# Morphology of Polymer Wear Debris Resulting from Different Contact Conditions

S. M. HOSSEINI and T. A. STOLARSKI*

Department of Mechanical Engineering, Brunel University, Uxbridge, Middlesex, UB8 3PH, United Kingdom

**SYNOPSIS**

An investigation into the wear process of five polymers tested under different contact conditions is presented. Polymer pin on metal plate and metal pin on polymer plate configurations were used. The metal pin on polymer plate configuration gave significantly lower wear rates compared to that observed for the polymer pin on metal plate configuration. The results are discussed in terms of morphology of wear debris generated.

## 1. INTRODUCTION

Practical utilization of polymers in machine sliding components and other tribology-related applications depends, to a considerable extent, on the understanding of the ways in which their wear behavior is influenced by the imposed operating conditions. The wear process involves a number of complex interactions, but it can be considered to be caused by the energy created by the frictional work and released during sliding within the contact zone.[1-3] The mode in which the frictional energy is dissipated depends, undoubtedly, on the contact configuration, which, therefore, should be considered as an important factor in the friction and wear behavior of polymers.

Two basic contact configurations can be distinguished (Fig. 1). The first is formed by a rigid asperity traversing a deformable polymer substrate. The second one is usually associated with the sliding of a deformable polymer over a rigid substrate. The first configuration involves relatively large volume deformations beneath the contact and is a good approximation for rolling and efficiently lubricated sliding contacts. The polymer substrate is deformed in either a viscoelastic or a plastic manner and a net restoring force is created through this deformation. In contrast, the second configuration consists of the formation of adhesive junctions and the dissipation of shear work in regions very close to the interface. Addition of a lubricant to the contact zone interposes a weak layer at the interface that effectively prevents formation of adhesive junctions.

These two processes are generally regarded as being noninteractive, and while the distinction between them is rather tentative, it serves, however, as a useful simplification when dealing with wear processes, since both obviously contribute to wear in different ways.

The main objective of the investigation reported in the present paper has been to determine the relationship between the contact configuration and the morphology of wear debris and, in consequence, to improve the understanding of the wear process.

## 2. APPARATUS, EXPERIMENTAL PROCEDURES, AND MATERIALS

Figure 2 shows, in a schematic way, the test apparatus used to carry out the wear experiments. An electric motor (A) with variable speed drives the disc (B). The rotational speed of the disc is converted to a reciprocating motion of the stage (K) by means of a crank mechanism. The stroke of the shaft is adjusted by moving the crank pin (L) together with the connecting rod (C) down the T-shaped groove machined in the disc (B). The stage (K) is supported by a plane sliding bearing (H). A specimen in the form of a flat, smooth metal plate is fixed to the reciprocating stage, the upper part of

* To whom correspondence should be addressed.

Journal of Applied Polymer Science, Vol. 45, 2021–2030 (1992)
 CCC 0021-8995/92/112021-10$04.00

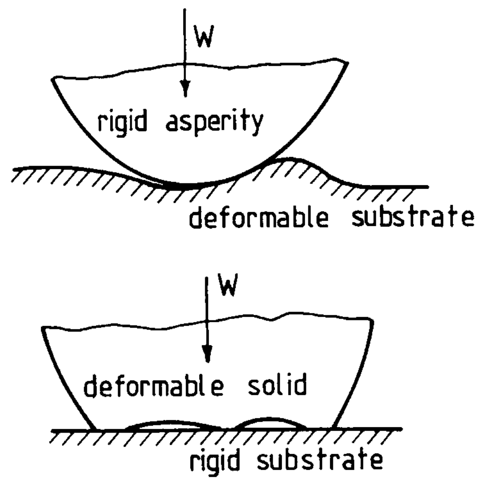


**Figure 1** Two basic contact configurations.

which forms a lubricant container (D) for testing under lubrication conditions. Polymer specimen (P), in the form of a 5 mm-diameter pin, is fixed to a stationary arm (N), which, in turn, is used to load the contact. Dead weights (W) were used to impose a normal load on the contact.

In reverse configuration, the plate (T) was made of a polymer and the pin (P) was replaced by the metal slider shown in Figure 3. Special care was

