The Effect of Water Lubrication on Polymer Wear under Rolling Contact Conditions

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SYNOPSIS

The results of studies into the performance of three selected engineering polymers in rolling contact are presented. Both dry and water lubrication conditions were used. The polymers were machined into a cup simulating the outer race in a rolling contact bearing. Ceramic balls were used in order to create corrosion resistant combinations of materials. Post-test studies were carried out using a scanning electron microscope. On the basis of microscopy examinations the effect of water on the morphology of contact path surfaces was assessed and the abilities of tested polymers to operate in the presence of water in a rolling contact were ranked. © 1994 John Wiley & Sons, Inc.

INTRODUCTION

The virtues of using polymers as materials for the components in dry sliding contact are widely known. To date, numerous papers have been published on the sliding wear of polymers. However, much less research has studied the performance of polymers in rolling contact.[1]

With polymers coming to the forefront of the list of popular engineering materials, there are many advantages to be gained by replacing traditional bearing materials with polymers. Modern engineering polymers offer many special features such as reduced weight, low cost and ease of manufacturing of the finished product, corrosion resistance, and ability to operate without external lubrication. Therefore, it is becoming increasingly necessary to determine the performance characteristics of such materials and their properties under a variety of operating conditions. These include rolling contact and water lubrication.

In the case of water-lubricated polymer contacts there are two aspects of the problem.[2] It is known that the presence of water in a contact can result in fluid film lubrication, boundary lubrication, or a mixture of the two, depending on the particular operating conditions. Because of their relatively low moduli of elasticity, polymers may operate with full fluid film in conditions which, with metals, could lead to solid–solid contact.[3] Clearly, polymers ought to wear less than metal under comparable contact conditions. Another consideration is the effect of water on the physical and mechanical properties of the surface layers. In most practical situations, polymers are in contact with metallic counterfaces and both surfaces may be affected by water. The metal may suffer some loss in strength as a result of the Rebinder effect,[4] but the relevance of this to wear has not yet been confirmed. Furthermore, corrosion of the metal may also occur and the effect of that on wear of the mating polymer material can be favorable or deleterious, depending on the scale involved.[5] The metal surface may also acquire a layer of transferred material from the polymer, a process known to be influenced by the presence of water.[6]

Polymeric materials interact with water in a number of ways. Absorption of water, for instance, can lead to a variety of effects relevant to wear.[7] These could include: (i) a reduction in strength and modulus of elasticity and an increase in the elongation to break, and/or (ii) swelling of the surface layers, which leads to differential expansion and possible stress concentrations.

All these effects have been observed or are anticipated in cases of polymer sliding contact lubricated with water. Virtually nothing is known in this respect about water-lubricated polymer rolling con-

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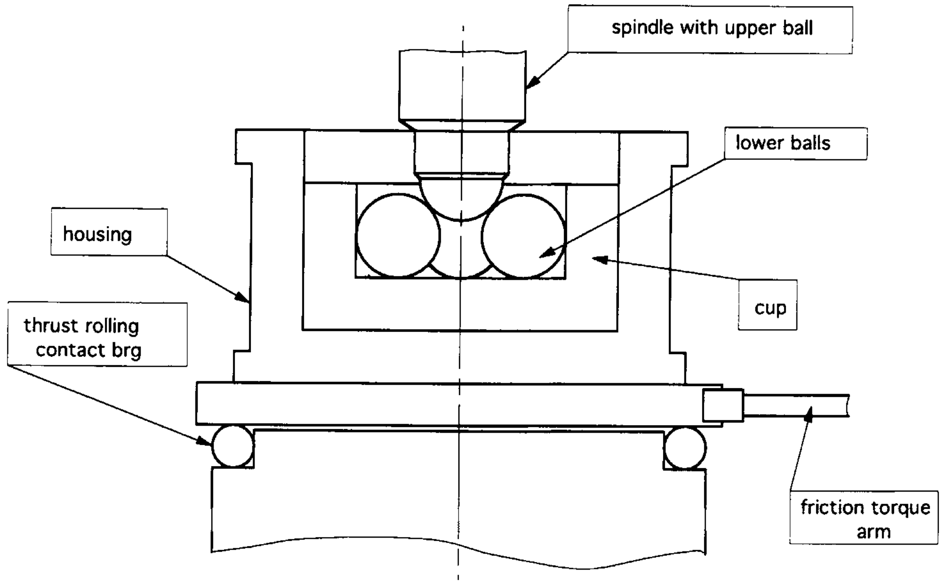

Figure 1 Schematic of essential components of the apparatus.

tact. Therefore, the main objective of the study reported in this paper was to determine the behavior of a number of engineering polymers in rolling contact and in the presence of water. The results obtained are discussed in terms of morphology of wear debris generated and the appearance of a polymer surface subjected to a cyclic loading in the presence of water.

