direct contact between the substrate and counterpart.
3.2. Stribeck Curve Test

The typical evolution of the friction coefficient with time and speed during PEEK-based coating sliding against 38CrMoAlA and ZQPb17-4-4 is shown in Figure 6a,c, respectively. Figure 6b,d shows the Stribeck curves that are drawn according to the friction coefficients at the start and end times at different speeds in Figure 6a,c, respectively. According to Figure 6a,b, at the beginning of the test, the sliding friction coefficients of the PEEK-based coating against 38CrMoAlA and ZQPb17-4-4 decreased first and then increased. The decrease in friction coefficient occurs because the PEEK-based coating acts as a solid lubricant between the counterfaces, whereas the slight increase may occur because of the increased roughness of the counterfaces.

![Figure 5: Friction coefficient behavior of the PEEK-based coatings sliding against 38CrMoAlA and ZQPb17-4-4 during the scuffing tests.](image)

![Figure 6: The Stribeck curve test: (a) friction coefficients of the PEEK-based coating sliding against 38CrMoAlA; (b) Stribeck curves derived from (a); (c) friction coefficients of the PEEK-based coating sliding against ZQPb17-4-4; (d) Stribeck curves derived from (c).](image)
When the PEEK-based coating slid against 38CrMoAlA at 1.2 m/s, the starting friction coefficient was ~0.117 and the ending friction coefficient dropped to ~0.105 with the increase in sliding displacement, which indicates that the sliding pair exists under the boundary lubrication condition. When the velocity reached 2.2 m/s, the ending friction coefficient dropped to ~0.094. As the speed increased gradually to 6.0 m/s, more PEEK-based coating wear debris was interlocked mechanically on the counterface, which resulted in a continuous reduction of the friction coefficient, and the sliding pair was always under the mixed condition from 2.2 to 6.0 m/s. At 6.0 m/s, the friction coefficient decreased continuously in the first 8 min, and increased slightly in the second 2 min, which may occur because of the increased solid-solid effect that is caused by the coating transition wear [1].

When the PEEK-based coating slid against ZQPb17-4-4 at 1.2 m/s, the starting friction coefficient was ~0.144 and the ending friction coefficient was ~0.111. When the speed reached 2.2 m/s, the ending friction coefficient dropped to ~0.102, which indicates that the sliding pair was always under a boundary condition from 1.2 to 2.2 m/s. With the gradual increase in speed, the sliding pair transitioned gradually to the mixed lubrication state. When the velocity varied from 1.2 to 3.1 m/s, the friction coefficient decreased continuously because of the formation of the tribofilm. The friction coefficient remained stable from 3.1 to 6.0 m/s. Therefore, it can be inferred that the shape of the internal tribofilm changed little at this stage, and the friction system tended to be stable [20].

3.3. Constant Load Test: 1000 N (3.46 MPa), 2200 r/min (5.3 m/s)

3.3.1. Short Test

The 3D morphology of the wear scar of PEEK-based coating sliding against 38CrMoAlA and ZQPb17-4-4 for 20 min under a load of 1000 N (3.46 MPa) and at 2200 r/min (5.3 m/s) is shown in Figure 7a,b, respectively. The wear scar contour marked by the rectangular window in Figure 7a,b is shown in Figure 7c,b, respectively. Compared with 38CrMoAlA, the worn surface of the PEEK-based coating against ZQPb17-4-4 was more even, so the friction coefficient was smaller, as shown in Figure 7d.

To study the wear mechanism of the PEEK-based coating, SEM analysis was conducted, as shown in Figure 8. The worn morphology of the PEEK-based coating sliding against 38CrMoAlA is shown in Figure 8a–c, and the worn morphology of the PEEK-based coating against ZQPb17-4-4 is shown in Figure 8d–f. The arrow is the direction of velocity. From Figures 7a and 8a–c, we can see that the PEEK-based coating is covered with furrows of varying depth and width in the parallel sliding directions and a number of different shapes of wear particles because 38CrMoAlA with a high hardness cuts the soft PEEK-based coating asperities, and the wear particles that are formed gradually accumulate and form large particles or flake fragments with time. Under the action of a load, the abrasive particle microcutting coating surface leads to the ploughing phenomenon. Analysis shows that with PEEK-based coating sliding against 38CrMoAlA, the wear mechanism is mainly abrasive wear.