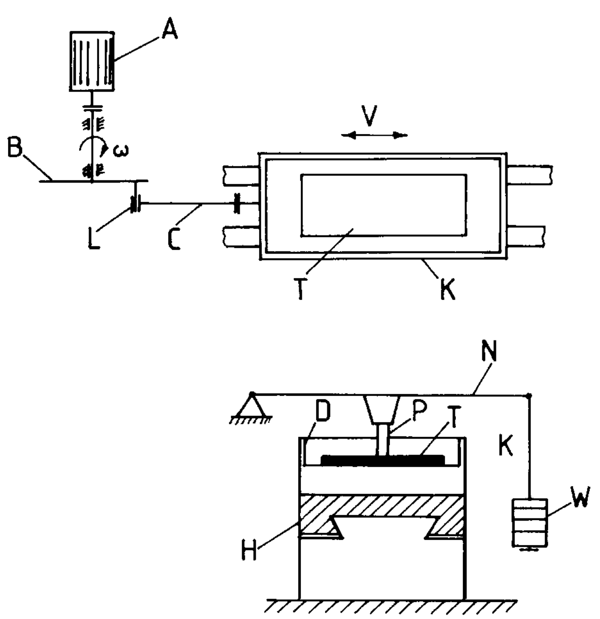


**Figure 2** Schematic representation of the apparatus used. A, electric motor; B, disc; C, connecting rod; D, lubricant container; H, sliding bearing; K, stage; L, crank pin; N, stationary arm; P, specimen; T, counterface; W, dead weight.

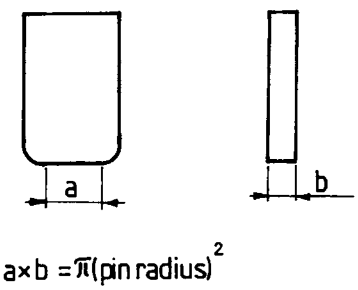


**Figure 3** Metal slider used in slider on polymer plate configuration.

taken to ensure the same nominal contact pressure in both configurations. The amount of wear was measured by means of a displacement transducer sensing the vertical movement of the arm (N). This method was supplemented by an accurate weighing of the sample before and after the test.

Both the metal plate and metal slider were made of EN24 steel, randomly abraded to a surface roughness of 0.10 $\mu$m $R_a$ and finally cleaned ultrasonically in propyl alcohol. The range of normal loads on the contact was 5-500 N. The maximum velocity of the reciprocating motion used during testing was 0.0125 $ms^{-1}$.

Five polymers were tested: polypropylene (PP), polytetrafluoroethylene (PTFE), high-density polyethylene (HDPE), nylon 6.6, and polyetheretherketone (PEEK). All polymers were chemically pure and represented typical commercially available grades. Wear was continuously measured over the period of 5 h, and the length of the wear path during a single stroke was 25 mm.

Wear tests were combined with the microscope examination of the wear debris. A scanning electron microscope was used and the material for examination was prepared with the help of E5000 sputter coater evaporation unit. The thickness of evaporated gold/palladium film was approximately 600 Å.

## 3. RESULTS AND DISCUSSION

### 3.1. Polymer Pin on Metal Plate Configuration

Wear test results for this configuration are shown in Figure 4. Wear is expressed as a volume loss of material of the pin per unit sliding distance and plotted against normal load on the contact. The general observation is that under dry conditions wear increases with increasing load, but the rate of increase is different for the five polymers examined.

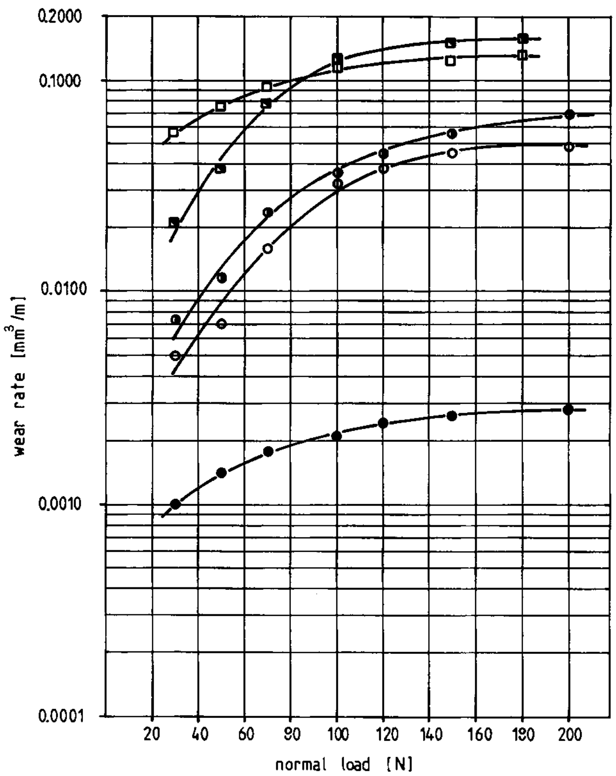


**Figure 4** Wear rate expressed as a volume loss of material per unit sliding distance against normal load on contact. Polymer pin on metal plate configuration. (◪) PTFE; (□) PP; (○) Nylon 6.6; (●) PEEK; (◑) HDPE.

This trend is in agreement with published results.[4,5] As expected, the highest wear rates were measured for a PTFE pin sliding against the metal plate. This is in agreement with the wear behavior of PTFE reported previously[6,7] and could be associated with the transfer process.

