Wear Mechanism of Nomex/PTFE Fiber Reinforced Composites

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Abstract

This paper is aimed at the problems of abnormal tribological damage and fluctuation of tribological performance in the self-lubricating composite serving in heavy load spherical plain bearing in aerospace field. The Nomex/PTFE fiber reinforced composite was used to carry out a reciprocating block on ring tribological test, investigating the tribological performance of the material and its wear evolution. Results show that the influence of oscillating frequency on material wear is obviously higher than that of load under high load condition (more than 90 MPa or 180 kN). Under a certain load and frequency condition, friction temperature is a key factor to affect wear behavior of the material. Friction heat plays a dominant role in the process of worn out failure of the material. Too high friction temperature greatly weakens the friction and wear performance, resulting in material failure in a short time. Thermal fatigue is the main tribological damage mode of the material under the high load and high frequency condition, with local worn out occurred. This finding was also verified by SEM analysis of the worn surface and wear debris.

Introduction

Nomex/PTFE fiber reinforced composite is used as the ideal self-lubricating material in spherical plain bearing used in aviation and high-speed rail, etc., due to its high strength, low friction coefficient and stable lubrication properties[1–6]. For the material, the friction and wear performance and serving life directly determine the performance and service life of the spherical plain bearing[7–8]. Under the server conditions, abnormal damage often happens on spherical plain bearing because of the tribological performance degradation or local damage of self-lubricating layer, leading to the actual service life far lower than its rated life. Therefore, study on the wear properties and damage mechanisms of self-lubricating fiber reinforced composite is crucial to obtain the performance and life characteristics of spherical plain bearings. It is also important to select and evaluate the self-lubricating materials [9–12].

Many works have been done to study the tribological properties and wear damage mechanism of the self-lubricating fiber reinforced composites. Podra et al. [13] used a pin-on-disk tribological tester to investigate the relation between wear loss of the self-lubricating material and sliding distance, and found that the contact state of friction pair has an important influence on tribological behavior of the material. Cui et al. [14] discussed the tribological mechanism of the self-lubricating material, and pointed that the Nomex/PTFE fabric could form stable transfer film on the spherical plain bearing under low temperature. Yu et al. [15] carried out the ball-on-disk and bearing tribological tests to study the friction and wear behavior of the PTFE-Nomex and the PTFE-Nomex/Nomex composites. He obtained that the tribological behaviors of two kind composite were different with increasing sliding distance. Vail et al. [16] stated that the PTFE composite has lower wear rate and this is mainly due to the transfer film (including PTFE, filler, oxide, et al.) formed on the friction pair interface. Aderikha et al. [17] analyzed the transfer film of the PTFE composite and summarized the friction and wear mechanism of the self-lubricating composite. It is noted that most works are mainly focused on the effects of material composition and working conditions during a short time on the tribological behaviors of self-lubricating composites [18–25]. Whereas the published literatures about the wear damage process during a long time life test and the self-lubricating behavior are rare, but this is crucial to the development and application of this material in engineering.

In this study, according to serving conditions of the Nomex/PTFE fiber reinforced composites in spherical plain bearing, a high frequency oscillating tribological tester was employed to test the friction and wear performances under varied loads and temperatures. Wear mechanisms and wear life of the material were analyzed in order to provide reference for improving the tribological performance of self-lubricating material and revealing the life characteristics of spherical plain bearings.

Experimental

2.1 Materials

The Nomex/PTFE fiber reinforced composite was developed for spherical plain bearing applied under high load condition. Nomex fabric, knitted with the Nomex fibers from DuPont, has a twill weave with a weight/area ratio of 1.35 g/cm^2, shown in Fig. 1. The material was prepared with a thickness of 0.38 ± 0.02 mm and the PTFE content is 21%~25%. The specimen was made by using phenolic resin to adhere the composite on a base (surface roughness of 0.45 mm) with a radius of curvature of 50 ± 0.05 mm and a radian of 60 ± 0.5°. The schematic of friction pair is given in Fig. 2. The peel strength of material adhered was from 0.35 to 0.38 N/mm, and the peel angle between the composite and base surface was 140 ± 40°. Fabric tightness was not more than 0.07 mm. The counterpart sliding against the specimen was 9Cr18Mo, with a diameter of 100 mm and a surface roughness of 0.16 μm. It was processed with sub-zero treatment temperature minus 55°C and with thermal insulation time not less than 1 h according to the requirement of high carbon chromium bearing stainless steel technology (GB/T3086). The counterpart was degreased with acetone before test. The experiment was performed with maintaining environment temperature of 25°C and relative humidity of 60%.

2.2 Experimental methods

The friction temperature was measured by thermocouples mounted at the position with a distance of 0.5 mm from the surface below the composite, and was controlled under the same load and frequency by varying the environment temperature. Wear depth was measured by a laser displacement sensor.

In order to ensure the measurement accuracy of friction and wear properties of the composite, the material was pre-grinded for 20 min before the test to make the material surface in a stable lubrication state and the friction coefficient reaching a relatively stable stage.

According to the actual working conditions, overall life friction and wear tests were carried out at 90 MPa (180kN), 100 MPa (200kN) and 110 MPa (220kN), with the environment temperature held at 20°C and 75°C, respectively. The tests were performed for about 200–300 h. If the friction coefficient of the friction pair was changed abruptly or friction temperature monitored suddenly raise, lubrication effect of the specimen became worse and the test was terminated immediately. The environment temperature was controlled at constant by an temperature control box, as shown in Fig. 3. The friction coefficient, wear depth and friction temperature were monitored and recorded in real time.

Results And Discussion

3.1 Effect of load and frequency on lifetime

Fig. 4 shows the change of material wear life. Wear depth is relatively large at the beginning and the difference of wear life is only 40 h at 100 MPa compared to that at 110 MPa. It can be seen that the wear loss fluctuates greatly with time under two conditions. The main reason is that the dynamic change of tribological behavior and the coupling effect of mechanical impact lead to the lubrication state of contact surface being extremely unstable. Besides, the thickness of the fabric is only 0.38 mm, and thermal deformation of the friction pair has a great effect on the measurement results due to accumulated friction heat generated during the friction. So after each test, static load is maintained to eliminate the influence of thermal expansion of friction pair. At 100 MPa, wear depth has an apparent change until it reaches 70 h. It is analyzed that the factors such as friction temperature, equipment operation error and measurement error can be excluded, so it is probably caused by the change of tribological properties of the self-lubricating material. The fluctuation of wear depth in a small range can be attributed to the machine vibration and measurement accuracy (relative stable stage is more than 200 h). Whereas the fluctuation of wear depth in a large range is due to effect of self-lubrication behavior on the friction pair (mainly at the early stage), as shown in Fig. 5. In Fig. 6, because the oscillating frequency is unstable under high load, the data of two points at 1 Hz and 3Hz are recorded with the load is held at 110 MPa. It shows the change of wear rate with varying frequency. At 90 MPa and 100 MPa, wear rates rise abruptly, whereas the difference of wear rates under two frequencies is not obvious at 110 MPa.

Fig. 7 shows the initial surface topography of the Nomex/PTFE fiber reinforced composite. The actual contact area between the composite and its counterpart during friction depends on the fabric structure and material density. The actual contact area is far less than the apparent contact area between the fabric and its counterpart. Therefore, wear is firstly occurred on its outer layer of the fiber buckling peak protruding from the surface of the fabric, and then is gradually extended into interior. In fact, under such a high load (more than 90 MPa) the wave of fabric is not obvious, as shown in Fig. 8. The fibers tend to disperse uniformly under the action of load.

Because the fiber reinforced composite is mainly damaged by fatigue wear during long time friction, local high load of the friction surface has no direct effect on material wear under the normal lubrication. It is due to damage of the transfer film from contact surface, and then the reinforced fibers are exposed to be directly contact and abraded with the metal influencing tribological behavior of the material on this region. Figure 9 shows fatigue wear of the broken fiber. Normally due to self-healing mechanism of the transfer film, the exposed fibers are quickly supplemented by surrounding polytetrafluoroethylene fibers, maintaining the region in a better lubrication state. Only when the transfer film can not be formed in time or there is not enough fibers supplemented after serious wear, the fiber will be directly worn. Comparing to load, the change of frequency has a more obvious effect on the transfer film. Fatigue fracture will be occurred on the exposed fibers due to mechanical shear action under high frequency. Figure 10 shows the unworn fibers under normal condition. Figure 11 shows the fibers cut directly without friction test. The worn surface shown in Fig. 12 is obtained after 1200 oscillating friction cycles at 90 MPa and 7.5 Hz. The shear fracture of fibers can be seen clearly in the figure, which is similar to the fracture morphology in Fig. 11.

