Study of Fretting Wear Behaviors of FEP

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ABSTRACT: The fretting wear behaviors of perfluorinated ethylene–propylene copolymer (FEP) were studied on an SRV fretting wear tester with the plane contact of FEP against a bearing steel at room temperature of about 15°C. In our tests, the product of load (L) and total sliding distance (S) was preset to be a constant as the wear coefficient K_ω can be expressed as $K_\omega = W \cdot P_m/(L \cdot S)$, where W is the volume of material loss, P_m is the flow pressure of the softer material (FEP), L and S are the load and the total sliding distance, respectively. Under our test conditions, no wear of the bearing steel was observed when fretted against FEP. The sudden change of wear rate of FEP or its wear weight was governed by the critical *PV* value, an important parameter for polymers and polymer composites under sliding friction, which was the product of normal stress and average sliding speed. The critical *PV* value of FEP under study was 3×10^4 Pa·m/s. It was also found that the topography of wear trace formed on FEP were fairly well corresponding with that of their transferred films on steel surface. Both on worn surface of FEP and on metal surface, three sharply defined regions, wear debris formation region, high-stress region, and slightly sliding wear region, can be distinguished. It indicated that the higher the normal stress, the more difficult the formation of thick transfer film. © 1998 John Wiley & Sons, Inc. J Appl Polym Sci **67:** 1119–1125, 1998

Key words: fretting; FEP (perfluorinated ethylene–propylene copolymer); plane contact; wear coefficient; tribological behavior

INTRODUCTION

In tribology the term "fretting" is used to refer to any contact situation where two surfaces in mechanical contact are subjected to low-amplitude oscillatory displacements. It has long been recognized that the fretting type of contact must be distinguished from the case of reciprocating sliding at higher displacement amplitudes.[1,2] An important difference between fretting and sliding wear is the fact that both wear partners have an overlap ratio near or equal to 1 and, consequently, wear particles often cannot escape easily from the tribo contact.[3] It may be true for metallic contact. For polymers, as their pliability, they are easily extruded out of the contacting region at high load even at very small amplitude.[4] Thus, it is more difficult to distinguished the fretting from the case of reciprocating sliding of polymers. It may be the reason that less investigating works on the fretting wear behaviors of polymers have been systematically done comparing with that on metals. Thus, the term "fretting" for polymers must be judged in different criterion.

The factors that affect the fretting corrosion of vibrating metal surfaces in contact have been investigated for many years. Many attempts have been made to reduce or to eliminate fretting between surfaces by the use of lubricants, metal coatings, and polymers, with varying success.[5] Polymer and its composites are an important cate-

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Table I Some Properties of FEP Used

Content of C_3F_6	> 14%
Density	2.15 g/cm^3
Compression strength	15 MPa
Tensile strength	> 23 MPa
Elongation	> 300%
T_m	278 ± 5°C
T_g	130°C
Heat capacity	1.2 kJ/Kg·K
Thermal conductivity	0.21 W/m·K

gory of tribomaterials, and have been widely used in basic and applied tribology. Many polymers and polymer composites,[5–9] such as low- and high-density polyethylene (LDPE, HDPE), polyimide (PI), polyvinyl chloride (PVC), polysulfone (PSF), and Polytetraflouroethylene (PTFE) have been used to reduce fretting wear. PTFE as a most widely used tribomaterial possesses the characteristics of a low-friction coefficient, good ductility, and high thermal stability. Unfortunately, because of its cold flowing phenomenon, the PTFE must be mixed with the inorganic or organic filler to prepare PTFE-based composites, blends, or modified by chemical method for its tribological application. Perfluorinated ethylene–propylene copolymer (FEP) is the copolymer of PTFE with hexafluoropropylene. It possesses not only tribological properties similar with PTFE, but also the easily machined and higher hardness behaviors, and it has been used to replace PTFE in many situations. In this article, the fretting wear behaviors of FEP were investigated with the plane contact in the range of low contacting stress (below 4.5 MPa).

