

Tribological properties of transfer films of PTFE-based composites

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Abstract

PTFE-based composites containing 15 vol.% MoS₂, graphite, aluminum and bronze powder, were respectively prepared by compression molding at room temperature and subsequent heat treatment in atmosphere. Transfer films of pure PTFE and these composites were prepared on the surface of AISI-1045 steel bar using a friction and wear tester in a pin on disk contacting configuration. Tribological properties of these transfer films were investigated using another tribometer by sliding against GCr15 steel ball in a point-contacting configuration. Morphology of the transfer films and worn surface of the steel ball were observed and analyzed using SEM and optical microscopy. It was found all these fillers improved wear resistant capability of the composites. Compared with pure PTFE, introduction of the fillers made the corresponding transfer films have longer wear life. This is mainly attributed to strongly adhering transfer film and smaller wear debris particles lead by addition of the fillers. These smaller debris particles are prone to stay longer at the contacting region during the friction process. Introduce of fillers is helpful to improve load bearing capability of the transfer films when sliding against steel ball which are also favorable to prolong the wear life of the transfer films. Tribological properties of these transfer films are sensitive to load change. Generally, increased load shortened wear life of transfer film.

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1. Introduction

Formation and property of transfer film are crucial wear reduction factors for many tribological engineering materials, especially those used under dry friction situation. Increasing tribological use of polymer has made the study on transfer film of polymer very important and in urgent need. To many polymers, it has been found introduction of filler could greatly change their tribological behavior. Such change on tribological behavior of the bulk composite material is directly related to the change of tribological properties of the corresponding transfer film formed during the friction process.

Many research works have been conducted on the transfer behavior of polymer-based composite and the wear reduction mechanism of fillers has been proposed by many researchers [1–7]. Briscoe [1,2], Cadman and Gossedge [3,4] pointed out that some inorganic filler can reduce wear by increasing the adhesion of the first transfer layer of the filled polymer to the

counterface. Bahadur and Tabor [5,6] showed that the nature and stability of the transfer film and its adhesion to the counterface are central factor to the effectiveness of fillers in wear reduction. But Gong et al. [7] proposed a different idea on wear reduction mechanism of transfer film, especially which of the PTFE-based composite. Based on his study on transfer films of PTFE-based composite, Gong et al. concluded that the wear reduction of PTFE composite is not due to the increased adhesion between the transfer film and the counterface but to the increased cohesion of the transfer film itself.

In fact, fillers with different properties play different roles in the composite during the friction process, even though the matrix is the same. It is unreasonable to attribute wear reduction of different fillers to the same reason. What is the tribological behavior of the transfer film containing fillers? What roles would different fillers play in PTFE-based composite during the friction process? These are the crucial questions for us to probe into. Former researchers paid more attention to the tribological properties of the bulk polymer composite. In this work, transfer films of PTFE-based composites are prepared and their tribological behaviors are investigated to give answers to the preceding questions from another point of view. Two inorganic fillers, MoS₂ and

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graphite, two metal fillers, aluminum and bronze, all in powder form and at fixed content of 15 vol.% are selected to investigate the function and behavior of fillers in the friction system. Obviously, these fillers are very different in their basic physical and chemical character.

2. Experimental

2.1. Preparation of PTFE-based composite

The fillers selected were MoS_2 , scalelike graphite, aluminum and bronze, all in powder form and with average size of 50, 7, 50 and 50 μm , respectively. Those fillers were chosen because of the following two considerations. Firstly, they have simple components and broad applications. Secondly, these fillers are so different in physical–chemical properties that we can get a comprehensive understanding of the effect of fillers on properties of composite, especially, the wear behavior of the composite and corresponding transfer film. The proportion of fillers in the composite was 15 vol.%. Firstly, PTFE and the filler were mixed mechanically. After mixing, the uniform mixture was pressed in a mold at 7 MPa under room temperature for about 2 min to prepare cylindrical samples of $\phi 8 \text{ mm} \times 30 \text{ mm}$. After extruded from the mold, the samples were moved into an oven coupled with a temperature controller. The sintering process was carried out in the oven in atmosphere under a given temperature modulation procedure.

