JMEPEG (2024) 33:5667–5681
https://doi.org/10.1007/s11665-023-08337-y

TECHNICAL ARTICLE

Effect of Silicon Carbide Particles on Tribological Properties of Polytetrafluoroethylene Water-Lubricated Bearing Composites

Shengkang Dong, Zhiwei Guo, Hongshuang Zang, and Chengqing Yuan

Submitted: 6 April 2023 / Revised: 29 April 2023 / Accepted: 12 May 2023 / Published online: 23 May 2023

Polytetrafluoroethylene (PTFE) has great potential for applications in water-lubricated bearings; however, in heavy load conditions at low speeds, PTFE suffers from severe friction and abrasion because of its poor wear resistance. In this study, silicon carbide (SiC) content and particle size are investigated in relation to PTFE water-lubricated composites' tribological properties. The results show that the wear resistance of PTFE composites can be significantly improved when the filling amount of SiC particles was between 3 and 5 wt.%, and the composites containing 5 wt.% SiC reduced wear loss by 99.44%. The composites' friction and wear properties decreased as SiC particle size increased, and wear mechanism for the composites shifted from adhesive to abrasive. Wear loss on PTFE composites filled with 40 nm SiC particles was reduced by 97.03%, showing the best wear resistance. This study provides an experimental basis for the development of high-performance PTFE water-lubricated bearings.

Keywords PTFE, SiC particle, tribological properties, water-lubricated bearing, wear mechanisms

1. Introduction

In the shipbuilding and shipping industries, environmental protection and energy conservation are becoming a priority (Ref 1). Lubricant leakage during ship operations is one of the leading causes of water pollution and loss of ship's invisibility. Therefore, green lubrication technology with water or water-based as lubrication medium has been concerned by many researchers (Ref 2). Water-lubricated bearings use water instead of traditional lubricant as the lubrication medium, which is environmentally friendly, low cost, good safety, and easy maintenance. Because of water's low viscosity, insufficient lubrication and increased wear are common problems with water-lubricated bearings, which makes finding suitable materials challenging (Ref 3-8).

As a polymer material with excellent self-lubricating properties, PTFE is highly suitable for use in water-lubricated bearings. However, the poor wear resistance of PTFE limits its direct application as friction components and mechanical parts (Ref 9-11). At present, researchers mainly modify the shortcomings of PTFE by surface modification, blending modification and filling modification (Ref 12-14). The surface modification of PTFE with gamma-ray irradiation was studied by Chai et al. (Ref 15). Cracks generated after irradiation accelerated the spalling of large materials, increasing the wear rate of composites. Surface modification of PTFE is expensive, and it is easy to damage its structure, which reduces its performance. Wang et al. prepared a series of poly (p-phenylenediamine) (AP) modified PTFE composites by blending modification (Ref 16). According to their research, although blending modifications can improve wear resistance, performance improvement for PTFE composites was limited.

Filling modification is simple, can maintain the excellent properties of PTFE to improve wear, and has broad application prospects. Xu et al. investigated the wear resistance of Ti_3SiC_2 and graphite filled modified PTFE composites, respectively (Ref 17). In their experiment, only 1 wt.% of Ti_3SiC_2 can reduce the wear rate by two orders of magnitude. Past studies by different authors showed that SiC, as a filling material, has significant characteristics such as reliability, reduced friction and wear, high thermal conductivity, and low prices reduced manufacturing costs (Ref 18, 19). In addition, most researchers only focus on dry friction or oil lubrication for the relevant modification research of PTFE composites, while few studies have been carried out for specific engineering applications and water lubrication environment, ignoring the effect of the nature and size of micro-nano fillers on the properties of PTFE composites.

The purpose of this paper is to investigate how SiC particles affect the wear resistance of PTFE composites when lubricated with water. By means of filling modification, SiC content and particle size were analyzed to determine their effects on tribological performance of PTFE composites with water environment, and the influence mechanism was revealed. The results of this study provide data support and a theoretical basis for developing and optimizing PTFE-based water-lubricated bearings.

Shengkang Dong, Zhiwei Guo, Hongshuang Zang, and **Chengqing Yuan**, School of Transportation and Logistics Engineering, Wuhan University of Technology, Wuhan 430063 Hubei, China; and National Engineering Research Center for Water Transportation Safety, Reliability Engineering Institute, Wuhan 430063 Hubei, China. Contact e-mail: zwguo@whut.edu.cn.

2. Materials and Methods

2.1 Testing Material

PTFE suspension resin brand was JF-4TN-S; average particle size was 30 microns (Zhejiang Juhua Co., Ltd., Zhejiang, China); SiC particles had a diameter of 40 nm, 1 μm, 100 mesh (149 μm), made by Shanghai McLean Co., Ltd; The particle size of SiC was 400 meshes (37 microns), made by Shanghai Aladdin Co., Ltd. Water lubrication test used Watson's professional distilled water.

2.2 Sample Preparation

In order to make the PTFE resin suspension powder better mix with the filler, it was pretreated before the test. The PTFE resin suspension powder was placed in the oven at 80 °C for 5 h to remove the possible moisture and then, cooled for 30 min at 15-20 °C constant temperature to reduce agglomeration. After 60 mesh screening, the PTFE resin suspension powder was dispersed and dried. To further enhance the dispersion of filler, the particles were pretreated. A certain amount of filler particles was weighed and added to anhydrous ethanol to prepare a suspension. Then, the mixed solution was placed in a magnetic stirrer for high-speed stirring. During the high-speed stirring process, a coupling agent with a filler mass percentage of 2 wt.% was added to the mixed solution to ensure good dispersion. The mixing process was heated by water bath, the temperature was maintained at about 75 °C, and the time was 2 h. Eventually, it was dried in an oven, and the filling material after surface treatment was obtained after drying.

A series of composite samples were prepared by cold pressing sintering method for subsequent testing, as shown in Table 1. Figure 1 illustrates the experimental process. PTFE and SiC particles were fully mechanically stirred and mixed, and then, the mixture was cold pressed sintered to obtain PTFE composites. The process of mechanical mixing was carried out by a grinder. In the process of high-speed rotation of the grinder blade, the friction between the blade surface and the material as well as the thrust of the side on the material made the mixture move along the tangential direction of the blade. Since the speed of the high-speed mixer used can reach 25,000 r/min, and the intermittent mixing was 30 min, the filler and the PTFE suspension fine powder can be mixed at high speed, so that the filler was uniformly dispersed in the PTFE resin fine powder. The cold pressing method was as follows: the PTFE mixture was pre-pressed for 30 min at room temperature under 5 MPa pressure, and then pressed at 50 MPa pressure for 1 h. The sintering method was as follows: the mixture after cold pressing was heated to 330 °C in a high temperature sintering furnace for 30 min, then heated to 380 °C for 4 h, then cooled to 315 °C for 1 h at a cooling rate of 60 °C/h, and finally cooled to room temperature with the furnace. After cooling, it was machined into a ring sample of 18 mm inner diameter, 30 mm outer diameter, and 10 mm thickness.

The grinding pair of a ship water-lubricated stern bearing is mainly made from cast copper, so we chose QSn7-0.2 tin bronze disc as the grinding pair. The inner diameter, outer diameter, and thickness of the QSn7-0.2 disc were 16 mm, 32 mm, and 6 mm, respectively. Table 2 shows elements of the QSn7-0.2 tin bronze disc.

Table 1 Composition of PTFE composite samples (Mass fraction, wt.%)

Sample	1	2	3	4	5	6	7	8
PTFE	100	99	97	95	93	97	97	97
40, nm SiC	…	…	…	…	…	3	…	…
1, μm SiC		1	3	5	7	…	…	…
37, μm SiC	…	…	…	…	…	…	3	…
149, μm SiC	…	…	…	…	…	…	…	3

2.3 Tribological Test

Tribological testing was carried out on the CBZ-1 ship shafting wear tester. MIL-DTL-17901C, the US Navy's water-lubricated bearing test standard, was followed in setting up test conditions. Before the tribological test, surface roughness (Ra) of the friction pair was polished to 0.8 μm using a polishing machine with 400 mesh, 800 mesh, and 1200 mesh sandpapers, respectively. Then, the surface of the samples was cleaned with anhydrous ethanol and dried. The spindle speeds were set to 50, 150 and 250 r/min to simulate low-speed and normal conditions. Since the nominal load of the ship's water-lubricated stern bearing was less than 0.55 MPa, the friction pair was loaded with 0.5 MPa and 0.8 MPa, respectively, to simulate the normal load and heavy load conditions (Ref 20). For the purpose of simulating water lubrication and avoiding the influence of other factors, lubrication was performed with distilled water. Each group of samples was subjected to a tribological test for 120 min. To ensure reliability, the test was repeated twice under each operating condition.

The details of the testing machine were shown in Fig. 2. The ring specimen was fixed in the sink, and Qsn7-0.2 disc was fixed on the shaft. During the test, the load was transmitted upwards, and the friction surface of the samples was immersed in distilled water. The sensors collected torque, load, and other data in real time, and the friction coefficient was obtained by Eq. (1):

$$\mu = \frac{T}{R * F} \qquad \text{(Eq 1)}$$

where T is torque (N·m), R is radius (m), and F is load (N).

2.4 Characterization Equipment

Observing the surface morphology of the samples with scanning electron microscope (SEM; Vega 3, Tescan Co. Ltd, Czech). Wear loss of the composites was measured using a high-precision electronic balance (MS205DU, Mettler-Toledo International Inc., Switzerland). The wear morphology of the copper disk was observed and recorded by LI laser interference surface profiler. Repeat each test measurement at least twice.

3. Results and Discussion

3.1 Effect of SiC Content on Tribological Properties of PTFE Composites

3.1.1 Friction Coefficient Analysis. Figure 3 and 4 show the friction coefficient of PTFE composites under different experimental conditions. Figure 3(a) shows that SiC-1 sample

