Experimental study on tribological properties of CF/PTFE hybrid fabric reinforced composite under different PTFE proportions

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Abstract. A preparation was made by a new CF/PTFE mixed fabric reinforced composite. The friction and wear properties of the composites with different PTFE proportion hybrid fibers were studied. Experimental results showed that with the increase of PTFE proportion, the friction coefficient of the composite decreased, the temperature rise decreased, and the wear rate increased simultaneously. By SEM and EDX analysis of composites with different PTFE proportions, 20 percent hybrid fabric composite wear was mainly concentrated on the resin matrix and the counter part. The reason was discussed that the surface of the counterpart was formed a "transfer film" containing a large amount of “F” element, which effectively reduced the friction coefficient.

1. Introduction
Recently, The CFRP is increasingly used in the field of sliding friction pairs depending on the characteristics of high mechanical strength, low friction coefficient, less pollution and flexible preparation process. This composite is prepared by carbon fiber (CF) as reinforcement and Epoxy (EP) as a resin matrix, and solid lubricant additives such as graphite, MoS2 or talc is added in the resin. This composite has better self-lubricating properties than bronze and is ideal for sliding friction pairs such as bushings and nuts[1,2]. Polyethylene (PTFE), as a low friction coefficient solid material, is widely used in anti-friction and wear-resistant applications[3]. In the sliding friction pairs, the friction is directly forced to the reinforcement surface, so CF plain woven fabric is commonly used as reinforcement. In order to further reduce the friction coefficient, it is worthwhile to study and prepare the composite by mixing the PTFE fiber into the CF plain fabric. Preliminary studies have shown that the tribological properties of CF/PTFE hybrid fiber composites are significantly improved[4], and the friction coefficient and working temperature of friction pairs are reduced, too. In this paper, the effects on the friction and wear properties of different PTFE proportion on CF/PTFE hybrid fiber composites were further studied.

2. Fabrication of the samples
2.1. Experimental materials
CF reinforcement material: CF plain weave cloth, T300-3000, single long fiber with a fiber width of 1.65mm, a thickness of 0.25mm, produced by Toray Co. Japan(Table 1).
PTFE reinforcement material: PTFE long fiber: PTFE (500D), single long fiber with a fiber width of 0.32mm, a thickness of 0.11mm. produced by Zhejiang Gertaisi Co.,Ltd.(Table 2). Resin and additives: Epoxy resin: E51, industrial grade, produced by Yueyang Baling Petrochemical Co.,Ltd. Curing materials: 4-4’ diamino Diphenylmethane (DDM), analytical grade. Light yellow crystalline flake at room temperature; produced by Aladdin Reagent Co.. Other materials: Epoxy reactive diluent 501; dibutyl phthalat; Solid lubricating components: graphite, MoS₂, analytical grade, Tianjin Damao Chemical Reagent Factory. Tale powder, commercially available. Referring to forgone studies, a recipe for CF/PTFE composite is shown in Table 3.

| Table 1. The product specification of T300-3000 CF. |
|---|---|---|---|---|
| Type | Tow | Tensile strength(G Pa) | Elongation | Linear density (g/km) |
| T300-3K | 3000 | 3530 | 1.5% | 198 |

| Table 2. PTFE long fiber performance parameters. |
| --- | --- | --- | --- |
| Fiber grade | Tensile strength (N) | Elongation at break (%) | Thermal shrinkage (%) | Linear density (g/1000m) |
| 500D | ≥18 | ≤8 | ≤3 | 55.5 |

| Table 3. Composite material formula. |
|---|---|---|---|---|---|---|
| Epoxy | DDM | Active diligent | Elasticize | Graphite | MoS₂ | French chalk |
| 50 | 12.5 | 2.5 | 5 | 3.25 | 5 | 8.25 |

2.2. Fabrication of CF/PTFE composite samples

2.2.1. Preparation for CF/PTFE hybrid fabric: Hybrid fabric of PTFE/CF was rewoven for CF plain woven fabric, The PTFE type was 500D with the square section 0.32X0.11 mm². The plain woven fabric was knitted by the PTFE long fibers to take place of CF yarns from two directions of warp and weft in a certain proportion. The PTFE proportion was 5%, 10%, 15%, and 20%, respectively. Figure 1 is a schematic diagram of different proportion CF/PTFE hybrid braids (White is PTFE fiber and black is CF).