EXPERIMENTAL

The FEP used in this work was commercial fine powder with a grit size of 1–5 μm. Some properties of the material are listed in Table I. The specimens of FEP were directly formed to plates with a diameter of 13 mm and a thickness of 7.8 mm by heat compression molding without further machining. The wear behaviors of FEP were measured on an SRV oscillating wear tester with the plane contact of a bigger cylinder (metal) end to the smaller cylinder (FEP) end. Because of the pliability of polymers, the plane contact wear type can be used, particularly at higher load. The apparatus (Fig. 1) has a stationary lower specimen holder that contains the FEP cylinder with a diameter of 13 mm. The upper metallic (SAE 52100) cylinder with a diameter of 24 mm is held in place on an oscillating holder. All the friction tests were carried out at temperature of 15°C. Because of the reason of easily deformation under load, the measurement on wear volume is no longer true for polymers. Thus, in this article, the wear behaviors of FEP were evaluated by means of comparing the samples' wear weight. A sensitive balance with sensitivity higher than 0.00001 g was used in our study. In our tests, the product of the load (L) and the total sliding distance (S) was preset to be a constant considering the wear coefficient K_ω is an important parameter to define the wear degrade, which can be expressed as $K_\omega = W \cdot P_m/(L \cdot S)$, where W is the volume of material loss, P_m is the flow pressure of the softer material, L and S are load and total sliding distance, respectively. In our study, the value of $L \cdot S$ was preset to be 10^4 N·m. Before and after friction test, each specimen was carefully cleaned by supersonic cleaner and weighed.

RESULTS

Figure 2 shows the wear loss and wear rate of FEP calculated from the wear loss as functions of test duration (fretting cycles) under the test conditions of load 200 N, amplitude (actually the stroke) 50 μm, frequency 100 Hz. After the running-in stage, about 2×10^5 cycles (sliding distance 20 m), the wear weight of FEP increases linearly with the increasing of fretting cycles. While in the running-in stage, the wear weight increases sharply. The wear rate also sharply in-

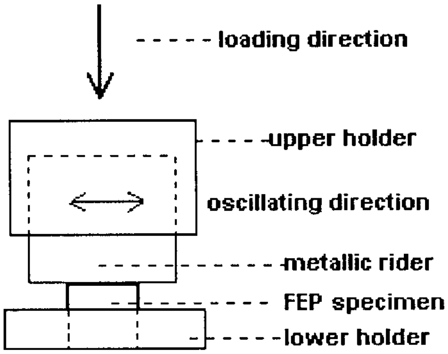


Figure 1 Schematic of oscillatory plane contact rig, where the couples are always keeping closed contact.

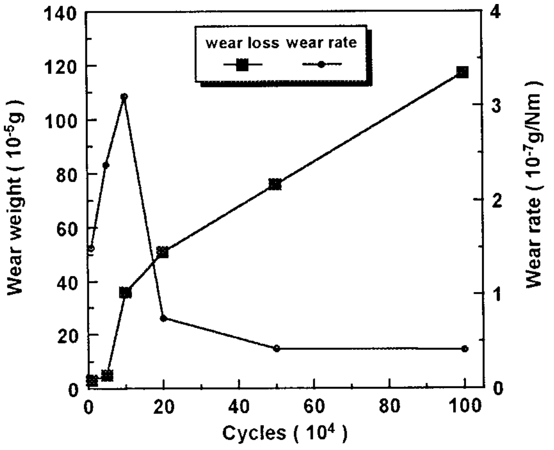


Figure 2 The wear loss and corresponding wear rate of FEP as a function of fretting cycles.

creases in the running-in stage and sharply decreases after the stage. But in the steadily increasing stage of wear weight, the wear rate of FEP changes smoothly in the range of fretting cycles from 2×10^5 to 1×10^6, and it is almost a horizontal line in Figure 2.

In this article, the product of load and distance was fixed to be 10^4 N·m. Thus, the wear weight measured is linearly related to the wear rate, and no difference between the two except a coefficient. To understand the correspondence between wear modes, fretting wear or sliding (reciprocating wear), and amplitudes, the tribological behavior of FEP as the function of amplitude under wear conditions of load 200 N, frequency 100 Hz, and the test duration calculated to be 50 m, was investigated and shown in Figure 3. It can be seen that the wear loss changes in three stages with the increasing amplitude, at first the wear loss of FEP increases smoothly at the lower stage in amplitude range of 20 to 70 μm, then a sudden increasing is observed at amplitude of about 90 μm, and at last the wear loss increases smoothly again but at the higher stage. Although both wear partners have an overlap ratio near or equal to 1, wear particles of FEP can escape easily from the tribo contact at higher amplitude. Thus, the wear type under study at higher amplitude more than 90 μm should be considered to be "oscillating or reciprocating wear." The friction curve shown in Figure 3 also supports the view. There is a sudden decrease of friction coefficient at amplitude of about 90 μm. It is because that the kinetic (sliding) friction coefficient is usually lower than static (fretting) friction coefficient. The critical amplitude under above test conditions can be obtained to be about 90 μm. This not the case for metals and ceramics[3]; it seems that the feasibility of debris escaping from the contact surface region is more important than the overlapping ratio of partners. From Figure 3 it can be concluded that the term "fretting" has relation with the maximum amplitude, below which the real fretting may be obtained. It is also found that the critical amplitude changes with the variation of load and frequency.