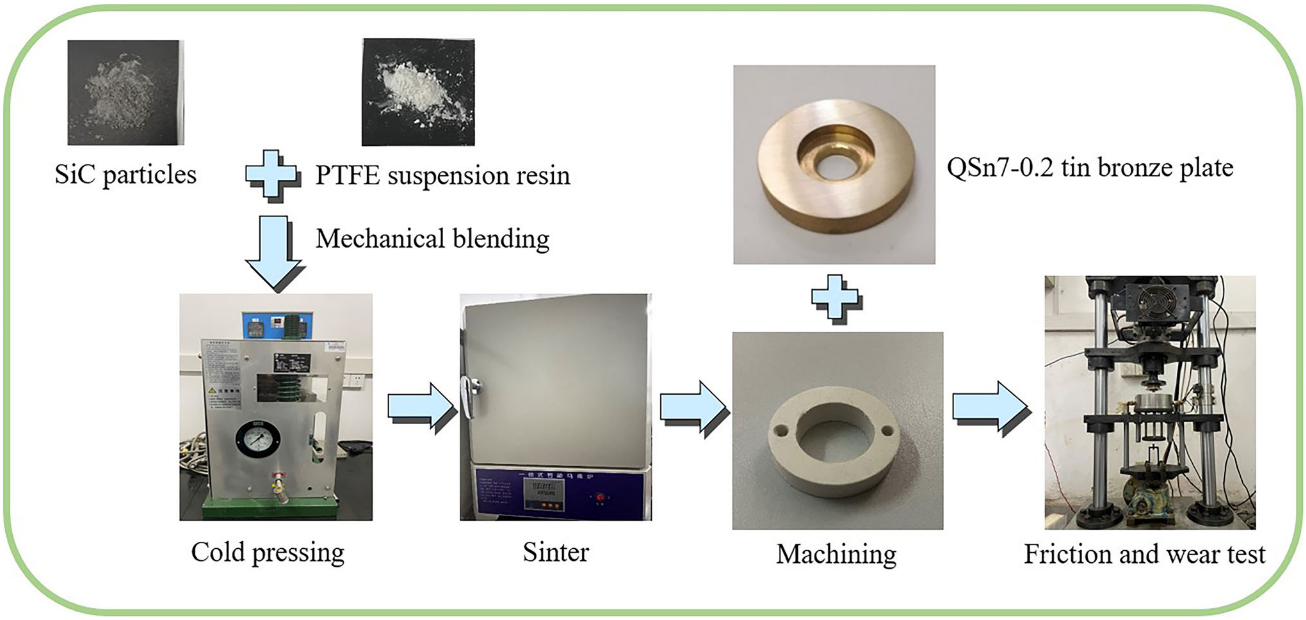

Fig. 1 Experimental flowchart

Table 2 QSn7-0.2 tin bronze disc elements

Cu, wt.%	Zn, wt.%	Sn, wt.%	Ni, wt.%	Al, wt.%	Pb, wt.%	Impurity, wt.%
90 ~ 92	0.3	6 ~ 8	0.2	0.01	0.02	0.15

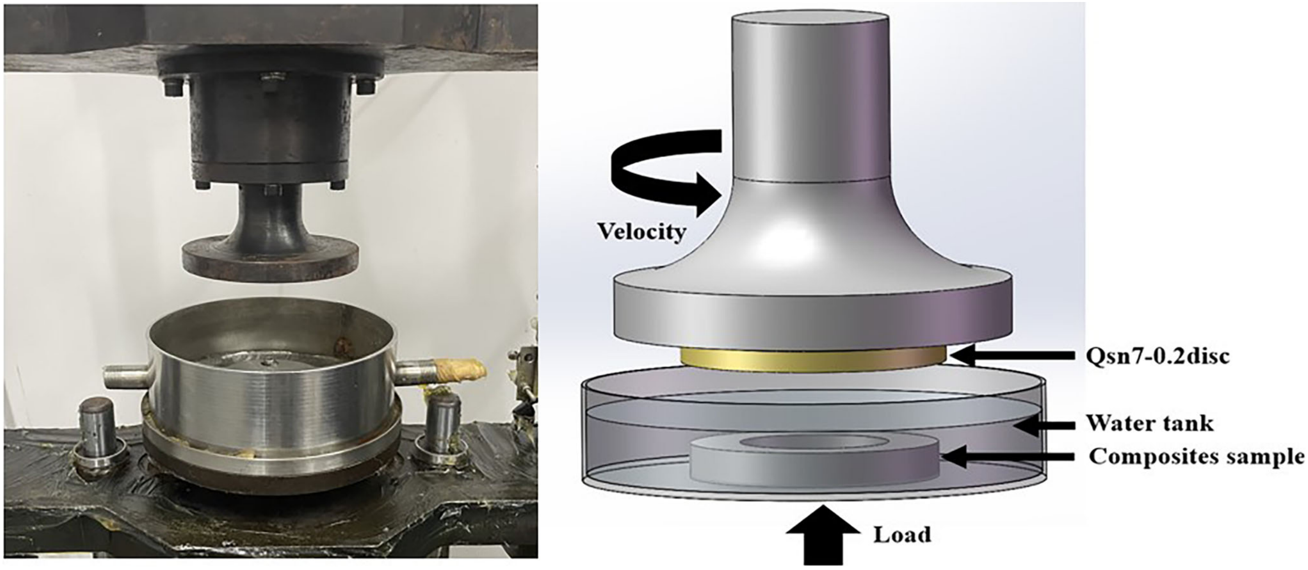

Fig. 2 Schematic diagram of CBZ-1 friction and wear tester

began to wear, and its friction coefficient increased briefly. After a period of time, the friction coefficient was declining and stabilized around 0.17. The friction coefficient of SiC-3, SiC-5, and SiC-7 samples showed a fluctuating downward trend and finally, tended to a stable value. The friction coefficient of SiC-3 sample decreased most obviously, and the friction coefficient was the lowest. Figure 3(b) shows that under the condition of 0.5 MPa and 150 r/min, SiC-1 sample's friction coefficient increased first with test progress. When the test was carried out to 1500 s, the friction coefficient of SiC-1 sample declined to about 0.1 and tended to be stable. The friction coefficient of SiC-3 sample was stable at about 0.075 after a sharp decline in

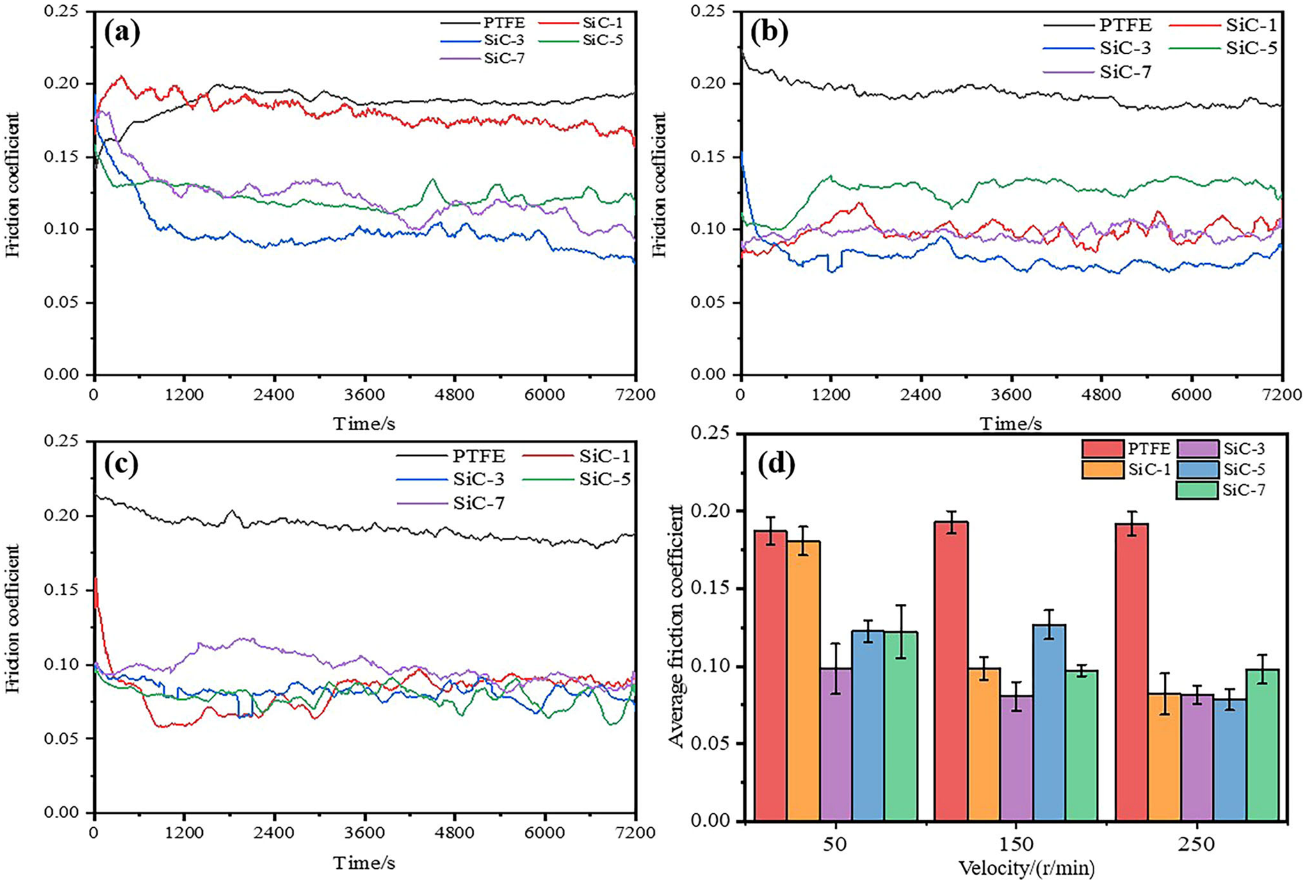

Fig. 3 Friction coefficients of SiC particle-reinforced PTFE water-lubricated bearing composites at different speeds for a load of 0.5 MPa (a) 50 r/min; (b) 150 r/min; (c) 250 r/min; (d) average friction coefficient

the initial stage. The friction coefficient of the SiC-5 sample reached 0.125 after 1200 s of testing, and then stabilized. The friction coefficient of SiC-7 sample fluctuated around 0.1 during the whole test. Similarly, among the five samples, SiC-3 still had the lowest friction coefficient.

Figure 3(c) shows that the friction coefficients of SiC-1, SiC-3, SiC-5, and SiC-7 were significantly lower than those of pure PTFE during the whole test under the condition of 0.5 MPa and 250 r/min. With the progress of the test, the friction coefficient variations of all PTFE composites were relatively stable and fluctuate within their respective stable values. As seen in Fig. 3(d), PTFE composites filled with SiC had a lower average friction coefficient than pure PTFE. At 50 and 150 r/min, the SiC-3 sample showed the lowest average friction coefficient. Over 3 wt.% of SiC filling, the average friction coefficient of composites would increase. When the velocity increased to 250 r/min, SiC-5 samples showed the lowest average friction coefficient, and as the SiC filling amount continued to increase, the average friction coefficient of the sample increased. SiC-5 sample had a slightly better friction coefficient than SiC-3 sample, but not by much.

As shown in Fig. 4(a), (b), and (c), SiC particles reinforced PTFE composites had a significantly lower friction coefficient than pure PTFE at 0.8 MPa. Friction coefficients fluctuated more steadily at three speeds in SiC-3 samples. The average friction coefficient of the composites is shown in Fig. 4(d). Similar to the 0.5 MPa, SiC-3 samples had the lowest friction coefficient even when speeds were 50 r/min and 150 r/min. When the filling content exceeds 3 wt.%, various degrees of increase would be seen in the composite's average friction coefficient. SiC-1 exhibited the lowest average friction coefficient at 250 r/min. However, it did not appear that SiC-3 and SiC-1 had much of a difference in friction coefficient.

Therefore, the addition of a small amount of SiC particles to the PTFE matrix in a water-lubricated environment can improve its tribological properties. Analyzing the reason, PTFE composites have the formation of transfer film during wear process (Ref 21). Within a certain range, a continuous transfer film forms more easily on copper disc's wear surface with increasing SiC content, while the SiC particles can play the role of taking the load, thus improving the tribological performance (Ref 22). Conversely, excessive SiC content will degrade the tribological properties and make the friction coefficient unstable. This may be due to the excessive amount of SiC filling will lead to increased plowing effect and the difficulty of forming a continuous transfer film on the surface of the grinding pair, thus increasing the friction coefficient of the composites.