Fig. 13(a) shows the morphology of the worn surface of the composite after 1200 oscillating cycles at 90 MPa and 7.5 Hz, and the contour curve along the black mark is shown in Fig. 13(b). It is noted that there are many wear pits on the surface of the worn material, and the internal fibers are exposed, and some fatigue fracture have occurred. These are the parts where the lubrication layer are damaged during the friction. Compared with Fig. 7, it can be seen from Fig. 13 that the smoothness of the material surface with good lubrication state is better than that in the initial state. At 90 MPa, 100 MPa and 110 MPa, there are three wear modes in the Nomex fiber reinforced composite. Firstly, the resin and PTFE fiber coated on the surface of material undergo adhesive wear under local high temperature during dry friction. Secondly, fatigue fracture has been occurred because the PTFE and Nomex fiber suffered mechanical shear force, as shown in Fig. 12. Thirdly, the micro convex peaks of the counterpart undergo fatigue wear at the instant high temperature of the friction surface, and thus some metal particles are formed. These particles exist in the friction interface to cause abrasive wear, as shown in Fig. 14.

3.2 Effect of friction temperature on wear loss

Fig. 15 presents the change of wear loss when the environment temperature is 20 °C and 75 °C . Environment temperature has an obvious effect on the material life. The wear life reaches 180 h at 20 °C, while it is only 70 h at 75 °C. Figs. 16 and 17 show the friction coefficient and friction temperature at 20 °C and 75 °C, respectively. At 20 °C, the highest friction temperature is 129 °C and the friction coefficient is relatively stable. Whereas the maximum of friction temperature at the environment temperature of 75 °C reaches 210 °C, and the friction coefficient fluctuates sharply and is extremely unstable. It is indicated that the self-lubricating behavior of the material and its service life decay rapidly under high environment temperature.

The failure mode of fiber reinforced composite at high friction temperature can be explained as follows. Friction heat causes the lubrication layer and transfer film on the material surface to become unstable, easily be destroyed. In Fig. 18, local material is peeled off and some reinforced fibers are exposed. Under the high temperature of the friction surface, the strength and wear resistance of material have been reduced, and shear fracture and thermal fatigue wear are easily to occur when the composite directly contacts with its counterpart, as shown in Fig. 19. When wear increases, the self-lubricating effect further reduces, and the fluctuation of the friction coefficient is increased and the friction temperature further rises. High temperature reacts on the material and wear loss increases. In practice, this effect could lead to an excessive fit clearance of spherical plain bearing, the increased impact force and the local high load. These all lead to a decrease in the lubrication performance and aggravation of the wear.

Wear debris generated during friction are analyzed as follows. The transfer film are mainly consumed by being squeezed out from material. After that the region is supplemented by the matrix, with the transfer film being in a dynamic stability. When the specimen is worn to be with a certain thickness, the remaining material is not enough to supplement the consumption, and it will be worn out. Seen from Fig. 19, the high environment temperature leads to the high friction temperature, and thus breaks the dynamic balance of self-lubrication layers and aggravates the material damage.

Through the analysis of the whole life test, it is concluded that the friction heat plays a leading role in the process of wear out failure. High friction temperature greatly weakens the friction and wear performance of the material, resulting in a failure of the material in a short time. The residual thickness of specimen worn under high friction temperature is larger than that at low temperature. This is the local wear failure.

Conclusions

(1) Effects of load and frequency on the tribological properties and wear life of the Nomex/PTFE fiber reinforced composite are nonlinear. Under different load and frequency range, the tribological properties and wear life of the material are significantly different. This is helpful for the selection of self-lubricating materials under different working conditions.

(2) Environment temperature has an significant influence on the self-lubrication property of the material. Higher environment temperature causes the friction temperature of the contact surface rising sharply, and weakens mechanical properties and self-lubricating properties of the material, leading to a local worn out and a great reduction of its service life.

(3) The key to improve the thermal stability and thermal damage resistance of the composite is to select the reinforced fiber with high thermal stability and additives with better thermal conductivity.

Declarations

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Availability of data and materials

The datasets supporting the conclusions of this article are included within the article.

Authors' contributions

JL was in charge of the whole research; FL translate the manuscript; TH and XP discussed and read the manuscript; YZ assisted with sampling and laboratory analyses. All

Competing interests

The authors declare no competing financial interests.

