JOURNAL OF MATERIALS SCIENCE 26 (1991) 2445–2450

Static and quasi-dynamic coefficient of friction of three engineering thermoplastics: UHMWPE, PA 66, POM

S. M. H. BENABDALLAH, H. YELLE*
*Department of Mechanical Engineering, Royal Military College of Canada, Kingston, Ontario, Canada K7K 5LO and *Department of Mechanical Engineering, Ecole Polytechnique de Montréal, Montreal, Canada H3C 3AF*

The principle of the slide-angle tester is simulated to measure the static and quasi-dynamic coefficient of friction. The gradual increase in the angle of inclination being replaced by a gradual increase in tangential force which tends to overcome the friction. As soon as a relative displacement of the slider is detected, the tangential force is maintained constant during a very short time allowing the slider to pick up speed. After that time, the tangential force is set equal to the friction force permitting a relative movement at a very small and constant speed. Under this condition, what we have called the quasi-dynamic coefficient of friction may be measured. Three thermoplastics widely used in engineering involving friction were investigated when sliding against steel in dry conditions at room temperature: UHMWPE, PA 66, POM. Results show a typical peak of static friction followed by different levels of the friction force depending on the polymer–metal combination. Data relating surface roughness of a polymeric specimen and normal load to the static coefficient of friction are discussed. The latter can be well described by a relation $\mu_s = \alpha F_N^n$, the constant α value depending on the roughness of polymeric specimen. However, an increase is obtained as the rugosity diminishes. Based on the experimental data, it was found that any increase in the normal load would increase the speed at which slip occurs.

1. Introduction

It is well known that before gross sliding occurs between two solids in contact, some micro-sliding has taken place from the original static (no sliding) position. Also, it is observed that the coefficient of friction that prevails before gross or micro-sliding has started (static), is generally larger than that existing afterwards (dynamic). These processes have been investigated mainly for combinations of steel rubbing on steel [1–3].

The objective of the work reported here was to evaluate the static and quasi-dynamic coefficients of friction of different engineering thermoplastics in contact with steel. The variables studied are the normal load, the surface roughness of the thermoplastic specimens and the sliding speed.

Using a newly designed apparatus, the critical location where gross slip occurs could be defined reasonably well over a wide range of tangential loading rates.

Three popular engineering thermoplastics were tested: an ultra-high molecular weight polyethylene (UHMWPE, Hercules 1900), polyoxymethylene (POM, Delrin 500) and polyamide 66 (PA 66, zytel 101). The plastic specimens have a rectangular shape of 1 cm × 2 cm × 1 cm (see Fig. 1a) giving 2 cm^2 apparent contact area. The specimens were machined from extruded plate. The directions of extrusion, sliding and machining are shown in Fig. 1a.

During the experiments, the plastic specimens were pressed against the steel slider as shown in Fig. 1b with a normal load varying from 8–160 N. The slider is machined from mild steel and ground to a surface roughness of 0.16 μm centre line average (CLA), measured in the direction of sliding. The surface roughnesses achieved on the plastic specimens are of the order of 0.8, 3, 18 and 35 μm CLA, measured in the direction of sliding (the exact values for each material are indicated later in Figs 6–8). These were obtained by varying the feed of the milling machine. The apparatus used to measure the surface roughness is a Clevite Brush-Surfindicator.

The sliding speed, although small, varied by a factor of over 10 from about 15–180 $\mu m\,s^{-1}$. All the tests were conducted in air at 50% r.h. and 23 °C and without lubrication. The plastic specimens were changed after each test and the steel slider was cleaned with tetrahydrofuran (THF) solvent and a soft brush (tooth brush).

2. Principle of measurement

The general principle that governs the experimental programme is the tilting inclined plane. With the tilting plane, it is easy to measure the static coefficient of friction by measuring the inclined plane angle at the precise instant at which the block starts to move.