APPARATUS, EXPERIMENTAL PROCEDURES, AND MATERIALS

Apparatus

The test apparatus used in this study was a modified four-ball machine shown schematically in Figure 1. This modified machine is usually used for accelerated testing of engineering materials in order to compare their rolling contact fatigue resistance.

The machine consists of an assembly that simulates an angular contact ball bearing. In order to evaluate the usefulness of certain polymers for rolling contact applications, the cup representing a bearing outer race is made of a polymer (see Fig. 2). Because water is used as a lubricating medium, the three lower balls (representing the rolling elements within a bearing) are ceramic. The upper ceramic ball, representing a bearing inner race, is located in a chuck carried by a vertically mounted spindle driven by an electronically controlled electric motor. It contacts the three lower balls. The assem-

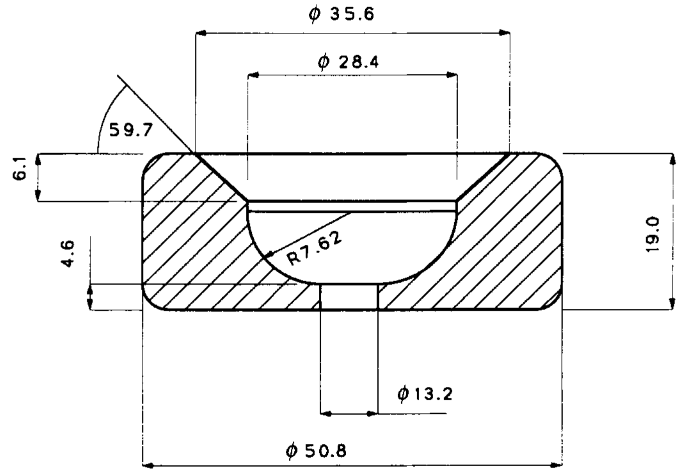

Figure 2 Overall dimensions of the test cup.

bly is loaded via a piston below the polymer cup located in a steel housing on a lever-arm load. The contact areas between the upper ball and lower balls are immersed in tap water.

The speed of the upper ball may be continuously varied up to 20000 rpm. Test time and number of revolutions are recorded by a timer and tachometer, respectively. The apparatus may be set to stop at either a revolution number or a maximum vibration amplitude.

Test Materials

Three polymers were chosen to be studied under rolling contact conditions and water lubrication. Each material was received in extruded bar form and then machined into a cup. The three commercially available materials were:

(i) nylon 66 (Zytel E 101 L)
(ii) polyacetal (Delrin 150)
(iii) high density polyethylene (Rhiamer)

Their exact physical and chemical specifications, determined by original manufacturers (ICI and Hoechst), were not changed for the purpose of the studies presented here.

Using these materials, cups were machined and tested under various tribological conditions. The form of the cup and its main dimensions are shown in Figure 2.

Test Procedures

Preliminary Tests

Prior to testing, preliminary tests were conducted to define the test conditions, parameters, and procedures. A static load was applied first in order to find out what contact pressure is required to cause a permanent deformation on the surface of a polymer cup. This showed that the dead weight of 1.5 kg suspended from the lever arm is a "safe" load, as no permanent deformations were identified.

Next, the polymer cup was cleaned with a laboratory grade solvent (Genklene) and weighed on a precision balance. The four ceramic balls and the collet were also cleaned. Tap water was put into the cup until it just covered the lower three balls. A rotational speed of 400 rpm was then adjusted and the test started.

After one hour the test was stopped and the cup removed from its housing for weighing. It was occasionally found that the cup had increased in weight, typically by 0.002 g. This was assumed to be due to water absorption of the polymer. This finding meant that it was not practical to determine the wear rate by weighing the cup. Instead, inspection under a microscope was necessary.

Main Test

The procedure of the main test was as follows:

- cleaning of all elements involved in testing.
- for the first test a speed of 400 rpm was used and the load of 1.5 kg applied on each cup.
- duration of the test: 6 h (which corresponds to 432,000 load cycles).
- inspection of the cup under an optical microscope.
- if inspection revealed no wear signs, the contact load was increased by 0.5 kg and a further 6-h test was run.

For comparison, all polymers were tested under dry conditions.