Consent for publication

Not applicable

Ethics approval and consent to participate

Not applicable

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Figures

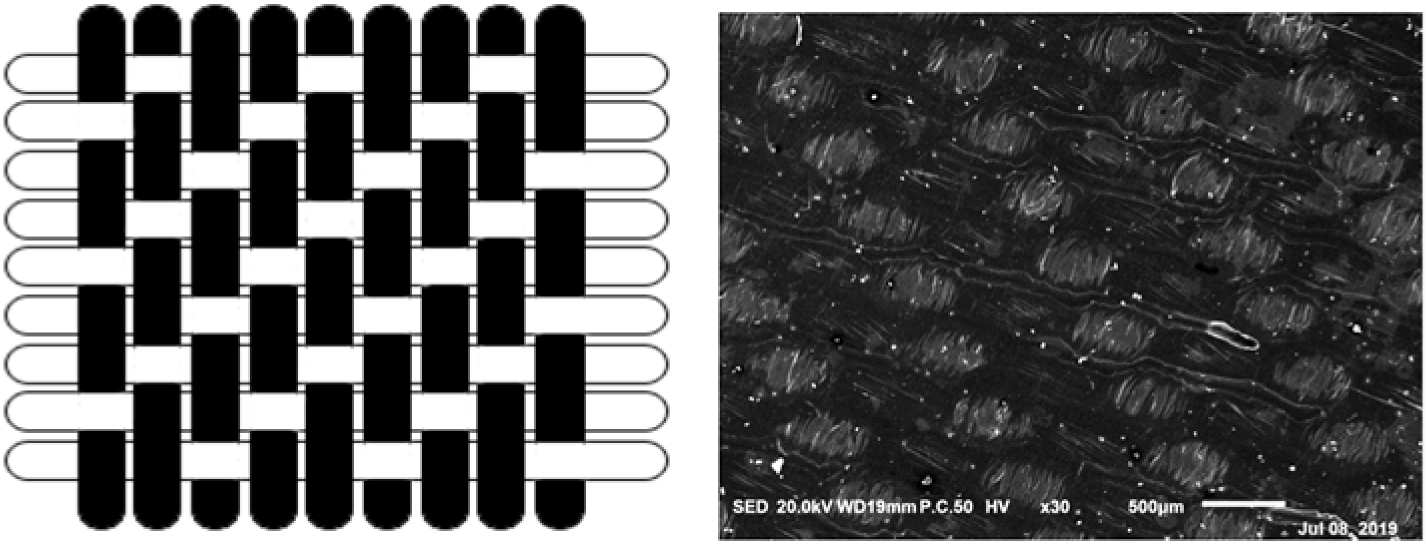


Figure 1

Structure and surface of the self-lubricating composite

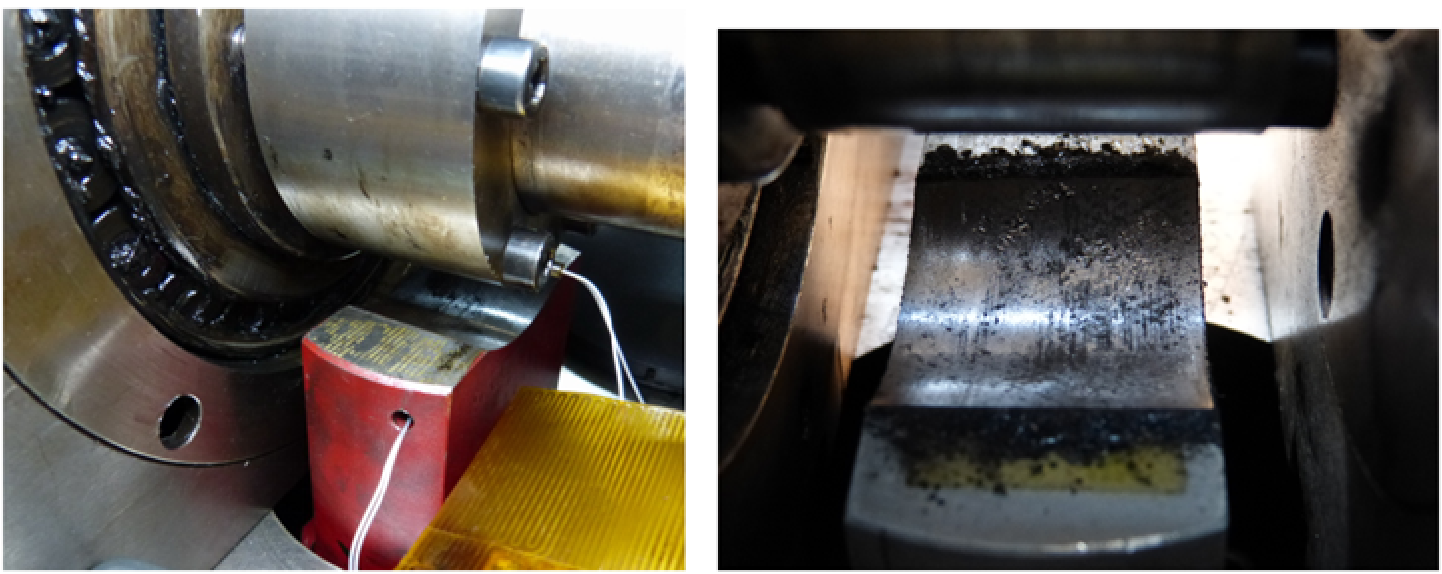


Figure 2

Schematic of friction pair

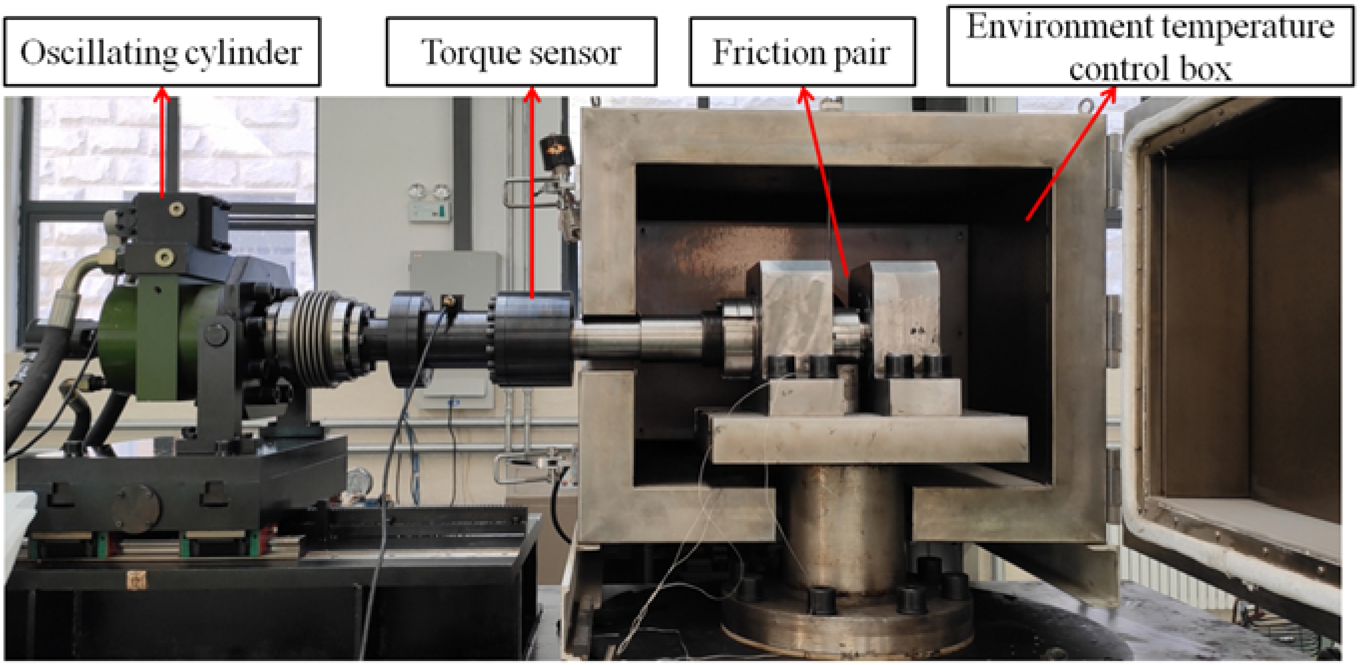


Figure 3

Tribological tester

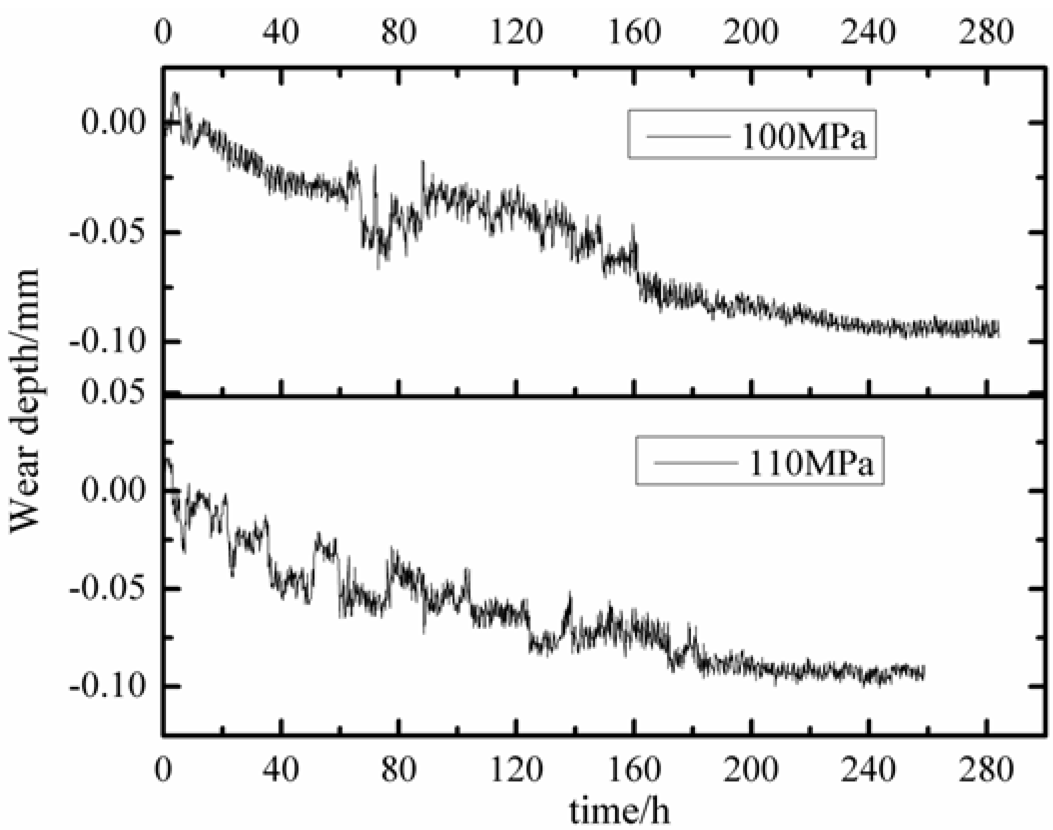


Figure 4

Wear depth as function of running time under 100 MPa and 110 MPa

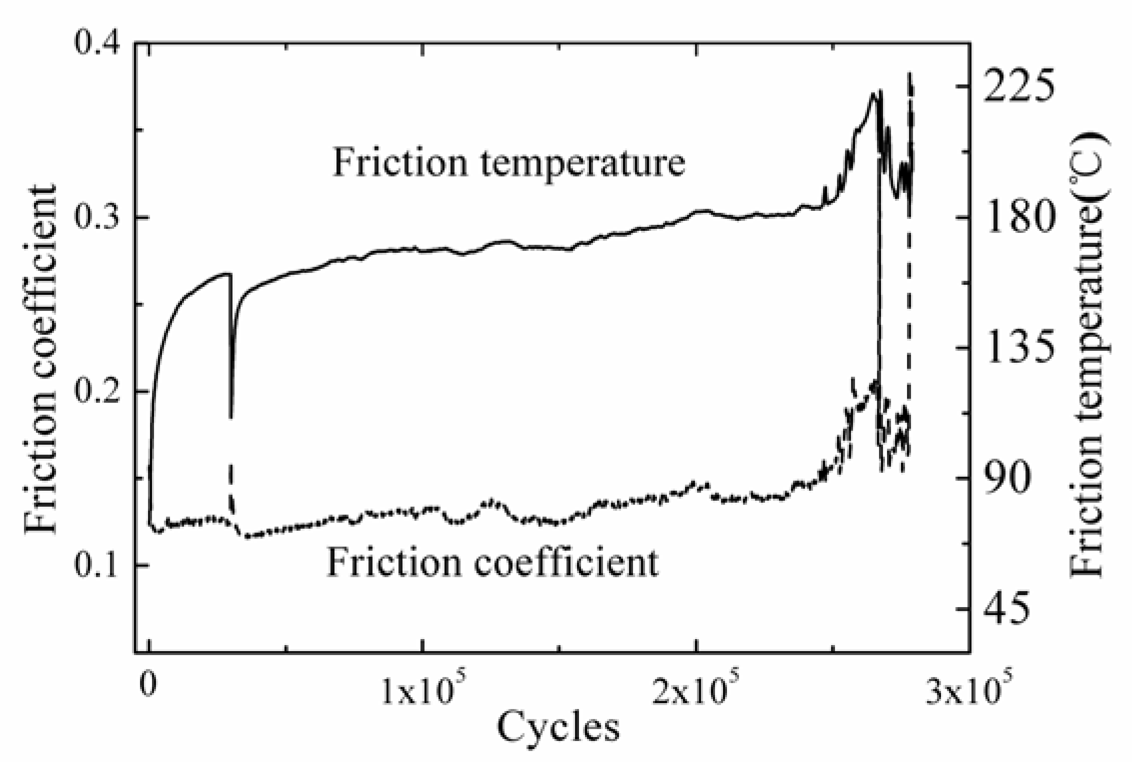


Figure 5

Changes in friction coefficient and friction temperature as function of running time

