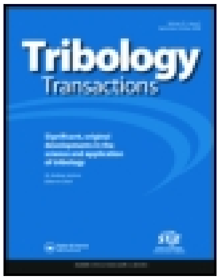

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Hysteresis Behavior in the Stick-Slip Mode at the Boundary Friction

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Abstract

The tribological system is considered, which consists of two atomically smooth solid surfaces separated by an ultrathin lubricant film. The thermodynamic model based on the Landau theory of phase transitions is built, which describes behavior of this system in the boundary friction mode. The free energy density for an ultrathin lubricant film is given in the form of expansion in series in terms of the powers of order parameter that is reduced to the shear modulus of lubricant. The kinetics of the system is studied on the basis of model describing first-order phase transitions between kinetic modes of friction. It is shown that in the presence of spring between the external drive and block the width of temperature hysteresis increases versus fixed coupling.

KEY WORDS

Nanotribology; Stick-Slip; Boundary Lubrication; Phase Transition; Non-Newtonian Behavior; Low Temperature; Viscosity

INTRODUCTION

Nomenclature

X coordinate of top block (m)

V shear velocity of top block (m/s)

F friction force between blocks (N)

M mass of top block (kg)

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h thickness of lubricant between blocks (m)

K rigidity constant of spring (N/m)

V_0 motion velocity of free end of spring (m/s)

ΔX spring extension (m)

t, t' time of motion (s)

σ_{el} elastic stress (Pa)

σ_v viscous stress (Pa)

$\sigma = \sigma_{el} + \sigma_v$ full stresses (Pa)

ε_{el} elastic strain (dimensionless variable)

γ coefficient of proportionality (dimensionless variable)

k coefficient of proportionality ($\mathrm{Pa \cdot s}^{\gamma+1}$)

T_c critical temperature (K)

T temperature of lubricant (K)

μ shear modulus (Pa)

f free energy ($\mathrm{J/m^3}$)

φ order parameter (dimensionless variable)

φ_0 stable stationary value of order parameter φ (dimensionless variable)

φ^m unstable stationary value of order parameter φ (dimensionless variable)

α positive constant ($\mathrm{J \cdot K^{-1}/m^3}$)

a positive constant (Pa)

b positive constant ($\mathrm{J/m^3}$)

c positive constant ($\mathrm{J/m^3}$)

τ_ε Maxwell relaxation time of internal stress (s)

T_{c0} temperature of melting (K)

T_c^0 temperature of solidification (K)

$\Delta T = T_{c0} - T_c^0$ width of hysteresis (K)

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V_{c0} velocity of melting (m/s)

V_c^0 velocity of solidification (m/s)

δ kinetic coefficient ($J^{-1}\cdot m^3/s$)

Δt time step at numerical solving (s)

ξ stochastic force (s^{-1})

W_n stochastic force, Box-Muller function ($s^{-1/2}$)

D fluctuation intensity (s^{-1})

r_1, r_2 random variables (dimensionless variables)

$F_{\max}$ maximum value of friction force (N)

$\sigma_{el,\max}$ maximum value of elastic stress (Pa)

$\sigma_{v,\max}$ maximum value of viscous stress (Pa)

$V_{\min}$ minimal value of velocity (m/s)

$V_{\max}$ maximal value of velocity (m/s)

a_{ac} acceleration (m/s^2)

In connection with swift nanotechnology development and devices parts miniaturization the problem of guaranteeing stable work of nanomechanism at the deficit or absence of lubricant is more actual. Therefore lately friction laws at the lubricant thickness of several molecular layers are very actively studied. This mode is called boundary friction and it substantially differs from mixed and hydrodynamic friction [1–5]. In the boundary friction mode the structure of lubricant can realize with domains of liquidlike and solidlike states [6–8]. There are several such states and their properties qualitatively depends both on friction surfaces properties and external parameters, like temperature, load, shear rate, etc.

Systems working in boundary friction mode have numerous features depending on friction conditions. In the present article the boundary friction of two atomically smooth surfaces is considered at the presence of homogeneous ultrathin lubricant film with nonpolar molecules between them.

Recently the experimental investigation of such systems becomes possible. It is worth noting that they show abnormal behavior in comparison with bulk lubricants which consist of such molecules. In boundary mode the periodical stick-slip regime is often observed [6, 7, 9, 10], which is explained as a film melting after surfaces shear and following solidification after their squeezing under the external load. Such transitions can be presented as a phase transitions of the first- [6, 7, 9, 11, 12] or second-order [13–15] between kinetic modes of friction which are not stable thermodynamic phases. The numerous experimental [6, 7, 16–20] and theoretical [5, 9, 13, 21] investigations were carried out for study of tribological and rheological properties of boundary lubricant. It is shown that if the thickness of lubricant decreases the physical properties of the friction process changes firstly quantitatively then, at some critical thickness, qualitatively. It allows one to construct phase diagrams for the lubricant state at different thickness experimentally and theoretically [22].