2.2. Preparation of transfer film of PTFE-based composite

The sintered samples mentioned above are used as pins to prepare transfer films on a RFT-III style friction and wear tester (made by Kyowa Kagaku Corporation Ltd., Japan) under normal load of 100N, double-way sliding speed of 120 cycles/min (0.2 m/s), with 50 mm sliding distance per pass for 5 min (as shown in Fig. 1A). The substrate is AISI-1045 steel bar with surface roughness of about 0.11–0.13 μm . During the friction process, the composite sample keeps immobile with the fixed normal load while the substrate moves to and fro over a 50 mm distance. All the transfer films used in the experiments are prepared by this method.

2.3. Friction and wear test of transfer films

Tribological properties of the transfer films were tested on a DFPM reciprocating tribometer (made by Kyowa Kagaku

Corporation Ltd., Japan) using single direction repeating stroke configuration with 17 mm sliding distance per pass (as shown in Fig. 1B). The counterpart is $\phi 3 \text{ mm}$ GCr15 steel ball. During the friction process, the steel bar with transfer film moves to and fro over a 17 mm distance and the steel ball repeatedly put up and drop down to the transfer film at given frequency. When the steel bar moves to the right end, the steel ball uplifts to leave the transfer film, when the steel bar moves to the left end, the steel ball falls down to the steel bar and sliding on the transfer film. All the tests were conducted under the follow conditions: dry friction, room temperature, relative humidity about 35–45%, normal load 0.5N, 1N, 2N, 3N and sliding speed 150 mm/min. Friction coefficient and sliding cycle number were recorded automatically. In the whole sliding process, the friction coefficient was kept stable with very little fluctuation for a period and then rose abruptly, sliding cycle number at this moment is recorded as the wear life of the transfer films. Three replicate tests were carried out for each specimen and the average friction coefficient and wear life of the three replicate tests were cited in this article. Relative errors for the data of friction coefficient and wear life are 5% and 15%, respectively.

2.4. Analysis method

Morphologies of the transfer film, worn surface and wear debris of the composites were observed on a JSM-5600LV scanning electron microscope (SEM) coupled with a KEVEX energy dispersive spectrometer (EDS). Optical microscopy was also used to observe surface of the transfer film from a broader visual angle.

A 2206 style surface profilometer was used to measure the surface roughness (R_a) of the steel bar and the transfer film. Each data are average of 15 replicates at different traversals.

3. Results and discussion

3.1. Characterization of transfer films

Table 1 shows the wear rate of PTFE and PTFE-based composites. The test was conducted under the experiment condition mentioned in Section 2.2. Obviously, all selected fillers remarkably reduced the wear rate of the composite.

Widely accepted wear reduction mechanisms of some fillers have been proposed by former researchers. Including, using of hard filler increased the supporting strength to the applied load [8], changing of crystalline structure of PTFE [9], as well

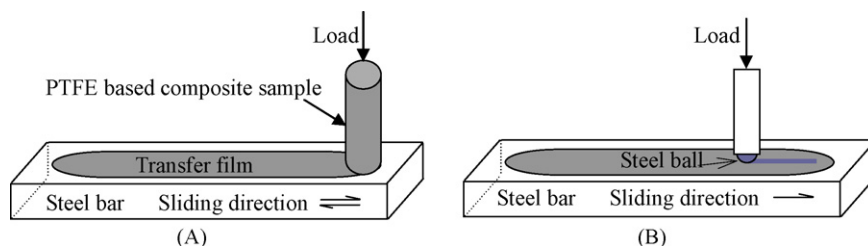


Fig. 1. Preparation of transfer films (A) and tribological property test of these transfer films (B).