Figure 5 shows a typical view of debris formed by a PTFE pin sliding against the metal plate under a normal load of 50 N. The debris has an appearance of thin flakes. The form of the wear debris correspond quite well with the wear rate observed. It is reasonable to say that when the PTFE pin was slid on the metal surface, a film of transferred material was deposited on the substrate. Because of subsequent sliding over the same track, the film was fragmented and peeled off.

Equally high wear rates were observed in case of a PP (Fig. 4). The wear debris produced by the PP pin sliding against metal plate under a normal load of 50 N is shown in Figure 6. The appearance of wear debris suggests that a significant softening of a polymer combined with transfer of the material to the substrate took place as a result of frictional heating. Subsequent traversals of the pin over the metal plate resulted in the rolling up of the adhering lumps of the material into small, cylindrically shaped debris. It is also possible that the debris underwent a partial chemical degradation initiated by the frictional heat and became substantially harder than the parent material. The consequence of that could be their secondary abrasive action. It is important, however, to note that no transfer of PP to the metal plate was detected, which suggests that the transferred lumps of molten or significantly softened material were removed from the substrate and turned into the debris of the form shown in Figure 6. This

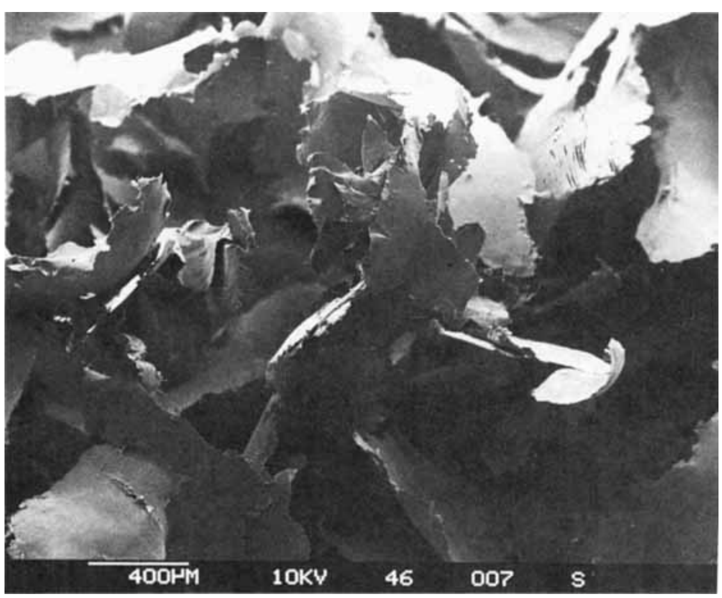


**Figure 5** PTFE pin debris produced at 50 N normal load.

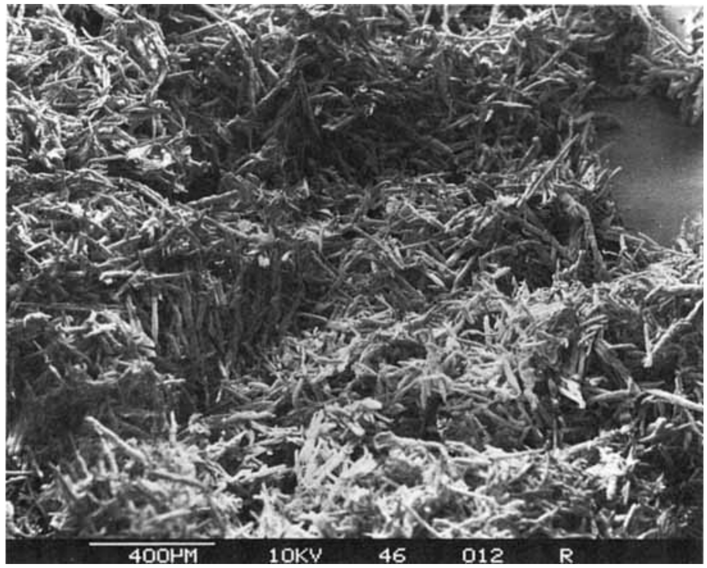


**Figure 6** PP pin debris produced at 50 N normal load.

mechanism could account for the rather high wear rates of PP observed in the polymer pin on metal plate configuration.

The wear rate of the HDPE pin is significantly lower than that of PTFE pin (Fig. 4). Although both PTFE and HDPE are regarded as being "transferring" polymers, it is generally accepted that HDPE has less propensity to deposit a film of material on a substrate. This is perhaps the reason for the substantially lower wear rates observed. Further confirmation of the above supposition is provided by the appearance of wear debris produced by the HDPE pin sliding over the metal plate under a normal load of 50 N, as shown in Figure 7. It is seen that the wear debris is smaller and much more fragmented than that produced by PTFE pin, although it is of a flakelike shape. It can be said that in the case of HDPE the transfer of material to the substrate was somewhat less spontaneous.

