Friction **5**(4): 414–428 (2017)
DOI 10.1007/s40544-017-0155-9

ISSN 2223-7690
CN 10-1237/TH

RESEARCH ARTICLE

Aqueous lubrication and surface microstructures of engineering polymer materials (PEEK and PI) when sliding against Si_3N_4

Anying WANG, Shuai YAN, Bin LIN[*], Xiaofeng ZHANG, Xiaoxue ZHOU

Key Laboratory of Advanced Ceramics and Machining Technology of Ministry of Education, Tianjin University, Tianjin 300350, China

Received: 11 October 2016 / Revised: 25 December 2016 / Accepted: 14 February 2017

Abstract: Polyether-ether-ketone (PEEK) and polyimide (PI) are two kinds of engineering polymer materials widely used as roller bearing cages and rings under extreme environment because of their noise reduction and corrosion resistance properties. The Si_3N_4 ceramic is the most common ball bearing material. Many current engineering applications of ball bearings require aqueous lubrication. Therefore, this study presents the aqueous lubrication of tribopairs formed by PEEK and PI material sliding against Si_3N_4 ceramic. Experimental results show that two tribopairs exhibited the similar tribological properties under the dry condition. Water as a lubricant for the PI–Si_3N_4 tribopair pairs effectively reduces both friction coefficients by 35.5% and wear rates by 32%. The water absorption of PI induces better tribological properties by changing the tribopair surface properties. In addition, the dimples appearing on the PI tribopair surface under water generate additional hydrodynamic lubrication and further improve the friction properties of surface. The PEEK–Si_3N_4 tribopair shows similar friction coefficients under two kinds of environments. The wear rates under water are approximately more than two times of that under dry sliding. However, water inhibits the appearance of the crush phenomenon and enhances the carrying capacity of the tribopair. Energy dispersive spectroscopy and X-ray diffraction spectra demonstrate no chemical corrosion. The 3D profiler and SEM morphologies illustrate that the transfer film would be formed from the surface of PEEK under water but hindered under dry friction. Overall, the PI–Si_3N_4 tribopair exhibits better properties than PEEK under water and is promising for future applications in the bearing industry.

Keywords: PEEK; PI; aqueous lubrication; dry friction; tribological properties; ceramic bearing

1 Introduction

Engineering plastic with excellent properties of mechanics and tribology and outstanding resistance to high temperature, chemical corrosion, and radiation is a kind of potential bearing material. PEEK and PI [1–5] are two kinds of widely used engineering polymer materials as roller bearing cages and rings in ceramic bearings [6–8]. Ceramic bearings are developed for industrial applications under extreme and special operating conditions in water.

The molecular structure of PEEK makes it not only own a high fracture toughness, high strength, superior corrosion, and excellent resistance to high temperature hydrolysis, but also possesses excellent biocompatibility and tribology properties [9–10]. Zalaznik et al. [13] investigated the influence of different processing temperatures on the properties of pure PEEK. The results of the dry-sliding tribological tests, hardness measurements, and X-ray diffraction (XRD) analyses show that the processing temperature greatly influences the hardness and the crystallinity of PEEK, which in turn affects the tribological behavior. Koike et al. [14] investigated the wear of the PEEK radial ball bearing

---

* Corresponding author: Bin LIN, E-mail: linbin@tju.edu.cn

composed of a PEEK ring, a PTFE composite retainer, and alumina balls. They found that the PEEK–PTFE adhesion film dramatically improved the wear and rotational performance of the bearing. Greco et al. [15] focused on the effect of the reinforcement morphology on the high-speed sliding friction and wear of PEEK polymers. Meanwhile, Theiler et al. [16] investigated the sliding performance of the PEEK composites in a vacuum environment.

PI shows excellent tribological properties, especially under conditions of high pressure, high temperature, high speed, and other extreme environments [11–12]. Guo et al. [17] studied the structural and chemical properties of polyimide ablated by a femtosecond laser. Liu et al. [18] concluded that the wear rate increased with the increase of the proton and combined radiation time and decreased with the electron radiation conditions. Samyn et al. [19] studied the effect of the processing method on the dry sliding performance of polyimides at high load/high velocity conditions. Jia et al. [20] conducted a comparative investigation of the friction and wear behavior of polyimide composites under dry sliding and water-lubricated condition.

During the past decades, different additives, except the modification of surface properties [21–30], were added into PEEK or PI to improve tribological properties. Many researchers conducted various experiments to investigate the friction coefficient and wear rate of various conditions, providing comprehensive mechanisms of friction and wear at different conditions. Yang and Dong [31] studied the tribological behavior and mechanical properties of PEEK-filled PTFE composites, which were investigated using a scanning electron microscope (SEM). Huang et al. [32–34] studied the friction and wear properties of the PI composites filled with PTFE and MoS_2 sliding against 45 steel, nickel–chromium alloy, copper, and aluminum under the dry sliding friction condition. The PI-based composites filled with various solid lubricants and reinforced with carbon fiber prepared by compression molding sliding against stainless steel registered lower friction coefficients and wear rates in water than in air. Samyn et al. [35] comprehensively investigated the tribological behaviors of a polymer–metal friction pair at different sliding velocities and loads.

Notably, tribological properties and wear mechanisms are closely related to material properties and external condition. The abovementioned researches mainly focused on the composite–steel triobopair [36–38], but there is little knowledge about the wear and friction behaviors of the trio-couple comprising composite materials and Si_3N_4 ceramic [39]. Hence, the tribological properties of triobopairs formed by PEEK and PI composite materials with the Si_3N_4 ceramic material will be studied in this paper. Water is used as a green lubricant to replace mineral oil and vegetable oil because of its low cost, flame retardancy, easy availability, and environmental friendliness [40]. Some friction and wear experiments of different composite materials under water lubrication have been conducted [41–48]. Tomizawa and Fisher [49] found that the friction coefficient between the Si_3N_4 ceramics with water lubrication became less than 0.002 after a running-in process, making it the first study to see that water used as a lubricant could achieve superlubricity [50]. Chen et al. [51] first introduced nanoparticles into the field of water-based superlubricity. Furthermore, the study of friction reduction and improvement of the mechanical efficiency and life in bearings under water lubrication are a major significant research.

Above all, this study focuses on the influence of a water-lubricated condition on the tribological properties of polymer–ceramics tribopairs to guide the application and popularization of ceramic bearings.

2 Procedure and specimens

2.1 Principle and procedure

The lubrication condition, normal load, and sliding velocity were the main variables considered [52]. The ball-on-disk form [53–56] was adopted on a ball-on-disk tribometer (MMW-200). The test lubricant was deionized water. The ball-on-disk tests were conducted in dry lubrication to set the contrast lubricating tests. A Si_3N_4 ball under a settable normal load F was placed on the surface of the rotating disk specimen under a certain ω. The test conditions were selected based on a series of low-load experiments of the effect of load on wear for the lubrication environment. The results of these wear-in tests showed that the wear rate was too small to be almost impossible to measure under a lower load. The wear rate correspondingly increased as the load increased. A load of 30 N was considered in our experiment to be the conventional condition, whereas a load of 120 N was the extreme condition. Extreme load was chosen to test the polymers' performance in extreme conditions and more comprehensively reflect their performance. Hence, the normal load value was set as 30 N, 75 N, and 120 N. The relative sliding distance was generally kept at 1,800 m to ensure that the tribopairs achieve a stable lubrication state. Therefore, the running time will be set according to linear speeds of 0.25 m/s (7,200 s), 0.5 m/s (3,600 s), and 1 m/s (1,800 s) to explore the effect of velocity. The test settings were shown in the test schedule (Table 1).

2.2 Specimens and theory

The specimens used in the tests were provided by China National Machinery Industry Corporation. The initial surface roughness was 0.03 μm, and the Si_3N_4 ball diameter was 9.525 mm. Tables 2 and 3 show the specimen properties.

Table 1 Test schedule.

