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Wear life of PTFE/Kevlar self-lubricating composite under high frequency oscillatory conditions

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Abstract

In this study, the PTFE/Kevlar self-lubricating composite was prepared for the service conditions of high frequency oscillation. The full-life cycle friction and wear characteristics was analyzed, and the tribological properties and failure mechanism at different life stages were studied. Fatigue life test of PTFE/Kevlar self-lubricating composite was performed by a self-developed heavy load reciprocating test machine. Results show that the self-lubricating performance of the material increases while the wear life decreases with the increase of stress and frequency. The main failure mode of the material consists of abrasive wear and adhesive wear, accompanied by extrusion fracture of the fiber. Tribological performance and surface state show distinct phase characteristics in the life cycle. The change of frequency affects the adhesive wear degree in the fiber fracture area. Differently, the change of stress affects the adhesive wear degree in the fiber fracture area as well as the uniform stability of the transfer film. The comparison of frequency and stress shows that the change of frequency has a greater influence on the material self-lubricating performance and life. This study could provide a research basis for the design and development of self-lubricating composites in high frequency oscillating conditions, and also provide reference data for the calibration of service conditions for PTFE/Kevlar self-lubricating composites.

1. Introduction

With the advantages of high strength, low friction coefficient, and stable lubricating performance, self-lubricating composite plays an important role in oil-free lubricating application environments, especially in self-lubricating components in the fields of aerospace and military industry [1–5]. At present, many self-lubricating composite contains polytetrafluoroethylene (PTFE) with low friction coefficient and aramid fiber (Kevlar) with high strength and easy bonding. The wear surface is mainly PTFE fiber and the back is mainly aramid fiber [6–8]. Due to the harsh working conditions of self-lubricating materials, the application environment of high-speed and overload can easily lead to unstable self-lubricating performance or even sudden failure [9–11]. Therefore, some researchers have carried on tribologica tests on the PTFE self-lubricating composite under different environment and service conditions [12–21]. For example, Li et al analyzed the effects of fiber type and braided structure on friction and wear behavior of PTFE/Kevlar self-lubricating composite and found that the use of lower density composites can significantly reduce the wear rate [5]. Zheng et al studied the tribological behavior and wear mechanism of PTFE composites at different temperatures, radiation and vacuum environments, and found that the friction coefficient of the liner increases with frequency and decreases with load in the atmosphere [19]. However, due to the long wear life time of PTFE/Kevlar self-lubricating composite and the limitation of test conditions, most of the relevant studies have focused on the short-term friction and wear performance under low-frequency oscillating conditions, and there is a lack of research on the wear characteristics of the
material during the whole life cycle. Therefore, in this study, PTFE/Kevlar self-lubricating composite applied to high-frequency reciprocating service conditions was prepared. By using a self-designed heavy-load reciprocating test platform, the full life test of the material was studied at high-frequency (5–10 Hz) and heavy-load conditions (15–50 MPa) to study the tribological properties and wear characteristics of the material at different wear stages through the changes in wear loss and friction coefficient. Moreover, through microscopic analysis, the changes in the failure mechanism at different wear stages, as well as the differences in the wear loss caused by different surface states were explored to provide basic data for material performance evaluation and application condition calibration.

2. Experimental details

PTFE/Kevlar self-lubricating composite was composed through twill weaving of PTFE and Kevlar fiber. Kevlar fabric was woven from Kevlar49 fiber provided by DuPont Company, see table 1 for the performance parameter. A silicone modified phenolic aldehyde-acetal resin was adopted as the adhesive resin, which was provided by Shanghai Xinguang Resin Factory. The preparation process was as follows. The blended PTFE/Kevlar fabric was washed with petroleum ether and ethanol respectively for more than 36 h to remove impurities on the fabric surface, and after drying with a 50 °C ambient temperature oven, it was repeatedly impregnated and brushed and dried in phenolic resin solution to control that the mass fraction of the fiber fabric from 65% to 70% and the thickness of 0.38–0.4 mm, bonded and cured on the sample holder (the disk diameter is 50 mm) with phenolic resin, with a curing temperature of 180 °C, a curing time of 2 h, and a curing pressure of 0.3 MPa. The adhesive peeling strength of test sample was 0.37–0.41 N mm⁻¹ (the angle of peeling is 140 ° ± 40 ° to the adhesive surface). The grinding pin sample material was GCr15 bearing steel after heat treatment, with hardness of 62 HRC and contact diameter of 3 mm. Before each test, the surface of pin sample was polished and cleaned.

