Debris Formation Process of PTFE and Its Composites

FENGYUAN YAN,* QUNJI XUE, and SHENGRONG YANG

Laboratory of Solid Lubrication, Lanzhou Institute of Chemical Physics, Chinese Academy of Sciences,
Lanzhou 730000, P.R. China

SYNOPSIS

The wear behaviors of polytetrafluoroethylene (PTFE), graphite–PTFE, and MoS_2–PTFE composites with volume content of filler from 0 to 50% were evaluated against a steel ball using an SRV wear tester under a severe wear condition (both at high speed and high load) and the wear debris produced during the friction process were clearly observed by scanning electron microscopy (SEM). Results indicate that the wear debris produced during severe friction tests are in the form of complete unbroken wavelike ribbons for the good ductility polymer-based composites, or in a form of flake for the poor ductility polymer-based composites. Based on the experimental results of the wear debris formation during the severe friction process, a wear model about extrusion wear of the polymer-based composites in the contacting region is proposed. From the mechanism of friction extrusion proposed in this article, the phenomenon that the wear debris is a multilayer and oriented film can be well explained. © 1996 John Wiley & Sons, Inc.

INTRODUCTION

For tribomaterials, it is very important to understand their wear mechanism from both scientific and practical standpoints. As polymers are macromolecular structures, their wear mechanism is different from inorganic materials and metals. Normally, wear in polymer materials occurs as a result of strong adhesive interaction, fatigue, macroshearing, abrasive action, thermal and thermooxidative interaction, corrosion, cavitation, etc.[1] These things may be true for certain test conditions, and the adhesive wear is thought to be a general rule for polymers. Unfortunately, in most cases, it is difficult to explain the formation of wear debris using the aforementioned mechanisms. Previous tests[2] conducted in our laboratory with a polymer pin against a steel block under a mild load have presented three physical models of adhesive wear. We found that the transfer film of PTFE or PTFE-based composites was formed layer by layer into multilayers on the steel counterface and that the wear debris which was in multilayer form was the result of detachment that occurs from the middle of the transfer film at some distance from the interface.[3-5] Furthermore, some researchers[6] pointed out that the transfer starts with an initial adhesion between the polymer and the countersurface and a shear in the near surface region of the polymer. From the physical models proposed by this laboratory,[2] it seems that the multilayer wear debris is pushed out from the friction surface of pairs, and there is no correlation between the single layers except for the packing action. In this case, the wear debris cannot show a form of unbroken ribbon. Blanchet and Kennedy[7] studied the sliding wear mechanism of PTFE and three kinds of PTFE-based composites and proposed a fracture-based model such that fillers reduce wear by interrupting subsurface deformation and crack propagation, which would otherwise lead to large wear sheets. Their tests were also carried out by sliding a polymer pin against a stainless steel plate at a mild load and under severe test conditions (high sliding speed). From their fracture-based model, it is also difficult to comprehend why the density of crack in the polymer subsurface is at the highest value during the friction process, while the distribution of cracks of one substrate is uniform before the friction test.

The debris formation process—that is, the wear process—can be directly related to the fracture pro-

---

* To whom correspondence should be addressed.

Journal of Applied Polymer Science, Vol. 61, 1223–1229 (1996)
CCC 0021-8995/96/071223-07

cess. According to the viewpoint of asperity configuration, the real stress at the contacting region must be higher than an average stress. Since the previous investigations were carried out at a mild load, the results might be different from those under a severe load, and the results observed under the severe load may perfectly reflect the real situation of wear. In this work, two kinds of PTFE-based composites were prepared, and the wear behaviors of these composites were evaluated at high load against a steel ball. It is expected that this effort will be helpful in understanding the wear mechanism of PTFE-based composites.

