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Friction Properties of PEEK under Different Lubrication Conditions

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Abstract

This study employed PEEK test blocks paired with 45# steel balls to conduct controlled variable tests using a self-made reciprocating friction and wear testing machine, systematically investigating the tribological behavior of PEEK materials under dry friction, wet lubrication, and three different water-lubricated conditions. The friction and wear mechanisms were thoroughly analyzed through surface morphology characterization. The results demonstrate that PEEK exhibits optimal tribological performance under soup-like water lubrication at a rotational speed of 100 r/min (linear velocity: 33.3 mm/s) and a load of 50 N. This research provides critical data support and theoretical guidance for the application of PEEK composites in water-lubricated bearings and guide rail materials for garbage truck compression devices.

Keywords

PEEK; Controlled variable experiment; Dry friction; Water lubrication; Friction and wear performance

Introduction

Polyetheretherketone (PEEK) is a semi-crystalline aromatic thermoplastic specialty engineering plastic successfully developed by British ICI Company in 1977 and officially produced in 1980. Due to the presence of rigid benzene rings, flexible ether bonds, carbonyl groups that enhance intermolecular forces, and a regular structure in its macromolecular chain, PEEK exhibits superior mechanical properties and dimensional stability compared to other traditional engineering plastics. It maintains excellent performance even at high temperatures, with heat resistance approximately 50°C higher than most engineering plastics[1-4]. It also demonstrates good aging resistance, exceptional corrosion resistance, and can withstand almost all chemicals except concentrated sulfuric acid. Additionally, PEEK possesses characteristics such as radiation resistance, inherent flame retardancy, and high wear resistance[5][6]. Owing to these outstanding properties, PEEK has been widely applied in automotive, aerospace, chemical, medical equipment, electronic, and electrical industries[7-10]. With advancements in technology, its application fields continue to expand. Water-lubricated bearings[11][12]require materials with high friction and wear performance. However, the practical performance of PEEK composites, particularly in terms of friction and wear, is influenced by factors such as rotational speed, load, lubrication conditions[13-16], and the surface roughness of the friction pair. These factors significantly impact the tribological properties of PEEK materials[17]. Literature [18] investigated the tribological performance of PEEK-GCr15 and PEEK-GCr15 friction pairs under dry friction conditions with varying loads and speeds. The results showed that as the load increased, the average friction coefficient and wear rate of both materials first decreased and then increased. Similarly, as the speed increased, the friction coefficient of PEEK followed a trend consistent with the effect of load, while the wear rate initially decreased and then increased. Literature [19] compared the friction and wear properties of PEEK, PEEK-CF30, and PEEK-GF30 against carbon steel AISI 1045 under dry friction conditions. The results indicated that PEEK-CF30 had the lowest friction coefficient, followed by PEEK, while PEEK-GF30 exhibited a relatively high friction coefficient throughout the sliding distance. Both PEEK-CF30 and PEEK-GF30 demonstrated superior wear resistance compared to pure PEEK, with PEEK-CF30 showing the best tribological behavior. Literature [20] explored the tribological characteristics of three stainless steel (AISI 316L, AISI 630, and S32750)/PEEK friction pairs in a seawater environment. The study found that the average friction coefficients of the three pairs were nearly identical; under heavy load conditions, S32750/PEEK exhibited the best frictional stability, while AISI 316L/PEEK showed the poorest.

However, research on the tribological performance of PEEK under different lubrication conditions has primarily focused on dry friction, with relatively limited studies on the friction and wear mechanisms in various water-lubricated environments, such as seawater, deionized water, or additive-enhanced water lubrication. The authors of this paper employed a systematic experimental approach to investigate the friction and wear characteristics of PEEK composites in different lubrication environments. Through controlled variable experiments, the tribological behavior of the material under dry friction, wet lubrication, and impurity-laden water lubrication conditions was compared and studied, validating the feasibility of applying PEEK in guide rails of garbage truck compression devices. The research findings provide critical data support and theoretical guidance for the application of PEEK composites in water-lubricated bearings and guide rail materials for garbage truck compression devices.

1. Experimental Section

1.1. Test Equipment and Parameters

The lower specimens used in this study were made of PEEK supplied by Dongguan Xinyao Plastic Products Co., Ltd., with uniform geometrical dimensions of 30 mm × 20 mm × 5 mm and a surface roughness (Ra) ranging between 0.2 μm and 0.25 μm. The upper specimens consisted of 45# steel balls with a diameter of 9.525 mm and a contact surface roughness of 0.02 μm.

