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Influence of high temperature on the tribological properties of hybrid PTFE/Kevlar fabric composite

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Abstract: The tribological properties of PTFE/Kevlar fabric is extremely important for the service behavior of joint bearings in aviation, aerospace and other fields. Reciprocating wear tests were carried out to investigate the tribological properties of hybrid PTFE/Kevlar fabric composite at high ambient temperatures. The results indicated that as the ambient temperature increased from 25 °C to 200 °C, both of the coefficient and the wear loss of PTFE/Kevlar fabric slightly decreased and then rapidly increased. At high temperatures above 100 °C, the wear rates of PTFE/Kevlar material first significantly decreased and then stabilized with increasing reciprocating cycles. Analysis of the wear mechanisms and their transitions showed that with the increase in the ambient temperature and reciprocating cycles, the wear mechanism of the PTFE/Kevlar composite underwent a transition from abrasive wear to mild adhesive wear, then to severe adhesive wear, and finally to the combined wear of severe adhesive and thermal fatigue. Correspondingly, the surface damage changed from slight PTFE fragment and adhesion to severe peeling of PTFE transfer film, remarkable deformation and fatigue fracture of Kevlar. This information could provide a guide to mastering the range of safe use and optimization of materials.

Keywords: PTFE/Kevlar fabric; Wear mechanism; Damage transition; Ambient temperature

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1. Introduction

The structure of polytetrafluoroethylene (PTFE) chain is $(-CF_2-CF_2-)n$, in which C-C and C-F atoms possess high binding energy, resulting in a very good stability. However, the molecules of PTFE are combined by weak van der Waals forces, so the molecules are prone to slippage during the friction process, and then forming a transfer film. The transfer film presents good shear resistance, which greatly reduces the friction coefficient and creates a perfect self-lubricating effect [1][2]. However, the PTFE transfer film is easily detached because of the low surface energy and poor adhesion of pure PTFE. Therefore, many researchers have attempted to make up for this shortcoming through filler modification, blending modification, and blending with high-strength fibers [3][4][5][6][7][8].

A PTFE/Kevlar fabric composite is generally a double-layer fabric made of PTFE and Kevlar fibers interwoven with a twill textile. The PTFE lubricating film generated by the PTFE/Kevlar fabric during a sliding friction process can adhere well to the friction surface and plays a vital role in providing continuous lubrication [9][10]. It is widely used in joint bearings for key load-bearing parts in aviation, aerospace, high-speed railways and other fields due to its high strength, good wear resistance and stable lubrication performance [11][12][13]. Specifically, the fabric liner in helicopter main rotor bearings is made of a PTFE/Kevlar composite. As shown in Fig. 1, between the inner ring and the outer race, a layer of self-lubricating PTFE/Kevlar fabric liner is bonded to the outer race. Tan et al. [14] analyzed the failure of the joint bearing of the main rotor of a Robinson R44 helicopter, and found that the failure mainly came from wear damage between the inner ring and outer race, and the reason for the wear failure of the bearing was severe damage to the fabric liner, with fracturing and tearing of the fibers. Therefore, studying the tribological properties of PTFE/Kevlar liner is crucial to understanding the service performance of joint bearings and extending their service life [15][16][17].

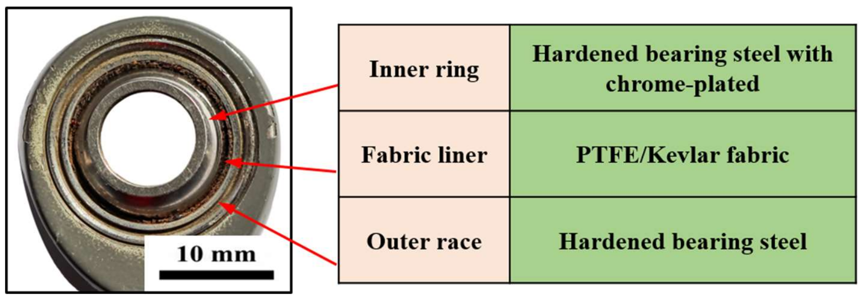


Fig. 1. Application of PTFE/Kevlar fabric composite in the joint bearings of the main helicopter rotor.

It is well known that the tribological properties of self-lubricating PTFE/Kevlar fabric are closly related to the formation of PTFE a transfer film [18]. The state of the transfer film during the friction process, however, is affected by many factors, such as contact parameters (contact stress [6][19][20][21], sliding speed [6][20] and frequency [20] etc.) and contact environment (water lubrication [22], vacuum [23][24], ambient temperature, etc.). Notably, the properties of the self-lubricating fabric and the state of the transfer film are extremly susceptible to temperature [6]. The melting point of PTFE is about 327 ℃ under normal condition (25 ℃, 100 KPa), while when the temperature exceeds 260 ℃, the tribological performance of the PTFE/Kevlar fabric will drop sharply, which will cause the loss of lubricating effect between the interfaces induced by excessive wear [18]. It was found that under high temperature conditions, the PTFE/Kevlar fabric quickly peeled off, resulting in exposure of Kevlar fibers and severe wear [25][26]. However, the specific wear mechanism and its corresponding evolution law of PTFE/Kevlar material under high ambient temperatures are still unclear.

The tribological performance of a fabric liner under high temperature conditions is extremly important for the service behavior of joint bearings in aviation, aerospace and other fields. In order to obtain the friction characteristics of the PTFE/Kevlar at high temperatures, the damage behavior and failure mechanism under different temperature conditions were investigated via reciprocating wear tests. The results could provide insights into the tracking of service performance and optimization of self-lubricating materials.

2. Experimental details

2.1 Materials and processing

A ball-on-flat contact mode was used in the present wear tests. The flat sample was PTFE/Kevlar fabric with a flexible double-layer fabric through twill weave. As shown in Fig. 2a, the black-brown part is PTFE with good self-lubricating properties, and the yellow part is Kevlar fiber with high strength and good wear resistance. To facilitate the friction test, the woven fabric was glued on the surface of a 45 steel-based material using epoxy resin, detailed information of preparation can be found in Ref. [21]. Subsequently, the flat PTFE/Kevlar fabric sample was cut with a size of $36 \times 17 \times 3$ mm^3, and the fabric thickness was 0.384 mm.

The ball samples, with a diameter of 6.35 mm, were machined from CGr15 bearing steel, as shown in Fig. 2b. The ball surface was hardened and electroplated with hard chromium, and the roughness was 0.05 μm.

Fig. 2c shows the contact interface of CGr15 bearing ball-on-PTFE/Kevlar fabric flat. The basic mechanical properties of Kevlar and PTFE fiber bundles, as well as the main components and mechanical properties of the GCr15 material can be seen in Ref [21].

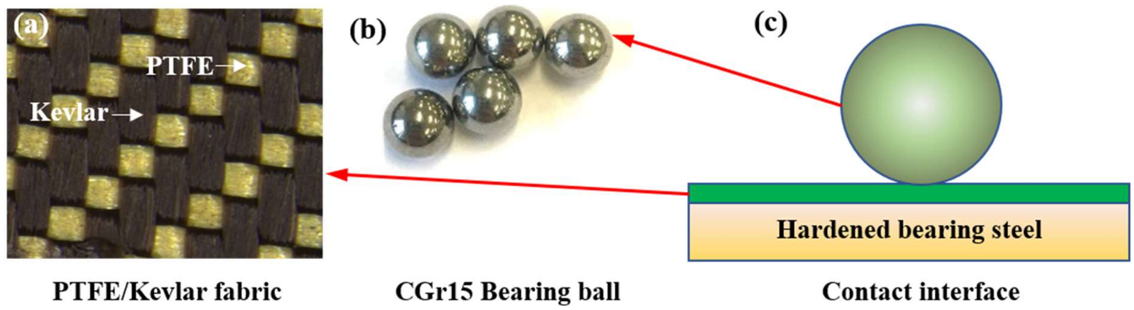


Fig. 2. Sample details: (a) PTFE/Kevlar fabric; (b) CGr15 bearing ball; (c) Contact interface in wear experiments.