The high load reciprocating tribo-tester HL-R700 was used, and the pin-on-disk friction contact mode was adopted. The load was applied to the friction contact surface through an automatic continuous loading mechanism. The material realized the reciprocating movement at the set frequency through the eccentric wheel with the test bench as shown in figure 1. During the test, the friction force was measured in real time by the torque sensor, and the friction coefficient was expressed numerically by dividing the loading force by the friction force. According to the service conditions of PTFE/Kevlar self-lubricating composite in high-speed spherical plain bearings of a helicopter, the test conditions were divided into two groups. Under 40 MPa, the reciprocating frequency was 6.6 Hz, and the stress was 15 MPa, 30 MPa, 40 MPa, and 50 MPa, respectively. The stress was held at 40 MPa, and the reciprocating frequency was 5 Hz, 6.6 Hz, 8.3 Hz, and 10 Hz, respectively. At the end of each test, the wear debris morphology generated in the wear stage was analyzed by JSM-T100 scanning electron microscope, and the surface morphology of the liners at different wear stages was analyzed by three-dimensional topography instrument and optical microscope.

3. Experimental results and discussion

3.1. Tribological performance analysis

Through the whole life test under different conditions, the wear life and friction coefficient of the material was directly obtained. Figure 2 shows the wear life and friction coefficient under different conditions. It can be seen that both the wear life and the average friction coefficient decrease with increased stress and frequency. The stress ranged between 15–30 MPa make a greater effect on the friction coefficient, while when the stress exceeds 30 MPa, the friction coefficient tends to be stable and the wear life decreases dramatically. Frequency ranged between 5–10 Hz has a nearly linear effect on friction coefficient and wear life. Through the comparison of (a) and (b) in figure 2, it can be found that the effect of frequency on friction coefficient and wear life is greater.
Figure 3 shows the change of friction coefficient under different conditions in the whole life cycle. It can be seen that the change of friction coefficient presents obvious stage characteristics. According to the change of friction coefficient, the wear life of the material can be divided into three stages: running-in wear stage, stable wear stage and severe wear stage. In the running-in wear stage, the friction coefficient fluctuates greatly, and the
self-lubricating performance is unstable, and the wear amount is high. In the stable wear stage, the friction coefficient decreases and is in the dynamic stability. In the severe wear stage, the friction coefficient increases dramatically, and fluctuates violently with serious material wear. To measure the stability of self-lubricating performance of materials under different conditions, the variance ($\delta$) of friction coefficient in the whole life cycle was given in Figure 3. It can be seen that the variance of friction coefficient is obvious higher under high stress and high frequency conditions, indicating that the self-lubricating performance is unstable. Especially under 50 MPa and 10 Hz, the friction coefficient fluctuates greatly, and its corresponding wear life is also the shortest. It can be seen that the friction coefficient can reflect the wear performance of self-lubricating material in real time, and the high friction coefficient value at the early stage is caused by the running-in process, and the sharp fluctuation increase at the later stage is a significant feature before the failure of material. Therefore, the performance of the self-lubricating material can be monitored in real time by the fluctuation characteristics of friction coefficient, and the wear life of the material can be predicted to terminate in advance once the critical value is exceeded.

Figure 4 is the scanning electron microscope photograph of wear surface and wear debris under different stresses. From Figure 4(a), it can be seen that the wear surface is relatively complete under low stress, with a small amount of fine wear debris generated due to flaking, and the main failure mode of material is adhesive wear. In Figure 4(b), the size of the wear debris generated on the wear surface becomes larger, and the main form of wear begins to transition from adhesive wear to abrasive wear. From Figure 4(c), it can be seen that with the further increase of stress, the lamellar wear debris content increases, and the broken reinforced fibers appear at the same time, when the main failure forms of the material are abrasive wear and fatigue fracture of the reinforced fibers. When the stress reaches 50 MPa, it can be seen from Figure 4(d) that the fine wear debris is accompanied by large flake flaking products, and the surface is flat and smooth. This is because that the reinforced fiber is compressed into flake under the action of high stress and extruded out the friction interface under the mechanical shear force. The main wear form at this time is extrusion and shear fracture caused by plastic deformation of the fiber. Due to the low hardness of the self-lubricating fiber composite itself, with the increase of stress, the extrusion and shear phenomenon caused by the uplift of the fiber is more notable, resulting in a dramatic shortening of the wear life of the material.