Test No.	Experimental factors		
	Load (N)	Sliding velocity (m/s)	Lubricant
1	30	0.25	Dry
2			Water
3		0.5	Dry
4			Water
5		1	Dry
6			Water
7	75	0.25	Dry
8			Water
9		0.5	Dry
10			Water
11		1	Dry
12			Water
13	120	0.25	Dry
14			Water
15		0.5	Dry
16			Water
17		1	Dry
18			Water

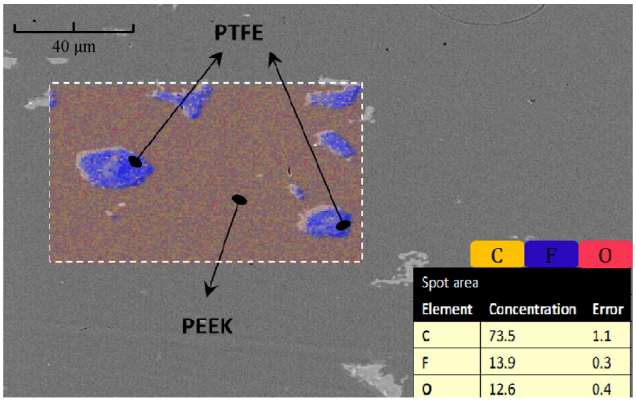
Table 2 Properties of Si_3N_4 ball.

Properties	Si_3N_4 ball
Vickers hardness (HV)	1,580
Fracture toughness (MPa·m$^{1/2}$)	6.0
Bending strength (MPa)	900
Density (g/cm^3)	3.5
Initial roughness (μm)	0.014

Table 3 Properties of PEEK and PI composite materials.

Properties	PEEK	PI
Vickers hardness (HV)	144	122
Tensile strength (MPa)	17	16
Compressive strength (MPa)	38	40
Distortion temperature (°C)	102	350

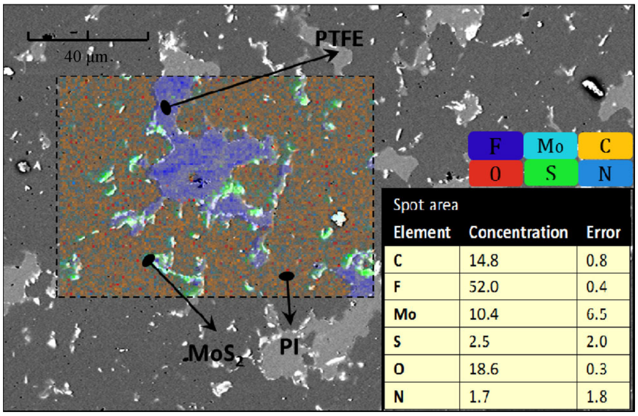
Energy dispersive spectroscopy (EDS) was performed at different locations to ascertain the elemental constituents of the different phases presented in the microstructure. The typical EDS spectrum of the disks observed in Figs. 1 and 2 further verified the presence



Spot area

Element	Concentration	Error
C	73.5	1.1
F	13.9	0.3
O	12.6	0.4

Fig. 1 Typical EDS spectra of PEEK disk at different locations.



Spot area

Element	Concentration	Error
C	14.8	0.8
F	52.0	0.4
Mo	10.4	6.5
S	2.5	2.0
O	18.6	0.3
N	1.7	1.8

Fig. 2 Typical EDS spectra of PI disk at different locations.

of the specimens. As shown in the figures, the PEEK composite materials used in this test were modified by self-lubricating PTFE particles and the PI modified by a certain percentage of PTFE and MoS_2.

The specimens were ultrasonically cleaned in industrial alcohol for 15 min before every experiment, then ultrasonically cleaned again in acetone for 15 min before thoroughly washing with deionized water and drying in an oven.

The friction coefficient curves were automatically recorded by a tribometer. The wear rate (w) was determined using the following volume method [57]. The wear volume of the ball and the disk was expressed using the two following equations:

$$V_{\mathrm{b}} = \frac{\pi \times D_{\mathrm{s}}^{4}}{32 D_{\mathrm{b}}} \tag{1}$$

where V_{b} (mm^3), D_{s} (mm), and D_{b} (mm) stand for the wear volume, wear scar diameter of the ball, and ball diameter, respectively.

$$V_{\mathrm{d}} = 2\pi R \times \left(\frac{S_1 + S_2 + S_3 + S_4}{4} \right) \tag{2}$$

where V_{d} (mm^3) and R (mm) are the wear volume and the sliding radius of the disks respectively, and S_1, S_2, S_3, and S_4 are the cross-section areas of the disk wear scar in four measurements.

The wear rate (w) was determined by the following equation:

$$w = \frac{V}{Fd} \tag{3}$$

where V (mm^3), d (m), and F (N) are the wear volume of the ball or disk, sliding distance, and normal load, respectively.

3 Results and discussions

3.1 Real-time friction coefficients

The ball and disk relatively slid when the motor rotated. The friction coefficient was automatically recorded with a real-time data acquiring system linked to the tribometer. The friction coefficients during the whole test were plotted as a function of the sliding distance in Figs. 3 and 4 for different lubrications when the sliding velocity was set as constant (0.5 m/s). The steady-state friction coefficient under all test conditions mostly ranged from 0.114 to 0.03.

Notably, the friction coefficients of the PI–Si_3N_4 tribopair under water in the following figures had an obvious reduction before a sliding distance of 600 m, then approximately trended to be stable. The PI–Si_3N_4 tribopair showed significant lower friction coefficients in water than that under the dry friction. Taking 120 N as an example, PI obtained the minimum value of the friction coefficient (i.e., 0.026) in water. Compared with PI, water generated little influence on the PEEK–Si_3N_4 tribopair. The minimum value of the friction coefficient was 0.0425.

3.2 Steady-state friction coefficients

Figures 5 and 6 show the steady-state friction coefficients of PEEK and PI as a function of the load and the sliding velocity in different lubrications, respectively.

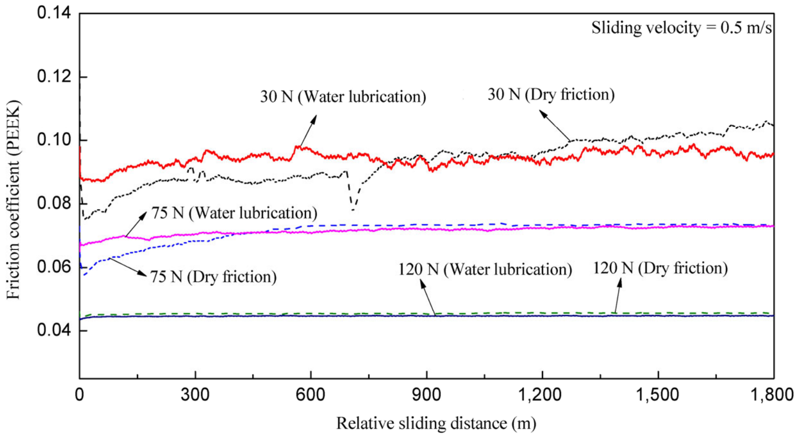


Fig. 3 Friction coefficient of PEEK as a function of relative sliding distance for different conditions.

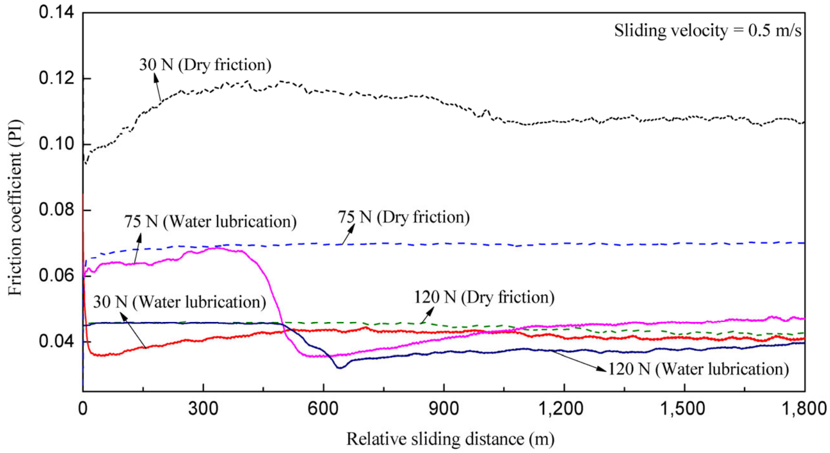


Fig. 4 Friction coefficient of PI as a function of relative sliding distance for different conditions.

