Pressure Effects on the Friction Coefficients of Thin-Film Solid Lubricants

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ABSTRACT

Thin solid films on harder backings are now widely used as dry-film lubricants. An early extension by us of the Bowden-Tabor adhesion theory of friction showed that the coefficient of friction of a coated backing was equal to only a fraction of that of the coating material, and this fraction was simply the ratio of the mean yield pressure of the coating material to that of the backing. However, we pointed out that the effect of pressure on the shear strength of the coating material was neglected. We have since analyzed and applied to this problem the data on the effect of pressure on shear strength of paraffin, gold, and molybdenum disulfide using the experimental data of Bridgman and of Boyd and Robertson. The principal complication in applying these data to the frictional problem is to allow properly for the elastic (or plastic) deformation of the two sliding solids in calculating the pressure exerted on the coating material during sliding. Our calculated coefficients of friction are in good agreement with the recent measurements of Takagi and Liu on gold-coated hard steel and the earlier data by Haltner and Oliver on molybdenum disulfide-coated steel. Recently we measured coefficients of friction of thin coatings of paraffin on steel and obtained results which were in good agreement with our calculated values. It is concluded that a sound basis now exists for calculating the coefficient of friction of dry-film lubricants. At high pressures, the shear strength is proportional to some power N of the mean yield pressure. When the elastic properties of the substrate determine the pressure on the film, the coefficient of friction μ will vary as the $(N-1)/3$ power of the load. At loads great enough to produce plastic flow of the substrate, μ will vary as the $(N-1)$ power of the substrate hardness and will be independent of the load. Further research on such systems requires more experimental data on the effect of pressure on shear strength in a variety of indicated polymers and inorganic solids.

PROBLEM STATUS

This is an interim report; work is continuing.

AUTHORIZATION

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PRESSURE EFFECTS ON THE FRICTION COEFFICIENTS OF THIN-FILM SOLID LUBRICANTS

INTRODUCTION

A class of lubricants which is finding wide application employs thin dry films to reduce friction and wear between sliding solids. Such lubricants are used where conventional oils or greases are unsatisfactory, especially where the liquid would be lost by creeping or evaporation (as at high temperatures or high vacuum) or would be an explosion hazard or a source of contamination. Examples are the common uses of dry-film lubricants in rockets and space vehicles, in inaccessible portions of submarines, and in food processing, packaging, and textile machinery. Especially advantageous is the permanency of dry films during storage and their ability to function over a much wider temperature range than oils or greases.

The coefficient of friction μ between two sliding solids is defined as the ratio of the frictional force F to the normal force or load W. Friction between two unlubricated sliding solids usually results from adhesion at the many small areas of intimate (or real) contact. Bowden and Tabor (1) pointed out many years ago that the frictional force is, to a first approximation, equal to the product of the shear strength S of the softer solid and the area to be sheared, the real area of contact A. However, A is equal to the ratio of W to the mean yield pressure P_M of the softer material; i.e., $W = P_M A$. Hence, they derived the well-known relation for two sliding solids:

$$\mu = \frac{F}{W} = \frac{SA}{P_M A} = \frac{S}{P_M} . \tag{1}$$

Subsequently, Bowden and Tabor concluded that the well-known effectiveness of journal bearings consisting of a hard metal coated with a thin, solid, metallic film of a much softer metal (such as lead, silver, indium, or alloys like babbitt) results from the low shear strength of the film material and the high mean yield pressure P_M of the hard substrate. Later, we generalized their proposition to include polymeric or plastic coatings on harder backings (2). It is convenient to rewrite Eq. (1) in the form

$$\mu = \frac{S_\sigma}{P_M}, \tag{2}$$

where σ denotes the properties of the film material. The coefficient of friction of the film material in the <u>bulk state</u> is

$$\mu_\sigma = \frac{S_\sigma}{P_\sigma}, \tag{3}$$

where P_σ is the mean yield pressure of the film material. Therefore, from Eqs. (2) and (3), it was concluded that

$$\mu = \mu_\sigma \left(\frac{P_\sigma}{P_M}\right) . \tag{4}$$

We also pointed out that Eq. (4) is applicable only when certain assumptions, which will be discussed later, are valid. The mean yield pressure P_M has been related to the Vickers Diamond Pyramid Hardness (DPH) number H by (3) the relation

$$H = 0.927 P_M, \tag{5}$$

where P_M is in kilograms/square millimeter. Therefore, the ratio P_σ/P_M in Eq. (4) may be replaced by H_σ/H.

Although it is generally observed that a dry-film lubricant has a lower coefficient of friction on a harder substrate, as Eq. (4) would predict (i.e., μ decreases as P_M increases), there can be very poor quantitative agreement between calculated and experimental values. Discrepancies are greatest when there are large differences in hardness, i.e., whenever H_σ/H is a small number. Two extreme examples of the poor agreement between measured values of μ and those calculated with Eqs. (4) and (5) are given in Table 1. In each example a very soft film has been used on a much harder substrate; the errors in the calculated values are from two to three orders of magnitude. It is the purpose of this report to explain the causes of these large discrepancies, to derive a more accurate theoretical basis for calculating μ, and to compare the calculated with available experimental data.

Table 1
Comparison of Measured and Calculated Values of μ for Thin Films on Hard Substrates

Solid	Film	μ_σ	H_σ	H	μ Measured	μ Calculated From Eq. (4)
52100 Steel	Stearic acid	0.2	0.25	800	4×10^{-2}	6×10^{-5}
Sapphire	Paraffin (m.p. 65°C)	0.14	0.1	1650	3×10^{-2}	8×10^{-5}

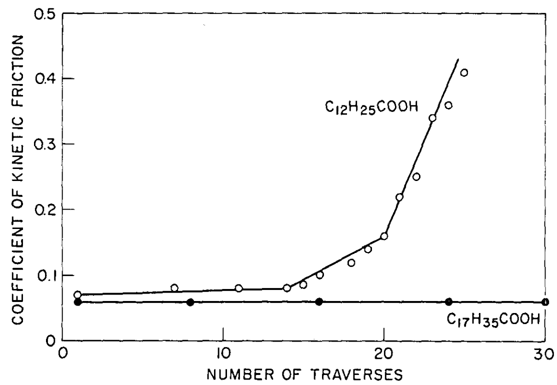
NATURE OF THE PROBLEM

In the original derivation of Eq. (4), we had assumed that (a) the normal load was essentially carried by the solid substrate, i.e., the film thickness approached 0, (b) there was no contact through the film, and (c) the shear strength of the film material was not very pressure dependent (2). Experiments with a monomolecular film deposited on a smooth solid can be used to determine the validity of assumption (a) provided that it is correct to assume that there is no contact through the film.

Stearic acid monomolecular films were deposited by retraction from the melt (4-7) on smooth platens of copper, platinum, chromium, iron, and 52100 steel. Methylene iodide contact angles (5,7) on these films were 66, 58, 63, 70, and 71 degrees, respectively. These agree reasonably with recent film studies by Timmons and Zisman (8). Friction was measured for one or more of the following sliders traversing each film: copper, 52100 steel, Pyrex, soda-lime glass, platinum, and sapphire. The results were inconclusive in regard to assumption (a), because some wear was always readily observed with the unaided eye. However, friction and wear were always less on films with higher methylene iodide contact angles, i.e., on the most condensed films and hence those allowing least contact of slider and platen. Another major factor in these experiments was the roughness of the slider. Increasing the slider roughness always increased friction and wear.

However, data from Levine and Zisman's investigation (9) of the friction and durability of monomolecular films deposited on glass microscope slides can be used to help clarify the effect of assumptions (a) and (b). They found no increase in the kinetic friction coefficient μ_k, and no wear on the glass platen (Knoop hardness 475) was detectable at a magnification of 150X with some of the close-packed monolayers of long-chain fatty acids and amines, even after many repeated unilateral traverses of a 1/2-in.-diameter stainless-steel slider at loads as great as 9 kg. A rapid increase in μ_k with the number of traverses is indicative of film destruction and slider-to-platen contact as illustrated in Fig. 1 for tridecanoic acid after 15 traverses. The fact that μ_k remained constant with stearic acid for at least 30 traverses is good evidence that this film was very durable and that little metal-to-glass contact occurred (Fig. 1).

