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Epoxy composite reinforced with three-dimensional polyimide fiber felt: Fabrication and tribological properties investigation

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ABSTRACT: Novel epoxy (EP) composite reinforced with three-dimensional (3D) polyimide (PI) fiber felt (PI_{3D}/EP) is first fabricated by vacuum assisted resin transfer molding. The tribological behaviors of pure EP and PI_{3D}/EP composite under dry sliding and water lubricated condition are comparatively studied. Results indicate that both wear rates and friction coefficients of PI_{3D}/EP composite are lower than those of pure EP. The wear resistance of PI_{3D}/EP composite is 9.8 times higher than that of pure EP under dry sliding of 1.5 MPa and 0.76 m s^{-1} while a 27-fold increase is achieved under water lubricated condition. The wear mechanisms of PI_{3D}/EP composite are investigated based on tribological testing results and scanning electron microscopy observations. The PI fiber felt provides strong 3D structure supports to sustain most of the loads on the composite, improving the mechanical and tribological properties significantly. © 2016 Wiley Periodicals, Inc. J. Appl. Polym. Sci. **2016**, *133*, 44160.

KEYWORDS: Epoxy resin; friction and wear; polyimide; three-dimensional composite

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INTRODUCTION

Special wear-resistant material as a core material in the high and new-tech areas of biology, information, energy, and space has become a hot spot both in science research and in practical applications.[1–3] Meanwhile, with the rapid development of petrochemical industry, aerospace, and automobile industry, the demands for wear-resistant material are proved to be more rigorous. Furthermore, water lubrication is welcomed in recent years and has vital function in industrial applications owing to its merits in protecting environment, saving resources, cooling and lubrication effects.[4] Nowadays, wear-resistant materials are also needed to play their functional role under water lubricated condition. Wear-resistant materials with superior functional stability under different conditions are urgently required in engineering applications.

Polymers and polymer-matrix composites have been emerging as important structural and tribo-engineering materials in various industrial fields. These materials can be used as friction components, which offer the possibility of achieving underwater operations due to their low water absorption, good corrosion resistance and excellent wear resistance.[5–8] Epoxy resin (EP), one of the most important thermosetting matrix of advanced polymeric composites, exhibits a series of special characteristics such as excellent dimensional stability, good adhesion, outstanding chemical corrosion resistance, high strength, and low curing shrinkage.[9–11] It has been widely utilized in the fields of automotive, petrochemical industry, architecture and aerospace for tribological applications.[12,13] However, EP presents cross-linking structure after curing, which may cause higher internal stress and brittleness, poorer fatigue and thermal resistance, inferior impact, and wear resistance.[14,15] Hence, it is imperative to modify the resin with reinforcements to adapt higher demands.

Recent research has found that polymers reinforced with 3D fibers exhibit high specific strength and modulus, high fracture toughness and excellent anti-wear properties which can fundamentally eliminate delaminated and fragile defects of materials.[16–19] In addition, 3D fabric can be easily handled without much change in the distribution of fibers during the manufacturing process. Polyimide (PI) fiber is regarded as a promising material to enhance the mechanical and tribological properties of epoxy matrix owing to its excellent properties, such as good thermal stability and chemical inertness under vacuum, high wear resistance, and self-lubricating ability.[20–23] Specifically, PI fiber with 3D structure have been applied in many fields such as high-speed rail construction, flame-retardant protection, and fabrication of high temperature filter material. According to the above description, PI fiber felt can be used as reinforcing material to strengthen epoxy matrix, which is expected to achieve a novel wear-resistant epoxy composite.[24,25]

To date, the tribological behaviors of epoxy composites reinforced with 3D fibers have been rarely investigated in literatures.

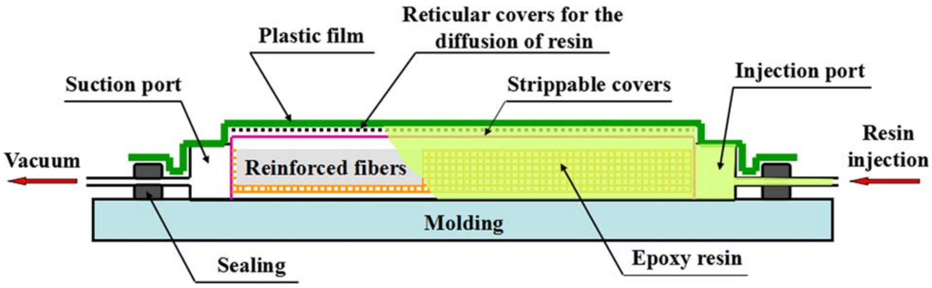

Figure 1. Schematic diagram of VARTM process. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

The aim of the present work is focused on the manufacturing and characterization of the 3D PI fiber felt reinforcing epoxy (PI_{3D}/EP) composite. The mechanical and tribological behaviors under dry sliding and water lubricated condition of PI_{3D}/EP composite and pure EP were comparatively investigated, to evaluate the enhancement function of PI fiber felt. The wear mechanisms were also discussed based on the tribological testing results and scanning electron microscopy (SEM) observations.

EXPERIMENTAL

Materials

In this work, 3D PI fiber felt was provided by Changchun HipolyKing (China). The dimensions of the PI fiber felt are 100 cm × 50 cm × 4 mm, and it can be cut to any desired size as needed. The diameter of single fiber is approximately 8 μm. Araldite LY 1564 bisphenol-A epoxy with low viscosity (purity: 99.9%) and matched curing agent XB 3487 (aliphatic polyamines) were supplied by Huntsman Advanced Materials (Nanjing, China). Vacuum bag was supplied by Beijing Inova Technology (China). Anhydrous ethanol was provided by Huadong Reagent Factory (China). Distilled water was obtained by an artificial process.