1.2. Test Methods and Related Characterization

This study employed a controlled-variable experimental approach [18] to systematically investigate the tribological properties of PEEK composites under different lubrication conditions. The test parameters were set with reference to the actual working conditions of garbage truck compression loading mechanisms and typical testing conditions for water-lubricated bearings: rotational speeds were set at 60, 80, 100, and 120 r/min (corresponding to linear velocities of 20.0, 26.7, 33.3, and 40.0 mm/s), loads at 35 N, 50 N, 65 N, and 80 N, and a fixed sliding time of 30 min (ensuring the friction and wear process reached a steady state), with a single-pass wear scar length of 10 mm.

The tests were designed to include dry friction, wet lubrication (deionized water applied at a rate of 90 drops/min), and three other water-based lubrication conditions. The latter included: A saline solution containing 3.5% NaCl (96.5% deionized water + 3.5% NaCl); An emulsion with 3.5% NaCl and 1% peanut oil (95.5% deionized water + 3.5% NaCl + 1% peanut oil); A turbid suspension containing 3.5% NaCl, 1% peanut oil, and 1.2% silt (94.3% deionized water + 3.5% NaCl + 1% peanut oil + 1.2% SiO_2).These lubrication conditions were designed to simulate practical scenarios such as contamination from food waste and intrusion of particulate impurities in garbage truck guide rail systems, as well as harsh operating environments like silt-laden seawater and oil leakage in marine water-lubricated bearings. Friction coefficient-time curves were recorded during the tests. To ensure reliability, at least three repeated trials were conducted for calculating the average friction coefficient and wear rate. All experimental data were acquired online at a sampling rate of 80 Hz using a self-programmed LabVIEW (National Instruments) application.

Before and after testing, the PEEK specimens and friction surfaces were cleaned with anhydrous ethanol, dried, and weighed using a high-precision electronic balance (accuracy: 1×10^{-4} g). The wear loss was determined by calculating the mass difference before and after the tests. To further elucidate the tribological behavior of PEEK, the worn surfaces of the samples were examined using a scanning electron microscope (Sigma 300 model).

2. Analysis of Friction and Wear Tests

Three sets of controlled variable experiments were conducted: The first set maintained a constant rotational speed of 100 r/min to evaluate the variation in the friction coefficient of PEEK under dry friction, wet lubrication, and impurity-laden water lubrication conditions at loads of 35 N, 50 N, 65 N, and 80 N. The second set maintained a constant load of 50 N to analyze the frictional characteristics of PEEK under the same lubrication conditions at rotational speeds of 60 r/min, 80 r/min, 100 r/min, and 120 r/min. The third set, under a fixed rotational speed of 100 r/min and a load of 50 N, compared the effects of dry friction, wet lubrication, saline water, soup-like water (emulsion), and impurity-laden water lubrication on the friction coefficient and wear loss of PEEK.

