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접촉 압력이 PEEK, PTFE 및 UHMWPE의 왕복 마모 거동에 미치는 영향

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Effect of Contact Pressure on Reciprocating Wear Behavior of PEEK, PTFE, and UHMWPE

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Abstract: Engineering plastics are macromolecular compounds composed of covalently bonded macromolecules, which have been widely used in sliding wear-resistance materials in isolation bearings. In this study, an MFT-5000 reciprocating friction testing machine was used to compare the friction and wear performance of polyetheretherketone (PEEK), polytetrafluoroethylene (PTFE), and ultra-high molecular weight polyethylene (UHMWPE) under heavy load conditions in dry friction condition. The results show that load has a significant effect on the friction coefficient, wear rate, and wear mechanism of three materials. The instant friction coefficient of PTFE fluctuates under high load, the wear rate clearly increases with the increase in load. Therefore, the application under high load conditions is limited. The wear rate of UHMWPE is the least affected by the load among the three materials. Even when the load exceeds the yield strength, the wear resistance is still good. The friction coefficient of PEEK decreases with the increase in load but maintains a high value that restricts its application in sliding friction pair materials to some degree.

Keywords: load, engineering plastics, dry friction, reciprocating friction, wear.

Introduction

Engineering plastics are macromolecular compounds composed of covalently bonded macromolecules, which have been widely used as mechanical moving parts instead of steel. The American Society for Standard Testing of Materials (ASTM) defines engineered plastics as plastics or polymer compounds having certain properties. Due to the characteristics of high strength, low density, good self-lubricating performance, and a relatively low friction coefficient (refers to the ratio of the friction force between two surfaces and the vertical force acting on one surface), engineering plastics are widely used as friction auxiliary materials under special stress conditions such as isolation bearings for bridges and sealing parts.[1-4] Isolation bearings are used to bear and connect the upper buildings and lower foundation. Their main function is to offset seismic energy to achieve seismic isolation by using sliding bearing materials and sliding panel as the reset function of movement of the reciprocating friction. Sliding materials are mainly polytetrafluoroethylene (PTFE), ultra-high molecular weight polyethylene (UHMWPE) and their composites, while sliding plates are mainly composed of 06Cr19Ni10 stainless steels.[5,6] The contact load of the friction pair can exceed 50 MPa, far exceeding the yield strength of polymer materials such as PTFE and UHMWPE,[7] which is a required condition of supercritical load. Studies have shown that PTFE is easily cooled and has a high wear rate under high load.[8-10] UHMWPE has excellent tribological properties.[11,12] However, the question

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arises as to whether its unique flow stress behavior beyond the yield strength affect the application of friction pairs under heavy loads. It is known that polyetheretherketone (PEEK) has the characteristics of high strength, good wear resistance, good chemical resistance.[13,14] Hence, it is worth exploring whether PEEK can be used as a friction pair material in shock absorption structures.

The influence of the contact stress (load) on the friction and wear behavior of engineering plastics has always been a subject of interest. A few researchers have investigated the influence of loads on the tribological properties of PTFE, UHMWPE and PEEK under different experimental parameters. Jia *et al*. studied the self-lubricating properties of PTFE and its nano-composites under loading conditions in the range of 1.43-8.55 MPa.[15] Saikko studied the influence of load on the multidirectional sliding friction and wear of UHMWPE.[16] Laux compared the friction and wear behavior of PEEK under 1.8 and 3.9 MPa loads.[17] Rodriguez *et al*. studied the dry reciprocating sliding friction wear performance of PEEK under the loads of 4, 8, and 10 MPa, respectively.[18] Zhang *et al*. investigated the effect of amorphous PEEK on the wear mechanism under different loads (1-9 N).[19] Under low load condition, the experimental parameters and materials show that the friction coefficient decreases with the increase in load, and the wear mechanism differs with the increase in load. A few researchers have conducted comparative studies on the friction and wear behavior of different types of engineering plastics under different loads. Huseyin *et al*. studied the tribological properties of PEEK, UHMWPE, glass-fiber reinforced PTFE, and other composite materials under different loads (50, 100, and 150 N) under dry friction and lubricating medium, respectively.[20] Zhiwei *et al*. studied the tribological properties and wear mechanisms of PTFE, PEEK, and thermosetting resins under low loads (15-60 N) by using a pin disc tester.[21] Wang *et al*. studied the tribological behavior of dry reciprocating sliding and fretting friction of six polymer materials including UHMWPE, PTFE, phenolic aldehyde, p-hydroxybenzaldehyde (PHBA), PEEK, and polyimide (PI) and GCr15 steel under 10 N load.[22] H. Unal *et al*. investigated the effect of loads (20, 30, and 40 N) on the friction and wear behavior of polyamide-6 (PA 6), polyformaldehyde (POM), and UHMWPE.[23] The above studies have compared the tribological properties of different materials under low loads, and the relevant experimental studies have focused on the tribological properties under the load range below the yield strength of the materials. Few studies have attempted to understand the laws of friction and wear performance of engineering plastics under the condition of large loads exceeding the yield strength of materials. The change compared to the case of low loads needs to be examined in detail.