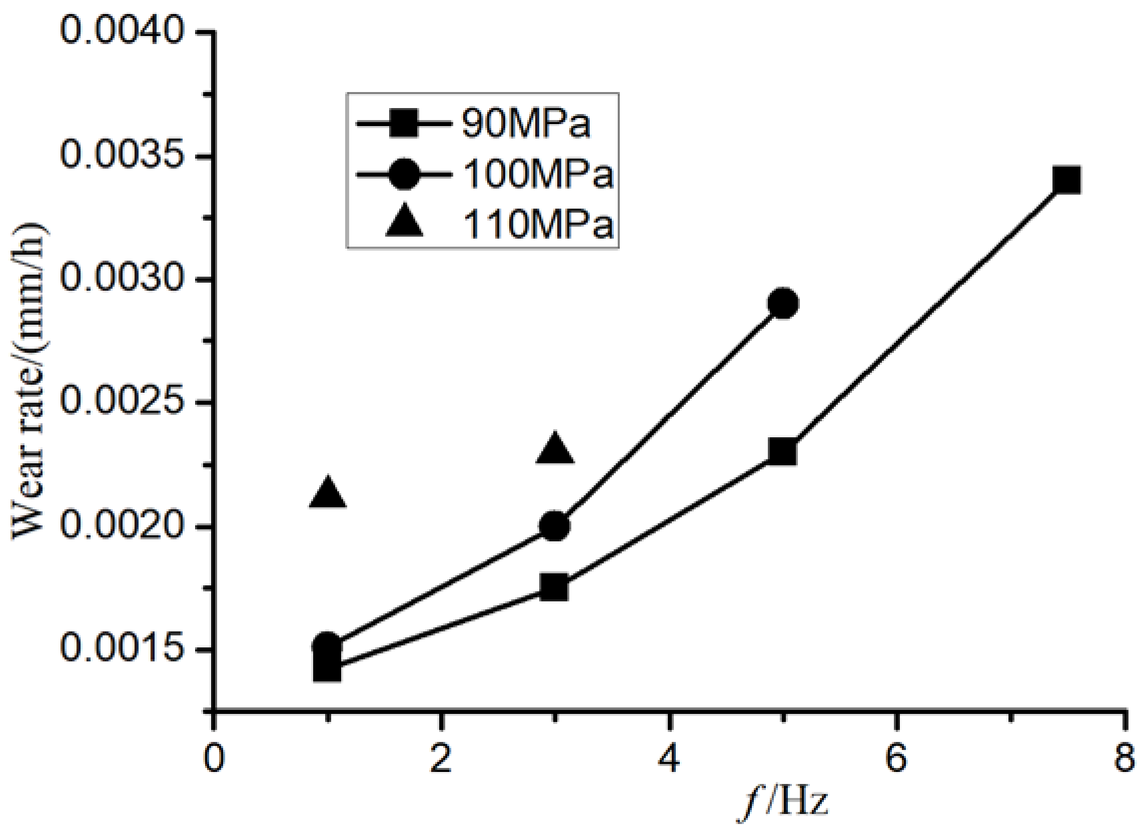


Figure 6

Change of wear rate with varying frequency at 90 MPa, 100 MPa and 110 MPa

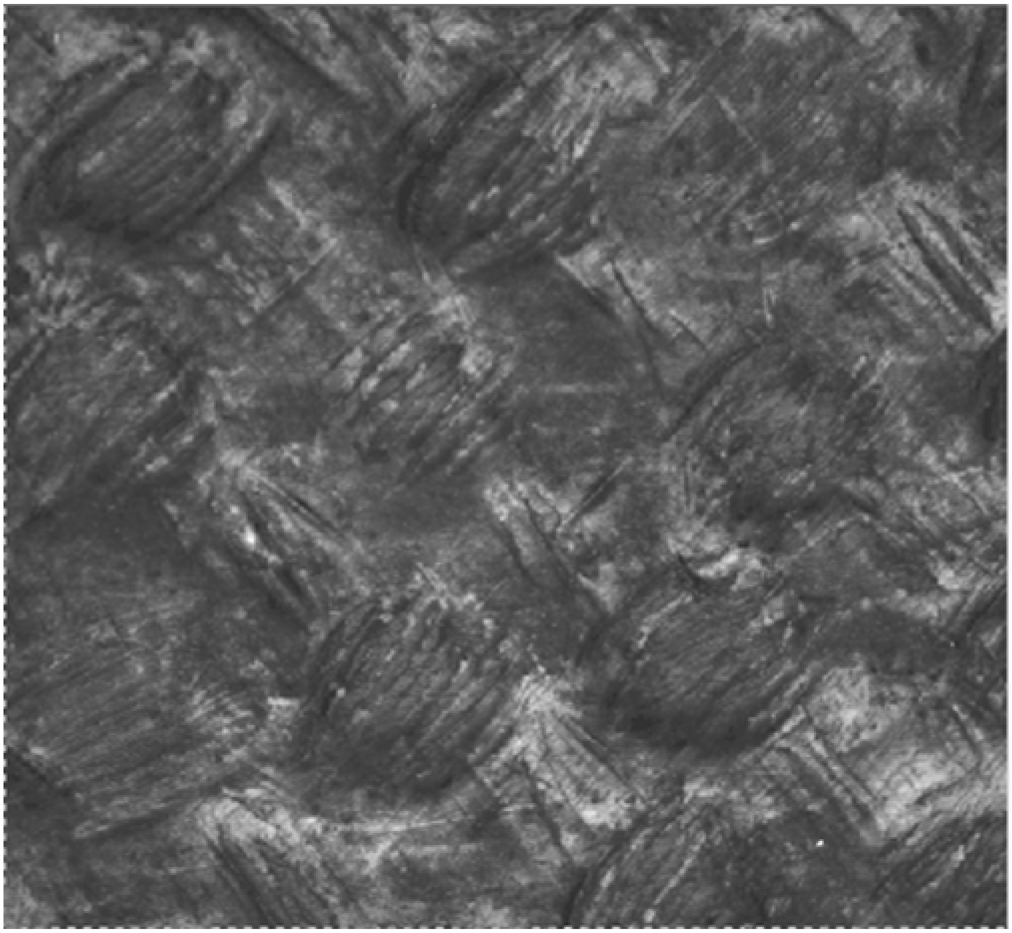


Figure 7

Initial surface topography of the Nomex/PTFE fiber reinforced composite

