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Tribology of polymers: Adhesion, friction, wear, and mass-transfer

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Abstract

Tribological behavior of polymers is reviewed since the mid-20th century to the present day. Surface energy of different coatings is determined with new contact adhesion meter. Adhesion and deformation components of friction are discussed. It is shown how load, sliding velocity, and temperature affect friction. Different modes of wear of polymers and friction transfer are considered.

Keywords: Polymers; Adhesion; Friction; Wear; Mass-transfer

1. Introduction

Friction is a very common phenomenon in daily life and industry, which is governed by the processes occurring in the thin surfaces layers of bodies in moving contact. The simple and fruitful idea used in studies of friction is that there are two main non-interacting components of friction, namely, adhesion and deformation. This idea is basic in the two-term model of friction, although the independence of these components is a matter of convention. Such approach is correct for any materials including polymers. Behavior of polymers has distinguishing features, some of which were described by Briscoe [1,2]. The present review is connected with his works. The main concept should be mentioned. It consists of three basic elements involved in friction: (1) interfacial bonds, their type and strength; (2) shearing and rupture of rubbing materials inside and around the contact region; (3) real contact area [3,4].

2. Adhesion

2.1. Adhesion bonds, their formation and breakdown

When two surfaces are brought into contact, the surface forces of attraction and repulsion act between the atoms and molecules of two approaching surfaces. These forces neutralize each other at some equilibrium separation z_0. When the distance between the surfaces is $z < z_0$ they will be repulsed from each other, when $z > z_0$ they will be attracted.

Due to these forces the bonds formed between the contacting surfaces are followed by junctions developed on the real contact spots. Formation and rupture of the junctions control the adhesion component of friction. The simple model of the junction formation has been proposed by Bowden and Tabor [3].

For the majority of polymers, the Van der Waals and hydrogen bonds are typical [5,6].

The hydrogen bond develops at very short distance in polymers containing the groups OH, COOH, NHCO and others, in which the hydrogen atom is linked with an electronegative atom. Under favorable conditions two approaching atoms are linked together by a common proton providing a strong and stable compound.

The junctions sheared under the applied tangential force result in the frictional force. That is, work done by the frictional force results from breakdown of the interfacial bonds. In general case, the interfacial junctions (their formation, growth and fracture) are influenced by nature of the surfaces, surface chemistry and stresses in the surface layers (loading conditions). The interfacial junctions together with products of their fracture and the highly deformed layers where shear deformation is localized, were named by Kragelskii as a 'third body' [4], the concept, which has been developed later in much broader sense by Godet [7]. This term implies that the polymer involved in the friction process may possess the properties, which differ drastically from its bulk properties.

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If the interfacial bonding is stronger than cohesive of the weaker material, then this material is fractured and the polymer transfer takes place. Otherwise fracture occurs at the interface. As a rule, in polymers the surface forces and forces acting between polymer chains are nearly equal and fracture often occurs in the bulk of polymers. This is not always the case. It was observed for metal–polymer contact that metal is transferred to the polymer surface under certain conditions [5,6].

Electrostatic attraction makes a contribution to the adhesion of polymer contact when electric double layer is formed owing to transition of electron from one surface to another. The polymer may be acceptor or donor depending on the origin of the counterbody. In contact with metal, for example, the metal is the electron donor, and when the contact is broken, the polymer surface gets a negative charge [8].

2.2. Johnson–Kendal–Roberts (JKR) model

There are some models designed for description of adhesion in contact. The Johnson–Kendal–Roberts (JKR) model [9] (sometimes termed as the model of contact mechanics) and the Derjaguin–Muller–Toporov (DMT) model [10] are best known. The comparative analysis of the models [11,12] shows that the JKR theory is applied to bodies of micrometer and greater sizes having the properties of polymers, mainly elastomers, whereas the DMT theory is valid for bodies of nanometer sizes having the properties of metals. Because of this, the JKR theory is briefly described below.

