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APPLIED PROBLEMS
OF STRENGTH AND PLASTICITY

Laws of the Sliding Friction of R6M5 Steel on Grade 45 Steel in the Litol-24 Lubricant Medium with Dispersed Graphite Particles

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Abstract—The sliding friction of R6M5 steel on grade 45 steel in the load range from 0 to 700 N in the medium of a plastic Litol-24 lubricant modified with dispersed graphite particles is studied. The dependence of the frictional force on the normal force is found to have a piecewise linear form with two linear sections. Both classical and generalized versions of the Amonton–Coulomb law are shown to be valid for the materials under study. Graphite particles are found to improve the antifriction characteristics in the load range 442–614 N and to increase the critical load from 390 to 540 N and the bearing capacity of the lubricating layer. A mathematical model is proposed to describe the viscosity of plastic lubricants with dispersed additives.

Keywords: sliding friction, generalized friction law, Amonton–Coulomb friction law, plastic lubricant, graphite, Litol-24, grade 45 steel, R6M5 steel, viscosity of lubricant

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INTRODUCTION

Plastic lubricants are actively used in sliding friction units, since they have such features as the manifestation of the properties of solids at low loads and normal temperatures, the ability to undergo plastic deformation and fluidity when the critical level of an external temperature–force action is reached, and the restoration of the properties characteristic of solids after a certain period of time after a load is removed [1–9]. To improve the tribotechnical and other operational properties of plastic lubricants, powdered additives are introduced into their composition, and the most widely used additive is a powder of graphite or other forms of carbon, e.g., graphene or carbon nanoparticles [2, 6–15]. The introduction of such additives has a positive effect on the antifriction properties and bearing capacity of a lubricating layer [6–15]. For the sliding friction of a steel–steel pair in such a medium, the validity of the well-known linear empirical Amonton–Coulomb law and its more complex version, which takes into account changes in friction conditions, has not been studied in detail [16–21].

The purpose of this work is to study the effect of addition of dispersed graphite particles to a plastic lubricating material (Litol-24) on the characteristics of sliding friction in the R6M5 steel–grade 45 steel pair.

EXPERIMENTAL

A widely used plastic lubricant Litol-24 was chosen as the basis of a lubricant composition, and its main technical characteristics are given in Table 1. Crushed artificial graphite GII-A with a fraction of 0.1 mm and a bulk mass of at least 850 kg/m^3 (TU 1916-109-71–2009) in an amount of 10 wt % was used as a dispersed additive.

Friction tests were carried out under conditions of sliding along a circular trajectory according to the roller–roller scheme using a universal II 5018 friction machine [1, 22]. The movable roller was made of R6M5 steel and the stationary roller, of grade 45 steel. Both rollers with a diameter of 50 mm and a length of 10 mm with a central axial hole 16 mm in diameter had a contact surface roughness $R_a \leq 1.6$ μm. They were preliminarily brought into contact interaction. A 3-mm-thick lubricant layer was evenly applied onto the movable roller. Contact interaction was provided by a normal force varying from 0 to 700 N at a rotational speed $n = 1500$ min^{-1} of the movable sample. The complete test time at a fixed load was 180 s.

The studies tested the effect of three versions of the empirical Amonton–Coulomb law [20, 23]. The first version was the simple classical dependence of the sliding frictional force on the friction coefficient. In the interpretation that takes into account the Deryagin molecular theory of friction, this version has the form [23–25]

$$F_f = f_t(F_N + F_M), \quad (1)$$

where F_f is the sliding frictional force, $f_t = dF_f/dF_N$ is the instantaneous (true) friction coefficient, F_N is the normal force pressing the rubbing bodies against each other, and F_M is the resultant force of the molecular attraction forces of the rubbing bodies.

The second version was a generalized Amonton–Coulomb law, which takes into account changes in fraction conditions and is used in case of deviations from law (1) [23, 26, 27],

$$F_f = f_t(F_N + F_M) + \frac{\Delta f}{r}\ln(1 + \exp(r(F_N - F_{cr}))), \quad (2)$$

where Δf is the increment of the friction coefficient when a frictional interaction mode changes and r is the parameter of the sharpness of the transition from one friction mode to another when the normal force reaches critical value F_{cr}.

We also tested the effect of a modified version of law (1), which postulates a linear change in the frictional force with a natural change in a frictional interaction mode [23, 26, 27],

$$F_f = f_t(F_N - F_{cr}) + F_{fM}, \quad (3)$$

where $F_{fM} = f_t F_M$ is the molecular component of the frictional force.