As a rule, when the temperature or stress exceeds critical values, the lubricant melts. In the papers [11, 14, 15] a model was built, which describes both situations: usual thermodynamic and "shear" melting. Additionally fluctuations are taken into account [5, 14, 15, 23], because they are important in such microscopical systems, and can be a reason for lubricant transition from solidlike to liquidlike state. Let us note that within the model [14] at the fluctuations presence the stick-slip mode is not strictly periodical, since it has expressed stochastic component. Such phenomenon was observed for polymeric chain molecules, which can not form strictly ordered spacial structures [6, 7]. The reasons for hysteresis, which was observed in boundary friction experiments [16, 17, 24], in detail studied within the framework of synergetic model in the paper [11]. Main aim of this research is investigation of hysteresis phenomenon using the thermodynamical model [13] at realization of the first-order phase transition [25–27].

TRIBOLOGICAL SYSTEM AND BASIC EQUATIONS

Let us consider boundary friction using as example the behavior of mechanical analogue of tribological system [6,7,28], presented in Fig. 1. The system consists of two blocks with atomically

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smooth surfaces. The bottom block is fixed, and upper block slides on it. The ultrathin lubricant film with thickness h is between them. The upper block of mass M is connected with a spring with stiffness K, whose free end is inclined to the motion with fixed velocity V_0. When the free end of spring moves the block shears too, but its velocity V differs from velocity V_0, because the friction force F is generated that opposes to motion.

Designating block coordinate as X, we write down the corresponding equation of motion [6, 7, 13, 28]:

$$M\ddot{X} = K\Delta X - F. \tag{1}$$

Here ΔX is the spring extension, which can be expressed in the form

$$\Delta X = \int_0^t V_0 \mathrm{d}t' - X, \tag{2}$$

where $t = t'$ is the motion time of spring free end.

Friction force F between blocks is calculated using equation [28–30]

$$F = \left[\sigma_{el} + k \cdot \mathrm{sgn}(V)\left(\frac{|V|}{h}\right)^{\gamma+1}\right] A, \tag{3}$$

where σ_{el} is the shear component of elastic stress which arises in the lubricant during motion, A is the friction surface contact area. Also in the equation we introduce a phenomenological coefficient k (Pa$\cdot$s$^{\gamma+1}$) and dimensionless exponent γ, which fixes the dependence of effective viscosity of non-Newtonian lubricant on velocity gradient [28–32]. The case $\gamma < 0$ corresponds to pseudoplastic liquids, value $\gamma > 0$ meets dilatant lubricant, and $\gamma = 0$ describes Newtonian liquid whose viscosity is independent of velocity gradient. For accounting the force direction effect the sign function sgn(V) is included in (3).

Let us write down free energy density for an ultrathin film in the form of expansion in terms of order parameter φ, which represents the amplitude of the periodic part of the microscopic density of the medium [13, 25, 26, 33]:

$$f = \alpha(T - T_c)\varphi^2 + \frac{a}{2}\varphi^2\varepsilon_{el}^2 - \frac{b}{3}\varphi^3 + \frac{c}{4}\varphi^4, \tag{4}$$

where T is the lubricant temperature, T_c is the critical temperature, ε_{el} is the shear component of elastic strain, α, a, b, c are positive constants. The parameter φ takes on nonzero value when lubricant is solidlike. The elastic stress is defined as derivative of potential (4) with respect to strain $\sigma_{el} = \partial f/\partial\varepsilon_{el}$:

$$\sigma_{el} = \mu\varepsilon_{el} = a\varphi^2\varepsilon_{el}, \tag{5}$$

where $\mu = a\varphi^2$ is the shear modulus [13]. Thus the shear modulus μ possesses zero value in liquidlike state.

Stationary values of order parameter are defined by condition $\partial f/\partial\varphi = 0$, according to which we obtain expression

$$\varphi_{\mp} = \frac{b}{2c} \mp \sqrt{\left(\frac{b}{2c}\right)^2 - \left(\frac{a}{c}\varepsilon_{el}^2 + \frac{2\alpha(T - T_c)}{c}\right)}, \tag{6}$$

where φ_- corresponds to the unstable state (maximum of the potential on the curve 2 in Fig. 2), and φ_+ meets the stable state (minimum of the potential in Fig. 2).

It is worth noting that if the upper block is in motion with velocity V the stationary elastic strain ε_{el} arises in the lubricant film [25, 26, 28–30]:

$$\varepsilon_{el} = \frac{V\tau_\varepsilon}{h}, \tag{7}$$

where the Maxwell relaxation time of internal stresses τ_ε is introduced. Analysis of the relationship (6) with a glance of expression (7) allows us to assign two critical temperatures

$$T_{c0} = T_c - \frac{a}{2\alpha}\left(\frac{\tau_\varepsilon V}{h}\right)^2 + \frac{b^2}{8\alpha c}, \tag{8}$$

$$T_c^0 = T_c - \frac{a}{2\alpha}\left(\frac{\tau_\varepsilon V}{h}\right)^2. \tag{9}$$

If $T < T_c^0$ one minimum of potential $f(\varphi)$ exists at $\varphi > 0$ corresponding to curve 1 in Fig. 2. In the intermediate range $T_c^0 < T < T_{c0}$ the potential has a form presented by curve 2 in Fig. 2, i.e., zero and non-zero minima coexist separated by maximum. In the last case $T > T_{c0}$ one extremum is realized corresponding to the stationary state $\varphi_0 = 0$ (curve 3 in Fig. 2). At small values of the strain ε_{el} and temperature T the lubricant is solidlike, since the stationary value of parameter φ_0 is nonzero and according to (5) the shear modulus is nonzero too (curve 1 in Fig. 2). When the temperature exceeds the critical value T_{c0} (8) the order parameter changes abruptly from value $\varphi_0 = 0.5b/c$ to zero and the lubricant transforms into a liquidlike state. This case meets the zero minimum of potential $f(\varphi)$ (curve 3). If after indicated transition temperature T decreases, then lubricant solidifies at lower value of temperature T_c^0 (9). In this case jump-like change of stationary value of order parameter is observed from zero to $\varphi_0 = b/c$. Thus dependence $\varphi(T)$ has hysteresis inherent in the first-order phase transition. The temperature width of hysteresis is defined by expressions (8) and (9)

$$\Delta T = T_{c0} - T_c^0 = \frac{b^2}{8\alpha c} \tag{10}$$

and depends only on expansion constants in (4).

