The tribological properties of multilayer hybrid PTFE/Nomex fabric/phenolic resin composite with two fabric structure under water lubrication

Ying Liu, Gao Gengyuan, Jiang Dan and Yin Zhongwei
School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai, People’s Republic of China
* Author to whom any correspondence should be addressed.
E-mail: gaoqi_1118@sjtu.edu.cn

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Abstract
In this paper, two polytetrafluoroethylene (PTFE)/Nomex hybrid fabric structures with different weaving methods under various working conditions were studied. A pin-on-disk tribometer was used to test the friction coefficient (COF), and a scanning electron microscope (SEM) was used to analyze the wear surface. The results showed that COF of the two fabric structures was significantly different under dry sliding but similar under water lubrication. The wear amount of the two fabric structures was also different. Fabric structure influences the COF and wear amount via affecting the surface topography and the bonding force between layers.

1. Introduction
Water-lubricated stern tube bearing is an essential part of the marine power systems. The water-lubricated material has an important influence on the performance of stern tube bearing. Fabric composite was the material with excellent mechanical and tribological properties [1–3]. Hybrid PTFE/Nomex fabric/phenolic resin composite is a suitable water-lubricated material for its excellent self-lubricating properties [4, 5].

PTFE has good lubrication, Nomex has good mechanical properties, and the hybrid PTFE/Nomex fabric combines the advantages of the both [6, 7]. But the poor adhesion between PTFE and phenolic resin causes reduced bonding force between layers and the tribological properties are decreased as a result [8–11]. Some literatures improve the tribological properties via different treatment of the PTFE fiber or using various fillers [12, 13]. Air plasma and cryogenic treatment to the PTFE fibers can improve the bonding force between layers to enhance the tribological properties finally [14–17]. The studies via adding reinforcement fillers to phenolic resin enhance the friction and wear properties, including graphite [18, 19], carbon fabrics [20], ZrB2, TiO2, SiO2 [22, 23], Mo2C [24], CuS, MoS2 [25].

The fabric structure also has important influence on the tribological properties [26]. Some studies devoted to different fabric structure under dry sliding. Li and Yin [27] investigated the effect of weave density on the tribological behavior of hybrid PTFE/Kevlar fabric composites. The results showed that the weave density had a significant influence on the tribological behavior. Yu and Wang [28] investigated the friction and wear behaviors of self-lubricating composites with two types of warp-knit fabric structures. The results showed that with the increase of friction distance, the friction and wear properties of the two fabric structures were different.

Some researchers dedicated to the tribological properties of the same fabric structure both under dry sliding and water-lubricated conditions [29]. Ren and Zhang [30] studied the tribological behaviors of hybrid PTFE/Nomex fabric/phenolic composite under dry sliding conditions and water-bathed sliding conditions. The results showed that the composites had a higher wear rate and lower friction coefficient under water-bathed sliding conditions. Meng and Sui [31] investigated the carbon nanotubes composites under dry friction and water-lubricated conditions. The results showed that the composites exhibited a lower friction coefficient and higher wear rate under water-lubricated conditions than under dry sliding.
Fabric structure and water lubrication conditions are two critical factors to the COF and wear amount of the fabric composite. However, many literatures only considered the single factor without combining the two. Therefore, it is significant to study the combined factors on the tribological properties of the fabric composite. Unfortunately, few studies have been performed to research the factors of fabric structure and water lubrication conditions at a time. In this paper, the tribological properties of multilayer hybrid PTFE/Nomex fabrics composites with two fabric structures were explored under dry sliding and water lubrication. The influence mechanism of multi-layer fabric structure under dry sliding and water lubrication is revealed.

2. Experiment

2.1. Materials and equipment
The PTFE (density: 2.2 g cm\(^{-3}\); elongation: 50%) and Nomex (density: 1.36 g cm\(^{-3}\); elongation: 32%) fibers were produced by DuPont. The two hybrid PTFE/Nomex fabrics were weaved using an SXACT-C weaving machine. The adhesive phenolic resin was commercially available. Tribological tests were performed using an RTEC MFT-500 pin-on-disk tribometer.

