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FRictionAL PROPERTIES OF POLYETHYLENES AND PERFLUOROCARBON POLYMERS

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ABSTRACT

Friction was measured at 25°C for steel sliding on polytetrafluoroethylene (TFE), a copolymer of tetrafluoroethylene and hexafluoropropylene (FEP), three high-density polyethylenes (HDP), and two low-density polyethylenes (LDP) at a velocity of 0.01 cm/sec and with a load of 1000 grams. The static coefficient of friction (μ_s) with a clean steel slider for all the polymers and the kinetic coefficient of friction (μ_k) for LDP are of the order predicted by the adhesion theory. The experimental values of μ_k are much smaller than the calculated values with TFE, FEP, and HDP because of the low specific adhesion between these polymers and their films which have transferred to the steel slider. The value of μ_k for FEP was found to be greater than that of TFE by a factor of three. Similarly, μ_k for LDP was three times that of HDP. These large differences are explained by the differences in the nature of the transferred polymer films and real areas of contact. All these polymers are potentially excellent dry-film lubricants when used as thin films on a hard backing.

Friction was also determined for FEP as a function of the load in the range 100 to 10,000 grams. Static friction was not proportional to the load and μ_s increased rapidly as the load was decreased below 1000 grams. It was concluded that the real area of contact was not proportional to the load and that the deformation of contacting asperities was not completely plastic.

PROBLEM STATUS

This is an interim report; work on this problem is continuing.

AUTHORIZATION

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FRICTIONAL PROPERTIES OF POLYETHYLENES AND PERFLUOROCARBON POLYMERS

INTRODUCTION

High polymers have become increasingly more important as dry-film lubricants and as materials for constructing unlubricated bearings and gears. They are especially suitable where liquid lubricants may be an explosion hazard, a source of contamination, or difficult to replenish. High polymers also promise a solution for lubrication of mechanisms which must operate in near vacuum where liquids may evaporate.

One of the most promising of these polymers is polytetrafluoroethylene (TFE). TFE has uniquely low frictional properties (1-3) but one limitation to its use is the difficulty in molding or forming it into a desired shape. Another perfluorocarbon polymer (FEP) has recently been prepared by the copolymerization of tetrafluoroethylene and hexafluoropropylene which, unlike TFE, can be processed in conventional plastic injection-molding and extruding equipment (4). Both perfluorocarbon polymers have remarkable resistance to chemical attack and are similar in most physical properties, but the FEP resin is softer and melts at a lower temperature (285°-295°C) than the crystalline melting point of TFE (327°C). TFE resins do not melt and flow in the same manner as conventional thermoplastics - at temperatures above 327°C they become an amorphous gel and retain considerable mechanical strength even in this noncrystalline state.

The frictional properties of FEP resin have been investigated and compared with the frictional properties of TFE resin. A similar study was also made of the frictional properties of high-density (or low-pressure) polyethylenes (HDP) and low-density polyethylenes (LDP) for comparison purposes.

Much of the experimental data on the friction of plastics has been successfully discussed in terms of the adhesion theory of friction. This theory, which evolved from the study of metallic friction (5), was subsequently applied to polymers (2,3,6). In the adhesion theory a careful distinction is made between the real and apparent (geometric) areas of contact. The real area is the sum of the many small areas where the surface irregularities (asperities) are in intimate contact, and the apparent area is the total area over which these contacting asperities are scattered. A major component of the frictional force is attributed to the force required to shear all the junctions and may be expressed by the equation

$$F = A_r S \quad (1)$$

where F is the friction, A_r the real area of contact, and S the force required to shear a unit area. It has been observed that with nearly all clean sliding solids, the adhesion at the contacting asperities is greater than the strength of the softer material. Shearing then occurs within the softer solid rather than at the interface so that S in Eq. (1) equals the shear strength of the softer material. If the contacting asperities are plastically deformed, the real area of contact is related to the load by

$$A_r = L/P. \quad (2)$$

In the above equation L is the load or normal force and P is the mean yield pressure of the softer material. The coefficient of friction μ is then determined by the physical properties of the softer solid and may be expressed by

$$\mu = \frac{F}{L} = \frac{A_r S}{A_r P} = \frac{S}{P} \quad (3)$$

EXPERIMENTAL TECHNIQUE

The apparatus (7) used is a modified Bowden-Leben machine which measures friction between an elastically restrained slider and a plane surface driven at a uniform velocity. In these experiments the sliders were 1/2-inch-diameter spheres of hardened 52100 steel. The plastic specimens were either rectangular parallelepipeds or disks with a minimum thickness of 1/4 inch. Sliders were degreased by repeated rinsing in a Soxhlet extractor using ACS grade benzene. The TFE and FEP specimens were cut from a thick sheet. Polyethylene samples were molded from powder and allowed to cool slowly in the press to permit maximum crystallization. The surface of the plastic specimen was prepared by gentle abrasion on 600-A grit silicon carbide paper under running water. They were then washed with Tide, rinsed in a stream of tap water, rinsed in distilled water for one hour, and then dried in a desiccator containing CaSO_4 for a minimum of 16 hours. After being abraded the specimens were handled only with grease-free tongs.