2.2 Reciprocating wear tests in high temperatures

The experiments were performed through a high temperature reciprocating friction and wear rig (MXW-1, China), which allows a ball to reciprocate linearly with a flat specimen under controlled forces and temperatures. The structure diagram of the rig is shown in Fig. 3. The set loads can be obtained by controlling the spring loading device. The motor drives the slide gear to make the flat specimen run a periodic reciprocating linear motion. In this study, the sliding direction was unified perpendicular to the PTFE fiber bundle and parallel to the Kevlar fiber bundle. The required ambient temperature conditions can be achieved and maintained through the coordinated action of the heating plate and the thermocouple. The reciprocating friction and the coefficient of friction (COF) of the sample were measured by the friction sensor on the lever.

All tests were carried out under a normal load of 10 N (143MPa) and a reciprocating frequency of 5 Hz. The sliding displacement was set to 5 mm. The temperatures used in this study were 25 °C, 50 °C, 75 °C, 100 °C, 125 °C, 150 °C, 175 °C and 200 °C. Each set of test was run a total of 10,000 cycles, and observations on contact surface of PTFE/Kevlar fabric were conducted at 200 cycles, 1,000 cycles, 2,000 cycles, 5,000 cycles and 10,000 cycles to expose the evolution of surface damage. However, to better present the results, only the wear and damage behaviors at temperatures of 25, 50, 100, 150 and 200 °C will be highlighted in the following sections.

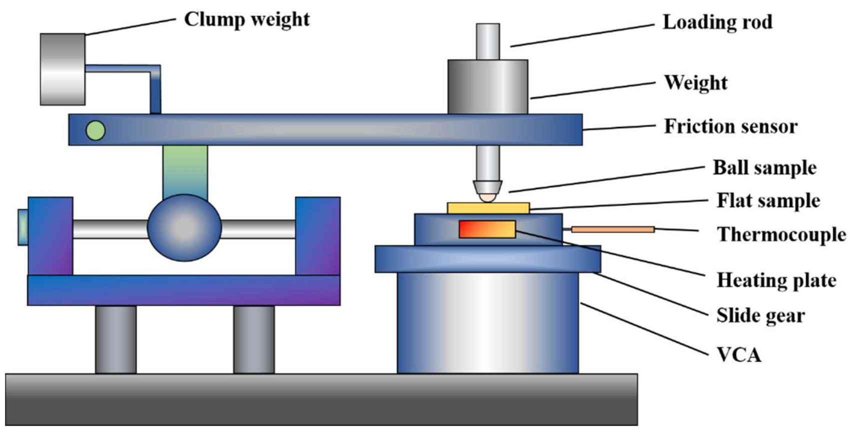


Fig. 3. Schematic diagram of MXW-1 high temperature reciprocating wear testing rig.

2.3 Measurements and observations

The wear loss of hybrid PTFE/Kevlar fabric was calculated by considering the depth of wear scar and measured using a three-dimensional optical profiler (3D-OM, NPFLEX, BRUKER). The wear performance was expressed by the specific wear rate calculated by the following equation:

$$\omega = \Delta V / (F \times L)$$

where ω is the specific wear rate in $m^3/(N\ m)$, ΔV is the volume loss in m^3, F is the applied normal load in N and L is the total sliding distance in m.

The microscopic morphology of the worn surface of the PTFE/Kevlar fabric was observed and analyzed by using a stereo microscope (SM, SZX7, OLYMPUS) and a field emission scanning electron microscope (SEM, Inspect F50, FEI). The three-dimensional profile of the worn surface of the fabric sample was measured through 3D-OM. Subsequently, the changes in the depth and width of the wear scar were analyzed. To further exploring the tribo-chemical behavior of the friction interface, energy-dispersive X-ray spectroscopy (EDS, Octane super, EDAX) was used to analyze the composition of the damage zone.

3. Results and discussion

3.1 Friction and wear

Fig. 4 shows the COF under different temperature conditions. It can be seen that the COF remains stable at about 0.26 at room temperature (25 °C). Interestingly, at a higher temperature of 50 °C, the COF drops to a value of 0.22. As the temperature continues to increase, the COF gradually increases, especially it is significantly higher at temperature of 200 °C than that at room temperature.

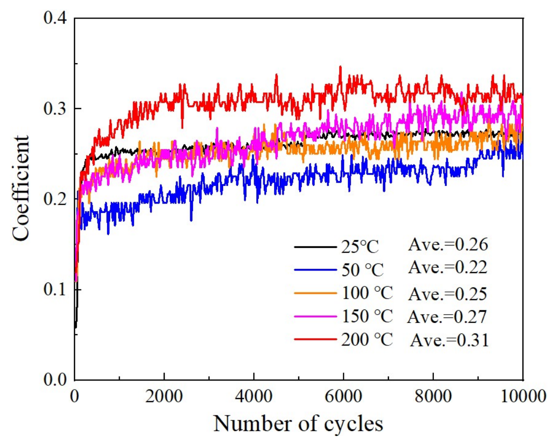


Fig. 4. Friction coefficient at different ambient temperatures.

The worn surface of PTFE/Kevlar fabric as a function of reciprocating cycle was detected using 3D-OM. Subsequently, the maximum depth of wear scar, volume loss and wear rate were obtained, and the results are shown in Fig. 5. The maximum depth increases overall as the test progresses, but slight decreases can be seen during some tests (Fig. 5a). This can be attributed to the formation and transfer of the self-lubricating PTFE film during the test. For different temperature conditions, the volume losses of hybrid PTFE/Kevlar fabric increase with the increase in cycle numbers (Fig. 5b). Notably, as the test progresses, the wear rates of

PTFE/Kevlar fabric first decrease and then stabilize under high temperature conditions (Fig. 5c). The significant decrease in the wear rate in the early stage of tests may be related to the formation of the self-lubricating transfer film.

Compared with the wear behavior at room temperature (25 ℃), the maximum depth, volume loss and wear rate of PTFE/Kevlar fabric are relatively lower at higher temperatures of 50 °C and 75 °C (not given here). A similar slight reducing trend with increasing temperature was observed in Ref. [27]. Besides, as the temperature continues to increase, the wear gradually increases. Higher volume losses and wear rates can be seen at temperatures beyond 100 °C than those at room temperature. Interestingly, the wear rates are significantly higher at high temperatures than that at 25 ℃ in the early stage of tests (Fig. 5c).