This work focuses on three engineering plastics i.e. PTFE, UHMWPE, and PEEK, and uses MFT-5000 reciprocating friction and wear testing machine (Rtec Instrument, USA) to determine the friction coefficient and wear rate under different loads (10, 15, 20, 25, and 30 MPa). Using scanning electron microscopy (SEM), white light confocal 3D topography, and energy dispersive X-ray spectrometry (EDS), we have comparatively studied the wear surface morphology and discussed the wear mechanisms of the three materials under different loads.

Experimental

Materials. Three commercial-grade engineering plastics (PTFE, UHMWPE, and PEEK) pin samples and 06Cr19Ni10 steel plate samples were used as friction pairs in the experiment. Their material properties were obtained from the Shenzhen senli plastic material co. Ltd, as shown in Table 1. The pin samples were prepared by turning the engineering plastic bars. The diameter of the frictional contact between the pin

Table 1. Mechanical Properties of the Materials Used

Materials	PEEK	PTFE	UHMWPE	6Cr19Ni10
Density (g/cm^3)	1.32	2.15	0.93	7.93
Compressive yield strength (MPa)	95	25	17	300
Poisson's ratio	0.4	0.4	0.46	0.3
Elasticity modulus (GPa)	3	0.28	0.6	193

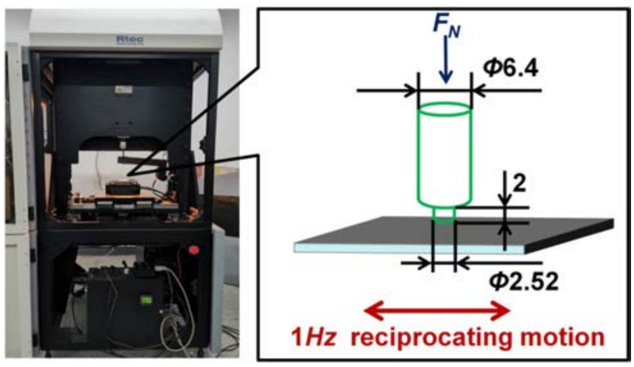

Figure 1. Schematic diagram of the contact and size of the friction pair.

samples and steel plate samples was 2.52 mm. The 06Gr19Ni10 steel plate was cut into 30×30×3 mm using wire cutting. The friction surface of the samples was mirror polished by metallographic polishing. The size and the contact form of the friction pair are shown in Figure 1.

Design. In order to achieve the specific pressure conditions required for the experiment and ensure the stable operation of the experimental equipment. The contact pressure was calculated as 30 MPa when the testing machine pressure was 150 N. The radius of the friction pin was calculated as *R*=1.26 mm. The engineering plastics are machined to the corresponding size by turning.

The engineering plastic pin samples and 06Gr19Ni10 piece samples were installed on the MFT-5000 reciprocating friction and wear tester (Rtec Instrument, USA) to conduct reciprocating sliding wear tests. The experimental method was dry rubbing under ambient temperature at 25 ℃ and relative humidity 70%. Before the test, the sample was cleaned by ultrasonic rays with anhydrous ethanol. In order to study the influence of load variation on the friction and wear properties of different engineering plastics, all the friction tests were conducted for 30 min under the condition of reciprocating friction frequency of 1 Hz and a contact pressure of 10, 15, 20, 25, and 30 MPa, respectively. The specific experimental parameters are shown in Table 2. After the test, the pin sample was removed from the test machine, soaked in anhydrous ethanol reagent for ultrasonic cleaning for 180 s, placed in an oven at a temperature of 40 ℃ for 24 h, and then removed and stored in a drying dish for analysis.

