JOURNAL OF APPLIED POLYMER SCIENCE VOL. 8, PP. 1477–1482 (1964)

Friction of Polymer Films. II. Effect of Deformation Properties

D. K. OWENS, *E. I. du Pont de Nemours & Company, Inc., Spruance Film Research and Development Laboratory, Richmond, Virginia*

Synopsis

The effect of mechanical deformation properties on the frictional behavior of cellulose film coated with vinylidene chloride–acrylonitrile copolymer was investigated. A device for measuring the deformation properties of thin polymer films by static indentation techniques was developed. The mode of deformation of the polymer coated cellophane was found to be intermediate between plastic and elastic with a measured deformation index m of 2.35. A mathematical relationship between surface roughness, load, deformation index, and coefficient of friction was developed. It was shown that the coefficient of friction of the polymer film varied with the number of surface asperities to the $(2/m)$-1 power, and that the friction also varied with load to the same power. The frictional behavior of polymers as a function of several variables could be expressed in terms of a single material constant, the deformation index. Although derived from static measurements, this index is applicable to dynamic systems.

I. INTRODUCTION

It is well established that the frictional process with polymers differs in several important respects from that occurring with metals. Unlike metals, the coefficient of friction of polymers is not independent of the applied load, but rises as the load is decreased.[1,2] The coefficient of friction of polymers decreases with an increase in surface roughness in contrast to the friction of metals which is independent of roughness.[3,4] It has been shown, despite these apparent differences, that a single relationship of the form $F = kW^n$ expresses the relationship of load W and frictional force F for a wide variety of metallic and nonmetallic materials.[3,5] The exponent n is determined by deformation characteristics of the substances undergoing sliding, and is a measure of the way in which the real area of contact varies with load. This exponent has been shown to have the limits of 1 for purely plastic deformation and $^2/_3$ for purely elastic deformation. Thus the friction of metals is a special case of the general relationship where $n = 1$. For any value of n other than 1, the coefficient of friction will not be independent of the load. It is apparent, then, that the frictional behavior of polymers is strongly influenced by their deformation properties.

Pascoe and Tabor[6] have shown that the deformation properties of polymers can be conveniently measured by means of spherical indenters pressed into a block of the polymer under a known load. Using a steel ball they found that the load W and the indentation diameter d were related by the expression $W = k_1 d^m$. The exponent m is a material constant of the substance under test and varies from 2 for plastic deformation to 3 for elastic deformation. They have further shown that the projected area of the indentation A_I is given by

$$A_I = \frac{\pi}{4}\left(\frac{1}{K}\right)^{2/m} W^{2/m} D^{(2m-4)/m}$$

where D is the indenter diameter. Assuming that the area of real contact of the indenter is a constant fraction of A_I, they concluded that the frictional force should vary as $W^{2/m}$ or the coefficient of friction, μ, as $W^{(2/m)-1}$. This conclusion was supported by experimental evidence.

Kaliski[7] suggested for nylon yarn that the friction is inversely proportional to the square root of the number of asperities in the case where plowing is assumed to occur. Plowing may be presumed to occur when the slider is a harder material than the substrate and has a radius which is small compared with the dimensions of the substrate. In the experimental apparatus used by Kaliski, however, a nylon thread was slid on a mirror chrome pin 2 in. in diameter under very low tension. Under these conditions it would seem that plowing is very unlikely. Moreover, an explanation of the reduced friction on a rough pin based on a plowing mechanism does not account for the observations of numerous workers that friction is also reduced when the roughness is in the softer member of the sliding pair. It should be possible to explain the effects of surface roughness on polymer friction in terms of the deformation behavior of the polymer using the adhesion theory of friction.