3.1.2 Wear Loss Analysis. Under various experimental conditions, wear loss of PTFE water-lubricated composites is shown in Fig. 5. As shown in Fig. 5(a), the wear loss of pure PTFE was the largest under 0.5 MPa and increased with the increase in speed. The reason for this was that, on the one hand, because of the low hardness of pure PTFE, it would produce obvious abrasive debris when grinding against the tin bronze disc, and during the wear process, PTFE transfer film would be

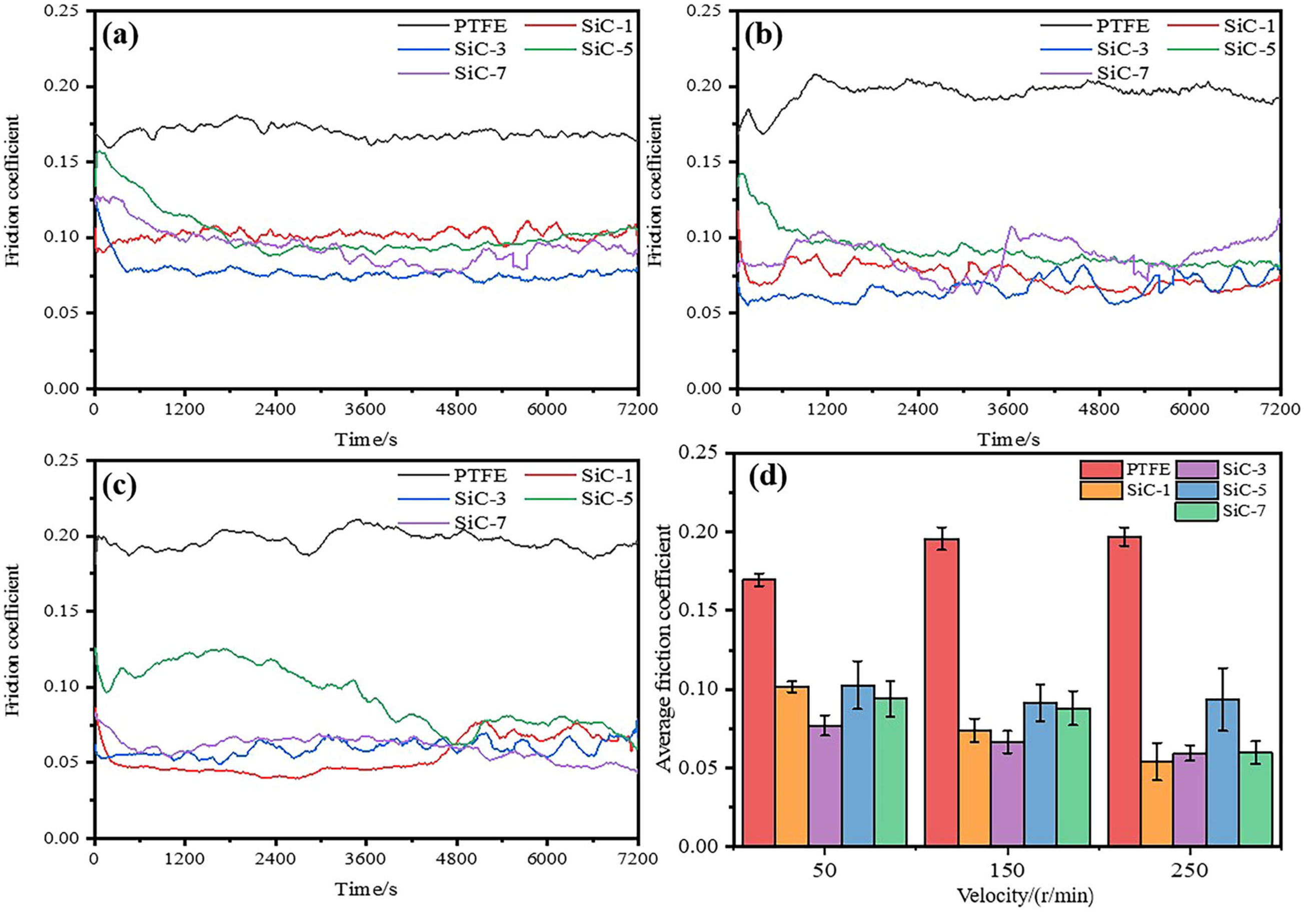

Fig. 4 Friction coefficients of SiC particle-reinforced PTFE water-lubricated bearing composites at different speeds for a load of 0.8 MPa (a) 50 r/min; (b) 150 r/min; (c) 250 r/min; (d) average friction coefficient

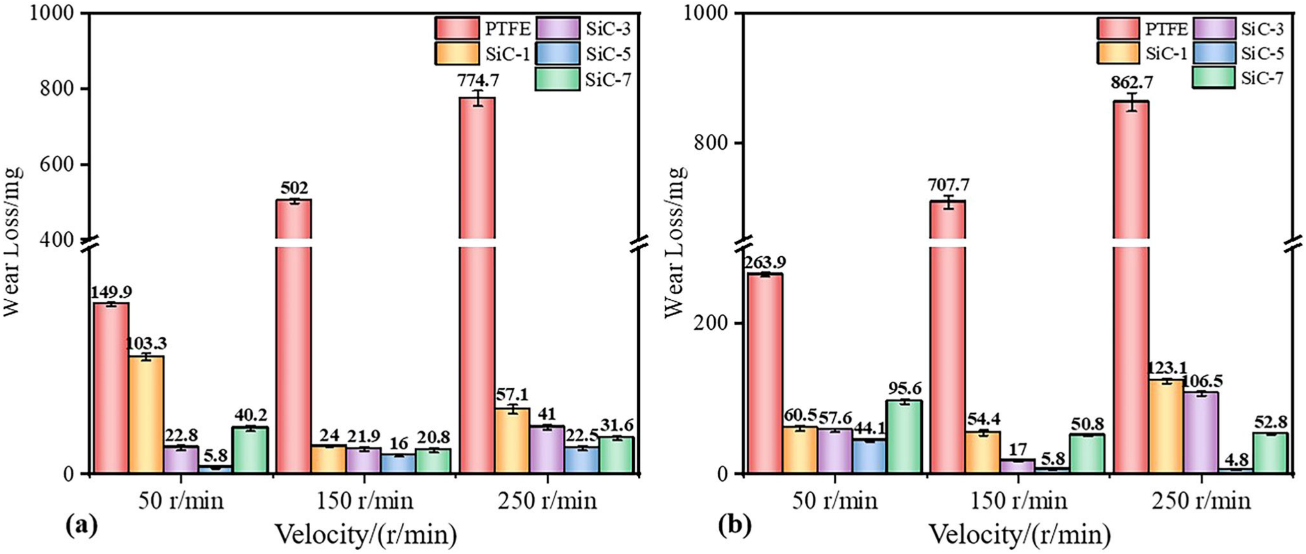

Fig. 5 Wear loss of PTFE water-lubricated bearing composites under different experimental conditions (a) 0.5 MPa; (b) 0.8 MPa

produced rapidly, and at the same time, it was easy to fall off, resulting in serious wear loss of pure PTFE (Ref 23, 24). On the other hand, during the wear process, the wear surface of pure PTFE collected large amount of frictional heat, which led to an increase in temperature and softening of the material, generating black abrasive debris during the friction process, and it was observed that the black abrasive debris increased as the speed increased. The wear loss of the SiC particle-reinforced PTFE composites was significantly reduced at 50 r/min, 150 r/min, and 250 r/min. At 50 r/min, the wear loss of the composite was reduced by 31.1% when the filling content of SiC was 1 wt.%. As the filling content of SiC continued to increase, the wear loss of the composite continued to decrease, reaching a minimum at 5 wt.% filling content, with a 96.1% reduction in wear loss. And when the filler content of the composite was 7 wt.%, the wear loss increased compared to the composite with 5 wt.% filler content. At 150 r/min versus 250 r/min, the filler content of only 1 wt.% was able to significantly reduce the wear loss of the composite, and the lowest wear loss of the composite was achieved when the filler content reached 5 wt.%. By continuing to add SiC particles to the PTFE matrix, the decreasing trend of the wear loss of the composite slowed down.

Figure 5(b) shows that even at 0.8 MPa, the SiC particle-reinforced PTFE composites exhibit lower wear loss than pure PTFE. Similar to the case at 0.5 MPa, the wear loss of the samples decreased as SiC content increased, and SiC-5 sample had the lowest wear loss, and the wear loss was reduced by 99.44%. When the filling content was further increased, the wear loss reduction was reduced. The reason may be that as the filling content of SiC increased, the brittleness of PTFE composites increased, and the ability of the matrix to fix some of the SiC particles was weakened, and the abrasive particles were formed after shedding, which exacerbated the wear of the composites to a certain extent. Comparing the trend of the average friction coefficient of PTFE composites, the trend of the wear loss of SiC particle-reinforced PTFE composites with filling content was more similar to it, and only the optimum value was different. The SiC-3 sample with 3 wt.% filling content had the optimum value of the friction coefficient under most conditions (including 0.5 MPa, 50 r/min; 0.5 MPa, 150 r/min; 0.8 MPa, 50 r/min; 0.8 MPa, 50 r/min;). The SiC-5 sample with 5 wt.% filling content had the optimum value of wear loss, and the wear loss of the SiC-3 sample and the SiC-5 sample did not differ much under most experimental conditions. Therefore, the optimal values of the filling content of the SiC particles were between 3 and 5 wt.% under the experimental conditions in terms of friction coefficient and wear loss. Overall, the filling of the PTFE matrix with different mass fractions of SiC particles was able to reduce the wear loss and improve the wear resistance of PTFE, confirming the superiority of SiC particle-reinforced PTFE composites.

3.1.3 Wear Surface Morphology Analysis. To analyze the wear mechanism of SiC particles reinforced PTFE composites with different filling contents under water lubrication, the wear surface morphology of the samples at 0.5 MPa and 250 r/min was observed by SEM, and the results were shown in Fig. 6.

As shown in Fig. 6(a), plastic deformation occurred when the pure PTFE was worn against the copper disc. During the test, the continuous contact stress caused the wear debris to peel off, and a layer of PTFE transfer film was rapidly generated (Ref 25). During the wear process, the transfer film fell off rapidly, causing serious mass loss. From the microscopic point of view, the special molecular structure of PTFE led to the extremely low attraction between PTFE molecules, and the PTFE molecular chain was prone to slip or fracture under the action of external force and finally, presented in the form of flake debris on the macro-level. Because there were a large number of flake debris on the wear surface of pure PTFE samples, there were no abrasive particles and furrows, and the wear mechanism was typical adhesive wear. As shown in Fig. 6(b), when the content of SiC in the composite was 1 wt.%, the flake debris on the worn surface of the sample was significantly reduced, and the surface was observed to have abrasive particles and furrow marks. As SiC was a hard inorganic particle, which can effectively bear the load during the wear process, reduced the effective contact area between the grinding surfaces to a certain extent, reduced the wear amount of PTFE material, and reduced the adhesive wear. Additionally, the wear debris formation mechanism changed. The addition of SiC particles reduced the flaky wear debris of the composites and changes to granular, and the flaky wear debris also decreased. It can be judged that the wear mechanism of the sample began to change from adhesive wear to abrasive wear.