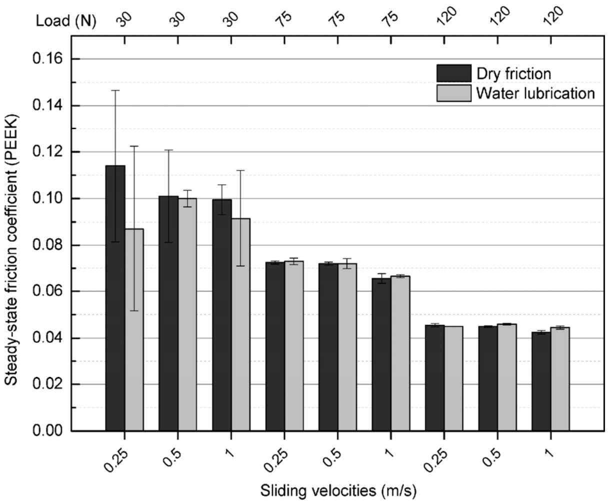


Fig. 5 The steady-state friction coefficients of PEEK–Si_3N_4 tribopair at dry-friction and water-lubricated conditions under different loads and sliding velocities.

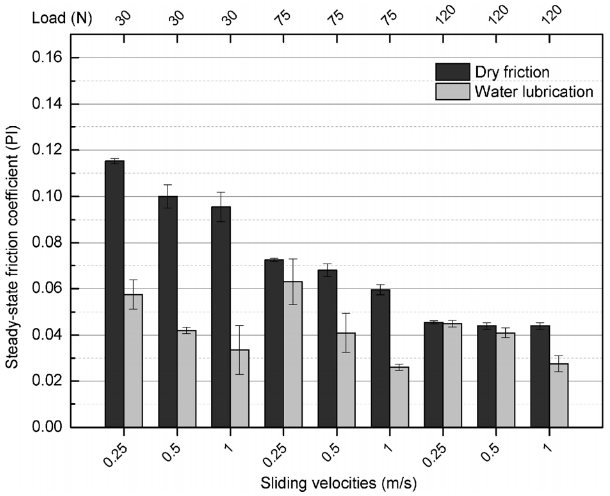


Fig. 6 The steady-state friction coefficients of PI–Si_3N_4 tribopair at dry-friction and water-lubricated conditions under different loads and sliding velocities.

Figure 5 shows that the PEEK coefficients under water were almost equal to those under dry friction. The results indicated that the tribological performance of the PEEK–Si_3N_4 tribopair was not improved under water. Moreover, the friction coefficients of PEEK exhibited a tendency to decrease with the increasing loads. The sliding velocity at medium and high loads exhibited a slighter effect on the friction coefficients compared to the load. These findings showed that the load became the main factor of the friction coefficients instead of the speed, thereby agreeing with the results of the regression analysis from Satapathy [58].

Figure 6 illustrates the typical friction coefficient values of PI under different lubrications. A comparison of all the conditions showed that the friction coefficients under water were smaller than those under dry friction, indicating that the tribological performance of the PI–Si_3N_4 tribopair could be improved under water.

The load for the PI tribopair was the main factor of the friction coefficients instead of the speed under dry friction. This result was similar to that of the PEEK tribopair. However, the coefficients were almost unaffected by the loads and decreased with the increase of the sliding velocities under water. In other words, water could weaken the effect of the load on friction while enhancing that of the sliding velocity.

3.3 Wear rates

The hardness of the Si_3N_4 ball was far greater than that of the PEEK and PI disks. Hence, the wear volume losses of the ball were too little to be measured. So in this paper only wear rates of disks are analyzed and discussed under the influence of different conditions.

Figure 7 shows the specific wear rates of the PEEK–Si_3N_4 tribopair varying with the setting conditions. Please note that the substrate irregular wear occurred on the PEEK disk surface at 120 N and 1 m/s. Hence, the wear rates were not measured. The wear under water was much more severe than that under dry friction, which was pretty consistent with Mens [59]. He also found that these effects may well be caused by the water penetration into the surface zones of the polymers, causing a corresponding decrease in the "strength" of the polymer surface zone under combined normal and tangential loading conditions. Taking 0.5 m/s from Fig. 7 as examples, the values of the wear rates were 24.8×10^{-6} and 57.8×10^{-6} $mm^3/(N \cdot m)$ at 30 N under dry and water, respectively, showing an increase of 2.3 times. Similarly, the values increased for approximately 2.9 and 2.7 times at 60 N and 120 N, respectively.

The wear rates of PEEK increased with the increasing loads under dry friction. Salant [60] found the same phenomenon. The adhesive wear at a low load occupied the main position. We may learn from Unal [61] that the deformation of the material caused damage when the load increased. The wear rate then increased. The same tendency occurred under water. The wear rates slowly descended with the velocity increase, which was attributed to the plastic flow acceleration caused by softening and melting on the composite surface proposed by Jia [62].

Figure 8 shows the specific wear rates of the PI–Si_3N_4 tribopair. The obvious difference from the PEEK–Si_3N_4 tribopair was that the PI–Si_3N_4 tribopair under water acquired less wear rates than under dry friction. From the nine experiment samples, we could calculate that the wear rates in the water reduced by 32% on average. The minimal wear rate 26.6×10^{-6} $mm^3/(N \cdot m)$ occurred at 30 N and 1 m/s under water. A reasonable interpretation could be that water reduced the friction surface temperature and further reduced the wear caused by the material softening due to heat, which was supported by Unal [61]. Similar to the PEEK tribopair, the wear rates of the PI tribopair exhibited a tendency to decrease with the decreasing loads or the increasing sliding velocities under dry friction. The same tendency occurred under water lubrication. As is also known from Unal [61], fatigue wear was the main wear mechanism under dry condition, and the tribological performance was improved evidently in water.

From the numerical point of view, the wear property of the PEEK tribopair could be slightly better than PI under "no water" condition. However, water exacerbated the PEEK tribopair wear, but relieved the PI. Taking 0.5 m/s as an example, the wear rate values were 227.6×10^{-6} and 85.9×10^{-6} $mm^3/(N \cdot m)$ at 30 N for the PEEK and PI tribopairs, respectively. These values showed a reduction of 2.6 times for PI tribopairs. Similarly, the values reduced by 1.7 and 3.9 times at 30 N and 120 N in water, respectively.

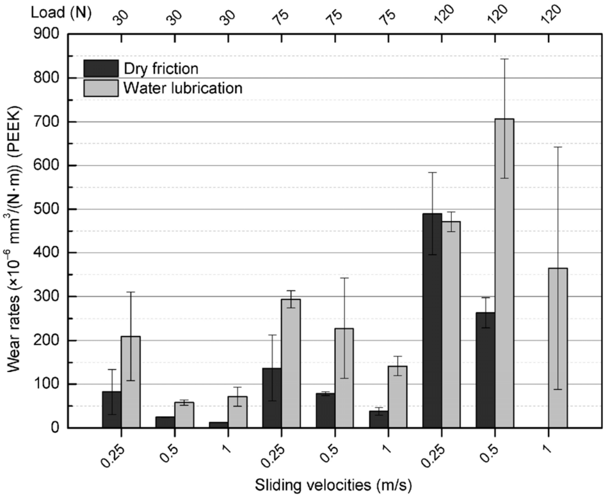


Fig. 7 The wear rates of PEEK at dry-friction and water-lubricated conditions under different applied loads and sliding velocities.

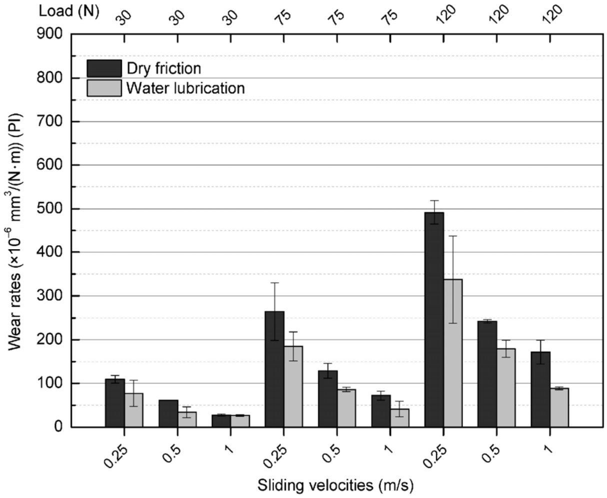


Fig. 8 The wear rates of PI at dry-friction and water-lubricated conditions under different applied loads and sliding velocities.