EXPERIMENTAL

Two kinds of PTFE-based composites filled with graphite and MoS_2, respectively, were prepared in a plate with a thickness of 8 mm by compression molding. The graphite and MoS_2 are both commercial products with a fine powder of 1 μm grit, and the volume content of graphite or MoS_2 was from 0 to 50%. The wear tests were carried out on an Optimol SRV wear tester with a steel ball moved in the form of reciprocating friction on the prepared plates of PTFE-based composites, which surface were not machined. The rider ball was made of GCr15 bearing steel (SAE 52100 steel) with a diameter of 10 mm. All wear tests were conducted at a load of 200 N, an amplitude of 1.5 mm, a frequency of 20 Hz, and a temperature of 20°C. The average reciprocating sliding speed corresponding to both the amplitude and the frequency was 0.06 m/s, and far more than the speed of 8×10^{-3} m/s above which Blanchet and Kennedy[7] considered that the mild–severe transition of wear would occur. The wear volume of each specimen after the wear test was calculated according to its longitudinal and sectional drawings measured by a profilometer. The wear debris of each specimen produced in the wear test was observed by a JEM-1200EX scanning electron microscope (SEM).

RESULTS AND DISCUSSION

The amplitude (single sliding distance) used in the tests was 1.5 mm, since such a single sliding distance was far longer than the maximum amplitude (300 μm) of fretting wear. Thus the actual wear form in this work was not fretting wear,[8] and the SRV tester was called a fretting wear tester. The wear tests were carried out at a very high load and high speed so that the tribochemical actions between composites and the counterface would be ignored in comparison with the mechanical actions.[3–5]

At steel-on-polymer system, usually the transfer of polymer to steel surface, occurs during the sliding process, and in most cases there will be no wear of the steel counterface. In this work, the rider ball was weighed by an extremely sensitive balance after each test. Results show that the rider ball gains little weight after the wear test, and observation by optical microscopy clearly shows the formation of a transfer film, which takes the circle form on the rubbed steel surface. Furthermore, investigation by X-ray photoelectron spectroscopy (XPS) indicates that no Fe element on the surface of wear traces of PTFE-based composites or in the wear debris exists.

Figure 1 shows the wear rates of graphite–PTFE and MoS_2–PTFE composites as a function of filler volume content from 0 to 50%. Results in Figure 1 illustrate that filling of either graphite or MoS_2 into PTFE in the proper volume content results in a reduction of the wear rate of PTFE. However, with the volume content of graphite or MoS_2 more than 40%, a sharp increase of the wear rate of the PTFE-based composites is observed. Previous evaluations have found that this phenomenon is related to the sudden change of microstructure.[9] Figure 1 also indicates that the optimum of graphite or MoS_2 content may correspond to the difference of chemical reaction of MoS_2 to PTFE, MoS_2 to steel, graphite to PTFE, or graphite to steel. For application in tribology, the maximum filler content of polymer-based composites should be less than 40 vol %.

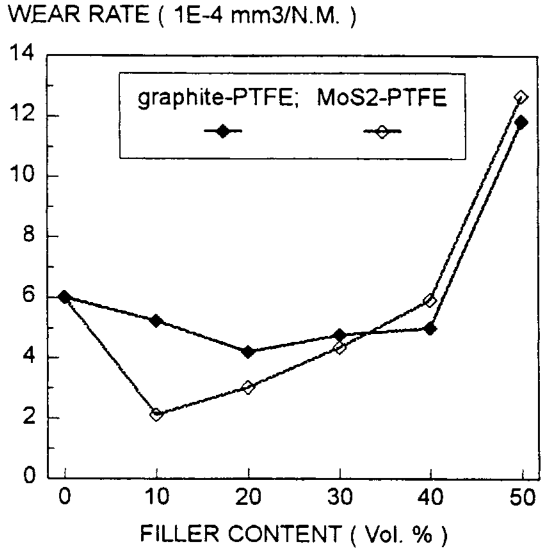


Figure 1 The relationship between wear rate and the filler content.