In the same way we can assign two critical velocities: if the velocity exceeds value

$$V_{c0} = \frac{h}{\tau_\varepsilon}\sqrt{\frac{2\alpha(T_c - T)}{a} + \frac{b^2}{4ac}} \tag{11}$$

the lubricants melts, and lubricant solidifies, when V becomes less than value

$$V_c^0 = \frac{h}{\tau_\varepsilon}\sqrt{\frac{2\alpha(T_c - T)}{a}}. \tag{12}$$

In contrast to previous case the velocity width of hysteresis $\Delta V = V_{c0} - V_c^0$ increases with temperature growth. The shear velocity and temperature differently influence hysteresis width, since the temperature T enters into potential (4) linearly and the shear elastic strain ε_{el} (and the velocity V, respectively) quadratically.

STICK-SLIP MODE

For the further investigation of system kinetics we write down the Landau-Khalatnikov-type equation [34]:

$$\dot{\varphi} = -\delta\frac{\partial f}{\partial \varphi}, \tag{13}$$

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where δ is the kinetic coefficient characterizing the inertia properties. After substitution of energy (4) into (13) the equation is obtained in the explicit form:

$$\dot{\varphi} = -\delta\left(2\alpha(T - T_c)\varphi + a\varphi\varepsilon_{el}^2 - b\varphi^2 + c\varphi^3\right) + \xi(t). \tag{14}$$

In Eq. (14) the term is additionally introduced representing additive fluctuations $\xi(t)$ which are similar to a white noise [23, 25, 26]. Their intensity is chosen so small that it doesn't change the deterministic behavior of the system. But they should be taken into consideration since in further numerical solution the root of Eq. (14) $\varphi^m = 0$ is stable even if it corresponds to a maximum of potential $f(\varphi)$ that is unstable stationary state. With introduction of $\xi(t)$ the system passes from an unstable state to a minimum energy stable state. Thereby fluctuations should be taken into account because of the particularities of numerical analysis. Using the Euler-Cromer method for numerical solution, we obtain the iteration procedure [25, 26]:

$$\varphi_2 = \varphi_1 - \delta\left(2\alpha\left(T - T_c\right)\varphi_1 + a\varphi_1\varepsilon_{el}^2 - b\varphi_1^2 + c\varphi_1^3\right)\Delta t + \sqrt{\Delta t}W_n, \tag{15}$$

where Δt is the time step and random force W_n is defined by the Box-Muller function [35]:

$$W_n = \sqrt{2D}\sqrt{-2\ln r_1}\cos\left(2\pi r_2\right), \quad r_i \in (0, 1], \tag{16}$$

where r_1, r_2 are uniformly distributed pseudorandom numbers. Below, fluctuation intensity is equal to $D = 10^{-25}$ s^{-1}.

The calculation results of the time evolution of the system are shown in Fig. 3. These dependencies were obtained by numerical solution of the system of kinetic equations (1), (14). The spring extension ΔX is defined from expression (2), friction force F is determined according to (3), elastic stress σ_{el} is fixed by expression (5), and strain ε_{el} is found from (7). While the system solving the relationship $\dot{X} = V$ is used. At the chosen parameters in the rest state lubricant is solid-like since at $\varepsilon_{el} = 0$ condition $T < T_{c0}$ is satisfied. At zero time, $t = 0$, external drive begins to move with the constant velocity V_0, at this block moves too (panel (a) in Fig. 3), but its velocity is less than external drive velocity $V < V_0$ (panel (b)), since spring extension grows. Friction force

F (c) arises between surfaces and increases with growth of both elastic and viscous stresses ((d) and (e)). According to the figure spring extension monotonically grows and velocity V increases. At the condition $V > V_{c0}$ lubricant melts, elastic stress takes on zero value $\sigma_{el} = 0$, and F abruptly decreases. At this spring compresses and block velocity abruptly rises. Accordingly viscous stress grows too (c).

At certain time the condition $V > V_0$ is fulfilled, therefore spring extension ΔX continues to fall. This is the reason for block velocity reduction V. It is worth noting that spring extension is so large that after lubricant melting block slips on the significant distance that leads to the spring pressing ($\Delta X < 0$) [6, 36]. After that block moves in the opposite direction (the spring becomes straight). At the temperature increasing the same effect is observed approximately to the value $T \approx 224$ K. At the moment $|V| < V_{c0}$ lubricant solidifies. As far as lubricant is solidlike and value V is close to zero the spring expands again. Mentioned process is periodic in time. Similar behavior of tribological system was investigated in the experimental studies [6, 7, 37, 38].

