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FRICTION AND WEAR OF POLYETHYLENE OXIDE POLYMER HAVING A RANGE OF MOLECULAR WEIGHTS

by Donald H. Buckley

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SUMMARY

An investigation was conducted to determine the effect of molecular weight of a polymer, particularly polyethylene oxide in sliding contact with itself and iron, on its friction and wear behavior. Experiments were conducted in pin (rider) on disk friction and wear experiments at loads of 25 to 250 grams, sliding velocities of 0.1 and 5.0 centimeters per minute, 23° C, and in an argon atmosphere. The polyethylene oxide molecular weights ranged from 100 000 to 5 000 000.

The results of the experiments in this study indicate that, the higher the molecular weight of the polymer, the lower the friction for the polymer sliding on itself and in contact with iron. Friction is higher for the polymer sliding on itself than it is for the polymer sliding on iron. At sufficiently high loads localized melting on the polymer occurs at the surface and friction coefficients are equivalent whether the polymer is in sliding contact with itself or iron. Tensile fracture cracks are observed in the wear track of the polymer at 5.0 centimeters per minute but not at 0.1 millimeter per minute, indicating strain rate sensitivity of the polymer to fracture crack formation. Where the polymer is in sliding contact with iron, a transfer film of the polymer to the iron surface develops. Friction coefficient is higher in the presence than in the absence of this film.

INTRODUCTION

Polymers and polymer composites are being increasingly used in place of metals in a host of industries (ref. 1). As a consequence, the friction and wear behavior of polymers and those properties which influence friction and wear are increasing in importance. Properties of polymers investigated in relation to their effect upon polymer friction and wear have included film forming tendencies (ref. 2), polar nature (ref. 3), deformation behavior (ref. 4), bulk mechanical properties (ref. 5), molecular structure (ref. 6), transfer behavior (ref. 7), and crystalline transitions (ref. 8).

Most polymeric materials used in components of lubrication systems can and do vary in molecular weight. Further, the molecular weight distribution can be different for different lots of the same material. It would therefore be desirable to know what effect, if any, molecular weight has on the friction and wear behavior of polymers.

The objective of the present investigation was to examine the effect of molecular weight on the friction and wear behavior of a polymer, polyethylene oxide in a range of molecular weights from 100 000 to 5 000 000 in contact with itself and iron. Friction and wear experiments were conducted with a hemispherical rider sliding in reciprocal motion on a flat disk surface. Reciprocal sliding was at velocities of 0.1 and 5 centimeters per minute, loads of 25 to 250 grams, and 23° C in a dry (<20 ppm H_2O) argon atmosphere.

MATERIALS

The polymeric compositions used in this investigation were prepared in the laboratory from research grade high purity well characterized polymers. Powders of the polymers were placed in metallurgical dies pressed to a pressure of 2.8×10^7 newtons per square meter and held at that pressure and a temperature of 150° C for 1 hour. Specimen configurations for friction and wear experiments were prepared from the molded material by dry machining. Typical properties of the polymer are listed in table I.

The iron used in these studies was 99.99 percent pure, large grained, and fully annealed. The specimens were polished on metallurgical papers down to 600 grit and were then electropolished. After electropolishing the specimens were rinsed with distilled water, rinsed with 200 proof ethyl alcohol, and then stored in a dessicator until ready for use.

APPARATUS

The apparatus used in this investigation is shown schematically in figure 1. It consisted essentially of the specimens, a 1.25-millimeter-radius iron or polymer rider, and a flat of iron or polymer 25.4 millimeters in diameter. The flat specimens were mounted in a vise on a miniature table which was driven back and forth by a mechanical drive system containing a gear box, a set of bevel gears, and a lead screw driven by an electric motor. Total distance of travel was 15.0 millimeters in one direction. Microswitches located at each end of the traverse reversed the direction of travel so that the iron or polymer retraced the original track from the opposite direction. This process was continuously repeated for a duration of 1 hour.

The iron or polymer rider was loaded against the flat disk with dead weights. The arm retaining the rider contained strain gages which continuously monitored the friction force.

The arm containing the rider could be moved normal to the direction of the wear tracks. Thus, multiple tracks could be generated on a single surface.