EXPERIMENTAL RESULTS

Friction of Steel Sliding on FEP and TFE

Friction between a steel slider and a FEP flat was measured at 25°C as a function of the number of unidirectional traverses using a sliding velocity of 0.01 cm/sec and a load of 1000 grams.

The first traverse, which was 4 mm long, was made perpendicular to the abrasion striations using a clean slider and a new area of the plastic. Subsequent traverses were made with the same slider over the central 2 mm of the wear path produced on the polymer surface by the first traverse. At the completion of each traverse the load was removed and the slider repositioned so that sliding was always in the same direction. The data are summarized in Fig. 1 in which the static coefficient of friction μ_s and kinetic coefficient of friction μ_k are shown as a function of the number of unidirectional traverses. A typical friction trace for a first traverse is shown in Fig. 2 with μ_s and μ_k indicated. Static friction was much higher on the first traverse (Fig. 1) than on the second. During subsequent traverses μ_s decreased slightly (from 0.26 to 0.24) and then remained nearly constant. In contrast, μ_k remained at 0.18 throughout all the traverses.

Several experiments were performed to determine whether a change in the surface of the slider or FEP was responsible for the abrupt decrease in μ_s between the first and second traverse. The effect of any change in the polymer surface was eliminated by first using a clean slider over a new area of the FEP and then making the second traverse with the same slider over another new area. The value of μ_s for the latter traverse was 0.29. On comparing this value of μ_s with that of the original first traverse (0.37) and that of a second traverse made over the same wear path (0.26), it was evident that most of the decrease in μ_s was a consequence of a change to the slider during the first traverse. The effect of any change of the slider was excluded by substituting a new slider before making a second traverse over the initial wear path ($\mu_s = 0.33$). The decrease in μ_s between the first and second traverses (0.37 to 0.33) was not as great as the reduction when the second traverse was made with the same slider over a new area of polymer surface. Thus, although both slider and FEP surfaces are altered by sliding, the change to the slider exerts the greater effect on friction. Evidently the steel slider was altered during the first traverse by the adhesion and transfer of some FEP resin to its surface. At the same time the traversed bulk FEP may have become work-hardened in the wear path and may even have developed a preferred orientation of the surface molecules. Either effect would be expected to cause some reduction in μ_s .

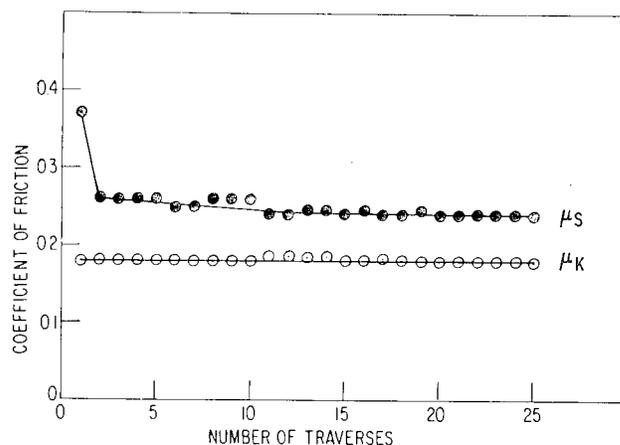


Fig. 1 - Coefficient of friction of steel sliding on FEP as a function of the number of traverses. Load = 1000 grams; velocity = 0.01 cm/sec; temperature = 25°C.

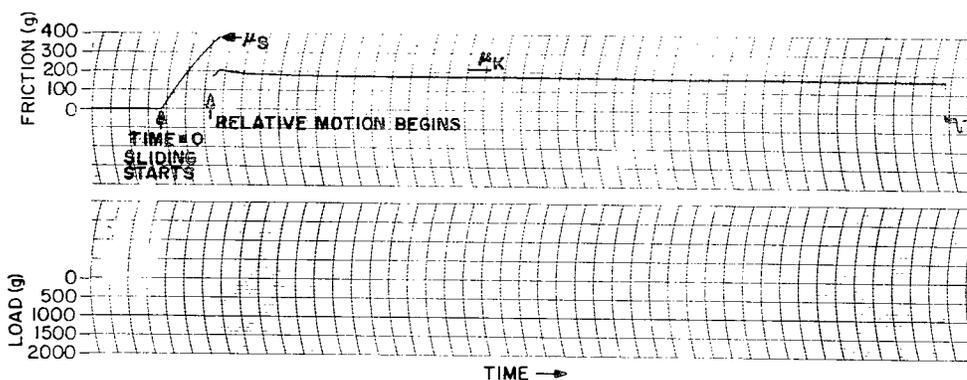


Fig. 2 - Typical friction trace for steel sliding on FEP (first traverse)