Figure 6(c) and (d) shows that compared to composites filled with 1 wt.% SiC, when SiC content was 3 wt.% and 5 wt.%, there were a small number of abrasive particles and furrow marks on the wear surface of the composites. The level of abrasive wear was low. This showed that within a certain range, when the content of SiC in the composites continued to increase, the abrasive particles and furrow marks on the wear surface of the composites gradually decreased. The wear surface morphology of composites was optimized. According to Fig. 6(e), when the SiC content of the composites was 7 wt.%, the number of abrasive particles and furrows on the worn surface of the composites increased, and the wear morphology deteriorated. This was because SiC agglomeration increased with increasing filling content, which led to the weakening of the binding capacity of SiC particles and PTFE matrix. During the wear process, some SiC particles fell off and formed abrasive particles, which participated in abrasive wear.

Figure 7 shows the wear surface morphology of the composites at 0.8 MPa and 250 r/min. The composites' wear morphology was similar to that under 0.5 MPa. In addition, the wear surfaces of SiC-3 and SiC-7 samples were scanned and analyzed by EDS. It was found that when the content of SiC increased, there was obvious agglomeration. Overall, the addition of SiC particles can effectively bear the load, reduced the effective contact area between the grinding surfaces, and reduced the generation of flake wear debris, so that the main wear mechanism of the composites changed from adhesive wear to abrasive wear. Within a certain range, with the increase in the mass fraction of SiC particles in the PTFE matrix, the wear surface morphology of the samples can be optimized. When the filling content of SiC was appropriate, the SiC particles could be evenly distributed in the PTFE matrix and could form a good bonding force with the PTFE matrix, thereby improving the wear performance of the composites.

In order to further study the friction and wear properties of SiC particles reinforced PTFE composites with different filling contents under water lubrication conditions, the anti-grinding copper disc's wear surface was observed in detail with 0.5 MPa and 250 r/min by LI laser interference displacement surface profiler. The results are shown in Fig. 8.

Figure 8(a) shows the wear surface morphology of copper discs. The copper discs grinded with pure PTFE, SiC-1, SiC-

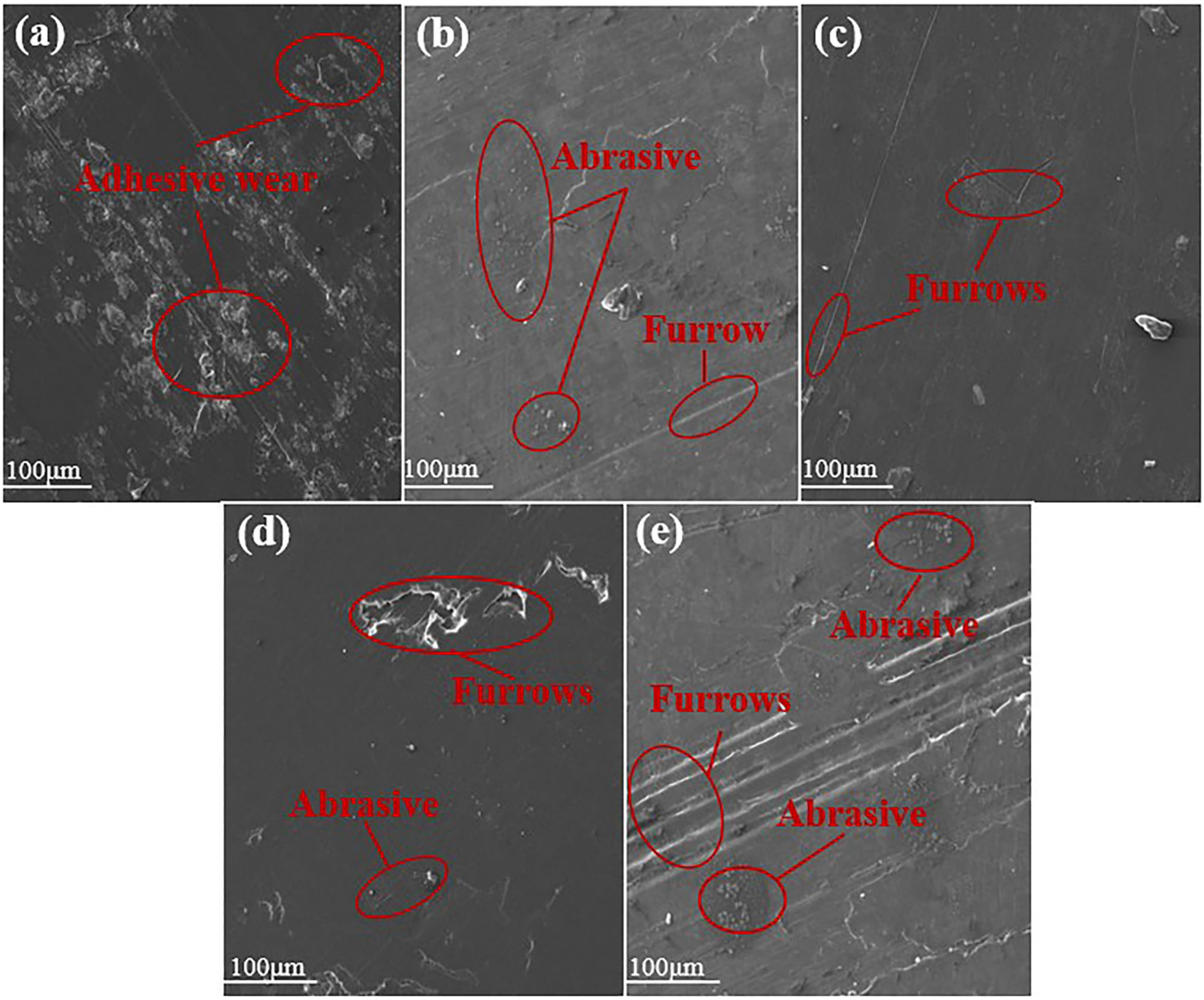

Fig. 6 SEM images of wear morphology of PTFE composites under 0.5 MPa, 250 r/min (a) PTFE; (b) SiC-1; (c) SiC-3; (d) SiC-5; (e) SiC-7

3, SiC-5, and SiC-7 composites were named D0, D1, D3, D5, and D7, respectively. D0 showed a large number of grooves on the wear surface. With the increase in the filling content of SiC particles, the number of grooves on the wear surface of copper discs was reduced to varying degrees, and D3 and D5 had relatively flat wear surfaces. The groove number of copper discs was not linearly related to the filling content of SiC particles. Compared with the D5, the groove number of D7 was increased, indicating that the surface morphology of Qsn7-0.2 disc was deteriorated by increasing the filling content of the SiC particles. Figure 8(b) shows the Sq and Sku of the wear surface of the copper discs, which were three-dimensional parameters characterizing the roughness. Compared with D0, the Sq and Sku of the wear surface of the copper discs against the composites were reduced. It was confirmed that SiC particles can improve the wear morphology of the copper disc, and the wear surface became smoother. In addition, the Sq and Sku of the copper disc decreased first and then, increased with the increase in the SiC filling content, which further confirmed that the excessive filling of SiC particles would lead to copper disc wear surface morphology deteriorated.

In summary, the addition of SiC particles can improve the wear surface morphology of the composites and the grinding copper disc to a certain extent. In a certain range, as SiC content in PTFE matrix increased, the wear surface morphology can be optimized for copper discs and composites. Under the experimental conditions, when the content of SiC in the PTFE matrix exceeded 5 wt.%, the wear surface morphology of the friction pair would deteriorate.

3.2 Effect of SiC Particle Size on Tribological Properties of PTFE Composites

3.2.1 Friction Coefficient Analysis. In order to investigate the effect of different particle sizes of SiC particles on the tribological properties of PTFE composites, the mass fraction of SiC filling was fixed at 3 wt.%, and tribological tests were conducted on SiC filled modified PTFE composites of different particle sizes and pure PTFE under experimental conditions. The results of the measured friction coefficients are shown in Fig. 9 and 10.

Figure 9(a), (b), and (c) indicates that the friction coefficients of PTFE composites with 40 nm and 1 μm SiC particle size were lower than those of pure PTFE at all speeds with a

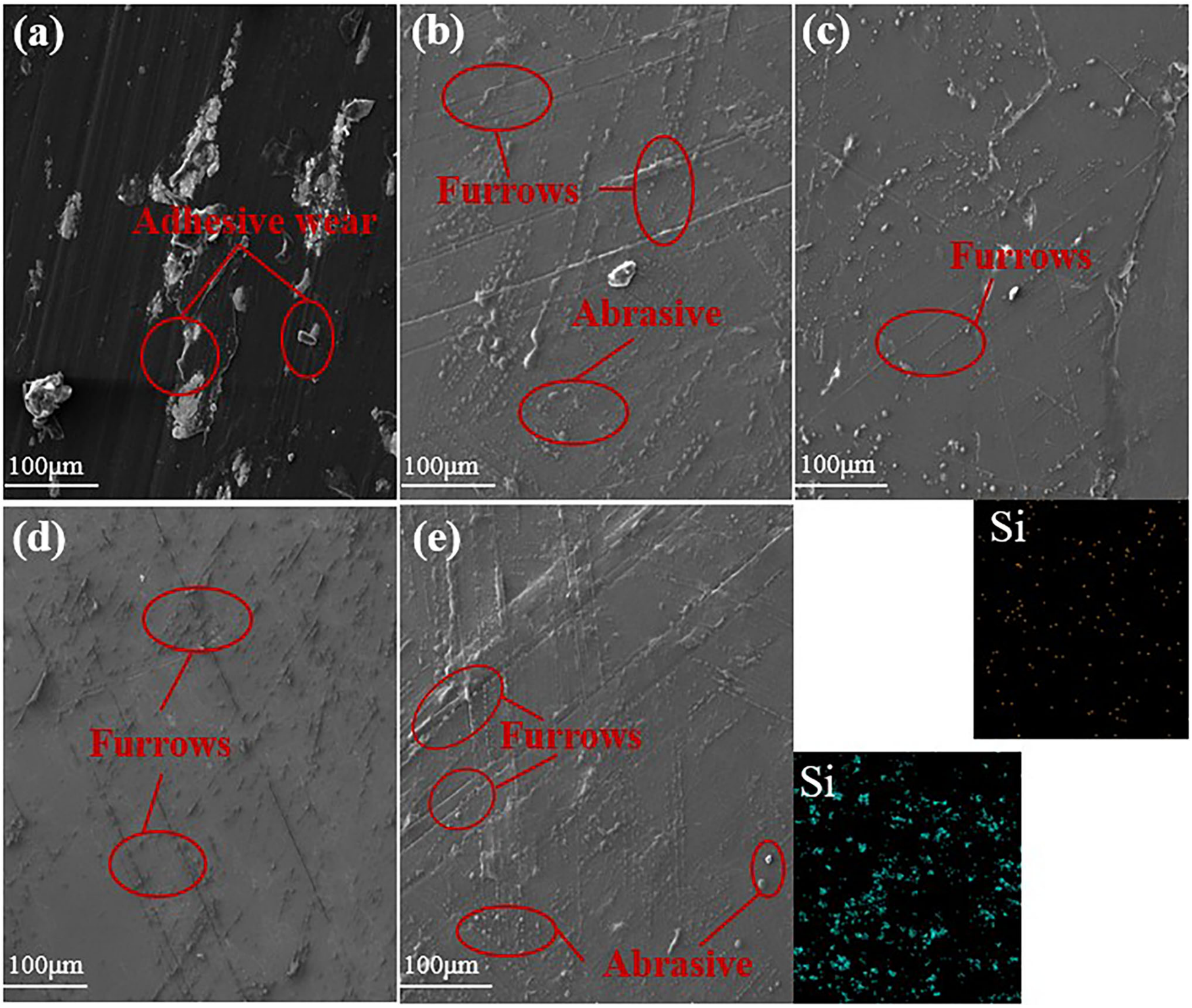

Fig. 7 SEM images of wear morphology of PTFE composites under 0.8 MPa, 250 r/min (a) PTFE; (b) SiC-1; (c) SiC-3; (d) SiC-5; (e) SiC-7