Fig. 1 - Durability of fatty acid monomolecular layers under a load of 5 kg (9)



We have measured μ_k at 25°C using a sliding speed of 0.01 cm/sec and a load of 1 kg for a 1/8-in.-thick, molded disk of stearic acid and obtained a value of 0.2. To calculate μ, it was assumed that the hardness of the condensed stearic acid monomolecular layer adsorbed on glass was equal to the measured Knoop hardness of bulk stearic acid (0.25). From Eqs. (4) and (5), the calculated value of μ is 5×10^{-5} for the stearic acid monolayer, which is approximately three orders of magnitude smaller than the experimental value of 0.06 obtained with a 5-kg load. Discrepancies of this kind are in agreement with the results in Table 1; however, here they cannot be attributed to the effect of film thickness or to contact through the film. It must be concluded that the major source of error in the calculations of μ by Eq. (4) was the result of a significant increase in shear strength of the film with pressure.

The above conclusion was also reached by Bowden and Tabor (10), who explained the difference between the measured value and the calculated value of μ for a close-packed calcium stearate monolayer on copper, by assuming an increase in shear strength of the calcium stearate at high pressure. Their radioactive tracer measurements confirmed that conclusion, because no significant contribution could be found from metallic contacts through the film.

Therefore, in Eq. (2) we must recognize that S_σ is a function of the pressure P to which the film is subjected during sliding. The possibility that this pressure is not necessarily equal to P_M of the substrate must also be considered; hence, Eq. (2) is rewritten as

$$\mu = \frac{S_\sigma}{P} . \tag{6}$$

The usefulness of Eq. (6) depends not only on expressing S_σ as a function of P but also on determining P as a function of either the elastic or plastic properties of the sliding solids (the substrate and superstrate).

Two special cases of deformation in solid-film lubrication need to be considered. In case A, the load and sliding geometry are such as to cause the solid substrate, or the superstrate, to flow plastically. At this load, or any greater load, the pressure on the film remains constant and equal to P_M of the substrate or the superstrate, whichever is softer. Since P is constant at these high loads, S_σ is constant, and μ is determined for a particular solid film only by P_M or therefore the hardness of the substrate or superstrate. In case B, the load and geometry produce a pressure in excess of P_σ but less than the elastic limits of the substrate and superstrate, i.e., $P_M/3 > P > P_\sigma$. Two types of substrate and/or superstrate deformation may be postulated for case B: (a) the asperites of the opposing solids deform plastically under the applied load as a result of stress being concentrated at these points—hence, the pressure is again determined by the substrate or superstrate hardness—or (b) the continuous solid film flows plastically to distribute the pressure over the entire contact area so that the real area of contact equals the apparent area as determined by the elastic properties of the substrate and superstrate.

CALCULATION OF μ FOR GOLD FILMS ON STEEL

Takagi and Liu (11) have recently reported their investigation of the friction of very thin gold films deposited on hard steel. The following calculations using the experimental conditions stated in their paper reveal that their pressures were within the range of case B. From the Hertz equation for elastic deformation, the areas of contact for the 1/8-in.-diameter steel sphere on the steel flat used in their experiments were 2.4×10^{-5} cm^2 for a 200-g load and 1.1×10^{-4} cm^2 for a 2000-g load. The value 2×10^{12} dynes/cm was used as Young's modulus for steel. The corresponding average pressures were 8300 kg/cm^2 for the lower load and 18,000 kg/cm^2 for the higher. The DPH values given by Takagi and Liu for the gold films, the steel sliders, and the steel platens were 78, 710, and 790, respectively. From Eq. (5) these values correspond to mean yield pressures of 8400 kg/cm^2 for the gold, 77,000 kg/cm^2 for the steel slider, and 85,000 kg/cm^2 for the steel platen. Since the elastic limit of metals is approximately 1/3 of the mean yield pressure (12), the pressure in the contact region was nearly equal to or greater than the mean yield pressure of the gold but much less than the elastic limit of the steels.

We have used Bridgman's (13,14) pioneering measurements of the shear strength of gold as a function of pressure in Eq. (6) to calculate μ for the Hertz pressures at the two loads. When these are compared with the measured values of μ, it may be possible to determine the plausibility of the hypothesis that the friction is controlled by the elastic properties of the solid substrate and superstrate.

Bridgman's experimental results need to be discussed carefully; hence, his apparatus is shown schematically in Fig. 2. A thin layer of the material whose shear strength was to be measured was placed at both locations marked A and squeezed by a hydraulic press pushing the two steel cylinders B against the disk-shaped anvil C. The anvil was rotated, and the cylinders were held stationary. The force required to rotate the anvil was measured. At low pressures the samples could slip over the faces of the steel pistons, in which case it was the frictional force that was measured. As the applied pressure was increased, a value was reached where the entire sample could no longer slip against the piston faces but seized, so that the disk material could exhibit only plastic flow. This plastic flow was distributed more or less uniformly throughout the layer material. Most of the investigated substances experienced this transition at a pressure in the neighborhood of 20,000 kg/cm^2 (13).

Values for S_σ at the two pressures corresponding to Takagi and Liu's loads of 200 and 2000 g (8300 and 18,000 kg/cm^2) were obtained by extrapolation and interpolation of Bridgman's data as plotted in Fig. 3 from the five data points which were given as the effect of increasing pressure on shear strength (13). In fitting a smooth curve in Fig. 3, we were guided by Bridgman's statement (14) that the original data curve was markedly S shaped. We obtained for each load a calculated μ of 0.08, whereas the experimental value reported by Takagi and Liu for their thinnest film was 0.10. Since their plot of μ vs film thickness indicated that μ would decrease further for thinner films, the agreement between our calculated and their experimental results is good.

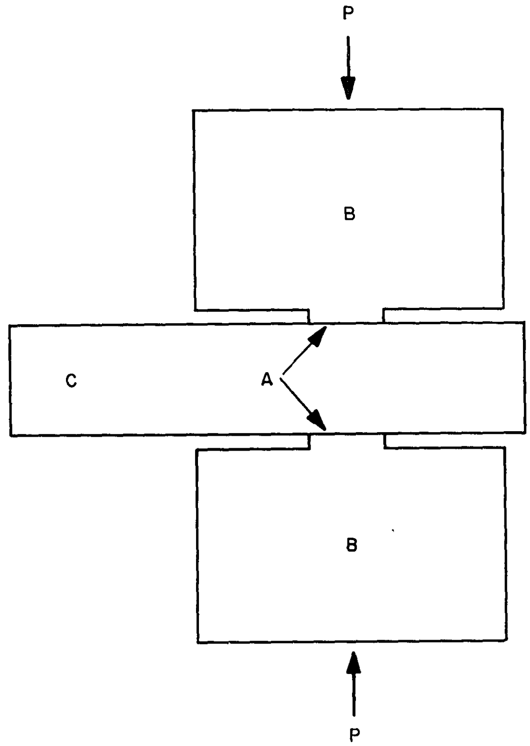


Fig. 2 - Bridgman's apparatus for measuring shearing stress (13)

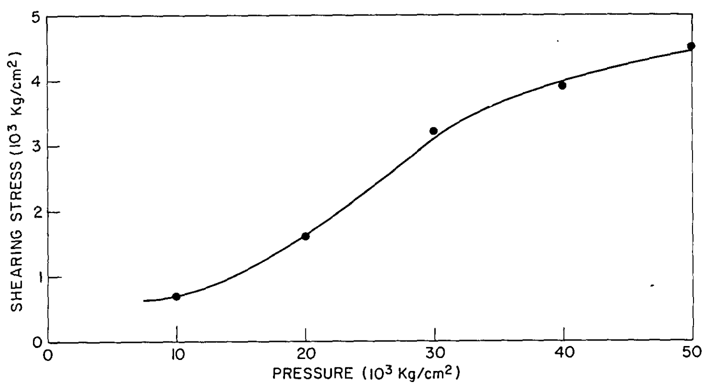


Fig. 3 - Shearing stress of gold as a function of pressures from Ref. 13

It should be noted that Bridgman's transition pressure for gold was near 30,000 kg/cm^2. The true shear strength of gold can be measured by his experimental method only at or above this transition pressure; hence, at lower pressures, the shear strength was greater than is indicated by the lower portion of the curve of Fig. 3. Therefore, the calculated coefficient of friction in the preceding paragraph should be greater than 0.08.