![Figure 1. CF/PTFE hybrid fabric of different PTFE proportion](image)

2.2.2. Preparation of resin and additives colloid. Before been used, Weighed the EP, curing agent, modified components, etc. according to the specific formula ratio, The EP and the modified component were mixed and stirred uniformly at room temperature, and the DDM curing agent was heated to 120°C to melt, in order to prevent the liquid DDM from cold crystallization again, the other components were pre-med at low temperature for 20 mainland then DDM was evenly mixed. Finally, the vacuum defoaming treatment was carried out at room temperature for 30 min.[5]

2.2.3. Preparation of CF/PTFE composite. The CF/PTFE fabric was cut into a certain size, and pre-install according to the sequence of: acetone cleaning, citric acid heating oxidant, coupling treatment. Using hand lay-up method, uniformly coated the glue on the surface of the CF fabric, stacking and placing them into the mold, pressed to the required thickness, the mold was placed in an oven and
heated in accordance with the 100°C/2h+160°C/2h curing step. After been cured, it was naturally cooled. Then demolished, processed and polished to samples.

2.2.4. Friction blocks manufacture. Figure 3 is a dimensional view of the test friction block. These friction blocks are composed of steel backing and composite lining. The composite liner has a thickness of 2 mm. A comparison was made with five sets of samples of different proportions of PTFE hybrid fabrics.

![PTFE Composite Liner](image)

**Figure 2.** CF/PTFE hybrid fabric photos

**Figure 3.** Size of friction sample

2.3. Experimental equipment

MRH-3 Block-on-ring sliding wear tester, Jinan Hengxu Tester Co.; S-3400N SEM, Japan Hitachi Co.; Vacuum drying oven, Shenzhen Kuaike Co.; CFT-I Multifunctional tester for material surface property; HT-1000 high-temperature friction and wear testing machine, Lanzhou Zhongke Kailhua Development Co., China.

2.4. Test conditions and methods

CF/PTFE composite sliding wear were tested on the MRH-3 block-on-ring sliding wear test machine according to GB/T12444-2006 (corresponding ASTM G77-1998) test requirements.

2.4.1. Test conditions. The rings whose diameter was 49.22 mm were formed by bearing steel GCr15 with roughness Ra0.4 and hardness HRC 60. In the first instance of the experiments, 100 N was first loaded to calibrate the friction block with a ring speed of 550 rpm and a working load of 1500 N. The wear test was started with preload force within 5 minutes and reached a stable wear stage after 10 minutes. The experimental run lasted for 1 hour. The condition for the invalid result of the experimental run is that the width of both ends of the groove of the wear groove after inspection is deviated from the average value by more than 20%. The results obtained are the average of five experiments per group.

2.4.2. Examination of friction coefficients (µ) and wear. During the experiment, the sample was pressed against a rotary friction ring. By testing the friction, the test instrument can analyze the friction coefficient of the friction pair. After the test, the sample was ultrasonically cleaned with acetone. After drying, the groove was scanned and the true groove volume was measured with a tester.

2.4.3. Measurement of temperature. In the test period, the friction pair was immersed in the oil. The temperature of the friction pair was indirectly obtained by the oil temperature measured by the temperature sensor.

3. Experiment result and analysis

3.1. Friction coefficients and volume wear

Figure 4(a) illustrates the µ-t curves of CF/PTFE composites with pure CF(0%PTFE) and different PTFE proportion(5,10,15, and 20 percent). It shows that the friction coefficient of the friction pair increases as the proportion of PTFE decreases. During the stable wear, the curve friction coefficient of 20% PTFE is the lowest, about 0.046. Figure 4(b) shows the temperature rise curves with different PTFE proportion. It shows that the temperature rise gradually decreased with increasing PTFE proportion.
It was indicated that for the mixed material, the PTFE long fiber had a certain improvement on the frictional property of the material under the action of shearing force. In addition, since the strength of PTFE was less than that of CF, the friction was not as serious as that of the CF. The wear was mainly concentrated between the resin and the counterpart, so that the coefficient of friction was low.

