Plastic and Tribological Properties of Polytetrafluoroethylene (PTFE) under Conditions of High Pressure and Shear

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Abstract. We investigate experimentally the behavior of a thin sheet of polytetrafluoroethylene between a steel plate and a cylindrical steel indenter under combined action of high normal force and torsion. Under these actions, the polytetrafluoroethylene layer is partially squeezed out of the contact area. The thickness of the remaining layer is studied as function of the applied normal force, the torsion angle, and the radius of the indenter. We suggest a simple semi-empirical material model which describes both the process of squeezing out of the layer and the force of friction produced by the layer.

Keywords: polymers, solid mechanics, sliding friction, tribophysics, plasticity, polytetrafluoroethylene (PTFE)

INTRODUCTION

Squeezing out of thin polymer sheets is of interest for applications of polymers in heavily loaded mechanical parts and for several manufacturing processes as extrusion [1], in context of the ultimate strength of bearings with polymer coatings [2] as well as for better understanding of wear of polymers [3, 4]. Earlier experimental studies show that the stress-strain curve of many polymers including PTFE starts with a linear Hook's behavior and is followed by linear strain hardening [5]. The yield stress shows strong pressure dependence: for example, in polymehylmethacrylate (PMMA) it is approximately linear with respect to pressure [6], so that Coulombs yield criterion [7] of the type $\tau_t = \tau_0 + \mu p$ can be used, where τ_t is shear modulus at pressure p and μ is the internal coefficient of friction. This behavior is very similar to that of granular materials [8].

In the present paper, we investigate the plastic and tribological behavior of PTFE under extreme pressures up to $p = 3500$ MPa. Such pressures are relevant for above mentioned applications but have not been studied so far. We conducted two types of experiments: (1) application of pure normal force, (2) application of a normal force with subsequent shear, induced by a rotation of the indenter. We come to the conclusion, that at high pressures, the material behavior of PTFE can be described very accurately by simple proportionality

$$\tau_t = \mu p. \qquad (1)$$

In the next section we provide the theoretical framework for the analysis of these experiments.

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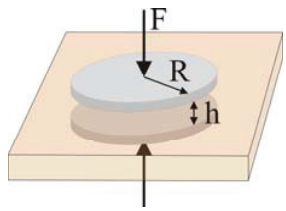

FIGURE 1. Scheme of the squeeze out experiment. A layer of PTFE is placed between two steel plate and a normal force is applied. The resulting thickness of the layer is investigated. Furthermore, the upper plate can be rotated

THEORY OF SQUEEZING OUT OF PLASTIC SHEETS

Assume a rigid base plate and a circular rigid counterpart with radius R. In between the two, there is a thin sheet of ideally plastic material with thickness h and the shear yield stress τ_0 (see Fig. 1).

Normal Loading. When a normal force f is applied, then the stress equilibrium has the form [7]

$$-\frac{\partial p}{\partial r}=\frac{2\tau_0}{h}. \tag{2}$$

Integration of this equation with the boundary condition $p(R)=p_0$ leads to

$$h=\frac{2\tau_0}{3}\frac{\pi R^3}{F}, \tag{3}$$

where the normal force F is obtained by integrating $p-p_0$ over the circular area. For given F, the material will be squeezed out [7] until the thickness achieves the minimum value Eq. (3). If the yield stress is pressure dependent, we can insert eq. (1) into Eq. (2). Integration then gives

$$p=p_0\exp\left(\frac{2\mu}{h}(R-r)\right). \tag{4}$$

For the relation of the normal force and layer thickness we get

$$\frac{2F}{\pi p_0 R^2}=\xi^{-2}(\exp(2\xi)-2\xi^2-1-2\xi), \tag{5}$$

where $\xi=\mu R/h$. The right-hand side of Eq. (5) depends very strongly on the argument ξ. In other words, ξ and thus h depend only very weekly on the normal force. For example, for F = 10 kN and R = 5 mm, it is on the order of $\xi\approx$ 6, so that the layer thickness can be estimated as

$$h=\frac{\mu R}{\xi}\approx\frac{1}{6}\mu R. \tag{6}$$

Normal Loading and Rotation. Now in addition to the normal loading, the indenter is rotated by an angle φ around the vertical axis, assuming stick-conditions between the layer and both steel supports. A rough estimation can be done using the idea of "effective viscosity" η_{eff} of the layer [9]. We introduce formally η_{eff}, such that the flow stress τ_t looks as if it was a fluid layer:

$$\tau_t=\eta_{\text{eff}}\frac{v}{h}, \tag{7}$$

where v is the relative velocity of the layer boundaries. In a truly fluid layer, we would have [7],

$$\frac{\partial p}{\partial r} = \frac{6\eta r}{h^3}\frac{\partial h}{\partial t}. \tag{8}$$

Substituting here the effective viscosity (7), we get an approximation for the plastic layer

$$\frac{\partial p}{\partial r} = \frac{6\tau_t r}{h^2 v}\frac{\partial h}{\partial t} = \frac{6\tau_t}{h^2}\frac{\partial h}{\partial \varphi}, \tag{9}$$

where φ is the rotational angle. Again, inserting the pressure dependence of the yield stress $\tau_t = \mu p$ according to (1), we can integrate (9) with boundary condition $p(R) = p_0$ and obtain

$$p = p_0 \exp\left(\frac{6\mu}{h^2}\frac{\partial h}{\partial \varphi}(r - R)\right). \tag{10}$$

Note that $\partial h/\partial \varphi$ is negative. Integration over the circular area gives the relation between the normal force and the squeeze out rate $\partial h/\partial \varphi$:

$$\frac{F}{2\pi p_0 R^2} = \zeta^{-2}(e^{\zeta} - 1 - \zeta) \text{ with } \zeta = -\frac{6\mu}{h^2}\frac{\partial h}{\partial \varphi}R. \tag{11}$$