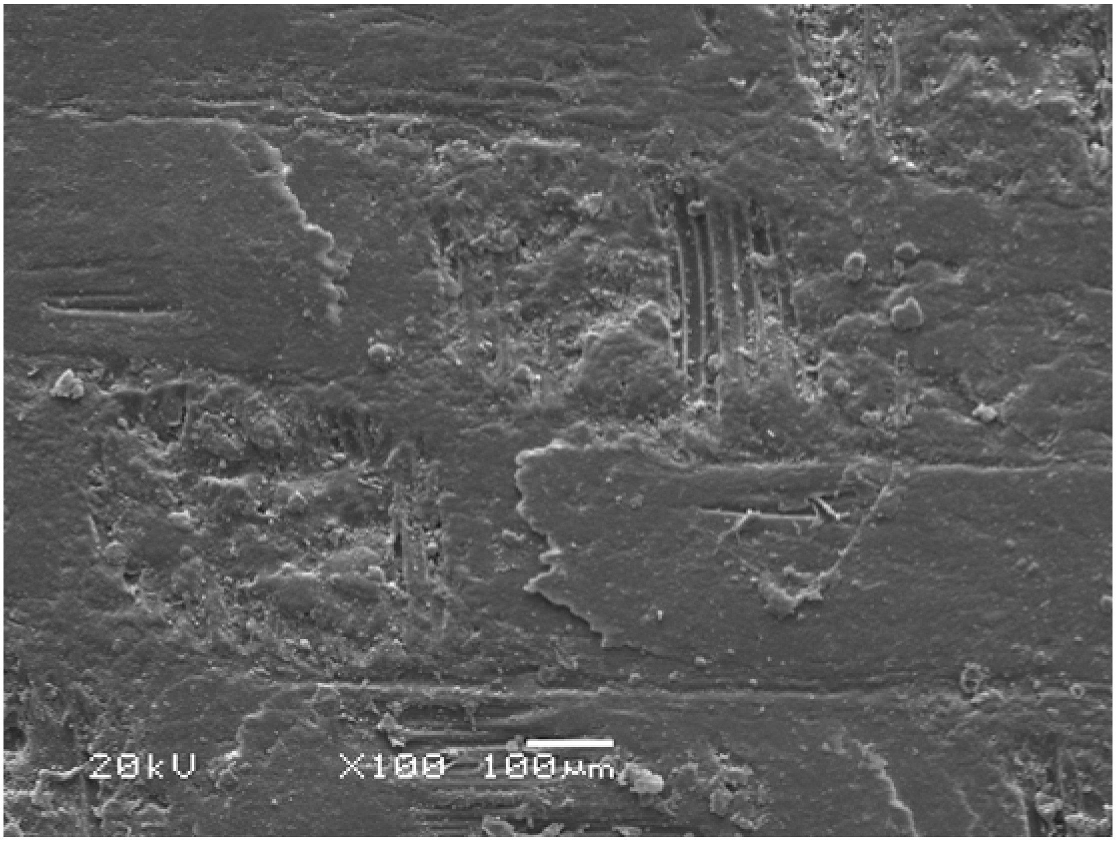


Figure 8

Wear surface of the Nomex/PTFE fiber reinforced composite

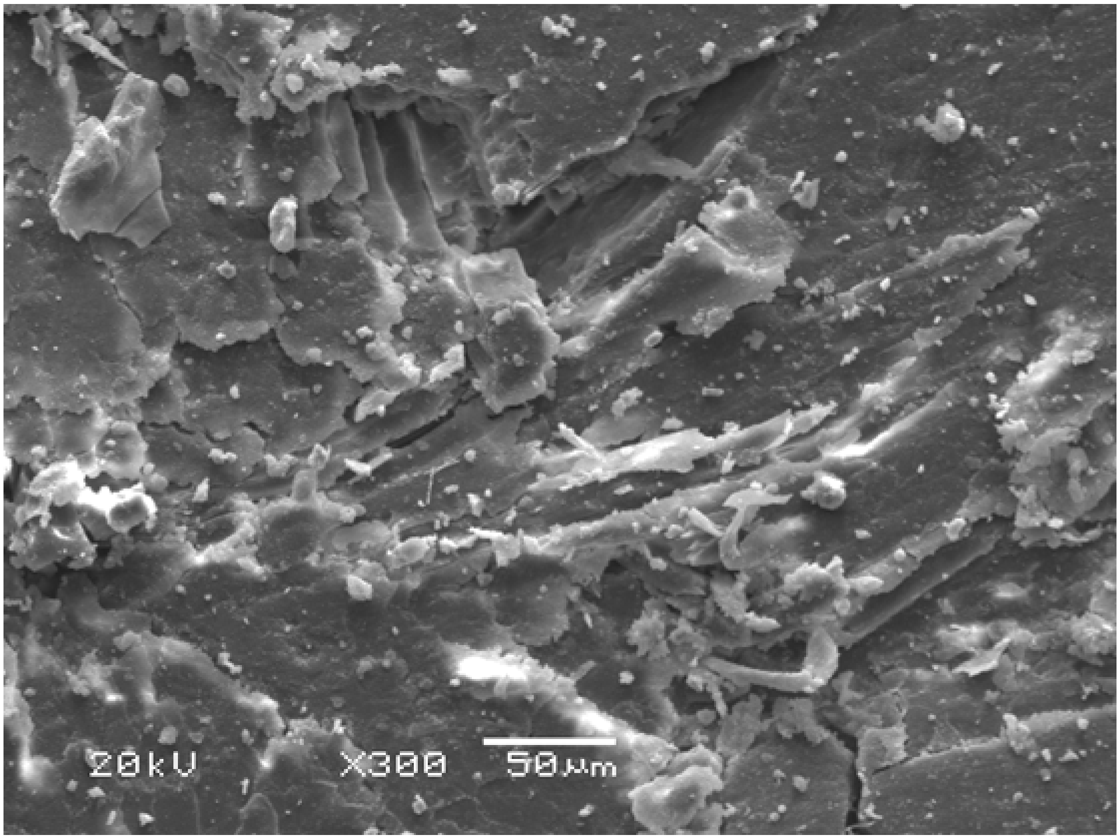


Figure 9

Fatigue wear under normal lubrication state

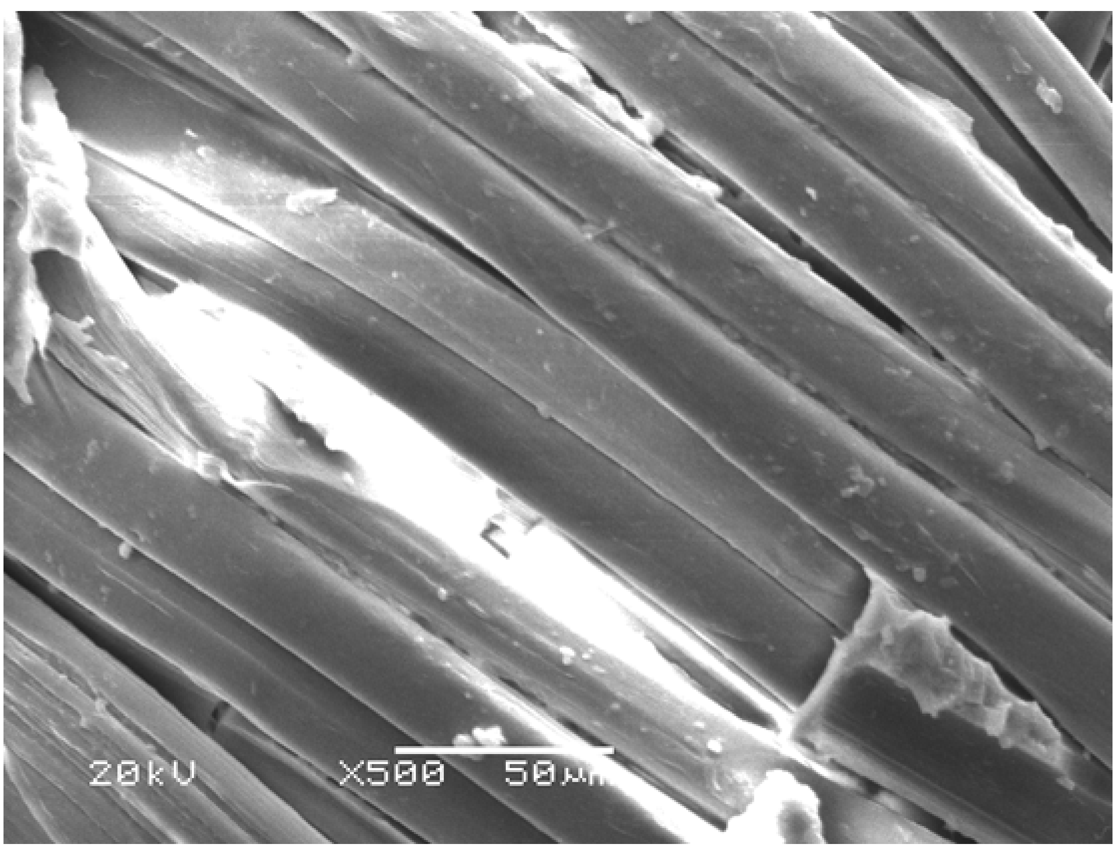


Figure 10

Initial morphology of fibers