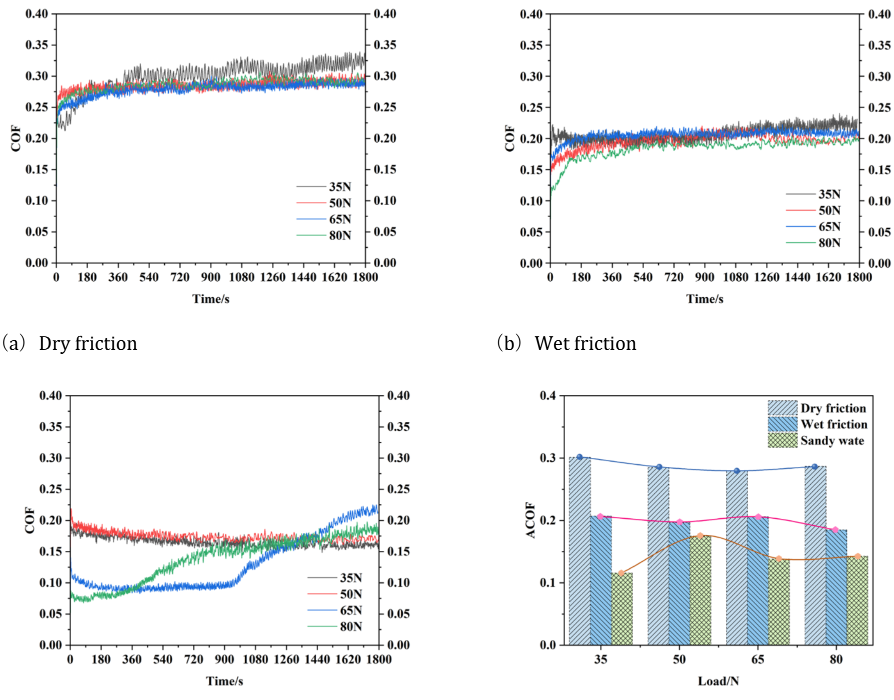
2.1. Friction Coefficient and Wear Loss

Figure 1 shows the variation in the friction coefficient of PEEK under a rotational speed of 100 r/min. The curve of PEEK is relatively smooth, exhibiting a rapid initial increase followed by gradual stabilization. Under dry friction conditions, the friction coefficient is higher due to direct contact between the two friction pairs. As the load increases, the friction coefficient demonstrates a non-linear trend, initially decreasing and then increasing. This behavior can be attributed to the following mechanisms: In the initial stage (35–50 N), the decrease in the friction coefficient is primarily due to enhanced elastic deformation of the PEEK surface under increased load, which improves the real contact area and promotes more uniform stress distribution. Simultaneously, the formation and gradual completion of a transfer film on the counterface partially improve the lubrication state and reduce shear resistance.When the load exceeds 65 N, the friction coefficient increases. This is caused by accelerated heat accumulation at the friction interface, leading to softening or even melting of the PEEK surface layer and significantly enhancing adhesive effects. Additionally, the increasing contact stress disrupts the established transfer film, resulting in a higher proportion of direct contact between the friction pairs and ultimately leading to an increase in the friction coefficient.

Under wet lubrication conditions, the friction coefficient is lower than that under dry friction due to the lubricating effect of water. In the lower load range (35–50 N), the reduction in the friction coefficient is mainly owing to enhanced hydrodynamic lubrication effects. The increased load promotes the formation of a lubricating film in the contact zone, improving the load-bearing capacity of the water film, effectively separating the friction surfaces, and reducing direct contact and frictional resistance. When the load reaches 65 N, the friction coefficient rebounds. This occurs because further load increase causes thinning or even local rupture of the water film, transitioning the friction pair into a mixed lubrication regime. At this stage, asperity contact increases, and the ploughing action of hard particles such as SiO_2 intensifies. As the load continues to rise to 80 N, the friction coefficient decreases again. This is attributed to the elastic deformation of PEEK under high temperature and load, promoting tighter surface contact and facilitating the formation of a continuous and stable boundary lubrication film, thereby improving the lubrication state and reducing the friction coefficient

In an impurity-laden water lubrication environment, the friction coefficient of the PEEK composite is significantly lower than that under conventional wet lubrication.

As the load increases, the friction coefficient exhibits a non-monotonic trend: Initially, the friction coefficient increases due to load-induced thinning of the lubrication film, exacerbated ploughing and micro-cutting by hard SiO_2 particles, and insufficient lubricating film formation from peanut oil. Abrasive wear dominates the friction behavior at this stage.At 65 N, the friction coefficient decreases. This is primarily caused by elevated temperature and pressure in the contact zone under higher loads, triggering tribochemical effects: the NaCl electrolyte environment accelerates the formation of a reaction film, peanut oil adsorbs under high pressure to form a lubricating layer, and SiO_2 particles embed into the soft PEEK surface to create a third-body lubrication layer. These factors collectively enhance boundary lubrication capacity.When the load increases to 80 N, the friction coefficient rises again. This is because extreme loads cause complete rupture of the lubrication film, frictional heat leads to softening and melting of the PEEK surface, adhesive effects intensify sharply, and hard particles are crush and displaced, exacerbating plastic deformation and material removal. The friction mechanism transitions from mixed lubrication to adhesion and severe abrasive wear.