Table 1
Wear rate of PTFE and PTFE-based composites sliding against steel bar

Samples	PTFE	PTFE/15 vol.% MoS ₂	PTFE/15 vol.% graphite	PTFE/15 vol.% aluminum	PTFE/15 vol.% Bronze
Wear rate $\times 10^{-5}$ mm ³ /N·m	75.75	11.58	20.16	18.48	6.719

as obtaining of stable and strong transfer film on counterface [6,10,11].

What deserves to be mentioned is the remarkable back-transfer behavior of the transfer film of the composite, namely, part of the transfer film on the steel bar transfer back on to the worn surface of the pin during the friction process (Fig. 2C–F). But back-transfer behavior is neglectable to transfer film of pure PTFE (Fig. 2B). These back-transfer films prevent further wear of the composites to some extent and more attention should be paid when discuss wear reduction mechanism of PTFE-based

composite. Difference in transferability of transfer film of pure PTFE and PTFE-based composite will be discussed again in the following text in this paper.

Fig. 3 shows the images of transfer films and the corresponding wear debris of pure PTFE and these composites. Images of the transfer films are optical photos and images of wear debris are SEM photos.

We note from Fig. 3A1 that the transfer film of pure PTFE is almost transparent and is composed of relatively bigger patchy flakes. Generally, most of the flake do not border on

