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A comparative investigation of the wear behavior of PTFE and PI under dry sliding and simulated sand-dust conditions

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ABSTRACT

The wear behavior of polytetrafluoroethylene (PTFE) and polyimide (PI) has been comparatively evaluated under dry sliding and simulated sand-dust conditions. An improved block-on-ring wear tester equipped with an attachment for simulating the sand-dust environment was used to evaluate the abrasive wear behavior of materials. The sand collected from the Yellow River of China was used to simulate the sand-dust environment, also different loads and sand-dust sizes were chosen for tribological tests. The two chosen polymers showed different wear behavior under sand-dust conditions and the wear rates of PTFE were much lower under sand-dust conditions than under dry sliding conditions. This was attributed to the formation of the tribolayer on the worn surfaces during the abrasive wear process. The sand-dust enhanced the wear resistance of PTFE, but reduced that of PI because, in contrast to PTFE, there was no tribolayer formed on the PI worn surface. The wear rate of PTFE increased under sand-dust conditions while the wear rate of PI decreased with the increase of applied load. The higher hardness of PI and fragmentation of abrasive particles under high loads accounted for the decrease in wear rate as load increased.

1. Introduction

Sand-dust and sandstorm have caused huge destruction to the environment and human society we rely on for living. Floating sand-dust, by way of producing severe abrasive wear, can cause catastrophic failure of the braking system of various vehicles, excessive wear of wheel–rail systems and trouble of the connector between the slider and electric wire of electrically driven automobiles and trains. It has been estimated that abrasive wear loss accounts for nearly 50% of all the wear problems in industry [1]. So, it is imperative to study the effect of sand-dust on the wear behavior of various materials used for the mechanical components running in the floating sand-dust environment, so as to seek for countermeasures for effectively reducing the wear loss and failure of the mechanical systems therein.

Polymers and their composites are useful materials for their applications in automotive components and other engineering applications such as conveyor aids, chute liners, power, mining, agriculture, etc. [2,3], which had to run in the sand-dust or sandstorm environment in some regions. In this paper, two kinds of typical polymers were chosen as the research subjects aiming at selecting matching materials for the application of mechanical components running in the sand-dust or sandstorm environment.

This research has two novel points that other literatures have not dealt with. Firstly, although many investigations have been conducted on the abrasive wear behavior of various materials as well as testing methods [4–11], few papers have been published on the comparison of the wear behavior of polymer materials under dry sliding and sand-dust conditions. Secondly, three-body abrasive wear has been widely studied using dry sand/rubber or steel wheel abrasion tester which was usually performed by using the sand feeder to introduce the sand into the contact zone of the frictional pair. However, these approaches have great limitations because the sand flowing rates used in above tests are significantly higher when compared with the sand-dust concentration in nature and sand particles do not freely enter into the contact zone. In this paper, sands were blown up uniformly distributing around the frictional pair to provide the simulated sand-dust environment, which is similar to the sand-dust environment in nature and distinctive from other test methods.

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2. Experimental

2.1. Material specimens

The particle sizes of polytetrafluoroethylene (PTFE) powder and polyimide (PI) powder used in this study were screened to be smaller than 50 μm and about 250 μm, respectively. All the polymer specimen blocks with a size of 6 mm × 7 mm × 30 mm were prepared by compression molding. PTFE powders were compressed in a mold at a pressure of 50 MPa for 2 min and after pulled off from the mold, the specimen block was sintered at a temperature of 375 °C for 4 h in a stove in air. Then, the specimen was cooled with the stove. PI powders were compressed in the mold at a pressure of 120 MPa for 2 min. Then the molded specimen in the mold was sintered at a pressure of 40 MPa and a temperature of 345 °C for 40 min in a stove and then cooled to the room temperature at the pressure of 40 MPa in the stove.

The properties of the tested specimens are listed in Table 1.