Assume that the relationship $\mu \propto 1/N^{1/2}$ found by Kaliski is correct and that this relationship is for the case where purely elastic deformation occurs, since friction is independent of asperity number when plastic deformation occurs (exponent of $N = 0$). Assuming that the exponent of N is a function of the deformation index, m, the following relations must be satisfied: $f(m) = 0$ when $m = 2$, and $f(m) = 1/2$ when $m = 3$. The expression $(m/2)-1$ satisfies both conditions. By substitution, the expression of Kaliski becomes $1/N^{(m/2)-1}$. This expression is in fair agreement with data to be presented later.

Exact agreement with the data is obtained if it is assumed that the term $(1/K)^{2/m}$ in the equation of Pascoe and Tabor contains a factor related to asperity number and that K is proportional to the $N^{(m/2)-1}$ factor derived above. By substitution for K the expression $(k_2/N^{(m/2)-1})^{2/m}$ is obtained, which simplifies to $k_3 N^{(2/m)-1}$, where N is taken as the number of asperities per unit of surface area. It then follows that the coefficient of friction of a polymer should be proportional to $W^{(2/m)-1}$ at constant asperity number and to $N^{(2/m)-1}$ at constant load. The relationships of load, friction, roughness, and static indentation diameter may then be formulated into the following equations:

$$W = k_1 d^m$$

$$\mu = k_4 W^{(2/m)-1}$$

$$\mu = k_5 N^{(2/m)-1}$$

These relationships were tested experimentally as described below.

II. EXPERIMENTAL

Films of regenerated cellulose coated with vinylidene chloride–acrylonitrile copolymer lubricated with stearamide were prepared as described in a previous paper.[8] The polymer to metal coefficient of static friction, μ_s, was measured against the polished metal drum of the capstan machine described elsewhere.[8] The drum had a 2 μ in. RMS finish and was cleaned with carbon tetrachloride between each measurement. The speed of rotation at the periphery of the drum was 0.01 cm./sec. The load for the purpose of these experiments was considered to be identical to the pretensioning weight used. A device of our own design, suitable for static indentation measurements on thin films was constructed. It consisted of a balanced beam carrying a stylus holder on one end and a counterweight on the other. Loads were applied by means of weights located on a pan directly above the stylus holder, and the beam could be gently raised or lowered with a fine-pitch screw. The film samples were mounted on glass microscope slides. Styli, or indenters, were made by welding a glass bead to the tip of a glass rod. The beads were selected under a microscope from commercially available glass beads. Styli having diameters from 150 to 500 μ were made. The selected stylus was pressed into the film for a time of 1 min. at different loads, and the apparent diameter of the indentation was measured microscopically.

The surface of the polymer coating was roughened by adding varying quantities of finely ground clay to the polymer solution used to coat the cellulose film. The protrusions produced in the polymer coating by the particles are considered the asperities. The number of clay particles or asperities per unit of area was determined microscopically. The average diameter of the particles was 7 μ. The coefficient of static friction was determined as described before[8] as a function of load at fixed asperity number and as a function of asperity number at fixed load.

III. RESULTS AND CONCLUSIONS

The indentation diameter as a function of load for the polymer film was plotted graphically as shown in Figure 1. The indenter diameter was 237 μ. The slope of the straight line obtained is equal to m and was found to be 2.35. Determinations of μ_s as a function of load (pretensioning

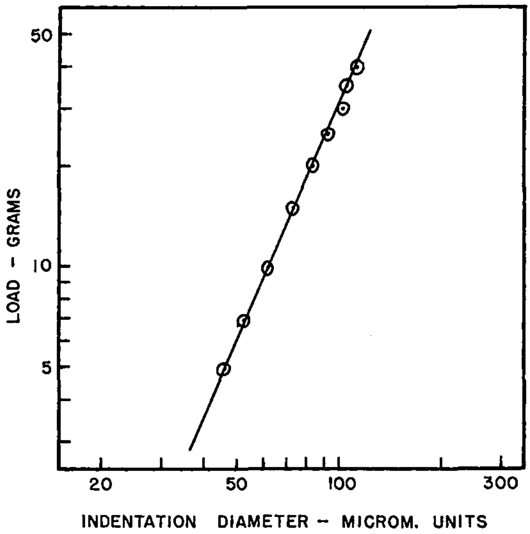

Fig. 1. Indentation diameter vs. load for polymer-coated cellophane.

