Research Article

Liu Ying, Gao Gengyuan*, Jiang Dan, and Yin Zhongwei

The tribological properties of single-layer hybrid PTFE/Nomex fabric/phenolic resin composites underwater

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Abstract: In this study, the tribological properties of hybrid polytetrafluoroethylene (PTFE)/Nomex fabric/phenolic resin composites were investigated under three operating conditions: dry sliding, dry sliding after soaking in water for 12 h, and water dripping lubrication. The friction coefficient (COF) was measured with a pin-on-disk tribometer. The wear surface was analyzed with a scanning electron microscope. The results show that water weakens the tribological properties of single-layer hybrid PTFE/Nomex fabric/phenolic resin composites. The fabric composites show slight abrasive wear with stable COF under dry sliding conditions, significant abrasive wear with oscillating COF after soaking, and destruction with severely oscillating COF under water dripping lubrication. Generally, water weakens the effect in two ways. The first is weakening the binding force between phenolic resin and Nomex fiber. The second is that Nomex fiber absorbs water and expands, which reduces its strength. Finally, the ideas to improve the tribological properties under water dripping lubrication are presented.

Keywords: PTFE/Nomex fibers, friction, water-lubricated bearings

1 Introduction

The water-lubricated stern bearing is an important component of the marine power system. The material of the stern tube bearing has always been a point of concern. Particular

attention has been paid to the development of composite materials. PTFE/Nomex hybrid fabric/phenolic composite is a material that can be used in stern tube bearing.

Some studies have examined the tribological properties of PTFE/Nomex hybrid fabric/phenolic reinforced composite under dry sliding conditions [1–7]. Yang et al. added fillers and different treatments to improve the tribological properties of the PTFE/Nomex hybrid fabric/phenolic reinforced composite under dry friction conditions [8–14]. Zhang et al. used air plasma treatment and cryogenic treatment to improve the tribological properties of the hybrid PTFE/Kevlar fabric/phenolic composite. Zhang also studied the filler of TiO₂, CuS, and ZnO on the tribological properties of the hybrid PTFE/Kevlar fabric/phenolic composite [15–18].

Some studies have noticed the influence of lubricating water on the tribological properties of composite materials [19–21]. Ren et al. [19] investigated the tribological properties of the hybrid PTFE/Nomex fabric/phenolic composite under dry and water-bathed sliding conditions, and the results showed that the composite had a higher wear rate and a lower friction coefficient (COF) under water-bathed sliding conditions. However, the stability of the COF under different operating conditions, the wear method, and the fabric material failure mode under the effect of water are also essential and need further research. This study focuses on these aspects, and has tested the COF under various speeds and loads to evaluate the stability of the COF. The fabric composite wear ways were observed and analyzed. The material failure mode under water dripping conditions was analyzed by checking the scanning electron microscope (SEM) images.

2 Experiment

2.1 Equipment and sample preparation

The PTFE and Nomex fibers were produced by DuPont. The hybrid PTFE/Nomex fabric was weaved using an

* Corresponding author: Gao Gengyuan, School of Mechanical and Power Engineering, Shanghai Jiao Tong University, Shanghai, China, e-mail: gaoqi_1118@sjtu.edu.cn

Liu Ying: School of Mechanical and Power Engineering, Shanghai Jiao Tong University, Shanghai, China, e-mail: liuying_abc123@163.com

Jiang Dan, Yin Zhongwei: School of Mechanical and Power Engineering, Shanghai Jiao Tong University, Shanghai, China

SXACT-C weaving machine. The adhesive resin (NR9420 phenolic resin) was provided by the Shanghai Xing-Guang Chemical Plant. The flat curing press was carried out by Wuxi Meiyu Machinery. Tribological tests were performed using an RTEC MFT-500 pin-on-disk tribometer.

PTFE and Nomex fibers were woven into hybrid PTFE/Nomex fabrics on the weaving machine. The PTFE/Nomex fabrics were cut into squares. Then the phenolic resin was applied to the fabrics as evenly as possible, and weighed, to calculate the relative mass fraction of the resin after drying 2 h at 80°C. The immersion was repeated several times until the relative mass fraction of the resin reached $40 \pm 5\%$. After that, a curing press was used to consolidate the pre-impregnated fabrics under 150°C at 3 MPa for 1 h. Finally, the samples were taken out, cut into 40 mm × 40 mm size, and pasted to the metal sheet using an adhesive.

2.2 Friction and wear test

Figure 1(a) shows the scheme of a pin-on-disk tribometer, with a stationary steel pin sliding against a rotating steel disk that was fixed with the fabric composite sample. Figure 1(b) and (c) shows the images of the dry sliding and water drip lubrication tests. The water lubrication method was carried out by dripping distilled water onto the fabric sample at the rate of 60 drops per minute. 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 disc was 16 mm. Then, the pin was polished with 600-grade waterproof abrasive papers. Friction tests were performed under laboratory conditions (temperature: 25°C; relative humidity: ~50%). The rotational speeds for the friction test were 100, 200,

300, 400, and 500 rpm respectively, the loads were 3, 5, 7, 9, and 11 MPa at every rotation speed, and the test was carried out at each load for 20 min.