The small electric motor had a variable speed gear box which allowed for altering the sliding velocities in reciprocal sliding. Load also could be varied from 0 to 250 grams. The entire apparatus was housed in a plastic box. The atmosphere in the box could be closely controlled.

EXPERIMENTAL PROCEDURE

The iron rider and flat specimens were cleaned with levigated alumina, rinsed with distilled water, and then rinsed with 200-proof ethyl alcohol. Surfaces were dried with dry nitrogen gas. The specimens were then mounted in the apparatus. Polymer riders and flats were abraded with 400-grit abrasive paper and rinsed with 200-proof ethyl alcohol.

Load was applied to the iron rider. The cover of the plastic box was closed and the entire system purged with a positive pressure of argon gas for a period of 15 minutes prior to the initiation of sliding.

After completion of the purge, sliding was initiated and continued for a period of 1 hour. Friction force was continuously recorded for the 1-hour period. The wear scar width on the flats of polymers was measured upon completion of the experiment.

RESULTS AND DISCUSSION

Sliding friction experiments were conducted with various molecular weights of polyethylene oxide polymer sliding against itself and iron. When in contact with iron in one set of experiments, the rider was iron and the flat was polymer, and in the second set of experiments the rider was polymer and the flat was iron. The results obtained in these experiments are presented in figure 2.

Examination of figure 2 reveals that with all three specimen combinations friction coefficient decreased with increasing molecular weight of the polyethylene oxide. The greatest reduction occurred with the lower molecular weights. It is apparent from figure 2 that, with polyethylene oxide, the higher the molecular weight, the lower the friction. A similar behavior may exist for other polymers.

Friction coefficient for the polymer sliding on itself in figure 2 is higher than for the polymer in contact with iron. Examinations of the wear surfaces revealed some differences in wear behavior.

With the polyethylene oxide sliding on itself a number of events are seen to take place in the contact zone of the surface as indicated in figure 3. In some regions a surface glaze appears indicating some localized surface melting of the polymer during sliding. This is localized and does not occur over the entire contact region. Two forms of polymer removal are also observed. In the first ribbons of polymer material were generated from the surface as indicated in figure 3. These stand above the flat surface of the polymer.

Cavities or pits are also observed in the rubbing surface. Their presence is indicated in figure 3. It appears that particles of polymer are removed from the bulk. Figure 3 is representative of what is observed for all molecular weights with the polymer sliding on itself.

In contrast, where the polymer is in sliding contact with both iron riders and iron flats, a high degree of localized surface melting of the polymer occurs as evidenced by the photomicrographs of figure 4. Figure 4(a) is the polyethylene oxide polymer surface after having been rubbed by an iron rider. Surface melting occurred over most of the contact zone.

Likewise, with the polymer rider sliding against the iron flat surface melting of the polymer occurs as indicated in figure 4(b). When the polymer was in sliding contact with the iron, there was not evidence for polymer ribbon formation or plucking out of polymer from the bulk as was observed in figure 3.

The differences in friction behavior seen in figure 2 may be explained by the differences in the surfaces of figures 3 and 4. Where iron contacts the polymer and melting occurs (fig. 4), lower friction would be observed than where plucking out of the polymer takes place (fig. 3). Thus, lower friction might reasonably be anticipated with the polymer in contact with iron as is observed in the data presented in figure 2.

With the polymer sliding on iron localized melting of the polymer occurs at the interface and the solid polymer is sliding on a thin film of itself. Because the interfacial film is melted, the shear strength and correspondingly the friction forces are low. When the polymer is in solid state contact with itself, strong adhesive bonds develop across the interface and the friction force now represents the force to fracture cohesive bonds in the polymer, a much higher force. While the iron is a good thermal conductor, the polymer is sliding on a thin film of transferred polymer for the iron-polymer couple and thermal conduction is poor.

With the polymer contacting iron a polymer transfer film was observed on the surface of the iron. This film did not transfer with a single pass but gradually built up with repeated passes. This is reflected in the friction coefficients measured in figure 5 with repeated reciprocal passes over the same iron surface.

In figure 5 the coefficient of friction was slightly greater than 0.5 during the first sliding pass. It continuously increased with repeated numbers of sliding passes to 25 passes, where the friction coefficient was in excess of 0.8. Beyond 25 passes the friction coefficient remained relatively unchanged. The higher stable friction value is for the polymer sliding on a thin film of itself. The higher value is still less than that observed for bulk polymer sliding on bulk polymer in figure 2.