2.2. Characterization

The compressive strength of polymer specimens were measured using a DY35 universal material tester (ADAMEL Corporation of France) in accordance with GB/T1041-92 (national standard of the People's Republic of China, test methods for determination of compressive properties of plastics, equivalent to ISO 604-1973). The testing speed was 10 mm/min. The shore-hardness figures of polymer specimens were determined by conducting on a LX-D rubber shore hardness tester (manufactured by Jiangdu Mingzhu Testing Machine Factory, China). The microhardness of the counterpart steel ring was examined on an MH-5-VM microhardness meter (manufactured by Shanghai Everone Precision Instruments COR. Ltd., China), at a load of 100 g for 5 s. All the compressive strength, shore-harness and microhardness test were conducted five replicate measurements. The average of the five replicate tests is reported in this paper.

The worn surfaces of the specimens were firstly coated with a thin layer of gold and then observed on a JSM-5600LV scanning electron microscope (JEOL, Japan). The elemental compositions of abrasive sands were determined by energy dispersive spectroscopy (EDS) attached to the JSM-5600LV scanning electron microscope.

Table 1
The properties of two polymers

Material	Density (g/cm^3)	Shore hardness (HD)	Compressive strength (5%, MPa)
PTFE	2.2	60 ± 1	13.6
PI	1.38	86 ± 1	109.1

Table 2
Chemical composition of abrasive sands determined by EDS

Element	Content (wt.%)
O	2.25–2.47
Si	65.91–69.61
Cl	0.61–0.74
Ca	6.44–8.66
Al	4.89–6.54
Fe	9.41–11.29
K	4.43–8.73
Mg	1.38–2.00

2.3. The wear tests under dry sliding and sand-dust conditions

The dry sliding and sand-dust abrasive wear tests were done using an improved block-on-ring tester (Model M-2000, manufactured by Xuanhua Material Testing Machine Factory, China) equipped with an attachment for simulating the floating sand-dust environment. A sealed chamber with a round slot at the bottom, for inletting abrasive sands carried by compressive air, was assembled with the block-on-ring tester. The details of the block-on-ring tester were given in [12,13], while the schematic views of the frictional pair and the attachment of simulating the sand-dust environment are shown in Fig. 1. The natural sands used as the abrasive were collected from the Lanzhou reach of the Yellow River of China. Two different particle size range of sands used in the abrasive tests are 97–150 μm and 150–356 μm. The chemical composition and morphology of abrasive sands are shown in Table 2 and Fig. 2, respectively. Before starting abrasive wear tests, a proper pressure of compressive air was introduced into the sealed chamber through the round slot to float the sand particulates pre-placed therein (see Fig. 1b). It is supposed to be able to simulate the floating sand-dust environment in nature. During the abrasive wear process, floating sand-dust was ensured to exist steadily surrounding the frictional pair.

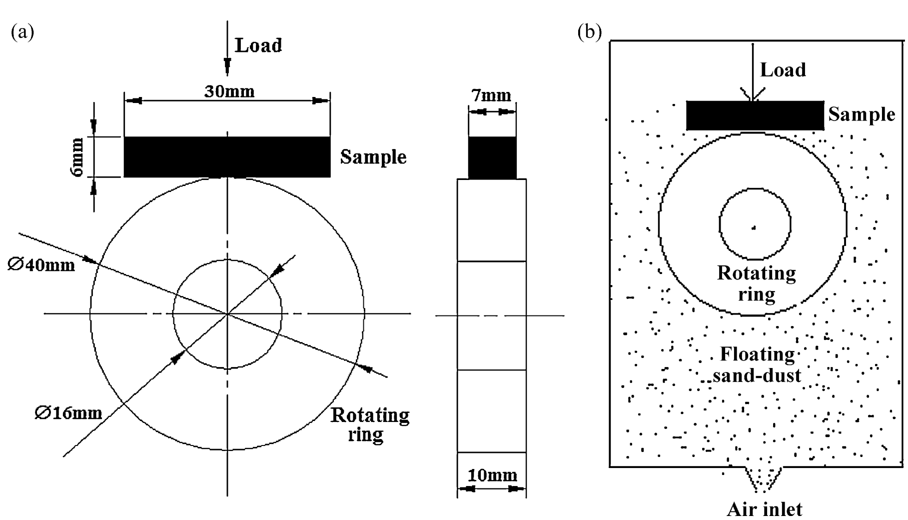

Fig. 1. Schematic illustration of (a) contact configuration of frictional pair and (b) the attachment of simulating sand-dust environment for block-on-ring tester.