The ultimate elongations of PTFE-based composites are shown in Figure 2. Since the elongation corresponds to the ductility of materials, it can be seen that the ductility of PTFE-based composites decreases with an increase of filler content. Many researchers[10,11] stated this viewpoint. Although the specimen size in our work was not standardized, the nonmonotonic relationship between the wear rate and ductility of PTFE-based composites still indicates that the ductility of the composite is not the sole factor influencing its wear rate. Observations of wear debris are often helpful to understand the wear mechanism of the steel-on-polymer system. Figure 3 gives the SEM micrographs of wear debris produced in wear tests of graphite–PTFE and MoS_2–PTFE composites. Micrographs in Figure 3 show that the shape of wear debris changes from the long net-ribbon to the flaky form with an increase of filler content. These two kinds of wear debris, also observed by other researchers,[2,7] appear at both edges of wear trace on the specimen in the direction of sliding under the reciprocating test conditions. The wear debris of the net-ribbon shape possesses some elasticities and ductilities; as a result, the wear debris is in a form of a complete unbroken ribbon on which there exist some cracks along the direction of friction. SEM analyses also indicate that the width of the ribbon form of wear debris varies with the content of graphite or MoS_2 in PTFE. The width of the ribbon form of wear debris decreases as the content of graphite or MoS_2 increases, and the widest ribbon form of wear debris is observed for the unfilled PTFE. These phenomena should be related to the ductility of the PTFE-based composites. It is reasonable to conclude that the ductility of PTFE-based composites becomes poorer with an increase of the content of graphite or MoS_2, and the poor ductility will result in easily broken wear debris. As a result, it is difficult for the wear debris to keep a ribbon form, and the form of this wear debris becomes large individual flakes.

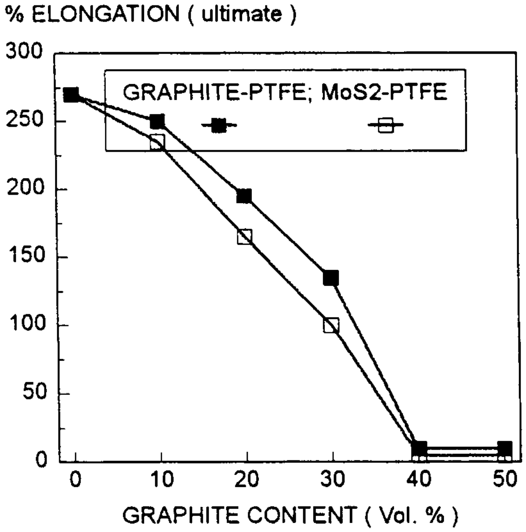


Figure 2 Ultimate elongation of graphite–PTFE and MoS_2–PTFE composites as a function of filler content (the size of each specimen is molded to 20 mm × 12.8 mm × 8 mm).

Figure 4 gives the micrographs of wear debris produced with the MoS_2–PTFE composites with the content of MoS_2 at 10% and 40%, respectively. The results illustrate the obvious difference in the shape of the wear debris. With the content of MoS_2 at 10%, the wear debris is in the form of a complete ribbon with cracks along with it (the same direction as sliding). The ribbon is folded into a wave shape with each sliding time, so the wear debris is really in the form of a folded ribbon or multiwave ribbon. However, with the content of MoS_2 at 40%, the wear debris is in the shape of a large flake. Observations of this flakelike wear debris show that it is in multilayers, and it is believed that this multilayer form of wear debris is produced by several sliding times.

Previous investigations in this laboratory of PTFE or metal-filled PTFE composite pins against steel block under a mild load have found the formation of a polymer multilayer transfer film on the steel counterface and the generation of a multilayer form of wear debris. Based on these facts the three physical models of adhesive wear of PTFE and its composites were established.[2] In this work, the tests were conducted with a steel ball sliding against the polymer plate under 200 N, so the contacting stress is much higher than that in the previous investigations. The average sliding speed is also far more than the speed of mild–severe wear transition mentioned by Blanchet and Kennedy.[7] Under such a severe friction condition, other than the transfer of PTFE to steel, the contacting region of PTFE or its composite might be softened or even be melted, and this region can be considered a new phase different from the substrate. Many cracks are produced or accumulate at the periphery between the softened layer and the substrate. In the actions of both load and friction force, this softened layer of PTFE is very easily extruded out of the contacting region from two edges of the wear trace in the direction of sliding; the front end of the extruded film (wear debris) was a free end, while the tail end was connected with one edge of the wear trace on the polymer substrate by the function of thermal compression. This process was repeated one by one, and finally the