The preceding calculation was determined by assuming that the substrate deformed elastically (i.e., case B, type b). To obtain some estimate of the value of μ if plastic deformation of the steel substrate or superstrate were operative, i.e., case B, type a, it is necessary to extrapolate Fig. 3 to much higher pressures. Bridgman's shear-strength data for these pressures of 30,000 kg/cm^2 and greater are plotted on log-vs-log coordinate

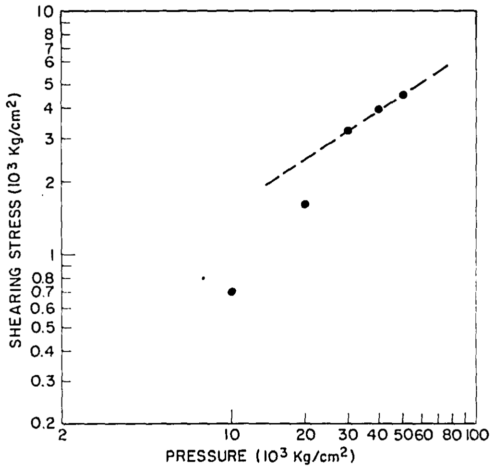


Fig. 4 - Relationship between pressure and shearing stress of gold

paper in Fig. 4. The extrapolation of this straight line plot to 76,000 kg/cm^2 (the mean yield pressure of the softer steel) allows one to estimate the shear strength of gold at this high pressure as 6000 kg/cm^2. Hence, the calculated value of μ from Eq. (6) is 0.08. Since calculations for both elastic and plastic deformation compare well with Takagi and Liu's observed values of $\mu = 0.10$, they cannot be used to determine the substrate deformation mechanism.

CALCULATIONS AND EXPERIMENTS ON THIN PARAFFIN FILMS

A more positive determination of the correctness of Eq. (6) and of the postulated mode of substrate deformation can be made by using a film material which is very soft compared to the solid substrate and by obtaining data which will relate the shear strength of this material to the pressure. We chose paraffin as the film material, because Bridgman had reported the shear strength of paraffin (m.p. not given) as a function of pressure (14). Although he published curves on Cartesian coordinates of shear strength vs pressure for both increasing and decreasing pressures, these curves nearly coincided. We have replotted in Fig. 5 on log-vs-log coordinates the average curve from his data. Bridgman concluded that this range of pressures represented the stage where shear was brought about by plastic flow (i.e., there was no slippage of the paraffin disk against the anvil face). The data appear to plot along three adjoining straight line segments. The equations which fit these segments are printed on the graph and are of the form

$$S_\sigma = K_1 P^N. \tag{7}$$

The rate of increase of S_σ with P for paraffin is higher than for any other material yet reported. In each case, N is greater than unity and increases with the pressure range. Equation (6) would predict an increase in μ with increase in pressure, at least between 4000 and 33,000 kg/cm^2. The manner in which μ for this paraffin would be expected to vary with pressure has been calculated with Eq. (6) and the results are plotted in Fig. 6. Therefore, the coefficient of friction of this paraffin can be predicted for a given substrate if the pressure on the film can be determined.

Thin films of paraffin (m.p. 65°C) were prepared on smooth, flat, solid surfaces of different hardnesses and elastic moduli. Materials and surface geometry of the substrate and superstrate were chosen to obtain pressures that were greater than the yield pressure of the paraffin but less than 1/3 the yield pressure of the substrates. Figure 7 illustrates how the Hertz pressures vary as a function of load for two slider diameters and various substrate and superstrate material combinations. The sliding combinations

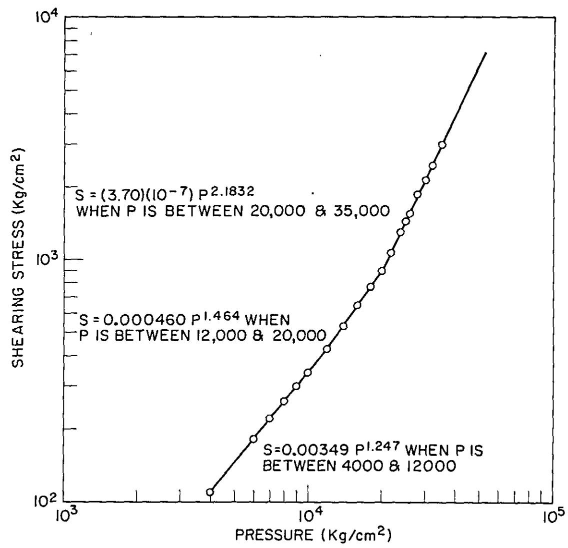


Fig. 5 - Relationship between pressure and shearing stress of paraffin

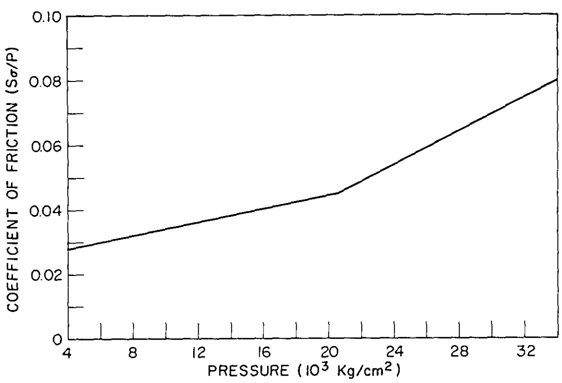


Fig. 6 - Predicted coefficient of friction for thin paraffin films as a function of pressure

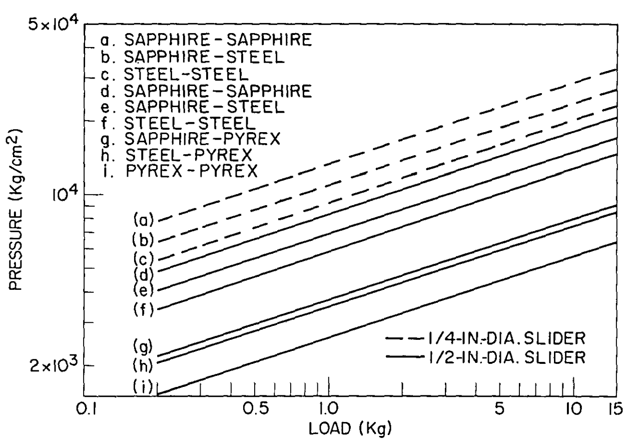


Fig. 7 - Hertz pressure as a function of load for selected-material combinations

investigated were 1/2-in. Pyrex, 1/2-in. 52100 steel, and 1/2-in. 440C stainless-steel sliders on Pyrex platens; 1/2-in. Pyrex and 1/2-in. sapphire sliders on both 302 stainless steel and Armco Iron platens; 1/2-in. sapphire, 1/4-in. sapphire, and 1/2-in. 440C stainless-steel sliders on 52100 steel platens; and a 1/4-in. sapphire slider on a sapphire platen. The mean yield pressure and Young's modulus of each material are listed in Table 2.