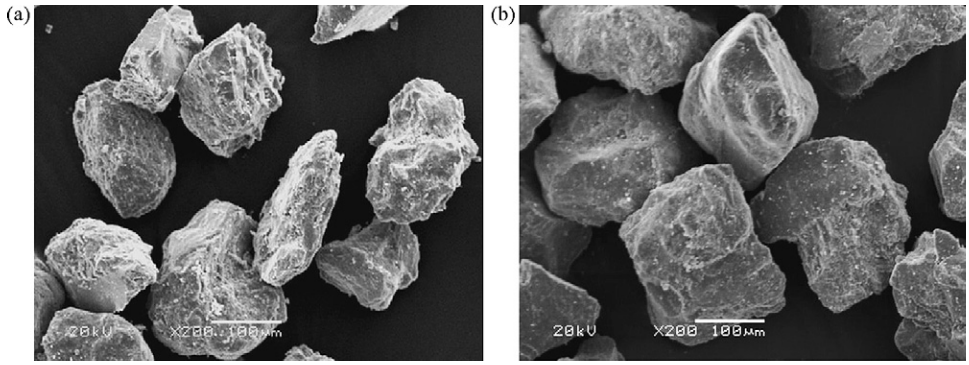

Fig. 2. SEM morphologies of the sand abrasives with the size of (a) 97–150 μm and (b) 150–356 μm.

All the wear tests were performed at a fixed sliding velocity of 0.424 m/s, ambient temperature about 20 °C, the relative humidity about 50%, and under different loads of 50 N, 100 N, 150 N, 200 N, 250 N and 280 N. The sand dosage of all the wear tests under sand-dust conditions was controlled to 25 mg/cm^3 ± 2 mg/cm^3 by properly adjusting the feeding amount of abrasive sands. The counterpart was AISI-1045 steel ring ($HV_{100\,g}$ 277–305) and driven by a motor to rotate against the stationary upper specimen block under a normal load. Before each test, the counterpart ring was polished with 1000-grade emery paper to a surface roughness of about 0.064 μm, and the specimen block and the counterpart ring were both cleaned with acetone and dried in air. The width of the wear scar on specimen blocks was measured with a digital-reading microscope to an accuracy of 0.01 mm and the wear rate ω of the specimen was calculated from the relationship:

$$\omega = \frac{[\pi R^2/180\ \arcsin(d/2R) - d/2\sqrt{R^2-(d/2)^2}]B}{SP}$$

where ω refers to the wear rate of the upper block (mm^3/N m), R to the radius of the counterpart ring (mm), d to the wear scar width of the upper block (mm), S to the sliding distance (m), P to the applied load (N), and B to the width of the upper block specimen (mm). Three replicate friction and wear tests were carried out and the average of the three replicate test results was reported in this paper.

3. Results and discussion

3.1. Effect of sand-dust on the tribological behaviors of PTFE and PI

The wear rates of PTFE and PI blocks sliding against AISI-1045 steel ring, under the three test conditions of dry sliding, 97–150 μm sand-dust and 150–356 μm sand-dust, as a function of the applied load are shown in Fig. 3. The wear rates of PTFE are much lower under sand-dust conditions than under dry sliding conditions (Fig. 3a) whereas the wear rates of PI are relatively higher under sand-dust conditions (Fig. 3b). As previously described by Deuis et al. [14], abrasive sands can enhance the wear resistance of materials by way of forming a tribolayer on contact surfaces. It was proved in Section 3.2 that abrasive particles can be embedded in the specimen surfaces of PTFE with low hardness and then the tribolayer was formed under the load, which results in the better wear performance of PTFE under sand-dust conditions. In contrast to PTFE, no tribolayer was formed on the specimen surfaces of PI, which leads to the poor wear performance under sand-dust conditions. It is relatively difficult for abrasive particles to be embedded in the specimen surfaces of PI with relatively high hardness, which may be the reason for the absence of the tribolayer formation on the worn surfaces of PI. As a result, sand-dust mostly played the role of three-body abrasives to attack the specimen surfaces of PI and aggravated the material damage.