Combining Figures 7b and 8d–f, the PEEK-based coating asperities are polished, and the surface shows many peeling pits and microholes with different areas because the adhesive force in the interfacial zone promotes local plastic deformation and microcrack initiation in the coating surface layer. Under a continuous repeated load, microcracks expand randomly and develop towards the surface, and eventually lead to a “ladder” structure. The local plastic deformation and shear stress inside the coating can lead to stripping of the unmelted hard additives from the coating, which also leads to the increased area of peeling pits and the formation of many microholes. The analysis indicates that the main wear mechanism of the PEEK-based coating sliding against ZQPb17-4-4 is fatigue wear.
Figure 7. The results of the short test: (a) 3D morphology of the wear scar of the PEEK-based coating sliding against 38CrMoAlA; (b) 3D morphology of the wear scar of the PEEK-based coating sliding against ZQPb17-4-4; (c) the wear scar contour marked by the rectangular window in (a); (d) the wear scar contour marked by the rectangular window in (b). Load: 1000 N, speed: 5.3 m/s, time: 20 min.

Figure 8. SEM images of the PEEK-based coating under the short test: (a–c) sliding against 38CrMoAlA; (d–f) sliding against ZQPb17-4-4.

Such a big difference for the PEEK-based coating against 38CrMoAlA and ZQPb17-4-4 may occur because (1) the 38CrMoAlA hardness is much higher than that of ZQPb17-4-4, so the cutting force of 38CrMoAlA is greater than that of ZQPb17-4-4 on the surface of the PEEK-based coating [25]; (2) the thermal conductivity of 38CrMoAlA is lower than that of ZQPb17-4-4, so the heat-transfer rate between the interfacial zone and circulating oil is slower, and the heat dissipation to the machine parts that are connected with the sliding pair is less in the same time. Therefore, the PEEK-based coating has a higher
interfacial temperature when slid against 38CrMoAlA. Because of the “thermal-softening” effect [26], the mechanical strength of the PEEK-based coating surface decreases correspondingly, and results in easier cutting.

3.3.2. Long Test

Figure 9 shows the results of the PEEK-based coating sliding against 38CrMoAlA for 210 min and against ZQPb17-4-4 for 180 min at a load of 1000 N and at 5.3 m/s. Figure 9a shows the 3D morphology of the PEEK-based coating against 38CrMoAlA. The surface differs from Figure 7a and is smoother, which can also be observed from the wear scar contour in Figure 9c. Combined with the SEM image of the PEEK-based coating in Figure 10a–c, it was found that the surface was covered with peeling pits and deep microholes. The appearance in Figure 10a–c is similar to that in Figure 8d–f, but differences exist. (1) The peeling pits in Figure 8d–f are deep, large in area, stratified, and few in number, whereas the peeling pits in Figure 10a–c are shallow, small in area, non-stratified, and numerous. (2) Many fine cracks can be observed in Figure 8d–f, but not in Figure 10a–c. Unlike the reason for peeling pit formation in Figure 8d–f, the reason for peeling pit formation in Figure 10a–c is that the adhesive force in the interfacial zone is higher than the shear strength of the PEEK-based coating, which leads to the transfer of PEEK-based coating material to 38CrMoAlA. The deep holes in Figure 10a–c are caused by cavities that are formed by additive separation. The cavities can cause fatigue cracks on the PEEK-based coating and lead to peeling pits. Figure 10a–c shows that the peeling pits and holes that were caused by adhesive wear are connected. It can be concluded that the main wear mechanism of PEEK-based coating sliding against 38CrMoAlA is adhesive wear accompanied by fatigue wear.

Figure 9. The results of the long test: (a) 3D morphology of the wear scar of the PEEK-based coating sliding against 38CrMoAlA; (b) 3D morphology of the wear scar of the PEEK-based coating sliding against ZQPb17-4-4; (c) the wear scar contour marked by the rectangular window in (a); (d) the wear scar contour marked by the rectangular window in (b). Load: 1300 N, speed: 5.3 m/s, time: against 38CrMoAlA for 210 min and against ZQPb17-4-4 for 180 min.
The wear mechanism of the PEEK-based coating has changed obviously because of the test duration. To analyze this phenomenon, SEM analysis was carried out on the counterpart surface.

SEM inspection of counterparts under short test is shown in Figure 11 and under long test in Figure 12. In Figure 11, only the extremely small surface area of 38CrMoAlA (Figure 11a) and ZQPb17-4-4 (Figure 11b) is covered by the tribofilm. An SEM image of the 38CrMoAlA worn surface under long test is shown in Figure 12a. Compared with Figure 11a, the tribofilm covers a larger wear scar area. It is concluded that in the initial stage of wear, the debris play an abrasive role and, as time passes, increased wear debris is linked mechanically to form a tribofilm, which reduces the friction and wear of the PEEK-based coating significantly. The interfacial zone becomes flatter and smoother, which results in the decrease of the friction coefficient. An SEM image of the ZQPb17-4-4 worn surface under long test is shown in Figure 12b. The counterface is covered by a small area of tribofilm which is more than in Figure 11b but less than in Figure 12a obviously.