The variation of μ_s and μ_k for a first traverse of steel on FEP as a function of the load is shown in Fig. 3. These measurements were made at 25°C and at a sliding speed of 0.01 cm/sec. It was found that μ_s decreased rapidly as the load was increased from 100 to 1000 grams and then decreased more gradually approaching asymptotically a value of about 0.3 at larger loads. This departure of μ_s from Amonton's 1st law - friction is independent of the load - has been observed with other polymeric solids (8-10). It has been proposed that the deformation of the polymer may not be completely plastic and hence the area of contact is not proportional to the load. Evidence supporting this idea is given in Fig. 4 in which the square of the track width, which is proportional to the apparent area of contact, is plotted as a function of load on logarithmic coordinate paper. The points lie nearly on two straight lines; the first includes loads from 100 to 1000 grams and the second includes loads from 2000 to 10,000 grams. It should be noted that the slope of the curve of μ_s vs load (Fig. 3) also changed at approximately 1000 grams. These straight lines may be represented by the equation

$$T_w^2 = a L^k \tag{4}$$

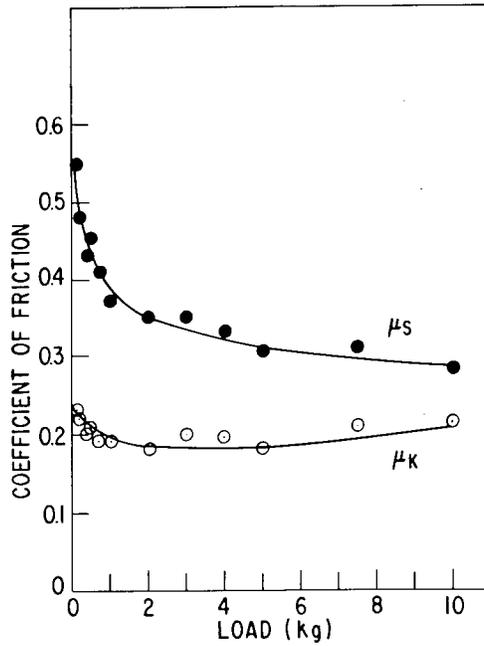


Fig. 3 - Coefficient of friction of steel sliding on FEP as a function of the load (first traverse). Velocity = 0.01 cm/sec; temperature 25°C.

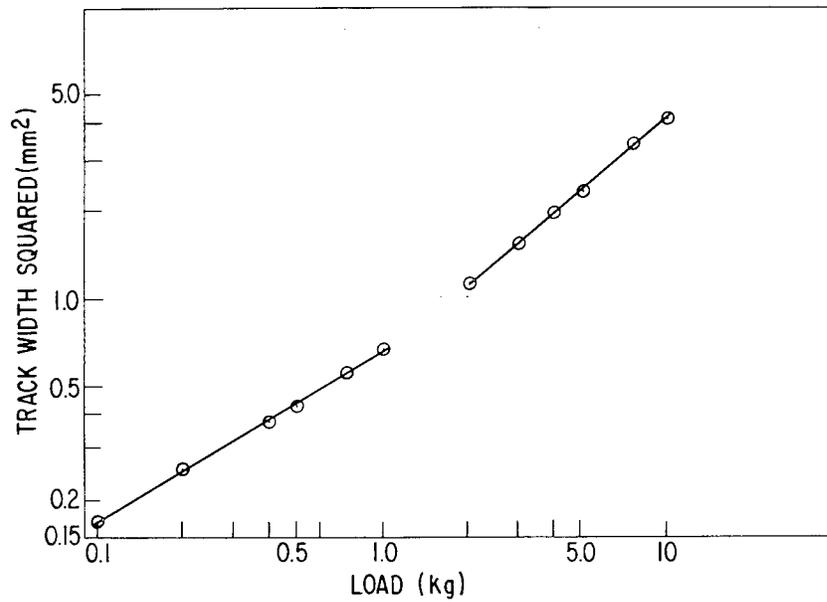


Fig. 4 - Track area as a function of the load for steel sliding on FEP

where T_w is the track width, L is the applied load, and a is a constant of the material. The slope of the line determines k . For perfectly elastic deformation $k = 2/3$ and for plastic deformation $k = 1$ (Ref. 5). When k was determined from Fig. 4 for both straight line segments, values of 0.6 and 0.8 were obtained at low and high loads, respectively. Therefore, it appears that whereas the deformation at the lower loads is essentially elastic, at the higher loads it is neither completely plastic nor elastic.

The preceding conclusion may be illustrated by plotting the apparent hardness, i.e., the ratio of the load to the apparent area, against the load and comparing this curve to the Vickers diamond pyramid hardness (Fig. 5). In computing the apparent area it was assumed that the area of contact is a circle whose diameter is equal to the track width. As the load was increased the apparent hardness approached the value of the hardness number which represents the region of full plasticity.

The manner in which the friction force varies with the square of the track width, and hence the area, is shown in Fig. 6. It is evident that friction is not proportional to the apparent area of contact. Each of two straight line segments may be represented by

$$F = cA_a^k \tag{5}$$

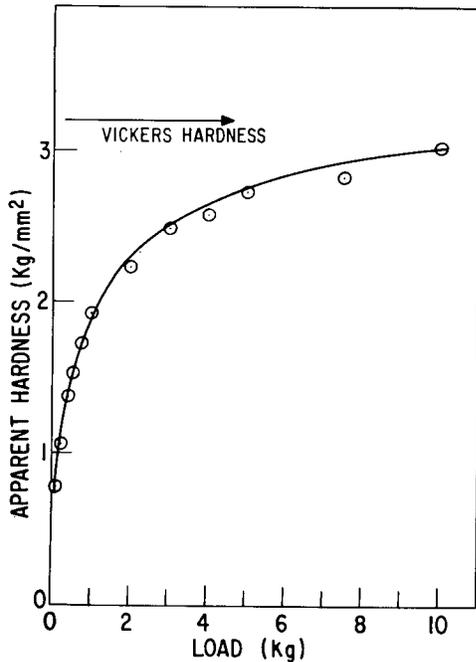


Fig. 5 - Effect of load on the apparent hardness of FEP. Apparent hardness approaches Vickers hardness as load is increased.