3.4 3D profiler micrograph analysis of wear surfaces

Figures 9 and 11 show the 3D micrographs of the wear surfaces of the PEEK and PI composite materials after the experiments. Figures 10 and 12 show the 2D cross-sectional profiles of the wear tracks from PEEK and PI surface. The wear losses for the PEEK tribopair increased, and the grinding crack widened and deepened under water. The wear was the main failure form at the normal working load of 30 N. The

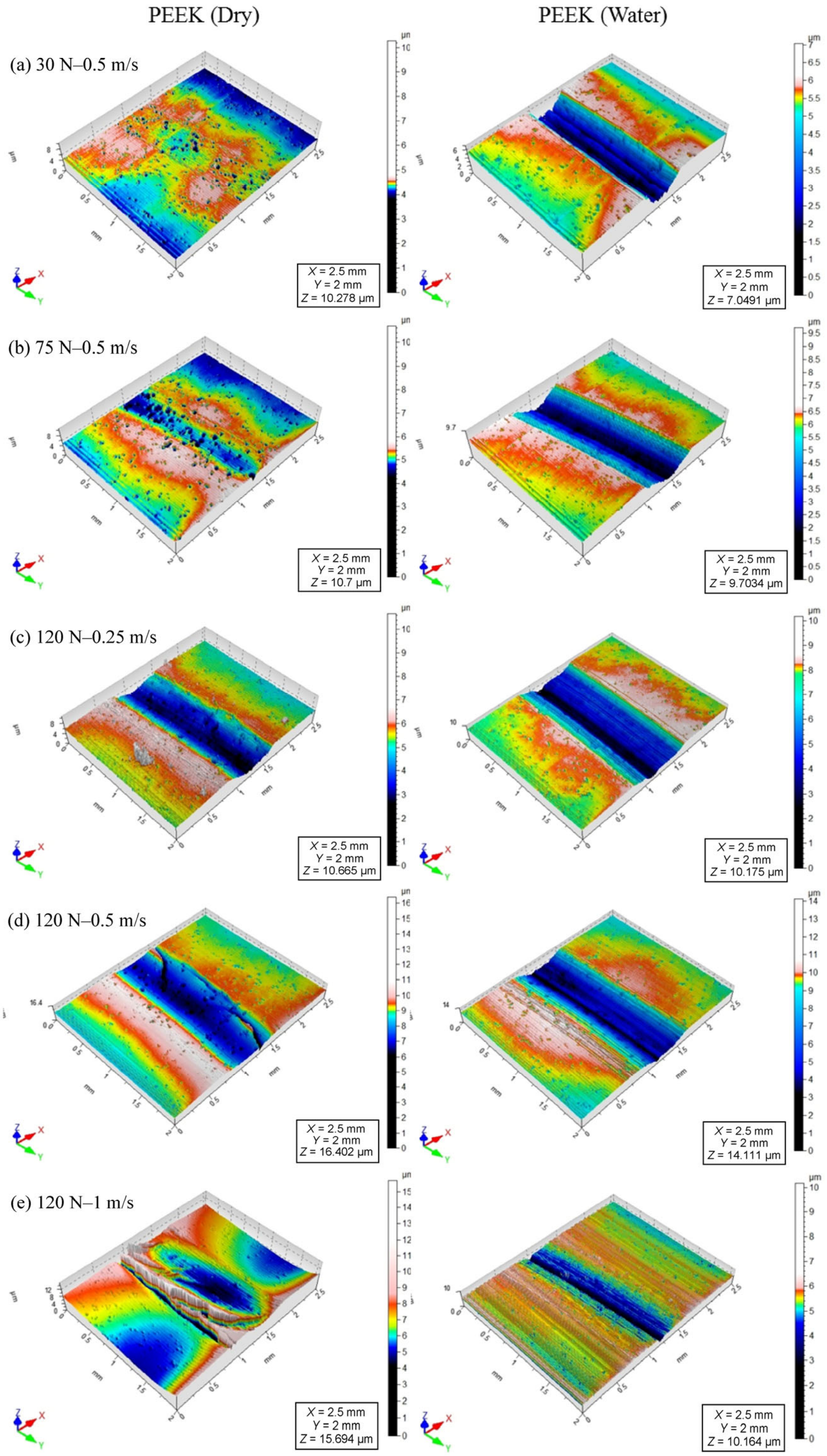


Fig. 9 3-D surface topography of PEEK materials after tests under different lubrications.

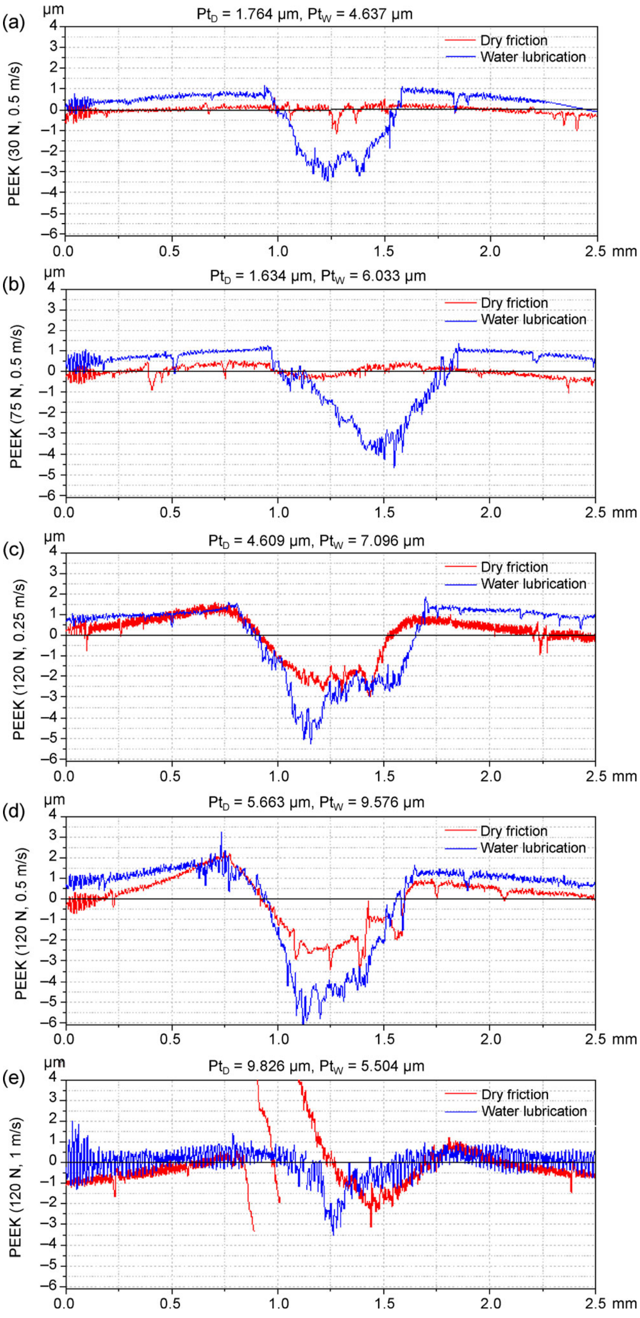


Fig. 10 Cross-sectional profiles of wear tracks from 2-D PEEK surface topography.

PEEK matrix surface could be crushed and cracked under dry friction when the load becomes extreme, such as 120 N. In this case, the shear failures of the polymers would dominate the material loss. This situation is beyond the normal working conditions of the PEEK polymer. Under the water-lubricated condition, the crack would not appear, and the wear rate increases. No crack would be observed on the surface of the PI polymer, for comparison. The wear was the main failure form. Water made the PI tribopair acquire less wear rates. Moreover, the values reduced by 32% on average than that at dry friction. It is worth mentioning that compared with PEEK, PI could withstand a greater applied load and sliding velocity under water. The comparison of the 3D micrographs between the two tribopairs also demonstrated that the PEEK tribopair obtained a smoother surface than PI under water.

