Enhancement of Underwater Tribological Properties of Hybrid PTFE/Nomex Fabric Laminate Composites by Epoxy Resins

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ABSTRACT: Hybrid poly(tetrafluoroethylene) (PTFE)/Nomex fabric laminate composites were prepared with phenolic and epoxy resins. A pin-on-disc tribometer was used to perform tribological tests with different applied loads and rotational speeds. The wear surface, transfer film, and cross section were analyzed by scanning electron microscopy (SEM) and optical microscopy. The results showed that the epoxy resin with high strength and good binding properties can enhance underwater tribological and mechanical properties. The underwater surface hardness was also improved by the epoxy resin. The underwater strength and adhesiveness of the phenolic resin reduced and the underwater surface hardness also decreased, causing a decrease in underwater tribological and mechanical properties of the phenolic resin.

1. INTRODUCTION

A hybrid poly(tetrafluoroethylene) (PTFE)/Nomex fabric laminate composite is a material with excellent tribological and mechanical properties that can be used in water-lubricated bearings of ships because the PTFE fiber has enhanced self-lubricating effects to ensure good tribological properties. Nomex fiber has a large binding force with an adhesive resin to ensure good mechanical properties.1−4 Excellent underwater wear and water resistance as well as high underwater strength are required for water-lubricated bearing liner materials, which are closely related to the adhesive resin.5,6

A phenolic resin is a commonly used adhesive resin in hybrid PTFE/Nomex fabric laminate composites.7,8 Professor Zhang and his colleagues have carried out enormous research work on a hybrid PTFE/Nomex fabric/phenolic resin composite.9−11 Ren et al. studied the effect of air−plasma treatment and different fillers on the tribological behavior of the hybrid PTFE/Nomex fabric/phenolic resin composite under dry sliding. The results showed excellent wear resistance and load carrying capacity under the influence of different fillers.12−16 Yang et al. used a layer-by-layer self-assembly method, Mo2C and ZrB2 fillers, and Polyfluor Wax to improve the tribological behavior of the hybrid PTFE/Nomex fabric composite under dry sliding. The results showed an improved tribological performance.17−21

Some research studies were dedicated to the underwater tribological properties of hybrid fabric phenolic resin composites.22 Ren et al. studied the underwater tribological properties of a hybrid PTFE/Nomex fabric composite, and the results showed a high wear rate and low friction coefficient under water lubrication.23 Liu et al. used modified UHMWPE microparticles and carbon nanotubes to improve the underwater tribological properties of glass fabric/phenolic laminate composites, and the results showed enhanced underwater tribological properties because of the increasing interfacial binding force between the glass/phenolic laminates.24,25 Overall, the underwater tribological properties of hybrid fabric composites are reduced by water but improved by the increasing interfacial binding force between interlayers. An epoxy resin has high strength and excellent adhesion properties that can improve the binding force between layers.26−28 Yan et al. studied the friction and wear properties of epoxy composites under water lubrication. The results showed a low friction coefficient and wear rate under water.27 An epoxy resin has excellent synergy with PTFE, high binding force with Nomex fibers, and high strength underwater.28,29

The underwater tribological properties can be enhanced by the interlayer binding force.30 Different fillers and various treatments improve the binding force between layers, thereby improving the underwater tribological properties. This paper proposes a novel simpler method using the epoxy resin to improve underwater tribological properties. The interlayer
adhesion is enhanced by the epoxy resin, achieving enhanced underwater tribological properties.

2. RESULTS AND DISCUSSION

2.1. Coefficient of Friction (COF) of Fabric Samples 1# and 2#. Figure 1a,b shows that the maximum static COF of 1# is 0.098 and that of 2# is 0.76 under dry sliding, but the maximum static COF of 1# is 0.28 and that of 2# is 0.11 under water lubrication. In Figure 1c,d, compared to dry sliding, the COF vs time of 1# increases from 0.1 to 0.2 and that of sample 2# drops from 0.085 to 0.05 under water lubrication. In Figure 1e−i, with different speeds and loads, the COF of sample 2# is lower than that of 1# with a little difference under dry sliding but a large difference under water lubrication. The average COF in Figure 1j is the average value of COF under different speeds and loads in Figure 1e−i. In Figure 1j, the average COF of 1# is 0.097 under dry sliding but increases to 0.12 under water lubrication. The average COF of 2# is 0.0748 under dry sliding and drops to 0.0549 under water lubrication.23 Figure 1 shows that the COFs of samples 1# and 2# have a little difference under dry sliding but a large difference under water lubrication because the underwater COF of sample 1# increases and that of sample 2# sample decreases. Sample 1# has good dry tribological properties with low dry COF but poor underwater tribological properties after soaking with high underwater COF.12,24 Because the underwater adhesiveness and strength of the phenolic resin of sample 1# decreases after soaking, water infiltrates between the layers, reducing the underwater strength and hardness of sample 1#, and thereby increasing the underwater COF. Sample 2# remains low COF with good tribological properties both under dry sliding and water-lubricated conditions. Because the epoxy resin has high underwater strength and excellent underwater binding force, improving the interlayer adhesion, water is hard for the water to infiltrate interlayers, and so sample 2# retains high strength and hardness underwater. Moreover, water on the surface with the cooling and lubricating effect is beneficial to reduce the underwater COF of sample 2#.