Figure 5 is a scanning electron microscope photograph of the wear surface and wear debris at different frequencies. As shown in Figure 5(a), the wear debris generated on the wear surface at 5 Hz and 6.6 Hz is small in size and low in content, and the main failure form is adhesive wear. At 40 MPa and 6.6 Hz, a small amount of shear-fractured fibers appear on the surface with aggravated wear, and the main failure form changes from
adhesive wear to abrasive wear, as shown in figure 5(b). In figure 5(c) and (d), it can be seen that with the increase of frequency, a large number of lamellar and strip products appear in the wear debris, which is caused by the shear fracture under friction force after the fiber uplift an extrusion, resulting in the flaky flaking and extrusion of the reinforced fiber from friction interface.

3.2. Analysis of running-in wear stage

Due to different running-in wear time of the material under different conditions, the friction coefficient of the first five hours for each group of tests is taken as a comparison, as shown in figure 6. Under variable stress condition, it can be seen in figure 6(a) that the friction coefficient increases continuously at the beginning and tends to a dynamic stable state after one hour, which is a typical running-in stage feature of self-lubricating material. It can be seen from the tests under different stresses that the friction coefficient decreases continuously...
with stress. Under the variable frequencies, the friction coefficient first increases and then decreases. Except for 10 Hz, the friction coefficient has an increasing trend, and the fluctuation of friction coefficient is significantly severe under different frequencies. As shown in figure 6(b), the main reason is that at the beginning the transfer film on the contact surface of the pin sample has not been completely formed, and the mobility of the attached part is large, resulting in poor lubrication effect. Therefore, the appropriate stress and frequency can form a uniform and stable transfer membrane in a short time and maintain a relatively stable friction coefficient.

Figure 7 shows the wear surface after 5 h of wear under different conditions. It can be seen in figure 7(a) that there are many cracks on the surface of the material under low stress, and the wear form is mainly adhesive wear after plastic deformation of the PTFE fiber, when the PTFE is transferred from the composite surface to the counterpart surface. In figure 7(b), under the high stress condition, the PTFE fiber extrusion phenomenon appears on the material surface, and the fiber fracture results in the Kevlar fiber exposed on the surface, and the adhesive wear generates at the fiber fracture. The presence of a PTFE transfer film on the surface of the Kevlar fiber also indicates that some PTFE is transferred back from the surface of the pin to the composite. Comparing figure 7(a) with figure 7(b), it can be found that the wear surface is mainly PTFE fiber and adhesive resin, and the PTFE fiber undergoes plastic deformation under stress by changing from fibrillar status to membrane lamellar status. The fiber gap is filled, and a transfer film is formed on the surface of the pin sample. The wear behavior of the material in this state mainly occurs on the PTFE fiber. In addition, there are many cracks and pits on the surface of the material under low stress. Moreover, although the failure behavior of the surface under high stress
is more complex, the surface defects caused by wear and fiber fracture are covered by the secondary transfer of the transfer film on the pin sample. This is why the friction coefficient of the material decreases at high stresses. Comparing figures 7(c) and (e), it can be seen that the wear phenomenon is aggravated after the frequency is increased from 5 Hz to 8.3 Hz, the aramid fiber exposed due to the wear consumption of PTFE fiber and resin can be observed at 8.3 Hz. There is a significant height difference between PTFE fiber and Kevlar fiber resulting in the uneven material surface, so the friction coefficient of the material increases at this stage. In figure 7(f), the wear surface at 10 Hz is similar to that at high stress, and the secondary transfer film is formed on the material surface. Compared with that at low frequency (figures 7(c)–(e)), the wear surface of the material at high frequency is more uniform, which also explains why the friction coefficient first increases and then decreases with the increase of frequency.

3.3. Analysis of stable wear stage
The stable wear stage is the longest stage with the smallest fluctuation of friction coefficient during entire life cycle, accounting for approximately 90%–95% of the entire wear life. The friction coefficient measured after the material has entered a steady wear stage under the stress of 15 MPa, 30 MPa, 40 MPa, 50 MPa and the frequency of 5 Hz, 6.6 Hz, 8.3 Hz, 10 Hz respectively. The effect of frequency on the friction coefficient of the material during the stable wear stage is significantly higher than that of the stress, and the friction coefficient under high frequency and low stress conditions is greater than that under low frequency and high stress conditions. The effect of stress on the friction coefficient decreases both with the increase of frequency and stress.