Preparation of Pure EP and PI_{3D}/EP Composites

The cured pure EP resin was prepared by mixing LY 1564 epoxy with curing agent XB 3487 under mechanical stirring (400 rpm) for 1 h in a 40 °C water bath, then the mixture was degassed by ultrasonic device at room temperature. The weight ratio of epoxy and curing agent was 100/34 according to the information provided by the company. After removing the bubbles, the mixture was transferred to silicon-rubber molds and cured at 80 °C for 8 h. Then, the cured material was machined and polished for mechanical and wear tests.

The PI_{3D}/EP composite was fabricated by means of vacuum assisted resin transfer molding (VARTM) method, as shown in Figure 1. The degassed mixed resin was immediately introduced into the sealed vacuum bag which contained PI fiber felt (8 cm × 5 cm × 4 mm). To remove bubbles in the resin, this process was carried out under the vacuum condition. The volume fraction of PI fiber in the composite was about 23%. After the procedure of vacuum suction, the resin-infiltrated PI fiber felt was cured by a plate vulcanizing machine under the temperature of 80 °C for 1.5 h followed by 100 °C for 5 h and the pressure of 1 MPa. Finally, the PI_{3D}/EP composite was trimmed, machined and polished.

Morphology of PI_{3D}/EP Composites

The morphologies of fracture surfaces of PI_{3D}/EP composites were investigated by a Zeiss SEM at an accelerating voltage of 7 kV.

Mechanical Behaviors Tests

The tensile properties, flexural properties, and elasticity modulus of fabricated composites were evaluated by mechanical tests following the American Society for Testing and Materials standard (ASTM, D638-10, D790-10, and D5934-02, respectively). The specimens were prepared according to the standard procedures. Five to seven specimens of each composite were tested and the average value from these measurements was used. Specimens were polished and those who have obvious flaws should be discarded. The crosshead speeds of tensile and flexural tests were 1.0 mm min^{-1} and 2.0 mm min^{-1}, respectively. The stress rate for measuring elasticity modulus was 50.0 MPa s^{-1}. The hardness was evaluated by means of a Shore hardness tester (LD-J, Wenzhou Haibao Instruments, China). These tests were conducted under a temperature of 23 ± 2 °C and a relative humidity of $50 \pm 5\%$.

Tribological Behavior Tests

The tribological tests were conducted by a pin-on-disk friction and wear tester (MPX-2000, China) under dry sliding and water lubricated condition. Figure 2 shows schematic diagrams of the testing apparatus, sample and counterpart ring. In consideration of bearing capacity and service conditions of composites, the applied loads ranged from 0.5 to 2.5 MPa were selected. And the sliding velocities were 0.51 and 0.76 m s^{-1}. The friction duration was 60 min. Before each test, steel ring (AISI 1045 Hardness ≤ 187 HB) and samples were polished with 1000-grit SiC abrasive paper to an average roughness of 0.15-0.3 μm and then cleaned with anhydrous ethanol.

During the tribological test, frictional torque was measured by a sensor on the friction machine and recorded by computer continuously. Then, the friction coefficient was calculated according to the following formula by the computer automatically:

$$\mu = \frac{M}{r \times F_N} \tag{1}$$

Here, M is the frictional torque (N m), r is the rotary radius of samples (m), F_N is the vertical load (N).

The wear rate was calculated as follows:

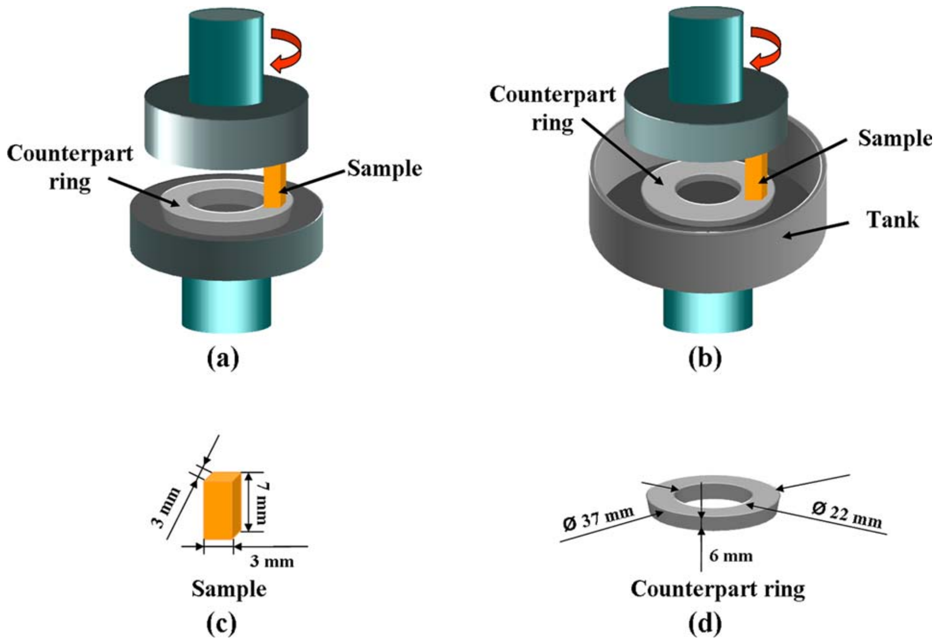

Figure 2. Schematic diagrams of wear tests under dry sliding (a), water lubricated condition (b), sample (c), and counterpart ring (d). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

$$Wr=\frac{\Delta m}{L\times\rho\times F_N} \tag{2}$$

where Δm is the mass loss (g), L is the sliding distance of samples (m), ρ is the density of the sample (g cm^{-3}), F_N is the vertical load (N).

