Research on the Effect of Temperature on Tribological Properties of PTFE Composites under Oil Lubrication Conditions

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Abstract. PTFE and its composites are widely used in various reciprocating sealing materials due to their extremely low friction coefficient. As pure PTFE has poor wear resistance at high temperature, it is necessary to study the tribological properties of PTFE with different fillers under the condition of high temperature and oil lubrication. The friction and wear properties of PTFE and PTFE composite material filled with bronze powder, carbon powder, carbon fiber, glass fiber and MoS₂ powder were studied by standard friction and wear test using SRV-4 tribotester. Results showed that the wear resistance was all improved indicating that the fillers increased the wear resistance of PTFE, PTFE composite filled with MoS₂ has the lowest coefficient at ambient temperature and the highest at high temperature, PTFE composites filled with carbon fiber have the lowest wear rate at all temperatures.

Keywords. Tribological Properties, PTFE, wear, friction, reciprocating seals.

1. Introduction
Polytetrafluoroethylene (PTFE), as an important plastic material, is widely used in bearing and sealing parts owing to its low friction coefficient and good chemical stability [1]. The friction and wear properties of materials are the key factors that affect the service life of sealing parts. Due to the poor wear resistance [2] of pure PTFE, premature failure and leakage of seals may occur while being used. Filling with bronze powder, carbon powder, carbon fiber [3], glass fiber, MoS₂ powder [4] and other fillers [5] can significantly improve the wear resistance of pure PTFE [6]. Fillers of various shapes and materials can reduce the wear rate of pure PTFE by several percentage points.

Over the years, scholars from all over the world have conducted extensive studies on the tribological and wear characteristics of PTFE and its composites [7], during which many kinds of materials with low friction coefficient have been developed, providing a lot of help for engineering practical application [8-14].

The sealing material studied in this paper is used for reciprocating sealing of aircraft actuator under oil lubrication conditions, and the sealing system is often in the state of high temperature due to the heat generated by the aircraft body. The purpose of this study is to find suitable sealing materials, reduce the friction and wear of reciprocating seals, improve the efficiency and the service life of the actuator. In this paper, different kinds of PTFE composites under the conditions of oil lubrication were studied, and 5 typical filling materials were selected to conduct experimental research on the friction and wear properties at normal and high temperatures. The friction and lubrication mechanism under
normal and high temperature conditions were analyzed, and the friction and wear properties of PTFE composites of these 5 filling materials were summarized, which serves as reference for selecting sealing ring materials under such conditions in engineering practice.

2. Experimental

2.1. Materials
Ball made by GCr15 bearing steel with a diameter of 10 mm and roughness Ra =0.4 μm is used as the upper sample, corresponds to the piston rod of the actuator. And a disc with 20 mm diameter and 8 mm thickness and roughness Ra =0.8 μm made of PTFE and PTFE composite (as shown in figure 1) material filled with bronze powder, carbon powder, carbon fiber, glass fiber and MoS₂ powder respectively is used as the lower sample, correspond to the piston rod seal rings of the actuator. Using PTFE and PTFE composites as the lower sample is easier to qualitatively compare the amount of wear between different materials by measuring the scar width of worn-out surface. Three samples of PTFE and its composites were used for standard compression tests to obtain their Young's modulus, the mean values and value ranges of Young's modulus are shown in table 1. Kunlun 15# aviation hydraulic oil produced by China National Petroleum Corporation is used as lubricating oil which relevant parameters are shown in table 2.

![PTFE and PTFE composites samples.](image)

**Figure 1.** PTFE and PTFE composites samples.

| No. | Samples                         | PTFE Content [vol%] | Young’s Modulus [Mpa] |
|-----|--------------------------------|---------------------|-----------------------|
| 1   | PTFE                           | 100                 | 51.1±0.9              |
| 2   | PTFE with bronze powder (Cu)   | 70                  | 80.9±0.6              |
| 3   | PTFE with carbon powder (C)    | 70                  | 97.8±1.2              |
| 4   | PTFE with carbon fiber (CF)    | 70                  | 118.9±0.9             |
| 5   | PTFE with glass fiber (GF)     | 70                  | 75.3±1.2              |
| 6   | PTFE with MoS₂ powder (MoS₂)   | 70                  | 79.5±0.8              |

