FRICTION OF SOLIDS WITH THE FORMATION OF A MELT LAYER

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Some regularities of high-speed friction of solids with the formation of a developed interlayer of a melt are considered. The layer thickness, melting rate, and frictional force as functions of the rubbing speed and the temperature of the solids are obtained based on mass and heat balance relations in the melt film.

In friction of solids at a high rubbing speed and an elevated temperature a transition of the material of the rubbing solids to a plastic and liquid state is possible in the zone of frictional contact [1, 2]. In the present work some regularities of friction of solids in the regime of a developed melt layer are considered, when the rubbing speed is sufficiently high and the thickness of the formed melt layer is $h > 10^{-5}-10^{-4}$ cm. For example, in friction on ice a regime of a developed melt layer is observed starting with the rubbing speed ~20 m/sec [3].

To study friction in this regime, we consider a plane model problem of formation of a melt film in friction of smooth solids (the film thickness is much larger than the characteristic size of roughnesses) that is described by viscous-liquid equations (a sufficient film thickness enables us to ignore plastic strains in the rubbing surfaces and the wedging effects of thin films).

Similar statements of problems of heat and mass transfer with a phase transition arise in high-speed melting of a solid material by a thin solid [4].

Let U be the relative velocity of sliding for solids 1 and 2 (Fig. 1), h be the characteristic thickness of the melt layer formed in melting of solid 1 as a consequence of dissipation of mechanical energy in friction or of the heat flux from solid 2, and v_0 be the rate of descent for solid 1 that arises because of the melting of the solid material and its removal from the frictional contact zone. Then the heat balance in the layer per unit time can be represented as

$$E_m + E_1 = E_d + E_w .$$

Here $E_m = \rho_s v_0/L_m$ is the consumption for melting the material of solid 1; E_1 is the outflow of heat into the melting solid; $E_1 = 0$ if solid 1 is at the melting temperature: $T_s = T_m$. Simple assessments show that taking account of the heat outflow in the main approximation results in the use of the effective specific heat of melting $L = L_m + c_s(T_m - T_s)$ instead of L_m (the subsequent terms that take account of the geometry of solid 1 and the melting zone have the order of $\delta' \sim \delta/l \ll 1$). Thus, the output portion of the heat balance has the order of $\rho_s v_0/L$. In the input portion of the balance the term E_d is associated with viscous dissipation, E_w is the inflow of heat from the wall (of solid 2). If the melt layer is caused mainly by the heat flux from solid 2 (sliding over a hot substrate) the temperature profile in the layer is similar to a linear one and $E_w = k(T_w - T_m)l/h$ ($E_d \sim 0$, T_w is the wall temperature). Otherwise, a substantial contribution to the formation of the melt layer is made by viscous dissipation. As a consequence of the small thickness of the melt film, the velocity profile can be considered parabolic in the layer, the quadratic terms being associated with the pressure gradient in the layer and having the order of $(h^2/2\mu U)\cdot(dp/dx) \sim (h^2/l^2)\cdot(P/2\mu U)$ as compared to the linear term. The contribution of the quadratic terms to E_d turns out to be proportional to the square of this small quantity. Consequently, in high-speed friction the magnitude of the pressing force has no effect on E_d and hence on the film thickness and the melting rate. Theoretical calculations based on the method of integral relations of boundary layer theory [5] and an experimental

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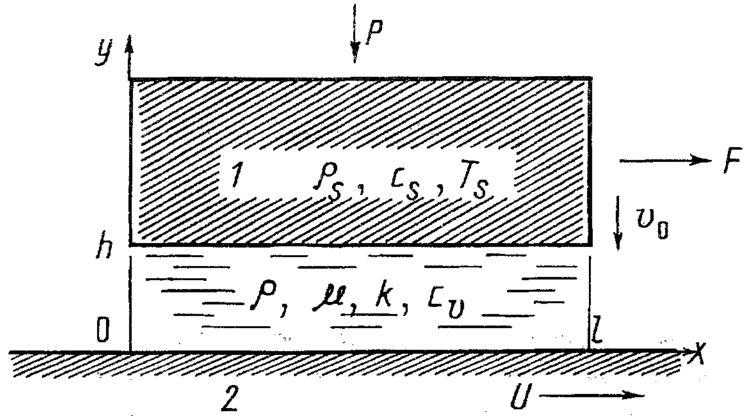

Fig. 1. Simplified scheme of frictional contact in high-speed friction of solids with the formation of a melt layer.