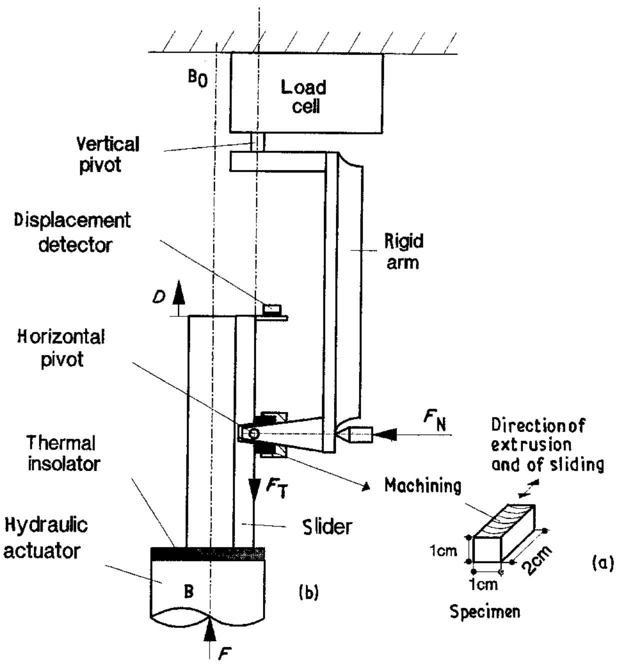

Figure 1 Schematic illustration of apparatus for the measurement of static and quasi-dynamic friction coefficients.

However, to measure the dynamic coefficient of friction with that apparatus, one has to either measure the acceleration of the block, then the sliding speed is not constant, or reduce the tilting angle to keep the speed constant which is not easy.

The apparatus that has been built to measure the static and quasi-dynamic coefficients of friction has the advantages of the tilting plane without the inconvenience. The apparatus is shown schematically in Fig. 1b and a general view of the experimental apparatus is shown in Fig. 2.

3. Measuring apparatus

Fig. 1b shows one half of the apparatus used. The other half is symmetrical relative to the vertical plane B–B_0. The apparatus consists of a steel slider attached to the head of the hydraulic actuator of a universal hydraulic testing machine (MTS). The plastic specimen is inserted into a holder that acts as a pendulum which can turn freely about a horizontal axis in a vertical rigid arm. The other end of that arm is attached to a load cell and it is free to turn about a vertical axis that lies in the interfacial contact plane between the plastic specimen and the steel slider. The two degrees of freedom at 90° ensure a uniform contact over the whole apparent area of the specimen with the slider. The normal force, F_N, is applied on the rigid arm by means of a pneumatic actuator and light cables (Fig. 2).

The normal force applied is measured by strain gauges placed on the steel plate on which is mounted the pneumatic actuator. The friction force, F_T, that exists between the plastic specimen and the steel slider is measured by a minibeam load cell (capacity 50 lb, 22.679 kg). A displacement detector (Wayne Kerr DIEMQ TE200, 10 μm resolution) detects and measures the relative motion, D, between the specimen and

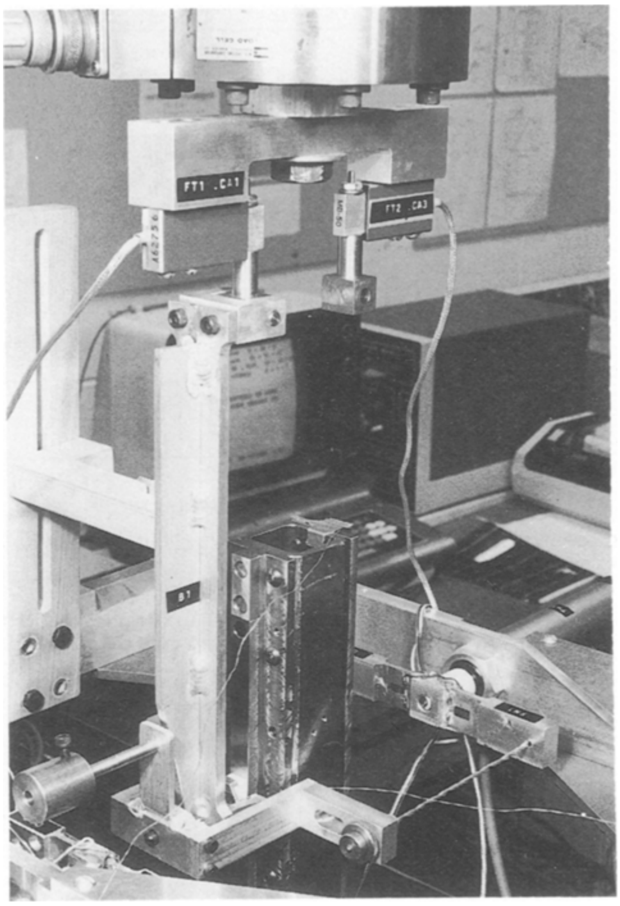

Figure 2 General view of the experimental apparatus.

the slider. A thermal insulation material is inserted between the steel slider and the hydraulic actuator to avoid heat flow and thermal gradient in the slider.