For F = 10 kN and R = 5 mm, the argument ζ is approx, $\zeta \approx 12$. Integration over φ gives

$$\frac{1}{h} \approx \frac{2}{\mu R}\varphi. \tag{12}$$

Eqs. (6) and (12) can be combined to an empirical equation

$$\frac{1}{h} \approx C_1(1 + C_2\varphi) \text{ with } C_1 = \frac{6}{\mu R} \text{ and } C_2 = \frac{1}{3}, \tag{13}$$

describing both pure application of (high) normal force and shear due to a rotation. The torque M needed for rotation, can be estimated using (10) as

$$\frac{M}{2\pi\mu p_0 R^3} = \zeta^{-3}(2e^{\zeta} - 2 - 2\zeta - \zeta^2). \tag{14}$$

Here we used the assumption of complete stick to the layer. For the quantity $\mu_{\text{ext}} = (3M)/(2FR)$ which often is considered as the macroscopic coefficient of friction in a torsional contact, we get

$$\mu_{\text{ext}} = \frac{3M}{2FR} = \mu\frac{3}{2\zeta}\frac{2e^{\zeta} - 2 - 2\zeta - \zeta^2}{e^{\zeta} - 1 - \zeta}. \tag{15}$$

For the above used typical value of $\zeta = 12$, we get $\mu_{\text{ext}} \approx 0.3\mu$. Thus, in the considered model, the apparent coefficient of friction will be about one third of the internal coefficient of friction.

EXPERIMENTAL INVESTIGATIONS

The studied layer of PTFE was placed between a massive support steel stamp and a steel cylindrical indenter. Normal forces up to 100 kN were applied, thereby effectively reaching forces of rolling mill or extrusion processes. The thickness of the layer was measured with an accuracy of ~30 μm.

Pure Normal Loading. Typical results are presented in Fig. 2. There is a slight trend of decreasing of the thickness with normal force, but the layer is not squeezed out completely even at the highest loads. This supports strongly a material law with linear pressure dependence of the yield stress.

The experimental results for R = 5.5 mm and R = 3 mm fit well the theoretical prediction. In the case of the largest indenter with R = 15 mm, the initial sheet thickness of 0.35 mm was already smaller than the calculated theoretical thickness of 0.65 mm (not shown).

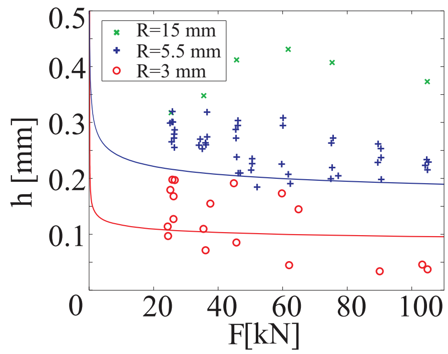

FIGURE 2. Experimental dependence of the thickness of the layer on the normal for pure normal loading. The bold lines are according to eq. (5) with $\mu = 0.24$, which provides the best fit for the Eq. (6). This value is approximately 2 times smaller than in the torsion experiment. We found the chosen normal force range to allow for plastic rolling deformation only with small specimen

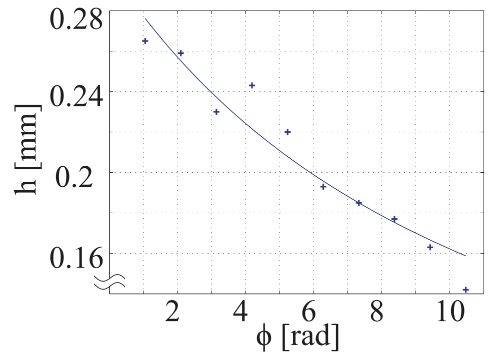

FIGURE 3. Experimental dependence of the layer thickness on the rotation angle at $F = 25$ kN and $R = 5.5$ mm. The solid line represents the fitting curve $h = C_1/(1 + C_2\varphi)$ with $C_1 =$ 0.301 mm^{-1} and $C_2 = 0.08561$, see Eq. (13)

Thickness of the layer as function of rotation angle. The indenter is pressed on the sample and the normal force is held constant, while the indenter is rotated and the lower support stays unmoved (see Figure). The dependence coincides with Eq. (13) qualitatively, but the coefficient C_2 is about 4 times smaller than predicted. The reason for this may be the inapplicability of the stick boundary condition. Here, further investigations are needed.

Coefficient of friction from measurement of torque. The apparent macroscopic coefficient of friction was calculated from the measured torque M using equation $\mu_{ext} = (3M)/(2FR)$. We found a practically constant value of 0.13 for all normal forces and radii. According to Eq. (15), this means the internal coefficient of friction is $\mu \approx 0.4$ which is two times bigger that the coefficient of friction determined from the squeezing out experiments.

SUMMARY

We come to the conclusion that the plastic behavior of PTFE, in the interval of normal pressures of about 10^8–10^9 Pa can be described by a simple proportionality $\tau = \mu p$. This confirms many previous studies and extends them to the region of higher normal pressures. The only discrepancy to the theoretical model is that the coefficients of friction obtained from the squeezing out experiments and torque experiments differ by a factor of about 2. The reason for this discrepancy could be the oversimplified theoretical description used in this paper. A more detailed modeling may be needed in order to obtain a unified description. Note that similar dependencies of the yield criterion on the hydrostatic pressure have been observed also in other polymers as well as in quasibrittle and frictional materials [5]. The regularities of the pressing out of thin layers may be therefore applicable also to other types of media.

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