As shown in Fig. 3a, the wear rate of PTFE increases with the increase of applied load under aforementioned three test conditions, which is in agreement with previous reports [2,5,11,15]. In contrast to PTFE, the wear rate of PI under sand-dust conditions is observed to decrease with the load. The similarly unexpected behavior was also observed by Ma et al. for the investigations on the abrasive wear behavior of D2 tool steel sliding against dry sand/rubber wheel [15]. The reason for this may be that it is more difficult for abrasive particles to enter into the contact zone under higher loads. This is testified by SEM analysis as shown in Fig. 8 (explained in detail in Section 3.2). Fig. 4 shows the SEM pictures of abraded sands collected from the contact zone after the wear test on PI. As for the abrasive wear test at low load, sand surfaces do not show significant changes in morphology by SEM observation

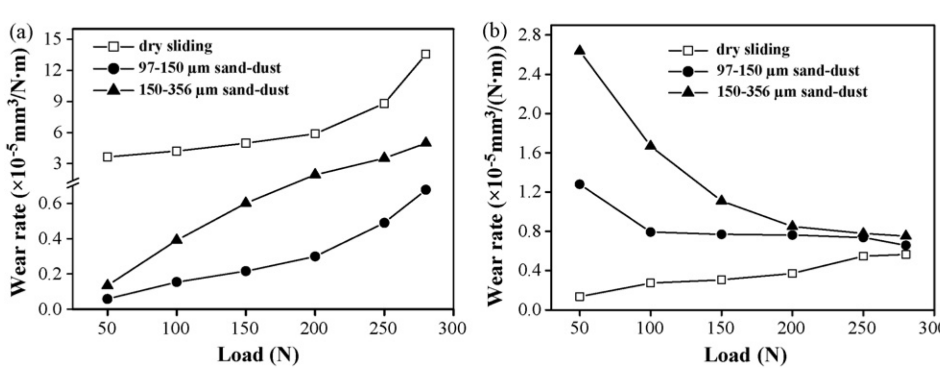

Fig. 3. Variations of the wear rates with applied load under three different test conditions for (a) PTFE and (b) PI.