The relationship curve of the wear depth of the PEEK-based coating with time is shown in Figure 13. Figure 13b shows a broken line diagram of the approximate linearization of the wear depth curve in Figure 13a. For 38CrMoAlA and ZQPb17-4-4, the wear process is divided into two stages, the running-in process and the stable process [27], because of the tribochemical reaction in the interaction zone [28–30]. In the running-in stage, the slope of the 38CrMoAlA wear curve is slightly higher than that of ZQPb17-4-4, whereas in the stable stage, the slope of the 38CrMoAlA wear curve is
extremely low and more gentle, which proves that the tribofilm that formed on the 38CrMoAlA surface is more beneficial. According to Equations (1)–(3) and the loss wear depth, the $w_s$ in the running-in process and the stable process was calculated. The tribological behavior PEEK-based coating under long test was summarized in Table 3.

Figure 11. SEM images of the tribofilm on the counterpart under the short test: (a) 38CrMoAlA; (b) ZQPb17-4-4.

Figure 12. SEM images of the tribofilm on the counterpart under the long test: (a) 38CrMoAlA; (b) ZQPb17-4-4.

Figure 13. (a) Wear curves of the PEEK-based coatings sliding against 38CrMoAlA and ZQPb17-4-4; (b) the broken line diagram of approximate linearization of the wear depth curve.
Table 3. Summary of the tribological behavior PEEK-based coating under long test.

| PEEK-Based Coating | Running-in $w_s$ \((\text{mm}^3\text{N}^{-1}\text{m}^{-1}) \times 10^{-8}\) | Stable $w_s$ \((\text{mm}^3\text{N}^{-1}\text{m}^{-1}) \times 10^{-8}\) | Special Friction Coefficient |
|------------------|-----------------------------|-----------------------------|-----------------------------|
| against 38CrMoAlA | 8.2                         | 1.4                         | 0.075                       |
| against ZQPb17-4-4| 6.3                         | 2.7                         | 0.081                       |

3.4. Strengthened Load Test: 1300 N (4.50 Mpa), 2200 r/min (5.3 m/s)

Figure 14 shows the results of the PEEK-based coating against 38CrMoAlA for 180 min and against ZQPb17-4-4 for 15 min at 1300 N (4.50 MPa) and 2200 r/min (5.3 m/s). The SEM image of the PEEK-based coating against 38CrMoAlA is shown in Figure 15a–c. Shallow pits and a few short scratches exist on the surface of the PEEK-based coating. Compared with Figure 11a–c, the number of pits has been reduced significantly. Combined with Figure 14a,c, it can be observed that the wear surface of the PEEK-based coating is smoother and flatter, which may be caused by the further extension of the PEEK-based coating as the load increases. According to the above analysis, the main wear mechanism of the PEEK-based coating against 38CrMoAlA is adhesive wear.

Figure 14b shows a severe plowed groove with a depth of nearly 4 µm. The clear appearance of the plow can be seen from Figure 15d–f which shows the SEM image of the PEEK-based coating against ZQPb17-4-4. This behavior occurs because of scratch of the adhesive with increased hardness and volume after oxidation reaction migration to the 38CrMoAlA counterface [30,31]. According to the above analysis, the main wear mechanism of the PEEK-based coating against ZQPb17-4-4 is abrasive wear.

![Figure 14](image-url)
4. Conclusions

The tribological behaviors of one advanced PEEK-based coating sliding against 38CrMoAlA and ZQPb17-4-4 under mixed and boundary aviation kerosene-lubrication condition were investigated. The following conclusions could be drawn:

1. Scuffing experiments showed that the PEEK-based coating had a good scuffing resistance against the 38CrMoAlA and ZQPb17-4-4 counterparts. It is presumed that the PEEK-based coating acted as a solid lubricant between the sliding pairs.

2. The Stribeck curve test showed that the lubrication state of the PEEK-based coating against the counterparts was related closely to the tribofilm, and compared with ZQPb17-4-4, the PEEK-based coating against 38CrMoAlA was more likely to enter the mixed lubrication state from the boundary lubrication state.

3. In the constant load short test, the PEEK-based coating had a lower wear rate with ZQPb17-4-4. However, in the long test, the PEEK-based coating against 38CrMoAlA had a better performance with a smaller friction coefficient and a lower wear rate. Especially in the special stage, the wear rate was only 1/5 of the running-in stage.

4. In the strengthened load test, the friction and wear performance of the PEEK-based coating against 38CrMoAlA was far better than that against ZQPb17-4-4, so the friction pair that is composed of the PEEK-based coating and 38CrMoAlA is more competent for use in fuel pumps.

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