3.5 Optical and SEM micrographs of surface wear tracks on tribopairs

Figures 13–14 show the optical micrographs of the worn scares of the Si_3N_4 ball and the SEM micrographs of the worn surfaces of the PEEK and PI disks. Under dry friction, the PEEK disk surface was bruised, and a surface slim crack could be observed. The wear mechanism in this condition was crushing wear. The reason for this phenomenon could be consistent with that mentioned by Samyn [35] that the molecular chains of PEEK do not have enough time to orient under such conditions, thereby inducing embrittlement, polymer degradation, and finally a brittle fracture of the PEEK composite material.

Under the water condition, the scratching phenomenon and the slight wear tracks appeared on the PEEK disk surface, verifying the result and explanation in Figs. 3, 5, 7, 9, and 10. Notably, the transfer film could be formed from the PEEK disk surface. The transfer film would reduce the friction during the friction process. Compared with the dry friction, water sped up the transfer of the PEEK surface material, causing more severe wear rates. In addition, water inhibited the appearance of the crush phenomenon, which manifested that water could enhance the carrying capacity of the PEEK tribopair.

The slight wear tracks for the PI–Si_3N_4 tribopair could be found on the PI disk under dry friction. The transfer film could also be observed on the ball. However, the transfer film was not obvious under the water condition, and significant dimples appeared on the surface.

The above data showed that PI had a more significant reduction of friction coefficients and wear rates under water. On the one hand, the PI surface had

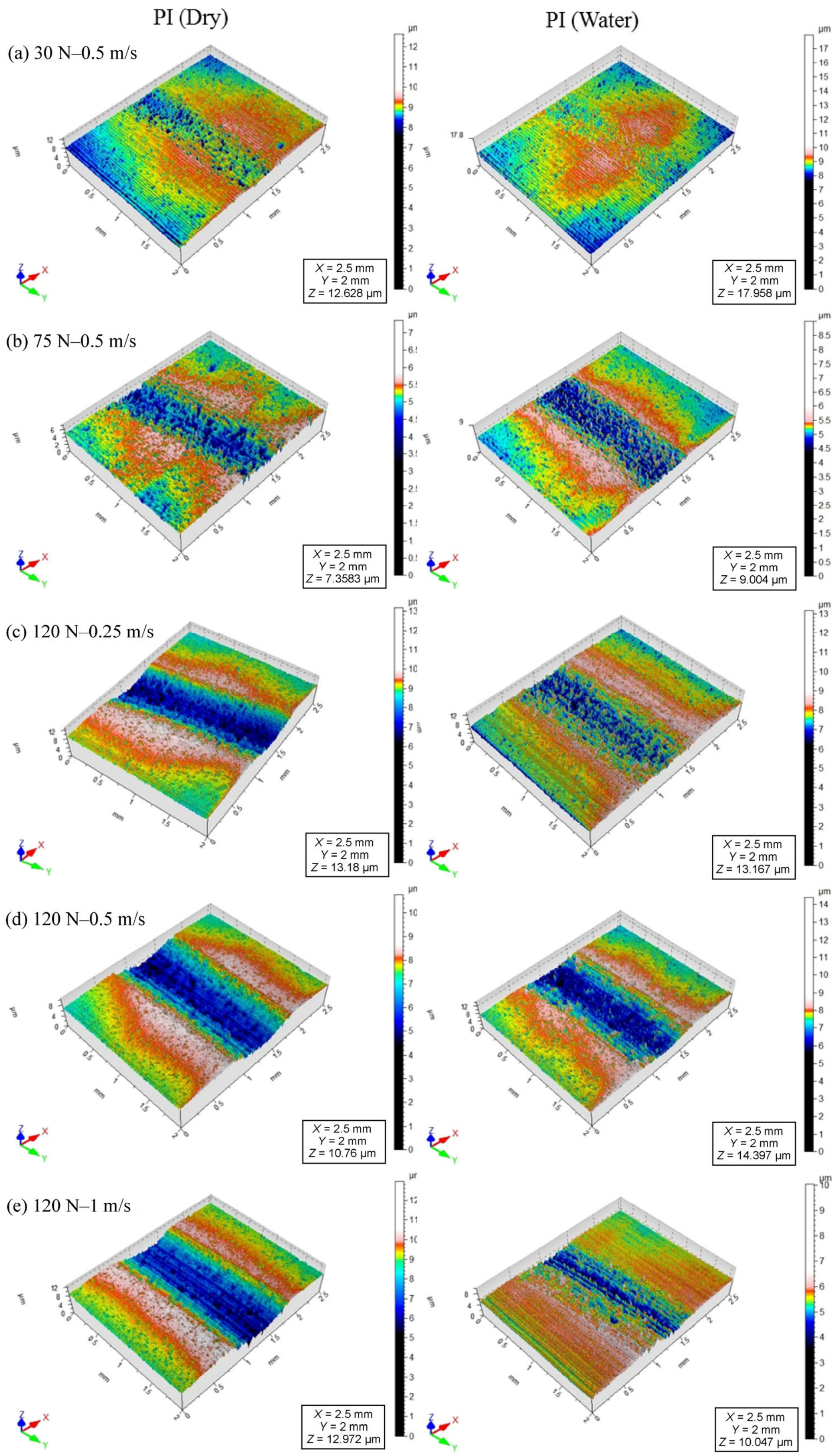


Fig. 11 3-D surface topography of PI materials after tests under different lubrications.

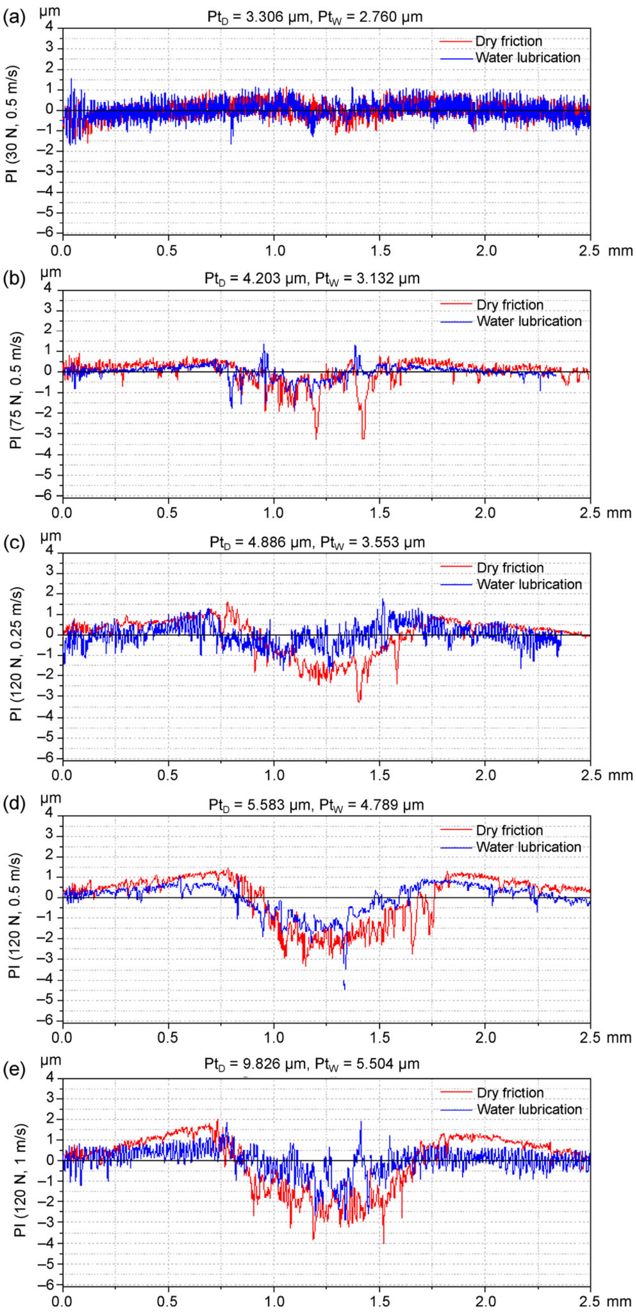


Fig. 12 Cross-sectional profiles of wear tracks from 2-D PI surface topography.

different degrees of water absorption, which brought about swelling to reduce the shear strength. The lower surface strength induced lower friction coefficients, which was consistent with Refs. [63, 64]. On the other hand, one reason supported by Jia [65] was that the PI composite material easily contained a polar amide group bonding with the water molecules through hydrogen, which could lubricate the friction surface and reduce the wear rate by forming an adsorption water film.