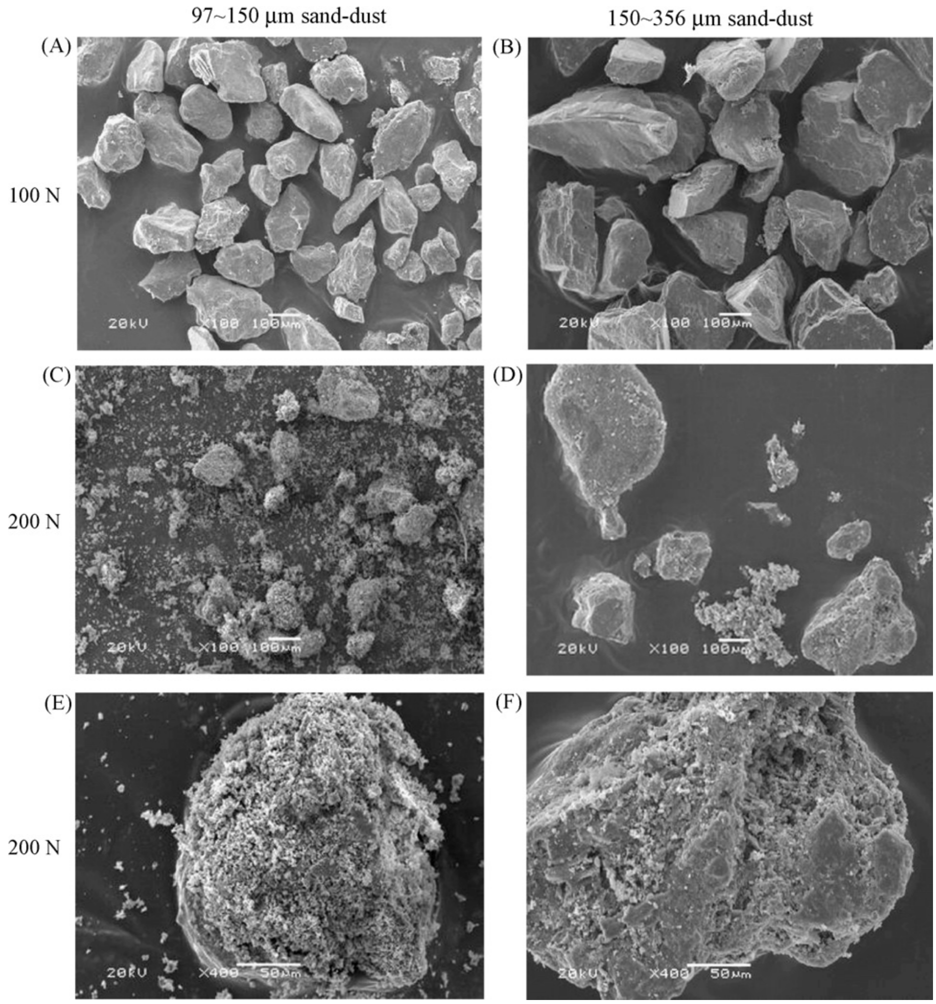

Fig. 4. SEM photographs of abrasive sands with two different sizes after the wear test of PI at: (A), (B) 100 N and (C), (D) 200 N. (E) and (F) are the magnified views for (C) and (D), respectively.

(Fig. 4A and B). Contrary to the above, the damage to abrasive sands at high load is considerably severe, and the obvious crack and fragmentation of the sand happened obviously (Fig. 4C–F). It can be concluded that smaller amounts of abrasive sands in the contact zone resulted in higher forces on each particle, and hence abrasive sands were fragmentized into smaller size particles when used to test PI under high loads. In case of PTFE, surface damage of abrasive sands was almost negligible for all applied loads.

The similar wear behavior both for PTFE and PI is that the wear rates produced by abrasion with 150–356 μm sand-dust were higher than those for abrasion with 97–150 μm sand-dust (Fig. 3). It is easier to enter into the contact zone for a small sand particle when compared with a large one and there would be more small size abrasive particles in the contact zone at the same load. Therefore, sand-dust with small size produced less damage to the specimen since the forces exerted on each small particle were relatively lower when compared with that exerted on each large one. As a consequence, the wear losses of polymer materials produced by small abrasives were lower than that produced by large ones.

3.2. Abrasive wear mechanism and scanning electron microscopy studies

In order to understand the effect of natural sands taken from the beach of Yellow River on the wear behavior of PTFE and PI, the morphologies of their worn surfaces were examined using SEM. Fig. 5 shows the worn surfaces of polymer blocks under dry sliding and different size sand-dust conditions at 280 N. It is observed that the worn surface abraded by 97–150 μm sand-dust (Fig. 5PTFE-B) is characterized by many white regions, with plastic deformation, craters and ploughing. Above white regions were proved to be abundant in element silicon and aluminum by EDS and were termed as “tribolayer” consisting of the matrix, abrasives and debris. The tribolayer formation would also be verified in the following section. However, the worn surfaces under dry sliding (Fig. 5PTFE-A) and 150–356 μm sand-dust conditions (Fig. 5PTFE-C) were both quite smooth and uniform. It is attributed to that the larger abrasive sand was difficult to enter into the contact zone at the high load of 280 N. So the worn surface abraded by 150–356 μm sand-dust was so similar to that suffered from dry sliding wear test. However, a few shallow grooves on the worn surface of dry sliding and some characteristics of fatigue wear on that of 150–356 μm sand-dust were observed. SEM analysis showed that the worn surfaces of PTFE abraded by 150–356 μm sand-dust at 250 N were also smooth with a few grooves, similar with Fig. 5PTFE-C. Except for this, the tribolayer on the worn surfaces were observed in the case of the other sand-dust test conditions for PTFE, with the evidence of plastic deformation and fatigue wear, which were similar with Fig. 5PTFE-B.