Since from examination of the polymer surface after sliding (figs. 3 and 4) evidence for localized melting was observed, it might be anticipated that the amount of this localized melting would increase with increases in the rate of energy dissipation at the interface. The rate of energy dissipation at the interface can be varied in a number of ways such as by increasing sliding velocity and/or load. Load was varied for the polymer polyethylene oxide, molecular weight 100 000, sliding on itself and in sliding contact with iron. Results obtained in these experiments are presented in figure 6.

As the load was increased for the polyethylene oxide sliding on itself, the steady state coefficient of friction continuously decreased as indicated in figure 6. The initial friction coefficient was 1.2 at a load of 25 grams. At 250 grams the friction coefficient had decreased to 0.4, a threefold reduction in friction with the increase in load. Evidence for interfacial melting, as was observed in figures 3 and 4, occurred in the entire contact zone after sliding with a 250-gram load.

With the polyethylene oxide in sliding contact with either a rider or flat of iron the friction coefficient is less than that for the polymer sliding on itself at 25 grams. Whether the rider or the flat is iron does not appear to affect the measured friction coefficient as it is essentially the same for both configurations. The friction coefficient decreased sharply with increase in load from 0.8 at a 25-gram load to 0.4 at a load of 100 grams. Beyond 100 grams there was essentially no further change in friction coefficient. It remained at a value of approximately 0.4.

The data of figure 6 indicate that, at a load of 250 grams, the measured friction coefficients for all three specimen combinations were essentially the same. Examination of the polymer surface from each set of experiments at a 250-gram load indicated evidence for localized melting of the polymer in the contact zone on each polymer surface. Since the friction force is being determined by the shear of the same highly viscous liquid, it is understandable that the friction coefficients would be essentially the same.

Wear to the polyethylene oxide was also examined. The sliding velocity was increased from 0.1 to 5.0 centimeters per minute, and sliding friction and wear experiments were conducted with a range of molecular weights for polyethylene oxide in sliding contact with itself and iron. The sliding velocity was increased to allow for sufficient wear to occur in a reasonable period of time and to increase the reliability of the resulting measurements. All wear measurements were to the polymer only as there was no evidence whatsoever for wear to the iron rider or disk.

Polyethylene oxide wear scar width as a function of molecular weight is presented in the data of figure 7. The wear scar width as a function of molecular weight indicates that the wear behavior of polyethylene oxide, in contrast to friction behavior, is not affected by the molecular weight of the polymer, for the polymer in contact with iron. With the polymer in contact with itself, molecular weight does have an effect on wear scar width to a molecular weight of 600 000, beyond which no further effect is detected.

The greatest amount of wear was observed for the polyethylene oxide sliding on iron. With reciprocal sliding, transfer and buildup of the polymer on the iron flat surface is observed. Adhesion of the polymer to the metal surface must first occur and then with tangential motion transfer to the metal results when shear occurs in the polymer. The development of the transfer film of polymer to the iron results from wear of the polymer rider.

When the polymer is in rubbing contact with itself, adhesion of the polymer to itself also occurs. With tangential motion shear occurs in an interfacial layer of polymer. Polymer is, however, not lost from one surface via a transfer mechanism as is observed for the polymer in contact with an iron flat.

Very strong adhesion of the polymer to itself occurs for the polyethylene oxide sliding on polyethylene oxide. This is reflected in friction measurements and in surface topography. In figure 8 the wear surface of the 200 000 molecular weight polyethylene oxide is presented. Fracture cracks are present in the wear track. These tensile fracture cracks develop with the adhesion of the polymer to itself and subsequent attempted tangential motion.

The tensile fracture cracks observed for the polyethylene oxide in sliding contact with itself were not observed in figure 3 at a lower sliding velocity. Since fracture is a strain rate sensitive mechanism, it is not surprising that with an increase in sliding velocity cracks begin to appear in the polymer surface.

