Sliding contact of coated viscoelastic solids: model and experiment

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Abstract. Sliding of a smooth indenter over a viscoelastic half-space with a rigid coating is considered. A quasistatic contact problem is formulated, and a numerical-analytical solution method using the boundary element method and iterative procedure is developed. The dependence of the distribution of contact pressure and dissipative losses on the sliding velocity, coating thickness is analyzed. Friction of polyurethane materials (with rheological properties) coated by relatively hard carbon-based material is studied experimentally. Calculation results and experimental data have good qualitative correlation.

1. Introduction
Coating of viscoelastic materials, which are used in frictional contact, as a rule, has two goals — reducing the adhesive component of the friction force and increasing the wear resistance of the material. Viscoelastic materials, such as rubbers, some other polymers, are compliant, and the applied coatings turn out to be substantially more rigid.

There are a number of experimental studies of the frictional interaction of hard coatings on a viscoelastic base with various counter bodies, for example, [1]. At the same time, in the field of modeling the corresponding papers could not be found. More common are the models of viscoelastic coating on a rigid base [2–5].

The aim of this work is to model the frictional interaction of relatively hard coatings on a viscoelastic base and to compare the results with experimental data. In the field of modeling, material models, methods, and approaches developed in [4–8] were partially used.

2. Contact problem
Let’s consider a contact problem for a rigid smooth slider and a layer with thickness $h$ bonded with a half-space. Indenter slides with constant velocity $V$ along the $Ox$ axis; and it is loaded with vertical force $Q$ (figure 1). Origin of coordinate system $(x, y, z)$ is placed at the center of indenter, the $Oz$ axis is directed normally to the unloaded surface of the layer. The origin of the coordinate system is located at the point of initial layer-indenter contact.

$$w(x, y) = f(x, y) + D, \quad (x, y) \in \Omega,$$
$$\sigma_z = 0, \quad (x, y) \notin \Omega,$$
$$\tau_{xz} = 0, \quad \tau_{yz} = 0.$$ (1)
Here $\Omega$ is the contact zone, $w(x,y)$ is the vertical displacement of the upper layer boundary, $D$ is the indentation depth, $\sigma_z, \tau_{xz}$, and $\tau_{yz}$ are normal and tangential stresses. The shape of indenter is specified by a smooth function $f(x,y)$. Contact pressure and contact area are to be found. Equilibrium condition is the following:

$$Q = \int\int_{\Omega} p(x,y) \, dx \, dy. \quad (2)$$

We use also the condition of zero normal stresses at the boundary of the contact zones. Conditions at the layer-substrate interface ($z = -h$) satisfy the case of perfect adhesion (equal boundary displacements):

$$w^{(1)} = w^{(2)}, \quad u_x^{(1)} = u_x^{(2)}, \quad u_y^{(1)} = u_y^{(2)}. \quad (3)$$

A model of viscoelastic half-space, coupled to a plate with bending stiffness, is used. The mechanical properties of half-space are described by the following relations [7]:

$$\gamma(t) = \frac{1}{G} \tau(t) + \frac{1}{G} \int_{-\infty}^{t} \tau(\tau)K(t-\tau) \, d\tau,$$

$$\gamma_x(t) = \frac{1}{E} \{ \sigma_x(t) - \nu[\sigma_y(t) + \sigma_z(t)] \} + \frac{1}{E} \int_{-\infty}^{t} \{ \sigma_x(t) - \nu[\sigma_y(t) + \sigma_z(t)] \} K(t-\tau) \, d\tau,$$

$$\gamma_y(t) = \frac{1}{E} \{ \sigma_y(t) - \nu[\sigma_x(t) + \sigma_z(t)] \} + \frac{1}{E} \int_{-\infty}^{t} \{ \sigma_y(t) - \nu[\sigma_x(t) + \sigma_z(t)] \} K(t-\tau) \, d\tau,$$

$$\gamma_z(t) = \frac{1}{E} \{ \sigma_z(t) - \nu[\sigma_y(t) + \sigma_x(t)] \} + \frac{1}{E} \int_{-\infty}^{t} \{ \sigma_z(t) - \nu[\sigma_y(t) + \sigma_x(t)] \} K(t-\tau) \, d\tau,$$

$$K(t) = k \exp \left(-\frac{t}{\omega} \right).$$

Here $\nu$ is Poisson’s ratio; $E$ and $G$ are Young’s modulus and shear modulus, respectively. The creep kernel is an exponential function which depends on relaxation time and retardation time.
The problem is solved using the boundary element method and iterative procedure. The use of double integral Fourier transforms allows one to obtain analytical relations, to which the inverse integral transformation is then applied to calculate the influence coefficients used in the boundary element method [5].

3. Results of calculation

The method, described above, was used to consider a sliding contact of a spherical indenter (with radius $R$) and a layered half-space with viscoelastic material used as a layer or as a substrate. The following dimensionless parameters were used for analysis: dimensionless coordinates $(x^*, y^*) = (x, y)/R$, velocity $V^* = V\omega/R = V'\omega a/R$, layer thickness $h^* = h/R$, load $Q' = Q/R^2G_l$ (here $G_l$ is longitudinal shear modulus) and contact pressure $p^*(x, y) = p(x, y)/G_l$.