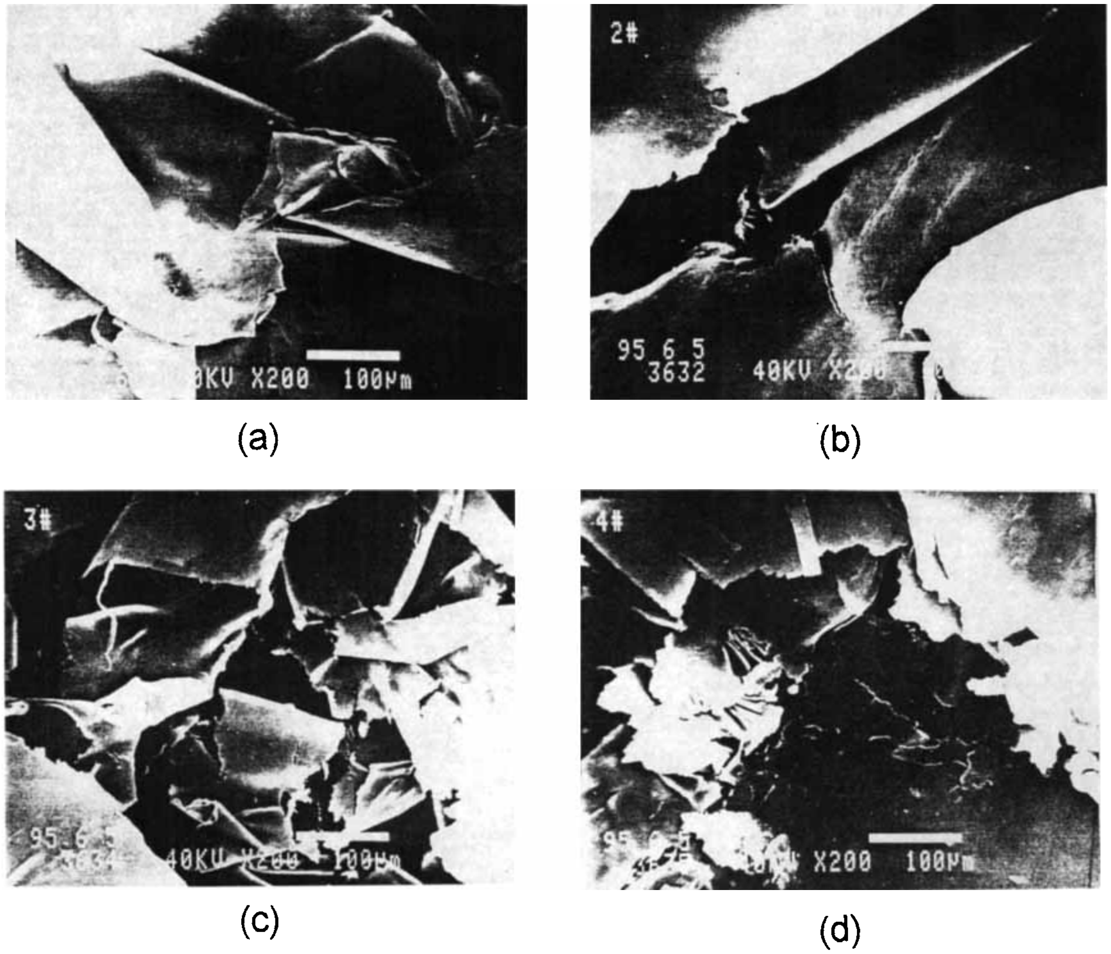
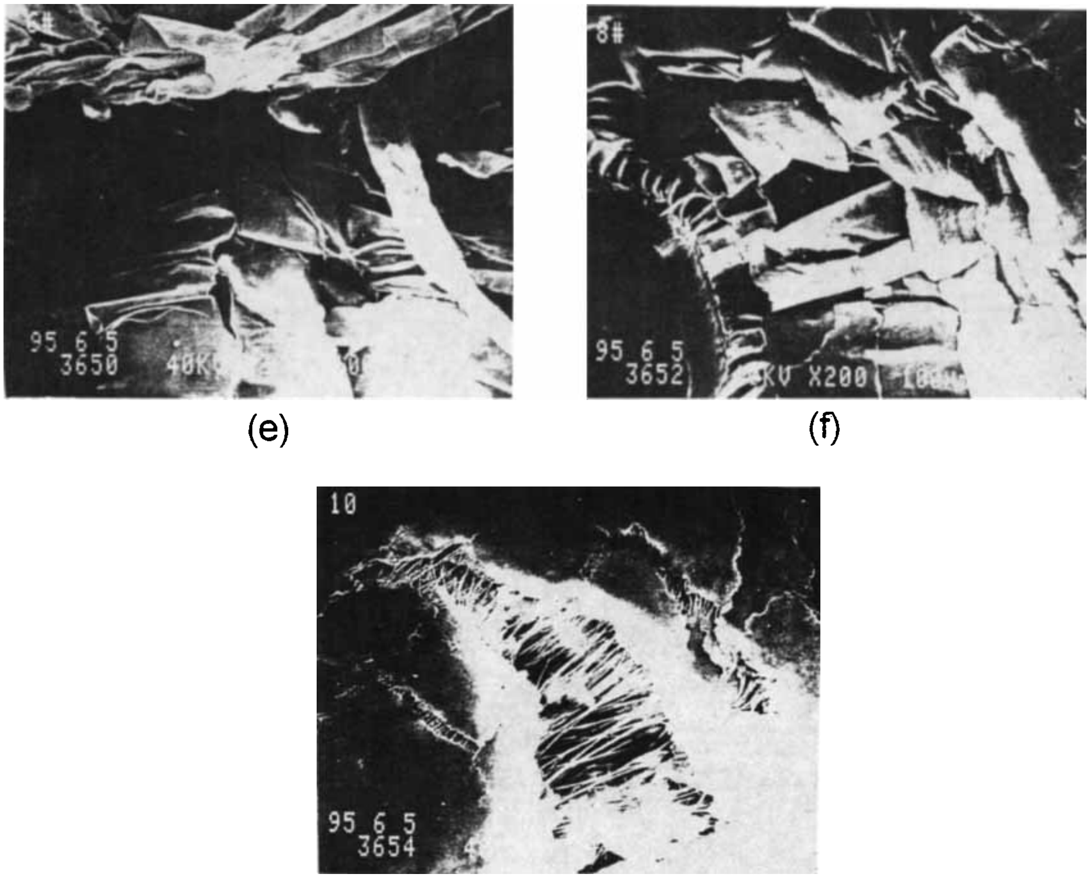