4. Experimental procedure

To reproduce the principle of the tilting plane, a gradually increasing force, F (Fig. 1b), is applied to the steel slider by the hydraulic actuator until it starts to move. The process and the data acquisition are under the control of a microcomputer. Fig. 3 shows a flow chart of the computer procedure. The chart is divided in three blocks: A, initiation of the variables and input of the constant for the test; B, control of the test and data acquisition; C, calculation and display of the results.

4.1. Block A

The input constants for the test at step 1 are the rate, f, at which the force, F, will be increased and the maximum duration time, K, of the test. Values of the rate, f, varied from 0.22–15 $N\,s^{-1}$. The value of K is dictated by the data acquisition rate (1 kHz) and the maximum storage capacity of the computer (640 kbytes). The increasing rate, f, is then set such that relative sliding occurs within the time, K.

Step 2 is to set all the storage memories to zero. Step 3 is to apply the pressure to the pneumatic actuator. At step 4, the operator hit a key to start the test at time $t = 0$.

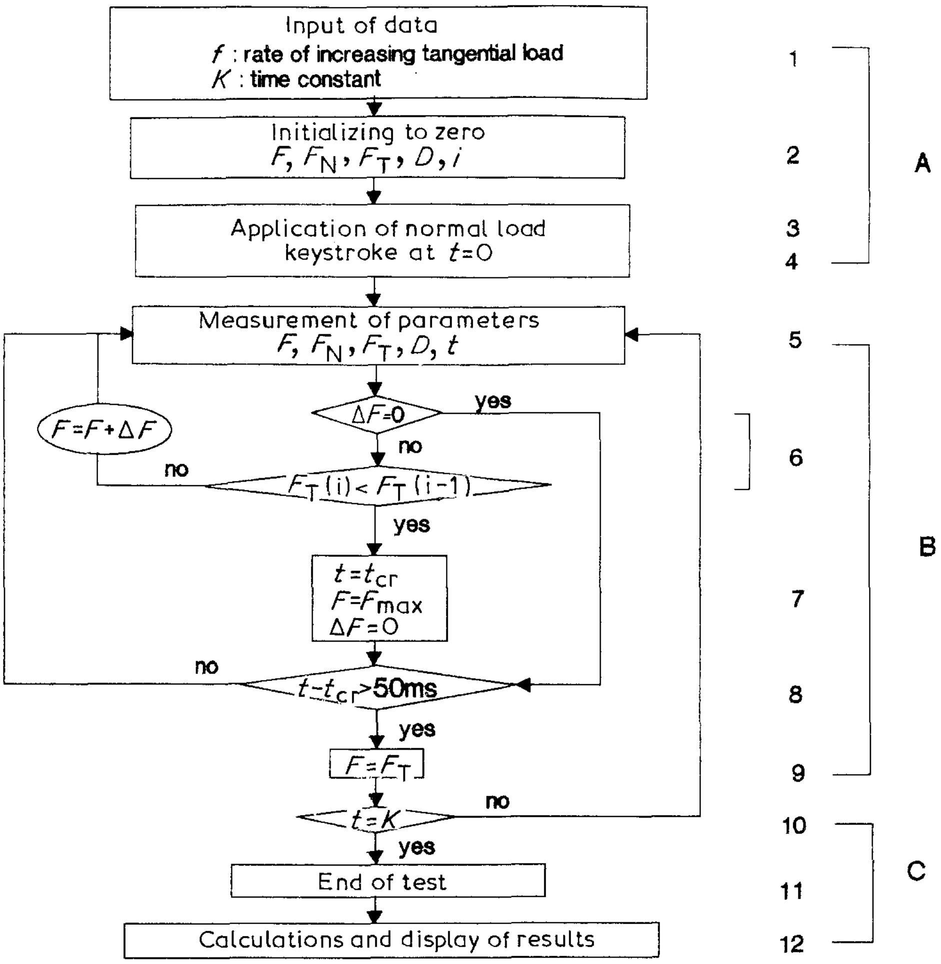

Figure 3 Flow chart of software to measure static and quasi-dynamic friction coefficients.

