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APPLIED PROBLEMS OF STRENGTH AND PLASTICITY

Sliding Friction of R6M5 Steel on Grade 45 Steel in Litol-24 Grease with Zinc and Cadmium Powder Additives

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Abstract—The sliding friction of R6M5 steel on grade 45 steel at a load of up to 1400 N under the lubrication conditions of Litol-24 grease modified with zinc and cadmium in an amount of 3 and 2 wt %, respectively, is investigated. The modified grease is shown to decrease the friction force by ~5 times and the coefficient of friction by 4–9 times. The dependence of the friction force on the normal force has four piecewise linear sections, in which a simple linear version of the Amonton–Coulomb law is obeyed, unlike friction in Litol-24 grease without additives, where the dependence consists of two sections. The generalized version of the Amonton–Coulomb law taking into account a change in the frictional interaction conditions is also obeyed.

Keywords: sliding friction, Amonton–Coulomb friction law, grease, Litol-24, grade 45 steel, R6M5 steel, zinc, cadmium

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INTRODUCTION

Greases are usually applied in closed friction units, especially at high contact loads, relatively low sliding speeds, and frequent changes in the motion direction [1]. To improve the performance properties, dispersed additives, in particular, metal-coating ones (remetallizing agents) [7–9] (e.g., powders of low-modulus metals (copper, cobalt, zinc, tin, silver, lead), their oxides, hydroxides, or salts [10, 11], are introduced into greases [2–6].

Metal powders with a low shear stress, a high ductility, and a low melting temperature are effectively used as metal-coating additives [12]. During friction in a modified lubricant medium, a protective film made of a low-modulus metal powder is known to form on the friction surfaces and to cover microasperities (self-healing effect). As a result, the coefficient of friction decreases and the wear resistance of the materials in a tribounit increases. Additives of two-dimensional nanomaterial powders exert a similar effect on the tribological characteristics [13].

Among the metal-coating additives, copper-containing additives have become the most widespread, since copper particles have a low melting temperature and the desired plasticity. In [14], the use of synthetic SAE 5W40 engine oil with an ultrafine copper additive in an amount of 0.2 wt % promoted the formation of copper boundary films on the friction surfaces, which significantly decreased the coefficient of friction and the wear by about 13% as compared to the oil without additives. In [15], the addition of copper, iron, or cobalt nanopowders to mineral oil decreased the coefficient of friction by 49, 39, and 20%, respectively. Nanolubricants containing Fe–Cu and Co–Cu facilitated a decrease in the coefficient of friction by 53%, and those containing Fe–Co, by 36%.

The introduction of a copper nanopowder significantly improves the oxidation resistance and the heat resistance of technical lubricants at a slight increase in their stability due to the formation of a protective tribofilm on the friction surfaces, which provides a lower coefficient of sliding friction and compensates for mass loss [16]. In addition to improving the properties of lubricants, copper-containing additives lead to a decrease in the microbiological corrosion of tribocontact due to antagonistic action against bacterial and fungal microflora [17].

In the case of sliding friction according to the disc–roller scheme (grade 45 steel) at a sliding speed of 1 m/s, a load of 200–900 N, and a contact area of 0.8 cm^2 under the conditions of Litol-24 lubrication with the addition of 3 wt % copper powder, the friction coefficient decreased by 10% and the wear intensity, by 15–18% [18]. In tribological tests, the contact interaction area under a metal film, which had a very high adhesion and provided a decrease in the moment of friction, was increased.

The introduction of copper nanoparticles 2–60 nm in size into paraffin oils in an amount of 0.02–0.2 wt % decreased the coefficient of friction by 26–30% and the wear by ≈30% [19, 20].

Lubricants with metal-coating additives, which form a protective servovite film on the friction surfaces, are also used in cold metal forming [21, 22]. For example, when drawing grade 45 steel through a die made of 9KhS steel in the technological lubricant I-40 medium, the use of a copper-containing additive allowed specific drawing force to be decreased by 1.5–1.6 times.

The modification of Litol-24 grease with powders of such remetallizing agents as zinc, cadmium, and bronze under the sliding friction conditions of ShKh15 steel (60 HRC) pairs improved the antifriction properties and the bearing capacity of the lubricating layer [8]. The increase in the friction characteristics was explained by the optimum heterogeneity of lubricating films.