The distribution of contact pressure obtained for two different sliding velocities is presented in figure 2. Both figures demonstrate the influence of the rheology of the substrate, which leads to a significant asymmetry of the contact area and pressure distribution. Therefore a force $M^*$ being opposite to sliding direction arises. It is the deformation component of the friction force (or sliding resistance). Problems under consideration are without tangential stresses at the surface, and the friction coefficient is defined as following [8]:

$$\mu^* = \frac{M^*}{Q^*} \frac{\int \int_{\Omega} x^* p^*(x^*, y^*) \, dx^* \, dy^*}{\int \int_{\Omega} p^*(x^*, y^*) \, dx^* \, dy^*}. \quad (5)$$

Figure 3 shows the distribution of contact pressure at two different sliding velocities and four layer thicknesses. Here, a decrease in pressure in the center of the contact zone can be observed more clearly. It is worth noting that this phenomenon occurs at relatively small values of the layer thickness, while with thicker layers the pressure distribution tends to be closer to the Hertzian one, which is predictable. The effect of layer thickness on the friction coefficient was also analysed. The results are presented in figure 4 for two values of sliding velocity. Curves 1 and 2 are almost of the same shape and arranged one above the other. Some non-monotonic dependence of sliding resistance on the coating thickness in the range of thin coatings can be observed. Herewith, generally the smaller value of sliding velocity shows the bigger amplitude of the friction coefficient.
Figure 3. Contact pressure distribution for different velocities and layer thickness: \( c = 6, \nu = 0.4, Q' = 2.0, V^* = 0.005 \) (a), \( V^* = 0.2 \) (b), \( h^* = 0.05 \) (curve 1), \( h^* = 0.02 \) (curve 2), \( h^* = 0.0133 \) (curve 3), \( h^* = 0.0066 \) (curve 4).

Figure 4. Dependence of friction coefficient on layer thickness: \( c = 6, \nu = 0.4, Q' = 2.0, V^* = 0.005 \) (curve 1), \( V^* = 0.2 \) (curve 2).

Figure 5 shows the dependences of the coefficient of friction arising due to imperfect elasticity [6] on the sliding velocity for various values of the coating thickness. Just as in the case of a viscoelastic half-space, these dependences are non-monotonic. Maximum values depend on the thickness of the coating. In general, the pattern is seen that the thicker the coating, the less the rheological properties of the substrate are manifested. In general, the thicker the coating, the less the rheological properties of the substrate are manifested. The last conclusion was verified experimentally.

4. Materials and methods of experimental study
Casting polyurethane was used as basic viscoelastic material. Three types of coated samples were compared with each other, and with uncoated one. Relatively hard carbon coatings were applied to the polyurethane surface. During sputtering, the fluence of the ion flux varied. It should be
Figure 5. The dependence of the coefficient of friction on the sliding velocity: $c = 5$, $\nu_1 = 0.3$, $\nu_2 = 0.4$, $Q' = 1.0$, $E_1/E_2 = 10$, $h^* = 0.0016$ (curve 1), $h^* = 0.0033$ (curve 2), $h^* = 0.0066$ (curve 3)

Figure 6. The dependence of the force on the penetration depth for samples with fluence during sputtering, ion·cm$^{-2}$: 1 — 0, 2 — $1 \times 10^{15}$, 3 — $5 \times 10^{15}$, 4 — $1 \times 10^{16}$

noted that the greater the fluence, the thicker the coating. The exact thickness of the coatings could not be determined. The dimensions of the samples were $20 \times 20 \times 3$ mm. Indentation experiments were carried out using a NanoScan-4D [9] scanning tester. During the tests, a corundum ball 3 mm in diameter was penetrated into the samples. For all samples the maximum penetration depth was 10 $\mu$m. Averaging was made over more than ten tests for each type of samples. The dependence of force on the depth of penetration (figure 6) shows, that coated samples are more rigid than uncoated material.

Samples were tested on a UMT-3 tribotester (Cetr, USA). The view of the working part of the tester is shown in figure 7.

The holder, which is a rectangular steel plate, was mounted on the desktop of the friction machine using screws. The sample was attached to the sample holder using double-sided adhesive tape. A corundum ball with a diameter of 1.5 mm, mounted on a special holder using a threaded connection, was used as a counterbody. A holder with a counterbody was installed in the tool head of the tribotester, equipped with sensors of normal and tangential forces. To reduce the negative effect of the adhesive component of the friction force, the surface of the sample was covered with a thin layer of talc. The counterbody moved in one direction; the friction track
was 15 mm. The load and sliding velocities for all test samples were 50 mN and 0.1 mm/s, respectively. The dependence of the friction coefficient, defined as the ratio of the tangential force to the normal, on the distance, showed that the process reaches a steady state, which is important, because the model of sliding contact described above is quasi static. As the test result, we used the average value of the coefficient of friction in the area of the friction path, characterized by the presence of the steady state. For each coating thickness, three experiments were performed.

5. Experimental results and discussion
The test results are summarized in the table 1.

The experimental results showed that the data of various experiments are in good agreement (the average error does not exceed 10%). Coated samples showed a significantly lower coefficient of friction than uncoated samples. With increasing fluence during spraying, the friction coefficient decreases. Thus, according to the results of modeling and experiments, there is a qualitative coincidence of the influence of the thickness of a relatively hard coating on the friction coefficient, which occurs due to dissipative losses in a viscoelastic material.

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