2.2. Laser Microscope Observations of the Working Surface and Wear Depth. In Figure 2a1−a3, the working surface is rich in PTFE fibers without furrows caused by abrasion, the peak of the working surface is PTFE fibers with a height of 24 μm and a surface roughness (Sa) of 6.7 μm before wear. In Figure 2b1−b3, furrows appear on the working surface with rolling deformation of Nomex and PTFE fibers after dry sliding.20 The wear scars do not penetrate to the bottom of the valley on the working surface; the wear depth is 12 μm and Sa is 4.7μm. In Figure 2c1−c3, wear scars are more serious with
the water-lubricated wear depth of 18 μm and Sa of 3.6μm. The Nomex fibers are severely deformed and worn, and PTFE fibers are worn deeper. Reducing the strength and binding force between Nomex fibers and the phenolic resin leads to more severe wear in water. As a result, the tribological properties of sample 1# are good under dry sliding but poor under water lubrication.

In Figure 3a1−a3, the epoxy resin of sample 2# fills between the PTFE fibers and Nomex fibers, exhibits excellent adhesion, resulting in a smaller Sa of 4.0 μm and a peak height of 20.0 μm. In Figure 3b1−b3, slight scratches appear on the surface with a wear depth of 14 μm and Sa of 2.8 μm under dry sliding. PTFE and Nomex fibers are firmly embedded in the epoxy resin matrix. In Figure 3c1−c3, Nomex fiber surfaces only appear slightly deformed because of the high strength of the epoxy resin in water. The surface of 2# becomes flatter with the underwater wear depth of 9 μm and Sa of 1.8 μm. The high strength and large interlayer binding force of the epoxy resin cause a underwater surface hardness. The hardness surface can improve the underwater wear resistance.

The dry friction wear depths of 1# and 2# are similar, but 1# has 18 μm underwater wear depth and 2# has 9 μm underwater wear depth. The epoxy resin enhances the interface binding force, thereby improving the underwater wear resistance of sample 2#. The surface roughness of sample 2# is always less than that of 1# before and after wear. The strong adhesiveness of the epoxy resin can be connected to form a sheet on the working surface. The phenolic resin mainly binds to Nomex fibers, and the diameter of fabric fibers has a greater impact on the surface roughness.

2.3. Microscopic Images of the Cross Section and Transfer Film on the Metal Pin. In Figure 4a, for sample 1#, the sides bind loosely because the weak binding force of the phenolic resin between layers cause the interlayers to separate easily. Water penetrates into the interlayer after soaking. As a result, the underwater interlayer adhesiveness and the underwater strength of Nomex fibers and the phenolic resin are further reduced because of absorbing water. Figure 4b is the binding surface of sample 1#, and the binding force and strength of Nomex fibers are reduced after absorbance. Finally,

Figure 2. Surface morphology of sample 1#: (a1) unworn surface, (a2) three-dimensional (3D) profile, and (a3) cross profile of the unworn surface. (b1) Wear surface under dry sliding, (b2) 3D profile, and (b3) cross profile under dry sliding. (c1) Wear surface under water lubrication after soaking, (c2) 3D profile, and (c3) cross profile under water lubrication.
the underwater tribological performance of sample 1# reduced with a high COF and a large wear amount.

Figure 4c,d shows the cross section of sample 2#. The layers are bound as a whole by the epoxy resin with strong adhesion. Sample 2# has higher hardness than sample 1# because of the larger underwater binding force between the epoxy resin and the hybrid fabric. Additionally, the tight interlayer adhesion can prevent water from penetrating into the layers, improving water resistance and maintaining high underwater strength. In Figure 4e, the multifilament fibers increase the binding area with the adhesive resin. The monofilament PTFE fibers provide enhanced self-lubricating effects. Finally, the water resistance and underwater strength are enhanced by the epoxy resin.

Figure 4f,h shows the transfer film on the metal pin of sample 1# under dry sliding and water lubrication. In Figure 4f, a thin continuous transfer film forms on the metal pin under dry sliding. In Figure 4h, no obvious transfer film forms on the metal pin because of poor underwater performance of the phenolic resin after soaking. In Figure 4g, the transfer film of sample 2# is formed on the metal pin both under dry sliding and water lubrication. In Figure 4g, the dense and continuous transfer film is beneficial in improving the underwater wear resistance and decreasing the underwater COF of sample 2#.

2.4. SEM Images of Samples 1# and 2# under Water Lubrication after Soaking. Figure 5a–c shows underwater SEM images of sample 1# with highest underwater COF and largest underwater wear amount after soaking. In Figure 5a, the PTFE fibers are severely worn, decreasing the content of PTFE fibers and increasing the Nomex fibers on the working surface. Nomex fibers are exposed more and severely peeled off on the working surface. The binding between the resin and the Nomex fibers is destroyed. Figure 5b shows the peeled Nomex fibers without the phenolic resin package on it. The phenolic resin reduces its strength and adhesiveness and is worn away fast. In Figure 5c, the exposed Nomex fibers absorb more water, causing Nomex fibers to lose strength and peel off easily. The residual phenolic resin particles bind to the Nomex fiber surface. The high underwater COF is because of the severe wear of PTFE fibers, and the large underwater wear amount is because of the decreasing strength and binding force of the phenolic resin. The underwater tribological properties of sample 1# are poor.