4.2. Block B

The computer first measures and stores F, F_N, F_T, displacement, D, and time, t, at step 5. Then, it checks if relative sliding has started ($D > 0$) in step 6. If not, the increase in force F continues. At the first detection of a relative movement, which corresponds to a sudden decrease in friction force, F_T, t is recorded as t_{cr} (critical time), F as F_{max} and the increment ΔF is set to zero, the whole in step 7. From that time, then, and for about 50 ms, the force, F, is kept equal to F_{max} to allow the hydraulic actuator–slider assembly to accelerate and pick up speed (step 8). After that time, F is set equal to F_T (step 9) and the whole assembly moves at constant speed.

4.3. Block C

The measurements of the parameters (forces, displacements and time) continue until at the end of time K (step 10). The hydraulic actuator is then stopped (step 11) and μ_s and μ_{qd} are calculated from stored data (step 12) according to the equations

$$\mu_s = \frac{F_{max}}{F_N} \quad \text{at } t = t_{cr} \tag{1}$$

and

$$\mu_{qd} = \frac{F_T}{F_N} \quad \text{at } t_{cr} < t < K \tag{2}$$

where μ_s is the static coefficient of friction, and μ_{qd} is coefficient of quasi-dynamic conditions.

5. Results

Fig. 4 presents schematically the evolution of the variables F (applied force), F_T (friction force), a (the acceleration), v (sliding speed) and D (relative displacement) during the course of the experiment as a function of the time, t (block B, in Fig. 3). It should be noted that the normal force, F_N, is kept constant during the test. On the time axis, one can identify four different zones.

1. $0 \leqslant t \leqslant t_{cr}$. In this zone, the force, F, increases at the rate f as does the friction force, F_T, in reaction to keep the actuator–slider assembly in equilibrium. In that zone, $a = v = D = 0$.

2. $t_{cr} < t \leqslant t_{cr} + \varepsilon$. Relative motion first started at t_{cr}. Then F_T started to decrease and F is set to F_{max} such that $a > 0$ and is given by

$$a = \frac{F_{max} - F_T}{m} \tag{3}$$

where m is the mass of the actuator–slider assembly. In this zone, D, a, v are larger than zero (Fig. 4a–c, respectively). The time, ε, is very short (about 50 ms) such that the actuator–slider assembly does not pick up much speed.

3. $t_{cr} + \varepsilon < t \leqslant t_{cr} + \Delta t$. At $t_{cr} + \varepsilon$, ΔF is set to zero such that $a = 0$ and v remains constant while the

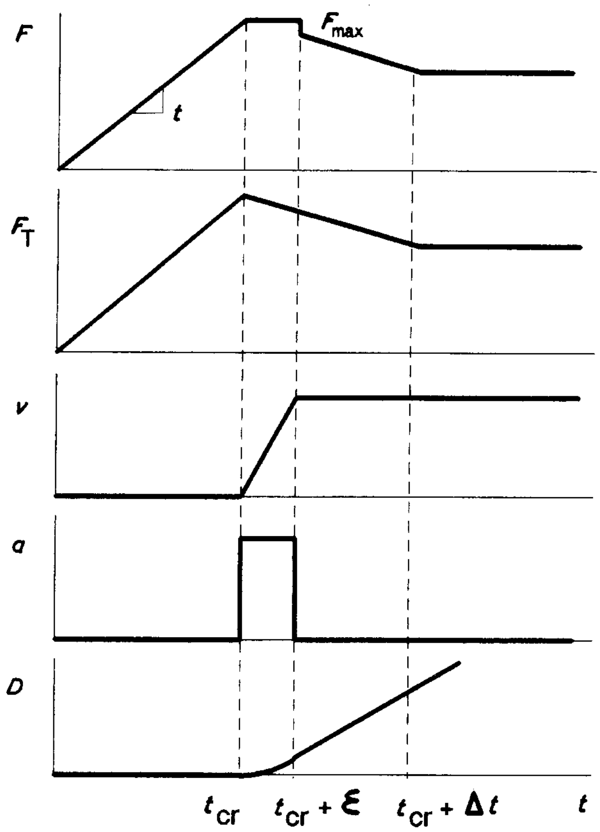

Figure 4 Schematic of the applied force F, friction force, F_T, sliding speed, v, acceleration, a, and relative displacement, D, as function of the time, t.