Nylon 6.6 proved to be one of the best polymers tested from the wear resistance point of view (Fig. 4). At first sight, wear debris produced by the nylon

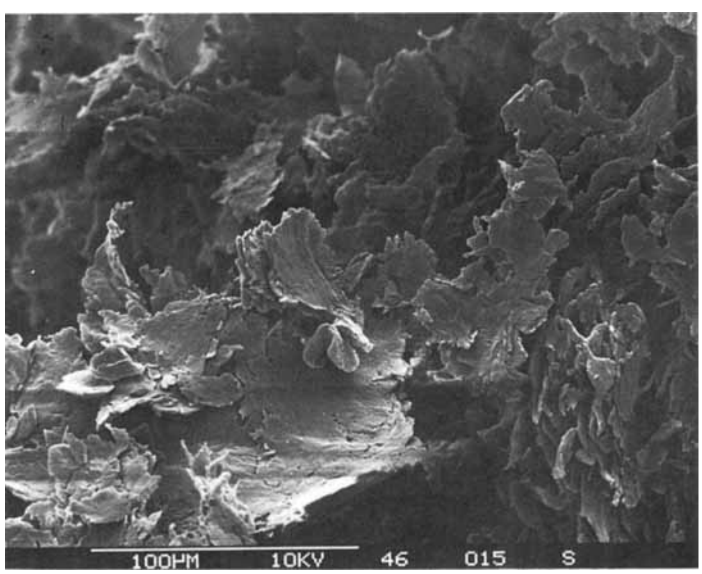


**Figure 7** HDPE pin debris produced at 50 N normal load.

6.6 pin sliding against the metal plate under a normal load of 50 N looks like those produced by the HDPE pin [Fig. 8(a)]. It is fragmented and has a similar aspect ratio. To obtain more details about nylon 6.6 wear debris, photographs were taken at higher magnification. It is seen [Fig. 8(b)] that the rodlike structure characteristic for PP wear debris is also present in nylon 6.6 debris, although it is not as common and obvious as it was there. The mechanism responsible for creation of a rodlike wear debris was probably similar to that operating in the case of PP. However, the fact that the rodlike structure is much less common in the case of nylon 6.6 must be attributed to the ability of nylon 6.6 to withstand higher operating temperatures. The reduction in the frictional heat-induced transfer of material could account for improved wear resistance of nylon 6.6. The most wear-resistant polymer turned out to be PEEK. Its wear rate was one order of magnitude smaller than that of nylon 6.6. This rather exceptionally good wear performance could be explained in terms of the energy dissipated within the contact zone. It is apparent that the amount of frictional energy dissipated was not sufficient to cause any significant damage to the surface. Figure 9(a) shows wear debris produced by the PEEK pin sliding