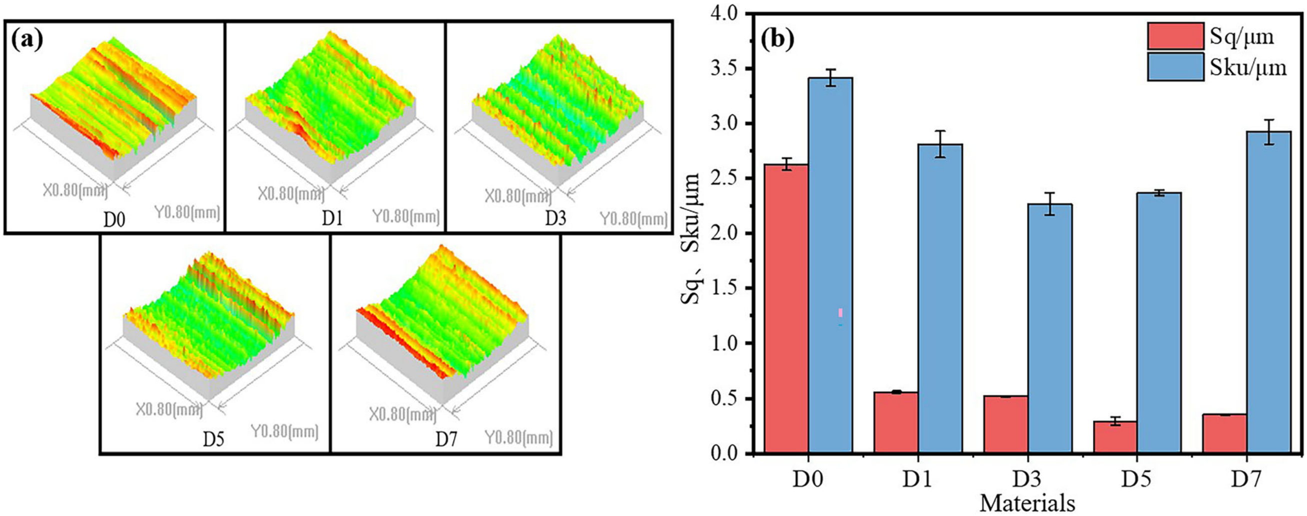

Fig. 8 Wear surface morphology and parameters of the copper disc at 0.5 MPa and 250 r/min (a) wear surface morphology; (b) Sq and Sku

load of 0.5 MPa, where PTFE composites filled with 40 nm SiC particle size presented the lowest friction coefficients at 50 r/min versus 250 r/min. The PTFE composites filled with 37 μm and 149 μm SiC exhibited higher friction coefficients than the pure PTFE at all speeds. This indicated that the addition of nano- and submicron-sized SiC particles can improve the tribological properties of PTFE composites under the test conditions. The friction coefficient of PTFE composites gradually increased with the increase in particle size of micron level SiC particles, and the friction coefficient of PTFE composites was the largest when the particle size increased to 149 μm. As shown in Fig. 10(a), (b), and (c), the friction coefficient varied with the particle size of SiC for PTFE composites at 0.8 MPa experimental condition was more similar to that at 0.5 MPa. With the increase in SiC particle size, PTFE composites had higher friction coefficients at 50 r/min and 250 r/min and were higher than those of PTFE. In addition, the friction coefficients of composites filled with 40 nm and 1 μm SiC particles were still consistently lower than pure PTFE at all speeds and showed lower friction coefficients under heavy load conditions. In comparison with pure PTFE, composites containing 37 nm and 149 nm SiC particles always had a higher friction coefficient. Overall, the friction coefficient of composites decreased with decreasing particle size of SiC at most test conditions (including 0.5 MPa, 50 r/min; 0.5 MPa, 250 r/min; 0.8 MPa, 50 r/min; 0.8 MPa, 250 r/min), and SiC particles with a particle size of 40 nm showing the best friction reduction effect.

To further analyze the effect of different particle sizes of SiC particles on the friction coefficient of PTFE composites, the friction coefficient of PTFE composites was plotted against time at the speed of 250 r/min, and the results are shown in Fig. 9(d) and 10(d). Figure 9(d) shows that the PTFE composites filled with 149 μm SiC particles had the largest friction coefficient, and its value fluctuated above 0.2. The friction coefficient of the PTFE composites filled with 37 μm SiC particles fluctuated around 0.2. The friction coefficients of both of them also fluctuated more and were higher than those of PTFE. The composites filled with 40 nm and 1 μm SiC particles showed relatively stable friction coefficients and tended to decrease gradually as the test proceeded and were lower than those of pure PTFE.

Figure 10(d) shows that the friction coefficient of composites filled with 37 μm and 149 μm SiC particles fluctuated more and had a higher friction coefficient than pure PTFE composites. Friction coefficient of PTFE composites containing 40 nm and 1 μm SiC particles fluctuated steadily around 0.05. The reason for this was that the PTFE composites had a frictional transfer film on the copper discs' surface during the process of grinding against the tin bronze disc, and the nano- and

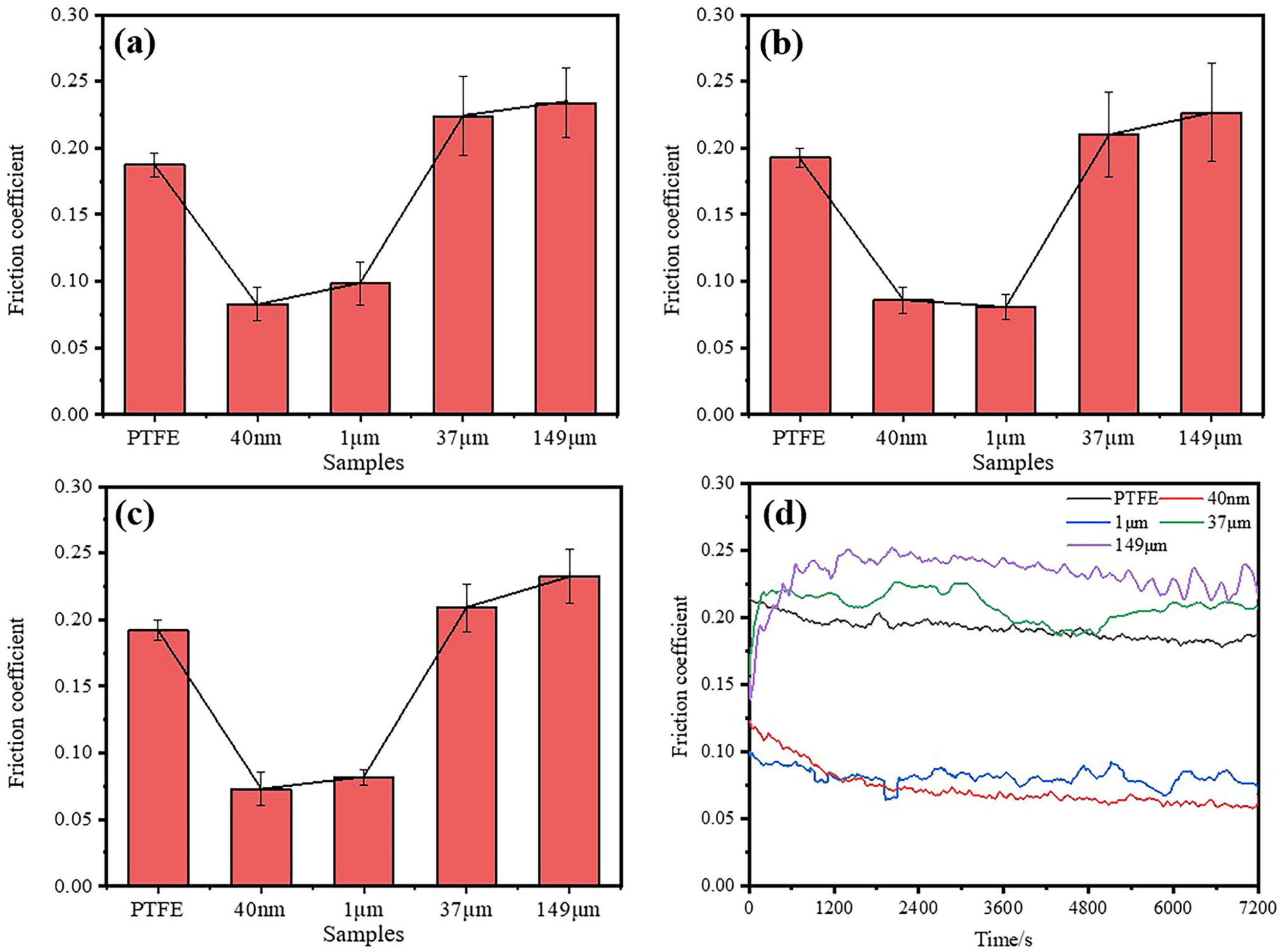

Fig. 9 Friction coefficients of PTFE and different particle sizes of SiC particle-reinforced PTFE composites under 0.5 MPa load (a) 50 r/min; (b) 150 r/min; (c) 250 r/min; (d) 0.5 MPa, 250 r/min