![Friction coefficient curves](https://example.com/friction.png)
![Temperature rise curves](https://example.com/temperature.png)
![Volume wear](https://example.com/volume.png)

Figure 4. The effects on the friction and wear properties of different PTFE proportion

From Figure 4(a) and 4(b), it could be seen that after tested for 1h, the temperature rise of 0% PTFE was 59.7°C, while that of the 20% PTFE was only 35.2°C, and that the volume wear of 0% PTFE was the lowest, at about 1.11 mm³, only 19.23% of the 20% PTFE. This was because that the CF itself had good wear resistance, and the loss was small under the same experimental conditions. After mixing into PTFE long fibers, PTFE fibers replaced some carbon fibers, and the diameters of the two fibers were different, resulting in a higher content of the matrix material than the pure CF composite, so there were more resins in CF/PTFE composite. The composite was worn out easily, so the volume wear was higher.

In addition, the friction coefficient curve and temperature rise curve of 0% and 20% PTFE composite were tested for 2h under load of 2000N. The 0% PTFE composite had the friction coefficient of 0.066, and the temperature rise was 53.4°C. The 20% PTFE hybrid composite has a friction coefficient of 0.056 and the temperature rise of 42.3°C. This showed that within a certain range, the friction coefficient increased as the load increased.

3.2. Analysis of surface morphology

Figure 5 shows the microscopic morphology of the pure CF composite, it could be seen that the furrow between the CF tow was deep and a large amount of self-lubricating component was distributed therein, and some CF tow had been worn off. The CF tow was exposed on the contact surface, and the wear debris particles were distributed between the gaps between the contact surface fiber tows, showing signs of abrasive wear[7]. The surface of the counterpart had scratches by fibers and a small amount of wear debris, which indicated that the wear was mainly happened between the fiber and the counterpart.

![Worn surface morphology and EDX analysis](https://example.com/surface.png)

Figure 5. Worn surface morphology and EDX analysis of 0%PTFE composite
Micro-area EDX analysis shows that the wear surface was not only the C element of the CF itself, but also Ca, Si, Mo and other elements. These elements were introduced by graphite, MoS₂, talc, etc., that indicated that the wear surface still existed more self-lubricating components. At the same time, there were a small amount of elements such as Cr and Fe on the composite contact surface, because the CF itself had a certain hardness, and the fiber tow was continuously scraped during the wear process, and the element of the counterpart were transferred to the surface of the composite. The EDX analysis of the surface of the counterpart from Figure 6 also showed a small amount of elements such as C, Si, Mo, and etc. that Indicated that the self-lubricating component was also transferred to the surface of the counterpart.

Figure 7 shows the microscopic morphology of the 20% PTFE composite. It could be seen that the wear on the contact surface was lighter than that of the CF composite and the resin in part of the area was not completely worn, and the fibers exposed on the surface were less; the furrow between the fiber tows was also lighter. From the EDX analysis shown in Figure 7, the surface of the composite had F element, this indicated that the PTFE composite was worn and adhered to the surface of the composite. Figure 8 shows the SEM micro-morphology of the corresponding counterpart. It could be
seen that a white transfer object was evenly distributed on the surface of the counterpart, and the micro-area EDX analysis was performed on the white area, in addition to the Fe, Mn, Cr and other elements of the metal itself, More F elements of the PTFE fibers were transferred to the even-shaped transfer film\cite{2,4}, and the elements of Si, Mg, and S also indicated the addition of the composite itself. The lubricating component was also partially transferred to the surface of the counterpart, and energetically with the PTFE fibers to lower the coefficient of friction.

4. Conclusion
For the CF/PTFE hybrid fiber composites, the tribological tests of 0% to 20% PTFE proportion composites under oil lubrication shows that the friction coefficient of the hybrid composites decreases with the increasing of PTFE proportion and the temperature rise decreases simultaneously. At 20% PTFE, the composite has the lowest friction coefficient and minimum temperature rise, with values of 0.046 and 35.2°C, respectively.

By SEM and EDX analysis, The worn surface of 20% PTFE composite has less exposed fiber, and the surface of the counterpart has obvious friction “transfer film”, there is a large amount of F element in the transfer film besides the composites lubricating components, it indicates that a relatively stable transfer film can be formed on the pairing metal surface, which plays a significant self-lubricating effect. Although the surface of the counterpart against the pure CF composite also appeared some transfer object, it is only from self-lubricating materials, the abrasive wear is the main, so the wear scar on the surface is more obvious.

Although the friction coefficient decreases with the increase of PTFE content, the wear characteristics and mechanical properties are degraded, the PTFE content of the CF/PTFE hybrid fiber composite should not exceed 20%.

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