investigation of friction of solids in the regime of a developed melt layer [3] confirm this. A weak dependence of the melting rate and the frictional force on the load on the frictional contact is a characteristic feature of friction with a developed melt layer. Thus, the assessment $E_d = \mu U^2 l/h$ is valid. Then the contribution of viscous dissipation will be predominant if $E_d >> E_w$ or Ec >> Ste/Pr (Ec = U^2/L is the Eckert number, Ste = $c_v(T_w - T_m)/L$ is the Stefan number, and Pr = $c_v\mu/k$ is the Prandtl number). For Ec << Ste/Pr it is the heat flux from the heated solid 2 that is basic in the heat balance. In the first case the temperature profile in the layer becomes quadratic, a temperature maximum is attained within the melt film, and outflow of heat into solid 2 is possible even at a surface temperature that is larger than the melting temperature. It is not difficult to write out the corresponding dependences in the case of a known temperature T_w, but for high-speed friction with the formation of a melt layer it is natural, because of viscous dissipation, to assume the temperature T_0 of solid 2 away from the contact zone to be prescribed and to determine the surface temperature T_w from consideration of the general problem of heat release in the layer and heat removal in solid 2. The heat outflow E_w can be determined by assuming that a heat spot (a section of the X axis) of temperature T_w moves over the solid surface at speed U and the remainder of the surface is heat-insulated. A temperature boundary layer of thickness $\sim l/\sqrt{\mathrm{Pe}}$ (Pe = Ul/a_2 is the Peclet number, $a_2 = k_2/\rho_2 c_2$ is the thermal diffusivity of solid 2) forms in the solid near the surface, and the geometry of the solid can be regarded as unimportant and the thermal conditions as undisturbed outside this layer. The equation for the heat outflow E_w with Pe >> 1 has the form $E_w = -2\rho_2 c_2 Ul(T_w - T_0)/\sqrt{\pi \mathrm{Pe}}$ (it corresponds to the self-similar solution of the heat conduction equation). By integrating the heat inflow equation (we take account of heat conduction and viscous dissipation) twice with respect to the layer thickness and knowing the temperature at $y = 0$ and the heat flux at $y = 0$, h we find:

$$E_w = -\left[\mu\frac{U^2}{2} + k(T_m - T_0)\right] l \Big/ \left(h + \frac{\sqrt{\pi}}{2}\frac{k}{k_2}\frac{l}{\sqrt{\mathrm{Pe}}}\right).$$

The wall temperature can be determined from the following relation:

$$k(T_m - T_w) + \mu U^2/2 = 2h\rho_2 c_2 U(T_w - T_0)/\sqrt{\pi\,\mathrm{Pe}}.$$

The law of mass conservation in the layer leads to the relation $hU = 2v_0 l$. For simplicity we take $\rho_s = \rho$ (we ignore the density change in melting). Then for the melt layer formed because of viscous dissipation in sliding over the heat-insulated surface:

$$\frac{h}{l} = \frac{2v_0}{U} = \sqrt{\left(\frac{2\,\mathrm{Ec}}{\mathrm{Re}}\right)}. \tag{1a}$$

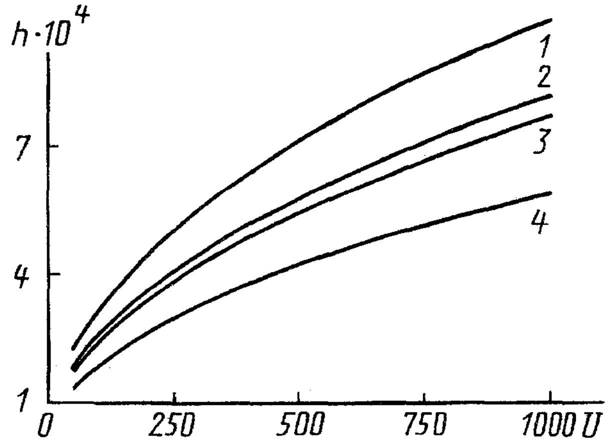

Fig. 2. Characteristic thickness of the melt layer h (cm) vs velocity of sliding U (m/sec) in friction on a heat-insulated substrate. Curves 1–4 correspond to ice, steel, aluminum, and copper.

With account for the heat transfer with solid 2, to determine h and v_0 we need to solve a cubic equation in the general case. However, with a rather high speed U when $h \gg (k/k_2)\cdot(l/\sqrt{\mathrm{Pe}})$ (this inequality is fulfilled for most pairs of solids in friction of them in the developed melt layer regime) the equation is simplified:

$$\frac{h}{l} = \frac{2v_0}{U} = \sqrt{\left((\mathrm{Ec} - 2\,\mathrm{Ste}_2/\mathrm{Pr})\frac{1}{\mathrm{Re}}\right)}\,. \tag{1b}$$

Here $\mathrm{Ste}_2 = c_v(T_m - T_0)/L$. In sliding over the hot substrate with the temperature T_w

$$\frac{h}{l} = \frac{2v_0}{U} = \sqrt{\left(\frac{2\,\mathrm{Ste}}{\mathrm{Re}\,\mathrm{Pr}}\right)}\,. \tag{1c}$$

The fact that with $\mathrm{Re} \gg 1$ the characteristic scale of the change in the vertical coordinate is $y \sim l/\sqrt{\mathrm{Re}}$ and for the change in the vertical velocity component it is $v \sim U/\sqrt{\mathrm{Re}}$ in the melt zone enables us to use the boundary-layer equations rather than the Navier-Stokes equations to describe in detail the flow in the melt film. Further assessments of the terms enable us to restrict ourselves to equations like lubrication ones in a number of cases [4].