Table 2
Mean Yield Pressure and Elastic Modulus of Sliders and Platens

Slider and/or Platen	Yield Pressure* (10^4 kg/cm^2)	Young's Modulus (10^6 kg/cm^2)
Armco iron	1.2	2.2 (15)†
302 Stainless steel	2.0	2.1 (15)
Pyrex	4.9	0.63 (15)
440C Stainless steel	8.3	2.1 (15)
52100 Steel (slider)	9.5	2.1 (15)
52100 Steel (platen)	8.3	2.1 (15)
Sapphire	16.5	3.7 (16)

*Determined from DPH measurements on the test specimens
†Numbers in parentheses refer to References

All friction measurements were made using a modified stick-slip machine, which is essentially the same as that described by Goodzeit, Hunnicutt, and Roach (17). The geometry of the rubbing solids was that of a sphere traversing a plane surface (the "platen"); hence, there was point contact or else contact at a cluster of points within a single circle. The spherical slider, which was clamped so that it could not rotate, was attached to an elastically restrained friction arm, and the platen was clamped to a sliding table. Relative motion was produced by an Air Draulic cylinder, which pushed the table along a pair of precisely made parallel tracks. The normal force was applied with a cam which depressed the friction arm and pressed the slider against the platen. Two pairs of bonded, resistance, strain gages were attached to the friction arm to serve as the force-measuring elements for load and friction. These data were recorded simultaneously on a Sanborn, Model 321, Dual-Channel Carrier Amplifier-Recorder. All measurements were made at 25°C using a relative sliding speed of 0.01 cm/sec.

The first experiments were conducted with paraffin-coated Pyrex platens (Corning Glass 7740). Each Pyrex platen was first cleaned with the detergent Tide, after which it was thoroughly rinsed with distilled water until it remained completely wet. Next, each platen was dried in a clean oven at 120°C, allowed to cool to room temperature, and then weighed. The paraffin coating was applied to each platen by resting it on a hot plate at a temperature just above the melting point of the paraffin (65°C). Some of the excess melted paraffin was then blotted up with the edge of a clean Whatman filter paper. After it had been cooled to room temperature, each Pyrex flat appeared slightly hazy. Each flat was then rubbed with Buehler 1567 AB Microcloth (which is produced free of abrasives and oily materials) until the haze had disappeared. The weight of the remaining paraffin was 0.2 ± 0.1 mg. Assuming the film was uniform, it had a calculated thickness of approximately 5 μ in.

Each film-coated platen was traversed by uncoated 1/2-in.-diameter sliders of Pyrex and 52100 steel. When a Pyrex slider was used under loads of 0.5, 1, and 2 kg, the coefficient of static friction μ_s was as large as 0.5. The coefficient of kinetic friction μ_k decreased after sliding the ball several millimeters until it reached a constant value between 0.04 and 0.06. During this decrease, stick-slip motion frequently occurred. The permanent damage to the surface of the Pyrex flat could be observed with the unaided eye; this demonstrated that contact with the slider had occurred through the paraffin film. Using the chrome-alloy steel slider (52100) and a load of 1 kg, μ_s was 0.18 and μ_k decreased from 0.18 to 0.03 and then remained constant after sliding had occurred for approximately 2 mm. Little damage to the Pyrex could be detected at 54X magnification.

A second unilateral traverse made with the same slider over the same track resulted in an initial value for μ_k of 0.03, which increased with sliding distance to between 0.04 and 0.05. During the tenth traverse the initial value of $\mu_k = 0.08$ increased to 0.10. The higher static friction and the more gradual decrease in μ_k with sliding distance observed with the Pyrex slider than the steel slider during the first traverse is attributed primarily to the greater surface roughness of the former slider rather than its greater adhesion. The rms roughness of the Pyrex slider was 5 to 10μ in. and that of the steel was only 1.5μ in. Probably, the decrease in μ_k with sliding distance was caused by the filling of slider surface irregularities by paraffin transferred from the flat.

A 52100 steel slider and a Pyrex platen were each precoated with a film of paraffin by a procedure similar to that used earlier to coat the platens. Friction measurements made with this slider at loads of from 0.5 to 10 kg resulted in a value of $\mu_s = 0.1$. After 1 or 2 mm of sliding, μ_k had decreased to 0.03. During each successive unilateral traverse, μ_k was nearly constant, but it gradually increased with the number of traverses until it reached 0.08 by the tenth. The use of a paraffin-coated Pyrex slider on a coated Pyrex platen resulted in a lower μ_s and initial μ_k at loads of 0.5 and 1.0 kg than that obtained with the uncoated slider. At higher loads μ_k varied erratically during each traverse, and it occasionally exceeded 0.15. In experiments with a coated 440C stainless-steel slider which had a roughness of only 1.0μ in. on a paraffin-coated Pyrex platen, μ_s did not exceed 0.07, and μ_k decreased rapidly during sliding from an initial value of 0.05 to a final value less than 0.03. The paraffin film was also much more durable when this slider was used. On using a 10-kg load, μ_k increased to only 0.038 after ten unilateral traverses.

Table 3 lists the results obtained with the 440C steel sliders at loads from 0.5 to 15 kg and also compares the calculated and measured values of μ_k. The measured values are the constant, or steady-state, friction coefficients obtained after 1 or 2 mm of sliding. The pressures used to calculate the coefficients of friction were assumed to result from the elastic deformation of both the slider and platen. Although there is only a small change in the measured value of μ_k with increasing pressure, the measured values are in good agreement with the calculated values. Equation (6) predicts an increase in μ_k of only 0.005 in this pressure range. If the assumption is made that the asperities of the softer substrate were plastically deformed, the pressure to which the film was subjected would equal the mean yield pressure of the softer material, i.e., the Pyrex, which from Knoop hardness measurements is 49,000 kg/cm^2. The value of μ obtained by extrapolation of Fig. 5 is 0.13 or about four times the measured value. Hence, this last assumption cannot be correct. It is concluded that the pressure on the film was determined by the elastic properties of the slider and platen.

Friction measurements were made using 1/2-in.-diameter paraffin-coated Pyrex or sapphire sliders (Linde, single crystal) on both coated 302 stainless-steel and coated Armco Iron platens. Although both types of platens had nearly the same value of Young's modulus, the mean yield pressures of the iron and steel were 12,000 and 20,000 kg/cm^2, respectively; hence, both were softer than the sliders. With the sapphire sliding on 302 steel under loads of 5 kg or more, or with repeated unilateral traverses at lower loads, μ_k ranged from 0.1 to 0.2. Stick-slip motion occurred at all times. When the load was 2 kg or less, μ_k was usually irregular and occasionally was as low as 0.05 without evidence of stick-slip motion. Although heavy wear occurred on the steel platen at all loads, the damage became much more severe under high loads. However, when the Pyrex sliders were used instead of sapphire, wear of the 302 steel was comparatively slight; usually, it consisted of one or several light scratches along the length of the track. The static coefficient of friction did not exceed 0.05, and the initial value of μ_k was 0.03, even though some slider-to-platen contact occurred.

Table 3
Kinetic Coefficient of Friction for
1/2-in. 440C Stainless-Steel Slider on Pyrex Platen
(both coated with paraffin)

Load (kg)	Pressure (kg/cm²)	μ_k (Calculated from S_σ/P)	μ_k (Measured)
0.5	2750	-	0.028
1	3500	0.027	0.027
2	4400	0.028	0.020
4	5500	0.030	0.028
5	6000	0.030	0.025
7.5	6800	0.031	0.023
10	7500	0.032	0.025
15	8600	0.032	0.023

Friction measurements using Pyrex or sapphire on Armco Iron were similar to those obtained with 302 steel; however, the iron was appreciably less damaged than the steel. Onset of plastic deformation occurred at a pressure approximately one-third of that necessary to cause complete plastic flow of the softer substrate, i.e., at 4000 kg/cm^2 for Armco Iron and 6700 kg/cm^2 for 302 stainless steel. This corresponded to loads of 0.2 kg (sapphire-Armco Iron), 0.9 kg (sapphire-302 stainless steel), 1.5 kg (Pyrex-Armco Iron), and 7.2 kg (Pyrex-302 stainless steel). Since the onset of plastic deformation occurred at loads of 1.5 kg or less for the first three combinations, the results for only the last combination are summarized in Table 4. The calculated values were determined by assuming that P was a function of the elastic properties of the slider and platen.