**Table 1.** Formulation of PTFE and PTFE composites.

**Table 2.** Kunlun 15# aviation hydraulic oil.

| Item                               | Numerical Values |
|------------------------------------|------------------|
| Kinematic viscosity [mm²/s] at     | 5.306            |
| different temperatures              | 13.84            |
| Flash point [°C]                    | 104              |
| Condensation point [°C]             | -74              |
| Density at 20 °C [kg/m³]           | 839.3            |
The average size of bronze and carbon powder particles is 20-40 μm. The average diameter of the carbon fiber is approximately 5-10 μm with an average fiber length of about 30-100 μm. The average diameter of the glass fiber is approximately 5-15 μm with an average fiber length of about 40-90 μm. The particle average size of MoS2 powder is approximately 20 μm. Above PTFE composites are provided by Guangzhou Mechanical Science Research Institute Co., Ltd. The PTFE and fillers were mixed in a high-speed mixer and then preformed under 40 MPa pressure at ambient temperature. Later sintering is carried out, and all samples were produced by free sintering in air at 380 °C for 1-2 h using 40 °C/h heating and cooling rates. And finally test samples were made by turning.

2.2. Experimental Equipment
SRV-4 high temperature tribotester from OPTIMAL company is a standard apparatus widely used in friction and wear tests for performance evaluations of lubricants and additives.

2.3. Experimental Parameters
Test parameters were determined by considering the contact pressure, reciprocating speed and working temperature of the friction pair in reciprocating seals of the aircraft actuator under actual working conditions. The frictional couple contact schematic diagram is shown in figure 2. Load was 20 N, and under this load, the experimental contact pressure is the same as the actual contact pressure. Reciprocating was stroke 1 mm, frequency 10–50 Hz, under these conditions, the reciprocating speed range of the experiment is the same as that of the actual actuator. The highest temperature of the hydraulic fluid in the aircraft actuator at high speed can reach 150 °C, so the experimental temperature was selected as 25, 50, 100, 150 °C.

![Figure 2. Contact schematic diagram for the frictional couple.](image)

2.4. Calculation of Friction Coefficient
The load value $F$ is measured by the load cell, and the friction force $f$ is measured by the tension sensor; then the friction coefficient is the ratio of friction and load: $\mu = f/F$.

The experimental process: At a given experimental temperature, 20 N load, and 20 Hz reciprocating motion frequency, the upper sample and lower sample were run in for 10 minutes. After PTFE and its composites entered the stable wear stage, the reciprocating motion frequency gradually increased from 10 Hz to 50 Hz every 5 Hz. Test was run for 10 minutes at each frequency, and then the average of the friction coefficient values at each frequency was taken. Three samples were used for each test parameter and material, and the average friction coefficient values of the three samples were taken for the final result.

2.5. Wear Calculation
The wear is caused by the combined deforming and abrading action of the ball. It is difficult to calculate the absolute wear of PTFE and its composites under different friction conditions. This paper only compares the wear of PTFE and its composites, and comes up with the material with excellent wear performance after the analysis. Under 20 N load, the sample is in the state of elastic deformation, and there is no plastic deformation, so the volume loss generated by the experiment is caused by wear.

The wear volume can be divided into a circular groove pressed by spheres bottom and an abrasion
groove with a length of reciprocating test stroke \( L \). The radius of steel ball of the upper sample is \( R \), and the width of abrasion groove is \( B \), then the section area of the abrasion groove is:

\[
S = R^2 \sin^{-1} \left( \frac{B}{2R} \right) - \frac{B}{2} \sqrt{R^2 - \left( \frac{B}{2} \right)^2}
\]

the bottom height of the spheres is:

\[
H = R - \sqrt{R^2 - \left( \frac{B}{2} \right)^2},
\]

the volume of the spheres bottom is:

\[
V = \pi H^2 \left( R - \frac{H}{3} \right),
\]

the wear volume is:

\[
V_{\text{wear}} = SL + V.
\]

The radius of the ball \( R = 5 \text{ mm} \), and the reciprocating stroke \( L = 1 \text{ mm} \). Therefore, the wear volume of the sample \( V_{\text{wear}} \) can be calculated by measuring the wear scar width \( B \) after wear test.

3. Results

3.1. Variation of Friction Coefficient with Different Reciprocating Operation Frequencies

The variation curve of friction coefficient with reciprocating motion frequency under the condition of reciprocating motion and oil lubrication of PTFE and its composites is shown in figure 3; in addition, curves at different temperatures were compared. As illustrated in figure 3, the friction coefficients of all materials have roughly the same trend with frequency, the friction coefficient first goes down and then goes up, and all materials have the lowest friction coefficient at 25 Hz; the friction coefficient of all materials increases along with the increase of temperature.