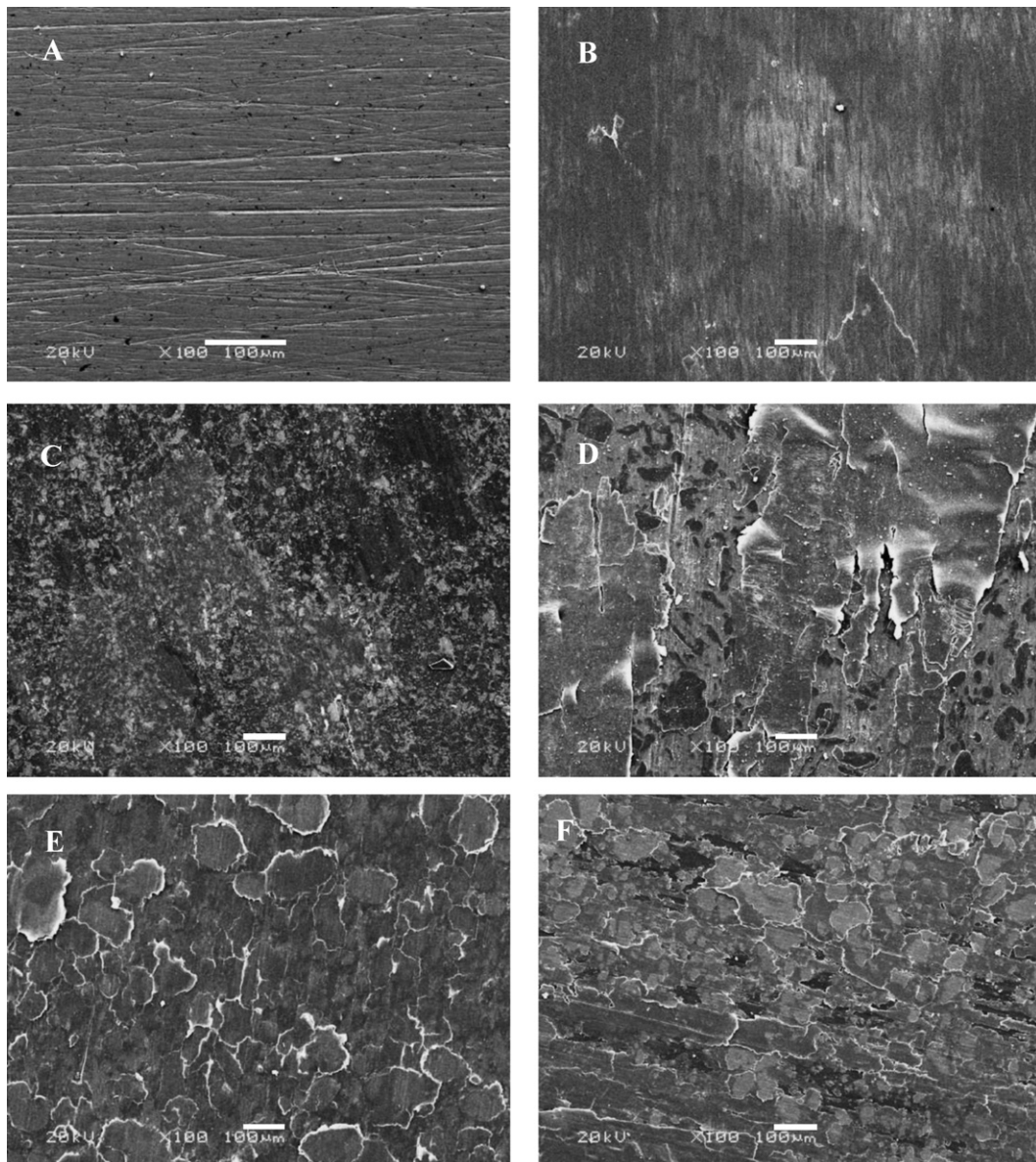


Fig. 2. SEM images of steel bar (A), worn surface of pin of: pure PTFE (B) PTFE/15 vol.% MoS₂ (C) PTFE/15 vol.% graphite (D) PTFE/15 vol.% aluminum (E) PTFE/15 vol.% bronze (F).