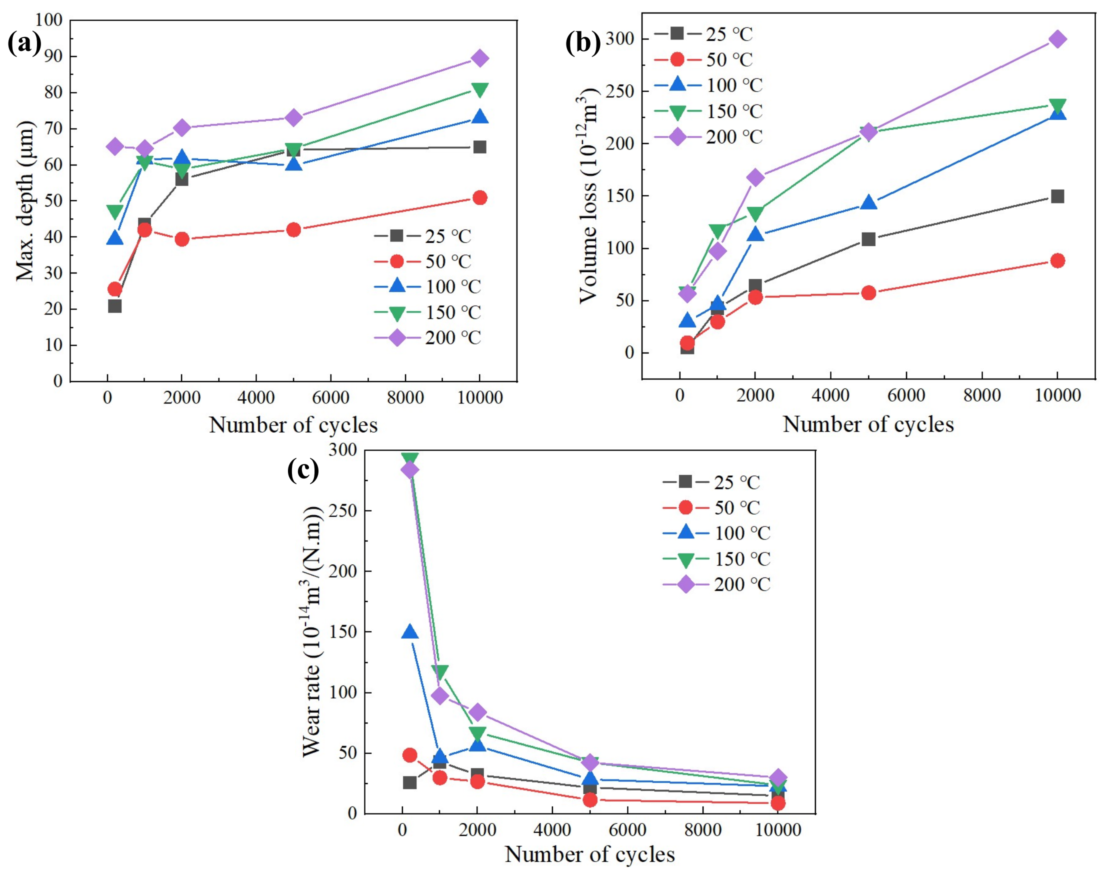


Fig. 5. Wear of PTFE/Kevlar fabric at different temperatures: (a) maximum depth; (b) volume

loss; (c) wear rate.

3.2 Microscope analysis of worn surfaces of PTFE/Kevlar fabric

3.2.1 SM observations

Figs. 6-9 show the evolution of PTFE/Kevlar fabric wear scars with reciprocating cycles at temperatures of 25 °C, 50 °C, 100 °C and 200 °C. It is observed that the width of the wear scar and the damage increase gradually as the number of cycles increases. The worn PTFE/Kevlar fabric at a temperature of 25 °C is characterized by fragmentation and abrasion of PTFE bundles, and gray-black fibrous debris caused by the mechanical shearing force during the friction process can be observed in Fig. 6.

At a higher temperature of 50 °C, the worn surface is still dominated by damage of PTFE fiber, while no obvious fractured PTFE debris is observed (Fig. 7). Therefore, compared with room temperature, the damage at 50 °C is milder, corresponding to the lower wear rate shown in Fig. 5.

When the temperature increases to 100 °C, the fabric wears fast and severely. After running 200 cycles, the broken PTFE fibers adhering to the Kevlar surface can be observed in Fig. 8a. At cycles of 2,000, the PTFE material in the center of the contact zone is completely broken and begins to shift in the sliding direction (Fig. 8b). When it reaches 10,000 cycles, the fabric damage is further aggravated, severe plastic deformation and loss of fabric feature has occurred. Specifically, the raised PTFE debris is observed at the edges of the wear scars, while only a little of PTFE material adheres to the concavity of the Kevlar fibers in the center of the wear scars. Meanwhile, the Kevlar bundles also begin to shift in the sliding direction.

The transfer of PTFE fibers and the plastic deformation and elongation of Kevlar fibers become more significant with increasing temperature, as shown in Fig. 9. At a temperature of 200 °C, the PTFE fibers wear rapidly, leaving the Kevlar materials completely exposed and elongated in the sliding direction, further forming a “wave-like” structure (Fig. 9c).

To sum up, the surface damage of PTFE/Kevlar fabric shows mainly fragmentation and transfer of PTFE, as well as the deformation and fracture of Kevlar fibers. High ambient temperature shows a great impact on damage behavior. Corresponding to the wear loss, the damage is relatively minor at temperatures of 50 °C and 75 °C, while the PTFE transfer and Kevlar deformation become severe at higher temperatures.

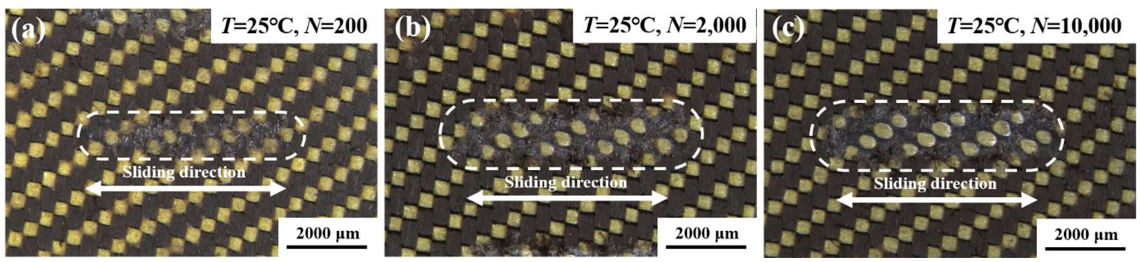


Fig. 6. SM images of worn surface of PTFE/Kevlar fabric at temperature of 25 °C: (a) 200 cycles; (b) 2,000 cycles; (c) 10,000 cycles.

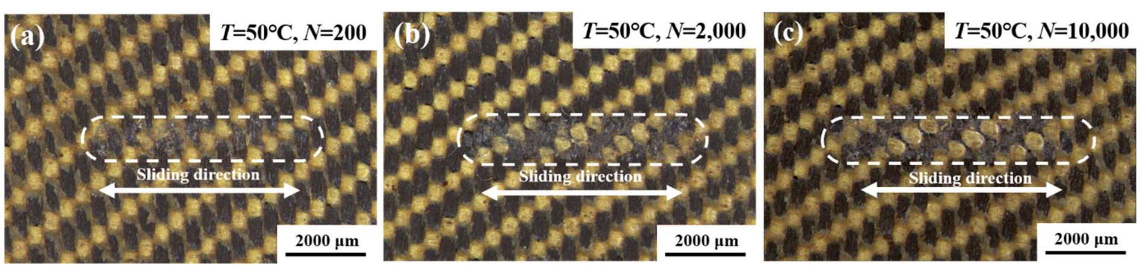


Fig. 7. SM images of worn surface of PTFE/Kevlar fabric at temperature of 50 °C: (a) 200 cycles; (b) 2,000 cycles; (c) 10,000 cycles.

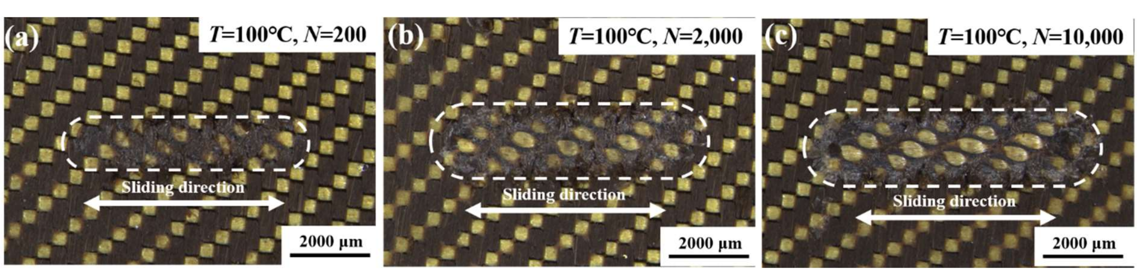


Fig. 8. SM images of worn surface of PTFE/Kevlar fabric at temperature of 100 °C: (a) 200 cycles; (b) 2,000 cycles; (c) 10,000 cycles.