Characterization. SEM (JSM-6510LV), white light confocal microscopy (CM, Micromeasure2 STLE France), and EDS were used to characterize the microscopic morphology and chemical composition of the worn surface, observe the wear morphology of the three engineering plastic samples under different loads, and discuss the law of influence of the load on the wear mechanism of the three materials. After the samples were dried in the oven, a precision analytical balance (precision ± 0.0001 g) was used to measure the mass loss of the friction pins five times. Then, the average value was converted to the material wear rate *W* (refers to the volume of wear per unit of load per unit of length) by the following calculation method:[24]

$$W = \Delta m/(\rho \times F \times d)[\text{mm}^3/(\text{Nm})] \quad (1)$$

Where, ρ is the material density (g/mm^3), F is the normal load (N), and d is the friction sliding distance (m).

Results and Discussion

Influence of Load on the Friction Coefficient of Materials. Figure 2(a-c) shows the variation of the friction coefficient with reciprocating sliding time of PTFE, UHMWPE, and PEEK under different loads, respectively. The friction coefficient curves of the three engineering plastics all show the characteristics of rapid rise and then smooth transition. The rapid rise stage is short, approximately 100-400 s. The initial slope of PTFE in the early rise stage increases with the increase in the load, while the time to enter the stable stage decreases. When the experimental load (10 and 15 MPa) is lower than the yield strength of the material, the slope is small, and the time to enter the stable friction state is longer. When the experimental load reaches 30 MPa, the time to enter the stable period is the shortest. When the experimental load is greater than the yield strength (> 20 MPa), the friction coefficient in the stable stage decreases. In the early friction rise stage of UHMWPE, the trend is opposite to that of PTFE i.e. the slope decreases with the increase in load. When the experimental load (30 MPa) is greater than the yield strength condition, the friction coefficient gradually decreases in the initial stage and then gradually increases. After reaching the stable friction state, the friction coefficient of UHMWPE still presents a trend of slow increase. In the early rising stage of PEEK, the slope does not change markedly with load variation. After reaching the stable stage, the friction coefficient still increases slowly under the experimental load of 10–20 MPa, while the friction coefficient is relatively stable under the experimental load of 25 and 30 MPa.

It can be observed from Figure 2 that the friction coefficient of the three materials in the stable stage all show a trend of

Table 2. Experimental Parameters of the Dry Sliding Wear Tests

Pin specimens		Flat specimens		Frequency (Hz)	Sliding time (s)	Contact pressure (MPa)
Material	Size (mm)	Material	Size (mm)			
PEEK/PTFE/UHMWPE	Φ2.52	6Gr19Ni10	30×30	1	1800	10/15/20/25/30