An analysis of experimental data and the approximation of the dependences of the frictional force and the friction coefficient on the normal force (load) were carried out by analogy with works [28, 29].

Table 1. Main technical characteristics of Litol-24

Characteristic	Value
Stability of oil, %	12
Evaporability at 120°C, %	6
Drop temperature, °C	At least 180
Density at 15°C, g/cm^3	892
Penetration at 25°C with stirring, mm^{-1}	220–260
Viscosity, Pa s, at temperature:	At most 650
–20°C	
0°C	At most 280
50°C	At most 8
Ultimate strength, Pa, at temperature:	
20°C	500–1000
80°C	At least 200
Lubricating properties at 20°C:	
welding load, N	At least 1410
critical load, N	At least 630
load wear index, N	At least 280

RESULTS AND DISCUSSION

Figure 1 shows the experimentally obtained dependences of the frictional force and the instantaneous friction coefficient on the normal force during the sliding friction of R6M5 steel on grade 45 steel in the Litol-24 lubricant medium. The dependence of the average frictional force on the normal force in Fig. 1a is well approximated by the equation

$$F_f(F_N) = 0.12F_N + 0.3 + \left(\frac{0.34}{0.5}\right)\ln(1 + \exp(0.5(F_N - 390))), \quad (4)$$

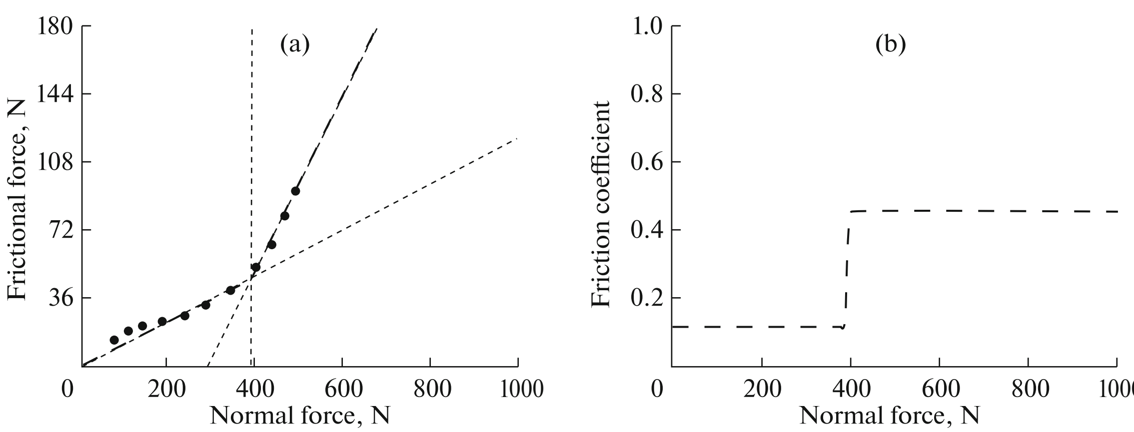

Fig. 1. (a) Frictional force and (b) instantaneous friction coefficient vs. the normal force during sliding friction of R6M5 steel on grade 45 steel in the Litol-24 lubricant medium.

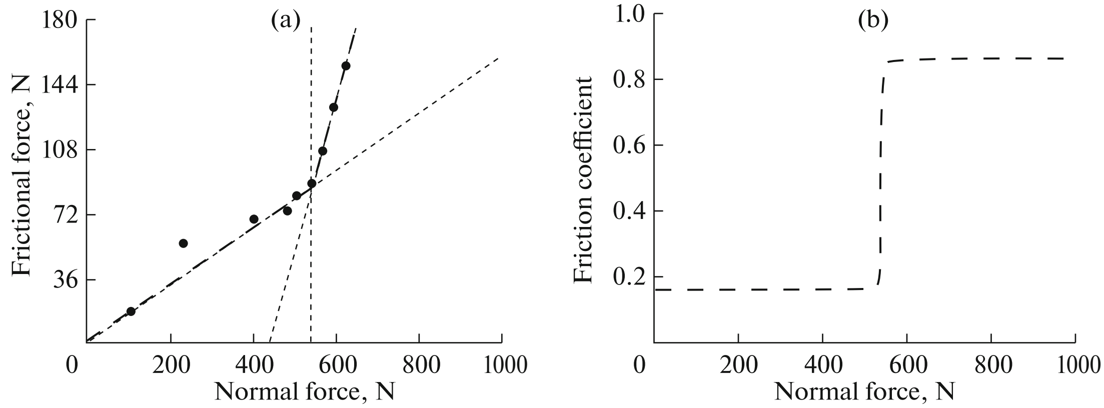

Fig. 2. (a) Frictional force and (b) instantaneous friction coefficient vs. the normal force during sliding friction of R6M5 steel on grade 45 steel in the Litol-24 + 10% graphite lubricant medium.