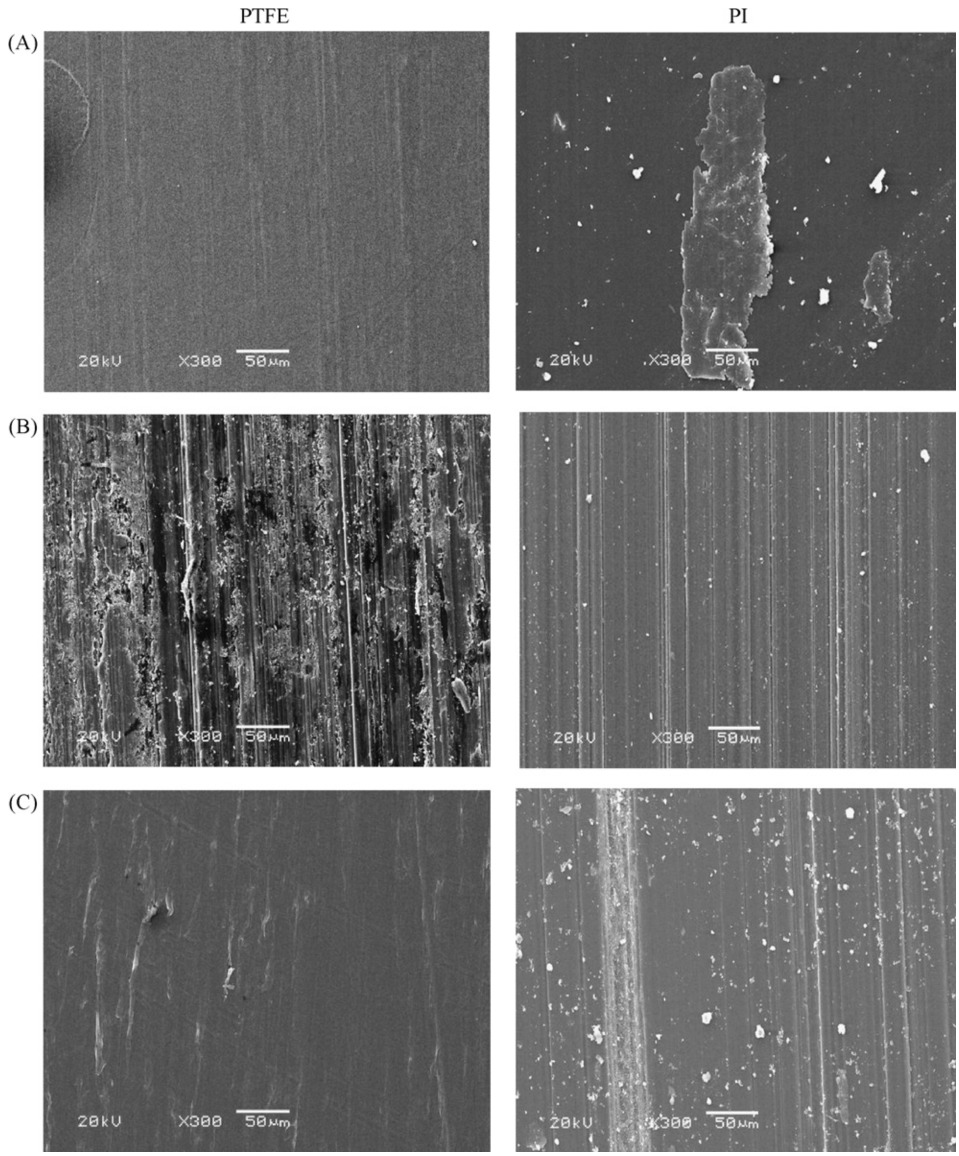

Fig. 5. SEM photographs of abraded PTFE and PI at 280 N under: (A) dry sliding; (B) 97–150 μm sand-dust condition; (C) 150–356 μm sand-dust condition.