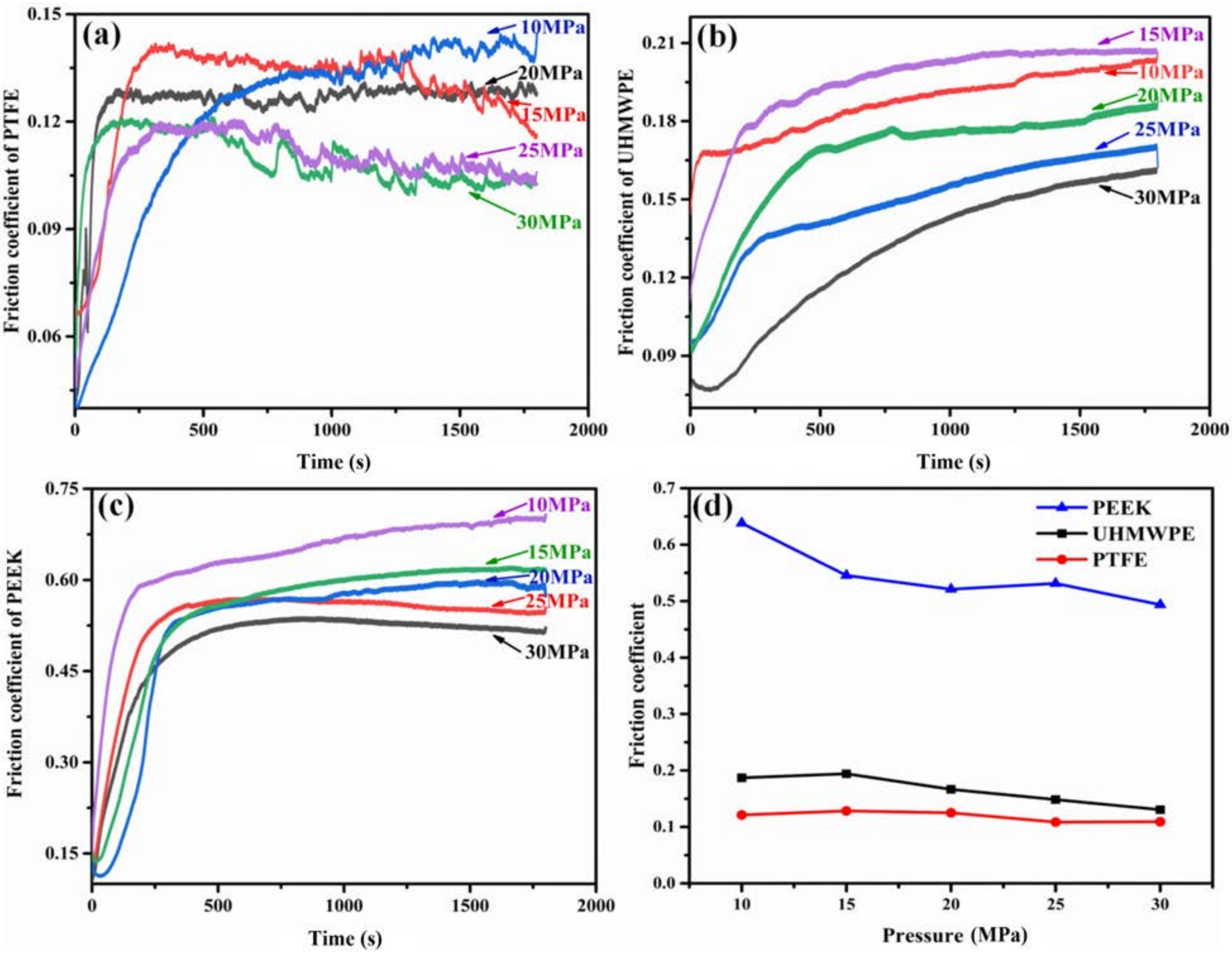

Figure 2. Reciprocating friction coefficients under different loads: (a)-(c) are the real-time friction coefficients of PTFE, UHMWPE, and PEEK, respectively; (d) average friction coefficient of the three engineering plastic materials.

decrease with the increase in load. Compared with PEEK and UHMWPE, the friction coefficient of PTFE appears to have the most fluctuation. The friction coefficient fluctuates more clearly for greater load. The reason is that: PTFE has poor mechanical properties i.e. its surface material wears off most easily in the process of friction, and as abrasive dust is formed on the friction interface (as shown in Figure 3(a)), the friction coefficient clearly fluctuates. The wear abrasive dust forms a uniform transfer film on the surface of the friction pair parts and has the effect of solid lubrication[25-27] (as shown in Figure 3(b)), resulting in PTFE having the minimum friction coefficient among the three materials.

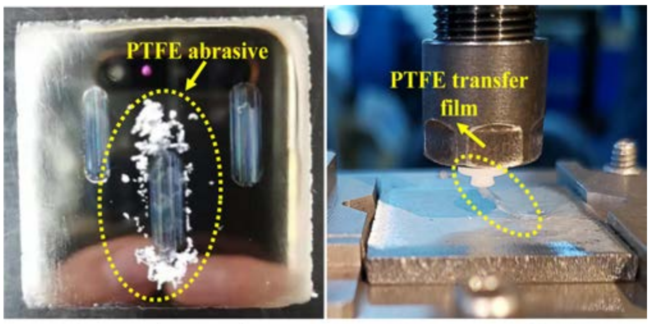

Figure 3. Material loss of PTFE in the friction process: (a) abrasive dust; (b) transfer film.