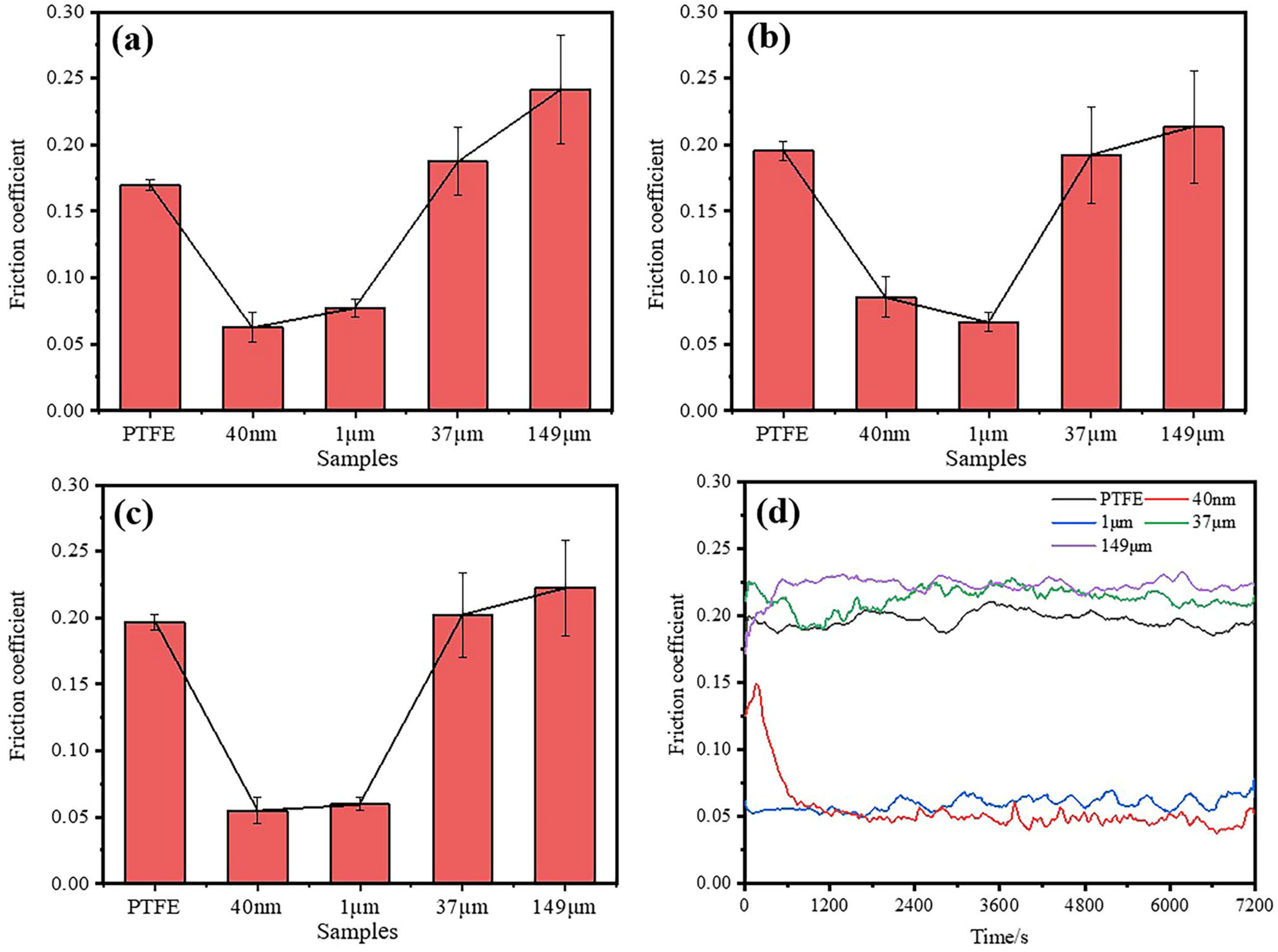

Fig. 10 Friction coefficients of PTFE and different particle sizes of SiC particle-reinforced PTFE composites under 0.8 MPa load (a) 50 r/min; (b) 150 r/min; (c) 250 r/min; (d) 0.8 MPa, 250 r/min

submicron-level SiC particles had a larger contact area with the PTFE matrix and were more closely bonded to the PTFE matrix in comparison. During the wear process, the nano and submicron SiC particles were able to form a transfer film on the wear surface while better supporting the load, thus the PTFE composites filled with 40 nm and 1 μm SiC particles had lower friction coefficients. As the particle size of SiC continued to increase, the depth of embedding in the PTFE matrix became deeper. The particles on the wear surface of PTFE composites were more likely to pierce copper discs' surfaces during the wear process and destroy the formation of transfer film. The worn surface of copper disc became rougher, resulting in higher friction coefficients for PTFE composites filled with 37 and 149 μm SiC particles.

3.2.2 Wear Loss Analysis. Figure 11 shows the wear loss of PTFE composites filled with different particle sizes of SiC particles under 0.5 MPa and 0.8 MPa. Under the experimental conditions, the wear loss of the composites was lower than that of pure PTFE, indicating the reduction in wear can be achieved by adding different sizes of SiC particles.

As shown in Fig. 11(a) and (b), in addition to 0.8 MPa and 150 r/min, 40 nm SiC particle filled composites had the lowest wear loss in most working conditions, with a maximum reduction of 97.03%. This was because the nanoscale SiC particles were better able to carry the load, thus improve the wear resistance. Also, under the experimental conditions, it was not true that larger SiC particles resulted in better wear resistance. After the test, the presence of yellow transfer was observed on the surface of the PTFE composites filled with 37 μm and 149 μm SiC particles, which made composites wear less. The presence of yellow transfer material may be due to the larger particle size of 37 μm and 149 μm SiC, which was embedded in the PTFE matrix at a deeper depth and was not easily dislodged, and due to the great hardness of SiC itself, copper discs were easily pierced by particles on the wear surface, causing the yellow material to fall off from copper disc's surface and transferred to the sample's surface during the wear process.

3.2.3 Wear Surface Morphology Analysis. To analyze wear mechanism of the composites reinforced with different particle sizes of SiC particles under water lubrication conditions, SEM was used to observe the wear surface morphology of the composites at 0.5 MPa and 250 r/min. The results are shown in Fig. 12.

Figure 12(a) shows that due to the low hardness and poor wear resistance of the pure PTFE, the wear surface produced deformation, and the wear mechanism was mainly adhesive wear. Figure 12(b) indicates the wear surface of PTFE composites filled with 40 nm SiC particles were relatively flat and smooth, with almost no furrow marks, and the levels of

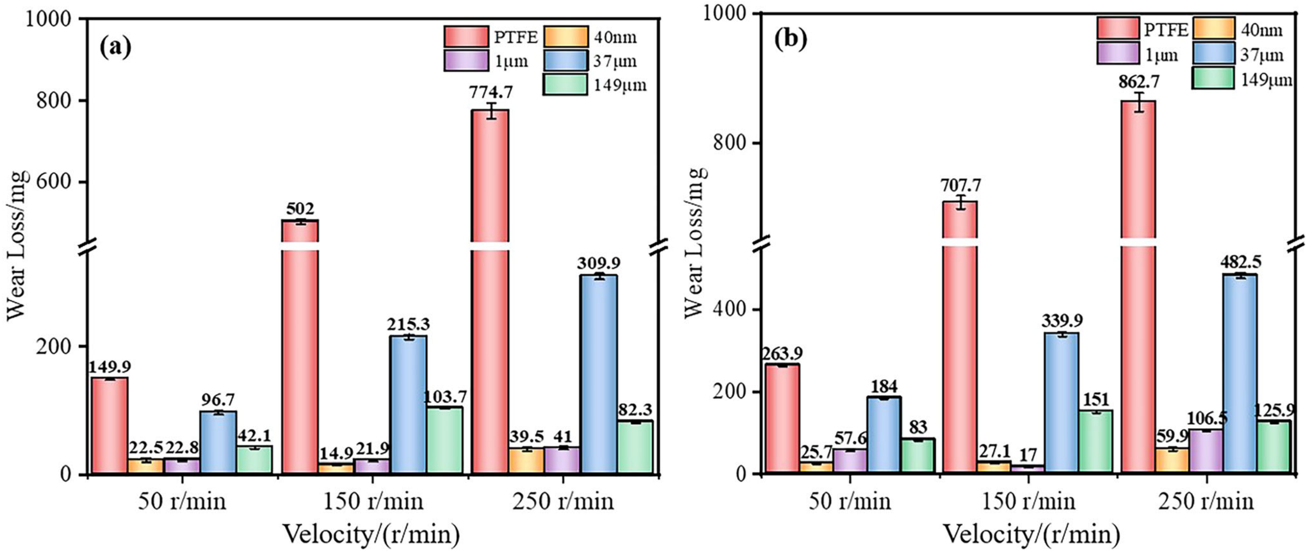

Fig. 11 Wear loss of PTFE composites reinforced with SiC particles of different particle sizes under experimental conditions (a) 0.5 MPa; (b) 0.8 MPa

abrasive and adhesive wear were both low. As shown in Fig. 12(c), the wear surface of PTFE composites filled with 1 μm SiC particle had only a small amount of abrasive particles and furrow marks, and the abrasive wear was low. This was because SiC was a hard inorganic particle; during the wear process, nano- and submicron SiC particles can effectively support the load and reduce the effective contact area while forming a transfer film on the wear surface of the copper disc, thereby reducing wear. From Fig. 12(d) and (e), it can be seen that the wear surfaces of PTFE composites filled with 37 μm and 149 μm SiC particles showed wide deep furrows and scratch marks, which were caused by the abrasive particles in the lubricating medium and the asperities on the wear surface of the copper discs; thus, the wear was mainly in the form of abrasive wear. In addition, copper transfer film formed because the larger SiC particles were embedded deeper into the PTFE matrix. Although large particle size SiC was not easy to fall off, but in the wear process, it was easy to pierce the surface of the copper discs, resulting in the increase in the surface roughness of copper discs and destroyed the formation of the transfer film on the surface of the copper discs. The copper material fell off from the wear surface of copper discs and transferred to the composite sample surface with the cyclic contact stress, forming a discontinuous copper transfer film.

Wear surface morphology of PTFE composites at 0.8 MPa and 250 r/min is shown in Fig. 13. Comparing with Fig. 12, the wear morphology of PTFE composites was more similar to that at 0.5 MPa. Meanwhile, the wear surface of PTFE composites filled with 37 μm and 149 μm SiC particles was analyzed by EDS scanning. It was further verified that the yellow transfer material was observed on the PTFE composites and was caused by copper material shedding from copper disc's wear surfaces during tribological test.

The wear surfaces of the copper discs were measured and recorded in detail using a LI laser interference displacement surface profiler at 0.5 MPa and 250 r/min, and the results are shown in Fig. 14. The copper discs ground against PTFE composites filled with 40 nm, 1 μm, 37 μm, and 149 μm SiC were named K1, K2, K3, and K4. From Fig. 14(a), it can be seen that D0 had a large number of grooves. The number of grooves on the wear surface of K1 and K2 was significantly reduced. The wear surface of K1 was relatively smooth. As the size of SiC particles increased, the number of grooves and convex peaks of K3 and K4 continued to increase. This indicated that continuing to increase the particle size of the SiC caused a serious deterioration of the wear surface morphology on the copper discs.

Figure 14(b) shows the Sq and Sku of the wear surface of the copper disc. The Sq and Sku of K1 and K2 were smaller than those of D0, and K1 had the smallest Sq and Sku, indicating the copper discs wear state can be improved by adding 40 nm SiC particles. The Sku of K3 and K4 was larger than those of D0, indicating that the wear surface of grinding copper discs became sharper as SiC particle size increased. In addition, the Sq and Sku of the copper discs gradually increased with the increase in SiC particle size. This indicates that the increase in the SiC particle size would increase the roughness of the copper discs' wear surface, and the surface morphology of the copper disc became worse.

In summary, the wear morphology of friction pairs deteriorated as the particle size of SiC in the PTFE composites increased. Under the experimental conditions, the SiC particles with a particle size of 40 nm showed the best optimization effect on the wear morphology of the composites and the copper discs.

3.3 Wear Mechanism Analysis

Based on the analysis of the friction experimental results and the phenomena observed in the experiment, the wear mechanism of SiC particles reinforced PTFE composites is shown in Fig. 15.