The COF was measured from the frictional torque gained by a load cell sensor, which could be read from the computer running the friction measurement software. The worn surfaces of the composites were analyzed using a JSM-5600LV SEM. The surface morphology of the metal pin was observed with a microscope as shown in Figure 1(d).

3 Results and discussion

3.1 Under dry friction

Figure 2 shows the COF of PTFE/Nomex fabric/phenolic composite under dry sliding conditions. Generally, the COF decreases with increasing speeds and loads. In Figure 2(a) and (b), the COF vs time is shown. The steps are produced under the action of abrasive particles. In Figure 2(d), the COF is higher during the initial running-in stage because of the high peak roughness of the sample surface. During the test, the COF decreases with the working surface becoming flatter gradually. Figure 2(c) and (d) shows that the load effect on the COF is more significant than speed. After the running-in stage, (load > 3 MPa), the working surface was flatter and the transfer film was formed. As a result, the COF remains lower and stable until the end of the test under dry sliding conditions.

In Figure 3(a), compared to the unworn area, the worn zone is flatter under the friction test which could

Figure 1: The schematics of (a) the pin-on-disk tribometer, (b) the friction test under dry friction, (c) the friction test under water lubrication, and (d) the microscope.

Figure 2: The COF under dry sliding conditions (a) COF vs time at different speeds, and (b) COF vs time at different loads; (c) average COF vs loads, and (d) average COF vs speeds.

modify the working surface. Temperature increases in the wear zone. The surface morphology of PTFE is flattened by rolling. Heat is generated during the dry sliding test, and local temperature increases in the wear zone [22].

The temperature on the metal pin is greater than that on the surface of the fabric sample. High temperature is conducive to the formation of the transfer film on the metal pin. In Figure 3(b), the surface of the PTFE becomes

Figure 3: SEM images under dry friction (a) wear area morphology, (b) magnified image of wear area, (c) wear morphology of Nomex, and (d) wear morphology of PTFE.

Figure 4: The COF after soaking for 12 h, dry friction (a) the COF vs time at different speeds, and (b) the COF vs time at different loads; (c) the average COF vs loads, and (d) the average COF vs speeds.

flatter after rolling deformation and adhesive wear. Nomex is still wrapped in phenolic and firmly bound in the resin matrix after the friction test. Figure 3(c) and (d) is the enlarged view of the Nomex and PTFE of Figure 3(b). The surface of Nomex has slightly abrasive wear without noticeable peeling. A small abrasive particle and a flatter friction surface was observed on the friction surface after test.

3.2 Dry friction after soaking for 12 h

Figure 4 shows the COF under dry sliding after soaking for 12 h. The continuously produced abrasive particles with oscillating COF can be observed during the friction test. In Figure 4(a) and (b), the steps are produced under the effect of abrasive particles, and the abrasive particles are embedded in the sample surface. However, a large amount of abrasive particles is generated at a time, with the COF significantly reducing in Figure 4(a), resulting in severe wear on the wear zone. Abrasive particles have a good lubrication effect that significantly reduces the COF at a time, but severe abrasive wear is generated at this time.

In Figure 4(c) and (d), the average COF was oscillating and had a large range compared to the COF under dry sliding conditions. Soaking in water weakens the strength of the Nomex as well as the adhesion between the Nomex and the phenolic resin. During the friction test, the surface of the Nomex is peeled and worn to different degrees. The surface morphology changes with different loads and speeds causing oscillating COF.

Figure 5 shows the SEM images during dry sliding after soaking for 12 h. Some holes appear in the non-wear surface in Figure 5(a). In Figure 5(b), a portion of the wear zone of Figure 5(a) is shown. The surface morphology of PTFE becomes flatter after wear with rolling deformation and adhesive wear. The Nomex peeled off the phenolic resin matrix at many places resulting in a rough working surface. Figure 5(c) and (d) shows the flatted PTFE and peeled Nomex. In Figure 5(d), Nomex exposes the outside directly with losing phenolic resin package. The severe abrasion is mainly due to the deteriorated adhesion between Nomex and the phenolic after soaking. Therefore, the phenolic is easier to separate from Nomex. Meanwhile, Nomex loses its phenolic package and forms abrasive particles during the friction test. The heat generated during the dry friction test process aggravates the peeling of Nomex further.

Figure 5: The SEM images of worn surface after soaking for 12 h, dry friction (a) wear area morphology, (b) magnified image of wear area, (c) wear morphology of Nomex, and (d) wear morphology of PTFE.

3.3 Water dripping lubrication

There is severe abrasion in Section 3.2 during the dry sliding friction test. Under water dripping lubrication,

the load is reduced to 0.5 MPa before starting the test. In Figure 6, the COF has severe oscillations at different speeds and loads. In Figure 6(a) and (b), the COF has greatly swung at 0.5 MPa with 100 rpm. In Figure 6(c)

Figure 6: The COF under water dripping lubrication (a) COF vs time at different speeds, and (b) COF vs time at different loads; (c) average COF vs loads, and (d) average COF vs speeds.

and (d), the average COF is also much higher than that at high speed (>300 rpm) and heavy load (>3 MPa). Abrasive particles generated on the sample surface are carried away by the lubricating water. The modification of the lubricating surface via abrasive particles is destroyed, and the surface morphology gradually deteriorates. Additionally, due to the effect of the lubricating water, the COF does not increase significantly before destruction.