Let's examine temperature T and velocity V influence on the interrupted mode. In Fig. 4,(a) the dependencies of friction force $F(t)$ on time at the temperature increasing T for the fixed velocity $V = 600$ nm/s are shown. On the first stage temperature $T_c^0 < T_1 < T_{c0}$ corresponds to the situation represented in Fig. 3, and stick-slip mode is observed. On the next stage temperature rises $T_2 = 240$ K and exceeds temperature of melting $T_{c0} \approx 222.4$ K. But complete melting of ultrathin film is not realized. The reason for this behavior is described in more detail in the next section. It is noteworthy that temperature T increasing leads to the phase transition frequency growth [6]. With the further temperature increasing $T_3 = 260$ K after melting lubricant has liquidlike structure and sliding friction mode SF is set in the system.

The influence of velocity V raising at constant temperature $T = 260$ K is shown in panel (b) in Fig. 4. At the value $V_1 = 300$ nm/s $< V_c^0$ ($V_c^0(T = 260$ K$) \approx 377.5$ nm/s) the stick-slip mode is observed. At the velocity growth $V_c^0 < V_2 < V_{c0}$ after melting the sliding friction mode SF is realized in the system, since $\sigma_{el} = 0$. With the further velocity rising $V_3 = 500$ nm/s block continues the steady-state sliding. The friction force value F increases with growth of viscous stresses σ_v. This situation is described further in detail. It is worth noting that at the realization of stick-slip mode in the system at $V < V_c^0$ increasing phase transition frequency and decreasing friction force F maximal value at the velocity rising V are observed. This fact is confirmed by several experimental investigations [6, 7, 36, 38, 39].

HYSTERESIS BEHAVIOR

Let us investigate in more detail behavior of tribological system at the conditions corresponding to Fig. 4. If the upper block is in motion with constant velocity V the temperature width of hysteresis is defined by expression (10). In the case of the system functioning depicted in Fig. 1 at the constant velocity of spring free end V_0 the block velocity V substantially depends on spring rigidity K and block mass M. For example, in the case shown in Fig. 1 the interrupted (stick-slip) motion [6, 7, 28] can be realized which is impossible at $V = \text{const}$.

In Fig. 5 dependencies are shown of maximal values of friction force F, elastic σ_{el} and viscous σ_v stresses [1] at the gradual lubricant temperature T increase. In accordance with the figures at low temperature value T the stick-slip motion is realized, when time dependence of friction force $F(t)$ has saw-like shape (inset A to the figure). In this case periodical phase transitions occur between liquidlike and solidlike lubricant structure. At the temperature increase in the interrupted mode the maximal values of friction force $F_{\max}$, elastic $\sigma_{el,\max}$ and viscous $\sigma_{v,\max}$ stresses decrease. Figure 5 is built at the spring's free end velocity $V_0 = 600$ nm/s. If the block velocity V is fixed, then at the value $V = 600$ nm/s the sliding kinetic regime, which corresponds to the liquidlike lubricant structure, arises at the temperature $T > T_{c0} \approx 222.4$ K (8). In Fig. 5 this temperature is shown by vertical dash and dot line. However, since between block and external drive the spring is placed with rigidity K, if the temperature exceeds the value T_{c0} the interrupted friction mode is realized. This regime is characterized by saw-like time dependence of the friction force $F(t)$, as it is shown

[1] The stress σ_v is equal to the second term in the brackets in expression for friction force F (3) [25, 26, 28, 29].

in the inset in the upper panel of Fig. 5 for the point A at the temperature $T = 230$ K. This mode is similar to the one depicted in Fig. 3.

Let us consider in more detail the behavior shown in the inset A in Fig. 3, (a). At the beginning of motion the lubricant is solidlike and spring free end starts motion with the velocity $V_0 = 600$ nm/s. Since at the motion friction force F (3) arises the spring stretches out and block velocity V increases slowly. If block velocity exceeds critical value V_{c0}, which according to (11) at the temperature $T = 230$ K is approximately 569.1 nm/s, the lubricant melts. And velocity V reaches the maximal value $V_{\max} \approx 45$ μm/s. Block slips on the significant distance, and spring extension ΔX rapidly decreases. The elastic force $K\Delta X$ reduces with the ΔX decreasing, that is the reason for block motion, therefore velocity V decreases too. If the velocity reduces bellow critical value $V_c^0 \approx 533.9$ nm/s the lubricant solidifies by a scenario of first-order phase transition. The velocity continues to decrease to the minimal value $V_{\min} \approx 4$ nm/s. It should be noted that while the lubricant temperature T increases, the maximal block velocity value $V_{\max}$ decreases and minimal $V_{\min}$ grows. When the temperature increases the peaks frequency rises up on the dependence $F(t)$ [26]. Particularly, at the temperature $T = 242$ K the block velocity reaches the maximal value $V_{\max} \approx 32.69$ μm/s and the minimal $V_{\min} \approx 23$ nm/s. The decreasing in maximal motion velocity explains the reduction of maximal values of viscous component of the stress σ_v (the second term in the brackets in the equation (3)), that is shown in the panel (c) in Fig. 5. Note that in Fig. 5 no friction force and stresses amplitudes are shown but their maximal values which are observed in the positive region. Thereby it is revealed that with the lubricant temperature T growth the maximal spring extension ΔX decreases and the minimal block velocity increases. At this at reaching temperature value $T \approx 244.6$ K (the arrow downward in the panel (a) in Fig. 5) the minimal block velocity $V_{\min}$ becomes larger than the critical value V_c^0 (12) and lubricant does not solidify. With the further temperature increase the lubricant always has liquidlike structure.