Figure 15(a) shows the effect of SiC filling content on the wear resistance of PTFE. The hardness of the pure PTFE was low. When grinding with the copper disc, slight deformation occurred due to the adhesion effect between the two. At the same time, under the action of interface stress, the pure PTFE had flake wear debris peeling off continuously, and a layer of PTFE transfer film was rapidly generated, which fell off

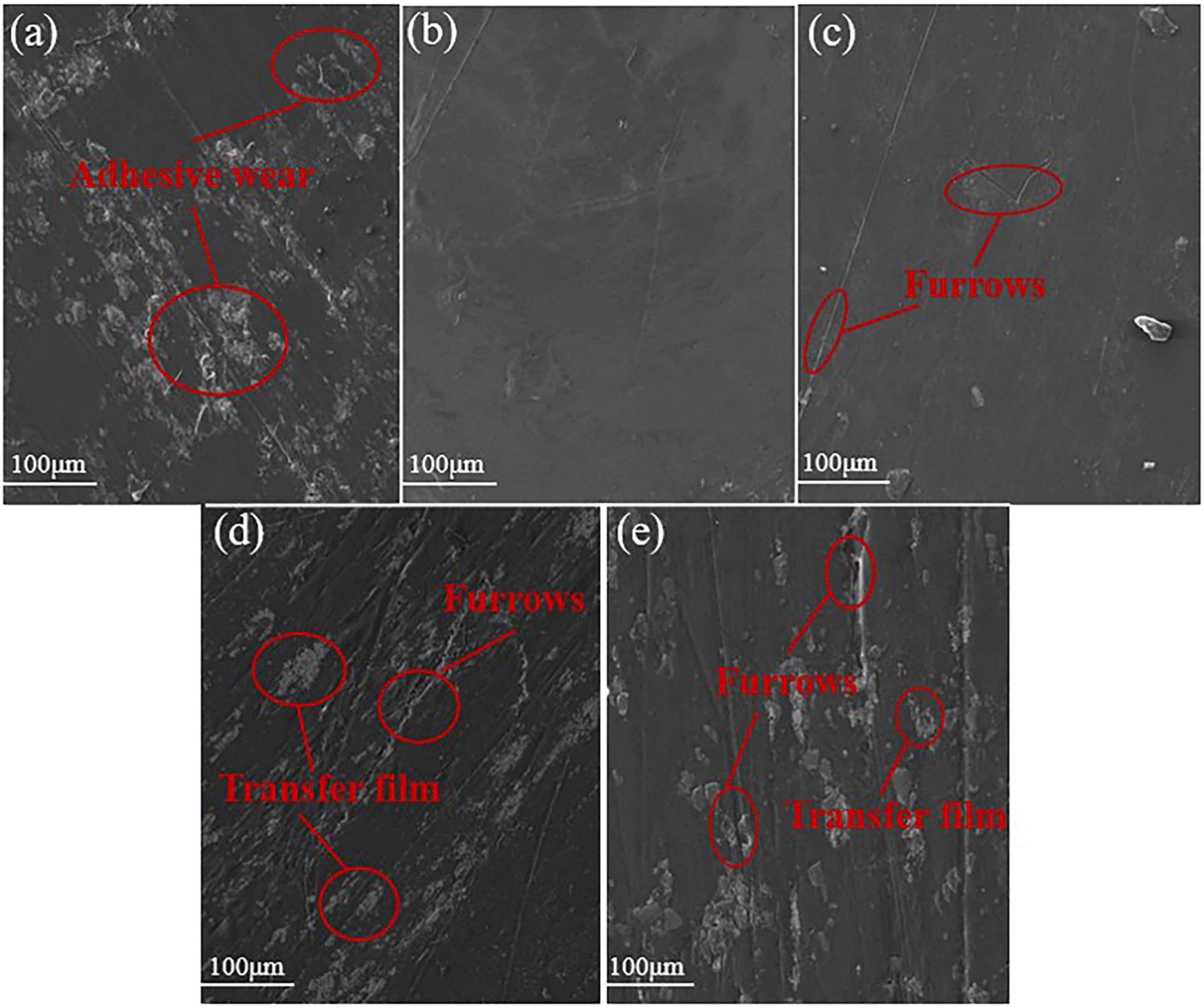

Fig. 12 SEM images of wear morphology of PTFE composites under 0.5 MPa, 250 r/min (a) PTFE; (b) 40 nm; (c) 1 μm; (d) 37 μm; (e) 149 μm

rapidly during the wear process, resulting in poor wear resistance of pure PTFE. The addition of SiC particles reduced the generation of flake wear debris to a certain extent, and the wear debris changed from flake to granular. When the filling content of SiC particles was appropriate, on the one hand, SiC particles can be evenly distributed in the PTFE matrix to form a good bonding force with the PTFE matrix. On the other hand, SiC particles can effectively carry the load during the wear process, reducing the effective contact area between friction pairs, thereby improving the wear resistance of the composites. When the filling content of SiC particles exceeded a certain range, the SiC particles were more likely to agglomerate, resulting in the weakening of their binding ability with PTFE matrix. During the wear process, some SiC particles fell off and formed abrasive particles, resulting in increased wear.

Figure 15(b) shows the effect of SiC particle size on the wear resistance of PTFE. The main wear mechanism of pure PTFE was adhesive wear. When the particle size of SiC was small, the adhesive wear and abrasive wear of PTFE composites were at a low level, which prevented PTFE molecular chains from pulling out from the matrix in a lamellar structure, and the wear debris became fine, and composites showed improved wear resistance. As the particle size of SiC increased, the plowing effect between the composites and the copper discs intensified, causing the surface roughness of copper discs to increase, which made it difficult to form a transfer film with lubricating effect on the wear surface of the copper discs, resulting in wide deep furrows and obvious scratch marks on the wear surface of the composites, and the wear resistance of the composites reduced. The main wear mechanism changed from adhesive wear to abrasive wear. In addition, because the copper disc was a soft metal material, under the cyclic contact stress, there was a serious mutual plowing between the large-size SiC particles and the copper discs. Copper disc wear surfaces shed material, which transferred to composite surfaces. A discontinuous copper transfer film was formed, which improved the wear to some extent.

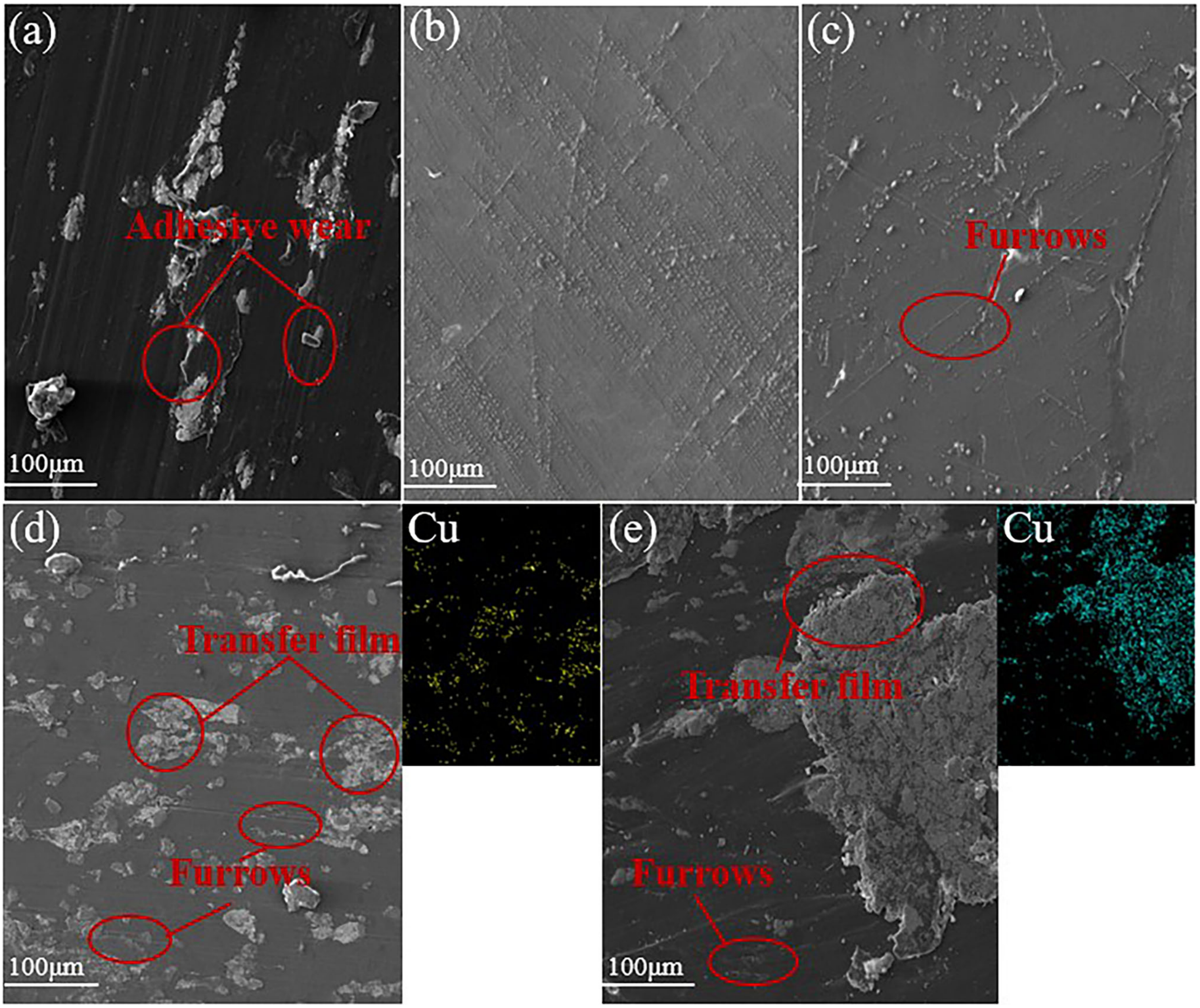

Fig. 13 SEM images of wear morphology of PTFE composites under 0.8 MPa, 250 r/min (a) PTFE; (b) 40 nm; (c) 1 *μ*m; (d) 37 *μ*m; (e) 149 *μ*m

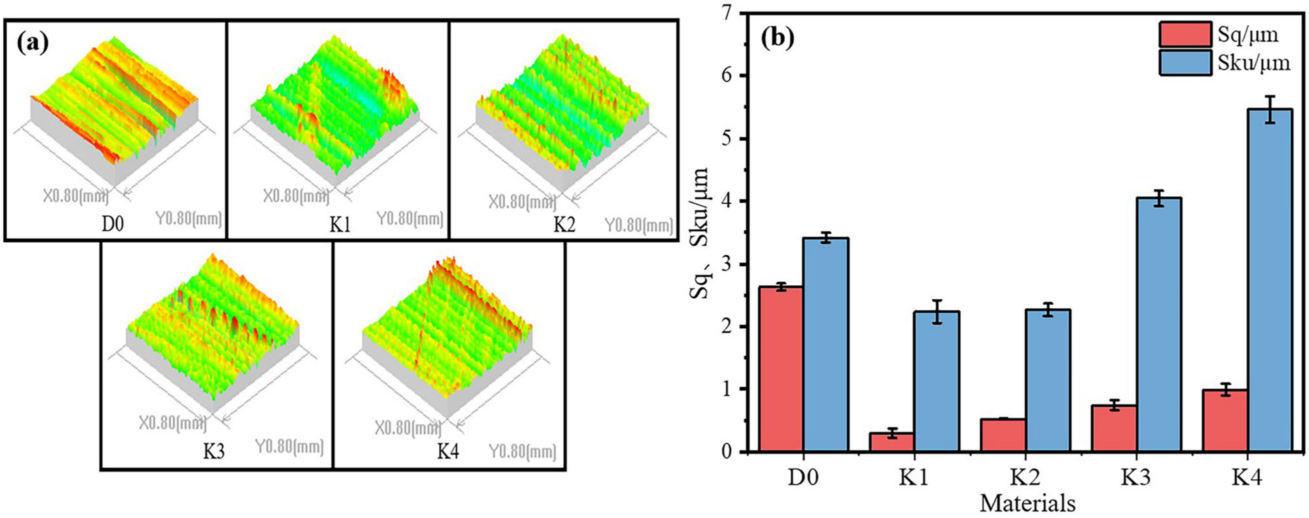

Fig. 14 The wear surface morphology and parameters of the copper disc at 0.5 MPa and 250 r/min (a) wear surface morphology; (b) Sq and Sku