Lubricating water will severely reduce the strength of Nomex. The adhesion between the Nomex and phenolic resin also weakens. Nomex quickly loses its phenolic resin package. The power of Nomex weakens more significantly during the test. Once the power of Nomex is not sufficient to withstand the increasing friction force, the Nomex breaks. Nomex continues to break along the friction direction of the sample rotation continuously. Finally, the sample is worn through. The metal pin slid against the metal sheet under the hybrid fabric layer, and the COF rose instantly, as showed in Figure 6(b).

In Figure 7, under water dripping lubrication, the sample is worn through and has failed. Nomex has a neat cross-section indicating abrasion failure. PTFE is stretched indicating tensile failure. There is no phenolic resin package on the surface of the Nomex in the wear failure area. Nomex is directly exposed outside. It shows that water dripping lubrication weakens the adhesion between phenolic and Nomex. The strength of the exposed

Nomex is further weakened underwater after losing the resin package. The power of Nomex is reduced, resulting in the hybrid fabric getting worn through with increasing speed and load. Compared to the dry sliding in Section 3.1 and the dry sliding after soaking in Section 3.2, the samples show the worst tribological properties under water dripping lubrications. Therefore, single-layer PTFE\Nomex hybrid fabrics are not appropriate for working under long-term water lubrication or humid environments.

3.4 The three-dimensional (3D) surface topography and transfer film

The 3D profile laser microscopy was used to measure the surface topography before and after wear in Figure 8. In Figure 8(a) and (b), the surface roughness (S_a) reduced from 4.44 to $4.18\ \mu\text{m}$, a flatter surface was got after friction test under dry sliding conditions. In Figure 8(a) and (c), the surface roughness (S_a) increased from 4.44 to $8.77\ \mu\text{m}$ with a rougher surface after soaking in water under dry sliding conditions. It also shows that the tribological properties of the fabric material have reduced after soaking.

Figure 9(a)–(c) shows the wear surface morphology of the metal pin. In Figure 9(a), there is transfer film

Figure 7: SEM images under water drip lubrication (a) surface morphology after wore through, (b) Nomex worn through, (c) partially enlarged morphology of (b), and (d) pulled PTFE.

Figure 8: The 3D profile of fabric samples, (a) non-wear, (b) under dry sliding, and (c) under dry sliding after soaking.

formation under dry sliding conditions; in Figure 9(b), there are obvious wear marks under dry friction after soaking for 12 h; in Figure 9(c), there are large undulating wear marks under water lubrication conditions. It shows that the dry sliding condition is beneficial to the formation of the transfer film. Figure 9(d) shows the abrasive particles of peeled phenolic and peeled Nomex. The little water droplets were observed in the peeled Nomex. It shows that Nomex fiber has poor water resistance, and its strength decreases after water absorption.

The COF is stable and the wear ways are slight abrasive wear under dry sliding conditions. The COF oscillates, and there is severe abrasive wear under dry friction after soaking for 12 h. The COF oscillates severely and the fabric sample is destroyed under water dripping lubrication.

To improve the tribological performance of the composites under water lubrication, a fiber with better water resistance can be used, such as glass fiber instead of Nomex fiber [23]. Another option is to use a resin with excellent performance in water and better adhesion to Nomex fiber, such as an epoxy resin [24].

4 Conclusion

This study mainly examines the tribological properties of single-layer PTFE\Nomex hybrid fabric composite under three working conditions with different speeds and loads. The conclusions are as follows:

Figure 9: The surface morphology of counterpart pins, (a) dry sliding, (b) dry sliding after soaking in water for 12 h, (c) water dripping lubrication, and (d) abrasive particles dry sliding after soaking in water for 12 h.

- (1) Under dry sliding conditions, the exposing PTFE and the phenolic are worn. PTFE becomes flatter because of adhesive wear with a lubricating film formation on the pin surface steadily. The peeled phenolic particles fill in the lower part gradually, and the friction surface becomes flatter. During the friction test, the COF becomes lower after the running-in phase. The higher the speed, the greater the loads, and the COF remained lower and stable until the end of the test.
- (2) After soaking for 12 h, the water penetrates into the Nomex fabric gradually. Nomex absorbs water and swells, leading to reduced strength. Water soaking weakens the adhesion between the Nomex fabric and phenolic resin. Therefore, it becomes easier for the phenolic particles to peel off and the Nomex is easier to wear also. A large number of abrasive particles are produced during the friction test.
- (3) Under water dripping lubrication, the abrasive particles are carried away by the lubricating water. Abrasive particles cannot modify the worn surface. When the phenolic is worn away, the Nomex is directly exposed to the water. Nomex easily absorbs water and swells. Its strength gets lowered and is more easily worn out. The process is repeated during the friction test. Nomex is worn off, the PTFE is pulled off, and the surface of the sample gets damaged.

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