

FRICITIONAL PROPERTIES OF ELASTOMERS IN VACUUM UNDER HIGH NORMAL PRESSURES

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Studies of frictional behavior of elastomers under high normal pressure are now acquiring great importance due to the application of these materials in various sealing joints.

Ordinary friction apparatus does not permit the study of frictional properties of elastomers under high normal pressures due to the increase of the nominal area of contact. Lavrent'ev has developed an apparatus for studying friction in elastomers under high pressure [1] and has conducted studies of elastomers at up to 300 kgf/cm^2 [2]. The authors of the present paper have studied the friction of some filled rubbers in the atmosphere under pressures up to 10^3 kgf/cm^2 . To prevent misalignments, the apparatus [1] requires additional cumbersome equipment and its use for work in vacuum is difficult. An instrument which allows the study of frictional properties of polymers not only in atmospheric conditions, but also in vacuum, and which secures stability of the nominal area of contact under any pressures, was developed at the Research Laboratory of the Physics of Polymers at the V. I. Lenin Moscow State Pedagogical Institute. Like the apparatus of [1], the instrument is based on the use of hydrostatic pressure applied to elastomers satisfying approximately Pascal's law as for non-Newtonian fluids, which ensures the generation of controlled stress at the friction surface. A basic diagram of this instrument is presented in Fig. 1.

A thick-wall steel cylinder 1, with axial opening of 8 mm diameter and a hole 3 mm in diameter perpendicular to the axis, is installed in the vacuum chamber. A steel rod 2, ground to the cylinder's wall, is inserted in the hole.

Two specimens of the studied polymer 3, cylindrical in shape, 8 mm in diameter and 10 mm

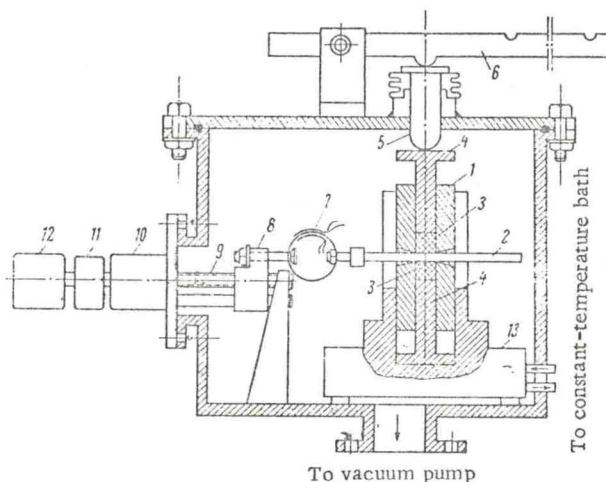


Fig. 1. A basic diagram of the instrument for studying in vacuum frictional properties of elastomers under high normal pressures.

high, are placed in the axial opening of cylinder 1 on both sides of the rod 2 to which they are pressed by steel pistons 4. Therefore, the measurement is of the friction between the elastomer specimens and the surface of rod 2. The specified compressing force is transmitted to pistons 4 from lever system 6 by push-rod 5 sealed with a metal bellows. Translational motion of rod 2 is produced with the required speed by the micrometric screw 9 which is revolved through magnetic clutch 10 by motor 12 with reducing gearbox 11. Between the nut of the micrometric screw 8 and the rod 2 a dynamometer ring is mounted with wire transducers whose signals are recorded by electronic automatic potentiometer ÉPP-09. The instrument is equipped with thermal unit 13 for producing temperatures from -100°C to 150°C . A vacuum of 10^{-4} to 10^{-6} mm Hg can be produced in the chamber.

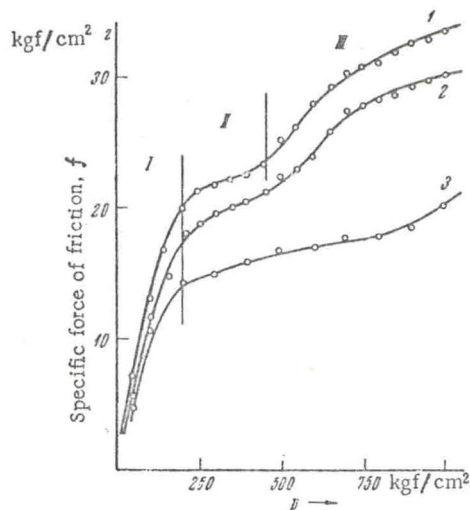


Fig. 2. Variation of the specific force of friction with normal pressure for elastomer material of natural rubber with equilibrium modulus 18.1 kgf/cm². 1) in vacuum; 2) in air at 20°C; 3) in vacuum at 40°C. Velocity of sliding 0.8 mm/min.

Some experimental results of the dependence of frictional force on the normal pressure and on the velocity of sliding in vacuum and in atmospheric conditions, which are described below, refer to the stabilized process of rubbing reticular materials made of natural rubber.