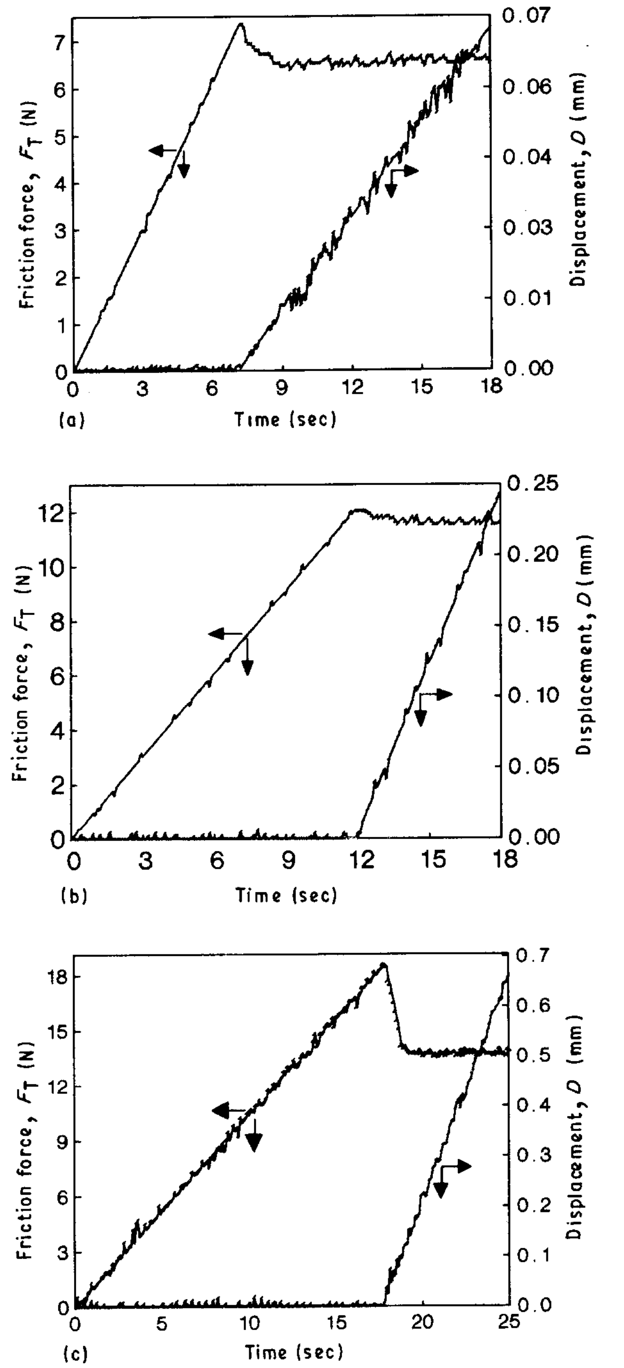

Figure 5. Relative displacement and friction force as function of time: $F_N = 50$ N, CLA = 0.70 μm; (a) UHMWPE, (b) POM, (c) PA 66.

relative displacement, D, increases. F_T continues to decrease from F_{max} corresponding to μ_s, towards a new lower value corresponding to μ_{qd}.

4. $t > t_{cr} + \Delta t$. At this point, F_T has reached that new value corresponding to μ_{qd}. Then $a = 0$, v is constant and D increases linearly.

Fig. 5 is a plot of the values of F_T and D recorded during a typical test. The figure shows clearly that F_T increases linearly until t_{cr} is reached. At t_{cr}, the relative displacement, D, starts to increase while F_T decreases. F_T reaches a new stable value at $t = t_{cr} + \Delta t$. The period of time, ε, during which $a > 0$ is not apparent at the scale of Fig. 5.

To ensure consistency in the results, several tests were run at each set of conditions of normal load and surface roughness investigated for the three thermoplastic materials. The average of the five best results at each point was used to prepare Figs 6–8.

The data points on the dotted lines in Figs 6–8 represent the values of the static coefficient of friction, μ_s, calculated from Equation 1 taking into account F_{max} recorded at t_{cr} as a function of the normal load. The solid lines represent the best fit using a power law. A first observation is that μ_s decreases as the normal load increases at all surface roughnesses. Following Savkoor [4], it is permitted to believe that adhesion is the main component of friction in those tests.