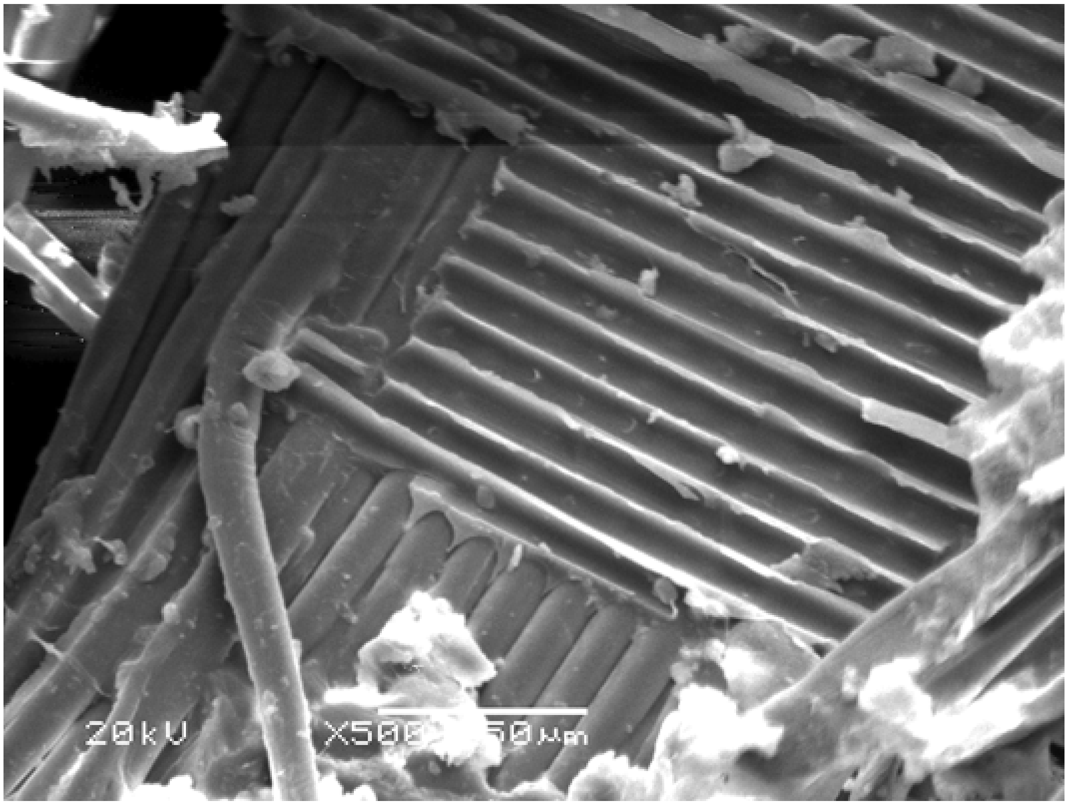


Figure 11

Morphology of fibers being cut

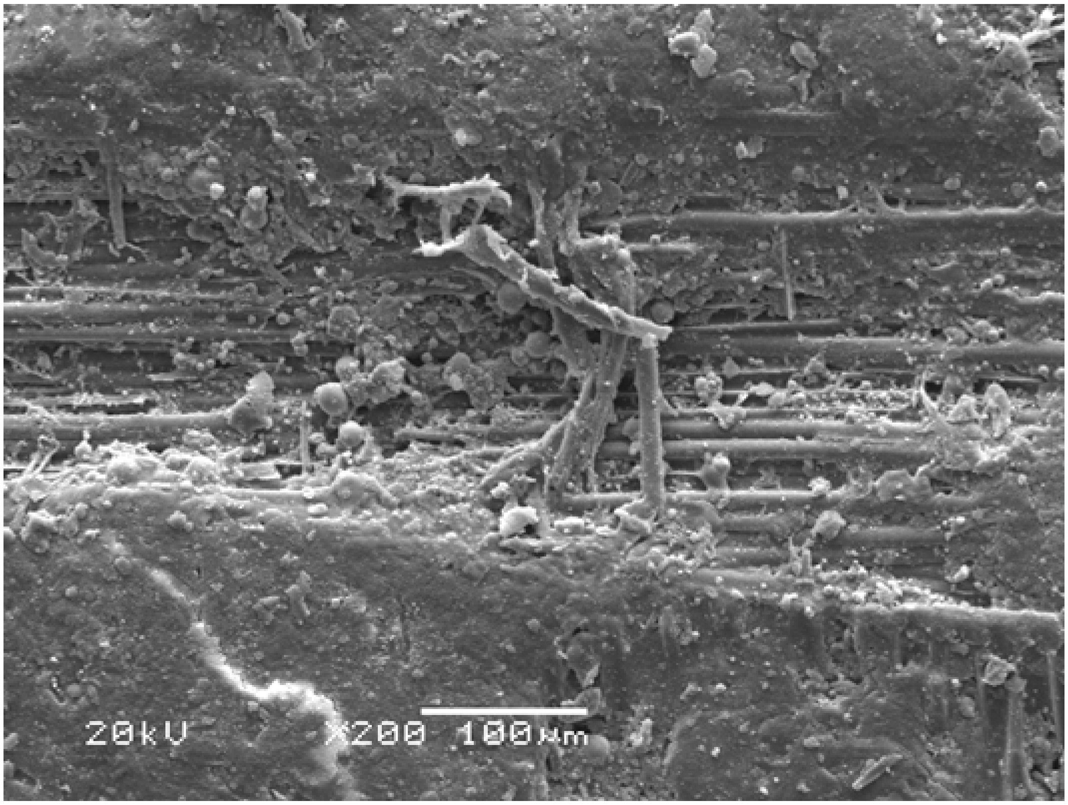
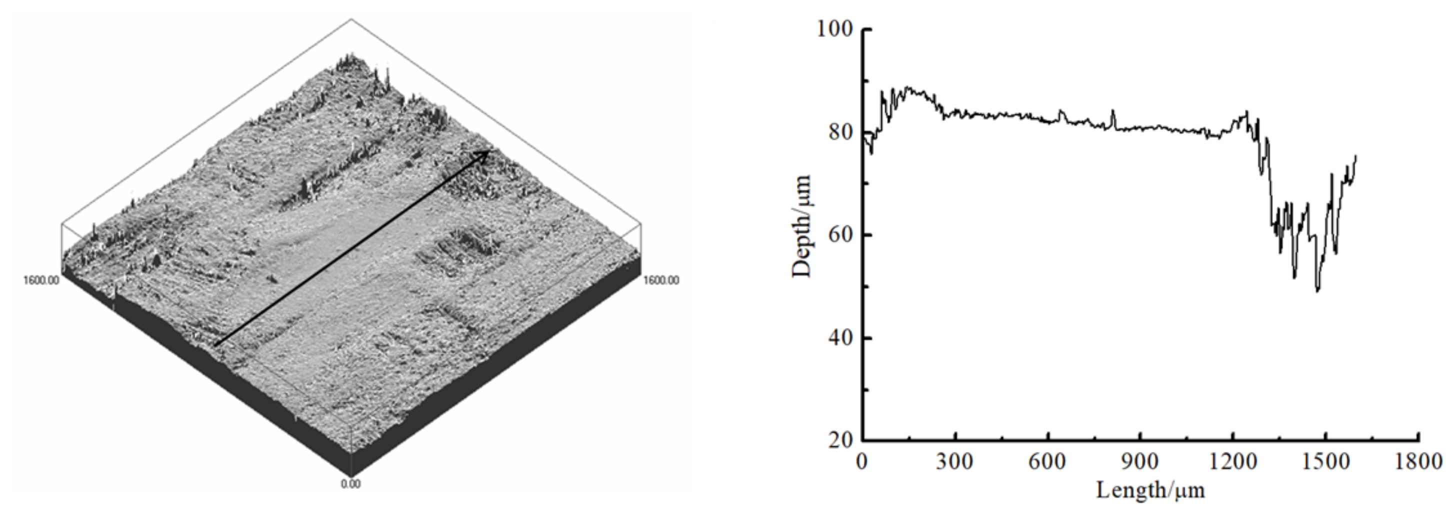


Figure 12

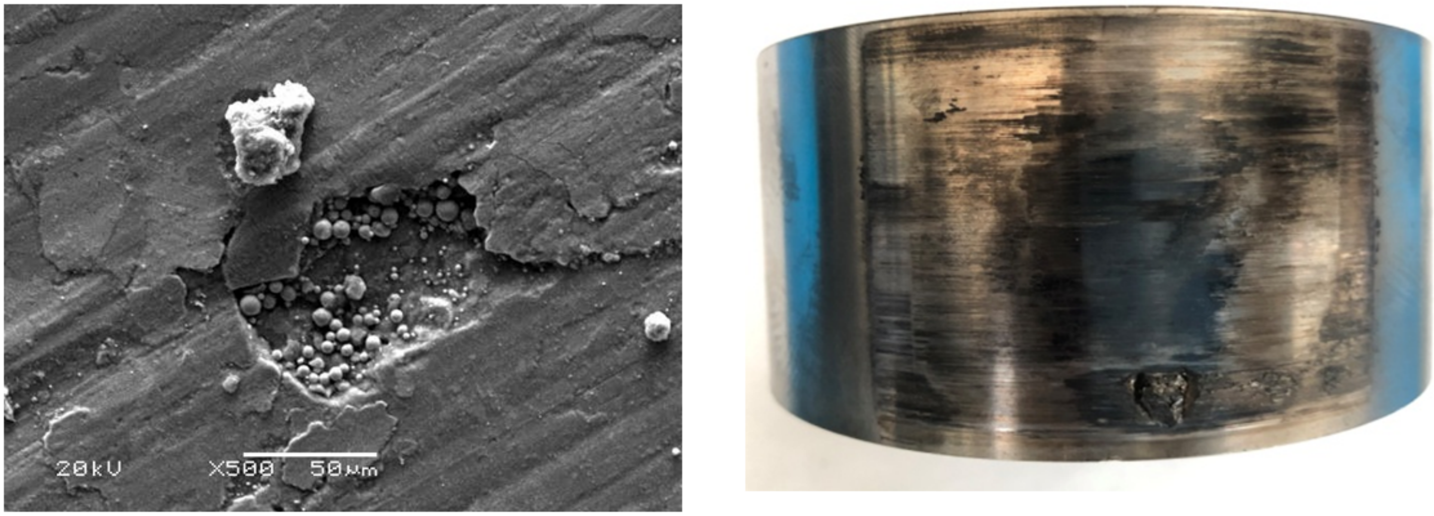
SEM of wear surface under high frequency