One of multilayer hybrid PTFE/Nomex fabric are plain weave fabric with a thicker PTFE fiber (diameter: 40 um) referred to as 1# fabric. The other is twill fabric with one PTFE fiber presses three Nomex fibers using a thinner PTFE fiber (diameter: 25 um), referred to as the 2# fabric. The working surface and bonding surface of 1# fabric both has 50% PTFE and 50% Nomex. The working surface of 2# fabric has 75% PTFE and 25% Nomex meanwhile the bonding surface has 75% Nomex and 25% PTFE. The weave structures of the two fabrics are shown in figure 1.

2.2. Sample preparation
Figure 2 shows the sample preparation process; in figures 2(a), (b), the PTFE and Nomex fibers were woven into hybrid PTFE/Nomex fabrics. Fabric PTFE/Nomex fabrics were cut into squares as shown in figure 2(c), Phenolic resin was applied to the fabrics squares as evenly as possible, as shown in figure 2(d), then weigh and calculate whether the relative mass fraction of the resin is reaches 50 ± 5% after drying 2 h at 80 °C. The immersion was repeated several times to reach the needed mass fraction, as shown in figure 2(e). After that, the pre-impregnated fabrics were pressed together layer by layer (usually ~50 layers) and put into the curing press under 150 °C at 3 MPa for 1 h, as shown in figure 2(f). Finally, the samples were taken out and processed to fabric samples with 40 mm × 40 mm shown in figures 2(g) and (h).

2.3. Friction test
Figure 3(a) shows the pin-on-disk tribometer, a stationary steel pin slides against the rotating steel disk with the test samples fixed on it. Figures 3(b) and (c) show the images under dry sliding and water lubrication. The method of water lubrication was to drip distilled water on the test samples at a rate of 60 drops per minute. A flat-ended GGr15 pin (diameter, 4 mm) was secured to the load arm with a chuck after being polished with 800-grade waterproof abrasive papers. The distance between the center of the pin and the center of the disc was 16 mm. The friction tests were performed under laboratory conditions (temperature, 25 °C; relative humidity, ~50%). The speed was 300 rpm, the loads were 1, 2, 3, 4, and 5 MPa, respectively, testing for 20 min at each load. Then the load was 3 MPa, the speeds were 100, 200, 300, 400, and 500 rpm, respectively, with 20 min for each speed. Every test was repeated three times, and the average value was the test result. The friction coefficient (COF), which is measured from the frictional torque gained by a load cell sensor, could be read from the computer via the friction measurement software. The worn surfaces of the composites were analyzed using
JSM-5600LV scanning electron microscopy (SEM). The 3D surface morphologies of 1# and 2# fabric samples are measured by a laser microscope, as shown in figure 3(d). The wear width and depth are measured by a micrometer with an accuracy of 0.001mm and the wear volume is the wear width multiplied by wear depth.

3. Results and discussion

3.1. Tribological properties results of two fabric samples

In figure 4(a), The COF of sample 2# is significantly lower than 1# under dry sliding. Because 1# fabric sample with thicker PTFE fiber causes larger surface roughness than 2# fabric sample with thin PTFE fiber. In figure 4(b), with increasing load, COF of sample 1# increased greatly at first and then decreased greatly, reaching the maximum of 0.18 at a load of 3 MPa. Because heat generated and temperature rose between the friction pair increasing the COF at first, then the friction surface flattened and transfer film formed decreasing the COF of sample 1# [27]. Generally, the COF of 2# was lower than that of 1# under dry sliding with the influence of fabric structure. In figure 4(b), the COF of 2# fabric sample remains stable, smaller heat is generated, and the friction surface has a little flatter after wear.

Under water lubrication, in figures 4(c), (d), The COF of 1# and 2# are similar. The lubricating and cooling properties of water is good to reduce the COF [31]. The rough surface of the 1# fabric sample is more conducive to storing water that reduces its COF greatly. Figures 4(e), (f) are the COF versus time under dry sliding and water lubrication. The COF of 1# is much larger than that of 2# in figure 4(e) and the COF of 1# and 2# were
similar in figure 4(f). The 1# fabric sample has great differences COF under dry sliding and water lubrication because of fabric structure affecting the lubrication state. There is no obvious difference of 2# fabric sample because of flatness surface storing little lubrication water.

In figure 5(a), the wear volume of 1# fabric sample is greater than that of 2# fabric sample, because adhesive and abrasive wear are prone to occur for the thicker fibers of 1# fabric. The wear volume of 1# and 2# is larger under water lubrication because the hardness of the fabric samples decreases under water lubrication [30]. In figure 5(b), the surface roughness of 2# fabric sample is lower than 1# fabric sample because of the thinner fiber. The surface roughness of 1# and 2# fabric samples is higher under water lubrication after wear because of easily worn. Therefore, the fabric structure has an important influence on the wear volume and the surface roughness of the fabric composite.