If after the complete lubricant melting and the stationary kinetic sliding mode setting up, for which $V = V_0$, the temperature is decreased the lubricant solidifies at smaller temperature T (the

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arrow upward in the panel (a) in Fig. 5), that is significantly fewer than the value of complete melting (the arrow downward). In the inset for point B in panel (a) in Fig. 5, which is built at the same temperature with point A, the interrupted mode is absent. The reason for this is that the block velocity V coincides with spring's free end velocity V_0, which is larger than value V_c^0, that is necessary for lubricant solidification. If the lubricant temperature decreases below than the critical value $T_c^0 \approx 214.2$ K the lubricant solidifies. In this case the temperature width of hysteresis is $\Delta T \approx 30.4$ K.

Now consider the case when the temperature is not increased but the spring's free end velocity V_0 gradually grows (see Fig. 6). In the case of rigid connection with external drive ($V = V_0$) the lubricant melts after exceeding the critical value $V_{c0} \approx 425.9$ nm/s, and solidifies at the velocity $V_c^0 \approx 377.5$ nm/s. These velocities are shown in the panel (a) in Fig. 6. Let us consider this figure in more detail. At the initial time $t = 0$ the upper block is at rest $V = 0$. At the moment of time $t > 0$ the spring free end is driven with velocity $V_0 = 320$ nm/s and acceleration $a_{ac} = 40$ nm/s^2. During the time period $t = 1$ s velocity V_0 increases to the value 360 nm/s smaller than the critical value V_c^0. At this the upper block velocity monotonically increases, but its value is smaller than V_0 because of spring presence. Then the spring free end moves some time with the constant velocity $V_0 = 360$ nm/s (the horizontal part of dashed dependence), and block velocity V grows. Although velocity V_0 is less than V_{c0}, which is necessary for melting, the lubricant melts with time, because the situation $V > V_{c0}$ is realized due to spring presence. If the velocity V grows the order parameter φ decreases (at the initial time the lubricant is solidlike, because the initial value $\varphi_0 = 0.5$ is chosen). For the total lubricant melting ($\varphi = 0$) after exceeding the critical velocity V_{c0} some time is necessary, because the system has inertial properties, which specified by parameter δ in Landau-Khalatnikov equation (14). But the liquidlike state is examined where shear modulus is not always equal to zero [6, 7, 28, 30]. Therefore we conditionally consider that lubricant is liquidlike when block velocity exceeds value $V \approx 890$ nm/s because the order parameter $\varphi < 0.01$ and the ratio of elastic stress σ_{el} (the first term in brackets in equation (3)) to the total stress σ (the sum of both terms in brackets in equation (3)) is less than 0.7%. At this the total friction force F abruptly decreases (the panel (b) and the inset to this panel in Fig. 6), and then it begins to increase at the expense of increasing in viscous stress component σ_v. This occurs since block velocity V abruptly increases after melting (see the inset to the panel (a) in Fig. 6). At this the spring contracts due to condition $V > V_0$. With the lapse of time the block velocity V decreases to the value less than the critical V_c^0 (12) and lubricant solidifies. Thereby the stationary mode of stick-slip motion sets in.

Then during the time of one second spring's free end velocity increases to the value $V_0 = 400$ nm/s (now it is larger than the critical V_c^0, as we can see in figure). According to the figure the lubricant melts again with the velocity rising to the value $V > 16$ μm/s (see inset to the panel (a) in Fig. 6). After corresponding extension of spring the block velocity V decreases to the value V_0, but if now $V_0 < V_c^0$ the lubricant does not solidify. With the subsequent spring's free end velocity V_0 increasing the kinetic mode of liquid friction is realized. If now velocity V_0 decreases the lubricant solidifies after fulfilment of condition $V < V_c^0$. If in the liquid friction mode in the stationary state the situation $V = V_0$ realizes at the very slowly velocity V_0 decreasing the lubricant solidifies at $V_0 < V_c^0$. Thus the velocity hysteresis is absent at the chosen parameters, because of spring presence. In this case the velocity can change on several digits. At this if the external drive velocity exceeds the critical value V_c^0 the block velocity becomes larger than V_{c0} with the further lubricant melting. The acceleration value a_{ac} critically effects on the described behavior features. It is expected that at the $a_{ac} \to 0$ at the velocity increasing from zero value the velocity width of hysteresis ΔV is observed. In this case in the solidlike lubricant state we can consider that spring's free end velocity V_0 coincides with block velocity V at each time moment. It is equivalent to the situation when block is rigidly connected to the external drive.