Table 4
Kinetic Coefficient of Friction for
1/2-in. Pyrex Slider on 302 Stainless-Steel Platen
(both coated with paraffin)

Load (kg)	Pressure (kg/cm²)	μ_k (Calculated from S_σ/P)	μ_k (Measured)
0.5	2750	-	0.025 to 0.03
1	3500	0.027	0.025
2	4400	0.028	0.022
5	6000	0.030	0.026
10	7500	0.032	0.026

Hertz pressures between 10,000 and 33,000 kg/cm^2 can be produced with loads of from 0.5 to 15 kg by using 1/4-in.-diameter sapphire-ball sliders on flat sapphire disks. This pressure range covers the major portion of the curve in Fig. 5. The earliest attempts to measure friction using the standard paraffin coating (5μ in.) yielded high values which did not decrease with sliding distance. Very small stick-slip motions were characteristic of the kinetic friction. A thicker coating of paraffin was obtained by omitting the final step of rubbing the disk with microcloth; the resulting film thickness was approximately 20μ in.

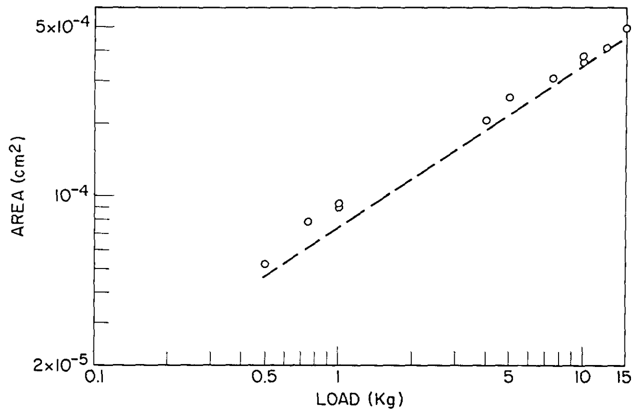


Fig. 8 - Area of contact as a function of load for thin paraffin films on sapphire. Dashed line is the Hertz area for 1/4-in.-diameter sapphire on sapphire flat.

After the friction measurements were made, track widths on the platen were carefully measured. The contact area for each load was calculated by using the track width as the diameter of the circle of contact. These areas are plotted as a function of the load by the circles in Fig. 8, and the Hertz areas are represented by the dashed line. Since all points fall above the dashed line, the contact area is not entirely determined by elastic deformation of the solid substrate. However, the difference is small and diminishes as the load increases. The effect of thickness appears to be secondary even for this thicker paraffin film. Measured values of μ_k are compared with those calculated from Eq. (6) in Table 5. These calculations were based on the assumption that the slider and platen were elastically deformed. The calculated value of μ_k was always greater than the measured value; however, the difference was always less than a factor of two. The measured values of μ_k for loads less than 4 kg (21,000 kg/cm^2) were appreciably less than the values for greater loads. The theoretical curve in Fig. 6 predicts a sharp increase at the pressure of 21,000 kg/cm^2. However, if it were assumed that the substrate had deformed plastically, the pressure on the film would equal the mean yield pressure of the sapphire (165,000 kg/cm^2), and the value of μ_k calculated from Eq. (6) should be independent of the load and much greater than 0.08 (Fig. 6).

A thicker paraffin film (average thickness > 25μ in.) was applied to a 52100 steel platen. Friction was measured with 1/2-in.- and 1/4-in.-diameter sapphire sliders and also with a 1/2-in.-diameter 440C stainless-steel slider. Values of μ_k measured with loads of from 0.5 to 15 kg are given in Table 6. An increase in μ_k always was found with increasing pressure regardless of whether this increase resulted from (a) increasing the load, (b) increasing the Young's modulus of the slider, or (c) decreasing the slider radius. Contact areas calculated from the track widths observed on these thicker films were appreciably greater than the Hertz areas.

Track-width measurements were not precise, because the tracks were not sharply defined and tended to increase with sliding distance. Apparently the paraffin transferred to the slider, accumulated there, and pulled some of the adjacent film from the platen at a distance beyond the contact zone. A more accurate estimate of the contact area was obtained by static indentation measurements on the same film by adapting a Tukon Hardness Tester to use each of the three ball sliders as indenters. Plotted as the ordinate in Fig. 9 is the ratio of the pressure determined from these measurements to the Hertzian pressure for uncoated surfaces as a function of the load for the 1/4-in.-diameter sapphire slider. This ratio increased from 0.24 at 0.1 kg to about 0.80 at 15 kg. It is concluded that the pressure on this film was greatly influenced by the film thickness.

Table 5
Kinetic Coefficient of Friction for
1/4-in. Sapphire Slider on Sapphire Platen
(both coated with paraffin)

Load (kg)	Pressure (kg/cm^2)	μ_k (Calculated from S_σ/P)	μ_k (Measured)
0.5	10,500	0.035	0.027
0.75	12,000	0.036	0.027
1	13,500	0.038	0.028
2	17,000	0.041	0.026
4	21,000	0.047	0.032
5	23,000	0.052	0.040
7.5	26,000	0.060	0.041
10	29,000	0.069	0.044
12.5	31,000	0.074	0.043
15	33,000	0.080	0.044

Table 6
Kinetic Coefficient of Friction for Thick Paraffin Film
on 52100 Steel

Load (kg)	Slider		
	1/2-in. 440C	1/2-in. Sapphire	1/4-in. Sapphire
0.5	0.02	0.02	0.02
1	0.02	0.02	0.024
2	0.016	0.020	0.020
4	0.022	0.021	0.029
5	0.020	0.022	0.029
7.5	0.023	-	-
8	-	0.025	0.031
10	0.023	0.025	0.032
12	-	0.025	0.031
12.5	0.023	-	-
15	0.023	0.025	0.035

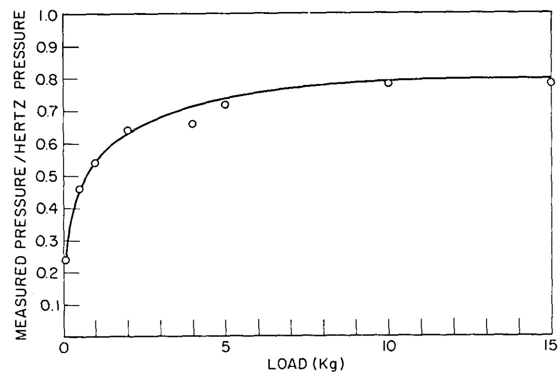


Fig. 9 - Ratio of measured pressure to Hertz pressure as a function of load (thick paraffin film on 52100 steel, 1/4-in. sapphire slider)

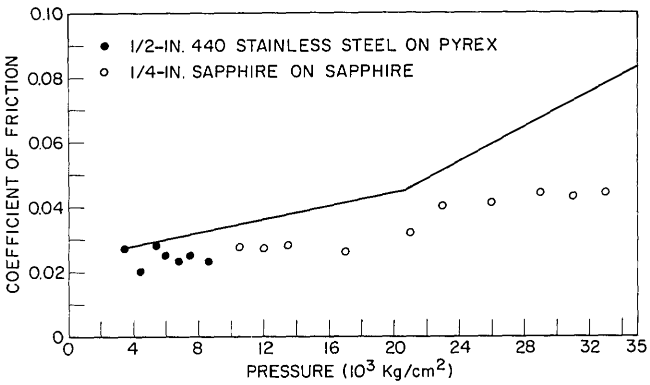


Fig. 10 - Predicted and measured coefficients of friction of thin paraffin films vs pressure

Results obtained on the coefficient of friction vs pressure using the 1/2-in.-diameter 440C slider on a Pyrex platen and the 1/4-in.-diameter sapphire slider on a sapphire platen are shown by the filled and open circles in Fig. 10. Of the measurements reported here, these are the most significant, because they were obtained with very thin paraffin films which gave no evidence of any contact between the slider and platen. The solid line represents the values calculated from Eq. (6) and from the data given in Fig. 5. Agreement between measured and calculated values was always within a factor of two when the pressure was assumed to be determined by the elastic properties of the substrate and superstrate. Better agreement could be expected if our paraffin were the same in molecular weight as that used by Bridgman. It is concluded from the above results that in the presence of a continuous solid film the pressure is distributed over the entire area of apparent contact rather than concentrated in many small areas of asperity contact scattered over the apparent area.