Figure 5d–f shows underwater SEM images of sample 2#. In Figure 5d, the working surface is rich in PTFE fibers; additionally, the adhesive wear of PTFE fibers helps to increase its content further on the working surface. The working surface with a high PTFE content reduces the
underwater COF. Figure 5e shows the most worn area in Figure 5d, and the Nomex fibers and epoxy resin are tightly bound together underwater without the peeled Nomex fibers. In Figure 5f, some PTFE fibers are above the Nomex fibers and exert enhanced self-lubricating effects underwater. The Nomex fibers and epoxy resin are combined together tightly, enhancing the hardness of the fabric sample and causing low underwater wear amount. The underwater tribological properties are improved by the epoxy resin.

3. CONCLUSIONS

This paper uses the epoxy resin to enhance the underwater tribological properties of hybrid PTFE/Nomex fabric composites. The conclusions are as follows:

(a) Fabric samples 1# and 2# all have low COF and high wear resistance under dry sliding. The underwater COF and wear depth of 1# increase after soaking because of the poor underwater adhesiveness and strength of the phenolic resin. Sample 2# has reduced underwater COF and wear depth after soaking because of the high strength and excellent adhesiveness of the epoxy resin. The underwater properties can improve by the adhesive resin.

(b) Sample 2# has hard working surface underwater because of the great binding force of the epoxy resin. The great binding force improves the water resistance. The hard surface enhances the wear resistance, protects the PTFE fibers from excessive abrasion, and facilitates PTFE
4. EXPERIMENTAL SECTION

4.1. Equipment and Sample Preparation. The PTFE (density: 2.2 g/cm³; elongation: 50%) and Nomex (density: 1.36 g/cm³; elongation: 32%) fibers were produced by DuPont as shown in Figure 6a. The phenolic resin and epoxy resin are thermosetting resins and commercially available. PTFE and Nomex fibers were woven into hybrid PTFE/Nomex fabrics on the weaving machine (SXACT-C) as shown in Figure 6b. Figure 6c shows the microscopic image of the hybrid fabric; its friction surface was rich in PTFE fibers (75%) and the binding surface was rich in Nomex fibers (75%). Then, the PTFE/Nomex fabrics were cut into squares. Figure 6d,e shows the phenolic resin denoted 1# and the epoxy resin denoted 2#; then, the phenolic resin (1#) and epoxy resin (2#) were applied to the fabric squares, respectively, as evenly as possible. The preimpregnations of resin fabrics 1# and 2# were weighed and the relative mass fraction of each resin was calculated after drying for 2 h at 80 °C; the immersion was repeated several times until the content of the two resins reached 45 ± 5%. After that, the preimpregnated fabrics were put together one by one to make a total of 20 floors for every resin. Then, the multilayer fabrics were put into the curing press as shown in Figure 6f under 150 °C at 3 MPa for 2 h. After curing, the fabric samples were taken out, as shown in Figure 6g, and cut into 40 mm × 40 mm to prepare the test samples, as shown in Figure 6h.

4.2. Friction and Wear Test. The tribological test used a pin-on-disk tribometer (RTEC MFT-5000, made in USA) as shown in Figure 7a, and a stationary steel GCr15 pin slides against a rotating steel disk with the test sample fixed on the disk. Figure 7b,c shows the friction test under dry sliding and water lubrication. The water-lubrication method was to drip distilled water onto the test sample at a rate of 60 drops per minute. Fabric samples 1# and 2# were soaked in water for 100 h before the water lubrication test. A flat-ended GCr15 pin (diameter 4 mm) was secured to the load arm with a chuck. The distance between the center of the pin and the center of the axis was 18 mm. Then, the pin was polished with 800-grade waterproof abrasive papers. Friction tests were performed under laboratory conditions (temperature, 25 °C; relative humidity, ~50%). The rotational test speeds were 100, 200, 300, 400, and 500 rpm, respectively, and the test loads were 1, 2, 3, 4, and 5 MPa at every speed; every process lasted for 10
min, and every test was repeated three times, using the average value as the test result.

The coefficient of friction (COF) was calculated by the friction force ($F_f$) and positive pressure ($F_N$). $F_N$ was added by the compression spring and measured by a load sensor. $F_f$ was measured by another load sensor when generated via sliding. COF was calculated as follows

$$\text{COF} = \frac{F_f}{F_N}$$

COF could be read from the computer running the friction measurement software directly. The worn surfaces were examined with a JSM-S600LV scanning electron microscope (SEM). The 3D surface morphology and wear depth of fabric samples 1# and 2# were measured with a laser microscope, as shown in Figure 7d.

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Notes
The authors declare no competing financial interest.

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