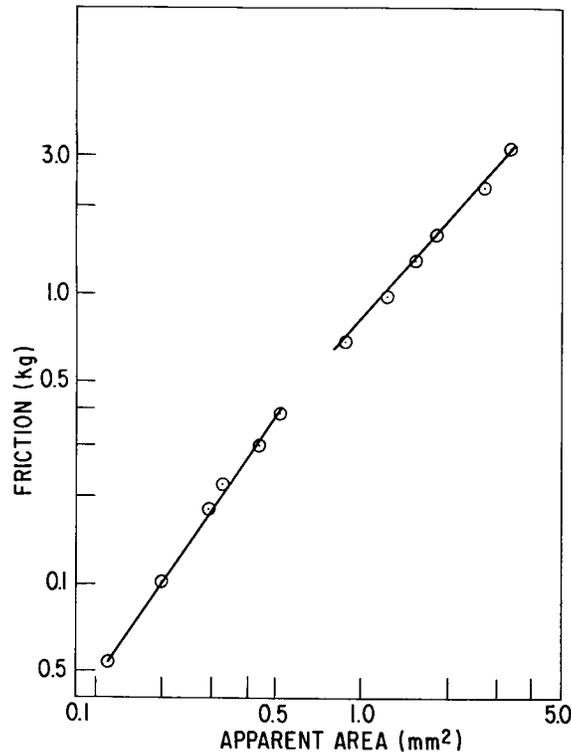


Fig. 6 - Relationship between friction and apparent area for steel sliding on FEP

where F is the total friction, A_a the apparent area of contact, and c and k are constants. At light loads (A_a is small) $k = 1.4$ and at heavy loads (A_a is large) $k = 1.1$. Therefore, friction becomes nearly proportional to the apparent area only at the heavy loads where k approaches unity. The fact that friction is not proportional to the apparent area implies that the real area is not proportional to the apparent area. The fact that μ_s increases with decreasing load implies that the real area of contact is not proportional to the load and hence the deformation of the asperities is not completely plastic. This is in contrast to the friction of most metals where asperity deformation is fully plastic and μ_s is constant over a range of loads extending well beyond those used in these experiments.

The variation of μ_s with load in subsequent traverses is not nearly as pronounced as in the initial traverse, but it yields the same type of curve. For example, during a second traverse at a 100-gram load μ_s was 0.30, at 1 kg it was 0.25, and at 10 kg it was 0.20. The decrease in μ_k (Fig. 3) with increasing load is much less than μ_s , but it is significant in the 100 to 1000 gram load range. The slight increase in μ_k at loads above 5 kg may be due to a significant increase in the plowing force, which is the force resisting the plowing or grooving of the FEP resin by the steel slider.

Some friction measurements were made with steel on FEP resin using sliding velocities varying from 0.01 to 1.0 cm/sec. An increase in both μ_s and μ_k of 0.03 was found in repeated traverses at the highest velocity. This small increase may indicate that the FEP platen or the FEP film transferred to the slider was made more amorphous at higher velocities as a result of surface melting of the polymer. Another possibility is that the real area of contact had become larger as the result of greater thermal softening produced by the higher sliding speeds (i.e., the mean yield pressure was decreasing). This explanation could be valid only if the effect of softening is greater than the effect produced by the decrease in shear strength accompanying an increase in temperature (Eq. 3).

Values of μ_s and μ_k for steel sliding on FEP are compared with those for steel sliding on TFE in Figs. 7 and 8, respectively. The TFE samples were prepared in the same manner as were those of FEP. Both μ_s and μ_k were measured at 25°C using unidirectional traverses with a 52100 steel slider, a load of 1000 grams and a velocity of 0.01 cm/sec. Except for the first traverse, μ_s of FEP is twice that of TFE; the value of μ_k is three times as great in all traverses. It is remarkable that there is such a large difference in frictional properties between two plastics having only minor differences in chemical and physical properties.

Comparison of Experimental Results with Calculations

Based on Adhesion Theory

In order to determine the friction that would be predicted for each solid by the adhesion theory, the shear strength (S) and mean yield pressure (P) were determined for five specimens of each polymer. The former property was measured by ASTM Method D732-46, and the latter was computed from Vickers hardness measurements (11). The ratio S/P , which is the predicted coefficient of friction, was found to be 0.42 for TFE and 0.45 for FEP. These values are much higher than the observed values of μ_k but are not much different than those of μ_s for the initial traverse.

