Polymer–Polymer Friction as a Function of Test Speed

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ABSTRACT: Tests of sliding friction between identical polymer films have been carried out at sliding speeds of 0.0001 to over 10 m/s. In order to make measurements over such a wide range of speeds, three devices are employed. In each apparatus, a moving member with two identical polymer surfaces slides between two stationary blocks covered with the same polymer. The slow-moving crossarm of a standard Instron tester provides speeds of 0.0085 to 0.21 cm/s. A horizontal sled apparatus provides speeds of 1 to 10 cm/s. Finally, a modified impact test machine uses a pendulum that moves at about 3 m/s. Results with four polymer films illustrate a variety of behavior. The coefficient of friction, μ, for cellulose acetate decreases with increasing speed. Films of low-density polyethylene and polytetrafluoroethylene show increases in μ with speed. A film of ultrahigh molecular weight polyethylene shows only a slight decrease in μ with speed. © 1998 John Wiley & Sons, Inc. J Appl Polym Sci **67:** 1831–1836, 1998

Key words: polymer sliding friction; coefficient of friction; dynamic friction; static friction

INTRODUCTION

There are many applications in which the sliding friction between polymer surfaces becomes important. The feeding of sheet material in automated equipment, the stacking of packages, and the movement of packages all are sensitive to the interaction of surfaces. Such one-time movement can be differentiated from the repetitive motions characteristic of bearings and gaskets. The field of tribology encompasses friction and wear of all kinds. However, most tests for bearing materials include a rotational motion and continuous rubbing, which can result in transfer of material from one surface to another and which can lead to an increase in surface temperature. Transfer is especially likely in the case when two different materials like a plastic and a metal are rubbed together. This is avoided in the present work because all of the sliding tests have the same material on both surfaces.

Many practical tests of friction do emphasize the abrasion and wear that occurs on repetitive (oscillating or rotational) sliding. These are used for predicting the life of bearings, gears, cams, and casters. In the present work, the tests are carried out as the single movements of sheet material over the same material, which is typical of film- and paper-handling equipment.

It is recognized that two types of contact are involved when one surface slides over another.[1] For very smooth surfaces, friction arises from the breaking of adhesive (van der Waals) forces. Electrostatic and hydrogen bonds may enter in also. On the other hand, when asperities from two rough surfaces interpenetrate, actual deformation and fracture may become the dominant mode of energy dissipation. In both cases, the energy dissipation can raise the temperature of the surfaces. The effect of speed of movement of one surface over the other has been explored to some extent.

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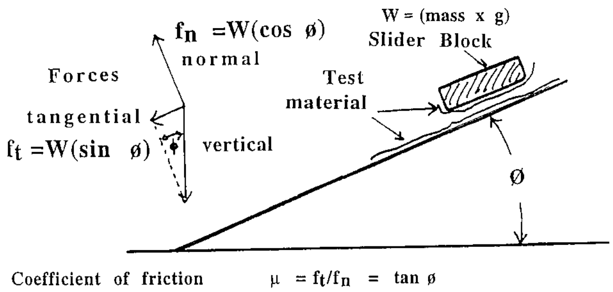

Figure 1 Visualization of friction measurement.

Some workers have observed a maximum in the friction coefficient with increasing speed.[1]

MEASUREMENT OF FRICTION

The measurement of friction between polymer surfaces is described in a number of standard ASTM procedures, many of which have been summarized.[2] Most of them involve slow movements of one surface over the other. An exception is the characterization of friction between shoe sole materials and polished floors. The British Pendulum Skid Resistance Tester uses a fast-moving, standard rubber element that slides over a polished plane in a prescribed manner.[3] It is not easily adapted to measuring the friction between two polymer films or sheets.