Fig. 9 is a plot of μ_s from Figs 6–8 for one surface roughness as a function of log F_N. A relation of the form

$$\mu_s = \alpha F_N^n \quad (4)$$

fits the experimental data well. Pascoe and Tabor [5] have shown that when a hard sphere is rubbed against a polymer surface, the coefficient of friction is well described by a similar relation. Table I lists the values of exponent n and α for the three thermoplastic materials at the four surface roughnesses studied. The proportionality constant has a value which depends on the roughness of the plastic specimen.

A second observation from Figs 6–8 is that, in all cases, the static coefficient of friction increases as the surface roughness decreases.

It is well known that the adhesion component of friction is given by

$$F_a = \tau A_r \quad (5)$$

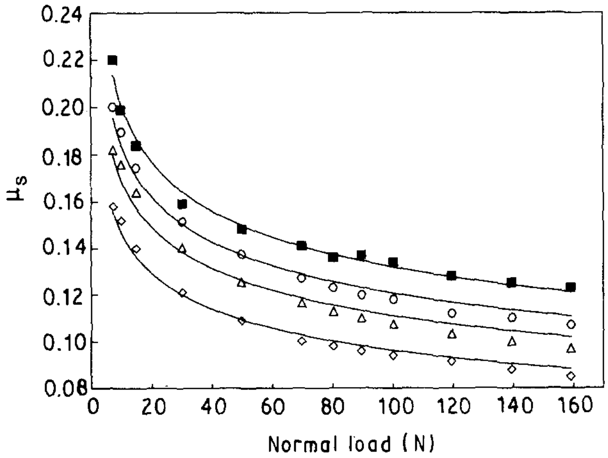

Figure 6 Static coefficient of friction versus normal load for the range of surface roughness tested of the UHMWPE. CLA: (■) 0.85 μm, (○) 3.2 μm, (△) 17.3 μm, (◇) 34.3 μm.

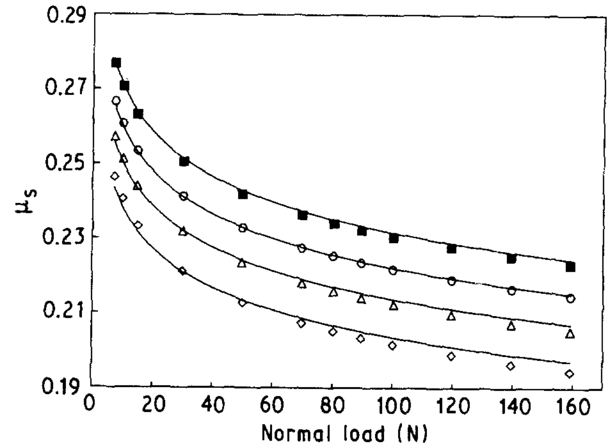

Figure 7 Static coefficient of friction versus normal load for the range of surface roughness tested of the POM. CLA: (■) 0.65 μm, (○) 3.0 μm, (△) 17.2 μm, (◇) 33.5 μm.

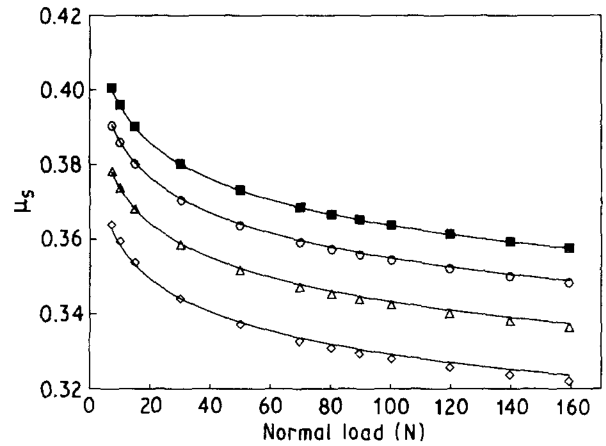

Figure 8 Static coefficient of friction versus normal load for the range of surface roughness tested of the PA 66. CLA: (■) 0.75 μm, (○) 3.7 μm, (△) 17.9 μm, (◇) 39.7 μm.

where τ is the shear strength at the interface of friction and A_r the real area of contact. The shear strength is given by

$$\tau = \tau_0 + \beta P \qquad (6)$$

where τ_0 and β are constants and P is the real contact pressure.