It had been previously suggested that Eq. (3) was not applicable to the friction of TFE (3) because the unusually low specific adhesion (adhesive force per unit area of intimate contact) of this polymer caused shearing to occur primarily at the interface rather than within the polymer. It would be expected that the same low specific adhesion would also occur between FEP and steel since this plastic has an even lower free-surface energy than TFE (12,13). Therefore, if the same amount of shearing of bulk polymer occurs with FEP as with TFE and approximately the same force is required to shear either

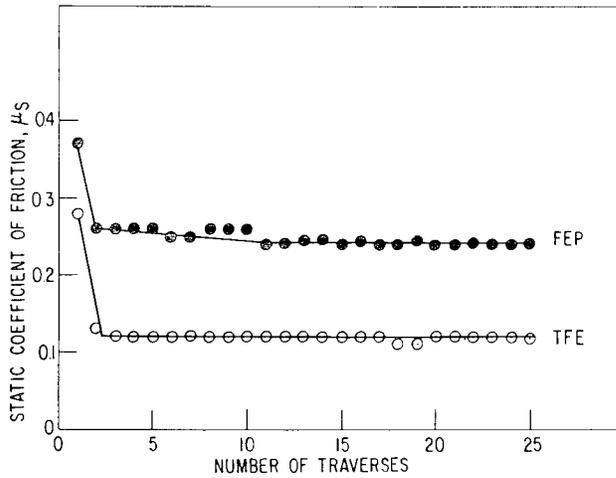


Fig. 7 - A comparison of μ_s for steel sliding on FEP and on TFE. Load = 1000 grams; velocity = 0.01 cm/sec; temperature = 25°C.

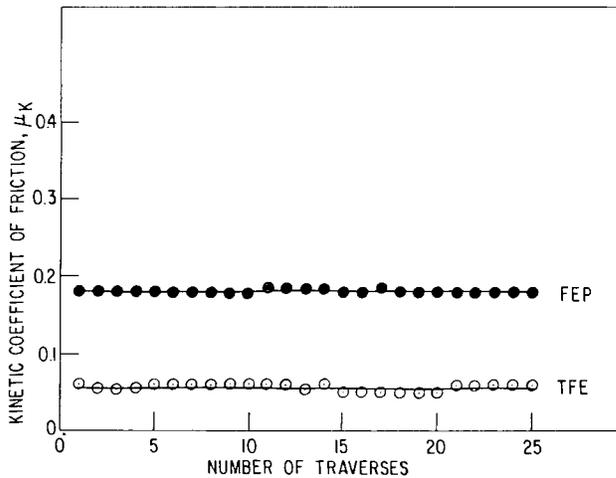


Fig. 8 - A comparison of μ_k with number of traverses for steel sliding on FEP and on TFE. Load = 1000 grams; velocity = 0.01 cm/sec; temperature = 25°C.

steel-polymer junctions or bulk polymer, then approximately the same coefficient of friction would be predicted for TFE and FEP. There must be some other factor to account for the large difference in friction between steel sliding on the two polymers.

One explanation may be the higher melt viscosity of TFE (about one million times that of FEP) which makes it a mass of well-sintered particles. In contrast FEP is a more homogeneous solid. The greater tendency toward frictional melting and the lower melt viscosity of FEP would also cause more intimate contact or wetting of the slider and, therefore, greater adhesion. Another explanation can be based on the manner in which the polymer film is transferred to the steel slider. The transferred TFE may be more readily oriented by sliding. The FEP, which melts at a lower temperature, may

transfer as a less crystalline film or as a film which is not as readily oriented. These ideas will be discussed later after comparing the difference in friction between the high-density and low-density polyethylenes with that observed between TFE and FEP. However, an attempt was made to orient FEP platens by stressing them in tension. Five 1/4-inch-thick samples were stressed for six minutes at 480 to 1510 psi (strain approximately 1 to 12 percent). No significant difference in either μ_s or μ_k was detected among these samples. Although it was not possible to demonstrate that the friction of these thick samples could be reduced by strain orienting at the stresses or strains used, there was a small decrease in hardness for those stressed more than 1000 psi.

Friction of High-Density and Low-Density Polyethylenes

The frictional properties of two low-density polyethylenes and three high-density polyethylenes were investigated. The surfaces of these polymers were prepared in the same manner as the fluorocarbons and measurements were made under the same experimental conditions so that the results would be comparable. In one respect the frictional behavior of the low-density polyethylenes differed from both the high-density polyethylenes and the two fluorocarbons. This is illustrated in Fig. 9, which is a typical frictional trace of steel sliding on the low-density material. In contrast to the traces with the other polymers, there is no sharp breakaway point between static and kinetic friction (see Fig. 2). The trace (Fig. 9) is rounded and it is difficult to determine when relative movement of slider and platen commenced; hence, the static friction cannot be as precisely determined. Apparently μ_s and μ_k of the low-density polyethylenes are nearly equal. With the high-density polyethylenes, as with the fluorocarbon polymers, static friction was greater on the first traverse (0.23) than on subsequent traverses (0.17). Static friction was also appreciably higher than kinetic friction in all traverses.