Our own preliminary tests indicated that the friction between sheets of a soft polymer, polyethylene, is affected more strongly by test speed than that of a hard plastic like poly(ethylene terephthalate).[4] Because there seemed to be a large difference between the static coefficient of friction, μ_s, and the dynamic coefficient measured at a very high speed, μ_z, it was thought useful to explore the behavior of some polymeric materials over a range of velocities. Four devices were used to achieve sliding speeds of 0.01 to 350 cm/s.

Friction Defined

The coefficient of friction is often characterized by a tilting-table method (Fig. 1). This is also a convenient method of visualizing the differences between static and kinetic coefficients. A block of mass W on a ramp making an angle ϕ exerts a normal force $f_n = W(\cos\phi)$ and a tangential force of $f_t = W(\sin\phi)$. The coefficient of friction μ is the ratio of forces, that is:

$$\mu = f_t/f_n = \tan\phi \qquad (1)$$

The angle at which movement first occurs (the angle of repose) yields the static coefficient, μ_s. The angle at which movement will continue when the block is set in motion is, of course, lower and yields the kinetic coefficient, μ_k. For most materials, μ is considered to be independent of the contact area. That is, because both normal and tangential forces are exerted on the same area of contact, the coefficients measured should be independent of the size and mass of the block. Also, velocity with which the block moves should not affect μ_k unless enough energy is dissipated to increase the temperature of the surface. In actual practice, the magnitude of the normal force and the relative velocities of the surfaces in the test do sometimes affect μ, especially for rubbery materials.

Tilt Table

A semiautomated tilt table was assembled (Fig. 2). The table is raised at a rate of about 0.6°/s by means of a constant speed motor with a string and pulley arrangement. As the table is tilted, an angle is reached at which the block starts to move. The tangent of the angle is the static coefficient, μ_s. In theory, μ_s should be independent of the vertical force on the block, but it is found to be somewhat affected in practice. In principle, a kinetic coefficient can also be obtained using the same apparatus with light tapping of the block, but the value is very hard to reproduce. The block has a contact area of 6.0 in^2 (39 cm^2). The mass of the material-covered slider block can be varied. This is a very fast and easily understood test. Of

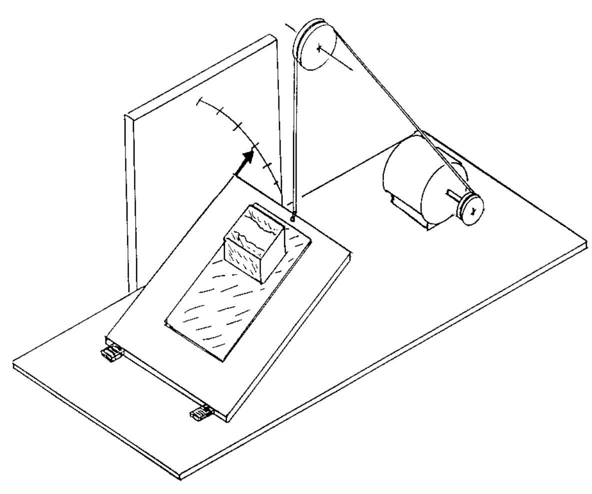

Figure 2 Tilt table apparatus.

course, the actual normal force applied varies with the angle at which sliding occurs. That is, the normal force is equal to the mass of the slider (times g) times cos ϕ (where $\mu = \tan \phi$).

Modified Instron Test

The Instron-based apparatus (Fig. 3), uses the standard tensile testing machine with a 2000 g_f load cell. A strip of the test material about 2.5 cm wide is suspended from the clamp (attached to the load cell). It passes between two brass surfaces that are wrapped with the same test material. The area of contact is 18 cm^2 on each side of the strip. A normal force is applied by means of a moment arm. Hanging masses on the extension of the arm transmit an equal horizontal force on the free brass block, which is pressed against the stationary block. The load cell is calibrated in the usual fashion by hanging masses directly on the clamp. In measuring friction, the crossarm is lowered at a selected speed varying from 0.2 in/min to 5 in/min (0.0085 to 0.21 cm/s). The force resisting the motion of the clamped strip as the crossarm moves is recorded. The ease and reproducibility with which speed can be controlled and varied make this device attractive. Because the modification to the standard tensile test configuration is minor, the friction test and a tensile test can be run on the same machine with only about 10 min needed for the changeover.