QUANTITATIVE TREATMENT OF FRICTION OF A HARD SOLID COATED WITH A THIN FILM

This discussion will be confined to friction and will not consider the wear resistance of the film or its adhesion to the substrate. The assumption was made that the film thickness was such that the area of contact was essentially determined by the substrate but that no contact occurred through the film. All friction was considered to result from adhesive forces. Other sources, such as resistance to sliding by plowing or losses caused by elastic hysteresis, were treated as negligible. Furthermore, the variation in shear strength with temperature or with the rate of shear was not considered.

Two special equations for μ can be derived from the general equation, Eq. (6) given earlier. Consider first the simpler case (case A), i.e., where the load and sliding geometry are such as to cause the substrate to flow plastically. Therefore, $P = P_M$; i.e., P will equal the mean yield pressure of the solid substrate. As will be shown later, the shear strength of many soft materials can be related to the pressure by the same equation, Eq. (7), which applies to paraffin. Therefore, for this condition

$$\mu = \frac{S_\sigma}{P} = \frac{K_1 P_M^N}{P_M} = K_1 P_M^{N-1}. \tag{8}$$

Thus, μ is independent of any further increase in load; for any particular film, it is determined solely by the hardness of the substrate.

Now consider case B, where the load and sliding geometry produce a pressure greater than the mean yield pressure of the soft film material but less than the elastic limit of the substrates. According to the classical equations of Hertz (18), the mean yield pressure over the region of contact (between an isotropic sphere and plane solid pressed together under normal load W) is proportional to the one-third power of the load; i.e., $P = K_2 W^{1/3}$. Therefore, from Eq. (7)

$$S_\sigma = K_1 (K_2 W^{1/3})^N = K_1 K_2^N W^{N/3}, \tag{9}$$

and from Eq. (6)

$$\mu = \frac{K_1 K_2^N W^{N/3}}{K_2 W^{1/3}} = K_1 K_2^{N-1} W^{(N-1)/3}. \tag{10}$$

The constants K_1 and N are the intercept and slope, respectively, of the plot of log S_σ vs log P of any material for which shear strength-vs-pressure data are available. The constant K_2 is a function of the elastic properties of the substrate and superstrate and of the sliding geometry.

In the special case of a sphere on a flat surface, K_2 is determined by the radius of the sphere and the Young's moduli of the slider and platen. The equation for elastic deformation given by Hertz (18) is

$$a = \left[\frac{3}{4} W r \left(\frac{1-\sigma_1^2}{E_1} + \frac{1-\sigma_2^2}{E_2}\right)\right]^{1/3}, \tag{11}$$

where a is the radius of the circle of contact, W is the normal load, r is the radius of the sphere, σ_1 and σ_2 are Poisson's ratio for sphere and platen, respectively, and E_1 and E_2 are the Young's moduli of those two solids.

When σ_1 and σ_2 are between 0.2 and 0.4, which is true for most metals, Eq. (11) can be rewritten as the following approximation:

$$a = 0.87\, W^{1/3} \left[r \left(\frac{E_2 + E_1}{E_1 E_2}\right)\right]^{1/3}, \tag{12}$$

and the area of contact A is

$$A = \pi a^2 = 2.4\, W^{2/3} \left[r\left(\frac{E_2 + E_1}{E_1 E_2} \right) \right]^{2/3} \tag{13}$$

Therefore, the pressure P is

$$P = \frac{W}{A} = \frac{W^{1/3}}{2.4\left[r\left(\frac{E_2 + E_1}{E_1 E_2} \right) \right]^{2/3}} . \tag{14}$$

Hence,

$$K_2 = \frac{P}{W^{1/3}} = \frac{1}{2.4\left[r\left(\frac{E_2 + E_1}{E_1 E_2} \right) \right]^{2/3}} , \tag{15}$$

with r in centimeters and E_1 and E_2 in kilograms per square centimeter. For example, the value of K_2 for a 1/4-in.-diameter steel sphere traversing a thin film deposited on a steel plate is 9200.

Listed in Table 7 are values of K_1 and N for gold, silver, lead, indium, and paraffin for the indicated pressure range. These values were obtained from Bridgman's data plotted in Figs. 4, 5, and 11. They are applicable in Eq. (8) when P_M is in kilograms per square centimeter and in Eq. (10) when W is expressed in kilograms.

Table 7
Constants of Film Materials Used to Calculate μ

Material	Pressure Range (10^3 kg/cm^2)	K_1	N
Gold	30-50	3.4	0.66
Silver	10-50	0.35	0.880
Lead	10-50	0.047	0.886
Indium	20-50	0.0013	1.222
Paraffin	20-35	3.7×10^{-7}	2.18

The numerical values of the coefficient of friction for thin films of the materials listed in Table 7 can be computed for sliding conditions which produce pressures in the range over which the constants were determined. For example, with a 1/4-in.-diameter hard-steel slider traversing a thin film on a hard-steel substrate, the Hertz pressures corresponding to a 2-kg and 40-kg normal load are 11,700 and 31,800 kg/cm^2, respectively. The higher value is near the elastic limit of a very hard steel whose DPH number is approximately 900. We have used Eq. (10) to determine μ at several loads for this sliding system. Since the values of N for gold, silver, lead, and indium are close to unity (between 0.66 and 1.22), the exponent of W, i.e., $(N-1)/3$, is a small fraction. A large change in load, therefore, results in a relatively small change in μ (see Table 8). Although these constants, and hence μ , are accurate to no more than two significant figures, a third figure was included to show a relative change in μ with load. There is only a 10% decrease in μ for silver and lead with a 20-fold increase in load. Gold and indium also show small changes in μ with increased load. The calculated μ for paraffin exhibits the largest change with load. Increasing the load produces a decrease in μ when $N < 1$ and an increase when $N > 1$.

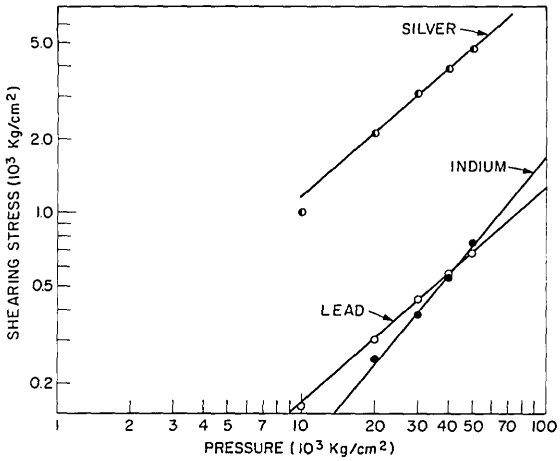


Fig. 11 - Relationship between pressure and shearing stress for three metals

Table 8
Coefficient of Friction for Thin Films
As Calculated from $\mu = K_1 K_2^{N-1} W^{(N-1)/3}$

Load (kg)	Pressure (10^3 kg/cm^2)	Coefficient of Friction				
		Gold	Silver	Lead	Indium	Paraffin
2	11.7	-	0.113	0.0162	-	-
5	15.9	-	0.109	0.0157	-	-
10	20.0	-	0.106	0.0153	0.0115	0.043
20	25.2	0.105	0.103	0.0148	0.0121	0.056
40	31.8	0.102	0.101	0.0145	0.0127	0.074

Table 9
Coefficient of Friction for Thin Films
As Calculated from $\mu = K_1 P_M^{N-1}$

Pressure (10^3 kg/cm^2)	Coefficient of Friction				
	Gold	Silver	Lead	Indium	Paraffin
10	-	0.116	0.0164	-	-
20	-	0.107	0.0152	0.0117	0.0440
30	0.129	0.102	0.0145	0.0128	0.0710
40	0.093	0.098	0.0141	0.0136	0.0995
50	0.086	0.096	0.0137	0.0143	-

As the normal load is increased on a sphere of small diameter sliding on a film-covered platen, a load will be reached where the platen will begin to flow plastically. At greater loads, μ will be independent of the normal load and the elastic constants of the platen; hence, Eq. (8) is applicable. If the slider is as hard or harder than the platen, μ is then determined solely by the mean yield pressure (or hardness) of the platen. Listed in Table 9 are the values of μ calculated from Eq. (8) for five kinds of films on substrates having mean yield pressures ranging between 10,000 and 50,000 kg/cm^2. Note that a fivefold increase in pressure causes only a 16% and a 17% decrease in μ for lead and silver films, respectively; $d\mu/dP$ is also negative for gold films but is greater in magnitude. In contrast, $d\mu/dP$ is positive for indium and paraffin films. If the shear strength of the film were not a function of pressure, μ would vary inversely with pressure, i.e., μ at 50,000 kg/cm^2 would be 1/5 of that at 10,000 kg/cm^2.