RESULTS AND DISCUSSION

As mentioned earlier, the attempt to express the wear in quantitative terms failed—mainly due to the absorption of water by the polymers tested. Also, the amount of material loss proved to be minute and difficult to measure with the required degree of certainty. Therefore the post-test examinations were confined to microscopy studies of polymer surfaces within the contact region. In order to do that it was necessary to cut out cup sections to gain access to the area of interest. Rolling contact regions were then examined using a scanning electron microscope. The following discussion emphasizes both the appearance of the polymer surface after the rolling contact test and the morphology of worn surfaces.

Nylon 66

Figure 3 shows the worn area of the nylon 66 cup. The dark band running from right to left in the direction of ball motion, through the center of the photograph, is where the lower balls have made contact with the cup and affected the surface. The smaller gray patchy area covering the bottom half of the contact region is where the material that was detached from the substrate has been reattached to the cup surface.

A close-up of the leading edge of this patch, Figure 4, shows vertical lines of reattached material that have started to form. If the test had continued, these

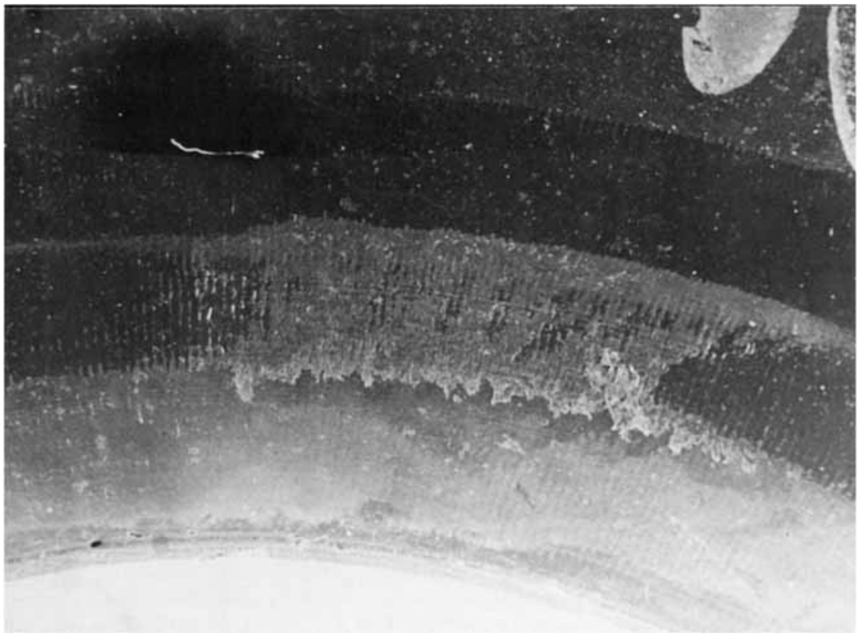

Figure 3 Section of the contact path at magnification (×12). Nylon 6.6 cup. Velocity: 400 rpm. Load on the contact: 120 N. Water lubrication.

lines would have eventually merged and formed an area as seen in Figure 3. There are a number of possibilities as to the reason the polymer has formed these vertical lines. One reason is that a slight vibration of the apparatus might cause the balls to run unevenly on the cup surface, thus attaching material at regular intervals. However, an alternative reason could be that the surface was rippled by the motion of the balls and that the flakes produced by fatigue of the polymer have been reattached to the ripples. Figure 5 shows the extreme bottom edge of the above-mentioned reattached flakes. Here it is

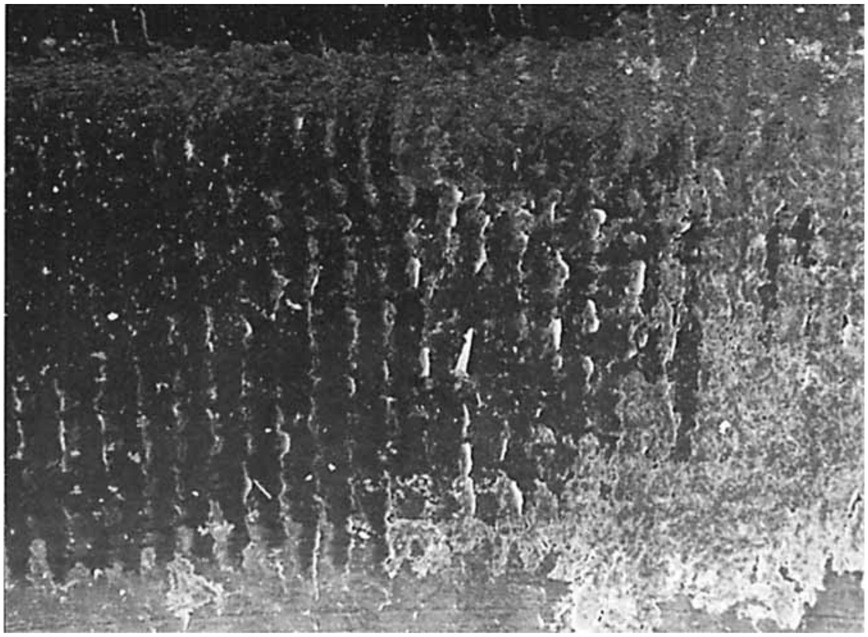

Figure 4 Trailing edge of reattached polymer at magnification (×50). Remaining data as in Fig. 3 legend.