(a) Dry friction　　(b) Wet friction

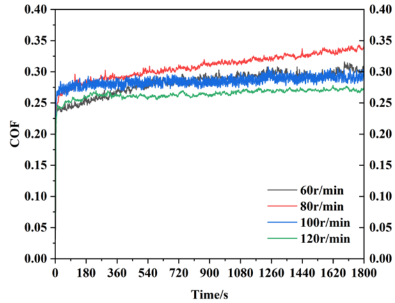
(c) Brine　　(d) Average Friction Coefficient

Fig 1. Frictional traces under different applied loads

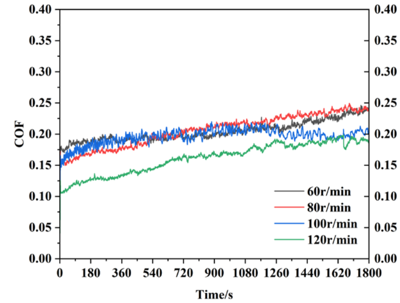
Figure 2 shows the variation of the friction coefficient of PEEK over time under a fixed normal load of 50 N and different rotational speeds. As observed in Figure 2(d), the friction coefficient under dry friction conditions is relatively high and exhibits a trend of first increasing and then decreasing with increasing rotational speed. This behavior can be explained as follows: When the rotational speed increases from 60 r/min to 80 r/min, the friction coefficient rises due to the increased sliding frequency leading to accelerated frictional heat accumulation. This causes softening or even melting of the PEEK surface layer, significantly enhancing adhesive effects. When the rotational speed further increases to 120 r/min, the friction coefficient decreases because the elevated temperature promotes the formation of a more complete transfer film on the PEEK surface, which covers and lubricates the contact interface. Simultaneously, the high-speed shear action reduces the duration of adhesive point connections, thereby improving the sliding state and reducing frictional resistance.

Under wet lubrication conditions, the friction coefficient of the PEEK-45# pair shows a trend of first increasing and then decreasing. This is mainly attributed to the following: When the rotational speed increases from 60 r/min to 80 r/min, the friction coefficient increases due to insufficient hydrodynamic effects at this stage. The increased speed accelerates the contact frequency of the friction pair, intensifying the micro-cutting and ploughing actions of abrasive particles (e.g., SiO_2) on the material surface, making abrasive wear the dominant mechanism. When the rotational speed further increases to 120 r/min, the higher speed significantly enhances the hydrodynamic effect, promoting more lubricant entering the contact zone to form a more continuous water film. Meanwhile, frictional heat causes local softening of the PEEK surface and generates a lubricating transfer film, collectively improving the lubrication state and resulting in a noticeable reduction in the friction coefficient.

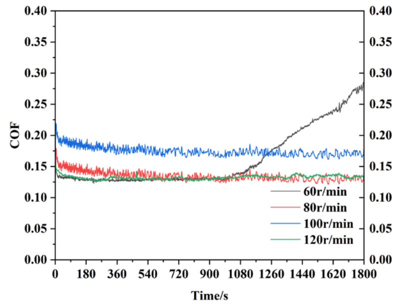
In an impurity-laden water lubrication environment, the friction coefficient exhibits non-monotonic changes, which can be explained as follows: At the initial speed increase (up to 80 r/min), the friction coefficient decreases due to enhanced hydrodynamic effects—the higher rotational speed promotes the entry of lubricating medium into the contact area, forming a thicker water film that effectively separates the friction surfaces and reduces direct contact. When the speed continues to increase to 100 r/min, the friction coefficient rebounds. This is because the increased speed leads to higher sliding shear rates and contact frequency, exacerbating the grinding action of hard SiO_2 particles, which damages the integrity of the lubrication film and makes abrasive wear the dominant process. When the speed further increases to 120 r/min, the friction coefficient decreases again, primarily due to significantly increased frictional heat causing local softening or even melting of the PEEK surface, generating a lubricating transfer film. Additionally, the elevated temperature may alter the viscosity and lubrication characteristics of the impurity-laden solution, enhancing interfacial lubrication.