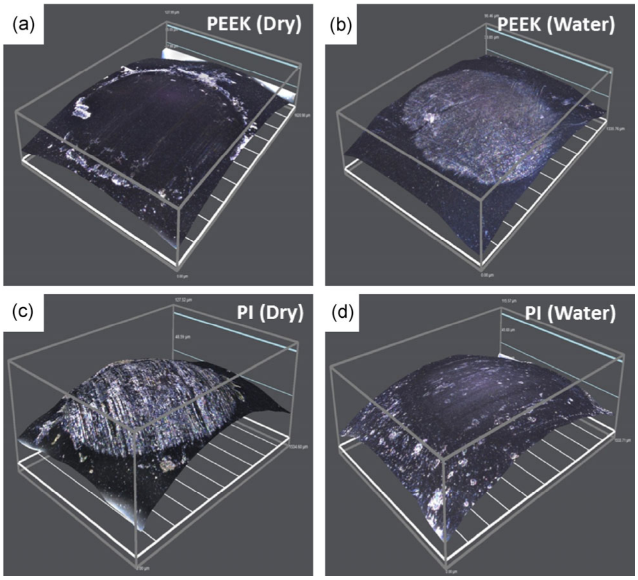


Fig. 13 Optical micrographs of Si_3N_4 ball sliding against PEEK disk (a, b) and PI disk (c, d) after tests under different lubrications.

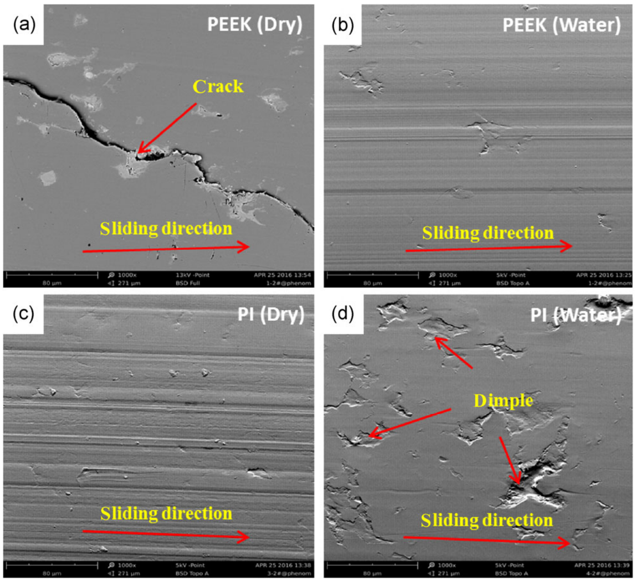


Fig. 14 SEM micrographs of PEEK disk (a, b) and PI disk (c, d) after tests under different lubrications: dry environment (a, c) and water environment (b, d).

The apparent dimples appeared on the PI tribopair surface under water after the test. Gao and Luo proposed that the friction coefficient was closely related to the surface topography and the lubricant viscosity. The resulting micro-textured surfaces significantly reduced the friction of the tribopair contact during hydrodynamic lubricated sliding. The pits on the surface appeared and grew during the running-in process [68]. The generation of dimples on the worn surface was caused by the excessive wear and peeling of the solid lubricant MoS_2 added in the polymer. Moreover, the water absorption of the PI surface brought about a low shear strength, which would further aggravate the MoS_2 peeling.

The dimples in our experiments could be simplified into a circle, and the average diameter of the dimples was approximately 35 μm (Fig. 15). As reported in Refs. [66, 67], the surface of the specimens with a dimple diameter of 40 μm exhibited better lubricating effects than the untextured surface. The appearing surface dimples in our specimens also improved the tribological properties mainly because of their ability to generate hydrodynamic pressure lubricating effects. The dimples revealed more potential in improving the load-carrying capacity and friction properties than the smooth surface.

3.6 Microstructure analysis based on X-ray diffraction (XRD)

Some literatures reported that the tribochemistry of Si_3N_4 in a water medium played an important role on the tribological performance. A typical XRD spectrum of the composite PEEK and PI was designed to investigate the possibility with the hypothesis that the surface chemical corrosion may induce the changed tribological properties of specimens. Figure 16 shows that no new material was generated after the tests. With reference to Section 2.2, the Si_3N_4 ball hardness was far greater than that of the polymers. Furthermore, the wear volume losses of the Si_3N_4 ball were too little to be measured. Hence, the surface chemical corrosion was not responsible for the main wear mechanism.

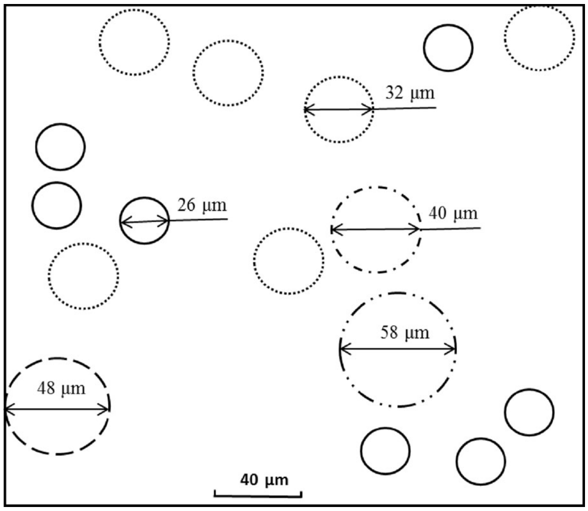


Fig. 15 Simplified patterns of PI surface texture under water after experiment.

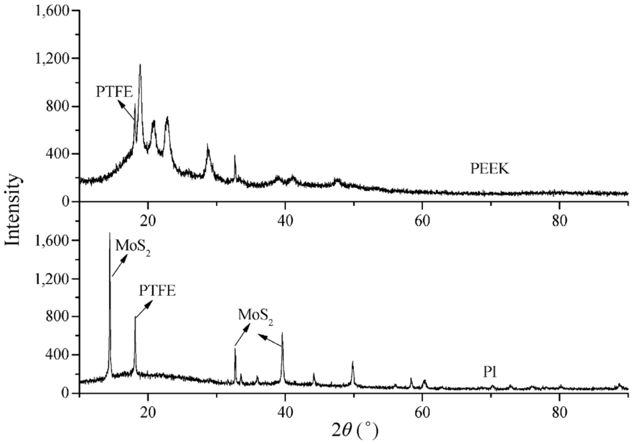


Fig. 16 Typical XRD spectrum of PEEK and PI materials after test.

5 Conclusions

This study presented the aqueous lubrication of tribopairs formed by PEEK and PI composite materials sliding against a Si_3N_4 ceramic. Two kinds of tribopairs showed different tribological properties. The conclusions drawn are as follows:

1. Water generates little influence on the PEEK–Si_3N_4 tribopair, and the minimum of the friction coefficient is 0.0425. However, the PI tribopair has lower friction coefficients under the lubricating condition. The minimum of which is 0.026, which is 41% lower than the minimum under the dry condition.
2. The wear rates of the PEEK tribopair under aqueous lubrication are approximately more than two times of those under dry sliding. Water makes the PI tribopair acquire less wear rates, and the values reduce by 32% on average than that at dry friction.
3. The wear surfaces of the PEEK– and PI–Si_3N_4 tribopairs have no chemical corrosion.
4. Water speeds up the transfer of the PEEK surface material in the PEEK–Si_3N_4 tribopair, thereby causing more severe wear rates. However, water inhibits the appearance of the crush phenomenon.