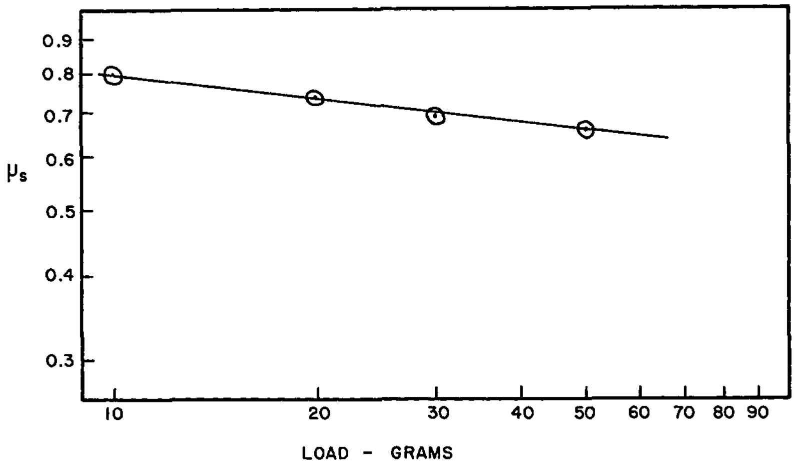

Fig. 2. Static friction vs. load for polymer-coated cellophane.

weight) at constant asperity number were made and are shown graphically in Figure 2. The slope of the line was -0.14. Static friction as a function of asperity number for a constant load was measured and is shown in Figure 3. The slope of the line was -0.15. The results are tabulated in Table I. This table shows the measured value of m and the value of m calculated from the relationships shown.

Excellent agreement for the value of the deformation index was found by three different methods of determination. The relationship $\mu = k_4W^{(2/m)-1}$ given by Pascoe and Tabor and substantiated by them was

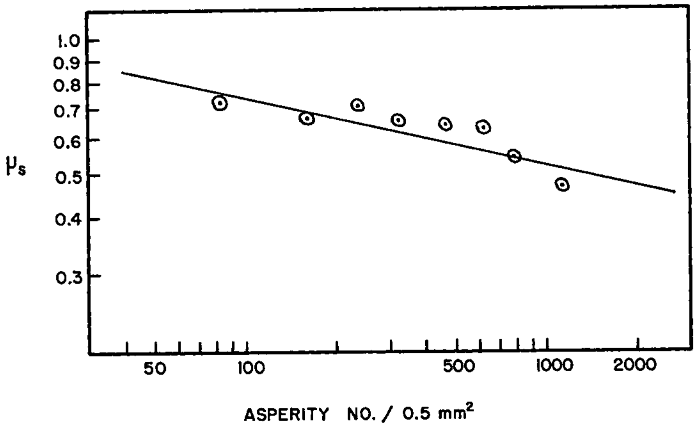

Fig. 3. Static friction vs. asperity number for polymer-coated cellophane.

ound to be valid for the polymer coated cellulose film used in this study. The proposed relationship between asperity number and μ_s was found to agree exactly with the experimental evidence. With the use of only the relationship derived from Kaliski, where $\mu \propto 1/N^{(m/2)-1}$, a value of 2.30 is found for m. While it is fairly certain that all of the asperities on the film surface do not participate in the sliding process, it is assumed that the number participating is a constant fraction of the total number present. This assumption appears to be justified by the experimental results. The relationship $\mu_s = k_5N^{(2/m)-1}$ agrees with theory. For the case where plastic deformation occurs ($m = 2$) and the coefficient of friction is known to be independent of roughness, the exponent $(2/m)-1$ becomes zero and μ_s becomes independent of N.

Surface roughening is a well known method of reducing polymer friction, especially with textile fibers and yarns. The relationship of friction to roughness described above implies a limit to the amount of friction reduction which can be accomplished by a given value of roughness. This limit is the case where complete elastic deformation occurs ($m = 3$). The coefficient of friction then should be inversely proportional to the cube root of the asperity number.