Figure 3 SEM images of wear debris produced during friction (×200): (a) PTFE, (b) 10% graphite-PTFE, (c) 30% graphite-PTFE, (d) 40% graphite-PTFE, (e) 10% MoS_2-PTFE, (f) 30% MoS_2-PTFE, (g) 50% MoS_2-PTFE.

complete unbroken ribbon with many cracks caused by extruding stress was formed for a polymer of good ductility. For the low-ductility composites, the extruded film was easily ruptured at both edges of the wear trace by stress; thus, a cluster of packing wear debris in the form of multilayer flakes could be observed.

On the basis of the SEM observations mentioned earlier, it is easy to understand that the main wear of PTFE or PTFE-based composites under tested conditions in this study is caused by the extrusion of polymer materials from the contacting region, and thus a physical wear model of PTFE and PTFE-based composites under severe test conditions (high load) is proposed (Fig. 5). For good ductility polymer materials, such as unfilled PTFE, 10% graphite, or MoS_2-filled PTFE, the initial sliding of the steel ball on the surface of a polymer-based composite results in the transfer of polymer to steel, and continuous friction causes the contacting region to be softened or even melted and cracks to accumulate or propagate. The continuous extrusion of the polymer material in this softened area by load or friction force makes the formation of wear debris in the shape of a long wavelike ribbon, as illustrated in Figure 5(a). For a poor ductility polymer-based composite such as 50% graphite or MoS_2-filled PTFE, the wear debris extruded out of the contacting region is very easily broken into large pieces. As a result, no wear debris in the form of a long ribbon is formed, and the wear debris only takes the shape of packed wear pieces in the form of multilayers, as described in Figure 5(b).