Figure 4 shows the relations of tribological behaviors of FEP and test load under wear conditions of frequency of 100 Hz, and amplitude of 50 and 150 μm, respectively. At a lower amplitude of 50 μm the wear weight of FEP sharply increases at about the point of load 400 N, but at a higher amplitude of 150 μm the sudden increasing of wear weight is observed at a load about 200 N. When the testing load lower than the limited load, the debris of FEP is difficult to be extruded out of the contact surfaces. The test results indicate that the lower the amplitude, the higher the critical load. The friction coefficient of FEP is usually getting lower and lower with the increase of load, just as shown in Figure 4.

Figure 5 shows the wear loss and friction coefficient of FEP as functions of frequency in the range from 10 to 150 Hz under wear conditions of load 200 N, amplitude 50, 100, and 200 μm, respectively. It can be seen that the wear weight of FEP increases slightly with the increasing of frequency at amplitude of 50 μm under study. But there exist critical frequencies for fretting wear with amplitude of 100 and 200 μm, respectively. It is interesting to notice that the product of amplitude 100 μm and the corresponding critical fre-

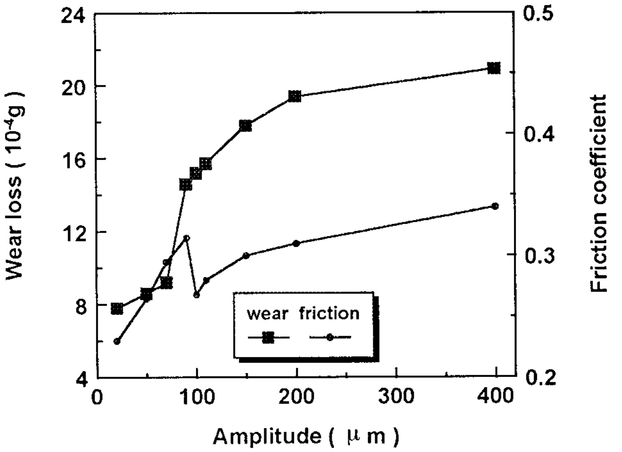


Figure 3 The wear behaviors of FEP as a function of amplitude.

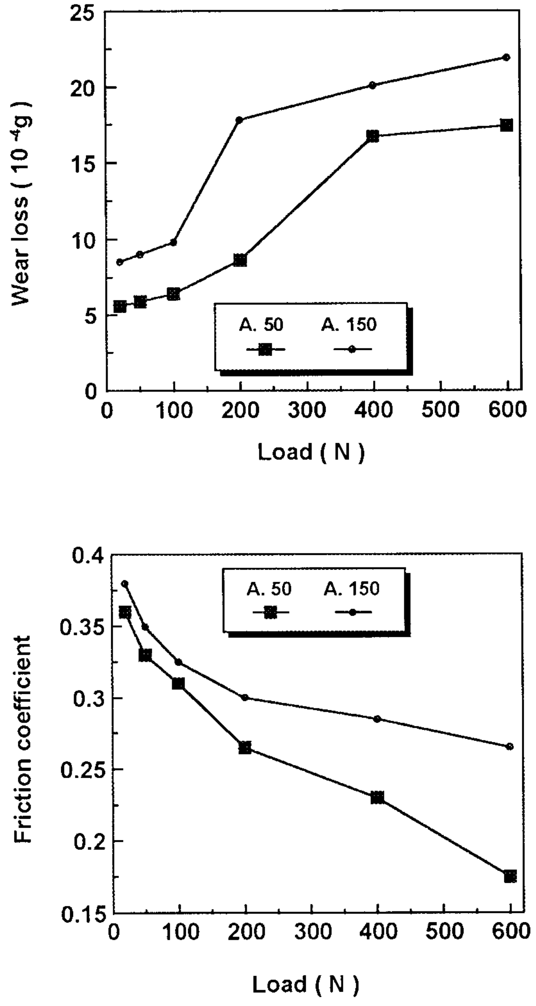


Figure 4 The wear behaviors of FEP as a function of load at amplitude of 50 and 150 μm, respectively.