In this work, three repeated tribological tests of each condition were carried out and the average value of three testing results was adopted. The microstructures of the worn and counterpart surfaces were studied with a Zeiss SEM at an accelerating voltage of 7 kV.

RESULTS AND DISCUSSION

Configuration and Structure of PI$_{3D}$/EP Composite

Figure 3 shows the configuration of 3D PI fiber felt. The PI fibers are overlapped with each other in "*XY*" orientation, and they exhibit tridimensional structures in "*Z*" orientation [Figure 3(b)]. Accordingly, the PI fibers braided in "*XYZ*" orientation present a three-dimensional (3D) cross-linked structure in the matrix EP, which form backbone of the whole composite. The "*XY*" plane is chosen as the friction direction. When the friction direction is parallel with the "*XY*" plane, the tridimensional fiber bundles in "*Z*" orientation play an important role in the aspects of reinforcing compressive property, heat conductivity and interlaminar shear strength of the materials, improving the tribological properties of composites. From the SEM image of the cross section of PI$_{3D}$/EP composite in Figure 4, we can clearly observe a robust interpenetrating structure in a 3D pattern. There are no gaps and pockets of fabric in the composites; a strong bonding strength is formed between PI fibers and epoxy matrix in varying degrees.

Mechanical Properties of PI$_{3D}$/EP Composite

The mechanical properties of PI$_{3D}$/EP composite are summarized in Table I. It can be clearly observed that the tensile strength, flexural strength, flexural modulus, elastic modulus and hardness of PI$_{3D}$/EP composite increase by 52.8, 94.4, 69.7,

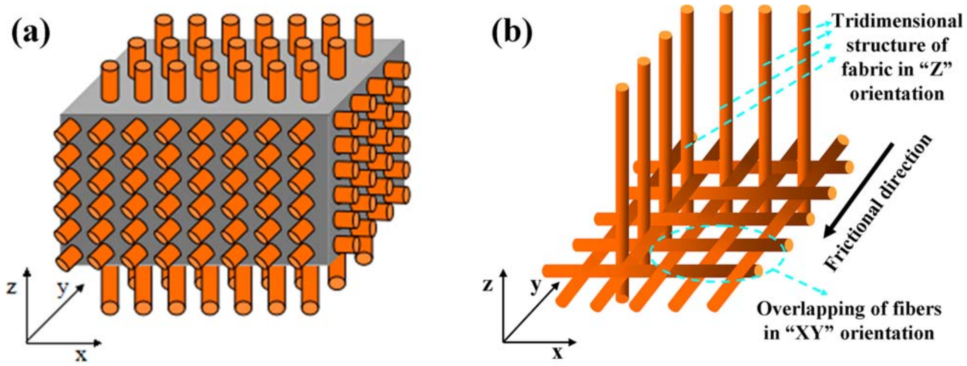

Figure 3. Whole structure of 3D PI fiber felt (a) and internal braid structure (b). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

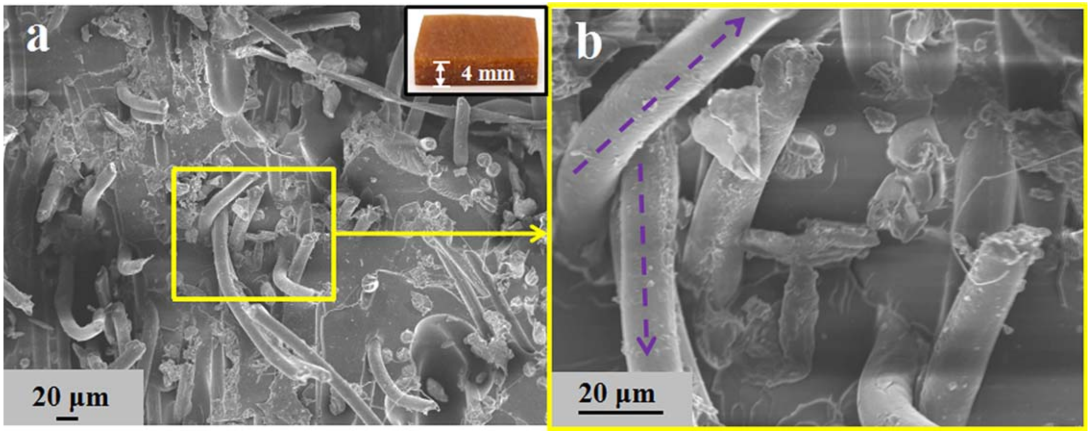

Figure 4. SEM images of cross section of PI_{3D}/EP composites (a) and (b) is the magnification of (a). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

258.5, and 13.3%, respectively, compared to those of pure EP. For PI_{3D}/EP composite, tridimensional fiber bundles in "*Z*" orientation improve the compressive and interlaminar shear strength of the composites. Thus, the robust 3D structure of PI fiber felt shares the most impact on the composite. Moreover, the strong interaction between epoxy molecules and PI fibers can maintain the strong structure of composite and prevent the PI fibers peeling from the composite. Besides, the introduction of PI fiber improves brittleness of EP-based composites and further enhances the toughness and elasticity of the composite effectively, further enhancing the breaking elongation and elastic modulus of PI_{3D}/EP composites.