STICK-SLIP MODE AT THE VELOCITY INCREASING

Let us investigate the system behavior at the continuous increase in external drive velocity V_0

with fixed acceleration a_{ac}. In the panel (a) in Fig. 7 the dependence of upper block velocity V on time at the temperature $T = 220$ K is depicted by solid line. The time dependence of external drive velocity is shown by dashed line $V_0(t) = a_{ac}t$. Similar to the previous case with the velocity V_0 increasing the velocity V grows but more slowly, this is because of friction force F and tension ΔX increasing. If the block velocity V exceeds V_{c0} the lubricant melts due to that V abruptly rises. At this spring extension ΔX decreases and velocity V becomes less than value V_c^0 and lubricant solidifies. At the chosen parameters this process repeats in time, and since velocity V_0 grows the frequency of phase transitions increases too [26,28]. It is worth noting that in this mode the critical velocity value V_0 exists, after its exceeding the stick-slip motion transforms into sliding kinetic mode with the stationary velocity $V = V_0$. It is noteworthy that increasing frequency of phase transition (slips and sticks) at velocity V rising is observed in the experimental investigations [6,7].

The temperature T change influences on the systems behavior critically. The panel (b) in figure is built at the larger temperature $T = 260$ K. At this temperature the lubricant is solidlike in the rest state like in panel (a) in figure, because it is less than value T_c^0 (9). At this condition the system behavior at the parameters of panel (b) in Fig. 7 in initial stage (before melting) qualitatively coincides with behavior in panel (a) in figure. In the case $T = 260$ K after melting the block velocity abruptly increases and after relaxation it does not fall bellow value V_c^0. The execution of this condition is necessary for lubricant solidification. According to this the lubricant is always liquid-like, and the liquid friction mode sets in. Since velocity V_0 continues to increase monotonically after melting and the friction force F (3) acts, which grows with the velocity V, then the condition $V < V_0$ is realized at the motion.

CONCLUSIONS

In the proposed study using Landau theory of the first-order phase transitions the thermodynamic model is built of an ultrathin lubricant film melting confined between two atomically smooth solid surfaces. The kinetics of the system is studied on the basis of simple analogue of tribological system. It is shown that in a wide range of parameters the stick-slip mode is realized when lubricant periodically melts and solidifies. It is found out that with the temperature or velocity increasing the interrupted mode disappears and the sliding kinetic mode sets in with constant velocity. It is revealed that if in tribological system the spring is present the temperature and velocity hysteresises have different properties. For example, at chosen parameters the velocity hysteresis is possible only at the very slow increase in spring's free end velocity, when the block velocity at solidlike state can relax to the spring's free end velocity. In other cases the velocity hysteresis is not observed. Thus the spring (the elastic properties of system) presence substantially changes the nature of frictional behavior. It is shown that with the velocity increasing the frequency of phase transitions increases between liquidlike and solidlike states.

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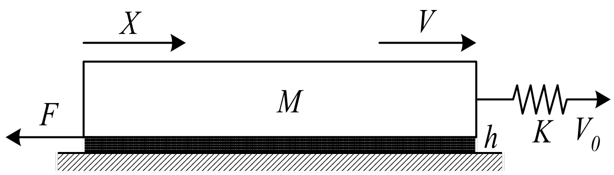

Figure 1: The scheme of tribological system.

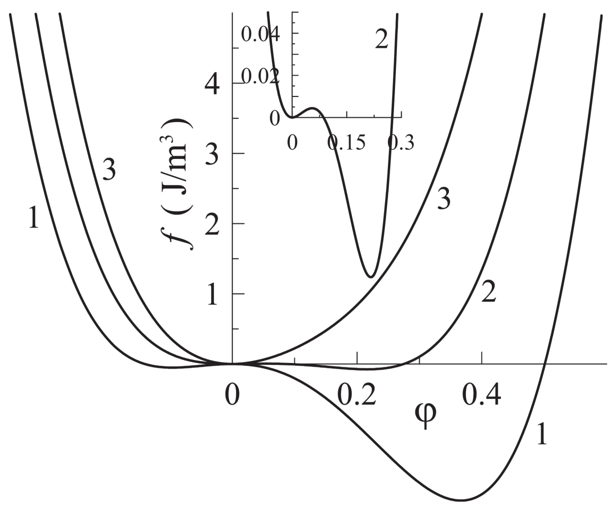

Figure 2: The dependence of the free energy density f (4) on the dimensionless order parameter φ at $\alpha = 0.95$ J$\cdot$ K^{-1}/m^3, $T_c = 290$ K, $a = 4 \cdot 10^{12}$ Pa, $b = 230$ J/m^3, $c = 850$ J/m^3. Curves 1–3 correspond to the temperatures $T = 265, 286, 310$ K, respectively, and the elastic shear strain $\varepsilon_{el} = 2.1 \cdot 10^{-6}$.