Figure 2 gives the characteristic thickness h of the melt layer as functions of the rubbing speed U for some materials (we assume the heat exchange with solid 2 as unimportant (1a), $T_s = T_m$, the length of the frictional contact zone l is taken equal to 1 cm).

In the melting of solid 1 the melt is removed from the contact region and forms a trace (Fig. 3). Squeezing out of the melt forward is also possible, a counterjet forming ahead of the melting solid. The shape of the jet surface can be determined by considering the dimension $y = b\sqrt{\nu(x + l_1)/U}$ (b is some constant, for the method of integral relations with a the quadratic velocity profile $b = \sqrt{30}$). Then the jet length is $l_1 = (U/\nu)(h/b)^2$, where h is the layer thickness in the cross section $x = 0$. For the estimates (1a), (1b), and (1c) we obtain

$$\frac{l_1}{l} = \frac{2\,\mathrm{Ec}}{b^2}\,, \tag{2a}$$

$$\frac{l_1}{l} = (\mathrm{Ec} - 2\,\mathrm{Ste}_2/\mathrm{Pr})\frac{1}{b^2}\,, \tag{2b}$$

$$\frac{l_1}{l} = \frac{2\,\mathrm{Ste}}{\mathrm{Pr}\,b^2}\,. \tag{2c}$$

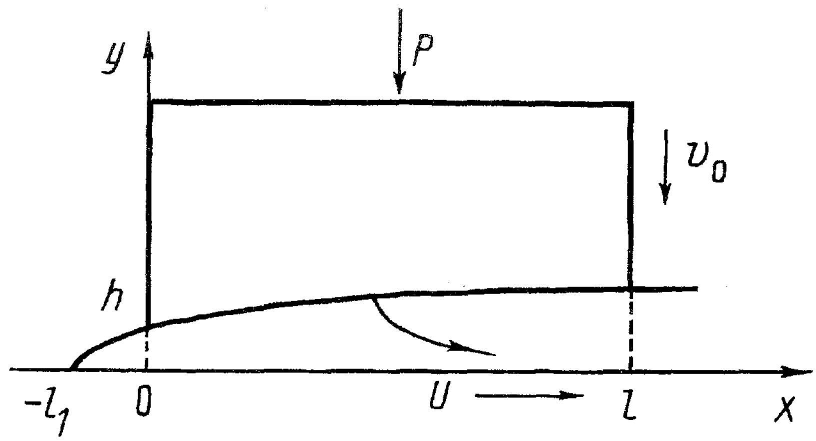

Fig. 3. Scheme of solid friction with account for squeezing out of the melt from the frictional contact region and formation of a counterjet ahead of the solid and a trace behind the solid.

For the frictional force we can obtain the following estimates:

$$F = \mu U \sqrt{\left(\frac{\mathrm{Re}}{2\,\mathrm{Ec}}\right)}, \tag{3a}$$

$$F = \mu U \sqrt{\mathrm{Re}/(\mathrm{Ec} - 2\,\mathrm{Ste}_2/\mathrm{Pr})}, \tag{3b}$$

$$F = \mu U \sqrt{\left(\frac{\mathrm{Re\,Pr}}{2\,\mathrm{Ste}}\right)}. \tag{3c}$$

If the formation of the melt layer is associated with viscous dissipation because of friction (case *a*), $F \sim U^{1/2}$, and for melting in friction on a heated substrate $F \sim U^{3/2}$.

A flaw in the above theory is that the melt layer thickness is assumed constant and the balance relations are fulfilled integrally for the entire layer. A more exact theory can be constructed using the method of integral relations of boundary layer theory [5–7]. For the same quadratic temperature and velocity profiles in the layer the balance relations are satisfied in each cross section x = const, and a system of two ordinary differential equations (ODE) must be solved to determine the layer thickness and the pressure as functions of the coordinate x. If the counterjet is ignored, the Cauchy problem is solved for the system of ODE (the melt layer thickness is taken equal to zero in the inlet section, the pressure has a logarithmic property [6]). Otherwise, it is necessary to conjugate the solution of the problem in the frictional contact region to solutions for free jets. For the ODE system in this case we need to solve a rather tedious boundary-value problem. Estimates of the quantities can be obtained by employing the proposed theory. Using the criterion formulated above, we can determine the main heat source of formation of the melt layer: viscous dissipation or heat transfer from the heated solid, we can estimate the characteristic thickness of the melt layer (1), and we can employ estimates (2) and (3) for the melting rate and the frictional force when the inequality $h > 10^{-5}$–10^{-4} cm is fulfilled.

NOTATION

U, rubbing speed of the solids; h, characteristic thickness of the melt layer; v_0, melting rate; l, characteristic length of the frictional contact zone; P, pressing force; F, frictional force; L_m, specific heat of melting for solid 1; L, effective specific heat of melting; ρ, μ, k, c_v, density, viscosity, thermal conductivity, and heat capacity of the melt; ρ_s, c_s, density and heat capacity of the material of solid 1; ρ_2, k_2, c_2, density, thermal conductivity, and heat capacity of the material of solid 2; T_m, melting temperature; T_w, wall temperature (of solid 2 at $y = 0$); T_0, temperature of solid 2 away from the contact zone.

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