Figure 2(d) shows the average friction coefficient of PEEK, PTFE, and UHMWPE under different loads (the calculation method is described in **Characterization section**). As shown in the figure, the average friction coefficient of PTFE is the least, followed by UHMWPE, and PEEK is the largest. The average friction coefficient of the three materials shows a decreasing trend with the increase in load, while the trend is the most pronounced in PEEK. The stability of the average friction coefficient with the variation of load is in the order PTFE > UHMWPE > PEEK.

Influence of Load on the Wear Rate of the Materials. Figure 4 shows the relationship between the wear rate and the load of PEEK, PTFE, and UHMWPE after 30 min of sliding reciprocating friction with a frequency of 1 Hz. It can be observed from the figure that the wear rate of the three materials increases with the increase in the load. Under the same friction condition, the wear rate and the rate of change are shown to vary as PTFE > PEEK > UHMWPE. The wear rate of UHMWPE is the lowest, and the wear rate change is relatively stable, which is 1.0753–0.1195×10^{-8} $mm^3N^{-1}{\cdot}m^{-1}$. Under small loads, the UHMWPE wear rate is negative. This may be because UHMWPE has good wear resistance, so that the wear mass loss is low, and in the process of friction, the elements of the steel plate pairs adhere and transfer to the surface of UHMWPE, which results in increased friction pin quality.[28] According to the element content analysis on the wear surface of the UHMWPE friction pin (Figure 5), the worn Fe content of the UHMWPE friction pin reaches 0.69% under 15 MPa load, indicating that Fe element is transferred to the UHMWPE surface during the reciprocating friction process, which may lead to negative wear. With the increase in load, UHMWPE gradually deforms plastically, which results in increased material wear. The wear weightlessness is greater than the increased weight caused by the transfer of elements, so that the weights of the material wear quantitative changes are positive. The changes of the wear rate of UHMWPE are the most stable, and the absolute value is the minimum, which shows that UHMWPE can exhibit good wear resistance even when the load is greater than the material yield strength.

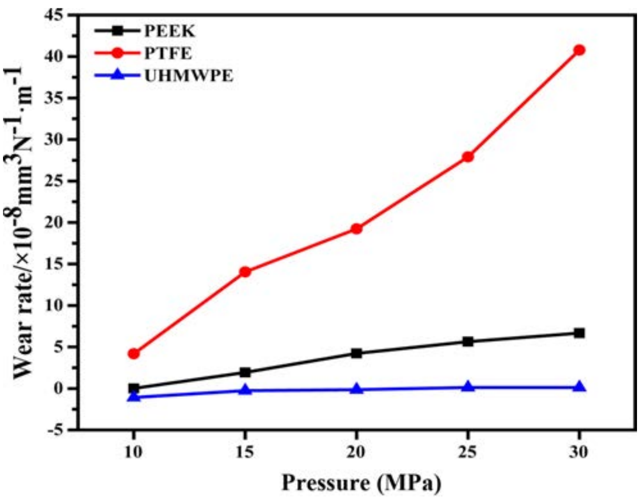

Figure 4. Wear rate curve of PTFE, UHMWPE, and PEEK with the change of load.

With the increase in load, the wear rate of PTFE increases almost linearly, and when the experimental load is greater than the yield strength, the wear rate increases much more than that at low load. The wear rate under a load of 30 MPa is 8 times that under 10 MPa, and the load has a significant impact on the wear behavior of PTFE. This is because the van der Waals attraction between the PTFE molecules is small, which facilitates bond slip. PTFE has good self-lubricating performance, and deforms with the increase in load under the condition of heavy load.[29,30] Table 3 shows the pin sample size measured by white light confocal microscopy. It can be observed that when the test load is less than 20 MPa, the friction end surface of the sample is basically round, and the long axis/short axis is close to 1. When the test load is 25 MPa (close to the yield strength), the deformation of the friction end surface of the sample increases, and it becomes longer along the direction of friction and shorter perpendicular to the direction of friction. At