It is well known that the extruded film of polymer (PTFE) applied in industry is a kind of oriented or semioriented film formed by thermal extrusion or stress–strain. So it is not difficult to understand why the wear debris of polymer produced during friction

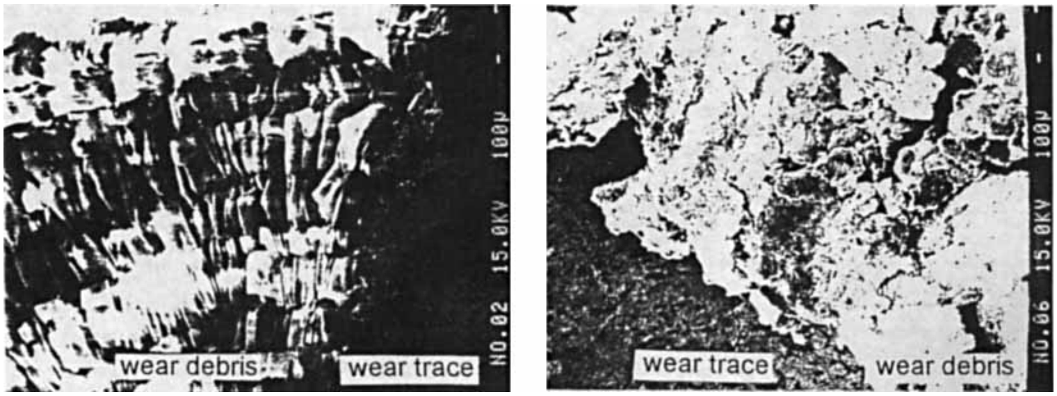


(e) (f)

(g)

Figure 3 (*Continued from the previous page*)

is oriented in a similar way. It seems that the cooperation between the steel ball and the substrate on which a strain and wear hollow exists completed a set of small extruders under the severe friction conditions (both at high load and high speed). By analyzing the distribution of temperature in the



(a) (b)

Figure 4 SEM micrographs of the connection between wear debris and one edge of wear trace (×100): (a) good ductility polymer-based composite (10% MoS_2-PTFE), (b) poor ductility polymer-based composite (40% MoS_2-PTFE).