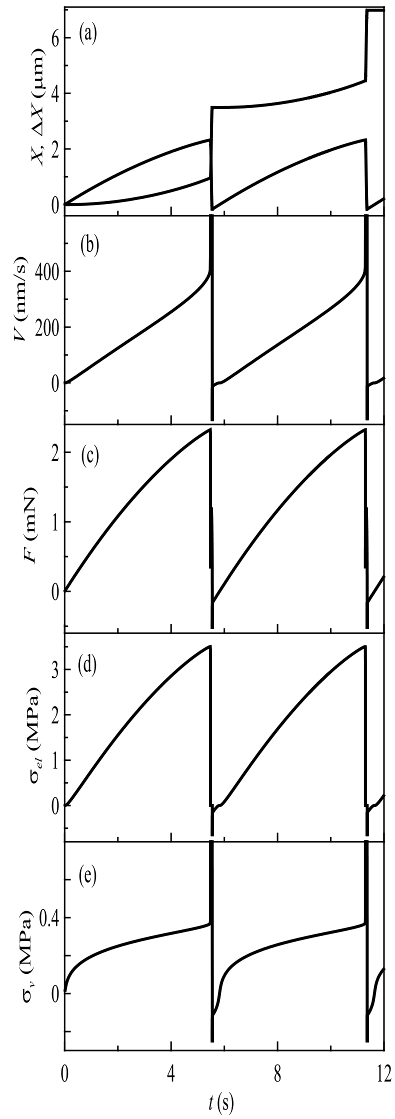

Figure 3: The dependencies of block coordinate X (a), spring extension ΔX (a), block velocity V (b), total friction force F (c), elastic σ_{el} (d) and viscous σ_v (e) stresses on time t for the parameters of Fig. 2 and $h = 10^{-9}$ m, $\tau_\varepsilon = 10^{-8}$ s, $\gamma = -2/3$, $A = 0.6 \cdot 10^{-9}$ m^2, $k = 5 \cdot 10^4$ Pa·s$^{1/3}$, $\delta = 100$ J^{-1}·m^3/s, $M = 0.4$ kg, $K = 1000$ N/m, $T = 215$ K, $V_0 = 600$ nm/s.

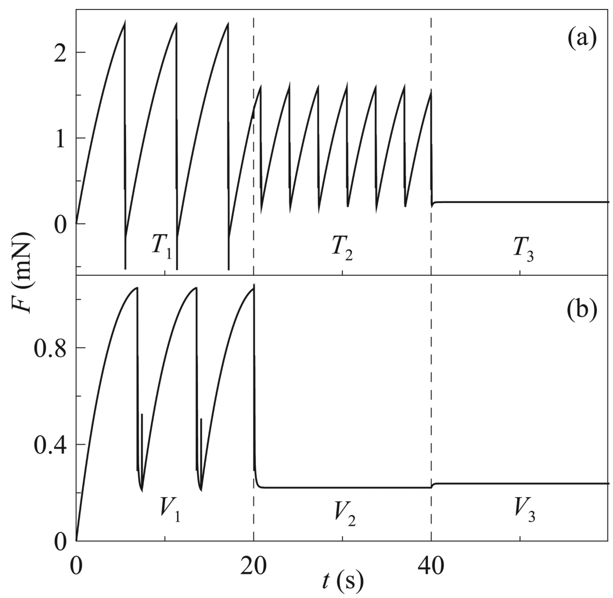

Figure 4: The dependencies of friction force F on time t at the temperature T (a) and velocity V (b) increasing for the parameters of Fig. 3, and panel (a) corresponds to the values V_0 = 600 nm/s, T_1 = 215 K, T_2 = 240 K, T_3 = 260 K, panel (b) – T = 260 K, V_1 = 300 nm/s, V_2 = 400 nm/s, V_3 = 500 nm/s.

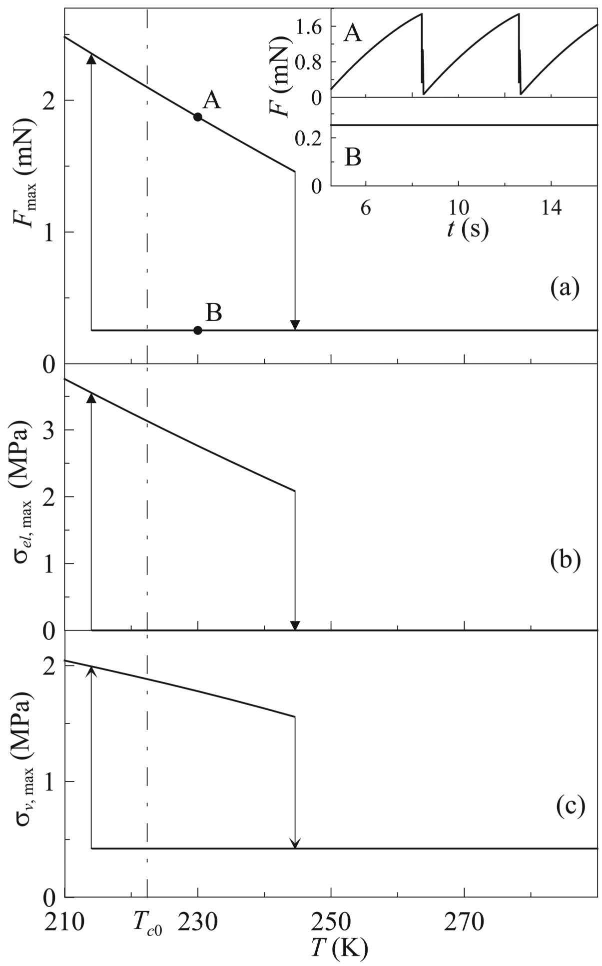

Figure 5: The dependencies of maximal values of friction force $F_{\max}$ (a), elastic σ_{el} (b) and viscous σ_v (c) stresses on lubricant temperature T for the parameters of Fig. 3. In the inset to the panel (a) the time dependencies $F(t)$ are shown corresponding to the points A and B.