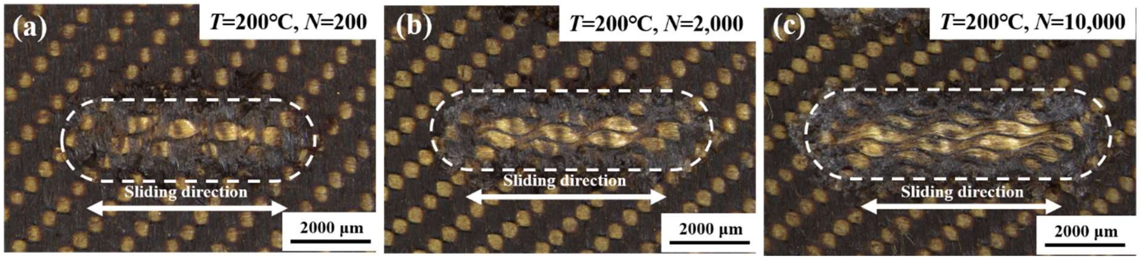


Fig. 9. SM images of worn surface of PTFE/Kevlar fabric at temperature of 200 °C: (a) 200 cycles; (b) 2,000 cycles; (c) 10,000 cycles.

3.2.2 3D-OM observations

The profile analyses of the fabric wear scar at different reciprocating cycles and temperatures were performed using 3D-OM. Fig. 10 shows the results of 2D and 3D profiles of PTFE/Kevlar fabric at a temperature of 100 °C. Obviously, the width and depth of the wear scar increase with the increasing cycles. After testing 10,000 cycles, the maximum width of the wear scar reaches 1.738 mm (Fig. 10a). Meanwhile, there is a raised structure on the edge of the wear scar, combined with SM observation in Fig. 8, it can be assumed to be the accumulation of transferred PTFE debris. An obvious peak and valley structure is observed in the center of the wear scar, and the peak should be the high-strength Kevlar bundle. At 10,000 cycles, the height of the peak is up to 38.04 μm. It is indicated that the PTFE material around the Kevlar fibers has been transferred and squeezed to the surroundings during the friction process (corresponding to Fig. 8).

Fig. 11 shows the partial 3D-OM results of the PTFE/Kevlar wear scar at different temperatures (after 10,000 cycles). Corresponding to the wear data in Fig. 5, the fabric material wears only slightly at 50 °C. When the temperature increases from 50 °C to 200 °C, both width and depth of the wear scars increase. At a temperature of 200 °C, the maximum width of the wear scar is 2.088 mm, and the height of the Kevlar peak is up to 56.61 μm. However, a low peak of 16 μm height in the center of the wear scar is observed, implying that the Kevlar material has undergone severe wear and breakage under this condition (Fig. 11b).

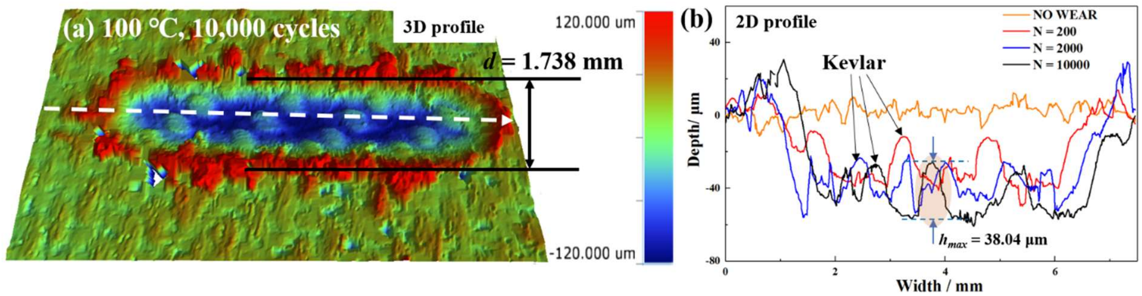


Fig. 10. 3D-OM results of worn PTFE/Kevlar fabric at temperature of 100 °C: (a) 3D profile after 10,000 cycles; (b) 2D profile as a function of cycles.

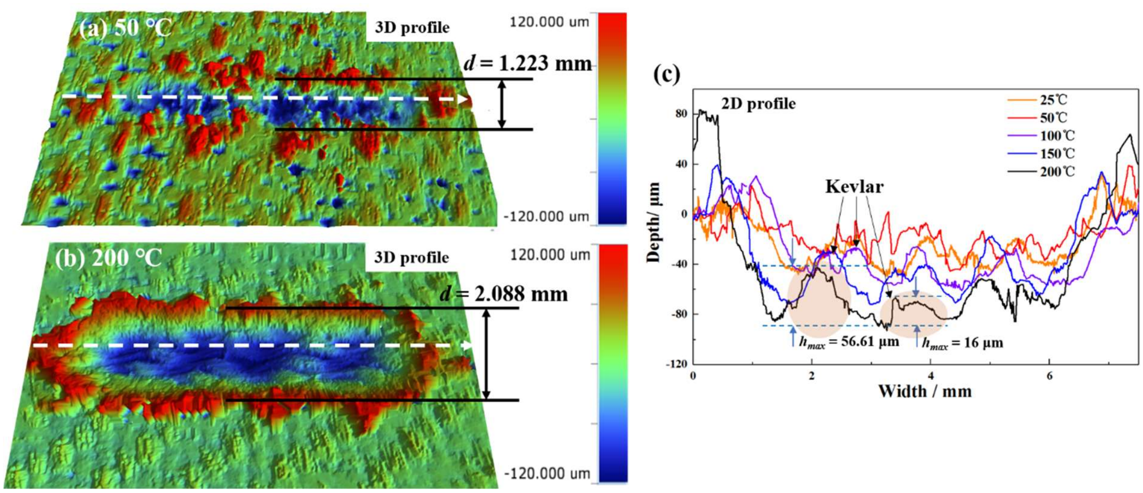


Fig. 11. 3D-OM results of worn PTFE/Kevlar fabric at different temperatures (10,000 cycles): (a) 3D profile at temperature of 50 °C; (b) 3D profile at temperature of 200 °C; (c) 2D profile as a function of temperature.

3.2.3 SEM observations

SEM was used to observe the worn surface of PTFE/Kevlar fabric to analysis the failure process microscopically. It should be noted that the SEM observation of the PTFE/Kevlar material at room temperature (25 °C) was performed in Ref. [21], and it was found that the fabric underwent visible abrasive wear, which was manifested by fiber breakage and peeling of the transfer film.

Fig. 12 shows the SEM results of the wear scar of PTFE/Kevlar fabric with reciprocating cycles at a temperature of 50 °C. In the early stage of this test (Fig. 12a), the PTFE material quickly adheres to the surface of the fabric under the action of sliding load and exhibits a good lubricating effect, resulting in a good wear resistance (Fig. 5). When it reaches 10,000 cycles, only slight fiber breakage is observed at the edge of the wear scar, as shown in Fig. 12c.

Fig. 13a-c presents the formation and accumulation of PTFE transfer film at a higher temperature of 100 °C. Comparing the SEM results at temperatures of 25 °C and 50 °C, it can be inferred that the increase in temperature will further aggravate the damage of the fabric material, which is manifested by an increase in the fiber fracture and its accumulation at the edge of the wear scar, as well as a stronger flow of PTFE. After testing 10,000 cycles, a large area of PTFE transfer film is formed in the middle of the wear scar. Meanwhile, it is hard to observe the fiber structure, as shown in Fig. 13c.

When the ambient temperature reaches 200 °C, severe damage rapidly occurs on the PTFE/Kevlar fabric. A large amount of fiber breakage and formation of transfer film are observed only running after 200 cycles (Fig. 14a). Under the combined action of cyclic loads and thermal effect, the transfer film is rapidly detached from the surface of the fabric material, as shown in Fig. 14b. When the test is carried out to 10,000 cycles, only a little PTFE transfer film remains in the middle of the wear scar, while a clear fiber structure could be observed behind the transfer film, which is the damaged Kevlar fiber (Fig. 14c).