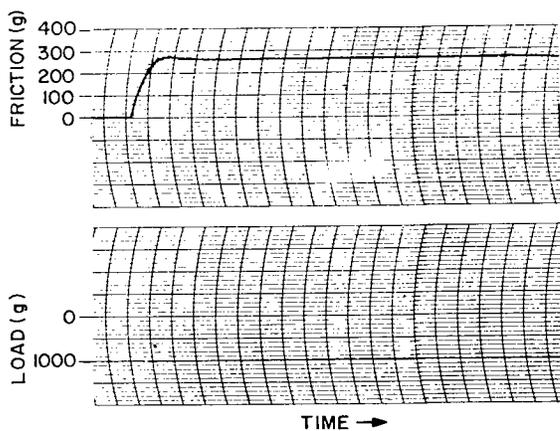


Fig. 9 - Typical friction trace for steel sliding on LDP

The kinetic coefficient of friction as a function of the number of unidirectional traverses is shown in Fig. 10 for each of the low-density and high-density polyethylenes. These results were obtained at 25°C using a steel slider, a velocity of 0.01 cm/sec, and a load of 1000 grams. For comparison, μ_k for TFE and FEP are shown by the dashed lines. There is a large difference in μ_k between the low-density and high-density polymers; μ_k for the LDP is greater than for HDP by a factor of three. This is the same ratio of μ_k found between FEP and TFE. Low coefficients of friction have recently been reported for HDP by Alter (14) for thin films on a hard backing and by Bueche and Flom (15) for bulk specimens.

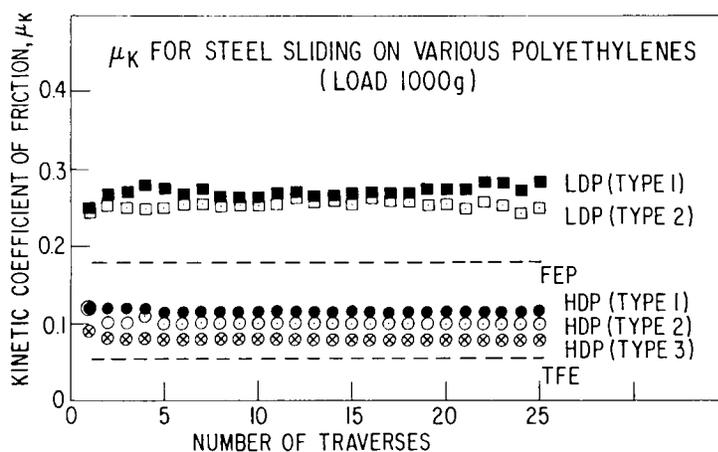


Fig. 10 - A comparison of μ_k for steel sliding on various polyethylenes. Load = 1000 grams; velocity = 0.01 cm/sec; temperature = 25° C.

The difference in μ_k for polyethylenes of different densities cannot be explained in terms of differences in the shear strengths and yield pressures of the polymers. Measurements of these properties were made on five samples of one high-density polyethylene and on five samples of one low-density polyethylene. The ratio of S to P was 0.28 for the former type and 0.18 for the latter. Calculations on the basis of the adhesion theory leads to the prediction that the low-density polyethylene should have the lower friction. The free-surface energies of the two types are essentially equal since the measured contact angles with several liquids (e.g., water and methylene iodide) did not differ significantly between the high-density and low-density polyethylenes. Therefore, no greater specific adhesion would be expected for the low-density polyethylene.

DISCUSSION

The values of the coefficient of friction calculated in terms of the adhesion theory are in best agreement with the experimental results on the coefficient of static friction for the initial traverse (Table 1). These values more nearly represent measurements with a "clean" steel slider, although there may have been a small amount of polymer transferred to the slider during loading. Corresponding calculated values differ from experimental data (μ_s , 1st traverse) by only 25 percent for the polyethylenes and FEP resin and are within 50 percent for TFE. This agreement is as good as could be expected in view of the oversimplified assumptions made in deriving Eq. (3), as well as the sources of error in measuring S, e.g., the variation of shear strength with pressure or rate of shear. The greatest discrepancy between the calculated and experimental values which occurs with TFE may be explained by its porous sintered structure. The adhesion theory is, therefore, adequate to explain μ_s for the initial traverse for all polymers and in addition to account for both μ_s and μ_k of low-density polyethylenes. This theory does, however, require some modification or new interpretation if it is to explain all the following experimental observations:

1. The values of μ_k are extremely low for TFE and HDP.
2. Both μ_s , for all traverses except the first, and μ_k are much lower than predicted with TFE, FEP, and HDP.
3. Both μ_s , for all traverses except the first, and μ_k are much lower for TFE than FEP.
4. Both μ_s , for all traverses except the first, and μ_k are much lower for HDP than LDP.

Table 1
Calculated and Experimental Values of μ_s and μ_k

Polymeric Solid	Calculated $\mu = S/P$	Experimental			
		μ_s		μ_k	
		1st Traverse	Repeated Traverses	1st Traverse	Repeated Traverses
TFE	0.42	0.28	0.12	0.05	0.05
FEP	0.45	0.37	0.24	0.18	0.18
HDP	0.28	0.23	0.18	0.09-0.12	0.08-0.12
LDP	0.18	0.25	0.25	0.25	0.25-0.27

If it is postulated that the adhesion between the slider and polymer is sufficiently low so that shearing occurs primarily at the interface rather than in the bulk of the polymer, observations 1 and 2 are consistent with the adhesion theory. But it is not obvious why TFE has lower friction than FEP and similarly why HDP has lower friction than LDP. Since both of the fluorocarbons or both of the polyethylenes have approximately equal free-surface energies, neither FEP nor LDP would be expected to have greater specific adhesion than TFE or HDP, respectively.