Elastic contact of sphere and half-space is analyzed with consideration of Van der Waals' forces which together with the applied load compress the mating bodies. The energy of molecular interactions is taken to be equal to $W_m = -\pi a^2 \gamma$. The elasticity of bodies counteracts the action of surface forces at compression. Using an energy balance the equilibrium of all the forces—load, surface ones, and elastic reaction—is found and the equations for main contact parameters are derived. Given this, a combination of Hertzian pressure distribution (loading) and Boussinesq distribution (unloading) is used. Such combination gives compression in the middle of the contact and an infinite tensile stress at the edges.

The relation between the load and the approach is frequently useful. It is written in the following dimensionless form:

$$\tilde{\delta} = \begin{cases} \left(3\sqrt{\tilde{P}+1}-1\right)\left[\frac{1}{9}\left(\sqrt{\tilde{P}+1}+1\right)\right]^{1/3}, & \tilde{\delta} \geq -3^{-2/3}; \\ -\left(3\sqrt{\tilde{P}+1}+1\right)\left[\frac{1}{9}\left(1-\sqrt{\tilde{P}+1}\right)\right]^{1/3}, & -1 \leq \tilde{\delta} \leq -3^{-2/3}, \end{cases} \quad (1)$$

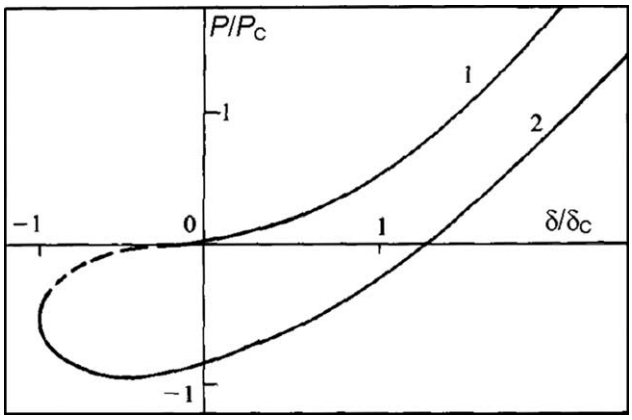

Fig. 1. The load on sphere as a function of approach: (1) Hertzian; (2) with consideration for adhesion (JKL).

where

$$\tilde{\delta} = \delta/\delta_c; \tilde{P} = P/P_c; \delta_c = \frac{1}{3R}\left(\frac{3RP_c}{K}\right)^{2/3} P_c; = \frac{3}{2}\pi R\gamma.$$

Fig. 1 shows the graph of this dependence.

The main concepts and conclusions of the JKR theory were successfully tested with good agreement of practice and theory. Below we will add some data obtained with the contact adhesion meter.

2.3. Measurement of adhesion

Measurement of the molecular forces acting between solids is one of the most difficult experimental tasks. Since the forces are small and distances at which they act are short the measuring instruments should meet the specific requirements. One of the main problems arising when measuring the molecular forces is that the latter increase rapidly with decreasing the distance between the specimens under testing. Hence, the measurements should be carried out at a very small speed that cannot be done using the design of the common balance.

Deryagin et al. [8] proposed to solve the problem by applying the principle of a feedback balance. This design with modification was used later in a number of experiments intended to measure molecular attraction forces. In particular, Israelachvili's surface force apparatus (SFA) measures the surface separation by multiple beam interferometry with accuracy ± 0.1 nm. The surface or interfacial energy can be measured with accuracy of about 10^{-3} mJ/m^2 (see [13]). Nowadays, the molecular forces are measured by an atomic force microscopy using a special technique [14,15].

When studying the surface forces we have developed the contact adhesion meter [16] (Fig. 2). When designing the apparatus we have chosen a vertical torsion balance with the negative feedback as a basic design scheme. This design eliminates the problems with balancing and errors caused by friction in the balance support.