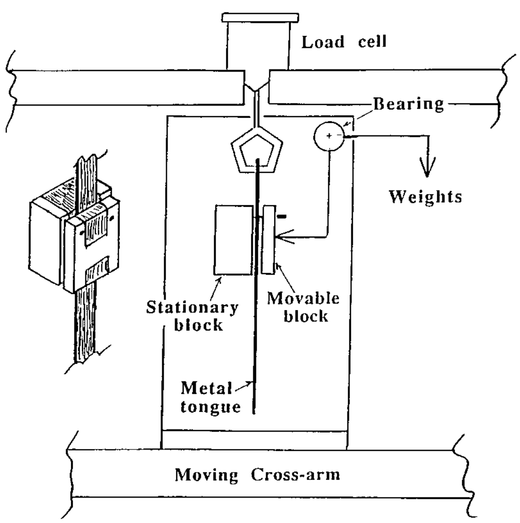

Figure 3 "Instron" device for measuring μ at slow speeds. The downward motion of the crossarm causes the material-covered tongue to slide over the material-covered blocks. A normal load is applied through the arm and bearing arrangement.

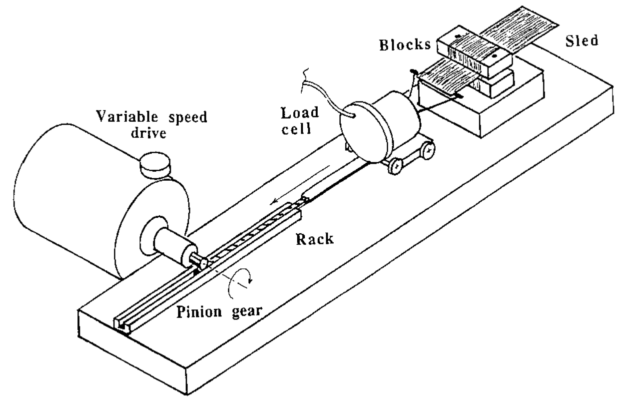

Figure 4 Horizontal sled device for measuring μ at moderate speeds. The load cell is calibrated for horizontal forces by masses on a string passing over a pulley. The variable speed pinion gear drives the sample forward by engaging a ratchet, which rides on a track.

Horizontal Sled

The horizontal sled apparatus (Fig. 4) uses a variable-speed drive (Graham) attached to a rack and pinion. Higher speeds are achievable than on the Instron. Speeds of 1 to 5 cm/s are convenient. The same load cell and recording equipment is used as on the Instron. The test material is wrapped around the surfaces of two blocks and also around a metal or paper "sled," which is attached to the load cell. The cell itself is mounted on a cart that is pulled by the rack at selected speeds. The normal force is applied directly to the upper block. The total area of contact is about 50 cm^2. Both of the modified Instron and horizontal sled devices bear some resemblance to the test tables in standard tests.[5]

Modified Impact Tester

A standard impact tester, often called the Izod tester, has been modified to examine friction at a high velocity. To measure friction, a metal sled is covered on both sides with the test material. The descending pendulum engages and accelerates the sled and draws it through two blocks that are also material covered (Fig. 5).