In addition to friction caused by shearing, there could also be a contribution due to plastic deformation (i.e., plowing of the steel through the polymer) or to elastic hysteresis losses arising from departure from perfect elasticity. The plowing term may be calculated by the method suggested by Bowden and Tabor (5) using

$$P_0 = \frac{d^3 p'}{12r} \quad (6)$$

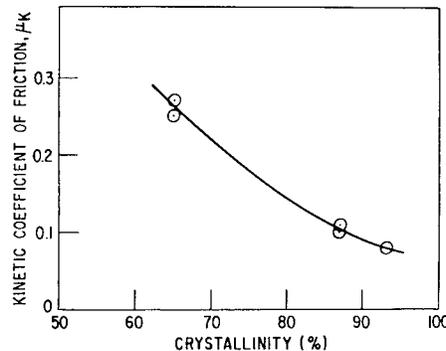
where r is the radius of the steel slider, p' is the pressure required to displace the metal and of the same order as the mean yield pressure, and d the track width. With a 1/2-inch-diameter slider and a 1000-gram load, the plowing force is 55 grams ($\mu_p = 0.055$) for the low-density polyethylene and 36 grams ($\mu_p = 0.036$) for the high-density polyethylene. The difference (0.02) is small compared to the total difference observed in μ_k (0.24 - 0.08 = 0.16). Similarly, it can be shown that the difference in the plowing terms between TFE and FEP is also insignificant.

Elastic hysteresis losses, while negligible in metallic friction, have been found to be of major importance in the sliding of lubricated rubber (16). With polymeric solids this type of loss is intermediate. Flom (17) has determined the hysteresis losses in a high-density polyethylene as well as in a low-density polyethylene by measuring the rolling friction of each against steel. Rolling friction was dependent upon the load, ball diameter, velocity, and temperature. When these factors were nearly comparable to the conditions used in this study, the hysteresis loss in the LDP was about twice that in HDP; however in neither material was the coefficient of rolling friction in excess of 0.01. Similarly, it was also found that the coefficient of rolling friction of TFE was less than 0.01. Although no information is available, elastic hysteresis losses in FEP would be expected to be greater than in TFE. McCrum (18) found that as the percent hexafluoropropylene was increased in the copolymer (FEP), the glass I peak increased in intensity and the temperature at which it occurred decreased. For example, with no hexafluoropropylene present (i.e., TFE), this peak occurred at 137°C and with 14 percent present, it occurred at 75°C. However, μ_k is 0.18 for FEP and only 0.05 for TFE. In view of the relatively minor effect with other polymers (17), it is highly improbable that elastic hysteresis loss would be the major contributor to the friction of FEP. Therefore, although the elastic hysteresis loss was greater in LDP than in HDP (and also in FEP than in TFE), it is not of sufficient

magnitude to account for the difference in the coefficient of kinetic friction; hence, some other mechanism is necessary to explain the results.

It was earlier suggested that the lower friction than that predicted by the adhesion theory is caused at least in part by the transfer of polymer film to the slider. Evidence of such transfer is the large decrease in μ_s between the first and second traverses. Evidently, this film transfers almost immediately since friction drops very rapidly once sliding commences. If this film is responsible for the reduction in friction, it must in some way differ from the bulk polymer. It is postulated that the film is more crystalline than the bulk plastic and rapidly becomes oriented in the direction of sliding. We had reported earlier that electron diffraction patterns obtained by examining a steel platen which had been traversed once by a polyethylene slider had established that polyethylene was transferred to the platen and had become well oriented with the long axes of the polymer molecules in the direction of sliding (3). Various investigators have reported that friction of polymers is less when the surface material was crystalline than when amorphous. For example, Bowers, Clinton, and Zisman (3) showed that when the surfaces of a series of polymers were made amorphous by pressing them briefly against a heated nickel disk and quickly cooling, friction was approximately double that of the same polymer after the surface layer was removed by abrasion. Summers-Smith (19) concluded that the friction of nylon decreased as the crystal size increased. Tabor and Williams (20) measured the shear strength of oriented TFE and found it to be 45 percent greater for shearing perpendicular to the direction of orientation than in the direction of orientation; they also found a 20-percent increase in the component of friction attributable to adhesion for steel sliding across the molecular chains of oriented TFE. Additional evidence that decreasing friction is associated with increasing crystallinity is shown in Fig. 11, where μ_k is plotted as a function of percent crystallinity; values for the five polyethylenes used here were typical values given by the producers. However, crystallinity is related to density, shear strength, and hardness, so that a similar curve could have been obtained by plotting μ_k against each of these variables. There is ample evidence that sliding friction is reduced with increased orientation of polymer surface because of the reduction in the force required to shear contacting asperities.