(a) Surface morphology (b) Contour profile

Figure 13

Surface topography and contour profile of wear surface



(a) Surface of the composite

(b) Surface of the counterpart

Figure 14

Surface of composite and its counterpart after material wear failure

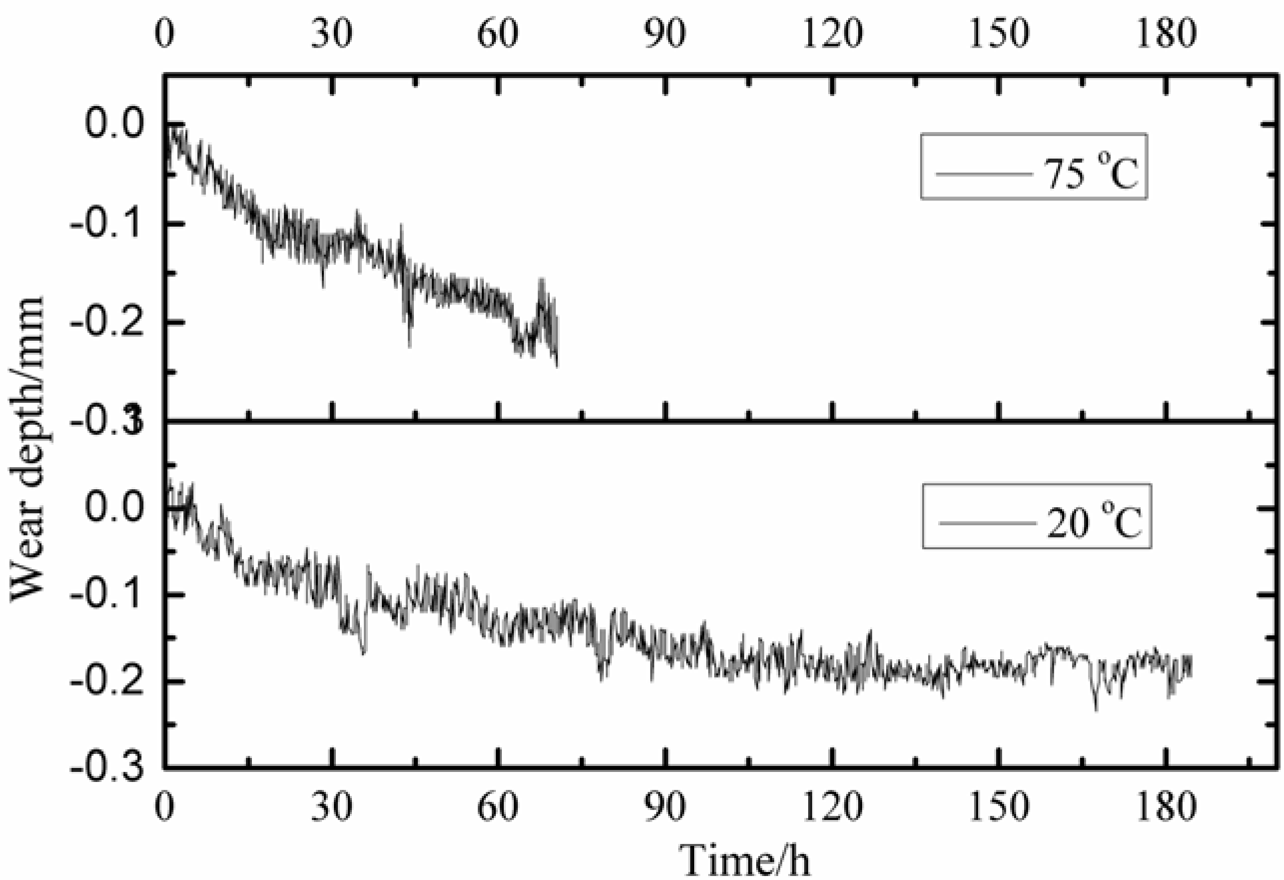


Figure 15

Comparison of wear loss under two environment temperatures