Figure 8 shows the wear surface state in the stable wear stage under different conditions. It can be seen that the wear surfaces are dominated by a large number of Kevlar fibers and some PTFE fibers and adhesive resins. The main failure form is extrusion of PTFE and aramid fibers, and the wear characteristics are abrasive wear and adhesive wear occurring at the fiber fracture. Comparing figures 8(a) and (b), it shows obvious fiber uplift on the wear surface under low frequency and low stress. Under the condition of high frequency and low stress, the extrusion of Kevlar fibers is more obvious, and the fracture site is covered by a mixture film produced by a large amount of adhesive wear, which makes the material surface more flat. In figures 8(c) and (d), a similar phenomenon can also be seen. Comparing figures 8(a) and (c), it is found that the high stress accelerates the mixing of substances at the fiber fracture, improving the film-forming quality of the mixture film at the fiber fracture, and makes the material surface at the fracture more flat. This phenomenon can also be observed by comparing figures 8(b) and (d), which explains why the friction coefficient decreases with increased stress.

Figure 8. Change of wear surface under different conditions during steady wear stage.
3.4. Analysis of severe wear stage

To compare the characteristics of severe wear stage in the whole life cycle, the curve of residual wear thickness is given in figure 9. Figure 9(a) shows a three-dimensional surface of residual thickness at 8.3 Hz and 40 MPa. Under this condition with wear life of 144 h, the wear of different regions on friction surface shows significant non-uniformity, and this non-uniform wear aggravates wear of the material, especially in the life range of 90–130 h, with more serious wear in the middle region than that at both ends of surface. Figure 9(b) shows the residual thickness of the sample under variable stress condition. It can be seen that wear life under different stresses has significant nonlinear characteristics. With the increase of stress, wear life continuously decreases from 372 h at 15 MPa and 6.6 Hz to 81 h at 50 MPa and 6.6 Hz. The wear thickness decreases sharply at the later stage of life under different conditions, especially at 15 MPa, 35 MPa, and 40 MPa, the later stage of life is a sudden wear failure, which lasts only 10–30 min. In order to further analyze the change of wear thickness in different wear regions, the three-dimensional morphology and contour of the surface of the sample at the late stage are given in figure 10, from which it can be seen that the penetration depth of the crack is as high as 100–120 μm. When the thickness of fatigue spalling reaches this value, the wear amount will show a serious nonlinear change as shown in figure 9 at the end of life. Therefore, spalling at the later wear stage can lead to sudden failure when the residual thickness is high.

Figure 11 shows the surface state of the material at the late stage of life under different conditions. It can be seen that the surface after failure under the two conditions is relatively close, which contains a small amount of PTFE and a large amount of reinforced fiber matrix and resin mixture. The wear behavior mainly occurs on the reinforced fiber and matrix. At this stage, the transfer film of the pin sample surface gradually decreases, and the film formation rate decreases. The wear resistance of the material is very poor, and a thick flaking layer is easy to appear on the surface, resulting in a dramatic increase in the friction coefficient. As a result, flaking occurs at the later stage can lead to worn out failure of the material for a short time when the remaining thickness is high.
In order to avoid sudden wear failure, according to the analysis results of section 2, the real-time monitoring of friction coefficient can be applied to effectively predict the life stage where the material is located and to prevent the metal gluing caused by the loss of self-lubricating performance of friction pair. According to the analysis results of the whole life cycle of PTFE/Kevlar self-lubricating composite, when the wear of material enters the failure stage, the spherical plain bearing may fail at any time due to the fluctuation of self-lubricating performance and the sudden failure. This could affect the safety of the whole machine. Therefore, the effective service life should be controlled within the stable stage in practical application.

4. Conclusion

(1) PTFE/Kevlar self-lubricating composite was prepared under high-frequency reciprocating use condition. The whole life wear test shows that the wear stage of this material can be divided into three stages: running-in wear stage, stable wear stage and severe wear stage. The different wear surface components at different stages lead to the change of tribological behavior of the material. The main components of the abrasion surface are PTFE fiber and resin in running-in wear stage, PTFE and Kevlar fiber in stable wear stage, and Kevlar fiber in severe wear stage.