3.2. The surface morphology of two fabric samples
From the surface morphology in figures 6(a) and (c), the thicker PTFE fiber of 1# fabric resulting in a large roughness of 1# fabric sample. The working surface of 2# was flat and rich in PTFE for a thinner fiber. The adhesion between the layers can be observed via the cross-sectional from figures 6(b) and (d). In figure 6(b), some holes appear in the cross-section of 1# fabric sample, indicating poor bonding force between layers. In figure 6(d), The bonding force of 2# fabric sample between the fibers and the phenolic resin was stronger.

In figures 6(e) and (f), the COF of 1# fabric sample was reduced via two ways under water lubrication. First because PTFE fibers were conducive to reducing the COF for its good self-lubrication. In figures 6(e) and (f), PTFE fiber was worn, rolled, and deformed, then boned to the friction surface after wear. Second, because of the
large surface roughness of 1# fabric sample. The roughness surface is favorable for storage water, which improved the lubricating state and reduced the COF markedly.

In figures 6(g) and (h), the PTFE fiber of the 1# fabric sample was first deformed and then rolled on the friction surface. A large surface roughness caused large COF under dry friction. With increasing load, the peak roughness of 1# reduced, heat generated, the surface became flatter, and the transfer film formed, as a result the COF was increased at first and then decreased. In figures 6(k) and (l), the friction surface of 2# sample was flatted and rich in PTFE fibers with good self-lubricating, causing a lower COF under dry friction.

In figures 6(i) and (j), under water lubrication, the surface of fabric sample 2# became flatter, and the PTFE fiber was firmly bound in the phenolic resin matrix. The flat surface was not conducive to store water and the PTFE fiber continued to function as the primary lubricant. Hence, the COF of 2# were similar under dry friction and water lubrication conditions.

3.3. Friction and wear process of 1# and 2# fabric samples

Figure 7 shows the friction and wear process of 1# and 2# fabric samples. The Nomex fiber was mainly bonded with the phenolic resin and supports the PTFE fiber. In figure 7(b), adhesive and abrasive wear occurred on the friction surface of 1# under dry sliding. There was much heat was generated rising local temperature, increasing COF, and accelerating the adhesive and abrasive wear. The friction surface became flatter with abrasive Nomex and phenolic particles being removed from the rough peaks. In figure 7(e), surface roughness of 2# fabric
sample was smaller than 1# fabric sample. Slight abrasive wear occurred on 2# sample and heat generated less than 1# sample. Adhesion wear was not apparent because thinner PTFE fiber of 2# fabric sample.

In figures 7(c) and (f), lubricating water dissipated heat well, served as a lubricant, and carried abrasive particles away. Thus, the COF of the 1# fabric sample was markedly reduced. Finally, the COF of 1# and 2# were similar under water lubrication. However, the bonding force between phenolic resin and Nomex fiber was weakened by water. Phenolic resin and Nomex fiber were more likely to produce abrasive particles, which were washed away by lubricating water. This process continues continuously, the 1# and 2# samples show a lower COF and a higher wear rate under water lubrication [26, 27].

4. Conclusion

The fabric structure has an important influence on tribological performance of hybrid PTFE\Nomex fabric composites. The conclusions can be drawn as follows:

(1) The fabric sample 2# has a lower COF and lower wear rate with a better interlayer adhesion than 1# fabric sample. The fabric sample of 1# and 2# have higher wear rate under water lubrication than dry sliding.
(2) Under dry sliding, the PTFE fibers of sample 1# were first worn and then bonded on the worn surface for further lubrication. The adhesion and abrasive wear of 1# fabric sample were more serious, and the heat generated of 1# sample was larger than sample 2#.

(3) Under water lubrication, the rough surface of 1# could more easily store lubricating water. The lubricating water could dissipate heat and reduce the local temperature rise. However, it was necessary to explore a way to improve the wear rate of the fabric sample under water lubrication.

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Data availability statement
All data that support the findings of this study are included within the article (and any supplementary files).

Disclosure statement
No potential conflict of interest was reported by the authors.

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ORCID iDs
Ying Liu https://orcid.org/0000-0002-8781-5987

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