and the dependence of the instantaneous friction coefficient (see Fig. 1b), by the equation

$$f_t = \frac{dF_f}{dF_N} = 0.12 + \frac{0.34}{1 + \exp(-0.5(F_N - 390))}. \quad (5)$$

The form of the dependences shown in Fig. 1 and approximating equations (4) and (5) show that the simple (first) version of the Amonton–Coulomb law is valid at F_N = 0–390 N. Taking into account the molecular theory of friction [23–25], the dependence is described by the linear equation

$$F_f = 0.12(F_N + 2.5). \quad (6)$$

At $F_N = F_{cr}$ = 390 N, a friction mode changes into to a more intense one. In the range F_N = 390–700 N, the Amonton–Coulomb law (first version) also holds true, but the dependence is approximated by another linear equation,

$$F_f = 0.46(F_N - 390) + 47.1. \quad (7)$$

Thus, for the case under study, modified version (3) of the law, which postulates a linear change in the frictional force with a natural change in a frictional interaction mode, is also valid. When comparing Eqs. (7) and (3), we can estimate the molecular component of the frictional force under new friction conditions in the Litol-24 medium; it was found to be F_{fM} = 47.1 N.

For the conditions of sliding friction of R6M5 steel on grade 45 steel in the Litol-24 medium with the addition of 10% graphite, the dependence of the average frictional force on the normal force (Fig. 2a) is approximated by the equation

$$F_f(F_N) = 0.16F_N + 0.4 + \left(\frac{0.7}{0.5}\right)\ln(1 + \exp(0.5(F_N - 540))), \quad (8)$$

and the dependence of the instantaneous friction coefficient (Fig. 2b), by the equation

$$f_t = \frac{dF_f}{dF_N} = 0.16 + \frac{0.7}{1 + \exp(-0.5(F_N - 540))}. \quad (9)$$

The dependences shown in Fig. 2 and approximating equations (4) and (5) demonstrate that the first version of the Amontons–Coulomb holds true in the normal force range 0–540 N; with allowance for the molecular theory of friction [23–25], it can be described by the linear equation

$$F_f = 0.16(F_N + 2.5). \quad (10)$$

At $F_N = F_{cr}$ = 540 N, the friction mode changes into a more intense one, as in the case of using Litol-24 without graphite. In the range F_N = 540–700 N, the Amonton–Coulomb law (first version) is described by the linear equation

$$F_f = 0.86(F_N - 540) + 86.8. \quad (11)$$

Thus, as in the first case, modified version (3) of the law, which postulates a linear change in the frictional force with a natural change in a friction interaction mode, is valid for the Litol-24 + 10% graphite lubricant. Using Eq. (11) and taking into account Eq. (3), we can estimate the molecular component of the frictional force in the friction mode in the Litol-24 + 10% graphite medium; it was found to be F_{fM} = 86.8 N.

According to approximating dependences (4) and (8), generalized version (2) of the Amonton–Coulomb law, which takes into account changes in friction modes, holds true for friction under Litol-24 lubrication conditions (with and without additives). Note that, according to Eqs. (6) and (10), the resultant of the molecular attraction forces F_M for both lubricants is ≈2.5 N. This finding indicates that, during the friction process, graphite particles weakly increase the actual contact area (surface smoothing). It can also be noted that the dependence of the friction coefficient on the normal force has a sigmoid shape for both lubricants.

In the normal force range F_N = 442–614 N, the Litol-24 + 10% graphite lubricant composition provides better antifriction characteristics as compared to Litol-24 without additives (Fig. 3). Note also that when, the load changes from 0 to 390 N, the frictional force for the Litol-24 + 10% graphite lubricant composition is higher than that when only Litol-24 is used. This fact can be explained by an increase in the viscosity of the lubricant on adding graphite particles, and this increase is not compensated by the antifriction action of these particles.

The dependence of the effective viscosity of a plastic lubricant on the average shear strain rate over a wide range of its variation is described by the equation [30]

$$\mu_{\bar{D}} = \mu_\infty + k_1\bar{D}^{k_2}, \quad (12)$$

where $\mu_{\bar{D}}$ is the effective viscosity of a plastic lubricant at a given average shear strain rate, μ_∞ is the viscosity of a plastic lubricant at a high average shear strain rate when the material is an almost Newtonian fluid, $\bar{D}$ is the average shear strain rate, and k_1 and k_2 are constants.