Tribological Results

Effect of the Applied Load under Dry Sliding. The effect of the applied load under dry sliding on the wear rates and friction coefficients for pure EP and PI_{3D}/EP composite is shown in Figure 5. The wear rate of pure EP rapidly increases with increasing applied load, which reaches the maximum value of 95.73×10^{-14} m^3 N^{-1} m^{-1} under 1.5 MPa [Figure 5(a)]. When the applied load is above 1.5 MPa, the accumulation of frictional heat and high loads lead to the plastic deformation and fragmentation of pure EP sample, thus the tribological test for pure EP cannot even proceed. Hence, there are no tribological data for pure EP after 1.5 MPa. As for PI_{3D}/EP composite, the wear rate can still maintain a low value under dry sliding condition, although it increases slightly when the applied load exceeds 1.5 MPa. Interestingly, the lowest wear rate of PI_{3D}/EP composite is also obtained in 1.5 MPa, which is 9.8-fold decrease than that of pure EP. It means that the wear resistance of PI_{3D}/EP composite has been significantly improved.

Table I. Mechanical Properties of Pure Epoxy and PI_{3D}/EP Composite

	Composite materials	
Properties	Pure EP	PI_{3D}/EP
Tensile strength (MPa)	72 ± 2	110 ± 1
Breaking elongation(%)	14 ± 5	29 ± 6
Flexural strength (MPa)	90 ± 2	175 ± 2
Flexural modulus (MPa)	2048 ± 46	3476 ± 31
Elastic modulus (MPa)	1320 ± 84	4732 ± 68
Shore hardness (HD)	75 ± 1	85 ± 1

EP, epoxy; PI_{3D}/EP, polyimide reinforced epoxy composite.

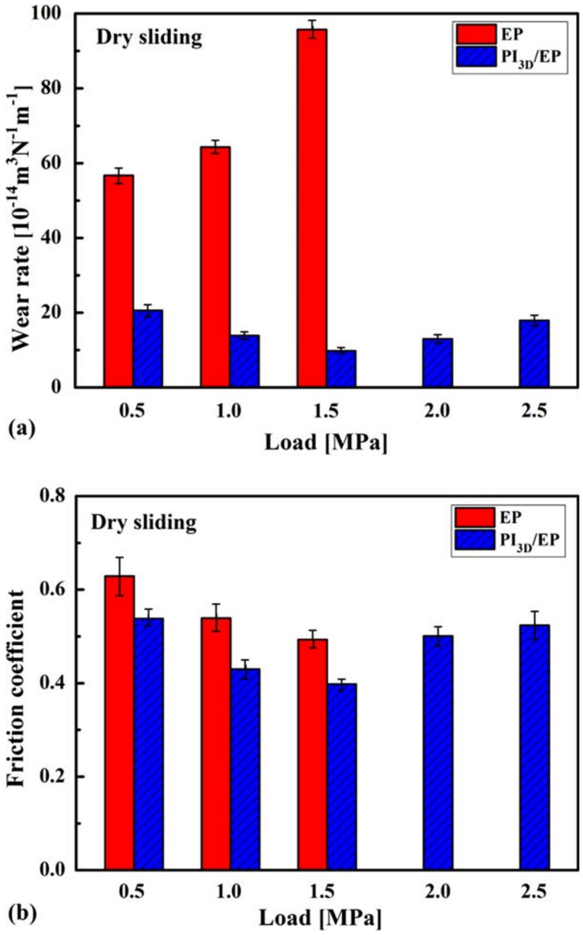

Figure 5. Wear rates (a) and friction coefficients (b) of pure EP and PI_{3D}/EP composite under dry sliding. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

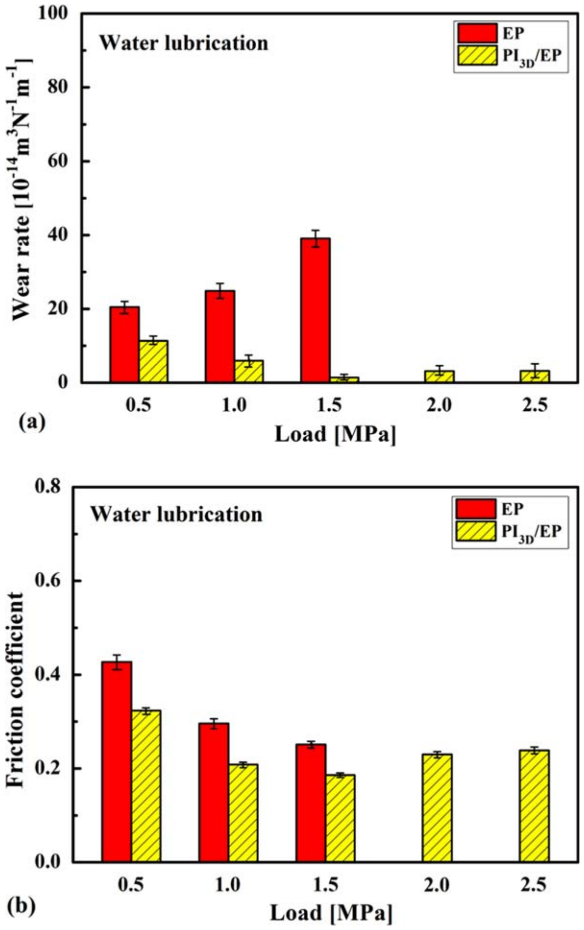

Figure 6. Wear rates (a) and friction coefficients (b) of pure EP and PI_{3D}/EP composite under water lubricated condition. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Figure 5(b) shows the variation trends of friction coefficients of pure EP and PI_{3D}/EP composite with increasing normal loads under dry sliding. Results indicate that the friction coefficient of pure EP decreases with increasing normal load under dry sliding, while the friction coefficient of PI_{3D}/EP composite decreases gradually at first and then increases, the lowest values of the two composites are both obtained under 1.5 MPa. Compared to pure EP, the friction coefficient of PI_{3D}/EP composite decreases by 23.9% under 1.5 MPa. This indicates that the tridimensional structures provided by PI fiber felt can endure most of the loads to support EP-based composite. Moreover, PI fibers with self-lubricating ability and excellent wear resistance make great contributions to the improvement in the friction and wear behaviors of PI_{3D}/EP composite.[23]