The above SEM analysis indicates that a desired high temperature can effectively promote the adhesion of PTFE material to the contact surface, enhance the self-lubricating effect, and produce adhesive wear (Fig. 12). However, as the temperature increases, the PTFE transfer film accelerates consumption and peels off from the surface under the combined action of mechanical and thermal effects, causing the Kevlar fiber to lose the protection of the self-lubricating PTFE material and become exposed. Finally, the exposed Kevlar fiber suffers severe fatigue damage (Figs. 13-14).

The varied damage behaviors at different temperatures indicated a change of wear mechanism occurring on PTFE/Kevlar fabric. Abrasive wear typified by PTFE fragment is the primary wear mechanism at room temperature [21], while adhesive wear and thermal fatigue wear would occur at high temperatures. The wear mechanism and its evolution at high temperature will be discussed in detail later.

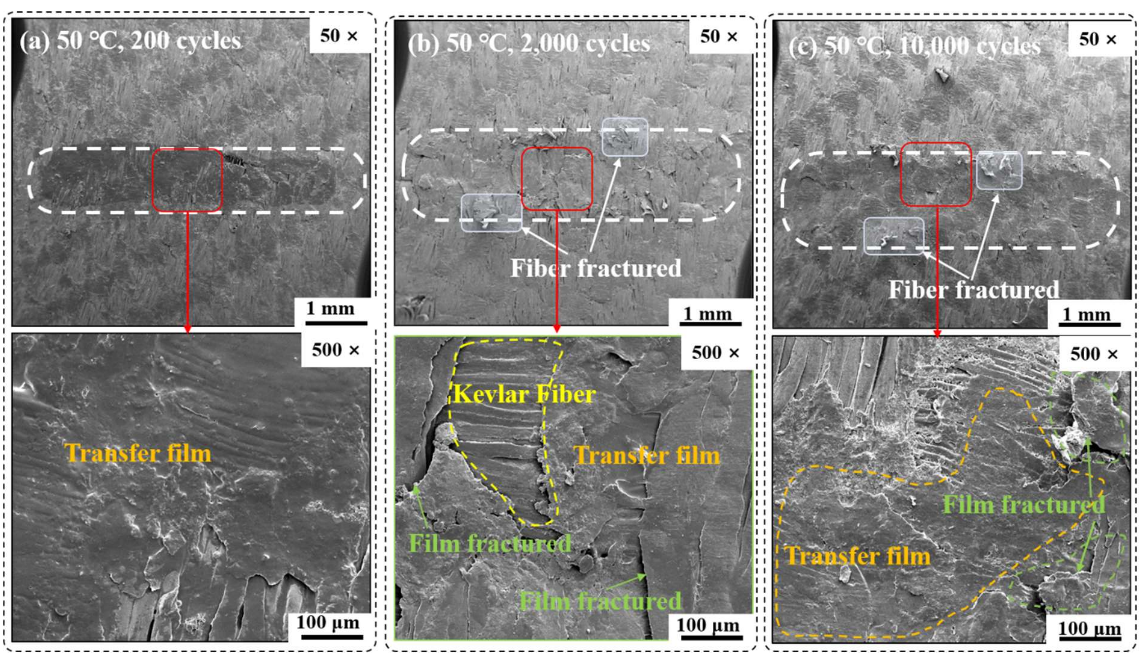


Fig. 12. SEM images of worn surface of PTFE/Kevlar fabric at temperature of 50 °C: (a) 200 cycles; (b) 2,000 cycles; (c) 10,000 cycles.

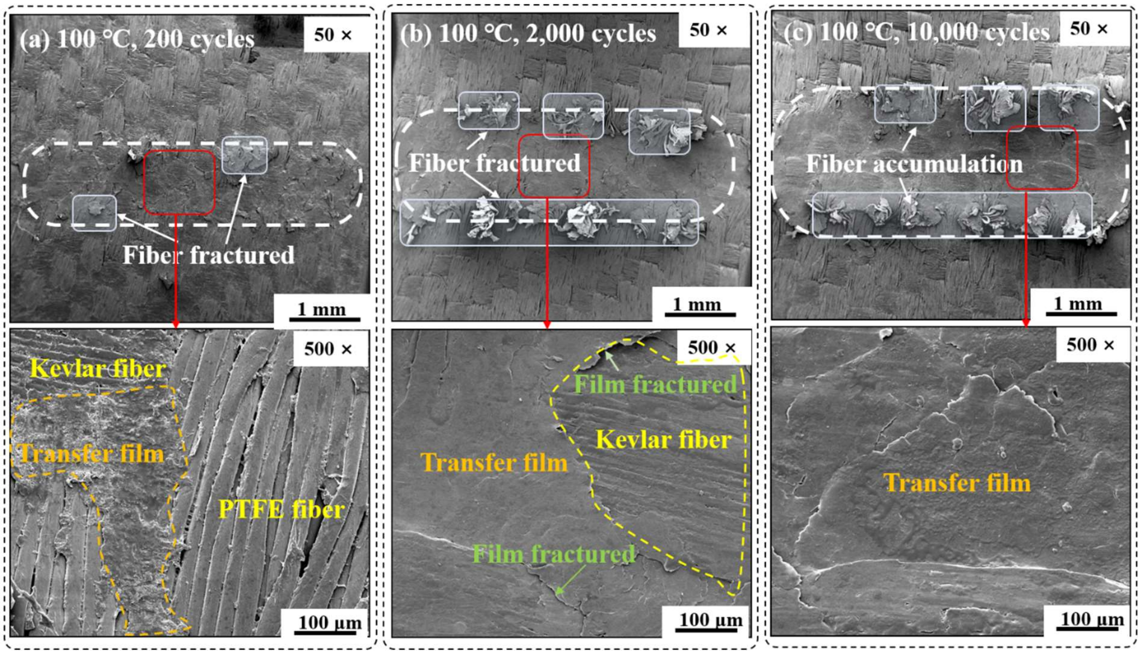


Fig. 13. SEM images of worn surface of PTFE/Kevlar fabric at temperature of 100 °C: (a) 200 cycles; (b) 2,000 cycles; (c) 10,000 cycles.

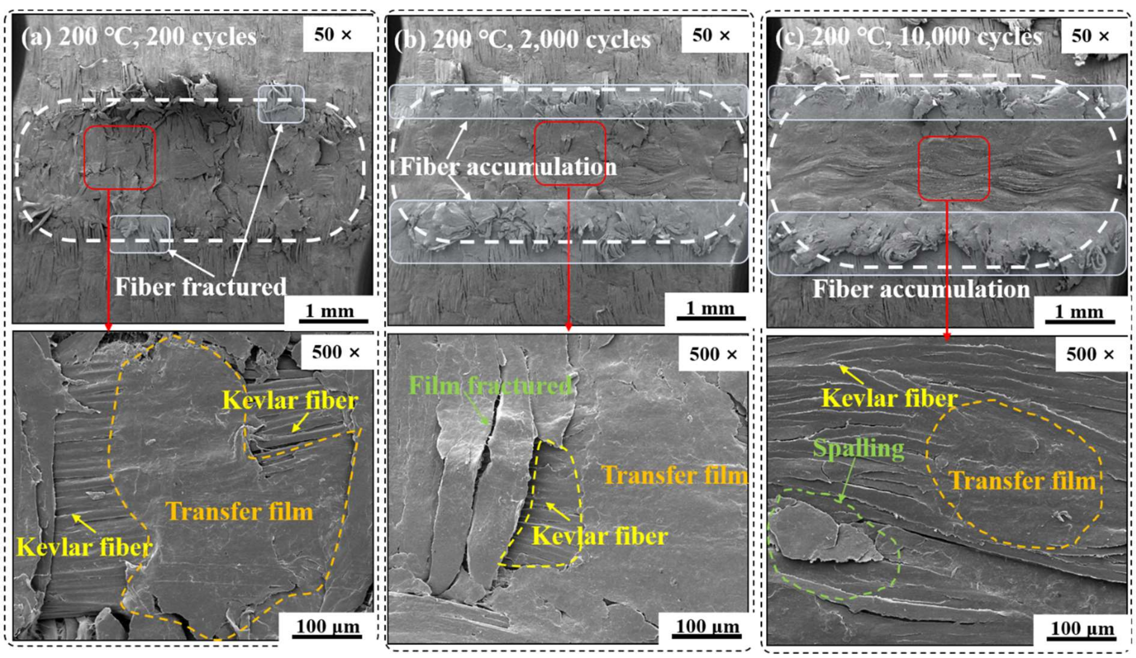


Fig. 14. SEM images of worn surface of PTFE/Kevlar fabric at temperature of 200 °C: (a) 200 cycles; (b) 2,000 cycles; (c) 10,000 cycles.