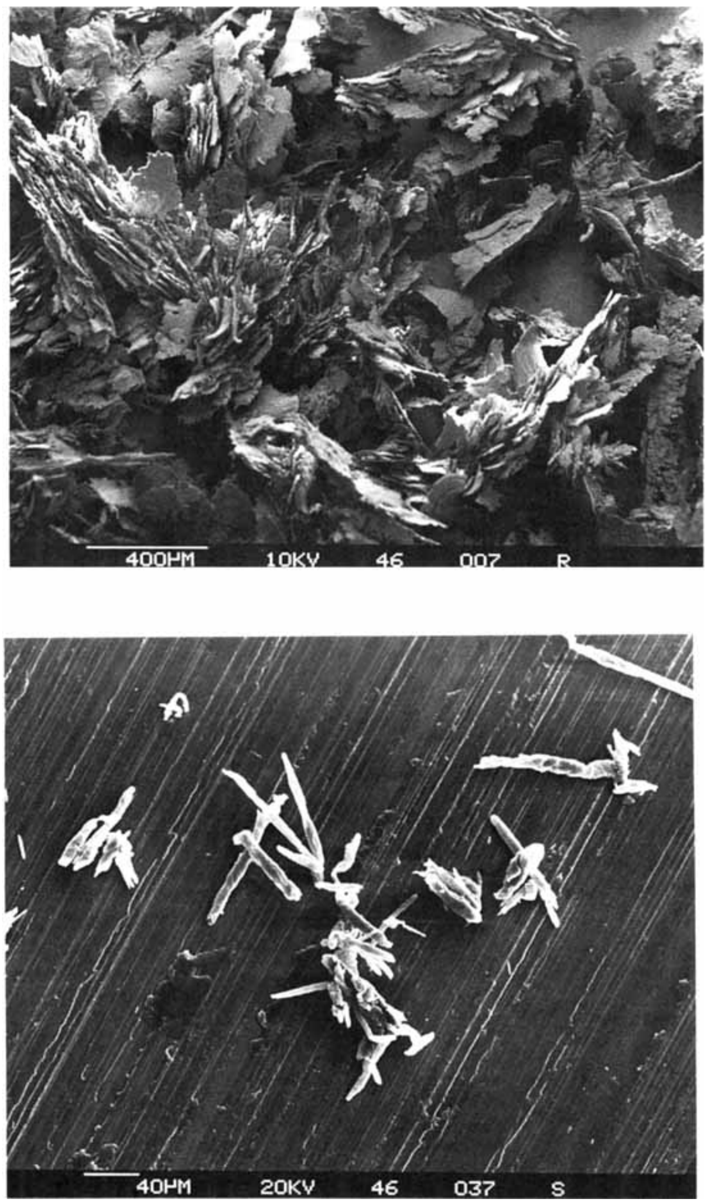


**Figure 8** Nylon 6.6 pin debris produced at 50 N normal load.

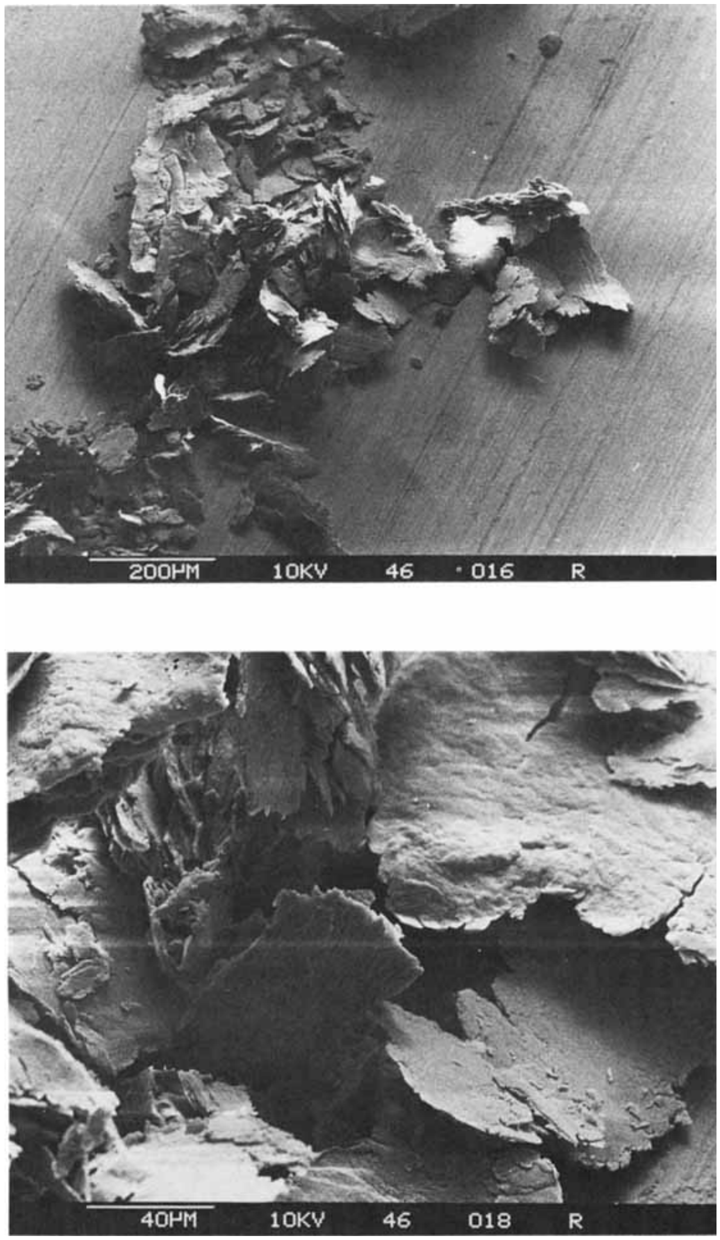


**Figure 9** PEEK pin debris produced at 50 N normal load.

against metal plate under a normal load of 50 N. The debris has a chiplike form. At higher magnification [Fig. 9(b)], a further structure is visible comprising small particles held together presumably by electrostatic forces. This structure of wear debris points to a high cohesive energy of PEEK and could account for its wear-resistance properties.

### 3.2. Metal Slider on Polymer Plate Configuration

Wear test results for the metal slider on the polymer plate configuration are shown in Figure 10. In this figure, wear rate is expressed as a volume loss of material per unit sliding distance. It was estimated by measuring only the depth of the groove produced on the polymer plate, as the width of the groove was constant.