In figure 7 the least amount of wear was observed with an iron rider sliding on a polyethylene oxide flat. The radius of the slider causes deformation in the polymer. Adhesion of the polymer to the rider occurs and ultimately the polymer is sliding against a thin film of itself just as with the polymer rider contact with the polymer disk. This accounts for the similarity in friction coefficients seen in figures 2 and 6. Unlike with the polymer sliding on the metal flat, however, the total area of metal contact with the polymer during sliding is appreciably less when the polymer is contacted by the iron rider.

The total metal surface area contacted by the polymer rises while in reciprocating sliding; it is the width of the scar times the total distance traveled and is 4×10^{-2} square centimeter, while for the iron rider it is only the tip of the rider and a circular area of 7.5×10^{-5} square centimeter. Thus, if adhesion to the iron and the subsequent shear in the polymer contribute to total polymer wear, then it is anticipated that the wear for polymer rubbing on the metal would higher than for the metal rubbing on the polymer.

The friction behavior of the polyethylene oxide was sensitive to the direction of sliding indicating an orientation effect. The effect can be seen in the data of figure 9 for the polyethylene oxide sliding on itself. The right side of the figure is the friction behavior in one direction of sliding and the left side is the measured friction force when the direction of sliding is reversed. Stick-slip is observed in both sliding directions. The amplitude in one direction is, however, much greater than in the opposite direction. This effect was observed with all molecular weights of polyethylene oxide but was more pronounced with the lower molecular weight specimens. Rotating the specimen 180° produces the same result. It is, however, not seen with polytetrafluoroethylene or high-density polyethylene.

CONCLUSIONS

Based upon the experimental results obtained in this investigation with polyethylene oxide polymer in rubbing or sliding contact with itself and iron, the following conclusions are drawn:

1. A relation between friction coefficient and molecular weight of the polymer exists. The higher the molecular weight, the lower the friction coefficient.
2. Friction coefficient is higher for the polymer sliding on itself than it is for the polymer in sliding contact with iron, at light loads.
3. At sufficiently high load localized melting of the polymer surface occurs resulting in an equivalence in friction coefficient whether the mating surface is the polymer itself or iron.
4. At sufficiently high sliding velocities tensile fracture cracking of the polymer occurs in the wear contact zone. This cracking is not observed at lower sliding velocities and reflects the strain rate sensitivity of the polymer for fracture crack formation.
5. For polymer sliding on iron the friction increases with repeated sliding on the same surface until a transfer film is formed and the polymer slides on a thin film of itself at which time no further changes in friction are observed.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, September 22, 1977,
506-16.

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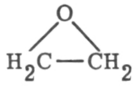
TABLE I. - PROPERTIES OF POLYETHYLENE

OXIDE POLYMER

Structure (monomer)	
Molecular weight (monomer)	44.05
Density at 0° C, g/cc	1.04
Refractive index (n^7 D)	1.3597
Melting point, $^{\circ}$C	65
Brittle temperature, $^{\circ}$C	-50
Tensile strength, N/m^2	1.26×10^{7} to 1.68×10^{7}
Yield strength, N/m^2	0.7×10^{7} to 1.05×10^{7}
Ultimate elongation, percent	700 to 1200
Extension at yield, percent	5 to 30
Tensile modulus, N/m^2	21×10^{7} to 49×10^{7}
Shore hardness (A scale)	99
Glass transition temperature, $^{\circ}$C	
100 000 mol. wt.	-20
1 000 000 mol. wt.	-55