Figure 5 Extreme bottom edge of contact path region at magnification (×500). Remaining data as in Fig. 3 legend.

possible to see how four lines of transferred material are forming into one continuous layer. The photograph also shows how the polymer flakes were pressed on top of each other to form this layer.

The reattached material was further investigated at higher magnification. The photograph in Figure 6 was taken in the center of the above-mentioned region. Again, this shows in more detail how the

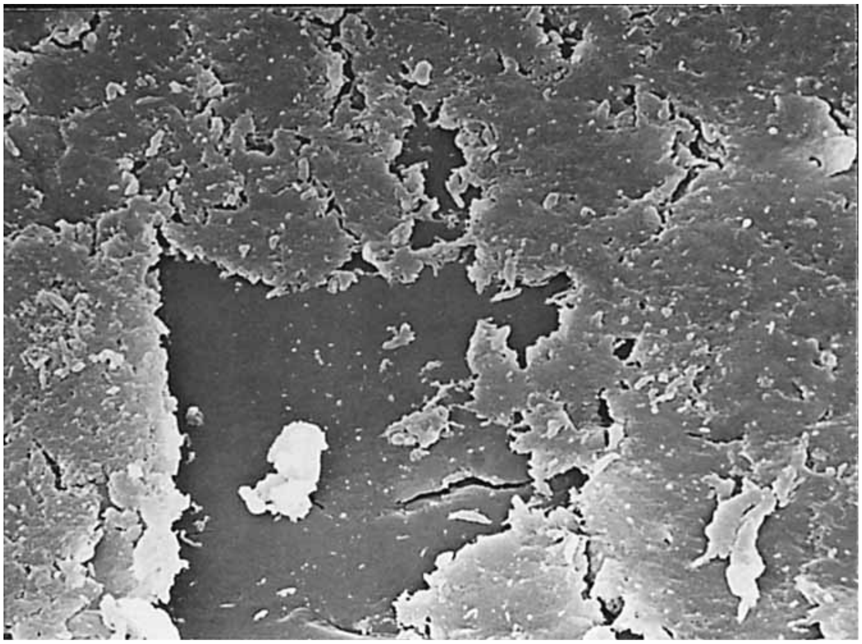

Figure 6 Center of area of reattached polymer at magnification (×2000). Remaining data as in Fig. 3 legend.

Figure 7 Section of the contact path at magnification (×12). Nylon 6.6 cup. Velocity: 400 rpm. Load on the contact: 120 N. Dry conditions.

flakes of polymer detached from the substrate have been reattached to the cup surface. In the region uncovered by the flakes a well-developed crack is visible. Two smaller cracks can also be seen to the left of the larger crack. These are undoubtedly fatigue cracks caused by repeated application of stress as the balls rolled over the cup surface.

Figure 7 shows a similar cup area to that shown in Figure 3, but after a test under dry conditions. A contact path is barely visible as a band running from