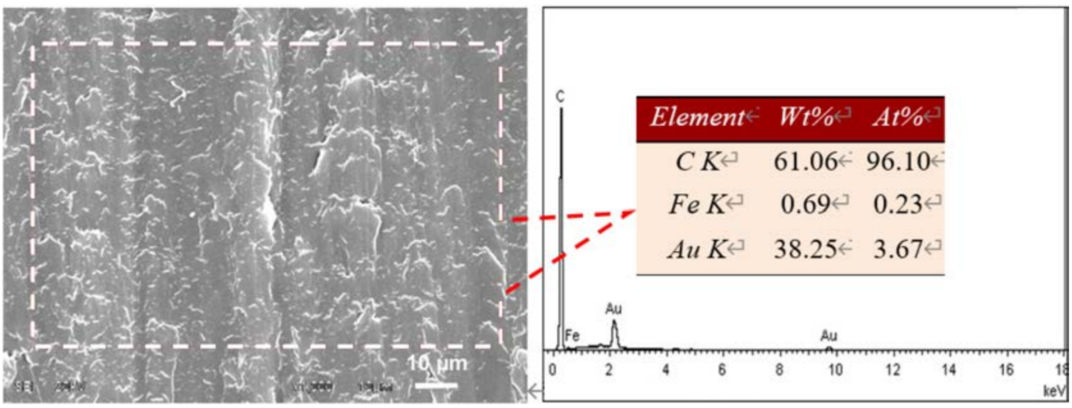

Figure 5. SEM photographs and EDS analysis of UHMWPE after the reciprocating friction experiment under the contact pressure of 15 MPa.

Table 3. Size Changes of PTFE and PEEK after Friction Test under Different Loads

Materials	Load (MPa)	Did not wear	10	15	20	25	30
PTFE	Frictional direction ‘a’ (mm)	2.5949	2.8296	3.1338	3.0758	2.7654	3.0846
	Perpendicular direction to friction ‘b’ (mm)		2.8693	3.2000	3.1768	2.2025	2.5753
	Long axis/short axis (a/b)	/	0.9862	0.9793	0.9682	1.2556	1.1978
PEEK	Frictional direction ‘a’ (mm)	2.4772	2.5288	2.5278	2.4665	2.5149	2.5089
	Perpendicular direction to friction ‘b’ (mm)		2.5133	2.5168	2.4466	2.5006	2.5064
	Long axis/short axis (a/b)	/	1.006	1.004	1.008	1.006	1.005

30 MPa, under the interaction of wear, the friction end surface of the sample presents an irregular ellipse. As the load increases, the change of diameter ratio of the friction direction/perpendicular direction to friction of PTFE indicates that the plastic rheology along the frictional direction is the main factor that affects the frictional and wear properties under the loading conditions close to and exceeding the yield strength.

The wear rate of PEEK is between 0.0561–6.6659×10^{-8} $mm^3N^{-1}\cdot m^{-1}$, and the wear rate and rate of change are between UHMWPE and PTFE. Its friction direction/perpendicular direction diameter is shown in Table 3. The shape of the friction surface of the material basically does not change with the load, which indicates that PEEK has relatively stable mechanical properties under this experimental condition.

Wear Mechanism Analysis. In order to better analyze and compare the friction and wear mechanisms of PEEK, PTFE, and UHMWPE under different loads, the microscopic wear morphologies of the three engineering plastics under reciprocating friction are studied by SEM. Figure 6 shows the microscopic surface morphologies of the three engineering plastics after reciprocating wear and tear after magnification to 1000×. It can be observed from the figure that the load has a significant impact on the wear morphology of the three materials, which is discussed as follows:

The wear morphology of PTFE is complex with change of load. When the experimental load (10 and 15 MPa) is less than the yield strength, the wear morphology of PTFE is characterized by material folding. The material folding under 15 MPa increases more significantly compared with that under 10 MPa, and a few furrows appear. The increase in load increases the material flow and thus aggravates the material wear. When the experimental load (25 MPa) is equivalent to the yield strength, the wear surface is gradually smoothed with the increase in material flow. When the experimental load (30 MPa) is greater than the yield strength, partial melting occurs on the surface of PTFE, which further accelerates the wear process of the material. Therefore, the wear rate of PTFE increases significantly with the increase in load, and the wear rate under load greater than the yield strength changes much more than that under lower load, which limits its application under large loads. Simultaneously, the increase in the load shortens the shedding process of the material in the friction process, such that the slope of the friction coefficient increases with the increase in load in the early rising stage. Due to the factors of material melting and stress distribution inequality, PTFE molecular chains break, resulting in part of the flexible chain separating from the matrix. As shown in Figure 3(b), the material separates from the matrix in the form of a transfer film. The transfer film on the surface of the friction pair of 6Cr19Ni10 causes the friction coefficient to have a downward trend in the stable stage when the experimental load is greater than the yield strength.