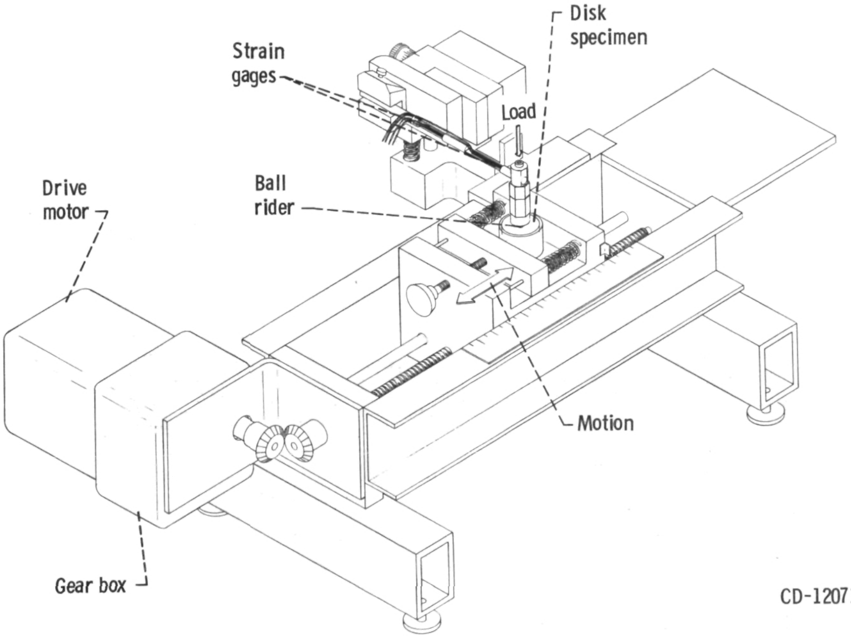


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Figure 1. - Friction and wear apparatus.

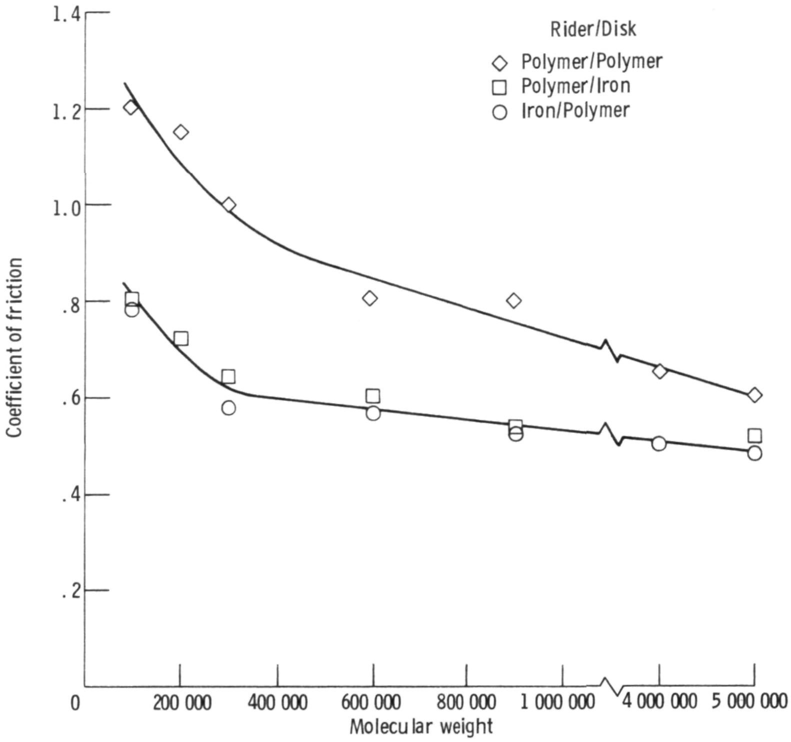


Figure 2. - Average coefficient of friction for polyethylene oxide polymer sliding on itself and iron as a function of molecular weight. Sliding velocity, 0.1 centimeter per minute; load, 25 grams; temperature, 23° C; argon atmosphere.

