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Abstract

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APPLICABILITY OF THE TWO-TERM LAW OF FRICTION TO THE FRICTIONAL PROPERTIES OF POLYMERS

The molecular theory of friction, developed earlier by one of the authors (^{1}), leads to the following two-term formula expressing the dependence of the force of external friction F on the normal load N:

$$F = \mu N + \mu p S, \tag{1}$$

$$\frac{F}{S} = \mu \frac{N}{S} + \mu p, \tag{1'}$$

where μ is the true coefficient of friction; S is the area of true contact; p is the specific molecular adhesion acting on the portions of area S.

The formula usually applied in practice for calculating friction forces,

$$F = \mu N$$

(Amontons' law), is in essence a special case of formula (1) when the values of the product $\mu p S$ are negligibly small. Although the influence of molecular attraction may appear even in point contact of bodies (^{2}), and in some cases even between surfaces separated by a gap of the order of 10^{-5} cm (^{3}), nevertheless the smallness of the second term of formula ($1'$) for pairs of friction ordinarily realized in engineering is a consequence of the discreteness of contact, as a result of which the area of true contact, at not excessively large pressures, constitutes a negligibly small fraction of the area of apparent contact (^{4}). In addition, the constant presence, under ordinary conditions, of adsorption layers screening the force field of the surface of the condensed phase greatly reduces the molecular attraction between the contacting surfaces. As a result, the magnitude of the second term in formula (1) often proves negligibly small even when the area of true contact is appreciable.

Fig. 1 and Fig. 2

Figure 1: Fig. 1 and Fig. 2

The basic idea of the proposed molecular theory of friction is that, in the case of smooth surfaces, friction is caused by molecular roughness, i.e., by the Born repulsion forces of the electron shells of atoms of the contacting bodies (or parts of bodies separated by the plane of sliding), while the forces of adhesion or molecular attraction should be regarded rather as a correction explaining deviations from Amontons' law that are observed in practice. This is the fundamental, principled difference between the theory of friction being developed and the views of Terzaghi—Bowden, according to which the principal role in the formation of the force of external friction belongs to the forces of molecular attraction at the points of true contact. However, from this point of view, i.e., when only attractive forces are taken into account, it is difficult to explain deviations from Amontons' law. Precisely in those cases where the forces of molecular attraction manifest themselves distinctly, causing adhesion of surfaces at low pressure, deviations from the law $F = \mu N$ are observed, demonstrated especially sharply by the fact that when $N = 0$, F does not vanish. At the same time, the two-term formula (1) simply explains deviations from Amontons' law in the realization of friction in all cases where the influence of molecular attraction may be significant. Thus, the applicability of formula (1) has been experimentally verified many times for the friction and adhesion of flat gauges (5-7), and for the friction of highly dispersed powders (8).

Since the magnitude of the true contact area is proportional to the normal load and depends on the mechanical properties of the contacting surfaces (mainly on hardness (9)), it is of interest to investigate the frictional properties of certain polymers for which, by increasing the normal load, one can readily achieve a sharp increase in the true contact area. In this case, if friction of an elastic polymer against a very smooth metal surface takes place, then, beginning with a certain load, the true contact area becomes equal to the apparent contact area and does not change with a further increase in pressure. It should therefore be assumed that the friction of a polymer against a carefully polished metal surface under large compressive loads will be described by formula (1).

Fig. 1. Plot of the dependence of the specific friction force f on the specific pressure at the contact point σ.
1 —for the steel—fluoroplast-4 pair; 2 —for the steel—polyethylene pair; 3 —for the steel—polyamide pair.

Fig. 2. Plot of the dependence of the specific friction force f on the specific pressure σ for the steel—fluoroplast-4 pair.

Testing the frictional properties of polymers under strong compression is of not only theoretical interest, but also practical importance in connection with the increasingly broad use of such materials in friction units.

Fig. 3 and Fig. 4: graphs of the dependence of specific frictional force on specific pressure for steel-rubber pairs.