The first general observation is that the wear rates are substantially lower than those observed for the polymer pin on metal plate configuration, although the test conditions (sliding velocity and nominal contact stress) were the same in both cases. This substantial reduction in wear for all polymers examined is quite important from an engineering

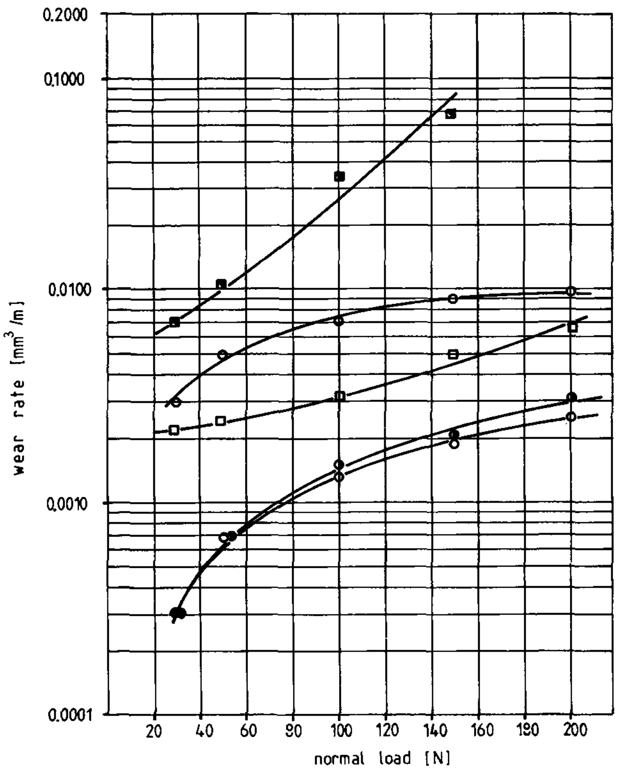


**Figure 10** Wear rate, expressed as volume loss of material per unit sliding distance and estimated by measuring the depth of groove produced on polymer plate, against normal load on contact. Metal slider on polymer plate configuration. (◪) PTFE; (□) PP; (○) Nylon 6.6; (●) PEEK; (◑) HDPE.

point of view and can be attributed to the differences in contact conditions between the two configurations. The characteristic feature of the metal slider on polymer plate configuration is its transient nature, which can be characterized by the contact time between metal slider and polymer plate. There are also significant differences between the two configurations in contact stress distribution. Judging by the results of microscopy examinations of the wear debris produced by the metal slider traversing polymer plate, the differences between the two configurations are rather small. This statement is substantiated by Figure 11, which shows debris resulting from wear of the PTFE plate. It is immediately obvious that the appearance of debris in Figure 11 is quite similar to the appearance of debris shown in Figure 5. The same can be said of wear debris resulting from wear of the HDPE, nylon 6.6, and PEEK plates. They are shown in Figures 12 to 14, respectively. The debris produced by the PP plate (Fig. 15) is the only exception. Instead of a rodlike appearance characterizing the polymer pin on the metal plate configuration, wear debris produced in the metal slider on the polymer plate configuration is closer to the flakelike shape. It is clear from Figure 15 that some debris was trapped in the contact zone smeared over the sliding path by the traversing slider. There is no evidence that rolling up of the particles adhering to the substrate took place.

The fact that there are almost no differences in appearance between wear debris produced in two different contact configurations while wear rates observed for respective configurations differ substantially required further elaboration. The metal slider on the polymer plate configuration can be considered to have a microscale equivalence to that of a rigid hemispherical asperity traversing the surface of a polymer plate. Two energy dissipation zones can be distinguished beneath a sliding contact. The interfacial zone is usually quite thin (~ 100 nm), whereas the second zone is much thicker and is of the order of the contact length. These two zones are not distinct, but for modeling purposes it is useful to consider the contribution of each zone to the wear process separately. Two main subgroups are usually used to rationalize the wear. There is a region close to the interface where the frictional work is dissipated in a very narrow region. Here the rates of energy dissipation are high and extensive thermal and chemical degradation may occur. In addition, the large strains may cause rupture of the polymer close to the interface and so produce a transferred layer of polymer on the counterface, provided that the transfer process is not hindered by the presence of a boundary film. The second dissipation region includes a greater volume of the interface zone and is characterized by much lower rates of energy dissipation. In this subgroup, wear properties that are primarily a function of the cohesive characteristic of the polymer can be included. The polymer can fail by propagation of subsurface cracks.

It is apparent from the wear data that the contact conditions in the metal slider on the polymer plate configuration were less severe than those in the polymer pin on the metal plate configuration. This could account for the differences in wear rates between the configurations studied. The metal slider on the polymer plate configuration helps the wear debris to be trapped in the contact zone. As a result, the initial contact between the metal slider and polymer plate changes to the one between the metal slider and wear debris smeared all over the contact path.