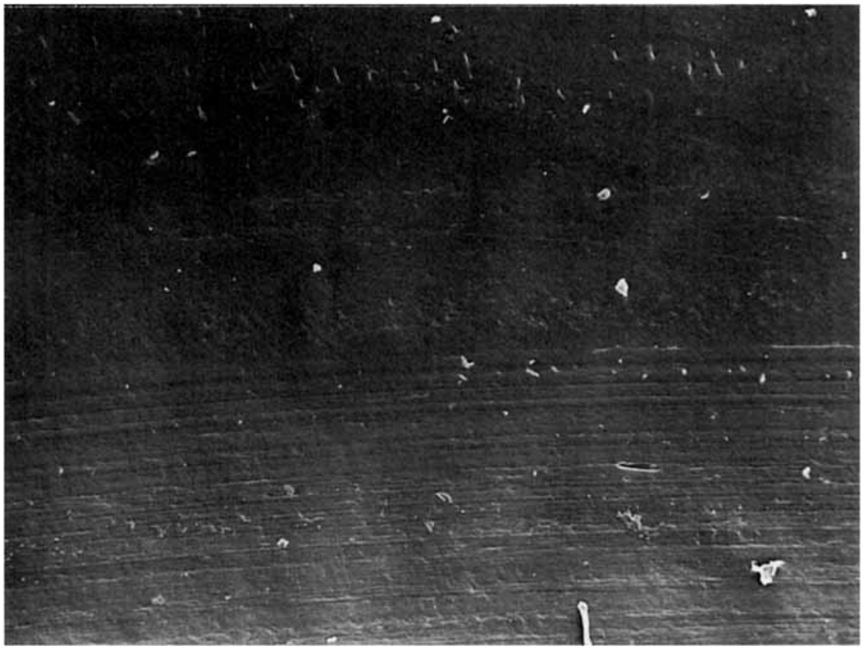

Figure 8 Bottom half of contact path at magnification (×50). Remaining data as in Fig. 7 legend.

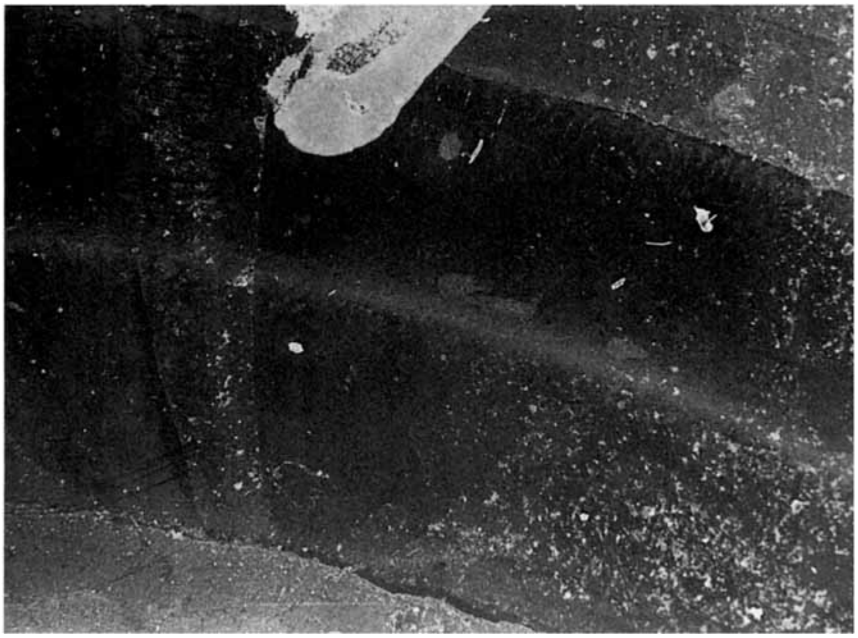

Figure 9 Section of the contact path at magnification (×20). Polyacetal cup. Velocity: 400 rpm. Load on the contact: 160 N. Water lubrication.

right to left across the photograph. Machining marks can still be seen above and below the contact path. Figure 8 shows the same region in more detail at higher magnification.

These results indicate that water used as a lubricating medium has an adverse effect on nylon performance in rolling contact, causing it to deteriorate into a damaged condition faster than when run dry under the same speed and load. Apparently, under rolling contact conditions the presence of water facilitates the weakening of the interchain bonds in the polymer, which results in removing pieces of

Figure 10 Line in the center of the section shown in Fig. 9 at magnification (×2000). Remaining data as in Fig. 9 legend.

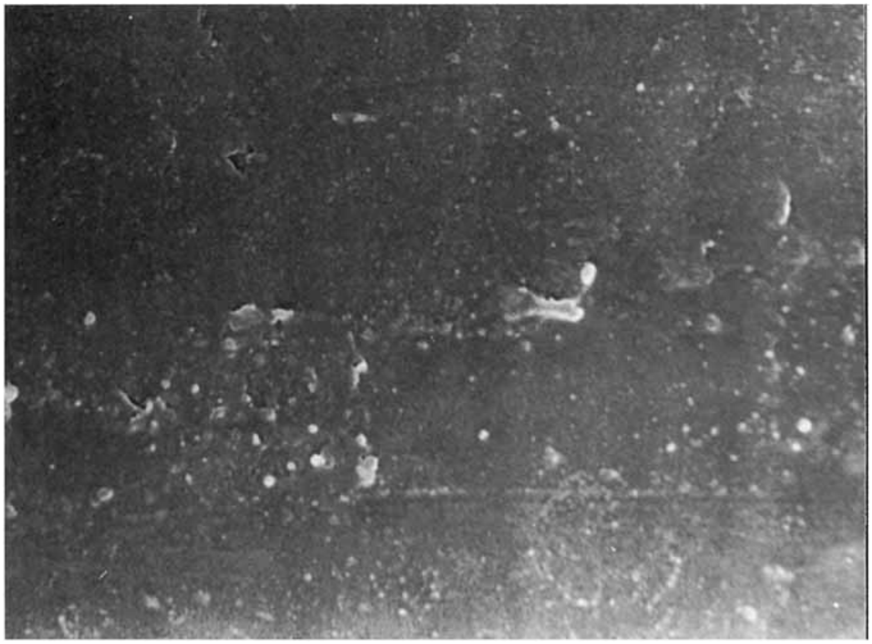

Figure 11 Contact area at magnification (×2000). Remaining data as in Fig. 9 legend.

material more easily than if water is not present. The precise mechanism of the process observed, however, is not known at present and requires further studies.