3.3 Tribo-chemical behavior analysis

3.3.1 EDS mapping scanning analysis

In order to explore the effect of high temperatures on the transfer and distribution of elements at the friction interface, EDS mapping scanning analysis of the PTFE/Kevlar wear scars was performed at temperatures of 50 °C, 100 °C, 150 °C, and 200 °C. The results are shown in Fig. 15. It should be pointed out that it is difficult for EDS to detect the C element in the PTFE because the F element covers the C-C main chain in the PTFE. Therefore, the F elements in the EDS observations all came from PTFE fibers, while the C and O elements were derived primarily from Kevlar fibers whose chemical structure is (-CO-C_6H_4-CONH-C_6H_4-NH-)n.

Fig. 15a shows that the distributions of C, F, and O elements on the surface of the fabric behave fibrous structures at temperature of 50 °C due to the slight wear. However, the decrease in the distribution of C (the "yellow" area is obviously darkened) and the tendency of F to transfer to Kevlar fibers can still be found in the wear scar.

When the temperature increases to 100 °C (Fig. 15b), the fabric is severely worn. It is hard to observe the element with fibrous distribution. Meanwhile, the distributions of C and O become weakened, and an "ellipse-like" C distribution is observed in the middle of the wear scar. On the contrary, the F element is distributed in the entire scanning area and covers the Kevlar fiber.

Fig. 15c shows that at a higher temperature of 150 °C, the distribution of the F at the edge of the wear scar is much stronger than that in the middle of the wear scar, which indicates that the PTFE transfer film is rapidly being worn or peeled off under this condition.

As the temperature further increases to 200 °C (Fig. 15d), the C element in the wear scar becomes strong again, and appears "wave-like" as similar as the Kevlar. Whereas, the distribution of F in the middle of the wear scar is further weakened. It is suggested that at high temperature, as the fabric wears rapidly, the PTFE is continuously flattened and squeezed to edges of the wear scar, exposing the Kevlar fiber, which is consistent with the result in Fig. 14.

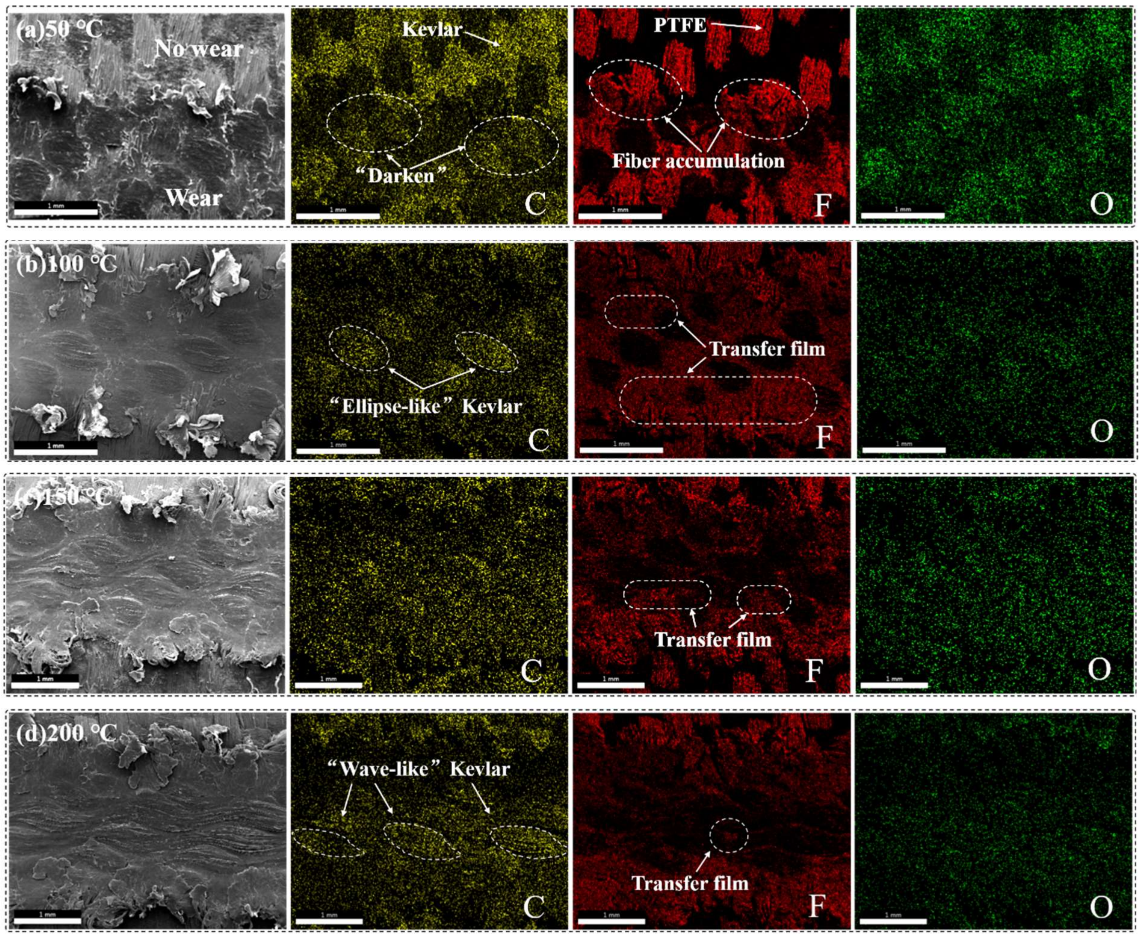


Fig. 15. EDS mapping scanning results of worn PTFE/Kevlar fabric at high temperature conditions (10,000 cycles): (a) 50 °C; (b) 100 °C; (c) 150 °C; (d) 200 °C.

3.3.2 EDS line scanning analysis

An EDS line scanning analysis of the wear scar was carried out to analyze the content and distribution of chemical elements along the cross-section of the wear scar under high temperature conditions. The scanning area is shown in Fig. 16a, and the distributions of F and O are presented in Fig. 16b and Fig. 16c, respectively.

Fig. 16b shows that under high temperature conditions, the F element is distributed strongly on both sides of the wear scar and weaker in the middle. This proves once again that the PTFE fiber is destroyed and squeezed to edges of contact interface during the reciprocating sliding process (corresponding to Figs. 6-9). Besides, the content of F in the middle of the wear scar at a high temperature of 100 °C is more than that under other temperature conditions. Combined with SEM images (Figs. 12-14), it is indicated that the PTFE transfer film is formed well at temperature of 100 °C.

Contrary to the distribution of F element, the distribution of O is stronger in the middle of the wear scar and weaker on both sides, as shown in Fig. 16c. Meanwhile, the lowest content of O in the middle of the wear scar at temperature of 100 °C once again proves its best formation of transfer film. In addition, the high content of O in the middle of the wear scar at a high temperature of 200 °C may be related to the exposure of the Kevlar fiber or oxidative wear.