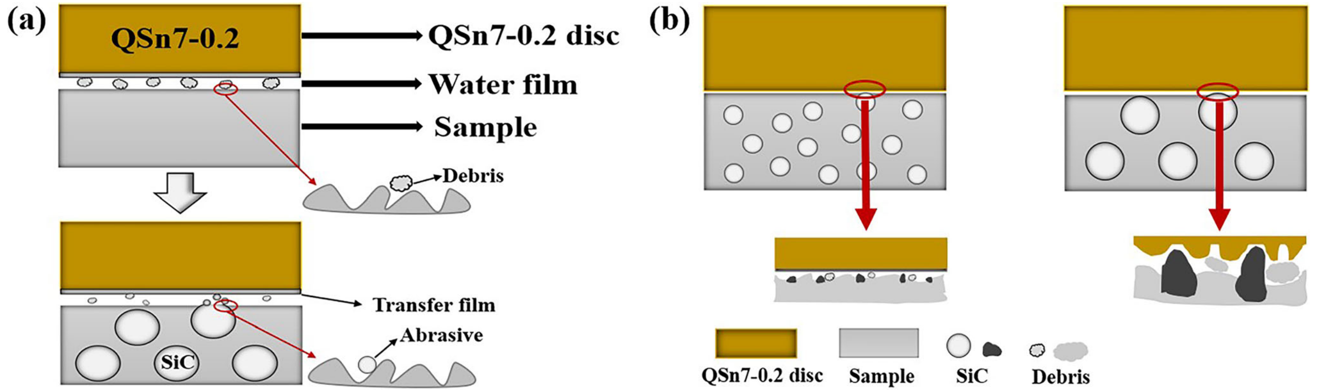

Fig. 15 Wear mechanism of SiC particles reinforced PTFE water-lubricated bearing composites (a) effect of filling content; (b) effect of particle size

4. Conclusions

In this study, the friction and wear properties of SiC particles reinforced PTFE composites under water lubrication were investigated. SiC content and particle size were evaluated for their effects on PTFE composite tribology. The results show that filling SiC particles in PTFE matrix can improve the wear resistance of the composites. By adding SiC particles to PTFE matrix in an appropriate amount, the friction coefficient and wear loss can be reduced, and the wear morphology can be improved. Under the experimental conditions, filling with SiC particles in the range of 3 to 5 wt.% was the best, and the wear loss of the composites filled with 5 wt.% SiC can be reduced by 99.44%. Under most experimental conditions, PTFE composite friction coefficient decreased with decreasing SiC particle size. The PTFE composites filled with 40 nm SiC showed the best tribological properties, and the wear loss was reduced by 97.03%. The size of SiC particle size will affect the wear mechanism of PTFE composites. With the increase in SiC particle size, the main wear mechanism changed from adhesive wear to abrasive wear. In addition, the wear resistance of PTFE composites had a certain correlation with the material of grinding pair.

Acknowledgments

The authors would like to express their sincere gratitude to the National Natural Science Foundation of China (Grant No. 52275209).

References

1. M. Perčić, N. Vladimir, and A. Fan, Techno-Economic Assessment of Alternative Marine Fuels for Inland Shipping in Croatia, *Renew. Sustain. Energy Rev.*, 2021, **148**, p 111363. https://doi.org/10.1016/j.rser.2021.111363
2. D.Z. Yue, X.Z. Jiang, H.Y. Yu, and D.B. Sun, In-Situ Fabricated Hierarchical Nanostructure on Titanium Alloy as Highly Stable and Durable Super-Lubricated Surface for Anti-Biofouling in Marine Engineering, *Chem. Eng. J.*, 2023, **463**, p 142389.
3. Z.W. Guo, S.K. Dong, Z.X. Yang, and W. Ouyang, Tribological Properties of Aramid Fiber-Microcapsule Modified Ultra-High Molecular weight Polyethylene Composites for Water Lubrication, *J. Mater. Eng. Perform.*, 2022, **31**, p 6000–6008.
4. Z.L. Xie, N.W. Shen, W.D. Zhu, W.C. Tian, and L. Hao, Theoretical and Experimental Investigation on the Influences of Misalignment on the Lubrication Performances and lubrication Regimes Transition of Water Lubricated Bearing, *Mech. Syst. Signal Process.*, 2020, **149**, p 107211.
5. Y.W. Sun, X.P. Yan, C.Q. Yuan, and X.Q. Bai, Insight into Tribological Problems of Green Ship and Corresponding Research Progresses, *Friction*, 2018, **6**, p 472–483.
6. Z.L. Xie, J. Jiao, K. Yang, and H. Zhang, A State-of-Art Review on the Water-Lubricated Bearing, *Tribol. Int.*, 2023, **180**, 108276
7. W. Litwin and C. Dymarski, Experimental Research on Water-Lubricated Marine stern Tube Bearings in Conditions of Improper Lubrication and Cooling Causing Rapid Bush Wear, *Tribol. Int.*, 2016, **95**, p 449–455.
8. Z.M. Jia, Z.W. Guo, and C.Q. Yuan, Effect of Material Hardness on Water Lubrication Performance of Thermoplastic Polyurethane under Sediment Environment, *J. Mater. Eng. Perform.*, 2021, **30**, p 7532–7541.
9. A.P. Vasilev, N.N. Lazareva, T.S. Struchkova, A.A. Okhlopkova, and S.N. Danilova, Mechanical and Tribological Properties of Polytetrafluoroethylene Modified with Combined fillers: Carbon Fibers, Zirconium Dioxide, Silicon Dioxide and Boron Nitride, *Polymers*, 2023, **15**, p 313.
10. Q.K. Zheng, M. Chhattal, C.N. Bai, Z.W. Zheng, D. Qiao, Z.B. Gong, and J.Y. Zhang, Superlubricity of PTFE Triggered by Green Ionic Liquids, *Appl. Surf. Sci.*, 2023, **614**, p 156241.
11. L. Kapitonova, N. Lazareva, P. Tarasova, A. Okhlopkova, S. Laukkanen, and V. Mukhin, Morphology Analysis of Friction Surfaces of Composites Based on PTFE and Layered Silicates, *Polymers*, 2022, **14**, p 4658.
12. M. Lv, L.T. Wang, J. Liu, F.D. Kong, A.X. Ling, T.M. Wang, and Q.H. Wang, Surface Energy, Hardness, and Tribological Properties of carbon-Fiber/Polytetrafluoroethylene Composites Modified by Proton Irradiation, *Tribol. Int.*, 2019, **132**, p 237–243.
13. N.E. Li, C.L. Dong, and Y.H. Wu, Reinforcement of Frictional Vibration Noise Reduction Properties of a Polymer Material by PTFE Particles, *Materials*, 2022, **15**, p 1365.
14. M.A. Sidebottom, T.F. Babuska, S. Ullah, N. Heckman, B.L. Boyce, and B.A. Krick, Nanomechanical Filler Functionality Enables Ultralow Wear Polytetrafluoroethylene Composites, *ACS Appl. Mater. Interfaces*, 2022, **14**, p 54293–54303.
15. L.Q. Chai, H.X. Jiang, B.B. Zhang, L. Qiao, P. Wang, L.J. Weng, and W.M. Liu, Influence of the Gamma Irradiation Dose on Tribological Property of Polytetrafluoroethylene, *Tribol. Int.*, 2020, **144**, p 106094.
16. H. Wang, A.N. Sun, X.W. Qi, Y. Dong, and B.L. Fan, Experimental and Analytical Investigations on Tribological Properties of PTFE/AP Composites, *Polymers*, 2021, **13**, p 244295.
17. J.G. Xu, H.B. Yan, and D.G. Gu, Friction and Wear Behavior of Polytetrafluoroethene Composites Filled with Ti_3SiC_2, *Mater. Des.*, 2014, **61**, p 270–274.
18. A.F. Boostani, S. Tahamtan, Z.Y. Jiang, D. Wei, S. Yazdani, R.A. Khosroshahi, R.T. Mousavian, J. Xu, X. Zhang, and D. Gong, Enhanced Tensile Properties of Aluminium Matrix Composites Rein-

forced with Graphene Encapsulated SiC Nanoparticles, *Compos. Pt. A. Appl. Sci. Manuf.*, 2015, **68**, p 155–163.

19. T.K. Meysam, J.B. Fergusona, F.S. Benjamin, S.K. Chang, C. Kyu, and K.R. Pradeep, Strengthening Mechanisms of Graphene- and Al_2O_3-Reinforced Aluminum Nanocomposites Synthesized by Room Temperature Milling, *Mater. Des.*, 2016, **92**, p 79–87.
20. Z.X. Yang, Z.W. Guo, Z.R. Yang, C.B. Wang, and C.Q. Yuan, Study on Tribological Properties of a Novel Composite by Filling Microcapsules into UHMWPE Matrix for Water Lubrication, *Tribol. Int.*, 2021, **153**, p 106629.
21. Q.H. Wang, Q.J. Xue, W.M. Liu, and J.M. Chen, Tribological Characteristics of Nanometer Si_3N_4 Filled Poly(ether ether ketone) under Distilled Water Lubrication, *J. Appl. Polym. Sci.*, 2000, **79**, p 1394–1400.
22. B. Lin, A.Y. Wang, T.Y. Sui, C.B. Wei, J.H. Wei, and S. Yan, Friction and Wear Resistance of Polytetrafluoroethylene-Based Composites Reinforced with Ceramic Particles under Aqueous Environment, *Surf. Topogr. Metrol. Prop.*, 2020, **8**, p 015006.
23. L.F. Tóth, P.D. Baets, and G. Szebény, Thermal, Viscoelastic, Mechanical and Wear Behaviour of Nanoparticle Filled Polytetrafluoroethylene: A Comparison, *Polymers*, 2020, **12**, p 1940–1956.
24. A.K. Bandaru, P.M. Weaver, and R.M. Higgins, Abrasive Wear Performance of Hygrothermally Aged Glass/PTFE Composites, *Polym. Test.*, 2021, **103**, p 107369.
25. M.A. Sidebottom, T.F. Babuska, S. Ullah, N. Heckman, B.L. Boyce, and B.A. Krick, Nanomechanical Filler Functionality Enables Ultralow Wear Polytetrafluoroethylene Composites, *ACS Appl. Mater. Interfaces*, 2022, **14**, p 54293–54303.