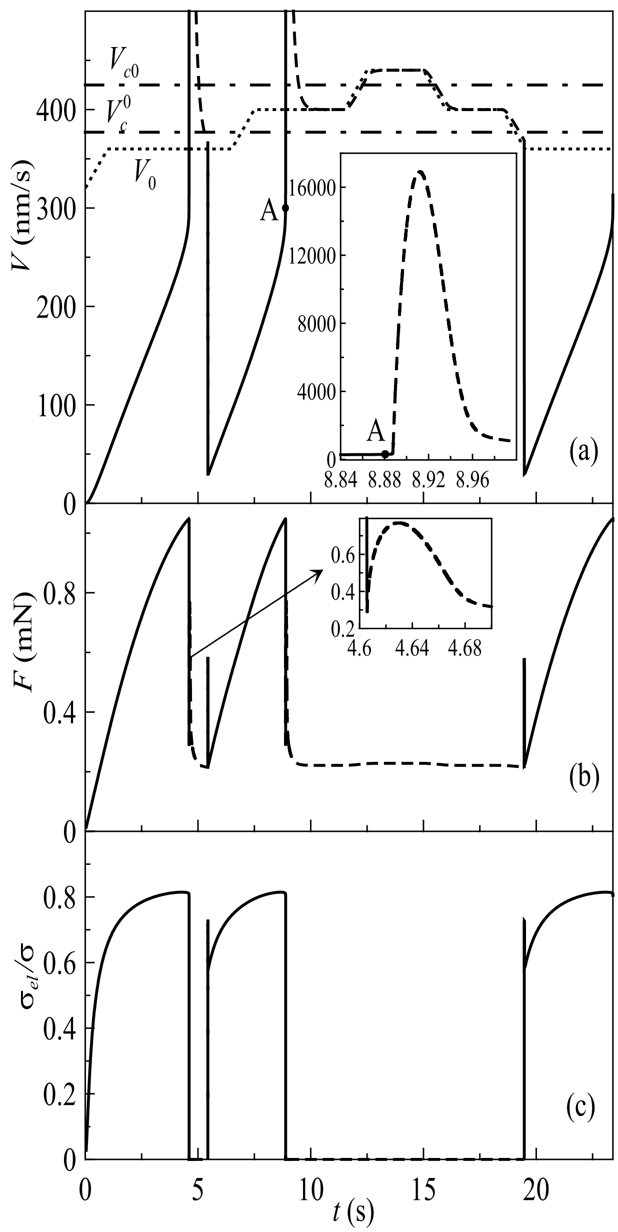

Figure 6: The time dependencies of block velocity V, friction force F and ratio of elastic to total stress σ_{el}/σ for the parameters of Fig. 5 and temperature $T = 260$ K. Spring's free end velocity V_0 is designated by dotted line in the panel (a), solid line shows block velocity in the solidlike lubricant state, dashed line in liquidlike state, critical values of melting V_{c0} and solidification V_c^0 are marked by dash and dot lines.

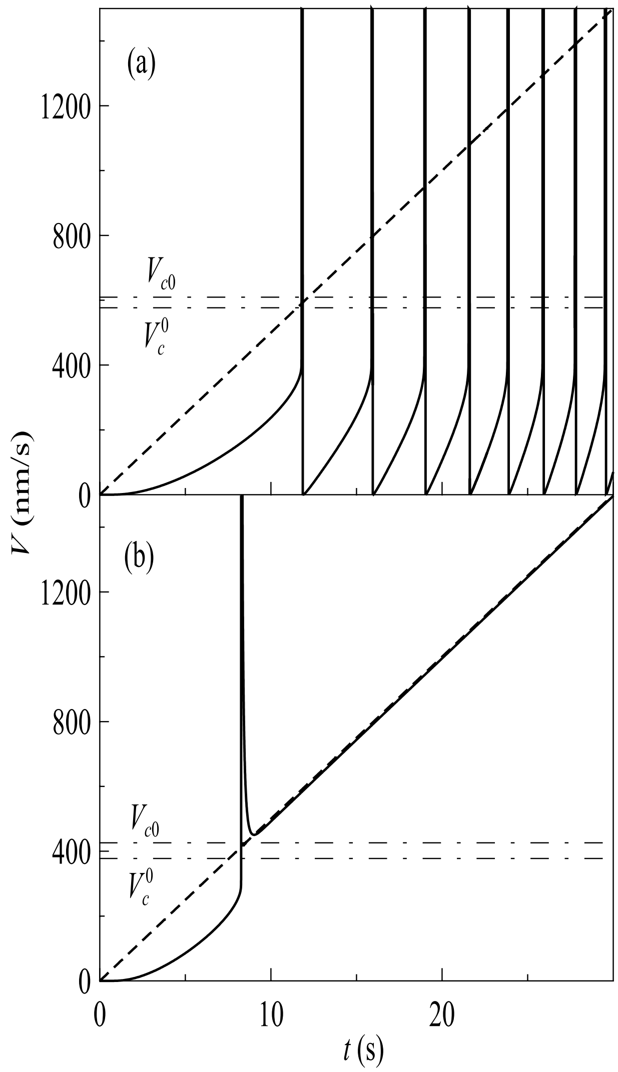

Figure 7: The time dependencies of block velocity V for the parameters of Fig. 5 and acceleration $a_{ac} = 50$ nm/s^2. The panel (a) corresponds to the temperature $T = 220$ K, the panel (b) meets the temperature $T = 260$ K. The block velocity V is shown by solid line, the external drive velocity V_0 by dashed line.