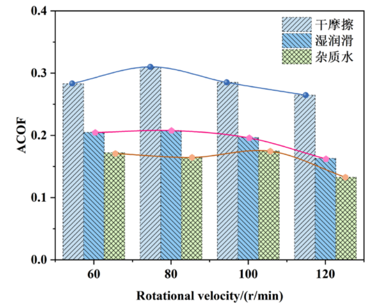
（a） Dry friction



（b） Wet friction



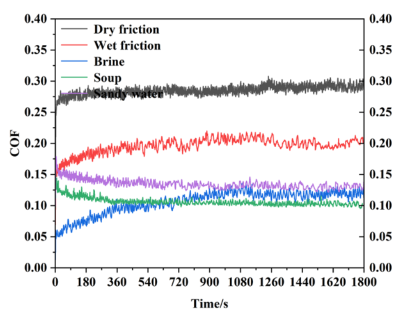
（c） Brine



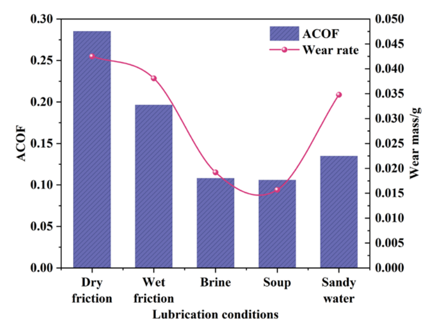
（d） Average Friction Coefficient

Fig 2. Fictional traces under different rotational velocities

Figure 3 shows the comparison of tribological properties of PEEK composites under different lubrication environments at a rotational speed of 100 r/min and a load of 50 N. Experimental data indicate that both the friction coefficient and wear loss of the material exhibit similar variation trends across different lubricating media. Specifically, the optimal performance is observed under soup-like water lubrication, followed by saline water environment, impurity-laden water condition, and wet lubrication state, while the poorest tribological performance occurs under dry friction conditions. This pattern demonstrates that the properties of the lubricating medium significantly influence the tribological behavior of PEEK composites.



（a） Friction Coefficient versus Time Curves under Different Lubrication Conditions



（b） Average Friction Coefficient and Wear Loss under Different Lubrication Conditions

Fig 3. Friction coefficient and wear amount of PEEK under five lubrication conditions

2.2. Analysis of Worn Surface Morphology

To further investigate the friction and wear mechanisms of PEEK materials, this study systematically characterized the surface morphology of worn specimens using scanning electron microscopy (SEM). Tests were conducted under a rotational speed of 100 r/min and a load of 50 N to compare and analyze the wear characteristics of PEEK samples across five different lubrication environments: dry friction, wet lubrication, saline water, soup-like water, and impurity-laden water lubrication. Figure 4 presents the SEM micrographs of the worn surfaces under these lubrication conditions.

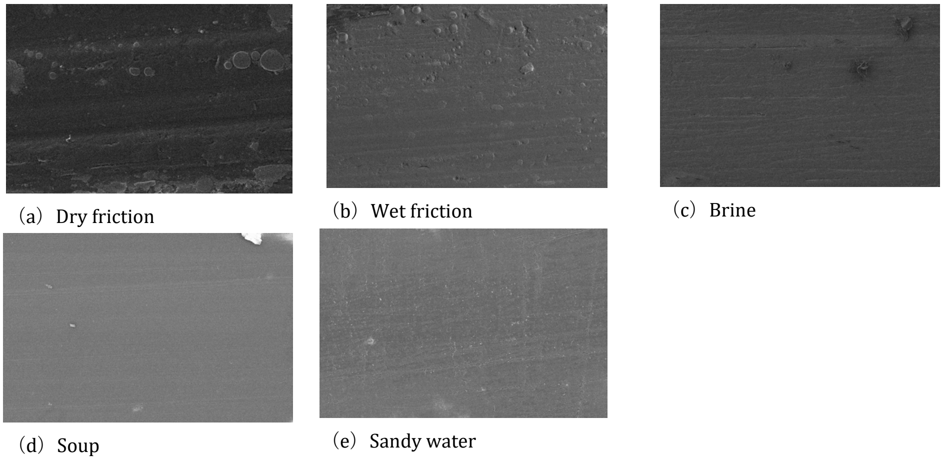


Fig 4. Surface morphology of PEEK wear under five lubrication conditions

Figure 4(a) shows the surface morphology of PEEK after wear under dry friction conditions. The worn surface is characterized by plastic deformation and melting phenomena, primarily due to the rapid accumulation of interfacial temperature rise caused by the absence of lubricating medium. The heat generated during the friction process cannot dissipate in time, causing the local temperature of the PEEK surface to exceed its glass transition temperature or even melting point. This leads to softening or melting of the material. Simultaneously, under cyclic loading and shear forces, the surface material undergoes plastic flow, exacerbating deformation accumulation and adhesive effects. Ultimately, a wear morphology dominated by thermal melting and plastic deformation is formed.

Figure 4(b) displays the surface morphology of PEEK after wear under wet lubrication conditions. The worn surface exhibits only shallow spalling pits and minor ploughing traces. The main reason is that the presence of the lubricating medium significantly suppresses temperature rise and mechanical damage at the friction interface. The lubricating film effectively shares the load, reducing direct cutting by hard asperities and abrasive particles. As a result, the wear mechanism is dominated by mild abrasive wear and fatigue spalling. Additionally, the cooling effect of water lowers the risk of material softening, avoiding plastic deformation and melting phenomena commonly observed in dry friction, thereby forming a relatively smooth and minimally damaged wear morphology.