Effect of the Applied Load under Water Lubricated Condition. Figure 6 shows the tribological results of pure EP and PI_{3D}/EP composite with increasing applied loads under water lubricated condition. The wear rates of composites under water lubricated condition [Figure 6(a)] exhibit the same variation trends with dry sliding condition [Figure 5(a)]. Pure EP obtains the highest wear rate of 39.07×10^{-14} m^3 N^{-1} m^{-1} while PI_{3D}/EP composite gains the lowest value under 1.5 MPa. At this time, the wear rate of PI_{3D}/EP composite is 1.45×10^{-14} m^3 N^{-1} m^{-1}, which is 27 times lower than that of pure EP. In Figure 6(b), the lowest friction coefficients of pure EP and PI_{3D}/EP composite are obtained under 1.5 MPa as well. As compared to pure EP, the addition of PI fiber felt decreases the friction coefficient by a factor of 35.1%.

It can be concluded that PI_{3D}/EP composite exhibits superior tribological properties under both dry sliding and water lubricated condition. That means the 3D PI fiber felt is proved to be an effective reinforcing material to improve the tribological properties of EP matrix. PI fibers overlap with each other in "*XY*" orientation and they are parallel with the frictional surface. Additionally, PI fibers exhibit tridimensional structures in "*Z*" orientation and these tridimensional fiber bundles enhance the compressive property and interlaminar shear strength of PI_{3D}/EP composite, thus improving the tribological properties of PI_{3D}/EP composite (as shown in Figure 3).

Results indicate that both the wear rates and friction coefficients under water lubricated condition are always lower than those under dry sliding condition. In particular, under 1.5 MPa, the wear rate of PI_{3D}/EP composite under water lubricated condition decreases by 85.2% compared to dry sliding, meanwhile the friction coefficient decreases by 53.3%. Under water lubricated condition, distilled water as a lubricant can reduce the direct contact between specimen and counterpart surface, which gives rise to the lower wear rates and friction coefficients.[12,26] In addition, water as coolant and cleaner plays important roles in transmitting the generated frictional heat and washing away the debris on the counterpart surface.[27] Consequently, composites exhibit more outstanding wear resistance under water lubricated condition.

Effect of the Velocity under Dry Sliding and Water Lubricated Condition. The effect of the sliding velocity on tribological properties of pure EP and PI_{3D}/EP composites is investigated. In Table II, it is clearly seen that the wear rate of specimen increases with the velocity increases from 0.51 to 0.76 m s^{-1} under dry sliding. It may be attributed to the fact that more frictional heat are generated with increasing velocity, which may further damage the surface texture of EP-based

Table II. Effect of Sliding Velocity on Tribological Properties of Composites under Dry Sliding, 1.5 MPa

	Wear rate (10^{-14} m^3 N^{-1} m^{-1})		Friction coefficient	
Composite	0.51 m s^{-1}	0.76 m s^{-1}	0.51 m s^{-1}	0.76 m s^{-1}
Pure EP	34.23 ± 2.62	95.73 ± 3.50	0.53 ± 0.010	0.49 ± 0.006
PI_{3D}/EP	6.37 ± 0.72	9.77 ± 1.28	0.41 ± 0.003	0.39 ± 0.005

EP, epoxy; PI_{3D}/EP, polyimide reinforced epoxy composite.

Table III. Effect of Sliding Velocity on Tribological Properties of Composites under Water Lubricated Condition, 1.5 MPa

	Wear rate (10^{-14} m^3 N^{-1} m^{-1})		Friction coefficient	
Composite	0.51 m s^{-1}	0.76 m s^{-1}	0.51 m s^{-1}	0.76 m s^{-1}
Pure EP	21.32 ± 1.86	39.07 ± 2.54	0.27 ± 0.009	0.25 ± 0.003
PI$_{3D}$/EP	0.84 ± 0.15	1.45 ± 0.20	0.19 ± 0.003	0.18 ± 0.006

EP, epoxy; PI$_{3D}$/EP, polyimide reinforced epoxy composite.

composites and thus result in a higher wear loss. PI$_{3D}$/EP composite shows lower wear rate and friction coefficient than those of pure EP under different velocities. Especially, the wear resistance of PI$_{3D}$/EP composite improves more notably under high velocity. This indicates that the interpenetrating structure between fibers and epoxy polymers can realize strong interfacial interaction during the sliding process. Hence, PI$_{3D}$/EP composite can still maintain excellent carrying capacity and wear resistance even under high velocity.

During the sliding process under water lubricated condition, the variation trends of friction behaviors are similar to those under dry condition. Compared to pure EP, PI$_{3D}$/EP composite demonstrates lower wear rates and friction coefficients under different sliding conditions (Table III). Additionally, it is worth to note that all the tribology data under water lubricated condition are lower than those under dry condition. During the sliding at a higher velocity, frequent contacts between composite and counterpart surface result in more heat generation and accumulation. Nevertheless, under water lubricated condition, cooling and lubricating effects of distilled water can considerably decrease the frictional heat and help to maintain a relatively stable wear period. Hence, serious plastic deformation of composites can be hindered in the presence of water and eventually better tribological properties are achieved.