A mass M on the end of a pendulum accelerates when it is released from a height h_o. The velocity, u, at the lowest position is independent of the size of M and is given by the conversion of potential ($M_g h_o$) to kinetic energy ($Mu^2/2$) (where g = 32.2 ft/s^2 or 9.81 m/s^2):

$$u^2 = 2h_o g \tag{2}$$

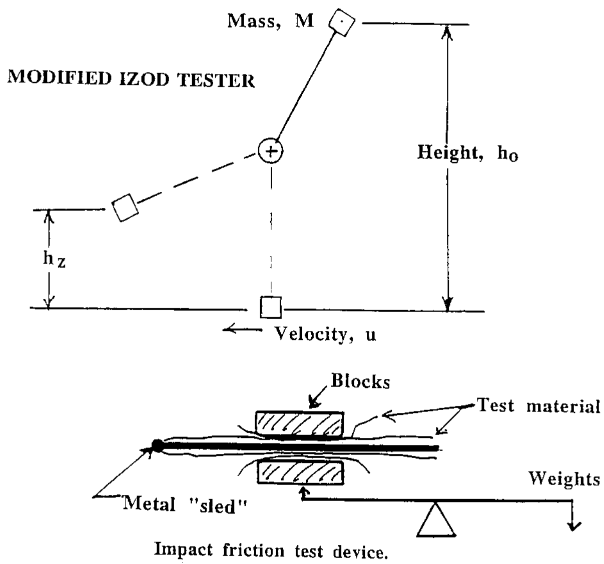

Figure 5 Impact friction test device.

Older devices like the one used here are set up in engineering units. Thus, h_o is 2.0 feet (6.10 m) and M is one pound (0.454 kg). Therefore, the initial potential energy available is 2.0 ft/lb$_f$ and the maximum velocity is 11.3 ft/s (136 inch/s or 3.45 m/s). The fraction of the initial energy that is dissipated after the pendulum swings through its arc is simply $(1 - h_z/h_o)$. The actual energy dissipated is read from a scale on the apparatus.

The sled material is 2 cm wide and the blocks are 6.5 cm long. The total length of material drawn through the blocks is 0.18 m (7.0 inch). Because we are measuring an energy rather than a force, defining a coefficient of friction is somewhat complicated.

Calculation of the Coefficient

The coefficient of friction can be calculated for each of the test methods simply from the applied normal force and the measured force in the direction of sliding. Neither the actual area of contact nor the speed of the test enters into the calculation. However, both the actual load and the speed may indirectly affect the value of the coefficient obtained.

In all of the tests except the tilt table, the normal force from the masses used is exerted on both the upper and lower surfaces of the sled (in parallel). However, the force in the sliding direction is twice what it would be for one surface. Thus, a horizontal force of 0.981 N (0.1 kg force) on a "sled" that has been weighed down with a 0.200 kg mass (1.96 N) corresponds to a coefficient of friction:

$$\mu = 0.100/(2 \times 0.200) = 0.250 \text{ (dimensionless)} \quad (3)$$

In the case of the impact test, the slope of the energy versus load diagram can be converted into a coefficient of friction in the following manner:

Let E = energy, J (1.356 × ft/lb$_f$), d = distance traveled by sled in contact with blocks = 0.15 m, f_N = normal load, N (kg × 9.81), and f_H = horizontal force, N.

Then,

$$E = f_H \times d \quad (4)$$

and

$$\mu = (f_H/2)/f_N = E/(2 \times d \times f_N) \quad (5)$$

If the slope of the energy versus load plot is 0.69 ft/lb$_f$/kg (machine units):

$$E/f_N = 0.69 \times 1.356/9.81 = 0.0954 \text{ J/N} \quad (6)$$

$$\mu = 0.0954/(2 \times 0.15) = 0.318 \text{ (dimensionless)} \quad (7)$$

RESULTS AND DISCUSSION

Various materials (see Table I) have been measured using the four different pieces of equipment. In each case, the materials were always tested with the same surfaces in contact (even where the two surfaces seemed identical) and with the same direction, usually the "machine direction," as indicated from surface topology or polarized light patterns.