Figure 4(c) presents the surface morphology of PEEK wear under saline water lubrication. The worn surface shows only slight wear, with almost no signs of plastic deformation or grooves. This is mainly attributed to the effective dual-protection mechanism of lubrication and cooling provided by the saline medium at the friction interface. On one hand, the continuous water film significantly reduces direct contact and shear stress between the friction pairs, inhibiting the ploughing action of asperities and plastic flow of the material. On the other hand, the sustained cooling effect of saline water effectively controls frictional temperature rise, preventing thermal softening-induced deformation and melting tendencies in PEEK. Consequently, the wear is characterized by ultra-low damage dominated by mild fatigue spalling.

Figure 4(d) illustrates the surface morphology of PEEK after wear under soup-like water lubrication. Under this condition, minor ploughing grooves parallel to the sliding direction and relatively slight spalling can be observed. The primary reason is that although the emulsion possesses certain lubricity, micro-cutting by hard abrasive particles and local rupture of the lubricating film still occur. The oil film formed by peanut oil and the saline water collectively share part of the load, reducing frictional temperature rise and adhesion tendencies. However, insufficient lubrication caused by NaCl crystalline particles and interfacial disturbances still induces mild abrasive wear and fatigue spalling, ultimately resulting in a mixed wear morphology dominated by shallow ploughing and local material detachment.

Figure 4(e) depicts the surface morphology of PEEK after wear under impurity-laden water lubrication. On the worn surface of the PEEK sample, ploughing grooves distributed along the direction of motion can be observed, accompanied by a small amount of spalling debris. The main reason is that hard particles (e.g., SiO_2) in the impurity-laden water embed into the relatively soft PEEK surface under normal load, causing micro-cutting and forming grooves. Simultaneously, cyclic loading leads to surface fatigue and local adhesion, triggering the detachment of small flaky debris. Although the impurity-laden water provides some cooling and lubrication, it fails to completely eliminate the ploughing effect of hard particles and interfacial stress concentration. final, the wear mechanism manifests as a mixed mode dominated by abrasive wear accompanied by mild fatigue spalling.

3. Conclusion

This study systematically investigated the tribological performance of PEEK paired with 45# steel under different lubrication conditions through controlled variable experiments and surface morphology analysis. The main conclusions are as follows:

(1) Lubrication conditions significantly influence the tribological behavior of PEEK. Under dry friction, the absence of lubrication and cooling resulted in the highest friction coefficient and wear loss, accompanied by noticeable plastic deformation and melting phenomena. Wet lubrication exhibited better performance than dry

friction due to the cooling and lubricating effects of water. Saline water lubrication demonstrated the optimal tribological performance, attributed to the continuous water film and effective cooling. Soup-like water lubrication further improved the lubrication state through the synergistic action of oil film and saline water. Impurity-laden water lubrication presented a mixed mechanism dominated by abrasive wear, caused by micro-cutting from hard particles.

(2) Load and rotational speed complexly affect the friction coefficient and wear mechanisms. As the load increased, the friction coefficient initially decreased and then increased, primarily related to factors such as lubricating film formation, transfer film integrity, heat accumulation, and tribochemical effects. Variations in rotational speed influenced the friction coefficient non-monotonically by affecting hydrodynamic effects, frictional heat accumulation, and lubricating film stability.

(3) The optimal tribological performance of PEEK was achieved under oil-water lubrication at a rotation3al speed of 100 r/min and a load of 50 N. Under these conditions, both the friction coefficient and wear loss were maintained at relatively low levels.

(4) Surface morphology analysis revealed the wear mechanisms under different lubrication conditions: dry friction was characterized by thermal melting and plastic deformation; wet lubrication was dominated by mild abrasive wear and fatigue spalling; saline water lubrication exhibited ultra-low damage with minor fatigue spalling; soup-like water lubrication showed a mixed mechanism of shallow ploughing and local material detachment; impurity-laden water lubrication was primarily abrasive wear accompanied by mild fatigue spalling.

This study provides important data support and a theoretical basis for the application of PEEK composites in practical engineering contexts such as water-lubricated bearings and guide rails for garbage truck compression devices. It confirms that PEEK exhibits excellent adaptability and reliability in complex lubrication environments.

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