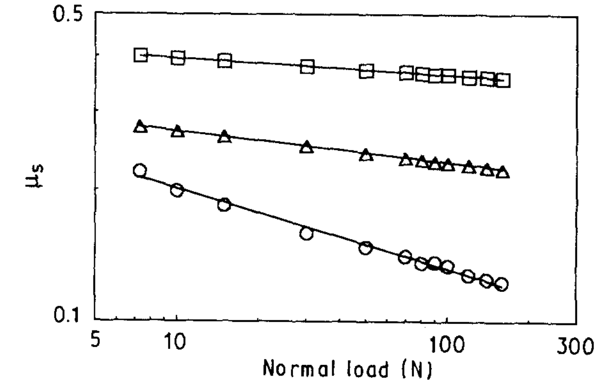

Figure 9 Static coefficient of friction versus normal load for (○) UHMWPE, (△) POM, (□) PA 66, CLA ≃ 0.7 μm.

TABLE I Experimental values of n and α in $\mu_s = \alpha F_N^n$

Plastic	n	α
UHMWPE	− 0.184	0.22–0.32
POM	− 0.069	0.28–0.32
PA 66	− 0.037	0.39–0.42

Taking that $P = F_N/A_r$ into account, the combination of Equations 5 and 6 gives

$$F_a = \tau_0 A_r + \beta F_N \qquad (7)$$

Gupta and Cook [6] have analysed theoretically the mechanism of junction deformation, their conclusions show that the coefficient of friction decreases with normal load for elastic contact and the adhesion is important in this case.

The experimental results in this study show a decrease of the static coefficient of friction as the normal load increases, therefore we can assume that $F_a = F_{max}$ then $F_a/F_N = \mu_s$ and when replaced in Equation 7, one obtains

$$\mu_s = \tau_0 \frac{A_r}{F_N} + \beta \qquad (8)$$

This equation shows that the increase of A_r, resulting from a decrease of the roughness, implies an increase of μ_s. Equations 4 and 8 imply that in this case the real area of contact should be expressed as $A_r = kF_N^n$ with n less than unity.

Coming back to Fig. 5, it appears that the evolution of F_T for $t > t_{cr}$ differs much from one thermoplastic material to another. In the case of PA 66, Fig. 5c, F_T shows a net, sharp decrease. However, for the POM, Fig. 5b, F_T remains almost equal to its maximum value. The evolution of F_T with the UHMWPE is intermediate between the two extreme cases.

Assuming that the accelaration of the actuator–slider assembly is constant as shown in Fig. 4, then

$$v = a\varepsilon \qquad (9)$$

Placing a from Equation 3 into equation 9, one obtains

$$v = \frac{\varepsilon}{m}(F_{max} - F_T) \qquad (10)$$

ε/m is a constant for all the tests, $\varepsilon = 50$ ms, m is the mass of the actuator–slider assembly. Then Equation 10 becomes

$$v = \text{constant}\ (F_{max} - F_T) \qquad (11)$$

According to the results shown in Fig. 5, it can be expected that

$$v_{PA\,66} > v_{UHMWPE} > v_{POM} \qquad (12)$$

Fig. 10 shows plots of the relative sliding speed, v, established from the corresponding portion of the displacement diagram (Fig. 5) as a function of the normal force, F_N. The figure shows that Equation 12 is verified for all values of F_N. That observation suggests that the PA 66 and the UHMWPE, in those tests, deposited a relatively thin film over the surface of the steel slider during the time $t_{cr} < t < t_{cr} + \Delta t$. From $t = 0$ to $t = t_{cr}$, the contact is between plastic and steel. The coefficient of friction is then μ_s. At $t > t_{cr} + \Delta t$, however, the contact is mainly between plastic and a film transferred to the slider consisting of molecules highly oriented in the direction of sliding. This leads to a lower value of μ. In the case of POM, almost no film is deposited such that the contact remains mainly POM against steel and μ does not change much [7].

These results indicate that the normal load will secure the firm attachment of the transferred film to the counterface. Under this condition, the friction becomes lower (decrease of the quasi-dynamic coefficient of friction, μ_{qd}) and consequently the speed at which slip occurs increases as predicted by Equation 12.