From Fig. 5PI-A, the peeling off in pieces of materials under the cyclic stresses during the wear process of dry sliding was observed. The wear scars of PI abraded by natural sands for all the applied loads showed similar morphologies with the evidence of sliding abrasive wear primarily but without the tribolayer formation, as shown in Fig. 5PI-(B and C). This can explain why sand-dust enhanced the wear resistance of PTFE and aggravated the wear of PI.

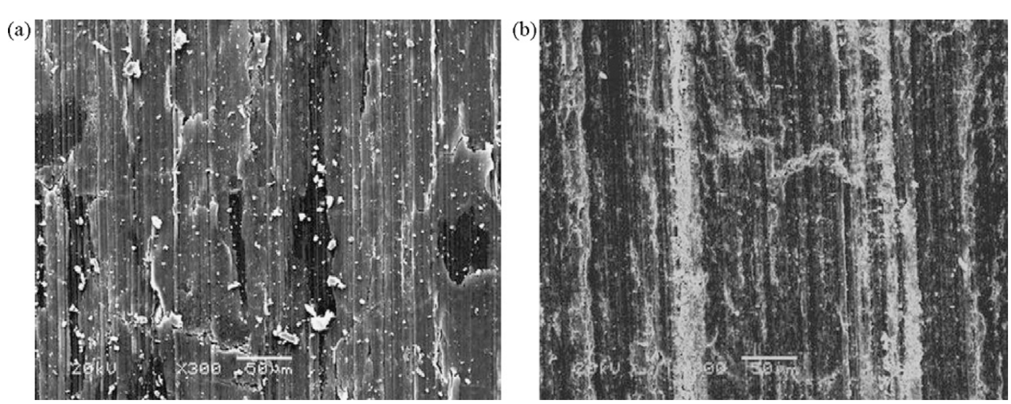

Fig. 6. SEM photographs of worn surfaces of (a) PTFE-based composite under 97–150 μm sand-dust at 200 N; (b) pure PTFE under 150–356 μm sand-dust at 200 N.

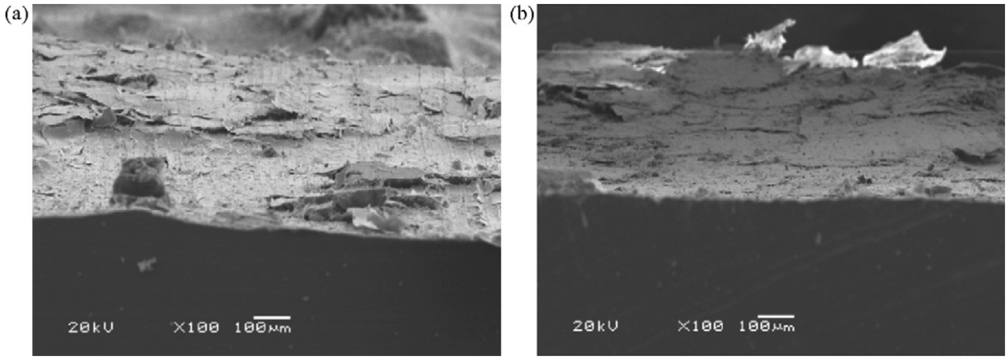

Fig. 7. SEM photographs of the cross-sections of the worn surfaces of PTFE abraded by sand-dust of (a) 97–150 μm and (b) 150–356 μm at 200 N.