Polyacetal

The polyacetal cups were also tested under water lubrication and dry conditions, then microscopically examined. Figure 9 shows an affected section of the contact path running from right to left across the photograph in the direction of ball motion. The photograph in Figure 10 was taken to investigate the grey line running through the center of the contact path. This shows how particles of acetal have been reattached to the substrate to form a patchy layer. In contrast, Figure 11 shows the contact area

Figure 12 Extreme edge of contact path at magnification (×250). Remaining data as in Fig. 9 legend.

Figure 13 Contact path at magnification (×20). Polyacetal cup. Velocity: 400 rpm. Load on the contact: 160 N. Dry conditions.

away from the gray line at the same magnification. This shows that the surface is very smooth except where particles of polymer have been removed to leave pits. Presumably, these are the particles that have been deposited to form the above-mentioned gray line. The position of this line indicates that the contact pressure is greatest in the central region of the contact path to press the loose polymer particles into the substrate.

The close-up of the extreme bottom edge of the contact path shown in Figure 9 shows how the material has been pushed out toward the bottom edge

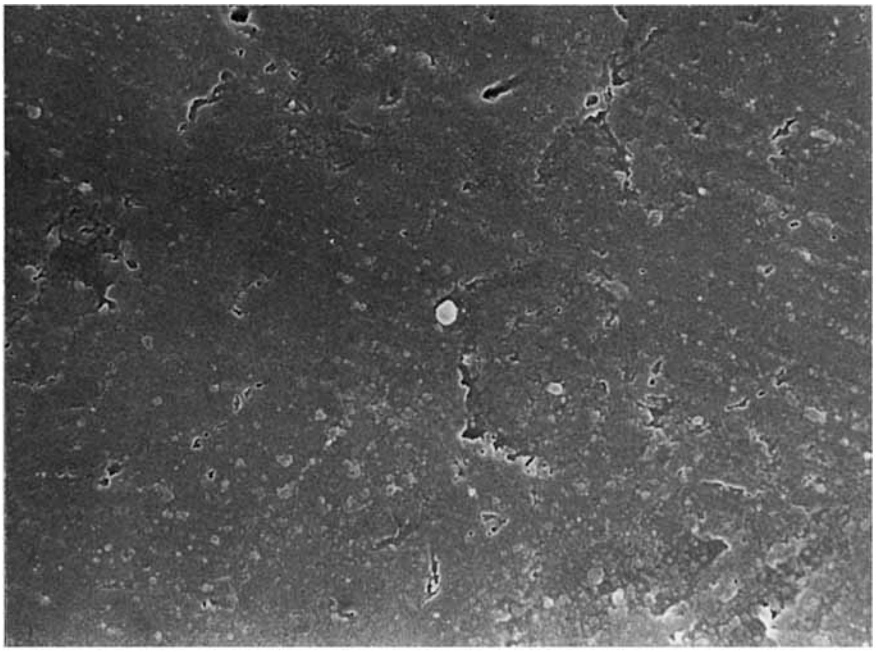

Figure 14 Center of contact area at magnification (×2000). Remaining data as in Fig. 13 legend.