The EDS results show that the distributions of C and F elements reflect the influence of temperature on the formation of PTFE transfer film. As the temperature increases from 50 °C to 200 °C, the transfer film first increases and then decreases. It was believed that the formation of transfer film could reduce damage [1][2][21]. However, the thermal effect has a more severe impact on the wear and damage of the fabric material in this work. Therefore, even if the film is formed well at temperatures between 100 °C and 150 °C, strong wear and damage behaviors could occur.

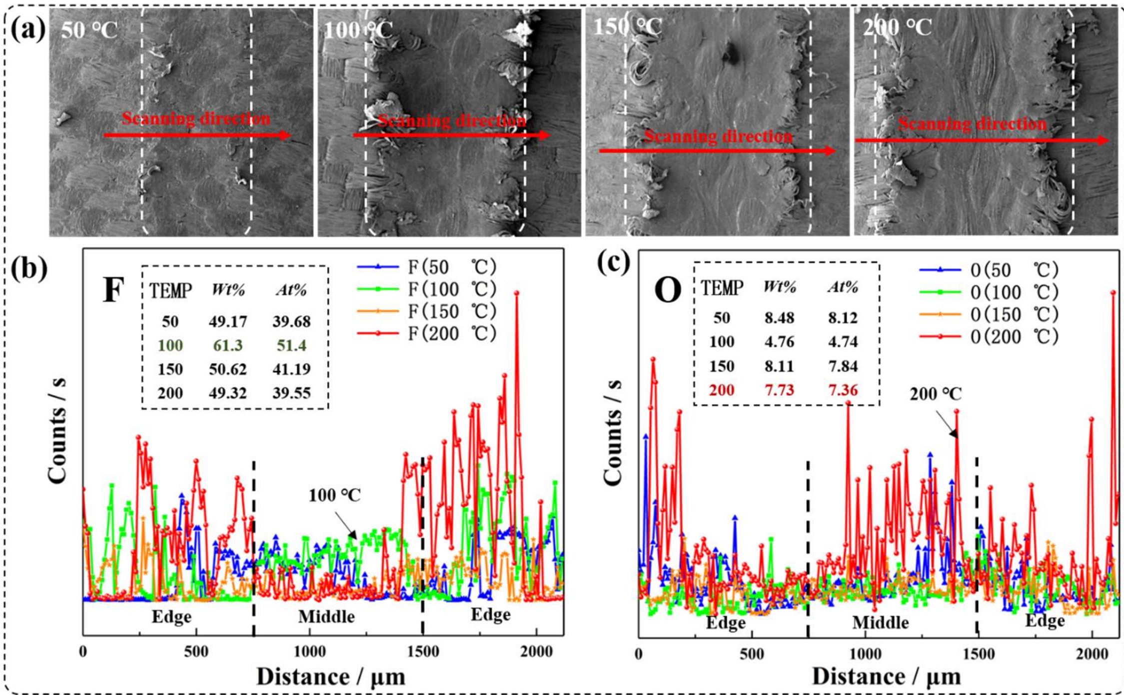


Fig. 16. EDS line scanning results of worn PTFE/Kevlar fabric at high temperature conditions (10,000 cycles): (a) 50℃; (b) 100℃; (c) 150℃; (d) 200℃.

4 Discussion

The wear and damage behaviors reflect and synchronously induce various wear mechanisms. The wear mechanism is extremely complicated and several mechanisms often coexist, as it is a multi-parameter and sensitive process in the friction of PTFE/Kevlar composites. For the soft to hard mating interfaces of PTFE/Kevlar against CGr15 bearing steel, a consistent law for friction and wear, which clearly identifies the mechanisms, so far, has not yet been established despite the artistic classification and summary of the wear map [28][29][30][31]. Hence, the wear mechanism and transition analyses below are simply explored based on the foregoing observations, as shown in Figs. 17-18.

4.1 Wear mechanism for high temperatures

Fig. 17 shows the schematic of the proposed wear mechanism and how it changes with increasing temperature. Theoretically, the contact interface between the CGr15 bearing ball and the fabric material inevitably have rough peaks, although it looks smooth (Fig. 17a). With the reciprocating sliding load, the softer PTFE fibers will break first, forming wear debris, and further aggravate the wear, as shown in Fig. 17b. Wear like this at room temperature due to particles or protuberances forced against and moving along a solid surface is abrasive wear (three/two body repsctively) [21][30][32].

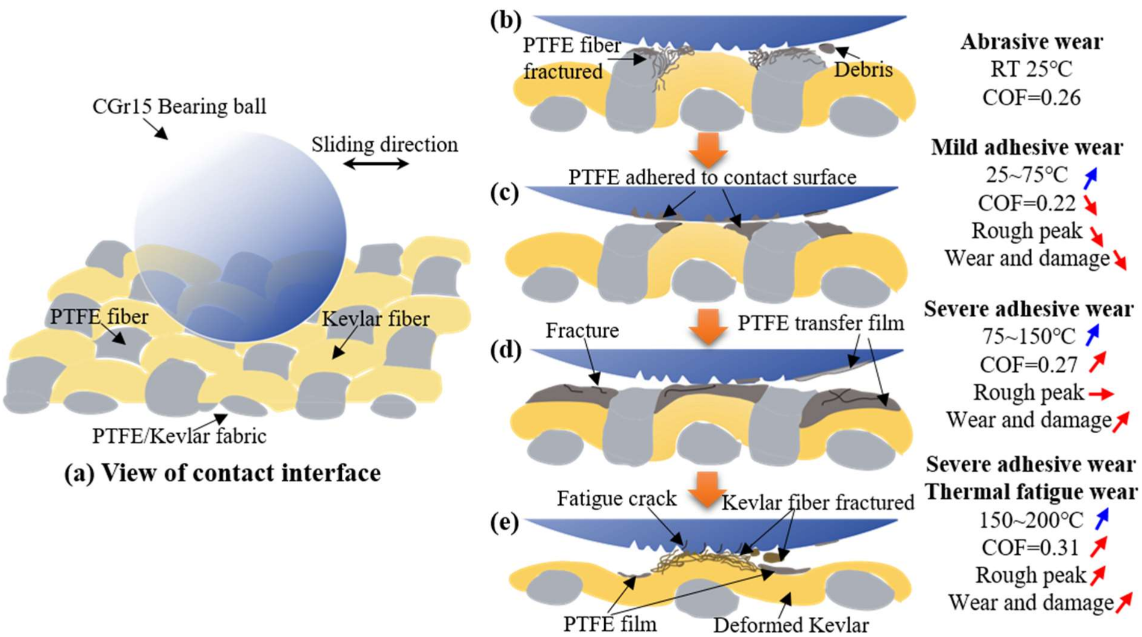


Fig. 17. Schematic of wear mechanism changes with the temperatures: (a) macroscopic view of contact interface; (b-e) magnified view of contact interface under high temperature conditions.

At high temperatures, the surface of PTFE/Kevlar will soften [33], whereas the wear debris will become easily susceptible to slip and dynamic adhesiveness, resulting in an adhesive wear mechanism [31][34]. When the ambient temperature was in the range of 25~75 ℃, the PTFE/Kevlar underwent slight adhesive wear, as seen in Fig. 17c. Specifically, the local softened PTFE flakes were torn from the fibers and adhered to the gaps in the fabric material and the recesses of the bearing ball, which reduced the roughness of the contact interface and increased the self-lubricating performance, thereby reducing COF (Fig. 4), and then wear and surface damage were decreased (Figs. 5,7,12).