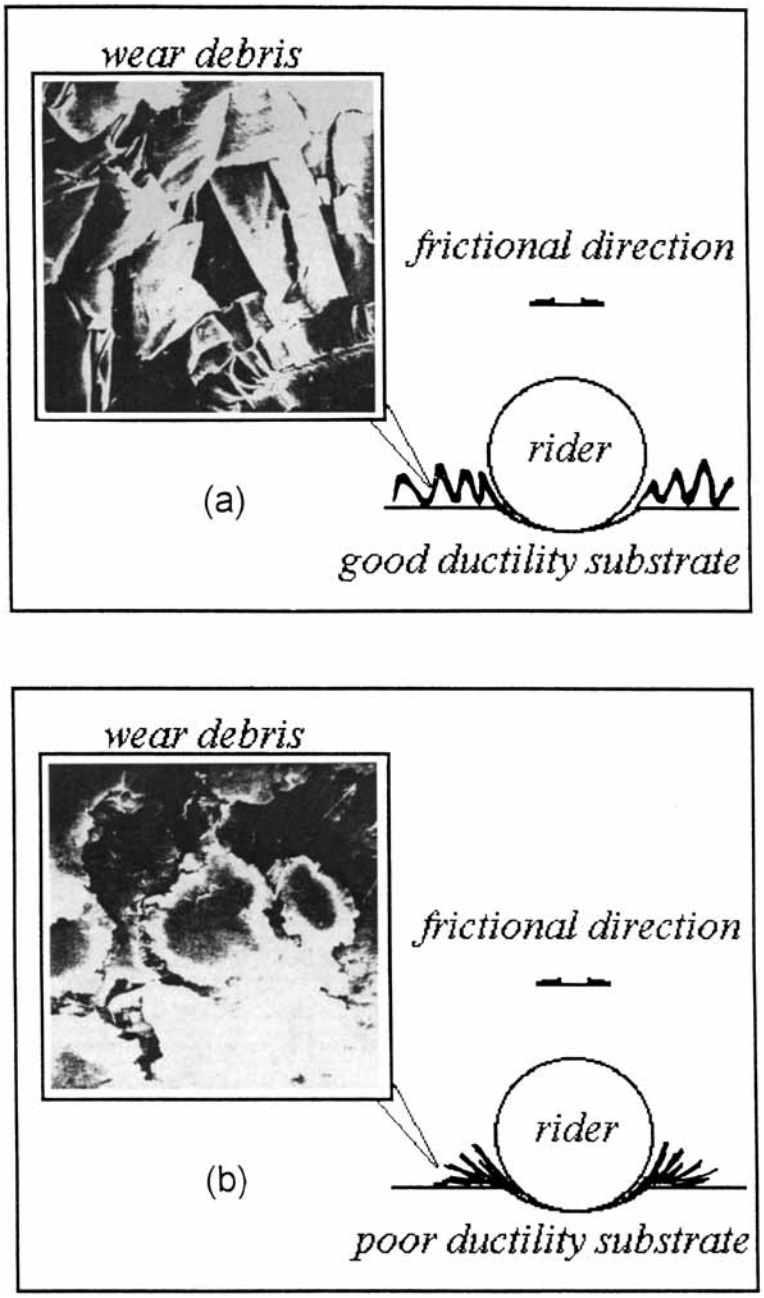


Figure 5 The friction extrusion mechanism for (a) good ductility substrate and (b) poor ductility substrate.

metal–polymer contacting system, it can be supposed that the highest temperature should appear in the region below the contacting surface to a certain distance in a matrix of polymer-based composites. The depth of this region is controlled mainly by friction conditions and thermoproperties of polymer and filler. The crack density near the periphery between this region and the substrate possesses the highest value. The region from contacting surface to some depth of substrate can be considered as the region of extrudate.

CONCLUSIONS

Under severe wear conditions (both at high load and high speed), the wear debris of PTFE or its composites with good ductility takes the shape of long wavelike ribbons, in which there are many cracks caused by stress; whereas the wear debris of PTFE-based composites with poor ductility looks like flakes but in multilayer form. Based on the observations of wear debris and mechanical analyses, the mechanism of the formation of wear debris is mainly caused by friction extrusion of the polymer materials in the contacting region. Based on the mechanism of friction extrusion under the severe friction conditions, the phenomenon that the wear debris is a multilayer and oriented film have been well explained.

REFERENCES

1. V. A. Bely, A. I. Sviridenok, M. I. Petrokovets, and V. G. Savkin, *Friction and Wear in Polymer-Based Materials,* A. Wheaton Co. Ltd., Exeter Press, Great Britain, 1982.
2. D. L. Gong, Q. J. Xue, and H. L. Wang, *Wear,* **147,** 9 (1991).
3. D. L. Gong, B. Zhang, Q. J. Xue, and H. L. Wang, *Wear,* **137,** 25 (1990).
4. D. L. Gong, B. Zhang, Q. J. Xue, and H. L. Wang, *Wear,* **137,** 267 (1990).
5. D. L. Gong, Q. J. Xue, and H. L. Wang, "Wear of Materials," in K. C. Ludema, Ed., ASME, New York, 1989.
6. E. L. Yang, J. P. Hirvonen, and R. O. Toivanen, *Wear,* **146,** 367 (1991).
7. T. A. Blanchet and F. E. Kennedy, *Wear,* **153,** 229 (1992).
8. K. G. Budinski, *Thin Solid Film,* **64,** 359 (1979).
9. F. Y. Yan, W. H. Wang, Q. J. Xue, and L. Wei, submitted to *J. Appl. Polym. Sci.* **61,** 1231 (1996)
10. J. K. Lancaster, *J. Phys. D: Appl. Phys.,* **1,** 549 (1968).
11. J. Bijwe, C. M. Logani, and U. S. Tewari, *Wear,* **138,** 77 (1990).

Received October 6, 1995
Accepted January 25, 1996