Regarding the similarities in wear debris appearance, it is evident that in both configurations the

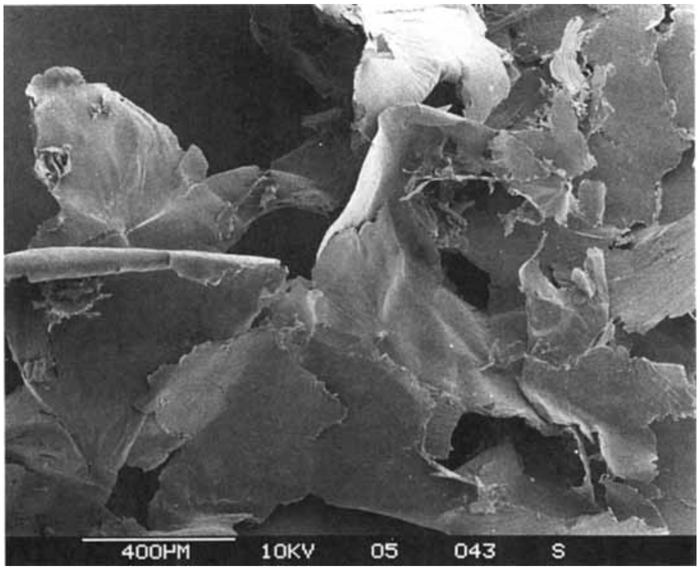


**Figure 11** PTFE plate debris produced at 50 N normal load.

mechanism of creation of a single wear particle is the same. It apparently involves creation of an adhesive junction that must be stronger in shear at the interface than the shear strength of the polymer. As a result, a thin, flakelike debris is created. High rates of energy dissipation characteristic for the interfacial zone facilitate transfer of material through significant softening of some polymers studied. Further history of wear debris is quite different in the two configurations studied. In the polymer pin on the metal plate configuration, wear particles are easily pushed aside by the traversing pin, although some of them might be trapped in the contact zone. In the metal slider on the polymer plate configuration, a majority of wear particles is trapped in the contact zone. This is especially true when the contact path on the polymer plate is of a certain depth.

## 4. CONCLUDING REMARKS

The most important observation emerging from the studies described in this paper is that, under the conditions used, a clear difference in wear rates ap-

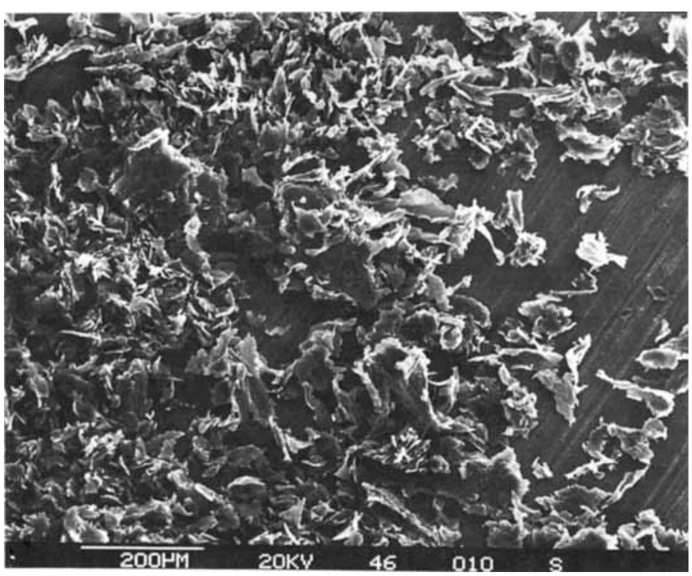


**Figure 12** HDPE plate debris produced at 50 N normal load.

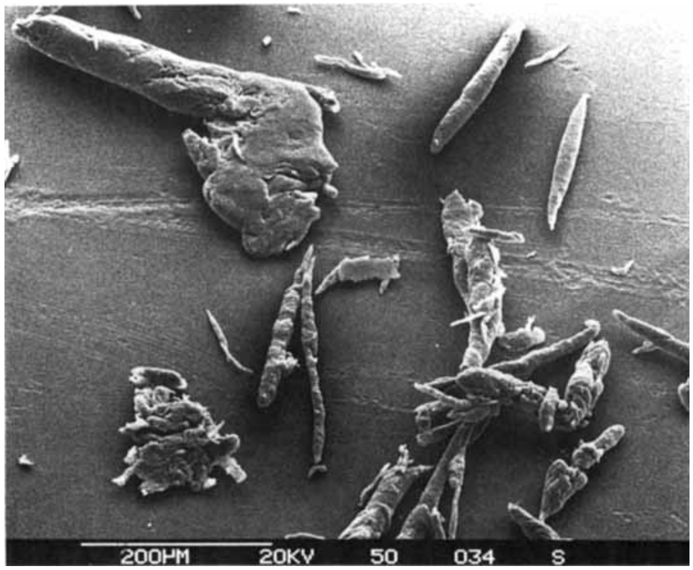


**Figure 13** Nylon 6.6 plate debris produced at 50 N normal load.

pears to exist between the contact configurations whereas the morphology of wear debris produced in these two configurations is almost the same. Wear rates obtained in the metal slider on the polymer pin configuration are, for instance, six times less for PTFE and almost 60 times less for PP than those observed in the polymer pin on the metal plate configuration. This very substantial reduction in wear rates suggests much less severe contact conditions in the metal slider on the polymer plate configuration. It also appears that the mechanism of wear particle creation is the same for both configurations; hence, the appearance of wear debris collected at the early stages of the wear test is almost the same despite differences in contact configurations. This is strongly supported by the appearance of wear debris examined under a scanning electron microscope. After the creation of a wear particle, however, its further history depends on the configuration. The polymer pin on the metal plate configuration helps the wear particles to be pushed aside by a traversing pin, and they are not, therefore, undergoing any ex-