![Figure 3](image_url)

Figure 3. The curve of friction coefficient with different frequencies respectively. (a)-(g) are the results for materials No. 1-6.
3.2. Variation of Minimum Friction Coefficient at Different Temperatures

In the above results, all materials have the lowest friction coefficient at 25 Hz. The friction properties of different materials can be compared according to the minimum friction coefficient. The variation curve of minimum friction coefficient of PTFE and its composites at different temperatures is shown in figure 4. As demonstrated in figure 4, at ambient temperature (25 °C), PTFE composite filled with MoS₂ powder has the smallest friction coefficient (0.0229); pure PTFE is a little bit higher at 0.0246; and the friction coefficient of PTFE composites respectively filled with carbon powder, bronze powder and glass fiber all exceeds 0.03, namely 0.0302, 0.0310 and 0.0324. PTFE composites filled with carbon fiber has the maximum friction coefficient of 0.0409. There is no significant correlation between Young's modulus and minimum friction coefficient of PTFE and its composites.

![Figure 4](image)

**Figure 4.** The curve of minimum friction coefficient at different temperatures.

The friction coefficient of each material increases with the increase of temperature. When the temperature increases to 150 °C, the friction coefficient of pure PTFE reaches 0.0729, the highest among the six materials, while that of PTFE composites filled with carbon and carbon fiber were 0.0713 and 0.0707, and the friction coefficient of the other three materials were similar to each other – 0.0595, 0.0584 and 0.0587 for PTFE composites filled with bronze powder, glass fiber and MoS₂ powder. PTFE composite filled with MoS₂ has the best stability of friction coefficient at different temperatures and pure PTFE has the worst.

As displayed in figure 4, the friction coefficient of PTFE composite filled with MoS₂ powder is always the lowest in the range of ambient temperature up to 150 °C. The friction coefficient of pure PTFE increases more with the increase of temperature while the friction coefficient of PTFE composites filled with bronze powder and glass fiber increases less, therefore the latter ones are relatively insensitive to temperature change. The friction coefficient of PTFE composite filled with carbon powder is always the highest at different temperatures. With the increase of temperature, the Young's modulus of PTFE and its composites decreases, and the viscosity of lubricating oil decreases, which leads to the increase of friction coefficient.

3.3. Investigation of Wear Surface

The micrograph of the worn surface of PTFE and its composites under oil lubrication at ambient temperature (25 °C) and 150 °C is shown in figure 5 and figure 6. The entire FOV of the microscope is part of the worn surface. Surface turning marks are still visible, the worn surfaces of all materials have small scratches formed during reciprocating motion, and there are no wear fragments on each worn surface due to the presence of lubricating oil. Worn surfaces of composites are smoother than the worn
surface of unreinforced PTFE. The carbon and glass fiber fillers are still closely bound to PTFE, and a small amount of bronze and carbon powders was peeled off PTFE. The spallation of the fiber reinforcement was less remarkable than the spallation of the powder reinforcement. From ambient temperature to 150 °C, the wear form of friction did not change.

**Figure 5.** Micrographs of worn surfaces of PTFE and PTFE composites under ambient (25 °C) conditions respectively. (a)-(g) are the results for materials No. 1-6.

**Figure 6.** Micrographs of worn surfaces of PTFE and PTFE composites under 150 °C conditions respectively. (a)-(g) are the results for materials No. 1-6.
3.4. Comparison of Wear

It can be seen in figure 7 that with the increase of temperature, the wear of all six materials increases as well, and the wear volume of pure PTFE was the largest at all temperatures. From 25 to 150 degrees, the wear volume of all materials increases by about 50%, and the wear volume increases approximately linearly with the increase of temperature. At 25 °C and 150 °C, PTFE composites filled with carbon fiber have the lowest wear rate, compared with pure PTFE, the bulk wear is reduced by 54.8% and 41.3% respectively. PTFE composites filled with carbon powder have the second lowest wear rate at 25 °C, PTFE composites filled with glass fiber have the second lowest wear rate at 150 °C. It can be concluded from the results that all fillers can increase the bearing capacity of PTFE composites and substantially reduce the wear of PTFE composites.

![Figure 7. The curve of wear volume with temperature.](image)

4. Conclusion

At ambient temperature (25 °C), the friction coefficient of PTFE composite filled with MoS₂ powder is the lowest, while that of PTFE composite filled with carbon fiber is the highest. At high temperature (150 °C), the result is reversed against the ambient temperature that the friction coefficient of PTFE composite filled with MoS₂ powder is the highest, while that of PTFE composite filled with carbon fiber is the lowest.

The worn surfaces of all materials have small scratches formed by reciprocating motion, and there are no wear fragments on each worn surface owing to the presence of lubricating oil at any temperature. All fillers can increase the bearing capacity of PTFE composites and reduce the wear of PTFE composites.

With the increase of temperature, the wear of all six materials increases as well, and the wear volume increases approximately linearly with the increase of temperature. Among them, the wear volume of pure PTFE was the largest at all temperatures; at 25 °C and 150 °C, PTFE composites filled with carbon fiber have the lowest wear rate.

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