As was shown in [27, 31], the viscosity of lubricating oil, which is a Newtonian fluid, with dispersed additives is described by the generalized Einstein equation

$$\mu_\infty(\varphi) = \mu_\infty(1 + \alpha_f\varphi), \quad (13)$$

where $\mu_\infty(\varphi)$ and μ_∞ are the viscosities of the Newtonian fluid with and without dispersed particles, respectively; α_f is the coefficient that takes into account the shape and interaction of particles; and φ is the volume fraction of dispersed particles.

With allowance for Eq. (13), Eq. (12) can be rewritten as

$$\mu_{\bar{D}}(\varphi) = \mu_\infty(1 + \alpha_f\varphi) + k_1(\varphi)\bar{D}^{k_2(\varphi)}. \quad (14)$$

Equation (14) explains the increment in the frictional force by an increase in the viscosity of the lubricating medium. In addition, coefficients k_1 and k_2 are likely to increase, decrease, or remain unchanged depending on the interaction of particles with the medium. In this work, a general change in all parameters of Eq. (14) leads to an increase in the viscosity and, accordingly, the frictional force.

It should be noted that the addition of a graphite powder promotes an increase in the critical load F_{cr} from 390 to 540 N. The change in the friction mode in the Litol-24 lubricant medium at a load F_{cr} = 390 N to a more intense one is due to the fact that the lubricating layer thickness decreases at a high normal force. Thus, the change in the dependences reflects a change from the mixed friction mode of "boundary and lubricating layers" to the friction mode of "boundary layers, oxide films, and juvenile surfaces."

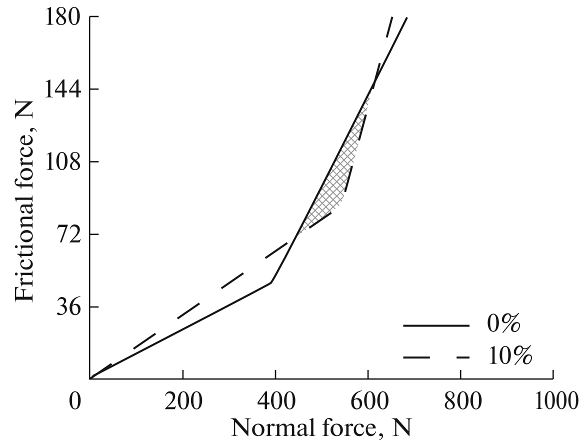

Fig. 3. Frictional force vs. the normal load in the lubricants Litol-24 and Litol-24 + 10% graphite.

In the case of the Litol-24 + 10% graphite lubricant, an increase in the normal load above the critical value (F_{cr} = 540 N) also brings about a decrease in the lubricating layer thickness, but dispersed graphite particles discretely shield the friction surfaces; therefore, the load of transition to the second mode increases. Thus, the addition of dispersed graphite makes it possible to significantly increase the bearing capacity of the lubricating layer.

In general, the results obtained indicate that graphite particles exert antifriction, antiwear, and antiscoring effects in a certain load range, which is in good agreement with [6–15].

CONCLUSIONS

(1) The normal-force dependences of the parameters of friction of R6M5 steel on grade 45 steel in the medium of plastic lubricant Litol-24 or Litol-24 + 10 wt % graphite have a piecewise linear shape with two linear sections, in which a simple linear version of the empirical Amonton–Coulomb law is valid. In addition, generalized versions of this law, which take into account changes in frictional interaction conditions, also hold true.

(2) The change (inflection point) in the linear dependences of friction reflects a change of the mixed friction of boundary and lubricating layers into more intense friction of boundary layers, oxide films, and juvenile surfaces.

(3) As compared to Litol-24, the Litol-24 + 10% graphite plastic lubricant increases the frictional force in the load (normal force) range from 0 to 390 N due to higher viscosity and provides better antifriction characteristics in the range from 442 to 614 N.

(4) The addition of a graphite powder leads to an increase in the critical load F_{cr} from 390 to 540 N.

(5) During friction, graphite particles weakly increase in the actual contact area (surface smoothening).

(6) The change in the friction modes of both lubricants is associated with a decrease in the lubricating layer thickness at a high normal force; However, dispersed graphite particles in the Litol-24 + 10% material discretely shield the friction surfaces and noticeably increase the bearing capacity of the lubricating layer.

(7) The proposed mathematical model of viscosity of plastic lubricants with dispersed additives makes it possible to explain changes in the frictional force using rheological parameters.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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