The wear morphology of UHMWPE is also significantly affected by the load. When the experimental load (10 and 15 MPa) is less than the yield strength, the wear morphology of UHMWPE is mainly furrow wear. When the load increases to 15 MPa, the number of furrows on the UHMWPE surface gradually increases, and a small amount of plastic deformation occurs. When the experimental load (25 and 30 MPa) is greater than the yield strength, the furrows on the surface of the material further increase in number than those under small loads. When the load is 30 MPa, due to the effect of high cycle contact stress, repeated deformation of the material accelerates fatigue. Hence, fatigue wear occurs and leads to not only furrow wear but also, cracks on the surface of UHMWPE. Therefore, the wear rate of UHMWPE increases with increase in load. However, compared to PEEK, under the same load, the furrows are more obvious, and hence the wear rate of UHMWPE is less than that of PEEK, indicating that the load has an insignificant effect on the wear rate. Under the load greater than the yield strength, both have good wear resistance, which is consistent with the result shown in Figure 4. When the load

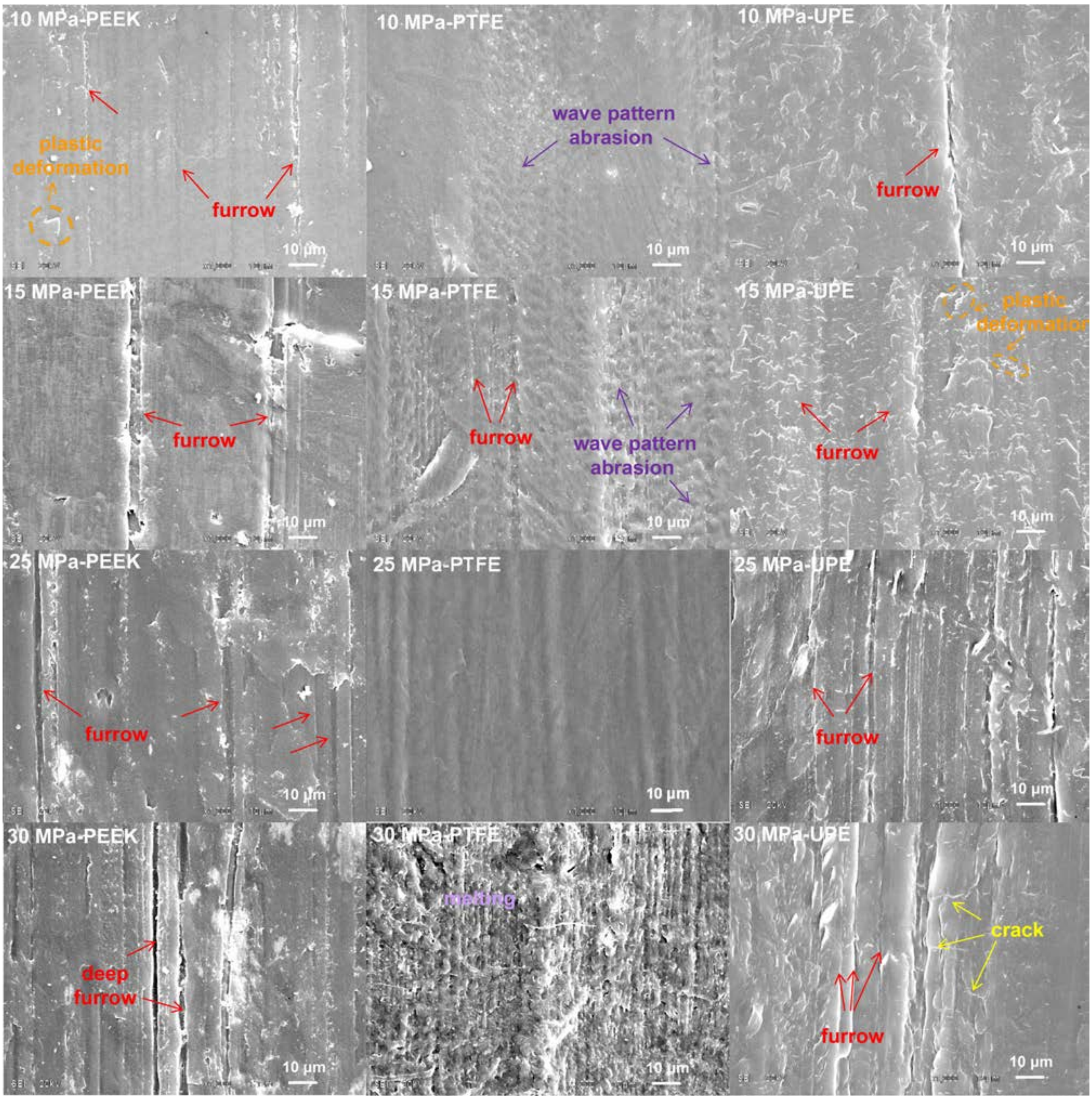

Figure 6. SEM images showing the worn surfaces of PEEK, PTFE, and UHMWPE under different contact pressures.

is greater than the yield strength, in the initial friction stage, the contact of the rough peaks of the UHMWPE surface leads to rapid increase in the actual contact stress, and the reduction of the friction coefficient. Subsequently, as the friction surface furrows and cracks appear due to friction, the roughness increases gradually. Therefore, under the load of 30 MPa, the friction coefficient of UHMWPE decreases first and then increases.

The strength of PEEK is so high that all the experimental conditions in this study have not reached the yield strength of the material yet. The wear surfaces are all shown as furrows or scratches along the direction of sliding friction. Under 10 MPa load, the wear surface appears to have shallow furrows with a small amount of plastic deformation. With the increase in load (15 and 25 MPa), the number of furrows gradually increases. At 30 MPa, the PEEK surface shows wear morphology consisting of more obvious furrows. The main reason is that the PEEK surface roughness peaks locally cause stress concentration on the furrows. With the increase in load, the roughness peaks and abrasive chips are embedded and generate a high contact stress under the action of normal loads. Hence, the degree of mutual embedding is strengthened, which results in more furrows. Therefore, with the increase in load, the wear rate increases gradually, and is slightly greater than that of UHMWPE, but assumes a low value.