DRY FRICTIONAL BEHAVIOR OF MoS_2 FILMS

Molybdenum disulfide, which today is one of the most widely used materials in solid-lubricant compositions, merits special attention. Although it was not included in Bridgman's experiments on shear strength vs pressure, the data for MoS_2 were later obtained with a similar apparatus by Boyd and Robertson (19). The graph shown in Fig. 12 was obtained by reading the shear strength as closely as possible from their family of curves for several pressures vs shearing arc. Also in Fig. 12 are graphs of the data on PbI_2 obtained by both investigators (8,14); obviously, Boyd and Robertson's results are in excellent agreement with Bridgman's. Values of K_1 and N in Eqs. (8) and (10) for MoS_2 are 0.192 and 0.816, respectively. Since N is less than unity, a decrease in μ with increasing load is predicted. For example, a 1/4-in.-diameter sphere of hard steel traversing a thin MoS_2 film on a hard-steel substrate under loads of 4 kg (14,800 kg/cm^2) and 40 kg (31,800 kg/cm^2) would have values of μ, as calculated from Eq. (10), of 0.033 and 0.028, respectively. Thus, increasing the load by a factor of ten will cause a reduction in μ of 15%. When the pressure on the MoS_2 film equals the mean yield pressure of the platen, Eq. (8) shows that μ will be 0.035 and 0.026 for substrates having mean yield pressures of 10,000 kg/cm^2 (DPH 93) and of 50,000 kg/cm^2 (DPH 464), respectively.

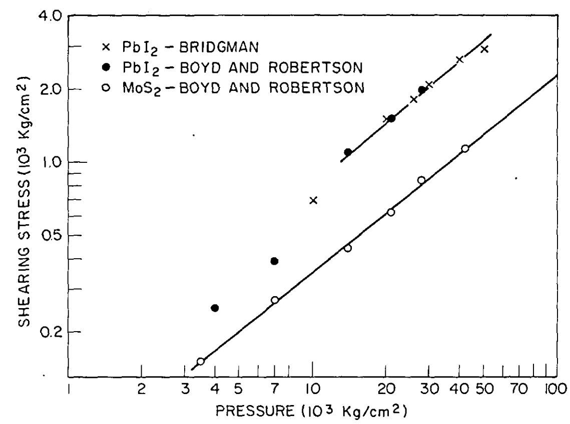


Fig. 12 - Relationship between pressure and shearing stress for PbI_2 and MoS_2

Haltner and Oliver (20) measured μ_k for thin films of MoS_2 on disks of mild (AISI 1020) steel, 1090 steel, and 347 stainless steel. Their sliders were hemispheres 1/8 in. in diameter of a hard chrome-alloy steel. From their hardness values we have determined the mean yield pressures P_M and the approximate elastic limits $P_M/3$ of these disks (Table 10). Calculations of the contact pressures on the films by means of the Hertz equation and the loads used by Haltner and Oliver resulted in pressures which were in excess of the elastic limit but below the mean yield pressure of the disk. Therefore, the deformation was neither completely plastic or elastic. Hence, the Hertz equation is not applicable. However, an upper and lower pressure limit can be obtained by a method illustrated in Fig. 13. The solid line is a log-log plot of pressure vs load for a 1/8-in.-diameter steel sphere on a steel flat when the deformation is completely elastic. A dashed line was drawn from the point on this line where the pressure was equal to the elastic limit of the stainless steel and the point where fully plastic deformation begins.

Table 10
Comparison of Calculated and Experimental Values of μ for Thin Films of MoS_2

Disk Material	P_M (kg/cm²)	$P_M/3$ (kg/cm²)	Load (kg)	Pressure Range (kg/cm²)	μ_k*	μ†
Mild steel	16,500	5500	0.25	7500-9000	0.13	0.037
1090 steel	18,500	6200	1.09	12,500-15,000	0.035	0.033-0.034
Stainless steel	22,200	7400	3.60	17,000-22,000	0.015	0.030-0.032
Stainless steel	22,200	7400	3.02	16,000-21,000	0.022	0.030-0.032

*From Ref. 20
†Calculated

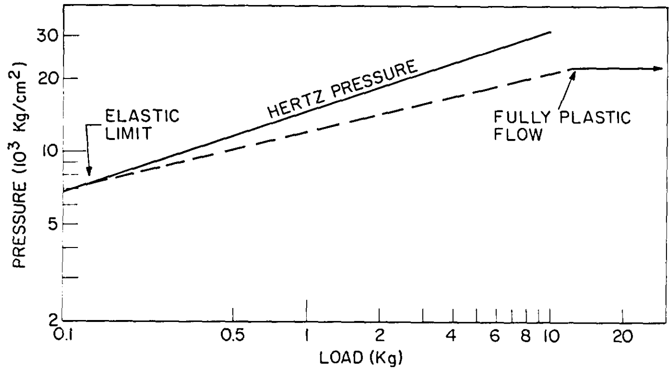


Fig. 13 - Pressure range as a function of load for a 1/8-in.-diameter steel sphere on a steel platen (DPH 206)

The latter point occurs at a load which is approximately 100 times as great as the load corresponding to the elastic limit. Therefore, the pressure at any load lies between these lines. The pressure range for each disk at the load at which friction was measured is shown in the fifth column in Table 10. In the sixth and seventh columns are given the experimental values of μ obtained by Haltner and Oliver and the values we have calculated from Eq. (6) and Fig. 12 for the specified pressure range. Except for mild steel, the experimental and calculated values of μ are in reasonably good agreement.

DIRECTIONS FOR FUTURE RESEARCH

Bowers, Clinton, and Zisman (2) first reported the dry-film lubricating properties of thin films of organic polymeric solids deposited on much harder solid surfaces. They also discovered the opposite effects of fluorine and chlorine substitution on the bulk dry coefficients of friction of the polyhaloethylenes (2,21). The latter results are given graphically in Fig. 14, where the abscissa is the atom percent of halogen substituted for hydrogen in an unbranched high-molecular-weight polyethylene (2,22). Thus, increased fluorine substitution has a steady and linear effect in decreasing μ, whereas increased chlorine substitution raised μ much more dramatically. These results were explained qualitatively as follows: chlorination of a linear polyethylene increases the intermolecular

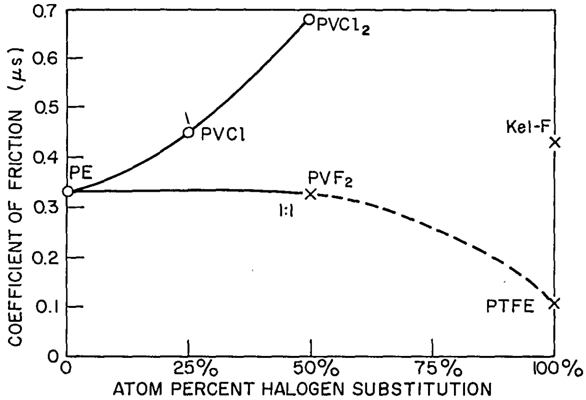


Fig. 14 - Effect of halogen substitution on static coefficient of friction of polyethylene (22)

cohesion and hardness of the solid, whereas fluorination has comparatively little effect on these bulk properties. The fundamental cause of these differences is the greater molecular polarizability of the covalently bonded chlorine than the covalently bonded fluorine atom.