Fig. 11 represents the variation of quasi-dynamic coefficient of friction, μ_{qd}, as function of the product of the normal load and the relative sliding speed. These results indicate a rapid decrease of μ_{qd} then a constant value is reached as $F_N\,v$ increases. This is well represented by the solid lines obtained by fitting the data to an exponential function $\mu_{qd} = k_1 + k_2 \exp(F_N v)$ where k_1 and k_2 are constants using a least-squares fit.

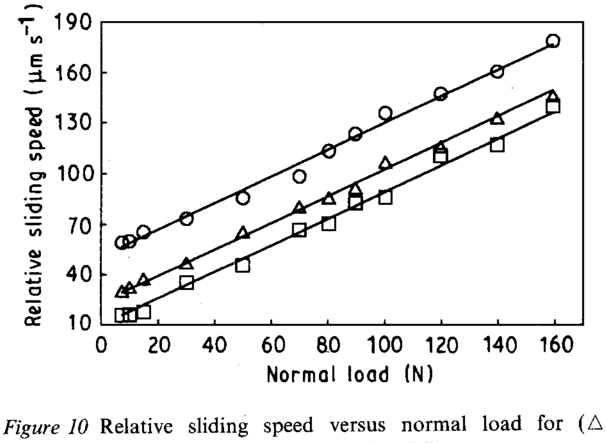

Figure 10 Relative sliding speed versus normal load for (△) UHMWPE, (□) POM, (○) PA 66, CLA ≃ 0.7 µm.

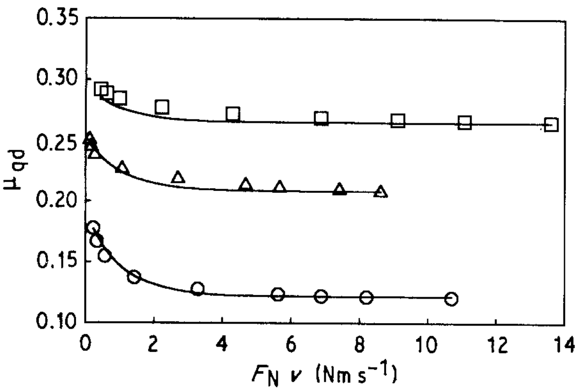

Figure 11 Quasi-dynamic coefficient of friction as function of normal load and relative sliding speed for (○) UHMWPE, (△) POM, (□) PA 66, CLA ≃ 0.7 µm.

6. Conclusion

The experimental apparatus and procedure have been shown to give consistent and repeatable results. The procedure is useful to determine easily and accurately the coefficient of static friction in a variety of useful conditions.

The experimental measurements have confirmed that the static coefficient of friction decreases when the normal load and the roughness increases in the range of values tested.

The work is continuing, to obtain reliable values of the real contact area, using the same plastic specimens as used in the present study, to be used in Equation 8. When these results are available, it might be possible to have a better knowledge of the per cent friction caused by adhesion and plastic deformation.

The experimental procedure allowing a constant speed when relative movement starts shows that any increase in the normal load would increase the speed at which slip occurs.

Acknowledgement

The authors thank the National Research Council of Canada for financial support.

References

1. M. EGUCHI and T. YAMAMOTO, "Dynamic Behavior of a Slider under Various Tangential Loading Conditions", in Proceedings of the Japan Society of Lubrication Engineer, International Tribology Conference, Tokyo, Japan (1985) pp. 1074–1152.
2. Z. BRONIEC and W. LENKIEWICZ, *Wear* **80** (1982) 261.
3. E. W. GAYLORD and H. SHU, *ibid.* **4** (1961) 401.
4. A. R. SAVKOOR, "Adhesion and Deformation Friction of Polymer on Hard Solids", in "Advances in Polymer Friction and Wear", Vol. 5A, edited by D. H. Lee (Plenum Press, New York, 1974) pp. 69–121.
5. M. W. PASCOE and D. TABOR, *Proc. Roy. Soc. London* **A-235** (1956) 210.
6. P. K. GUPTA and N. H. COOK, *Wear* **20** (1972) 73.
7. D. TABOR and D. E. WYNNE WILLIAMS, *ibid.* **4** (1961) 391.

Received 19 March and accepted 18 June 1990