Conclusions

In this study, we have examined the effect of loads on the tribological and wear properties of PTFE, UHMWPE, and PEEK. The conclusions are summarized as follows:

(1) PTFE has good running performance, with the lowest average friction coefficient and is least influenced by load. However, at the instant the friction coefficient fluctuates under high load, the wear rate clearly increases with the increase in load. When the load exceeds the yield strength, the rheology of the material aggravates the wear. Therefore, the application under high load conditions is limited.

(2) The average friction coefficient of UHMWPE is slightly higher than that of PTFE, and the friction coefficient gradually decreases with the increase in load. The wear rate of UHMWPE is the least affected by the load among the three materials. Even when the load exceeds the yield strength, the wear resistance is still good. Therefore, it is widely used under the load condition of 30 MPa or higher.

(3) PEEK has high mechanical strength. The test conditions in this study are not as high as its yield strength, and the wear rate gradually increases with the increase in load, which is slightly greater than UHMWPE, but assumes a low value. The friction coefficient decreases with the increase in load, but maintains a high value that restricts its application in sliding friction pair materials to some degree.

(4) The wear mechanism of the three materials evidently differs with the load. The wear mechanism of PTFE under small loads (10 and 15 MPa) is material folding. As the load increases, the folding increases. When the load reaches 30 MPa, PTFE melts. Under low loads (10 and 15 MPa), the wear mechanism of UHMWPE is furrow wear and a small amount of plastic deformation occurs. As the load increases, the furrows gradually increase in number and become more obvious. When the load reaches 30 MPa, the wear mechanism is furrow wear and crack fatigue wear. The wear mechanism of PEEK is mainly furrow wear, and the furrows increase in number and become more obvious with the increase in load.

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