We have attempted to explain quantitatively why the coefficient of friction of some of these bulk dry polymeric solids were much less than the values calculated from Eq. (3). Polytetrafluoroethylene is an outstanding example of a material exhibiting a serious disagreement. However, calculations relative to its chemical cousin, a commercial copolymer of tetrafluoroethylene and hexafluoropropylene, were in much better agreement with the observed μ_k (23). We are now in a better position to explain these discrepancies between theory and experiment; they should disappear when S_σ in Eq. (3) is treated as a variable which is dependent on the pressure created in the region of contact between the rubbing solid surfaces.

Good quantitative evidence has been given here to explain reasonably accurately the dry-film lubricating properties at various loads of a thin film of gold, paraffin, or molybdenum disulfide when used as a coating on a much harder solid substrate. Obviously, data are needed on the effect of pressure on the shear strength of polytetrafluoroethylene, the copolymers of tetrafluoroethylene and hexafluoropropylene, low-density and high-density polyethylene, the polyacetal Delrin, various nylons, graphite, boron nitride, tungsten disulfide, tungsten diselenide, and many other materials of current or future interest as dry-film lubricants. In other words, the corresponding values of K_1 and N in Eq. (7) are needed in order that comparisons can be made between the calculated and the experimental values of μ for each of the existing or promising dry-film lubricant materials.

An empirical formula recently proposed by Towle (24) which relates the pressure and temperature dependence of shear strength of crystalline solids may find some application toward increasing the available information. This can be expressed by

$$S = S_0 \exp\left[-aT/T_M\right], \tag{16}$$

where S is the shear strength of the sample at the temperature of measurement T and T_M is the melting point of the sample at the pressure at which S was measured; both temperatures are in degrees Kelvin. The constants S_0 and a are properties of the material.

Therefore, if the pressure-vs-melting point curve is available for a material, the shear strength-vs-pressure curve can be constructed from measurements of s at several temperatures. Conversely, from shear-strength determinations at several pressures, the shear strength at different temperatures can be estimated.

SUMMARY

At low or moderate pressures the shear strength of many solids may be nearly independent of pressure. However, high pressures are encountered in many sliding systems, particularly in pivot bearings, gears, and between a sphere and flat. At these pressures, shear strength may increase markedly with pressure and can be expressed by $s_\sigma = K_1 P^N$. Therefore, to calculate the coefficient of friction μ for thin solid films, the shear strength of the film material at the existing pressure must be known. The shear strength of many materials at high pressures is nearly proportional to the pressure, and a large change in load produces only a relatively small change in μ. Loads great enough to produce plastic flow of the film may still be well below the elastic limits of the substrate and superstrate. Our measurements with paraffin films have revealed that at such loads the film distributes the pressure over the entire contact area; in the absence of a continuous solid film, pressure is concentrated at highly localized areas of asperity contact. Since the pressure on the film, and hence μ for loads in this range, are determined by the elastic properties of the substrate, μ will vary as the $(N-1)/3$ power of the load. At loads great enough to produce plastic flow of the substrate, μ will vary as the $N-1$ power of the substrate hardness and will be independent of load. When the pressure is above the yield pressure of the film and the elastic limit of the substrate, but below the yield pressure of the substrate, frictional behavior would be expected to be intermediate.

Appropriate equations have been derived to predict μ for both elastic and plastic substrate deformation for a spherical rider traversing a plane surface. Values of K_1 and N for gold, silver, indium, lead, and molybdenum disulfide have been calculated from the shear strength-vs-pressure data of Bridgman, as well as of Boyd and Robertson. Sample calculations of μ have been made for thin films of these materials under several specific conditions. These calculated values of μ agreed well with experimental values for materials for which experimental data were available (paraffin, gold, and MoS_2).

It is concluded that to advance theoretical and applied research in dry-film lubrication, shear strength-vs-pressure data should be obtained for a greater variety of materials, including the indicated organic polymers and various inorganic solids.

REFERENCES

1. Bowden, F.P., and Tabor, D., Chapter 5 in "The Friction and Lubrication of Solids," London:Oxford, 1954

2. Bowers, R.C., Clinton, W.C., and Zisman, W.A., Lubrication Eng. 9:204(1953); Mod. Plastics 31(No. 6):131 (1954)

3. Tabor, D., Chapter 7 in "The Hardness of Metals," London:Oxford, 1951

4. Baker, H.R., Shafrin, E.G., and Zisman, W.A., J. Phys. Chem. 56:405 (1952)

5. Levine, O., and Zisman, W.A., J. Phys. Chem. 61:1068 (1957)

6. Shafrin, E.G., and Zisman, W.A., J. Phys. Chem. 64:519 (1960)

7. Zisman, W.A., Advanc. Chem. 43:1, Washington:Am. Chem. Soc., 1964

8. Timmons, C.O., and Zisman, W.A., J. Phys. Chem. 69:984 (1965)

9. Levine, O., and Zisman, W.A., J. Phys. Chem. 61:1188 (1957)

10. Bowden, F.P., and Tabor, D., Chapter 19 in "The Friction and Lubrication of Solids, Part II," London:Oxford, 1964

11. Takagi, R., and Liu, T., ASLE Trans. 10:115 (1967)

12. Tabor, D., Chapter 4 in "The Hardness of Metals," London:Oxford, 1951

13. Bridgman, P.W., Proc. Am. Acad. Arts Sci. 71(No. 9):387 (1937)

14. Bridgman, P.W., Phys. Rev. 48:825 (1935)

15. Gray, D.E., Coordinating Editor, "American Institute of Physics Handbook," 2nd ed., New York:McGraw-Hill, 1963

16. Linde Industrial Crystals, Bulletin 3, Dec. 3, 1956

17. Goodzeit, C.L., Hunnicutt, R.P., and Roach, A.E., Trans. Am. Soc. Mech. Engrs. 78:1669 (1956)

18. Hertz, H.J., Reine angew. Math. 92:156 (1881); "Miscellaneous Papers," London, 1896

19. Boyd, J., and Robertson, B.P., Trans. Am. Soc. Mech. Engrs. 67:51 (1945)

20. Haltner, A.J., and Oliver, C.S., J. Chem. Eng. Data 6:128 (1961)

21. Bowers, R.C., Clinton, W.C., and Zisman, W.A., J. Appl. Phys. 24:1066 (1953)

22. Zisman, W.A., Record of Chem. Progr. 26(No. 1):13 (1965)

23. Bowers, R.C., and Zisman, W.A., Mod. Plastics 41(No. 4):139 (1963)

24. Towle, L.C., Appl. Phys. Letters 10(No. 11):317 (1967)

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13. ABSTRACT Thin solid films on harder backings are now widely used as dry-film lubricants. An early extension by us of the Bowden-Tabor adhesion theory of friction showed that the coefficient of friction of a coated backing was equal to only a fraction of that of the coating material, and this fraction was simply the ratio of the mean yield pressure of the coating material to that of the backing. However, we pointed out that the effect of pressure on the shear strength of the coating material was neglected. We have since analyzed and applied to this problem the data on the effect of pressure on shear strength of paraffin, gold, and molybdenum disulfide using the experimental data of Bridgman and of Boyd and Robertson. The principal complication in applying these data to the frictional problem is to allow properly for the elastic (or plastic) deformation of the two sliding solids in calculating the pressure exerted on the coating material during sliding. Our calculated coefficients of friction are in good agreement with the recent measurements of Takagi and Liu on gold-coated hard steel and the earlier data by Haltner and Oliver on molybdenum-disulfide-coated steel. Recently we measured coefficients of friction of thin coatings of paraffin on steel and obtained results which were in good agreement with our calculated values. It is concluded that a sound basis now exists for calculating the coefficient of friction of dry-film lubricants. At high pressures, the shear strength is proportional to some power N of the mean yield pressure. When the elastic properties of the substrate determine the pressure on the film, the coefficient of friction μ will vary as the $(N-1)/3$ power of the load. At loads great enough to produce plastic flow of the substrate, μ will vary as the $(N-1)$ power of the substrate hardness and will be independent of

— Continues

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Dry-film lubricants						
Thin-film solid lubricants						
Shear strength						
Paraffin						
Gold						
Molybdenum disulfide						
Lubrication						
Friction reduction						

the load. Further research on such systems requires more experimental data on the effect of pressure on shear strength in a variety of indicated polymers and inorganic solids.