quency 100 Hz is 10 mm·Hz and equal to the product of amplitude 200 μm and its corresponding critical frequency 50 Hz. While at the amplitude of 50 μm, the maximum product of amplitude and frequency is below the critical product 10 mm · Hz. As it is known, the average sliding velocity is linearly related with the product of amplitude and frequency. Under the test conditions in this article, the increasing of frequency means the increasing of the average sliding velocity. Thus, above phenomena indicate there exists a critical velocity under certain fretting wear conditions. From the friction curves shown in Figure 5, it is also found that at high frequency the friction coefficient of FEP increases along with the increasing of amplitude, but at low frequency the friction coefficient changes inversely. The tribological behaviors of FEP varying with frequency may be due to the compliance of the FEP specimen. Due to the compliance of the FEP specimen, the sliding amplitude can therefore be significantly lower than the imposed stroke, and the lower the frequency the smaller the real sliding amplitude at the contact interface. In fact, the wear modes studied will involve the transition from fretting to sliding wear with the increase of frequency. So, the increasing of wear weight and relatively decreasing of friction coefficient at high frequency can be observed.

As the product of frequency and amplitude represents the average sliding velocity, which can be expressed as: V = 2 × Am × Fr (V is velocity, Am amplitude, and Fr the frequency), the influencing of amplitude together with frequency on the wear behaviors of FEP at a certain load was investi-

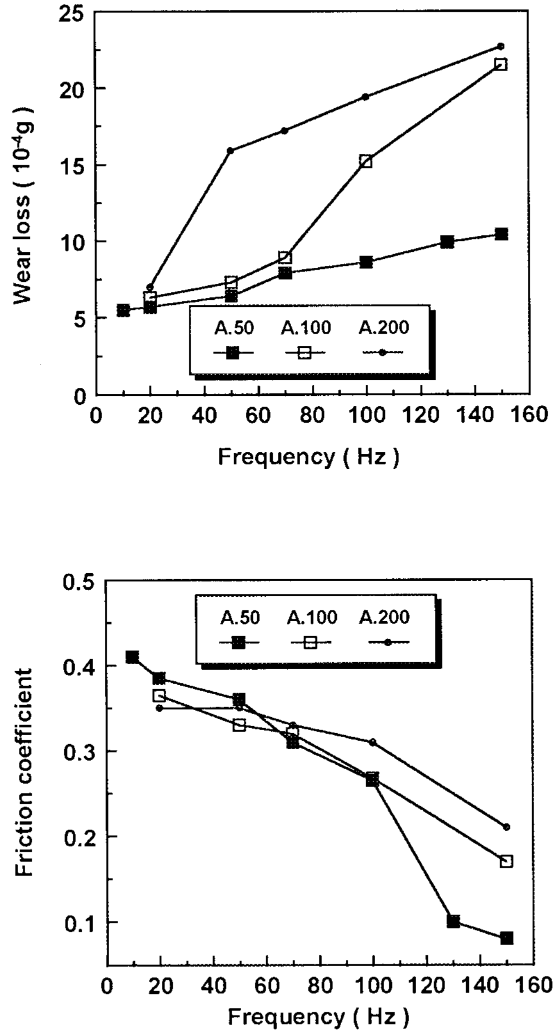


Figure 5 The wear behaviors of FEP as a function of frequency.