Worn and Counterpart Surfaces under Dry Sliding Condition. To have a better understanding on the friction and wear mechanism of composites, the worn surfaces of pure EP and PI$_{3D}$/EP composites at the applied load of 1.5 MPa and velocity of 0.76 m s^{-1} are analyzed. Figure 7 shows the SEM images of worn surfaces of specimens under dry sliding condition. On the worn surface of pure EP shown in Figure 7(a), it is very rough, covered with serious adhesive traces, many nicks and debris, which is corresponding to high wear loss. Such characteristics of worn surface reveal that serious plastic deformation, adhesive and abrasive wear mechanisms are the main reasons for the wear loss of pure EP. On the contrary, the worn surface of PI$_{3D}$/EP composite is relative smooth, and some fiber traces are exposed on the worn surface [Figure 7(b)]. Besides, the phenomenon of slight adhesive can be observed in Figure 7(b). This superior worn surface can be attributed to the following factors. The 3D PI fiber felt acts as skeleton, which improves the load-carrying capacity of the matrix. Therefore, no plastic deformation occurs during the sliding process. Moreover, the exposed PI fibers on the worn surface sustain most of the loads, which decrease the contact area between the matrix and counterpart surface. Hence, the worn surface of PI$_{3D}$/EP composite is better maintained and the wear resistance of the composite improves greatly.

The SEM pictures of counterpart surfaces of pure EP and PI$_{3D}$/EP composite under dry sliding condition are exhibited in Figure 8. The counterpart surface of pure EP is quite rough. And this surface is characterized by lots of debris and furrows. While compared to pure EP, PI$_{3D}$/EP composite exhibits a relative smooth counterpart surface [Figure 8(b)]. There are merely some debris and slight scratches on the counterpart surface. Moreover, the uniform and coherent transfer film is detected on

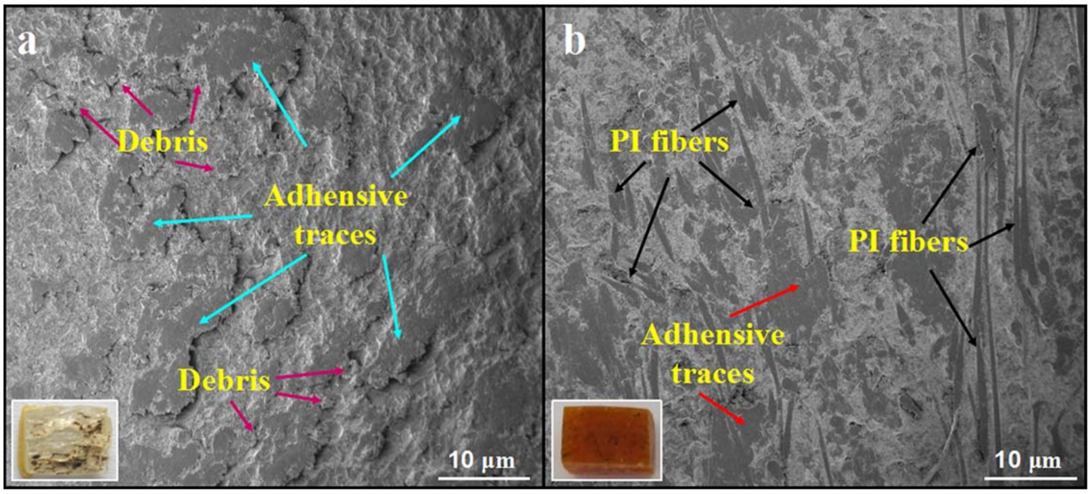

Figure 7. SEM and optical images of worn surfaces of pure EP (a) and PI$_{3D}$/EP composite (b) under dry sliding condition (1.5 MPa, 0.76 m s^{-1}). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

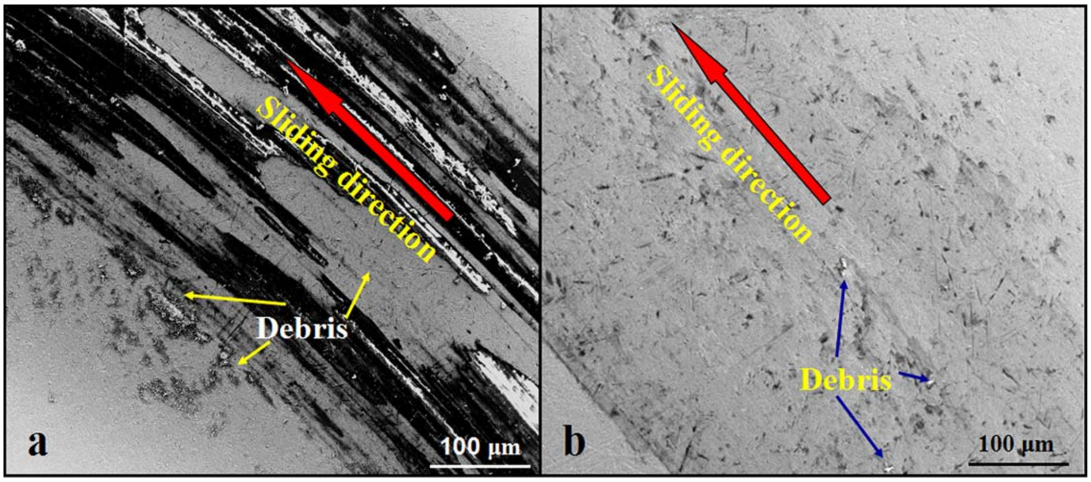

Figure 8. SEM images of counterpart surfaces of pure EP (a) and PI_{3D}/EP composite (b) under dry sliding condition (1.5 MPa, 0.76 m s^{-1}). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

the counterpart surface, which can prevent direct contact between specimen and counterpart steel, and thus improve the tribological properties of PI_{3D}/EP composite effectively.