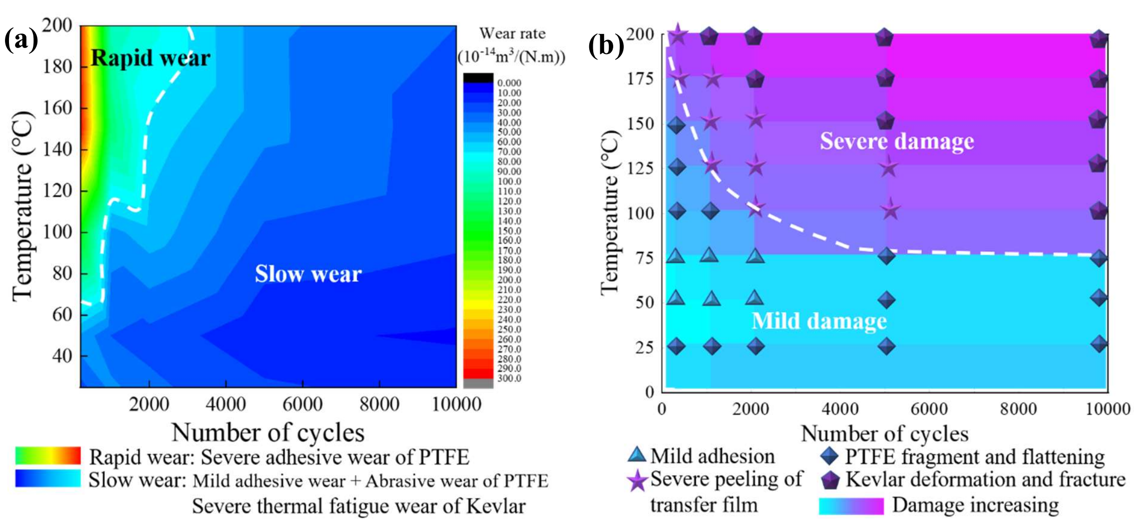
When the ambient temperature rose to 75~150 °C, severe adhesive wear occurred on the surface of the fabric material (Fig. 17d). At this moment, it was observed that PTFE material adhered to the Kevlar fiber in a large area to form a transfer film (Figs. 8,13,15b-c). Usually, the existence of the transfer film is conducive to self-lubrication that reduces wear and damage [27]. However, the transfer film is prone to fracture under the thermal-mechanical action, peeling off from the surface and forming shear furrows, which will further expose Kevlar fibers, or clumps adhering to the surface of the bearing ball for repeated friction. Therefore, a more severe wear loss and surface damage was detected in Figs. 5, 8 and 13 compared with the lower temperature conditions.

At a high temperature of 200 °C, the PTFE/Kevlar will be severely softened, further aggravating the tearing. In the middle of the wear scar, Kevlar was found to be exposed in large areas, indicating a direct contact between the harder Kevlar fiber and the ball bearing. As a result, the roughness of the interface increased, and as a result the COF rose to 0.31 (Fig. 4). Under the action of the strong thermo-mechanical effect, Kevlar deformed significantly and suffered from fatigue fractures (Figs. 9,14), and fatigue cracks may also occur on the surface of the ball bearing. At this stage, severe adhesive wear and thermal fatigue wear mechanisms occurred simultaneously in the contact surfaces, as shown in Fig. 17e. The rapidly occurring or accelerating damage, deterioration, or change of shape caused by wear to such a degree that the service life of PTFE/Kevlar will be appreciably shortened or its function will be destroyed.

In summary, with the increase in the ambient temperature, the wear mechanism of the interface between the PTFE/Kevlar fabric and ball bearing varied from abrasive wear to mild adhesive wear, then to severe adhesive wear, and finally to the combined wear of severe adhesive and thermal fatigue. Correspondingly, the damage behavior changed from slight PTFE fiber breakage to mild adhesion, then to severe peeling of the transfer film and finally to fatigue fracture of Kevlar fiber.

4.2 Transition of wear and damage behaviors

From the analysis above, there is a transition of wear mechanism and damage behaviors with the increasing temperatures and testing cycles. As it is known, the wear map, which was widely applied in the prediction and numerical simulation, is an effective way to distinguish the wear regimes and transition processes [31][35], as well as to understand the influence of various test conditions on the contact surfaces in the space-time framework of wear. In the present study, the transition maps of wear and damage behaviors in terms of reciprocating cycle and ambient temperature were concluded by examining the successive changes in the wear loss and surface damage of the PTFE/Kevlar fabric, as shown in Fig. 18.



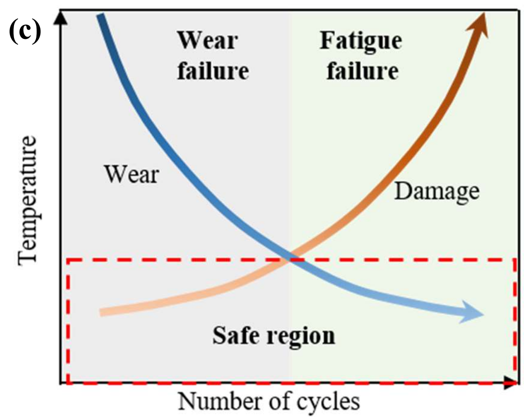


Fig. 18. Wear and damage transition map of PTFE/Kevlar fabric: (a) wear map; (b) damage map; (c) the interaction of wear and fatigue damage.

Considering the wear rate in Fig. 5, two regimes, rapid wear (the wear rate ≥ $100\times10^{-14}m^3/(N.m)$) and slow wear (the wear rate < $100\times10^{-14}m^3/(N.m)$), are identified in the wear map (Fig. 18a). Among them, the rapid wear regime is dominated by severe adhesive wear mechanism of the softer PTFE, while the slow wear regime includes mild adhesive wear and slight abrasive wear of PTFE, as well as the thermal fatigue wear of the harder Kevlar at high temperatures.

Subsequently, the damage map in Fig. 18b can be divided into two regimes based on the severity of the surface damage of PTFE/Kevlar fabric: mild damage and severe damage. Specifically, the damage behaviors in the mild damage regime include the slight adhesion at temperatures of 50~75 °C and slight PTFE fragment at room temperature, whereas severe surface damage behaviors, such as severe peeling of PTFE transfer film, exposure, deformation and fatigue fracture of Kevlar induced by thermal-mechanical load at high temperatures of above 100 °C, can be usually observed in the severe damage regime.

Fig. 18c presents the relationship between wear loss and surface damage. A mechanism of competition and restriction between wear and damage can be concluded [36]. The failure plot of PTFE/Kevlar fabric can be divided into wear failure and fatigue failure, and the service life is determined by the lower part of the two regimes. This study indicates that within a certain temperature threshold (which here is below 75 °C) there is a safe region of the PTFE/Kevlar material, where its wear and damage behavior can be controlled within a limited range.

5. Conclusions

In this work, the tribological properties and their transitions at high ambient temperatures were investigated through a series of reciprocating wear tests. The following main conclusions can be drawn:

1. As the ambient temperature increased from 25 °C to 200 °C, both of the COF and the wear loss of PTFE/Kevlar fabric slightly decreased at temperatures of 50~75 °C and then rapidly increased. At high temperatures above 100 °C, the wear rates of PTFE/Kevlar material first significantly decreased and then stabilized with the increasing reciprocating cycles.
2. With the increase in the ambient temperature, the wear mechanism of the interface between the PTFE/Kevlar fabric and CGr15 ball bearing underwent a transition from abrasive wear to mild adhesive wear, then to severe adhesive wear, and finally to the combined wear of severe adhesive and thermal fatigue.
3. As the temperature and reciprocating cycles increased, the surface damage of PTFE/Kevlar fabric changed from mild damage regime, including the slight adhesion and PTFE fragment, to severe damage regime which was typified by severe peeling of PTFE transfer film, remarkable deformation and fatigue fracture of Kevlar.

4. A desired high ambient temperature condition can effectively promote the adhesion of PTFE material to the contact surface, thereby enhance the self-lubricating effect. However, the service life of the PTFE/Kevlar composite would be greatly reduced beyond a certain temperature. Therefore, the establishment of wear and damage mechanism maps will be very beneficial to master the safe use range of materials.

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