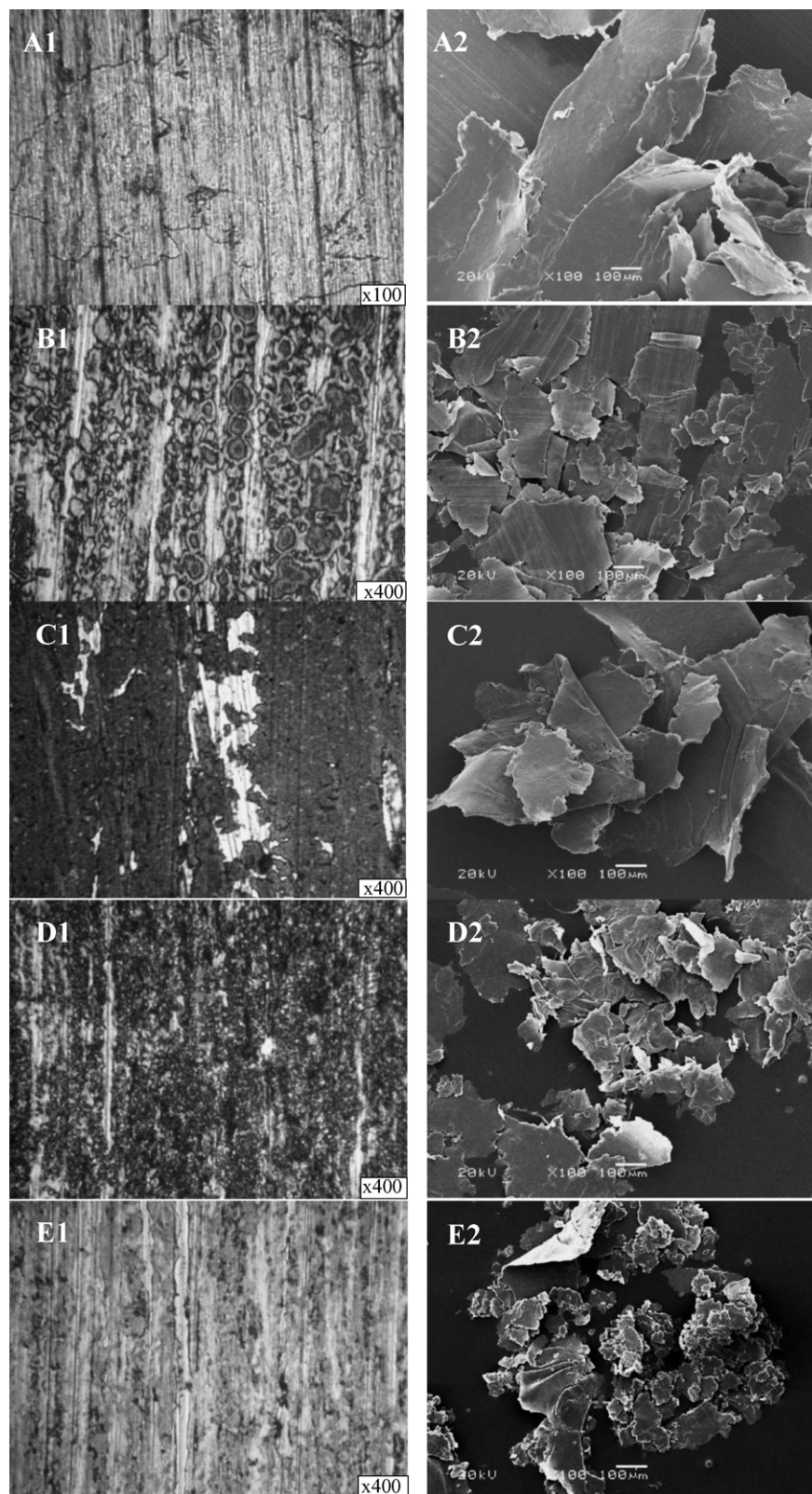


Fig. 3. Transfer film on the steel bar (left column) and wear debris (right column) of PTFE (A) PTFE/15 vol.% MoS₂ (B) PTFE/15 vol.% graphite (C) PTFE/15 vol.% aluminum (D) PTFE/15 vol.% bronze (E).

Table 2
Surface roughness (Ra) of steel bar and transfer films

Ra (μm)	PTFE	PTFE/15 vol.% MoS ₂	PTFE/15 vol.% graphite	PTFE/15 vol.% aluminum	PTFE/15 vol.% bronze
Steel bar	0.13	0.12	0.12	0.13	0.13
Transfer films	0.19	0.09	0.19	0.12	0.10

each other. During the sliding process, these flakes are easily extruded out from the contacting region and large number of them piled up at outer edge. Compared with transfer film of pure PTFE, transfer films of these composites are composed of relatively smaller flakes and have good continuity. During the sliding process, transfer film of the composite stay stably on the steel bar and fewer flakes are extruded out from the contacting region. This difference indicates these fillers are helpful to produce a strongly adhering film of polymer on the counterface. Briscoe et al. [10] even believe that is the main role of the filler.

From Fig. 3A2, B2, C2, D2 and E2 we can see, compared with pure PTFE, introduction of fillers produced some relatively smaller wear debris. Chances are good for these smaller debris particles to stay longer at the contacting region during the friction process. Some smaller debris particles and very fine fillers could even stay in roughness valleys.

But the nature of the filler obviously affects the morphology and continuity of the transfer film. Transfer film of PTFE/15 vol.% MoS₂ is composed of smaller patch (Fig. 3B1). It seemed in these patches a phase is encircled by another phase. Graphite makes the transfer film discontinuous (Fig. 3C1) while

bronze make transfer film smooth and continuous (Fig. 3E1). Transfer film containing aluminum is loose (Fig. 3D1).

Data on surface roughness of transfer films also testified such difference in morphologies (Table 2). The average roughness of steel bar with a transferred layer of pure PTFE or PTFE/15 vol.% graphite are larger than the clean bar surface, which can point to a lumpy debris. Transfer films of PTFE/15 vol.% MoS₂ and PTFE/15 vol.% bronze made steel bar smoother, which was due to fill of fine fillers and smaller wear debris particles [12].