5. Compared with those of PEEK, the friction coefficients and wear rates of the PI tribopair could be reduced under water. Reasons are listed as following: (a) the PI surface has different degrees of water absorption, which brings about swelling to reduce the shear strength; (b) the polar amide group on the surface of the PI composite material bonding with the water molecules easily accelerates the formation of the lubrication water film; and (c) the dimples appearing on the PI tribopair surface under water generate additional hydrodynamic lubrication and further improve surface the friction properties.

Overall, compared with the PEEK tribopair, PI could withstand a greater applied load and a higher sliding velocity under water, making it promising for future applications in the water-based ceramic bearing industry.

Acknowledgements

This research was supported by the National Natural Science Foundation of China (Nos. 51375333, 50975199 and 51205285). Also the author thanks for all the members who have contributed their time and help in this research.

References

[1] Cong P H, Li T S, Xue Q J. Friction and wear of Polyimide and composite materials. *Lubrication Engineering* (04): 2–7 (1998)

[2] Cai H, Yan F Y, Chen J M, Xue Q J. Review on the Modification of Polyimide. *Journal of Materials Science and Engineering* **1**: 026 (2003)

[3] Hammouti S, Beaugiraud B, Salvia M, Mauclair C, Pascale-Hamri A, Benayoun S, Valette S. Elaboration of submicron structures on PEEK polymer by femtosecond laser. *Applied Surface Science* **327**: 277–287 (2015)

[4] Czichos H, Klaffke D, Santner E, Woydt M. Advances in tribology: the materials point of view. *Wear* **190**(2): 155–161 (1995)

[5] Michaljaničová I, Slepička P, Rimpelová S, Slepičková Kasálková N, Švorčík V. Regular pattern formation on surface of aromatic polymers and its cytocompatibility. *Applied Surface Science* **370**: 131–141 (2016)

[6] Hammouti S, Pascale-Hamri A, Faure N, Beaugiraud B, Guibert M, Mauclair C, Benayoun S, Valette S. Wear rate control of peek surfaces modified by femtosecond laser. *Applied Surface Science* **357**: 1541–1551 (2015)

[7] Mizobe K, Honda T, Koike H, Santos E C, Kashima Y, Kida K. Effect of PTFE retainer on friction coefficient in polymer thrust bearings under dry contact. *Advanced Materials Research* **683**: 90–93 (2013)

[8] Koike H, Mizobe K, Oyama S, Kashima Y, Kanemasu K, Kida K. Observation of wear on PEEK-PTFE hybrid radial bearings. *Advanced Materials Research* **683**: 385–390 (2013)

[9] Zhang Z, Breidt C, Chang L, Friedrich K. Wear of PEEK composites related to their mechanical performances. *Tribology International* **37**(3): 271–277 (2004)

[10] Aurélie D, Huong H T, Ahmad F, Aurore L, Guy L, Jalal B, Aissam A, Emmanuel A, Jean-François C. Improving adhesion of powder coating on PEEK composite: Influence of atmospheric plasma parameters. *Applied Surface Science* **357**: 1196–1204 (2015)

[11] Samyn P, Schoukens G, De Baets P. Micro-to nanoscale surface morphology and friction response of tribological polyimide surfaces. *Applied Surface Science* **256**(11): 3394–3408 (2010)

[12] Sun C, Zhou F, Shi L, Yu B, Gao P, Zhang J, Liu W. Tribological properties of chemically bonded polyimide films on silicon with polyglycidyl methacrylate brush as adhesive layer. *Applied Surface Science* **253**(4): 1729–1735 (2006)

[13] Zalaznik M, Kalin M, Novak S. Influence of the processing temperature on the tribological and mechanical properties of poly-ether-ether-ketone (PEEK) polymer. *Tribology International* **94**: 92–97 (2016)

[14] Koike H, Kida K, Mizobe K, Shi X, Oyama S, Kashima Y. Wear of hybrid radial bearings (PEEK ring-PTFE retainer and alumina balls) under dry rolling contact. *Tribology International* **90**: 77–83 (2015)

[15] Greco A C, Erck R, Ajayi O, Fenske G. Effect of reinforcement morphology on high-speed sliding friction and wear of PEEK polymers. *Wear* **271**(9): 2222–2229 (2011)

[16] Theiler G, Gradt T. Friction and wear of PEEK composites in vacuum environment. *Wear* **269**(3): 278–284 (2010)

[17] Guo X D, Dai Y, Gong M, Qu Y G, Helseth L E. Changes in wetting and contact charge transfer by femtosecond laser-ablation of polyimide. *Applied Surface Science* **349**: 952–956 (2015)

[18] Liu B, Pei X, Wang Q, Sun X, Wang T. Effects of proton and electron irradiation on the structural and tribological properties of MoS_2/polyimide. *Applied Surface Science* **258**(3): 1097–1102 (2011)

[19] Samyn P, Schoukens G. The effect of processing method on dry sliding performance of polyimides at high load/high velocity conditions. *European Polymer Journal* **44**(3): 716–732 (2008)

[20] Jia J H, Zhou H D, Gao S Q, Chen J M. A comparative investigation of the friction and wear behavior of polyimide composites under dry sliding and water-lubricated condition. *Materials Science and Engineering: A* **356** (1–2): 48–53 (2003)

[21] Riveiro A, Soto R, Comesana R, Boutinguiza M, del Val J, Quintero F, Lusquiños F, Pou J. Laser surface modification of PEEK. *Applied Surface Science* **258**(23): 9437–9442 (2012)

[22] Aurélie D, Huong H T, Ahmad F, Aurore L, Guy L, Jalal B, Aissam A, Emmanuel A, Jean-François C. Improving adhesion of powder coating on PEEK composite: Influence of atmospheric plasma parameters. *Applied Surface Science* **357**: 1196–1204 (2015)

[23] Tavenner E, Wood B, Curry M, Jankovic A, Patel R. Graphitic structure formation in ion implanted polyetheretherketone. *Applied Surface Science* **283**: 154–159 (2013)

[24] Laurens P, Sadras B, Decobert F, Arefi F, Amouroux J. Modifications of polyether-etherketone surface after 193 nm and 248 nm excimer laser radiation. *Applied Surface Science* **138**: 93–96 (1999)

[25] Feng Y, Gottmann J, Kreutz E W. Structuring of poly ether ether ketone by ArF excimer laser radiation in different atmospheres. *Applied Surface Science* **211**(1): 68–75 (2003)

[26] Almasi D, Izman S, Assadian M, Ghanbari M, Abdul Kadir M R. Crystalline ha coating on peek via chemical deposition. *Applied Surface Science* **314**: 1034–1040 (2014)

[27] Mackova A, Malinsky P, Miksova R, Khaibullin R I, Valeev V F, Svorcik V, Slepicka P, Slouf M. The characterization of PEEK, PET and PI implanted with Co ions to high fluences. *Applied Surface Science* **275**: 311–315 (2013)

[28] Faruque Ahmed S, Lee K R, Yoon J I, Moon M W. Nanoporous structures of polyimide induced by Ar ion beam irradiation. *Applied Surface Science* **258**(8): 3841–3845 (2012)

[29] Sun C, Zhou F, Shi L, Yu B, Gao P, Zhang J, Liu W. Tribological properties of chemically bonded polyimide films on silicon with polyglycidyl methacrylate brush as adhesive layer. *Applied Surface Science* **253**(4): 1729–1735 (2006)

[30] Ran J, Zhang J, Yao W, Wei Y. Properties of Cu film and Ti/Cu film on polyimide prepared by ion beam techniques. *Applied Surface Science* **256**(23): 7010–7017 (2010)

[31] Yang D, Dong Y, Gong J. The Tribological Behaviors of PEEK Filled PTFE Composites. *Lubrication Engineering* **38**(10): 60–63 (2013)

[32] Wang X. Investigation of tribological performance and simulation of temperature field during sliding contact for polyimide composites. Master Thesis. Nanjing Industrial University, 2005.