(2) During the whole wear life cycle, the friction coefficient decreases with increased stress and frequency, and the self-lubricating performance improves. Wear life, on the other hand, decreases dramatically with increased stress and frequency, and the main form of wear changes from adhesive wear to abrasive wear and mechanical shear caused by fiber uplift. The effect of variable stress conditions on the lubricating performance of materials is greater than that of variable frequency conditions. The effects of frequency and stress on the self-lubricating properties of the material are decreased during the severe wear stage.

(3) The damage of self-lubricating material has significant nonlinear dynamic characteristics, and friction coefficient can reflect the self-lubricating performance and life characteristics of PTFE/Kevlar self-lubricating composite in time. Therefore, real-time monitoring of the friction coefficient and its fluctuation is an effective means to judge the performance and life stage of self-lubricating materials.

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Data availability statement

All data that support the findings of this study are included within the article and can be found online at https://doi.org/10.1088/2053-1591/ac7e22.
Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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References

[1] Aderikha V N and Shapovalov V A 2011 Mechanical and tribological behavior of PTFE–polyoxadiazole fiber composites Effect of filler treatment Wear 271 970–6
[2] Gu D et al 2016 Tribological properties of hybrid PTFE/Kevlar fabric composite in vacuum Tribol. Int. 103 423–31
[3] Kumar R et al 2020 Performance of polyimide and PTFE based composites under sliding, erosive and high stress abrasive conditions Tribol. Int. 147 106282
[4] Ding L et al 2020 Study on the characterisation of the PTFE transfer film and the dimensional designing of surface texturing in a dry-lubricated bearing system Wear 448–449 203238
[5] Li H L et al 2016 Tribological behavior of hybrid PTFE/Kevlar fabric composites with different weave densities Industrial Lubrication & Tribology 68 278–86
[6] Ma J, Yang Y and Tribological Q I X 2015 Performances of fabric self-lubricating liner with different weft densities under severe working conditions Indian Journal of Fibre & Textile Research 40 293–300
[7] Wang C et al 2018 Research status and prospect on new materials for spherical plain bearings Bearing 467 67–71
[8] Ren G et al 2014 Influence of lubricant filling on the dry sliding wear behaviors of hybrid PTFE/Nomex fabric composite J. Mater. Sci. 49 3716–24
[9] Liu J et al 2020 Friction and wear behaviors of kevlar/polytetrafluoroethylene braided composite in oscillatory contacts J. Mater. Eng. Perform. 29 2605–11
[10] Golchini A et al 2015 Tribological behavior of carbon-filled PPS composites in water lubricated contacts Wear 328–329 456–63
[11] Bhargava S, Makowiec M E and Blanchet T A 2019 Wear reduction mechanisms within highly wear-resistant graphene- and other carbon-filled PTFE nanocomposites Wear 444–445 203163
[12] Mya B et al 2016 A biomimetic approach to improving tribological properties of hybrid PTFE,Nomex fabric,phenolic composites - ScienceDirect Eur. Polym. J. 78 163–72
[13] Qiu M et al 2014 Effect of liner modification on the tribological properties of self-lubricating spherical plain bearings under tilting oscillation Tribology 34 59–64
[14] Vail J R et al 2011 Polytetrafluoroethylene (PTFE) fiber reinforced polyethyetherketone (PEEK) composites Wear 270 11–2
[15] Gu D et al 2018 Reciprocating sliding wear of hybrid PTFE/Kevlar fabric composites along different orientations RSC Adv. 8 20877–83
[16] Khare H S et al 2015 Interrelated effects of temperature and environment on wear and tribochemistry of an ultralow wear PTFE Composite J. Phys. Chem. C 119 65318–27
[17] Sun W et al 2018 Enhanced tribological performance of hybrid polytetrafluoroethylene/ Kevlar fabric composite filled with milled pitch-based carbon fibers
[18] Yahong X et al 2018 Finite element simulation and experimental test of the wear behavior for self-lubricating spherical plain bearings Friction 6 59–68
[19] Fei Z, Wang Q and Wang T 2015 Effects of aramid fiber and polytetrafluoroethylene on the mechanical and tribological properties of polyimide composites in a Vacuum Journal of Macromolecular Science Part B 54 927–37
[20] Wei C et al 2020 Study on the tribological properties of a self-lubricating spherical plain bearing at a cryogenic and wide temperature range Scientia Sinica Technologica 6 775–85
[21] Wang X et al 2019 Calculation model of elastic properties of polytetrafluoroethylene-aramid/phenolic resin twill fabric liner at different wear stages