Worn and Counterpart Surfaces under Water Lubricated Condition. Figure 9 demonstrates the worn surfaces of pure EP and PI_{3D}/EP composite under water lubricated condition. The worn surface of pure EP is rather rough [as shown in Figure 9(a)]. Obvious exfoliating, crack regions and debris can be seen on it. Such characteristics of the worn surface of pure EP are mainly due to the inferior water-absorbing resistance of pure EP.[12] Water can infiltrate into the EP matrix, leading to the swelling, malacia and plastic deformation of the matrix.[28] It indicates that delamination and abrasive wear are the main mechanisms for pure EP under water lubricated condition. As for the worn surface of PI_{3D}/EP composite [Figure 9(b)], it is more smooth under water lubricated condition. The slight abrasive wear is the main reason for the wear loss of PI_{3D}/EP composite under water lubricated condition.

Figure 10 exhibits the counterpart surfaces of pure EP and PI_{3D}/EP composite under water lubricated condition. The counterpart surface of pure EP is relatively rough, covered with some furrows on the surface [Figure 10(a)]. On the contrary, the counterpart surface of PI_{3D}/EP composite is very smooth [Figure 10(b)] compared to pure EP. During dry sliding wear (Figure 8), the transfer film makes great contribution to improve the friction and wear behaviors. Nevertheless, under water lubricated condition, the counterpart surface of PI_{3D}/EP composite is smooth and there are few debris of fibers and polymer matrix on it under the scouring action of water, which limits the formation of transfer film. While the boundary lubricating film is formed on the counterpart surface during friction process under water lubricated condition. Research shows that the cracks of matrix and furrows on the hard rough counterpart surface may lead to the fracture of boundary lubricating film.[29] In Figure 10(a), it can be obviously observed that there are plenty of furrows and scratches on the counterpart surface of pure EP. Thus, the boundary lubricating film of pure EP is easily damaged, and we cannot observe the trace of boundary

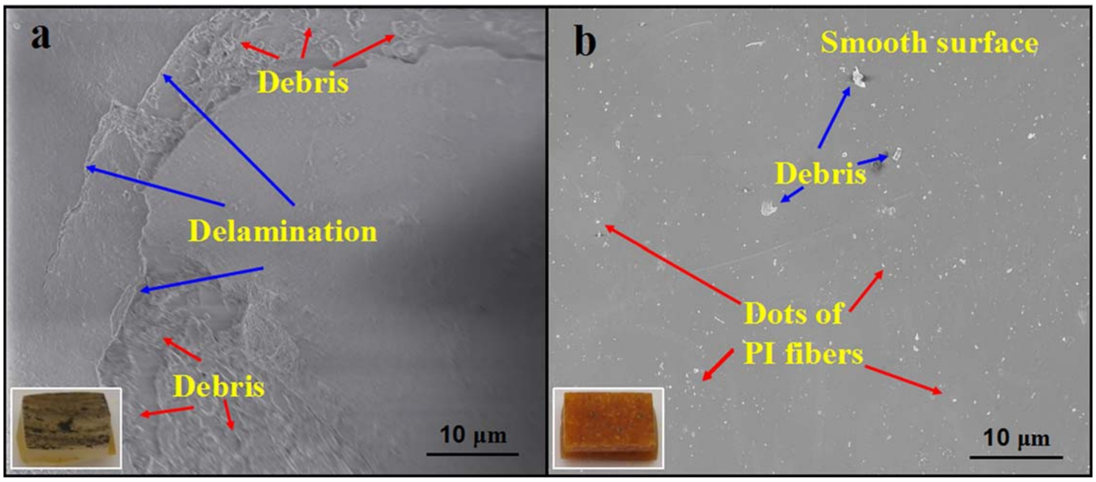

Figure 9. SEM and optical images of worn surfaces of pure EP (a) and PI_{3D}/EP composite (b) under water lubricated condition (1.5 MPa, 0.76 m s^{-1}). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

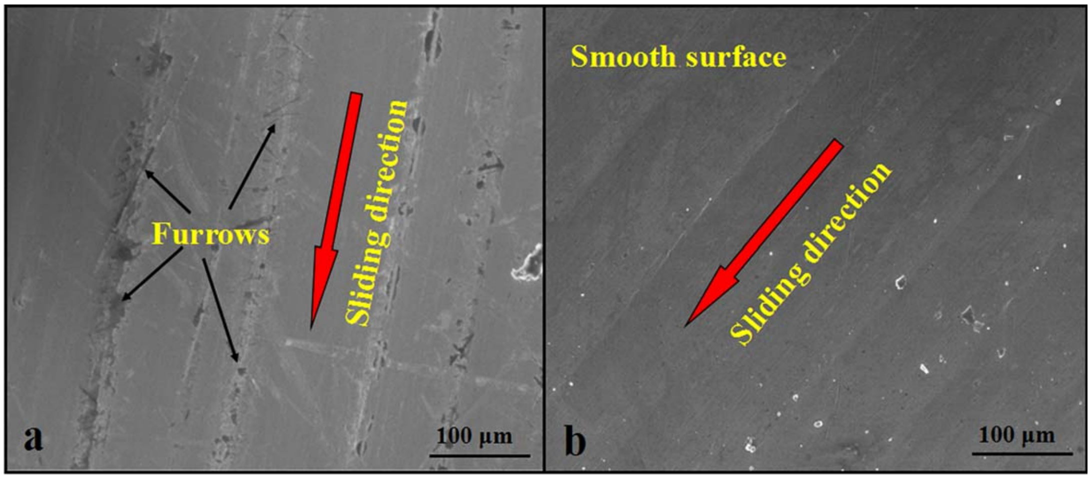

Figure 10. SEM images of counterpart surfaces of pure EP (a) and PI_{3D}/EP composite (b) under water lubricated condition (1.5 MPa, 0.76 m s^{-1}). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

lubricating film in SEM images. Interestingly, the counterpart ring of PI_{3D}/EP composite with smooth surface can ensure the integrity of boundary lubricating film, further enhancing the tribological properties of composites.