3.2. Tribological properties of transfer films

Tribological properties of the transfer films were tested on a DFPM reciprocating tribometer as described in Section 2.2 (Fig. 1B) and Section 2.3. Fig. 4 shows the friction coefficient change of the transfer films sliding against steel ball under selected normal loads of 0.5N, 1.0N, 2.0N and 3.0N. Generally, the number of sliding cycle at the inflexion of the friction coefficient curve represents the wear life of the transfer film.

Among these transfer films, the wear life of the transfer film of PTFE is the shortest. Its friction coefficient keeps at 0.15 only for about 30 cycles. Then a sudden rise in the friction coefficient

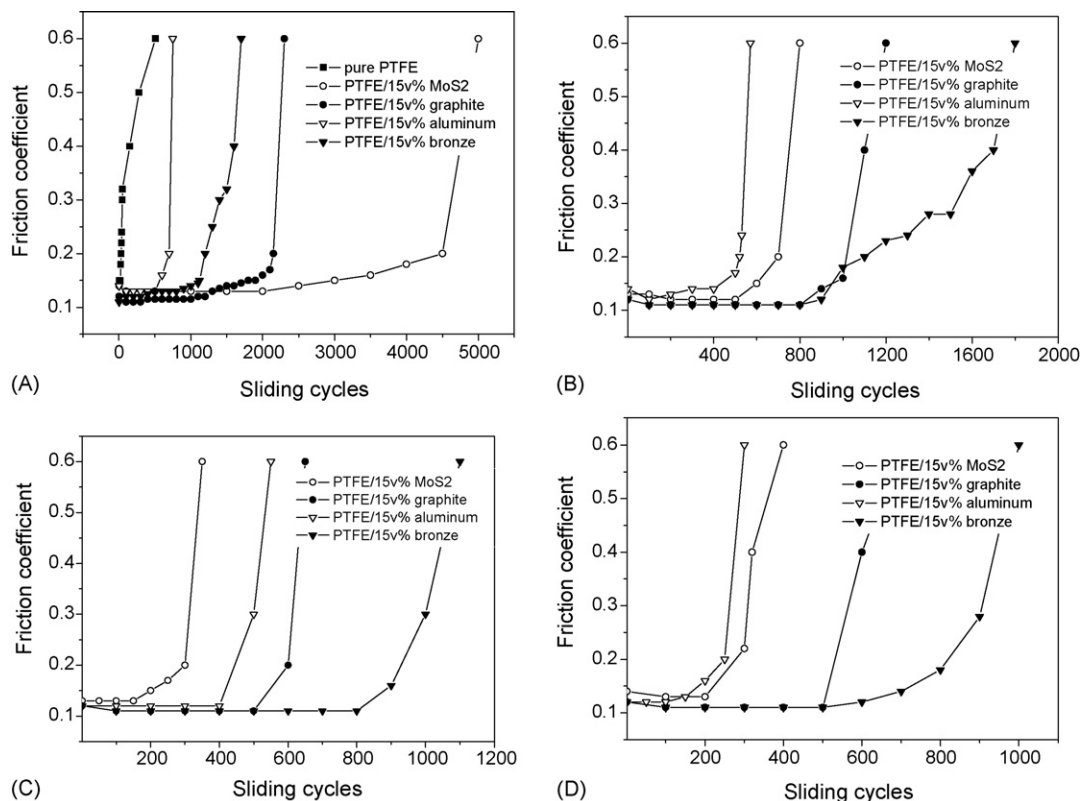


Fig. 4. Changes in friction coefficient of transfer films under given load (A) 0.5N, (B) 1.0N, (C) 2.0N, (D) 3.0N.