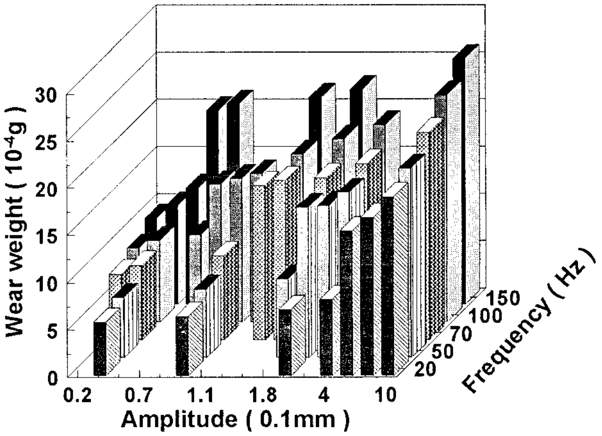


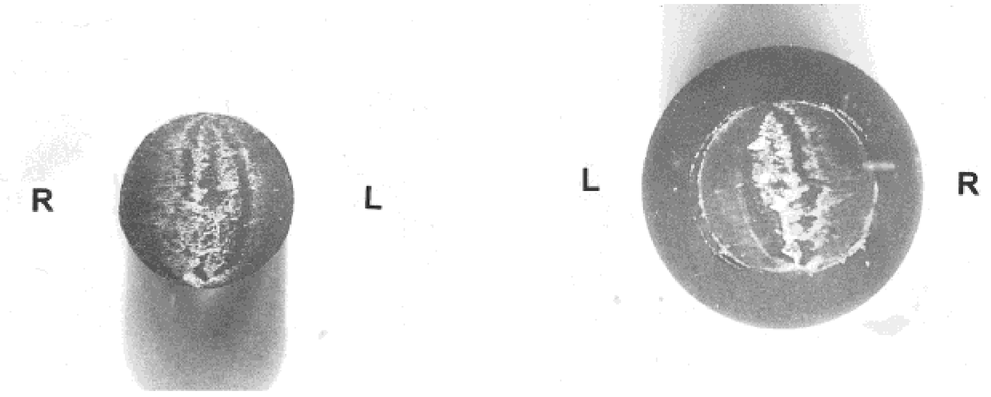
Figure 6 Three-dimensional wear map of FEP as functions of amplitude and frequency at load of 200 N.

gated systematically in this article. Figure 6 shows the wear map of FEP as functions of amplitude and frequency at a constant load of 200 N. It can be seen that the higher the critical frequency, the larger the critical amplitude. The critical product is about 10 mm · Hz. When the product of amplitude and frequency is lower than this value, the wear weight of FEP is usually on the lower stage, while the product over the value the wear weight on the higher stage. This phenomenon indicates that the fretting wear behaviors of FEP are directly restricted to the average sliding velocity.

Another interesting phenomenon was found during this investigating process. It is the correspondence between topography of transferred film of FEP on metal surface and wear trace on FEP. Figure 7 shows the optical graphs of transfer film and wear trace, respectively. It can be seen that the topography of wear trace is strictly corresponded to that of transfer film. Three obviously defined regions on both pair surfaces were observed. In the center region of wear trace, the fatigued FEP surface with serious excoriation was found, and much transferred FEP wear debris on metal surface film. An elliptic belt around the center region was corresponding to the high-pressured region during fretting wear process as FEP was pressured to be lucid, and almost no transfer film of FEP was observed. The outer regions on the wear trace, mild wear phenomenon was characterized by slight and uniform nicks, and a thin transfer film was observed on the surface of metal pair.

DISCUSSION

Unlike metals, polymers are easily extruded out of the frictional surfaces during friction process especially under wear conditions with high load. Thus, the investigating methods for fretting wear behaviors of polymers should be different from for metals or ceramics. In this article, the fretting wear tests with plane contact were used to minimize the contacting stress. Two regimes of fretting wear of FEP, running-in wear and smoothly wear, can be obviously distinguished with increasing number of cycles. When the number of cycles less than 2×10^5, the fretting wear weight, as well as the corresponded fretting wear rate, sharply increased with increasing number of cycles. When the number of cycles more than 2



(a)

(b)

Figure 7 The optical graphs of wear trace (a) and transfer film (b) of FEP.

$\times 10^5$, the fretting wear weight increased smoothly, and the fretting wear rate almost became to be a constant after a sudden decrease. This is because both original surfacial topographies of pairs are relatively rough, and some high stress regions exist at the contacting interface. The real contacting area is far less than the area of sample surface. During the running-in stage, these asperity with high stress will be smoothed by frictional shearing force. After this rudely wear process, the real contacting area is near to equal the area of the sample surface, and the distribution of contacting stress becomes uniform. In this case, the wear weight will linearly relate with the test duration, and the wear rate corresponded to the wear weight is almost a constant. This changing process of fretting wear rate indicates that the fretting wear tests should be conducted under a longer test duration, to compare the fretting wear behaviors of one polymer to the others.