Table I Materials Tested, Sources

Cellulose acetate, CA
"Grafix Acetate" clear overlay sheet, 0.125-mm thick
Low-density polyethylene (LDPE)
"Film-Gard CK 412" 0.100-mm thick (Carlisle Plastics)
Ultrahigh molecular weight polyethylene (UHMWPE)
Commercial film, 0.125-mm thick (McMaster-Carr)
Polytetrafluoroethylene (PTFE)
Skived tape, 0.125-mm thick (Teflon™, McMaster-Carr)

Two of the materials tested at high speed (Impact tester) are compared in Figure 6. The linearity of the plot implies that μ_z is independent of normal load. The intercept of each plot (0.20 ft-lb$_f$) is also the value obtained when the sample-bearing sled is accelerated and propelled without being placed between the stationary blocks. As calculated from equations 4, 5, and 6, μ_z for low-density polyethylene (LDPE) is considerably higher than that for cellulose acetate (CA).

When the same two materials are tested in all four devices, the outstanding feature is the reversal of the order of μ, depending on the test speed (Fig. 7). The CA shows a marked decrease in μ with speed, whereas the LDPE shows a corresponding increase. The static coefficients also are indicated in Figure 7. The difference between static and slow speed (Instron) tests is much greater for CA than it is for LDPE. The temptation to generalize the behavior on the basis of structure is quickly tempered by observing the behavior of two more materials (also shown in Fig. 7). The μ for UHMWPE changes very little over four decades of speed. PTFE, often regarded as the epitome of a low-friction material, has a μ less than half that of UHMWPE at low speeds, but about the same value at the highest speed used.

Before making any sweeping generalizations about the behavior of μ with speed, the various cautions should be observed. Friction depends on the individual sample of the material in question. We have observed, especially with polyethylenes, that electrostatic charges can alter μ greatly. By rubbing a polyethylene sample with another material (say, polyester fabric) the μ measured on the tilt table can be increased by a factor of two or more. The surface charge is a function of humidity and temperature as well as other forms of conditioning. A simple washing with detergent solution or with organic solvents proved to change μ drastically. Although the polymer films tested here show little change with repeated testing, other materials may be quite sensitive. Ordinary copier paper tested in the impact tester at a low load (0.2 kg) decreased steadily in μ over the first seven or eight repeated tests to a value of less than half the μ from the first try. It is to be expected that fibrous materials in general will show such tendencies.

The tilt table is the least reproducible of the various tests. Even with automated operation, the observation of slight motion can be complicated by slip-stick behavior as well as the previously cited dependence on humidity and conditioning.

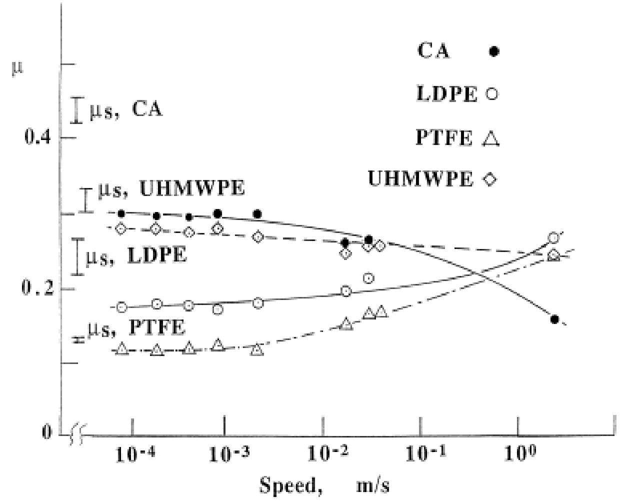

Figure 7 Coefficients of friction for the materials described in Table I as a function of speed. The data group at the slowest speeds came from the Instron apparatus, the next highest (0.01 to 0.1 m/s) from the horizontal sled, and the highest speed came from the impact tester. The μ_s values were obtained using the tilt table, which gives results that vary over the indicated ranges, chiefly due to changes in normal loading. The dynamic tests were obtained with comparable, but not identical normal loadings.