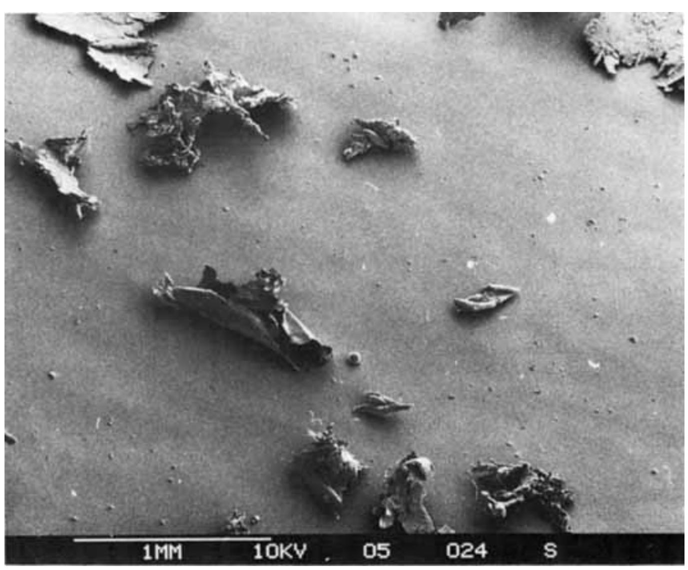


**Figure 14** PEEK plate debris produced at 50 N normal load.

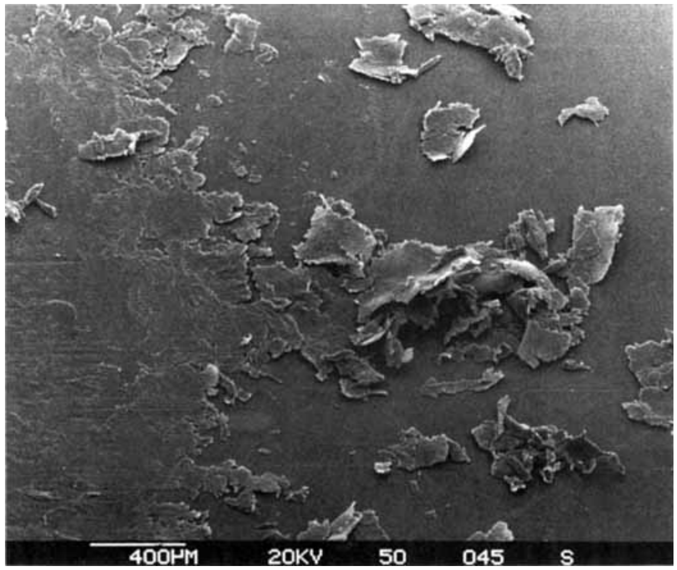


**Figure 15** PP plate debris produced at 50 N normal load.

tensive secondary transformation. In contrast to that, the metal slider on the polymer plate configuration facilitates the entrapment of wear particles in the contact zone. Therefore, a majority of wear particles undergo an extensive secondary transformation and almost completely change their initial appearance.

## REFERENCES

1. B. J. Briscoe and D. Tabor, in *Proceeding of the International Conference on Fundamentals of Tribology*, MIT, June 1978.
2. J. K. Lancaster, in *Friction and Wear in Polymer Science*, A. D. Jenkins, Ed., North-Holland, London, 1972, Chap. 14.
3. S. M. Hosseini and T. A. Stolarski, *Surf. Eng.*, **4**, (4), 322–326 (1988).
4. D. C. Evans and J. K. Lancaster, *The Wear of Polymers: Treatise on Materials Science and Technology*, Academic Press, New York, 1979, Vol. 13, pp. 85–139.
5. K. Taneha, Y. Uckiyame, and S. Toyooke, *Wear*, **23**, 153–172 (1973).
6. B. J. Briscoe and T. A. Stolarski, ACS Symp. Ser. 287, *American Chemical Society, Washington, DC*, 1985, pp. 303–313.
7. B. J. Briscoe and T. A. Stolarski, *Wear*, **104**, 121–137 (1985).

*Received August 12, 1991*
*Accepted October 21, 1991*