The coefficient of wear (K_ω) is a dimensionaless number appearing in the equation $W = K_\omega \cdot L \cdot S / P_m$ relating the volume of material loss (V) to the product of the load (L) and the distance of sliding (S) divided by the flow pressure of the softer material (P_m). In this article, the product of L and S was preset to be a constant 10^4 N·m so that the material loss W can be expressed as $W = C \cdot K_\omega$, where C is another constant, and W can be considered as the wear weight for the same substrate. From this formula, the wear grades may be distinguished.

The wear of FEP may be achieved by two possible ways—fretting and sliding. The fretting wear is often characterized by fretting fatigue and fretting corrosion (mainly for metals), and considered to be a type of mild wear. Because the sliding wear is usually severer than fretting wear, one can roughly distinguish the wear modes from the wear loss. Actually, there is no exact criterion exist as the fretting wear and sliding wear are always concomitant in the wear process. How to represent the fretting wear behaviors of materials is also an open question. Considering the wear depth of polymer is only a one-dimensional parameter, which cannot represent the situation of the whole contact area when wear conditions with the plane contact was used, the wear coefficient may be a better relevant parameter for polymers then. Though some detached wear particles may remain penetrated to the FEP counterface and are, therefore, not taken into account in the total wear weight, the wear weight measured in this article can primarily reflect the wear behaviors of FEP, as the wear weight is an integrated parameter controlled by worn area and depth both. The value of wear weight shown in this article is always linearly corresponding to that of wear volume as the density of FEP is considered to be a constant.

It is found that there exist a critical amplitude, a critical load and a critical frequency, respectively, when two of the three parameters are fixed. When exceeded the critical values, the higher wear weight might be obtained. Because the product of amplitude and frequency represents the average sliding velocity, the two parameters, amplitude and frequency, influencing the fretting wear behaviors can be simplified to be the average sliding velocity. It is also found that the product of the critical load and the critical velocity are approximately a constant. Thus, the critical *PV* value is an important parameter for the fretting wear behaviors of FEP, where *P* was the normal stress or the load in this paper, and *V* the relative sliding velocity. The critical *PV* value of polymer FEP under fretting wear conditions was found to be about 3×10^4 Pa·m/s or 4 N·m/s. As it is known, the critical *PV* value is a very important parameter for polymers or their composites in tribological applications, and has been widely used in investigation of polymers' sliding wear behaviors.[10,11] The results in our study for FEP indicated that the fretting wear behaviors were also controlled by the critical *PV* value. It is guessed that the *PV* value may present the general wear behaviors of polymers. This is different from the case of metals or ceramics.

In our study, the correspondence of topographies between wear traces on FEP and FEP transferred film on metal surfaces was also found. Three obvious regions, debris formation region, high-stress region, and slightly sliding region, can be distinguished. As both temperature and initial stress in center region are higher than in outer regions, the fretting wear debris formed mainly in this region and so-called the "debris formation region." After the formation process, the wear debris will escape from the center region to the outer under the effect of fretting. Because the wear debris cannot easily escape under fretting with plane contact, a high-stress region where topography is an annular zone is formed surrounding the central region to prevent further escaping of wear debris. This annular zone is so called a "high-stress" region. In this region, wear debris may be repressed into the substrate of FEP. This phenomenon may be the self-cured function of polymers.

While in the outer region near the annular zone, the slight nicks on FEP surface caused by relative sliding is observed. In debris formation region, thick transfer film of FEP can be seen on the metal surface. But no transfer film was found in the annular zone with high stress. In the outer region, a thin, uniform transfer film of FEP was observed. The process of wear debris formation and removal and the correspondence between wear trace and transfer film indicate that the higher the normal stress, the more difficult the formation of transfer film of FEP on metal surface.

CONCLUSIONS

The fretting wear process of FEP can be divided into two major regimes, running-in and steady wear process, with increasing the fretting cycles under fretting wear conditions of plane contact. In our study, the product of normal load and sliding distance was fixed to define the wear degrades of FEP. In this case, the critical *PV* value was found to be an important parameter for the fretting wear behaviors of FEP. Both on the worn surface of FEP and on the metal surface, three sharply defined regions, wear debris formation region, high-stress region, and slightly sliding wear region, can be distinguished. It indicated that the higher the normal stress, the more difficult the formation of thick transfer film. In this article no wear of metal was found when fretted against FEP.

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