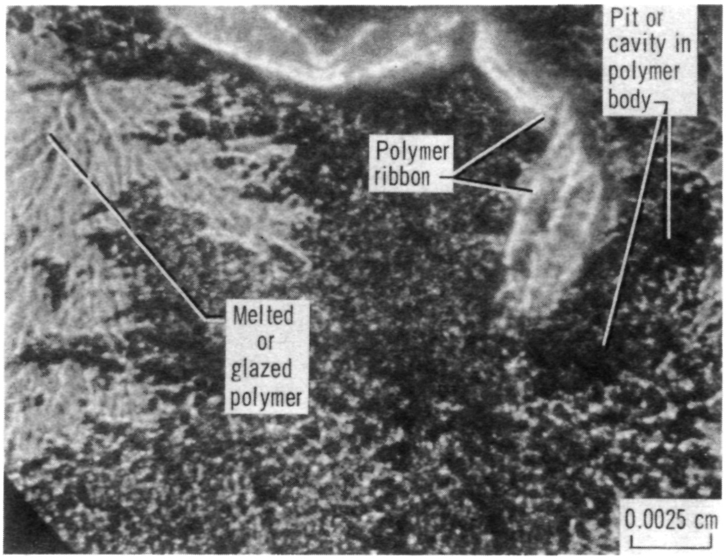
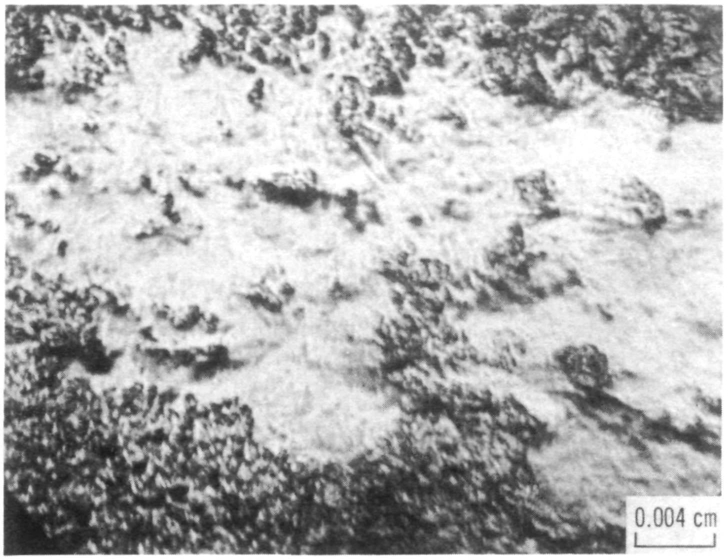
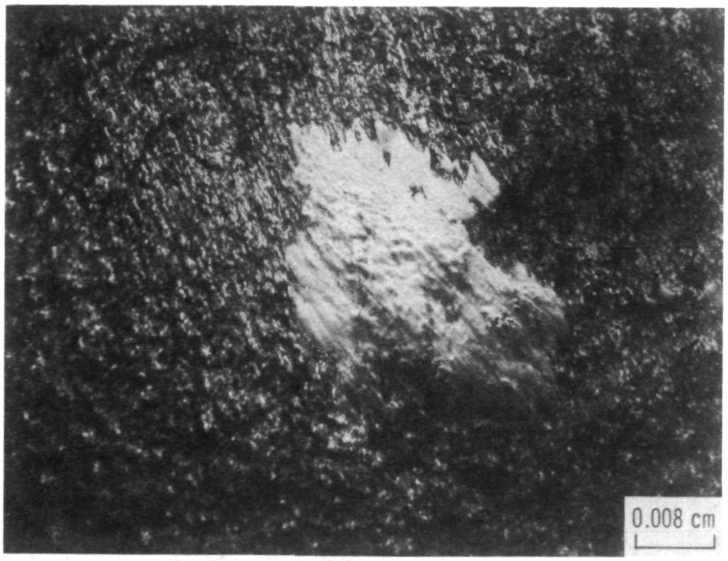


Figure 3. - Wear surface of polyethylene oxide disk (200 000 mol. wt.) after sliding contact with polyethylene oxide rider (200 000 mol. wt.). Sliding velocity, 0.1 centimeter per minute; load, 25 grams; temperature, 23° C; duration, 1 hour; argon atmosphere.



(a) Disk (iron on polymer).



(b) Rider (polymer on iron).

Figure 4. - Wear scar of polyethylene oxide polymer with 200 000 molecular weight after sliding against iron. Sliding velocity, 0.1 centimeter per minute; load, 25 grams; temperature, 23° C; duration 1 hour, argon atmosphere.

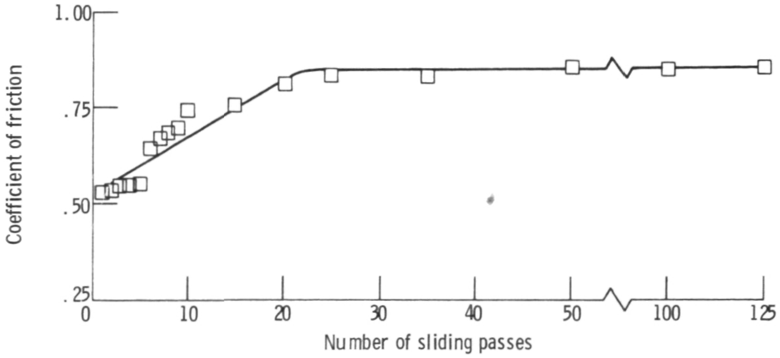


Figure 5. - Average coefficient of friction as a function of number of repeated passes of 100 000 molecular weight polyethylene oxide polymer sliding on iron. Sliding velocity, 5.0 centimeters per minute; load, 25 grams; temperature, 23° C; argon atmosphere.