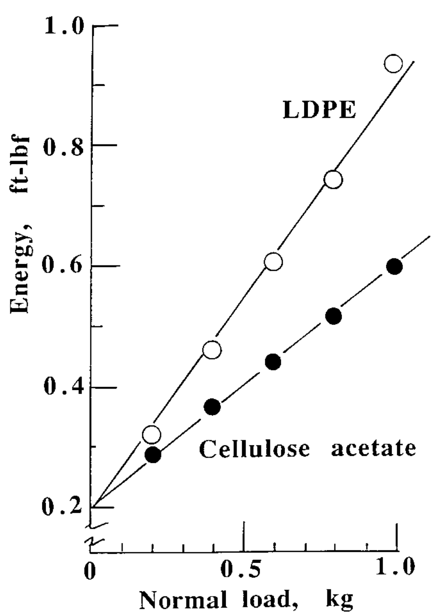

Figure 6 Impact test results for two polymer film materials. The slope for low density polyethylene (LDPE) corresponds to a $\mu = 0.27$, and that for cellulose acetate (CA) corresponds to a $\mu = 0.15$.

Surface Temperature Rise

To estimate the increase in surface temperature due to frictional energy dissipation, it is useful to employ a classical unsteady heat conduction equation. This particular equation has been derived for the case where an infinitely thick slab at temperature T_o is heated to a new surface temperature T_s at time zero.[6] In this case, the total heat energy transferred into the slab, Q', per unit of surface area, A, over time interval θ after the change in surface temperature is

$$Q'/A = 2k(T_s - T_o)(\theta/\pi\alpha)^{1/2} \quad (8)$$

and

$$\alpha = k/c\rho \quad (9)$$

where k is the thermal conductivity, c is the specific heat, ρ is the density, and α is the thermal diffusivity.

For our purposes, we can change the conditions to calculate the change in surface temperature needed to deposit a certain amount of energy. In a typical high speed (impact device) test, we are measuring the energy dissipated directly. As a rough estimate, we can use the equation to calculate a corresponding rise in surface temperature, $\Delta T = (T_s - T_o)$. For example, some typical conditions are

$$Q' = 0.40 \text{ ft-lb} = 0.13 \text{ cal} = 0.54 \text{ J}$$

$$A = 4 \times 14 \text{ cm (there are four surfaces involved)}$$

$$\theta = \text{a 7-in. strip of polymer}/140 \text{ inch/s} = 0.05 \text{ s}$$

Order-of-magnitude values for polymers are: $\rho = 1.0$ g/cm, $k = 3 \times 10^{-4}$ cal/s · cm · °C, $c = 0.6$ cal/g · °C. Thus, $\alpha = 5 \times 10^{-4}$ cm^2/s.

Now,

$$Q'/A = 0.130 \text{ cal}/(4 \times 14 \text{ cm}^2) \quad (10)$$

and

$$2k(\Delta T)(\theta/\pi\alpha)^{1/2} = 2(3 \times 10^{-4} \text{ cal/s} \cdot \text{cm} \cdot °\text{C}) \times \Delta T(0.05s/\pi \times 5 \times 10^{-4} \text{ cm}^2/\text{s})^{1/2} \quad (11)$$

Thus,

$$\Delta T = (T_s - T_o) = 0.69°\text{C}$$

A temperature rise of 0.69°C does not appear to be enough of a change to influence the frictional resistance in any significant way.

CONCLUSIONS

Inexpensive equipment has been developed and described for measuring the coefficient of friction as a function of speed and applied load. Dynamic tests appear to be more reproducible than the static test. Both increasing and decreasing changes in μ with speed have been observed. In viscometric phenomena, one characterizes speed-sensitive materials as shear thinning or shear thickening. The analogous behavior with friction might be termed speed slipping or speed sticking. It is apparent that sample conditioning is of tremendous importance in making any measurements.

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