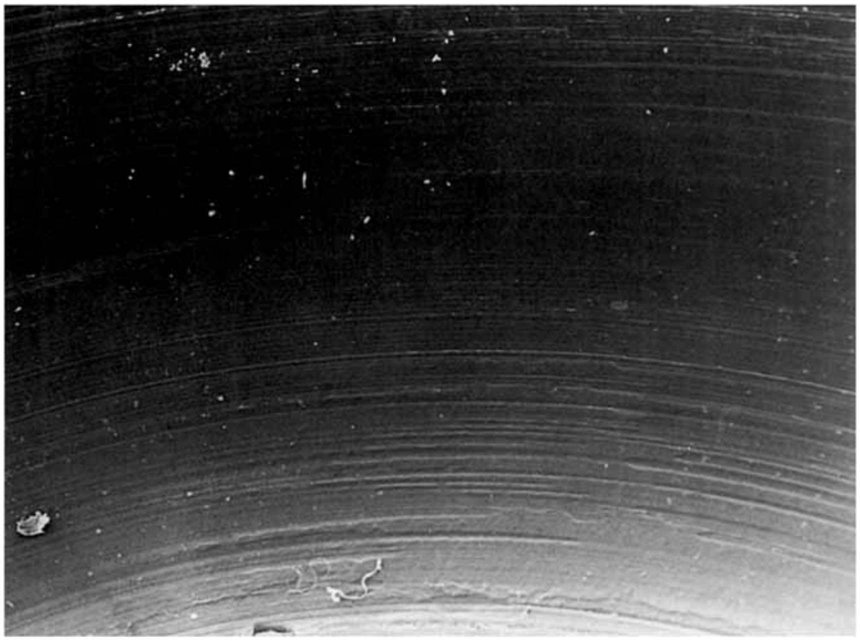

Figure 15 Contact path at magnification (×12). High density polyethylene cup. Velocity: 400 rpm. Load on the contact: 160 N. Water lubrication.

of the cup as the balls rotated (Fig. 12). It points to the considerable flow taking place as a result of combined action of contact stress and the effect of water on the polymer.

For comparison, a polyacetal cup was also tested under dry conditions. Figure 13 shows that in dry conditions the contact area is affected less than it is under water lubrication conditions. At higher magnification, shown in Figure 14, it is seen that some damage has occurred. This could be produced by the action of ball motion causing flattening of machining marks within the contact path.

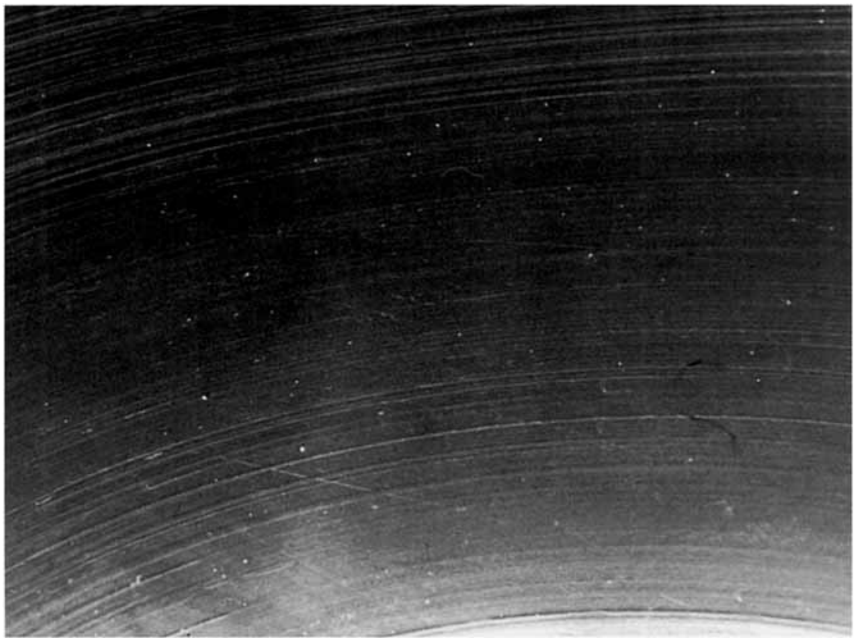

Figure 16 Contact path at magnification (×12). High density polyethylene cup. Velocity: 400 rpm. Load on the contact: 160 N. Dry conditions.