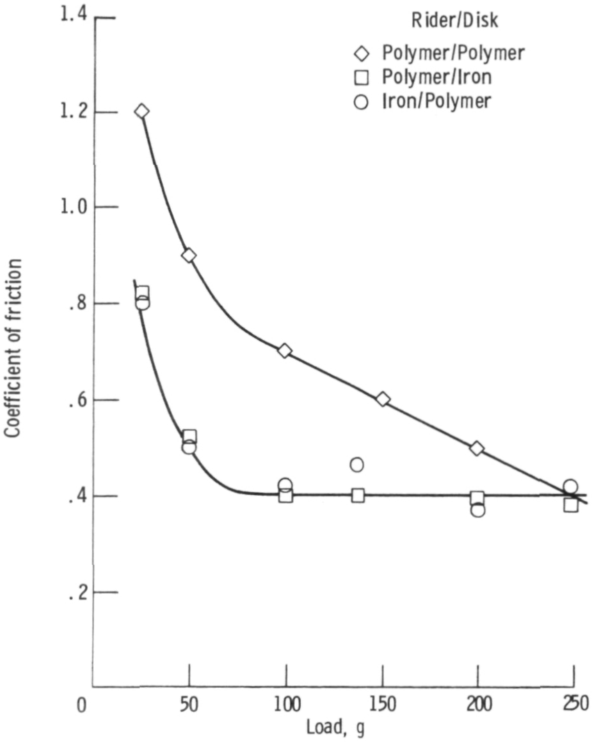


Figure 6. - Average coefficient of friction as a function of load for polyethylene oxide polymer sliding on itself and iron. Sliding velocity, 0.1 centimeter per minute; temperature, 23° C; argon atmosphere.

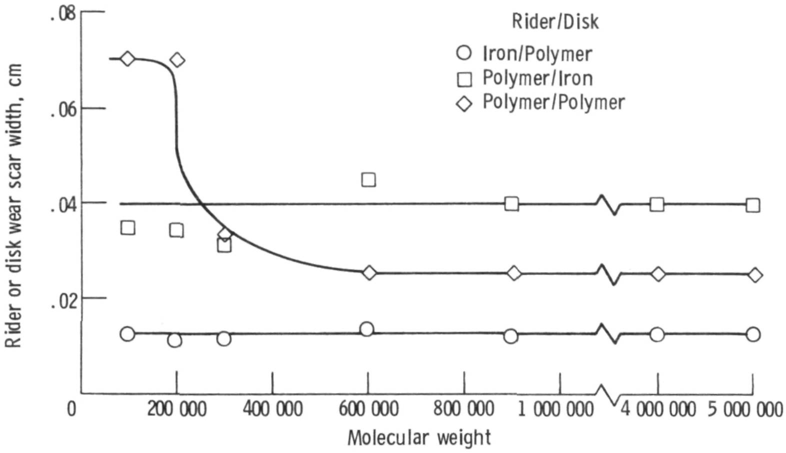


Figure 7. - Rider or disk of polymer wear scar width as a function of polyethylene oxide polymer molecular weight. Sliding velocity, 5.0 centimeters per minute; load, 25 grams; temperature, 23° C; argon atmosphere.