[33] Huang L J, Yang C C, Wang X D, Huang P. Tribological properties of polyimide composites against different metal under dry sliding friction condition. *Materials for Mechanical Engineering* **10**: 016 (2009)

[34] Wang X D, Wang X, Zhu P, Huang P. Mechanical properties and tribological performance of plastic. *Materials for Mechanical Engineering* **11**: 013 (2005)

[35] Samyn P, Schoukens G, Verpoort F, Van Craenenbroeck J, De Baets P. Friction and wear mechanisms of sintered and thermoplastic polyimides under adhesive sliding. *Macromolecular Materials and Engineering* **292**(5): 523–556 (2007)

[36] Dong W, Nie S, Zhang A. Tribological behavior of PEEK filled with CF/PTFE/graphite sliding against stainless steel surface under water lubrication. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology* **227**(10): 1129–1137 (2013)

[37] Zhang Z, Nie S, Yuan S, Liao W. Comparative Evaluation of Tribological Characteristics of CF/PEEK and CF/PTFE/Graphite Filled PEEK Sliding against AISI630 Steel for Seawater Hydraulic Piston Pumps/Motors. *Tribology Transactions* **58**(6): 1096–1104 (2015)

[38] Chen B, Wang J, Yan F. Friction and wear behaviors of several polymers sliding against GCr15 and 316 steel under the lubrication of sea water. *Tribology Letters* **42**(1): 17–25 (2011)

[39] Wu D, Liu Y, Yang S, Yang Z, Tang H. Friction and wear characteristics of WC–10Co–4Cr/Si_3N_4 tribopair lubricated under silt-laden water. *Wear* **294**: 370–379 (2011)

[40] Shi Y, Minami I, Grahn M, Björling M, Larsson R. Boundary and elastohydrodynamic lubrication studies of glycerol aqueous solutions as green lubricants. *Tribol Int* **69**: 39–45 (2014)

[41] Chen B, Wang J, Yan F. Microstructure of PTFE-based polymer blends and their tribological behaviors under aqueous environment. *Tribology Letters* **45**(3): 387–395 (2012)

[42] Guan X, Wang L. The tribological performances of multilayer graphite-like carbon (GLC) coatings sliding against polymers for mechanical seals in water environments. *Tribology Letters* **47**(1): 67–78 (2012)

[43] Liu H, Wang T, Wang Q. Tribological Properties of Thermosetting Polyimide/TiO_2 Nanocomposites Under Dry Sliding and Water-Lubricated Conditions. *Journal of Macromolecular Science, Part B* **51**(11): 2284–2296 (2012)

[44] Zhao H, Zhang J, Ji T, Yang M, Chao M, Kou K. Investigation of tribological properties of PI/FEP laminated composites under dry sliding, water-and oil-lubricated conditions. *Tribology Letters* **45**(2): 333–339 (2012)

[45] Deleanu L, Georgescu C. Water lubrication of PTFE composites. *Industrial Lubrication and Tribology* **67**(1): 1–8 (2015)

[46] Chen B, Wang J, Liu N, Yan F. Synergetic Effect of Lubricant Additive and Reinforcement Additive on the Tribological Behaviors of PEEK-Based Composites under Seawater Lubrication. *Tribology Transactions* **56**(4): 672–680 (2013)

[47] Zhang Z, Nie S, Liao W, Li L, Yuan S. Tribological behaviors of carbon fiber reinforced polyetheretherketone sliding against silicon carbide ceramic under seawater lubrication. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology* **228**(12): 1421–1432 (2014)

[48] Mimaroglu A, Unal H, Ozel A. Tribological Performance of Polyetheretherketone and its Composites under Water Environment. *Macromolecular Symposia* **327**(1): 108–113 (2013)

[49] Tomizawa H, Fischer T E. Friction and wear of silicon nitride and silicon carbide in water: hydrodynamic lubrication at low sliding speed obtained by tribochemical wear. *ASLE Transactions* **30**(1): 41–46 (1987)

[50] Li J J, Luo J B. Advancements in superlubricity. *Science China Technological Sciences* **56**(12): 2877–2887 (2013)

[51] Chen Z, Liu Y, Luo J. Superlubricity of nanodiamonds glycerol colloidal solution between steel surfaces. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* **489**: 400–406 (2016)

[52] Lifang C, Chengya H, Xing H. Actuality and Prospect in Research on Friction and Wear Properties of Polymers and Polymer-based Composites. *Lubrication Engineering-Huangpu* **6**(172): 183 (2005)

[53] Zhao J, He Y, Wang Y, Wang W, Yan L, Luo J. An investigation on the tribological properties of multilayer graphene and MoS_2, nanosheets as additives used in hydraulic applications. *Tribology International* **97**:14–20 (2016)

[54] Yang Y, Zhang C, Wang Y, Dai Y, Luo J. Friction and wear performance of titanium alloy against tungsten carbide lubricated with phosphate ester. *Tribology International* **95**: 27–34 (2016)

[55] Xie G, Liu S, Guo D, Wang Q, Luo J. Investigation of the running-in process and friction coefficient under the lubrication of ionic liquid/water mixture. *Applied Surface Science* **255**(12): 6408–6414 (2009)

[56] Ma Z Z, Zhang C H, Liu S H, Luo J, Lu X, Wen S. Study of lubrication behavior of pure water for hydrophobic friction pair. *Science in China Series E: Technological Sciences* **52**(11): 3128–3134 (2009)

[57] Heshmat H, Jahanmir S. Tribological behavior of ceramics at high sliding speeds in steam. *Tribology Letters* **17** (3): 359–366 (2004)

[58] Satapathy B, Bijwe J. Analysis of simultaneous influence of operating variabales on the abrasive wear of phenolic Composite. *Wear* **253**: 787–794 (2002)

[59] Mens J W M, Gee A W J. Friction and wear behaviour of 18 polymers in contact with steel in environments of air and water. *Wear* **149**: 255–268 (1991)

[60] Zhang Z Y, Zhang M Q, Zeng H M, Liu Z R. On the tribological behavior and mechanism of Poly (etherether ketone). *Acta Materiae Compositae Sinica* 4 (1995)

[61] Unal H, Mimaroglu A, Kadıoglu U, Ekiz H. Sliding friction and wear behaviour of polytetrafluoroethylene and its composites under dry conditions. *Materials & Design* **25**(3): 239–245 (2004)

[62] Jia Z N, Hao C Z, Yan Y H. Effects of different operation conditions on the self lubricating properties of PI/PTFE composites. *CHINA PLASTICS INDUSTRY* **11**: 021 (2014)

[63] Jia J, Zhou H, Gao S, et al. The tribological behavior of carbon-fiber-reinforced polyimide composites under water lubrication. (in Chinese). *Mocaxue Xuebao* **22**: 273–276 (2002)

[64] Xiong D, Ge S. Friction and wear properties of UHMWPE/Al_2O_3 ceramic under different lubricating conditions. *Wear* **250**(1): 242–245 (2001)

[65] Jia J, Gao S, Chen J, et al. Tribological properties and wear mechanisms of PTFE and carbon fiber reinforced PI composites. (in Chinese). *Materials Science and Engineering* **21**: 183–186 (2003)

[66] Wang X, Adachi K, Otsuka K, Kato K. Optimization of the surface texture for silicon carbide sliding in water. *Applied Surface Science* **253**(3): 1282–1286 (2006)

[67] Wang X, Kato K, Adachi K, Aizawa K. Loads carrying capacity map for the surface texture design of SiC thrust bearing sliding in water. *Tribology International* **36**(3): 189–197 (2003)

[68] Gao Y, Ma L, Luo J. Pitted Surfaces Produced by lactic acid lubrication and their effect on ultra-low friction. *Tribology Letters* **57**(2): 1–8 (2015)

Anying WANG. She joined the Key Laboratory of Advanced Ceramics and Machining Technology of Ministry of Education at Tianjin University from 2013. Currently, she is a Ph.D. student in mechanical engineering at Tianjin University. Her research interests include ceramics tribology and polymer composite materials tribology.

Bin LIN. He was the lecturer, associate professor, and professor in the School of Mechanical Engineering at Tianjin University in 1994, 1996, and 2007, respectively. His current identity is a Doctoral supervisor and the Vice-director of the the Key Laboratory of Advanced Ceramics and Machining Technology of Ministry of Education. His research areas cover machining theory and machining technology of hard, brittle materials, and structural ceramics application theory and technology.