Wear Mechanisms of PI_{3D}/EP Composite under Dry Sliding and Water Lubricated Condition. Based on the tribological results and SEM observations, the related wear mechanisms of PI_{3D}/EP composite under dry sliding and water lubricated condition are proposed (Figure 11). In Figure 11(a), large numbers of PI fibers are exposed on the worn surface of PI_{3D}/EP composite during dry sliding process. These exposed fibers sustain most of the loads between worn and counterpart surfaces and prevent the cutting effect of counterpart's asperities on the EP matrix, which improves the wear resistance of PI_{3D}/EP composite. At the later stage of wear process, fibers fracture and exfoliate, and debris fall on the counterpart surface. Then, the uniform and coherent transfer film is formed on the counterpart surface owing to the repeated deformation, squeezing, malacia, and transfer between exposed fibers and matrix debris. This transfer film contributes to the improvement of tribological properties of PI_{3D}/EP composite. Hence, slight adhesive and abrasive wear are the main wear mechanisms for PI_{3D}/EP composite under dry sliding.

As for water lubricated condition [Figure 11(b)], water film decreases the chemical affinity between composite and counterpart steel, leading to a relative slight abrasion of the composite. Moreover, no transfer film is formed on the counterpart surface owing to the washing effect of water, that is, no obvious adhesive wear is occurred. And the surface of this counterpart steel has bright and glossy images. In addition, the generated frictional heat can be timely transmitted to the surroundings due to the function of water, so no plastic deformation occurred on the composite. Besides, abrasion wear is formed owing to the abrasion, fracture, and exfliation of the fibers during the sliding process. Consequently, slight abrasive wear is the main mechanism for PI_{3D}/EP composite under water lubricated condition.

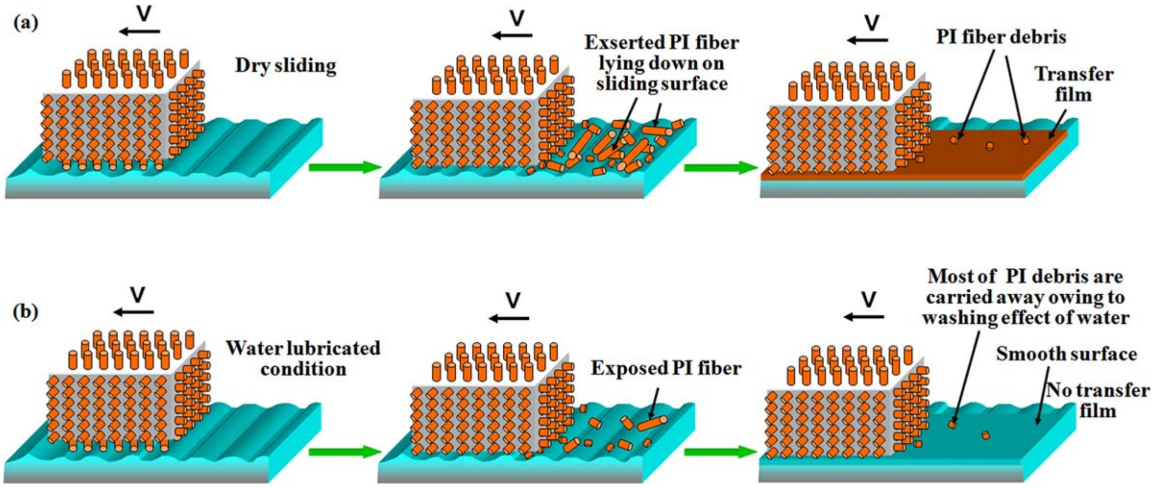

Figure 11. Wear mechanisms of PI_{3D}/EP composite under dry sliding (a) and water lubricated condition (b). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

CONCLUSIONS

In this work, robust PI_{3D}/EP composite is fabricated by means of VARTM method. The mechanical and tribological properties of PI_{3D}/EP composite are comparatively investigated. The following conclusions can be drawn:

1. The PI_{3D}/EP composite exhibits excellent mechanical properties with the addition of 3D PI fiber felt. As compared to pure EP, tensile strength, flexural strength, flexural modulus, elastic modulus, and hardness of PI_{3D}/EP composite increase by 52.8, 94.4, 69.7, 258.5, and 13.3%, respectively.
2. Based on the tridimensional structure supporting, good interface bonding strength and excellent load-carrying capacity, PI_{3D}/EP composite shows improved wear resistance compared to pure EP under dry and water lubricated conditions. Particularly, under water lubricated condition, the PI_{3D}/EP composite exhibits a 27-fold increase in wear resistance under 1.5 MPa, 0.76 m s^{-1}.
3. Under dry sliding, the uniform and coherent transfer film is formed on the counterpart steel of PI_{3D}/EP composite and this film can further protect the composite to achieve excellent wear resistance. Thus, slight adhesive and abrasive wear are the main wear mechanisms for PI_{3D}/EP composite. As for pure EP, the main wear mechanisms are serious plastic deformation, adhesive and abrasive wear.
4. Under water lubricated condition, the boundary lubricated film is established between the worn and counterpart surfaces due to the washing effect of water. In addition, water can also play a role as coolant which transmits the frictional heat to the surroundings timely. Thus, slight abrasive wear is the main reason for the wear loss of PI_{3D}/EP composite, and the main wear mechanisms for pure EP are delamination and abrasive wear.

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