Figure 2: Fig. 3 and Fig. 4: graphs of the dependence of specific frictional force on specific pressure for steel-rubber pairs.

Studies of the external friction of polymer materials were carried out on an apparatus whose scheme and design have been described in detail earlier (^{10}). The apparatus consists of two screw presses mounted on a single foundation. The first, vertical press serves to create normal forces in the contact being tested for friction, and the second, whose axis is perpendicular to the axis of the first, serves to obtain relative displacement of the contacting surfaces. This apparatus made it possible to study external friction at specific compressive loads up to 1000 kg/cm^2.

The tests of the frictional properties of polymers consisted in measuring the static friction force F between the lower and upper surfaces of a flat gauge, which moved in a horizontal plane, and the surfaces of polymer films fastened to two gauges fixed in the horizontal plane, pressed by the vertical press against the movable gauge with a force N. The surfaces of the gauges, made of ShKh-15 steel and finished to cleanliness classes 12–13, were carefully cleaned before the tests by wiping with degreased cotton wool moistened with distilled ether. The surfaces of the polymer films were cleaned in the same way.

Figure 1 shows plots of the dependence of the specific friction force $f = F/2S$ on the specific pressure at the contact point $\sigma = N/S$ (where S is the contact area) for films of Teflon (1), polyethylene (2), and polyamide (3). Graphs were constructed from points, each of which represents the average result of at least 10 measurements. It is evident from the graphs that the increase in frictional force with increasing normal pressure continues even when the area of true contact remains constant. Indeed, the pseudofluidity limit of Teflon (fluoroplastic-4), for example, at 25° is 142 kg/cm^2, and at higher pressures cold flow of the specimen material begins as a result of the recrystallization process (^{11}). Therefore, it may be assumed that, starting from a load corresponding to a specific pressure of about 200 kg/cm^2, no increase in contact area with increasing pressure will occur.

Fig. 3. Graph of the dependence of the specific frictional force f on the specific pressure σ for the pair steel—tread rubber

Fig. 4. Graph of the dependence of the specific frictional force f on the specific pressure σ for the pair steel—unfilled rubber

In Fig. 2, on a larger scale, the graph for a Teflon film of thickness 40 μ is shown separately. It is evident from the graph that the straight line expressing the dependence between the frictional force and the normal pressure follows a binomial formula, i.e., it does not pass through the origin, and the frictional force increases linearly with increasing normal load even at a constant contact area. The change in the angle of inclination of the curve $f = \varphi(\sigma)$ for polyethylene (Fig. 1) can be explained by the fact that at first the increase in frictional force also occurs as a result of an increase in the actual contact area, which by the moment of the bend in the curve reaches the maximum possible value.

In connection with the above, it is of great interest to study the friction of a smooth steel surface against the surface of rubber, which, like all highly elastic rubber-like network polymers, gives practically a perfectly elastic contact with hard surfaces. Thus, for example, the contact area of metal with rubber (with the compression modulus of the latter equal to 12 kg/cm^2) ceases to increase at compressive loads exceeding 250 kg/cm^2 ([12]). In Figs. 3 and 4 are shown, respectively, graphs of the dependence of the specific frictional force f on the specific pressure σ for the pair steel—tread rubber and steel—unfilled rubber. It is evident from the graphs that the specific frictional force continues to increase even when an increase in the area of true contact plainly does not occur.

According to the theoretical concepts of Terzaghi ([13]), Bowden ([9]), and their followers, the frictional force depends on the force of normal pressure only indirectly—through the area of true contact, on which molecular adhesion of the material of the rubbing bodies occurs. In this case, if a change in the normal load does not lead to a change in the area of true contact, then the frictional force, in their opinion, should remain constant.

The results obtained make it possible to conclude that the normal load affects the frictional force not only through the area of true contact, but, as follows from the binomial formula (1), also directly. This confirms the correctness of the main idea of the developing theory of friction

and at the same time demonstrates the possibility and necessity of applying the two-term law of friction to the frictional properties of polymers.

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Note: Figure translations are in progress. See original paper for figures.

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