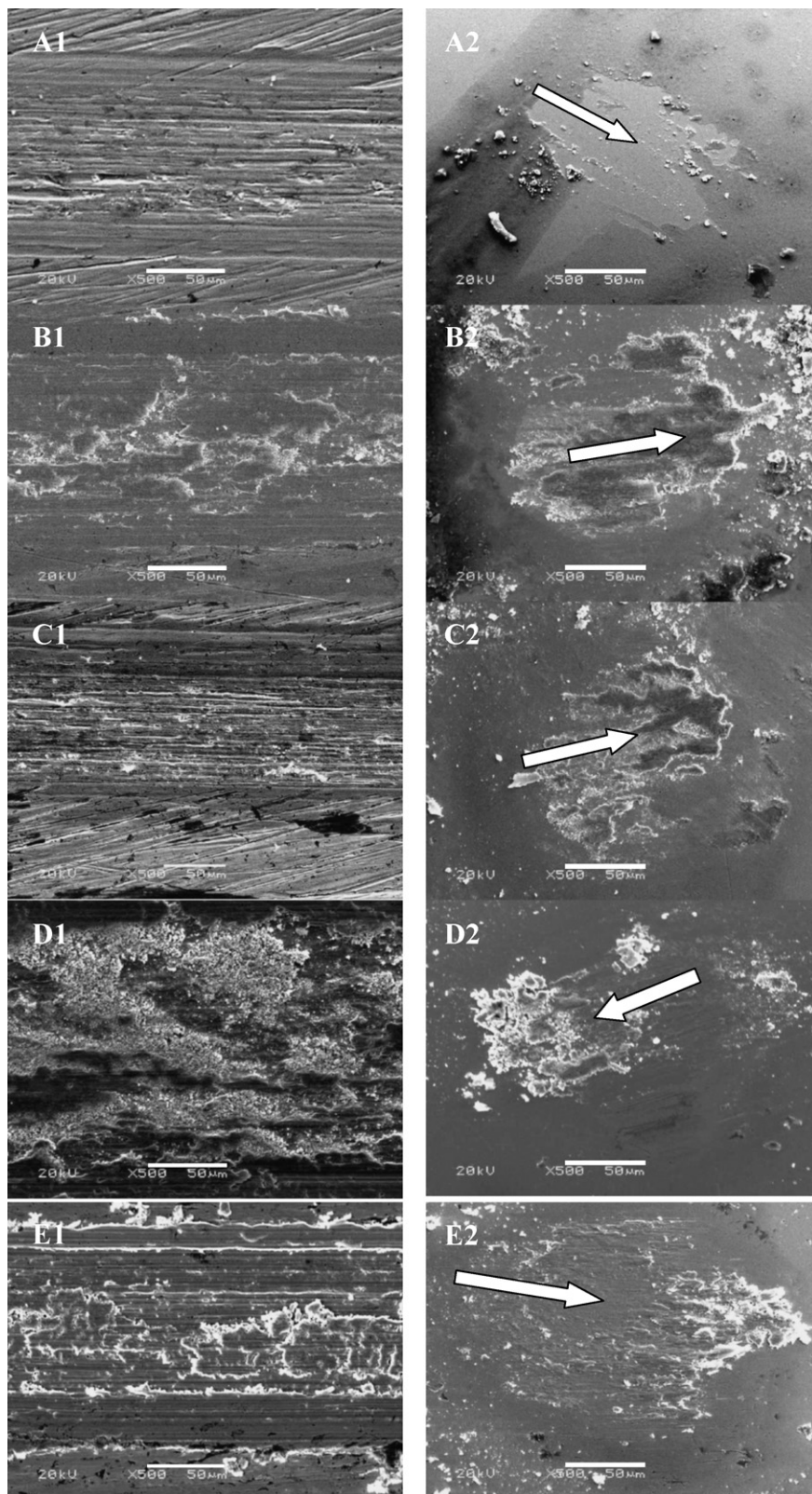


Fig. 5. Friction track on transfer films (left column) and worn surface of steel balls (right column) of PTFE (A), PTFE/15 vol.% MoS₂ (B), PTFE/15 vol.% graphite (C), PTFE/15 vol.% aluminum (D), PTFE/15 vol.% bronze (E).