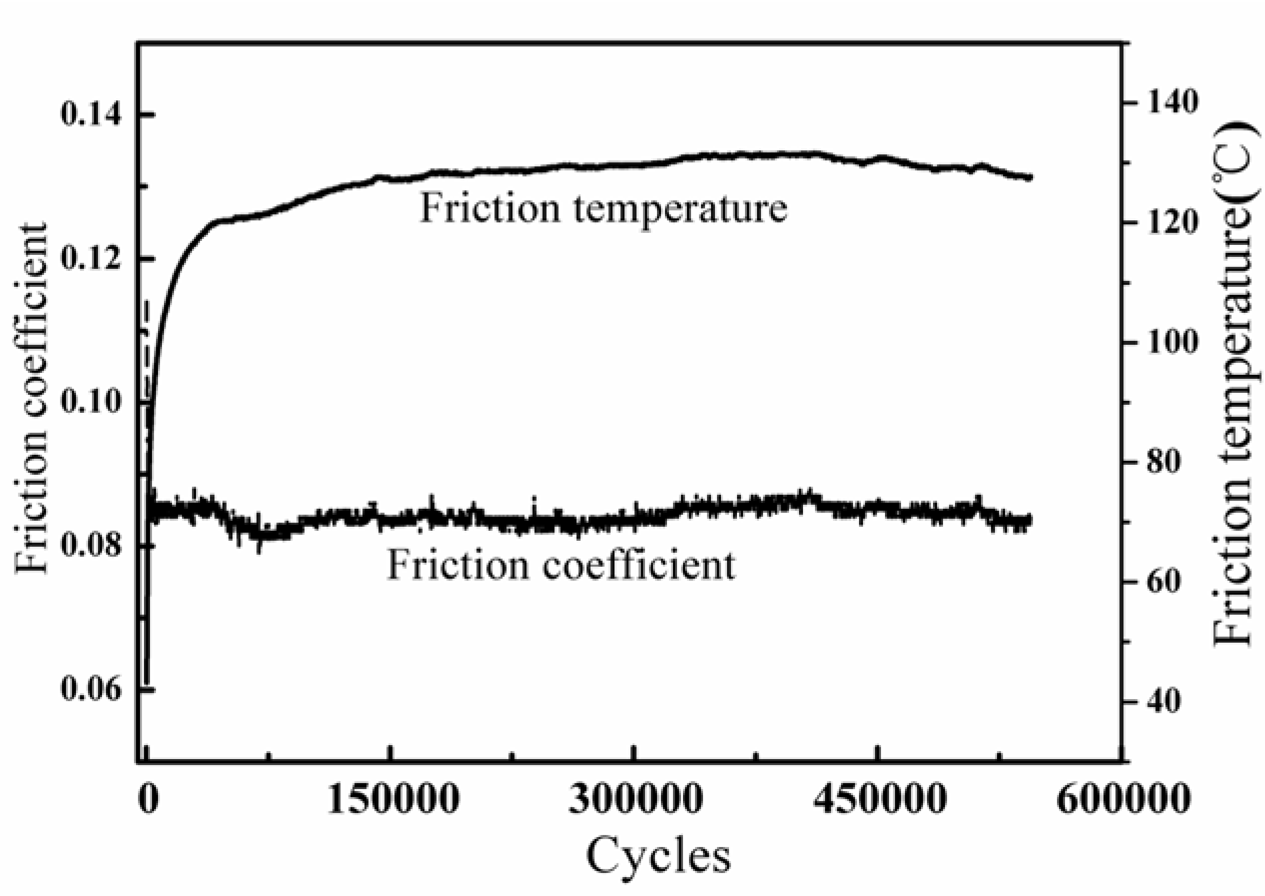


Figure 16

Change of friction coefficient and friction temperature at 20 °C

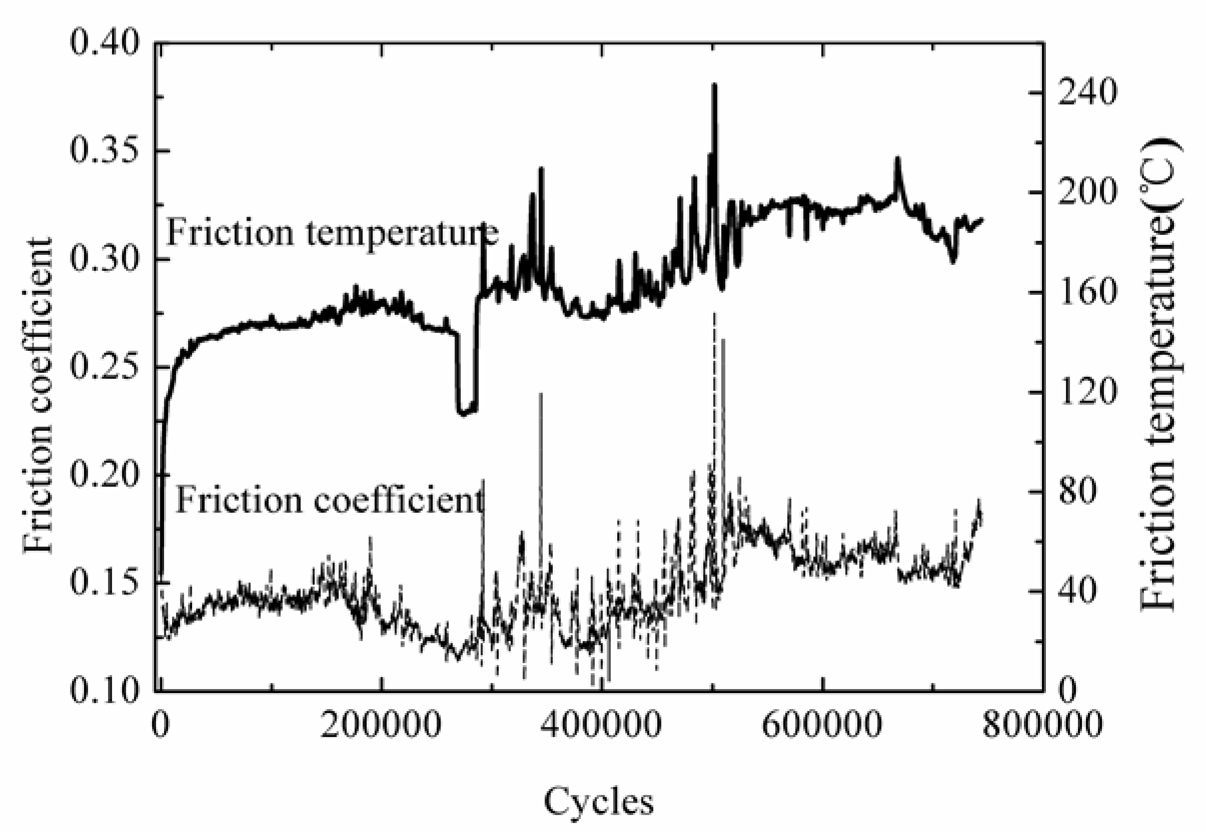


Figure 17

Change of friction coefficient and friction temperature at 75 °C

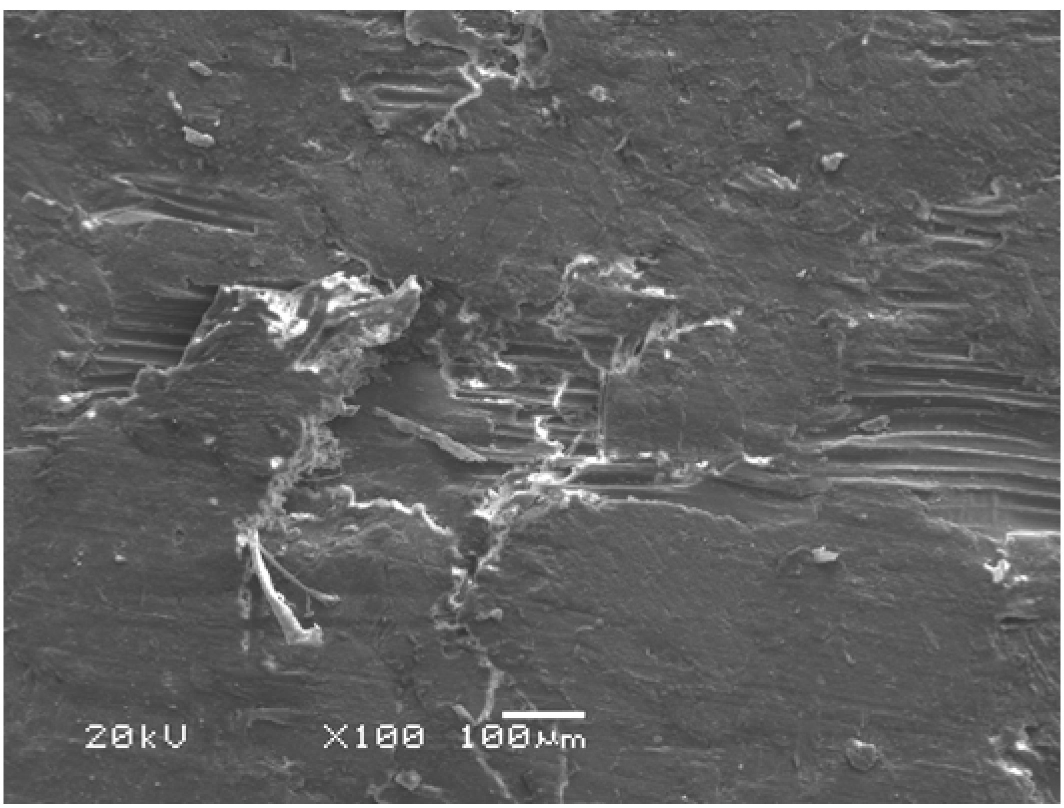


Figure 18

SEM image of worn surface

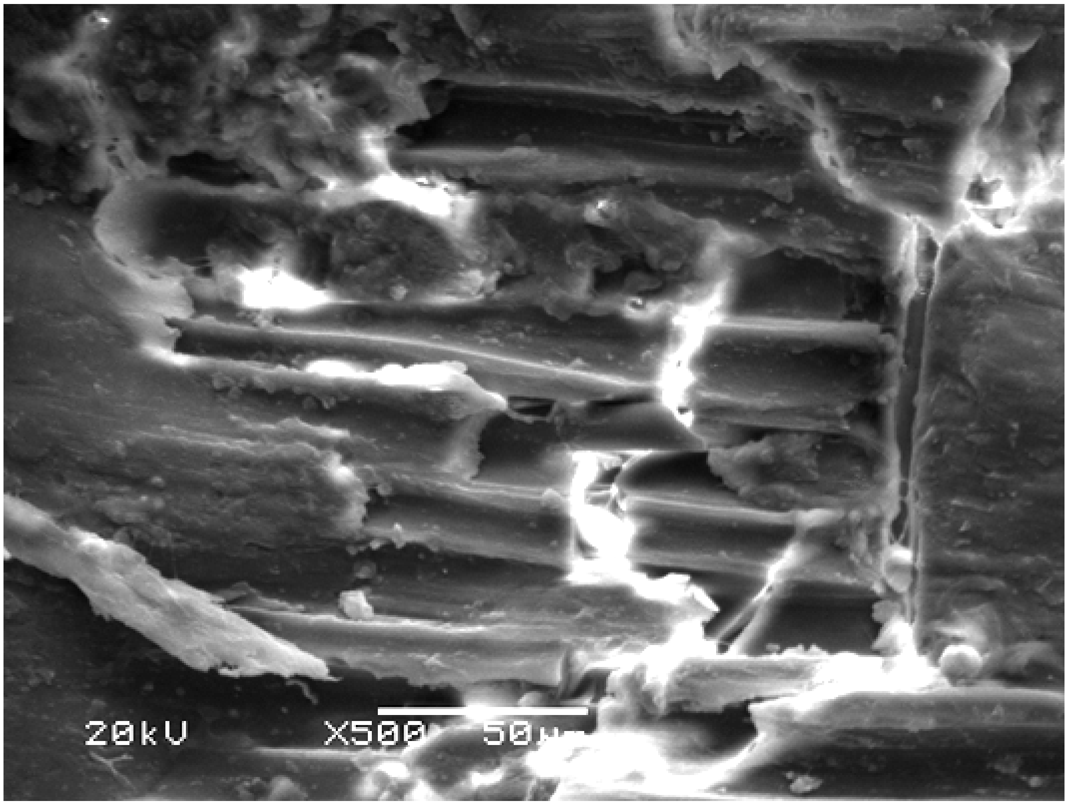


Figure 19

Thermal fatigue wear