It is concluded that the frictional behavior of polymeric substances as a function of load and surface roughness can be described in terms of a

TABLE I
Experimental Values of m for Polymer Film

Relationship	Experimental value of exponent	Calculated value of m	Method
$W = k_1d^m$	2.35	2.35	Static indentation
$\mu_s = k_4W^{(2/m)-1}$	−0.14	2.33	μ_s vs. load
$\mu_s = k_5N^{(2/m)-1}$	−0.15	2.35	μ_s vs. asperity no.

single material constant, the deformation index. This parameter, although derived from static measurements, is applicable to dynamic systems. The deformation index determines the manner in which the area of real contact varies with load and specimen roughness and therefore determines the dependence of the coefficient of friction on these variables.

References

1. Howell, H. G., *J. Textile Inst.*, **42,** T521 (1951).
2. Rubenstein, C., *Proc. Phys. Soc.*, **A69,** 921 (1956).
3. Lincoln, B., *Brit. J. Appl. Phys.*, **3,** 260 (1952).
4. Denny, D. F., *Proc. Phys. Soc.*, **B66,** 721 (1953).
5. Howell, H. G., and J. Mazur, *J. Textile Inst.*, **44,** T59 (1953).
6. Pascoe, M. W., and D. Tabor, *Proc. Roy. Soc.* (*London*), **A235,** 210 (1956).
7. Kaliski, E. J., *Textile Res. J.*, **28,** 325 (1958).
8. Owens, D. K., *J. Appl. Polymer Sci.*, **8,** 1465 (1964).

Résumé

On a étudié la relation entre les propriétés mécaniques (déformation) et la résistance à la friction de films de cellulose enduits de copolymères chlorure de vinylidène–acrylonitrile. On a développé également un appareil pour étudier la résistance à la déformation de films polymériques minces par des mesures statiques de pénétration. La cellophane enduite de polymères se déforme d'une manière intermédiaire entre celle d'un plastique et d'un élastomère. On a mesuré un indice de déformation m de 2.35. On a développé une relation mathématique entre la rugosité de la surface, la charge, l'indice de déformation et le coefficient de friction. On a montré que le coefficient de friction d'un film polymérique varie à la puissance $(2/m) - 1$ avec le nombre d'aspérites de la surface et également que la friction varie avec la charge à la même puissance. La résistance à la friction des polymères qui est fonction de plusieurs variables peut être exprimée en fonction d'une seule constante du matériel l'indice de déformation. Bien que calculé à partir de mesures statiques cet indice peut s'appliquer aux systèmes dynamiques.

Zusammenfassung

Der Einfluss der mechanischen Deformationseigenschaften auf das Reibungsverhalten von mit Vinylidenchlorid–Acrylnitril-Copolymeren überzogenen Cellulosefilmen wurde undersucht. Eine Vorrichtung zur Messung der Deformationseigenschaften mittels einer statischen Eindrückmethode wurde entwickelt. Die Art der Deformation des mit Polymerem bedeckten Cellophans liegt mit einem gemessenen Deformationsindex m von 2,35 zwischen plastischem und elastischem Verhalten. Es wurde eine mathematische Beziehung zwischen Oberflächenrauhheit, Belastung, Deformationsindex und Reibungskoeffizient aufgestellt. Der Reibungskoeffizient des Polymerfilmes ist der $(2/m) - 1$-ten Potenz der Anzahl der Oberflächenunebenheiten und die Reibung derselben Potenz der Belastung proportional. Das Reibungsverhalten der Polymeren in Abhängigkeit von mehreren Variablen konnte durch eine einzige Materialkonstante, den Deformationsindex, beschrieben werden. Obwohl dieser Index aus statischen Messungen hergeleitet wurde, ist er auch auf dynamische Systeme anwendbar.

Received June 27, 1963