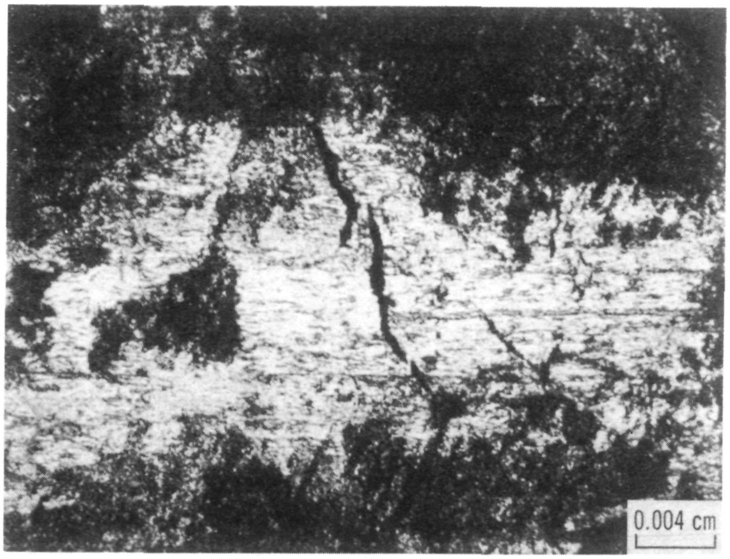


Figure 8. - Disk wear scar of 200 000 molecular weight polyethylene oxide polymer in sliding contact with itself. Sliding velocity, 5.0 centimeters per minute; load, 25 grams; temperature, 23° C; duration, 1 hour; argon atmosphere.

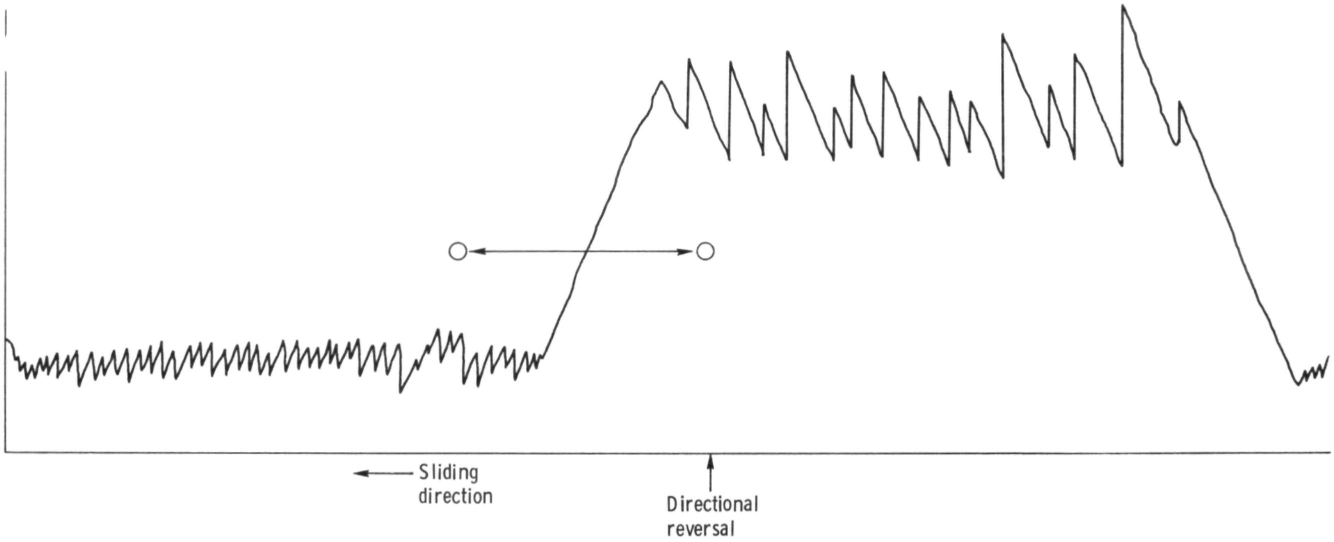


Figure 9. - Friction force for 100 000 molecular weight polyethylene oxide sliding on itself. Sliding velocity, 0.1 centimeter per minute; load, 25 grams; temperature, 23° C; argon atmosphere.

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16. Abstract

Sliding friction and wear experiments were conducted at light loads (25 to 250 g) with various molecular weights of polyethylene oxide polymer sliding on itself and iron. Results of the experimental investigation indicate that (1) the coefficient of friction for the polymer decreases with increasing molecular weight, (2) friction coefficient is higher for the polymer sliding on itself than it is for the polymer sliding on iron, (3) at sufficiently high loads localized surface melting occurs and the friction coefficient is the same for the polymer sliding on itself and iron, (4) fracture cracks develop in the sliding wear track at higher but not lower sliding velocities, reflecting a strain rate sensitivity to crack initiation, and (5) the friction coefficient for the polymer sliding on iron increases with the formation of a polymer film on the iron surface.

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