Fig. 11 - Effect of crystallinity on the kinetic friction of polyethylene



Next consider which of the polymer films transferred to the steel sliders would be the more crystalline and oriented. The FEP resin and LDP have many more branched chains and on transfer and sliding could not become as crystalline as TFE and HDP, respectively. The high kinetic friction of LDP indicates that little orientation occurs with this polymer. The softening points of the high-density polyethylenes and low-density polyethylenes are 125°C and between 90° and 100°C, respectively; similarly TFE softens at 325°C and FEP melts at 290°C. Since LDP and FEP melt at significantly lower temperatures than their more crystalline counterparts, they would be somewhat more susceptible to melting or softening by frictional heat and the transferred film would be more

amorphous. Also, in dealing with homologous polymers the lower the melting point of the polymer the greater should be the adhesion to the slider (13).

Evidence that frictional heat can increase the coefficient of friction of TFE has been reported by Flom and Porile (21), who found an increase in μ_k with increased sliding speed for TFE sliding on TFE. At sliding speeds of 1.1 cm/sec or less, μ_k was low (0.05 to 0.08), and remained low for at least 4100 traverses over the same track. But when the speed was 189 cm/sec, μ_k increased to 0.32 to 0.36. If friction was measured at the low speed over an area "worn in" at the high speed, the original low μ_k was no longer obtained; instead it was greater by a factor of two to three. This large increase was irreversible, for the original low values could be restored only by refinishing the surfaces with a sharp tool. Two possible mechanisms which the authors suggested were (a) surface degradation as a result of localized heating and/or viscous flow of noncrystalline polymer, and (b) orientation of the TFE surface with prolonged sliding. It is suggested as the result of the work reported here and other studies (3,19,20) that the opposite of the latter mechanism may be true, i.e., the higher value of μ_k with repeated sliding at high velocities indicates that the surfaces became more amorphous as the result of overheating.

It is concluded from this investigation that the ability of a polymer to transfer as an oriented film is a major factor in causing polymer friction to be less than that predicted by the adhesion theory. This effect coupled with the action of the higher melting point in causing decreased adhesion are responsible for the lower coefficient of friction of TFE than FEP and of HDP than LDP.

The greatest discrepancy between the values predicted by the adhesion theory and experimental results occur with TFE. The discrepancy between predicted and experimental results diminishes or disappears if (a) the specific adhesion increases, (b) orientation of the surface molecules is decreased, or (c) the area of molecular contact is increased. Allan (22) increased the specific adhesion of TFE by treating the surface with a solution of sodium in liquid ammonia and found that this not only increased the critical surface tension of wetting from 18 dynes/cm to 30 dynes/cm but also increased μ_k from 0.15 to 0.40. Flom and Porile's work (21) illustrates an increase in the friction of TFE by changing conditions (b) and (c). The irreversible change in μ_k , i.e., the difference between slow speed sliding with fresh surfaces and with surfaces "worn in" at high speeds, is probably the result of a more amorphous surface which was brought about by frictional heating. The reversible component, i.e., the difference in μ_k between high speed sliding and low speed sliding on a "worn in" surface, is a result of both an increase in adhesion because thermal softening increased the area of intimate contact and the formation of less oriented surface due to frictional heating and quick cooling.

The friction of steel sliding on polymers can, in general, be greatly reduced if the polymer is in the form of a thin film on a hard backing (3). This reduction is accomplished by reducing the area of contact (i.e., increasing P) while keeping S constant (Eq. 3). The minimum coefficient of friction obtainable for each plastic film on a particular substrate may be computed by

$$\mu_f = \mu_b \frac{P_1}{P_2} \quad (7)$$

where μ_b is the coefficient of friction of the bulk polymer and P_1 and P_2 are the mean yield pressures for the polymer and backing, respectively. Equation (7) predicts that on the same hard substrate μ_k would be 3 times greater for FEP than TFE. Similarly, μ_k would be 1.7 times larger for a thin film of HDP than for LDP, despite the lower bulk friction of the former, because of the much greater yield pressure (or hardness) of HDP. However, the minimum value of μ_k calculated from Eq. (7) for steel traversing a thin

film of each polymer on a hard backing such as 52100 steel (Vickers Hardness 850) is less than 0.001. Therefore, if low friction is the criterion, all these polymers are potentially excellent dry-film lubricants. One advantage of FEP is that, unlike TFE, its viscosity at the melting point is so much lower than it can be used to prepare continuous rather than porous film, which is of particular importance where the dry-film lubricant must also serve as a protective coating against atmospheric corrosion. Compared to LDP, HDP has the advantage of being harder, less soluble, and having a higher softening point.

CONCLUSIONS

Static friction of FEP was not proportional to the load in the range 100 to 1000 grams for an initial traverse with a clean steel slider. It was concluded that the real area of contact was not proportional to the load and that the deformation of contacting asperities was not completely plastic.

With all polymers μ_s for a clean steel slider may be predicted by the adhesion theory of friction. Both μ_s and μ_k with LDP are of the order predicted from the adhesion theory. Kinetic friction is much lower than the calculated value for TFE, FEP, and HDP because of the low specific adhesion between these polymers and their films which have transferred to the steel slider. The higher friction of FEP than TFE and of LDP than HDP is accounted for by the different nature of the transferred films and areas of contact. These polymers are potentially excellent dry-film lubricants when used as thin films on a hard backing.

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