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Phase Dynamic of Shear Melting

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The melting of an ultrathin lubricating film clamped between two atomically smooth solid surfaces that are in relative motion is analyzed. The influence of additive stresses fluctuations, strain and temperature on the process of lubricant melting is investigated taking into account the shear modulus deformation defect. The influence of the system parameters on the phase diagram, where the temperature noise intensity and the temperature of friction surfaces define the areas of dry, liquid and stick-slip friction, is analyzed.

Keywords: Boundary friction, Friction force, Shear stresses, Shear strain, Melting, Stick-slip mode.

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1. INTRODUCTION

The study of the influence of external and internal fluctuations on the boundary friction process has both fundamental and practical importance, since fluct-?ations may critically change the system behavior in the nanoscale systems, for example, providing conditions for the friction reduction. It should be noted that the thermal noise is present in all the friction experiments, and its effects in low-dimensional systems can be critical. In this regard, a considerable attention is given to the influence of noise and random impurities on static and dynamic boundary friction [1].

The synergetic model of boundary friction based on the system of three differential equations for the stress, strain and temperature [2,3], allows describing the nontrivial behavior of the ultrathin lubricant film clamped between two atomically smooth solid surfaces that are in relative motion. Using this model, the influence of fluctuations on the tribological behavior of the system has been studied [2]. The influence of shear modulus deformation defect on hysteresis phenomena is considered in [2,4]. The present work is a conti-?uation of [2,4]. The aim of this work is to study the influence of lubricant shear modulus deformation defect on the phase diagram of boundary lubrication modes when the system has the additive uncorrelated fluctuations (noises).

2. BASIC EQUATIONS

The model describing the behavior of the ultrathin lubricating film clamped between two atomically smooth solid surfaces is based on a system of dimensionless equations as follows [2-4] :

$$\tau_\sigma \dot{\sigma} = -\sigma + g(\sigma)\varepsilon + \sqrt{I_\sigma}\xi_1(t), \qquad (1)$$

$$\tau_\varepsilon \dot{\varepsilon} = -\varepsilon + (T-1)\sigma + \sqrt{I_\varepsilon}\xi_2(t), \qquad (2)$$

$$\tau_T \dot{T} = (T_e - T) - \sigma\varepsilon + \sigma^2 + \sqrt{I_T}\xi_3(t), \qquad (3)$$

where σ is a shear component of the stresses, ε is a shear component of the relative strain, T is a lubricant film temperature, and T_e is a friction surface temperature. The function $g(\sigma)$ is also introduced [2,4]:

$$g(\sigma) = g_\theta\left(1 + \frac{\theta^{-1} - 1}{1 + (\sigma/\alpha)^\beta}\right), \qquad (4)$$

that takes into account the shear modulus deformation defect which describes the transition of the elastic deformation mode into plastic.

In the future we will use the method described in [5]. Within the framework of the adiabatic approximation $\tau_\sigma \gg \tau_\varepsilon, \tau_T$ in the equations (2), (3) it is possible to consider $\tau_\varepsilon \dot{\varepsilon} \approx 0$, $\tau_T \dot{T} \approx 0$. Taking this into account, (1) takes the form of the Langevin equation (see in [2,5]

$$\tau_\sigma \dot{\sigma} = f(\sigma) + \sqrt{I(\sigma)}\xi(t), \qquad (5)$$

where the generalized force $f(\sigma)$ and effective noise intensity $I(\sigma)$ are specified by the expressions [2]:

$$f(\sigma) = -\sigma + \sigma g(\sigma)\left(1 - \frac{2 - T_e}{1 + \sigma^2}\right), \qquad (6)$$

$$I(\sigma) = I_\sigma + \frac{g^2(\sigma)}{(1+\sigma^2)^2}(I_\varepsilon + I_T\sigma^2). \qquad (7)$$

In the general case, the variety of forms of the Fokker-Planck equation may correspond to the equation (5). Here the Stratonovich calculus is used, since it allows considering correlations at small times automatically. Over time, the distribution of solutions (5) becomes stationary, and its explicit form can be found:

$$P(\sigma) = Z^{-1}\exp\{-U(\sigma)\},\; U(\sigma) = \frac{\ln I(\sigma)}{2} - \int_0^\sigma \frac{f(\sigma')}{I(\sigma')}\mathrm{d}\sigma'. \qquad (8)$$

The points of extremum distribution (8) are determined by the condition $\mathrm{d}U/\mathrm{d}\sigma = 0$, which leads to the equation $\mathrm{d}I/\mathrm{d}\sigma - 2f = 0$. It is possible to introduce