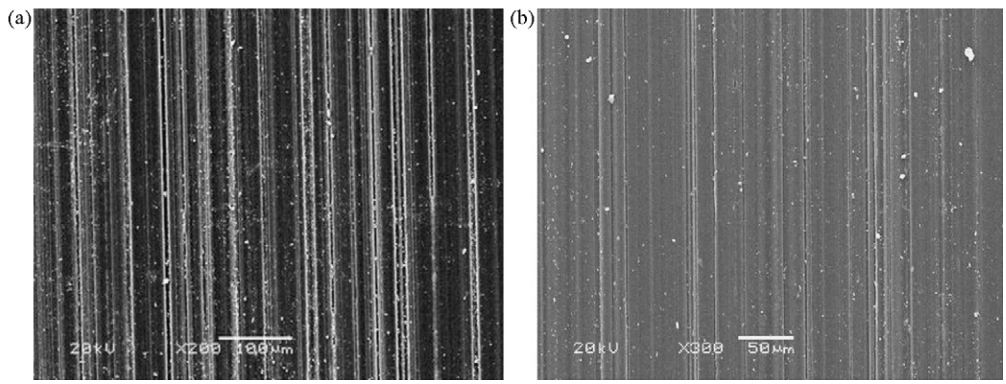

Fig. 8. SEM photographs of abraded PI under 97–150 μm sand-dust condition at: (a) 50 N and (b) 280 N, respectively.

In order to prove the formation of the tribolayer on the worn surfaces of PTFE, the PTFE-based composites reinforced with 5 vol.% natural sand were prepared by compression molding. The filling sands with the particle size of smaller than 56 μm and density of 2.6691 g/cm^3 were also collected from the Lanzhou reach of the Yellow River of China. Fig. 6a shows the worn surface of PTFE-based composite abraded by 97–150 μm sand-dust at 200 N. Fig. 6b shows the worn surface of pure PTFE block abraded by 150–356 μm sand-dust at 200 N, on which there are also many white regions of the tribolayer. When compare Fig. 6a with Fig. 5PTFE-B and Fig. 6b, it is seen that the worn surfaces of pure PTFE are very similar with the worn surface of PTFE-based composite reinforced with natural sands. It indicates that sand-dust can be embedded in the specimen surfaces of pure PTFE to form the tribolayer under sand-dust conditions, which enhances the wear resistance of PTFE. Additionally, cross-sections through the wear scars (see Fig. 7) also confirm the existence of the tribolayer with the thickness of about 250–500 μm.

Fig. 8 shows the SEM pictures of the worn surfaces of PI for abrasion with 97–150 μm sand-dust at 50 N and 280 N. Under the low load, abrasive wear happened severely, with deep and wide grooves on the worn surface. Under the high load, the worn surfaces are relatively smooth with some evidence of ploughing. Compare Fig. 8a with Fig. 8b, the aforementioned idea can be testified that there are smaller amounts of abrasive sands entered into the contact zone under high loads. In addition, there is no evidence of the tribolayer formation on the worn surfaces of PI abraded by sand-dust based on the SEM pictures. As a result, sand-dust played a role of aggravating the PI block damage.

4. Conclusion

Based on the comparison of the wear behavior of PTFE and PI under dry sliding and simulated sand-dust conditions, the following conclusions can be drawn:

(i) Floating sand-dust in the atmosphere may produce different effects on different materials by way of improving or deteriorating the wear performance.
(ii) Sand-dust in the contact zone of the frictional pair enhanced the wear resistance of PTFE in the range of applied loads, while it reduced the wear resistance of PI. The tribolayer formation seems to be a dominating factor for the wear behavior of PTFE and PI under sand-dust conditions, which determines that whether sand-dust provide positive or negative effect during the abrasive wear process of materials.
(iii) Under dry sliding conditions, the wear rates of PTFE and PI both increased with the increase of load. Under sand-dust conditions, the wear rate of PTFE still increased but the wear rate of PI decreased with the increase of load. The reason for this may be that abrasive sands suffered from more severe fragmentation under high load than under low load when used for testing PI.
(iv) A higher wear rate was observed for both PTFE and PI under larger size sand-dust. This is due to that the number of large abrasive particles capable to enter into the friction zone is less than that of small abrasive particles, so the forces exerted on each large particle are larger than that exerted on each small one. The large size particle under larger forces produced more severe damage to the specimen.

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