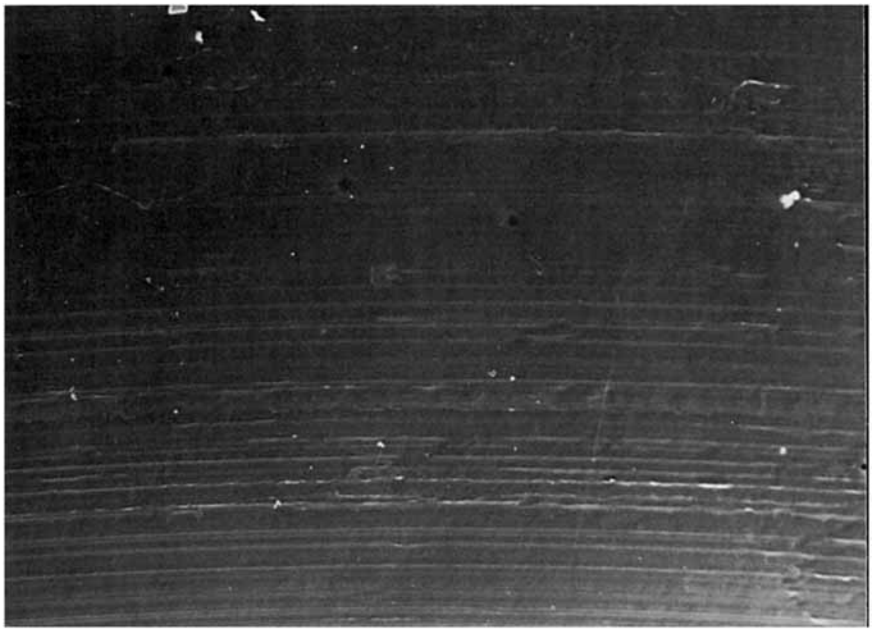

Figure 17 Bottom half of contact path at magnification (×50). Remaining data as in Fig. 15 legend.

Overall, the microscopy studies show that the water has a detrimental effect on the acetal. Water caused more damage than did the same test carried out under dry conditions. However, it should be noted that the acetal performed better than nylon under water lubrication.

High Density Polyethylene

Figure 15 shows the contact path on a high-density polyethylene (HDPE) cup tested under water lubrication conditions, while Figure 16 shows the HDPE cup tested under dry conditions. Both pho-

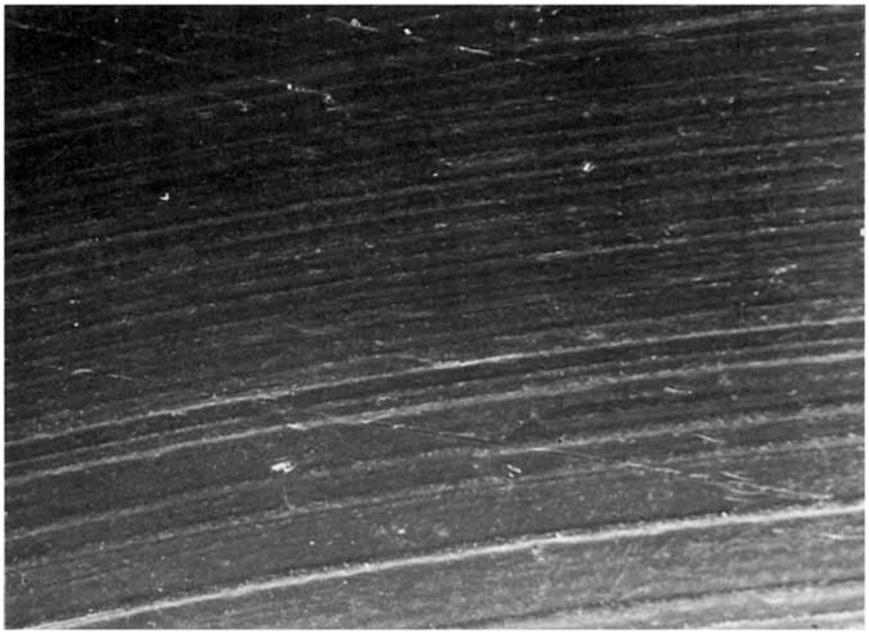

Figure 18 Bottom half of contact path at magnification (×50). Remaining data as in Fig. 16 legend.

tographs were taken at the same magnification, and it can be seen that the machining marks in Figure 16 are only slightly more visible than on the contact path in the center of Figure 15. This indicates that, under the test conditions used, there is very little difference between running wet or dry. Photographs taken at a higher magnification of the same area on both cups show that the cup tested in the presence of water (Fig. 17) has a slightly smoother surface in the top half of the contact path than does the dry-tested cup (Fig. 18). This suggests that the water helped to modify the surface features of the cup.

The general conclusion resulting from rolling contact tests on HDPE is that it is able to operate under water lubrication conditions, since the water affects HDPE to a much lesser extent than it does the other two polymers tested.

CONCLUSION

From the results of the tests it can be determined that water has an adverse effect, but to a different degree, on each of the three polymers studied.

1. When tested in the presence of water, the nylon cup showed fatigue wear. Flakes of polymer were produced and then reattached to the cup surface within the contact path. This transferred material formed a ripple-like layer. Fatigue cracks caused by the cyclic nature of loading were observed on the contact path surface.

   The tests carried out under dry conditions did not produce any of the features mentioned above.
2. Acetal, like nylon, was affected by the presence of water, but to a lesser extent. Similarly, small particles of material detached from the substrate were reattached to the surface of the contact path, but the pattern in which this transferred material was arranged was different from that seen in the nylon.
3. On the basis of available results, it can be said that water is not particularly detrimental to high-density polyethylene. It was found that the performance of high-density polyethylene in rolling contact is practically the same under both dry and wet conditions.

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