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$x \equiv 1+\sigma^2$ and to write the extremum condition in an explicit form:

$$\begin{aligned}&\left[1-g(\sigma)\right]x^3+g(\sigma)\left[2-T_e\right]x^2+2g^2(\sigma)\left[I_T-I_\varepsilon\right]-\\&-g(\sigma)\left[g(\sigma)I_T-\frac{-g_\theta\beta\sigma^{\beta-1}\left(\theta^{-1}-1\right)}{\alpha^\beta\left(1+(\sigma/\alpha)^\beta\right)^2}\left(I_\varepsilon+I_T\sigma^2\right)\right]x=0.\end{aligned} \tag{9}$$

In the case $\sigma=0$ from (9) we obtain the relation

$$T_e=1+\frac{\theta}{g_\theta}+\frac{g_\theta(I_T-2I_\varepsilon)}{\theta}+\frac{I_\varepsilon g_\theta\beta\left(\theta^{-1}-1\right)}{\alpha^\beta\sigma^{2-\beta}}. \tag{10}$$

The influence of the parameter β on the system behavior is displayed on the phase diagrams in Fig. 1. Fig. 1a is for the case $\beta=1$. There is a liquid (*SF*) mode of friction and the combination of a liquid metastable mode with a liquid stable (*MSF*+*SF*) mode. In the *SF* region the distribution function $P(\sigma)$ has a single non-zero maximum. The *MSF*+*SF* region is characterized by the coexistence of two nonzero maxima $P(\sigma)$. The phase diagram for $\beta=2$ is shown in Fig. 1b. In this case line 1 is shown by (10). It gives the border of the existence of a zero stationary solution $\sigma_0=0$. Below line 1 there is always a zero stationary solution $\sigma_0=0$. In the region of dry friction (*DF*) of the phase diagram there is only one maximum of the distribution function $\sigma_0=0$. The two-phase region (*SS*) of the diagram is characterized by the coexistence of distribution maxima $P(\sigma)$ at zero and non-zero values of stresses that corresponds to the realization of the stick-slip mode, in which transitions between dry and liquid friction take place. When $\beta=3$ and $\beta=4$ the phase diagrams have only quantitative differences as Fig. 1c and Fig. 1d show respectively. Below line 1 the region of stick-slip and sliding (*SS*+*SF*) friction is shown. In this region three maxima of the distribution function $P(\sigma)$ (zero and two non-zero) are realized.

In the present work the model describing the behavior of the ultrathin lubricant film clamped between two atomically smooth solid surfaces has been studied. The influence of shear modulus deformation defect on the phase diagram of boundary friction modes considering the additive fluctuations of the stress, strain and temperature is analyzed. It is shown that the value of system parameters critically influences on the form of the phase diagram. It is possible to find such conditions, when there are no areas of dry and stick-slip friction that is preferable for realization of friction reduction conditions.

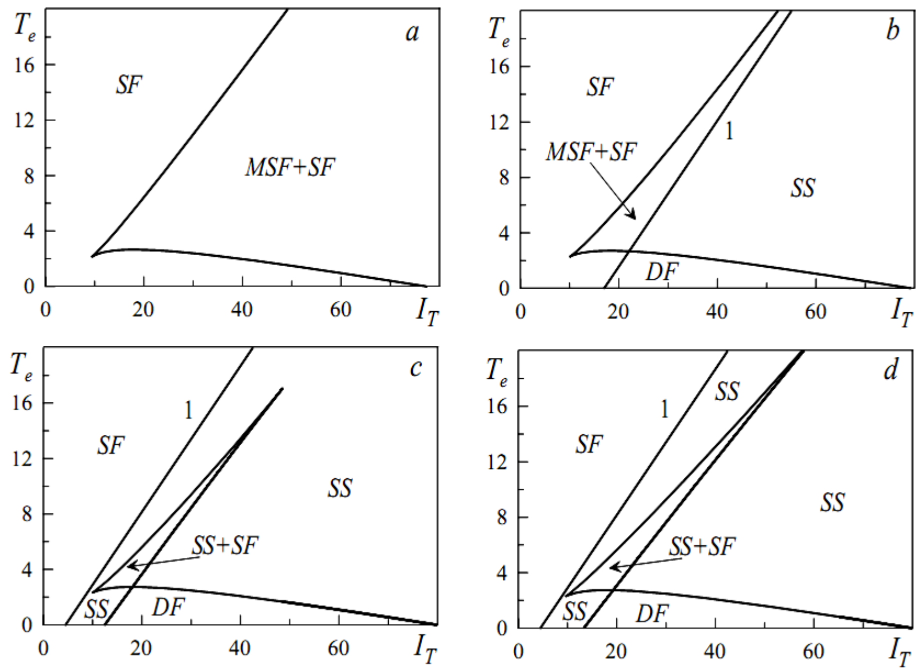

Fig. 1 – Phase diagrams at parameters $g_\theta=0.5, \alpha=0.2, \theta=0.95, I_\varepsilon=5$: a-d) $\beta=1-4$.

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