Variation of the specific force of friction with normal pressure for NR in air and in vacuum is shown in Fig. 2. Under low normal pressures, the data obtained in vacuum and in air practically coincide, as was shown previously [5]. Under pressure above 50 kgf/cm² the force of friction is somewhat higher in vacuum than in atmospheric conditions. Most probably, the effect of the air basically amounts to the formation of an air film on the surface of the contact, which prevents the formation of the area of real contact [6]. Under low normal pressures, when real contact is increasing, there are many vacant places where a new area of contact can be formed, and therefore the data in air and in vacuum coincide. Under high normal pressures, different data were observed in vacuum and in atmosphere, because all possible areas of contact have been formed when the air did not prevent their formation.

Let us analyze the dependence of the specific force of friction f on the normal pressure in vacuum (Fig. 2, curve 1). This dependence contains three characteristic ranges.

Within the range from 1 to 200 kgf/cm² the observed increase of the force of friction corresponds to equations [2, 7]

$$f = C\varphi, \quad (1)$$

$$\varphi = 1 - e^{-\frac{\beta}{E}p}, \quad (2)$$

where C is the coefficient of friction depending on the nature of the frictional pair, speed of sliding, and temperature, $\varphi = S/S_n$ is the relative area of real contact which depends on the elastic properties of the polymer and on the normal pressure p , S is the area of real contact, S_n is the area of nominal contact, β is the coefficient which characterized roughness, and E is the modulus of elasticity.

Under pressures of about 200 kgf/cm² the relative area of real contact, in correspondence with Eq. (2), attains its limiting value approaching unity, while C , the coefficient of friction, is practically constant under these pressures. In consequence, a plateau appears on the curve in range II.

Under higher normal pressures in range III, further increase of the force of friction commences with the increase of the pressure above 400-500 kgf/cm²; this phenomenon was first discovered in the atmosphere by Lavrent'ev and Voevodskii [8].

A considerable change of the free volume occurs in elastomers under normal pressures above 400-500 kgf/cm² [2]. This leads to the reduction of the specific volume which in turn causes an increase in the number of contacting chains per unit of area. In consequence, the specific force of friction increases, in agreement with the equation resulting from the molecular kinetic theory of friction [10]:

$$f = \frac{2}{\lambda} n_k (U - kT \ln v_0/v), \quad (3)$$

where λ is the mean magnitude of chain migration, n_k is the number of contacting chains per unit of area, U is the activation energy of the rubbing process, k is Boltzmann's constant, T is absolute temperature, and v_0 is a constant and v is the sliding velocity.

Furthermore, according to Ainbinder [11, 12], reduction of the specific volume leads to the increase of the modulus of volume compression and adhesive interaction, since the forces of adhesion are determined by the distance between surfaces of interacting bodies, in particular when the main effects are those of nondirectional van der Waals forces. Therefore, within range III the frictional force increases due to the increase of the number of contacting chains per unit of contact area n_k ,

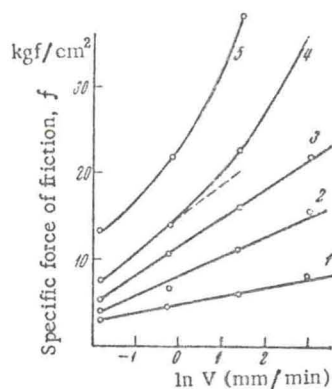


Fig. 3. Variation of the specific force of friction with logarithm of velocity of sliding for elastomer material of natural rubber with equilibrium modulus 3.4 kgf/cm^2 under various normal pressures; 1) 50 ; 2) 10^2 ; 3) $3 \cdot 10^2$; 4) $5 \cdot 10^2$; 5) 10^3 kgf/cm^2 .

and to the increase of the activation energy U appearing in Eq. (3). Extension of range II and shift of range III towards high pressures, with increase of temperature (Fig. 2, curve 3), demonstrates that the increase of frictional force in range III is associated with the reduction of the free volume.

It should be noted further that under high normal pressures the mechanical-chemical processes on the contact surface [13] can contribute to the relation $f(p)$. However, more rigorous study of the influence of specific volume on the frictional properties within range III under higher pressures is hindered due to considerable wear of the polymer under normal pressures above $8 \cdot 10^2$ – 10^3 kgf/cm^2 .

The study of the dependence of friction force on the logarithm of the sliding velocity (Fig. 3) shows a characteristic increase in the slope line of the graph with increase of normal pressure. Consideration of Eq. (3) reveals the cause of the increase in the value of the slope line of the $f(\ln V)$ graph with the increase of normal pressure. The slope line is determined by the coefficient of the term containing $\ln V$, that is, $2n_k kT/\lambda$. Under the experimental conditions, the temperature was kept constant, therefore, with the increase of normal pressure the increase of the slope line in the $f(\ln V)$ graph is associated only with the change of the ratio n_k/λ . This ratio increases with the increase of normal pressure owing to the decrease of mean length of migration of the contacting chains λ and simultaneous increase of the number of contacting chains n_k with the reduction of the specific volume.

Moreover, the increase of the normal pressure leads to appreciable deviation of the relation $f(\ln V)$ from linearity (curves 4, 5, in Fig. 3), which was observed previously [14] with uniaxial loading of specimens. The observed deviation from linear dependence of the friction force with the increase of velocity of sliding under high normal pressures is associated partly with the reduction of the lifetime of a frictional junction and its approximation to the time necessary for the migration of the chain after the separation to the new point of contact [15], and partly with mechanical-chemical phenomena.

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