Table 3
Wear life of transfer films sliding against the steel ball

Load	Wear life (cycles)			
	PTFE/15 vol.% MoS ₂	PTFE/15 vol.% graphite	PTFE/15 vol.% aluminum	PTFE/15 vol.% bronze
0.5N	4500	2150	700	1250
1.0N	700	1030	520	1100
2.0N	300	600	450	900
3.0N	280	520	250	800

cient comes forth. After about 280 cycles, the friction coefficient comes to 0.6, which is the friction coefficient of steel ball directly slides against steel bar under these normal loads.

Compared with the transfer film of pure PTFE, transfer films of PTFE-based composites have longer wear life. As discussed in Section 3.1, these fillers are helpful to produce a strongly adhering film of polymer on the counterface and produced smaller wear debris particles, which enter into roughness valleys along with fine fillers. All these behavior prolonged wear life of the transfer film.

The transfer film of PTFE/15 vol.% MoS₂ composite, especially, endures more than 5000 sliding cycles under a load of 0.5N before worn out. What should be mentioned is that, according to the point contacting friction configuration of this experiment, such a load implies a considerably high pressure. According to average the breadth of the sliding trace (about 0.12 mm), the estimated nominal contacting pressure is about 44 MPa at a normal load of 0.5N.

Results show that different fillers present different load bearing capabilities. Among the selected fillers, bronze exhibits better capability on load bearing under higher load (Fig. 3B–D). Transfer film of PTFE/15 vol.% graphite composite generally possesses the lowest friction coefficient.

Table 3 shows the wear life of transfer films sliding against the steel ball under different load. Herein, the number of cycles when friction coefficient reached 0.2 was designated as the wear life.

Obviously, all these transfer films are sensitive to load change. In the mass, increased load shortened wear life of transfer film. This is ascribed to increase of shear strength, which would more easily peel off the transferred material from the steel bar. But transfer film of PTFE/15 vol.% bronze is far less sensitive to load change than that of the other composite. The author believed bronze is more ductile than the other fillers, so it would more easily enter the roughness valleys and stably stay there. This is helpful to obtain longer wear life even under higher load (1.0N, 2.0N and 3.0N). Bahadur et al. [13] believed that Cu element is soluble in steel so that the formation of a stable transfer film is expected. But it is not always true that fillers containing Cu element could help to reduce wear. Bahadur et al. found that copper acetate as the filler could increase the wear rate of nylon because its transfer film can be easily peeled off from the substrate [13].

Worn surface of transfer films and steel balls were observed to obtain further understanding of tribological behavior of transfer films. Fig. 5 shows the SEM images of friction tracks on transfer films and wear scar of the steel ball. These images were took

when friction coefficient reach 0.2 under load 0.5N. Fatigue wear is clearly showed on transfer film of the composite.

The arrows in Fig. 5A2, B2, C2, D2 and E2 represent sliding directions. Some wear debris attached on the steel ball at the outer edge of the contacting region. Continuous island film was formed on the steel ball near the terminal of the sliding contacting region. This kind of second transfer, namely, part of transfer films transfer onto the steel balls during the friction process and form second transfer film, along with back-transfer behavior mentioned above could reduce wear and effectively protect the counterface.

4. Conclusion

- (1) The wear life of the transfer film of PTFE is short because PTFE cannot form durable transfer film on the steel counterface. PTFE is apt to form big flakes and left the contacting region during the friction process.
- (2) The transfer films containing different fillers have different morphologies and structures and hold different load bearing capabilities. Transfer film of the composite could carry out obvious back-transfer to the composite, which effectively reduced wear of the composite.
- (3) Some inorganic materials, for example, MoS₂, graphite, aluminum and bronze power as fillers could effectively prolong the wear life of transfer film of PTFE-based composites. This was mainly achieved by strongly adhering transfer film and smaller wear debris particles or fine fillers stably stay in the roughness valley.
- (4) Tribological properties of these transfer films are sensitive to load change. Generally, increased load shortened wear life of transfer film.

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