As was shown in [23], the addition of ultra- and nanodispersed zinc powders or a Cu–Sn alloy to Litol-24 lubricant decreases the wear rate of friction pairs. When these powders interact with the friction surfaces, the diffusion of copper and tin into the metal base and the formation of secondary composite ultrafine structures were detected.

The introduction of a nickel nanopowder into a lubricant based on paraffin oils caused the closure of defects on the friction surfaces, and the resulting film prevented direct contact of friction pairs, helped them to withstand the load, and decreased the deformation stresses [23]. Such an additive under test conditions on a four-ball installation (AISI 52100 steel) at a rotation speed of 300–1500 min^{-1} and a load of 50–300 N facilitated the filling of contact surface defects with other solid-lubricating additives. The resulting protective film had a high melting temperature and a large bearing capacity, which ensured high lubrication properties even under extreme conditions such as extremely high temperatures or pressures [24]. A slight decrease in the coefficient of friction and a decrease in the wear upon introducing 0.05 wt % nickel nanopowders into SAE 10 mineral oil were observed during tests on a four-ball machine at a force of 150 N and a rotation speed of 1450 min^{-1} [25].

In [26], nanoscale powders of plasma condensation BrO10F1 bronze (as an additive to TSP-15K transmission oil), iron, nickel, zinc, Cu–Pb, Al–Pb, and Cu–Sn (as additives to Litol-24 grease) were used. Sliding friction tests were carried out according to the roller–roller scheme (ShKh-15 steel, 60–62 HRC) at a frequency of 600 min^{-1} and a load of 2700 N for 3 hours in the case of using TSP-15K oil and at a frequency of 500 min^{-1} and a load of 1200 N for 6 hours in the case of Litol-24. In the former case, the addition of a bronze powder decreased the wear by more than 2 times. In the latter case, wear decreased as follows: by 17 times after the addition of iron powder; by 11 times, zinc powder; 3.4 times, Cu–Sn; 1.9, Cu–Pb; 3, Al–Pb; and 4.2, Fe–Ni. After the introduction of nickel or Fe–Zn powders, the wear became “zero”; that is, an increase in the roller mass was observed due to mass transfer.

The authors of [27] proposed a lubricant based on polyethylene glycol PEG 200 modified with a zinc nanopowder (particle size was 20–100 nm) in an amount of 0.5–2.0 wt % for the AISI 52100 steel (62–64 HRC)–Ti6Al4V alloy friction pair. The tests were carried out according to the disk (Ti6Al4Y)–ball (AISI 52100) scheme for 1 hour at a load of 100 N, an oscillation amplitude of 1 mm, and an oscillation frequency of 25 Hz. The introduction of the additive decreased the coefficient of friction by about 2.7 times. When the additive concentration increased, the run-in period and the wear decreased: at 2 wt % zinc in the lubricant, the wear decreased by almost 4 times. Continuous and strong boundary films consisting mainly of ZnO formed on the friction surfaces of titanium alloy and steel. The formation of protective films prevented adhesive wear, which was observed in the absence of such films.

The addition of a bismuth powder to heavy and light oils in an amount of 310–910 mg/L under the test conditions in a four-ball machine according to the finger–disk scheme (load of 392 N, rotation speed of 1200 min^{-1}) decreased the coefficient of friction by 1.6–1.75 times [28, 29], and the addition of a silver nanopowder under boundary lubrication conditions decreased the coefficient of friction by 30–35% and the wear by 70–85% [30].

Currently, zinc- or cadmium-modified greases have not been studied enough and are little used in industry. The efficiency of their influence on the tribological properties of lubricant can be estimated using the results of a comprehensive study, which also includes studying the dependence of the sliding friction force on the friction coefficient and determining the corresponding type of the Amonton–Coulomb, namely, empirical (linear dependence) or its more complex version taking into account changes in the friction modes [31–33].

The purpose of this work is to study the sliding friction of R6M5 steel on grade 45 steel (foreign analogues are steels HS6-5-2, T11302 and 1045, C45, respectively) under the lubrication conditions of Litol-24 grease modified with zinc and cadmium powders.

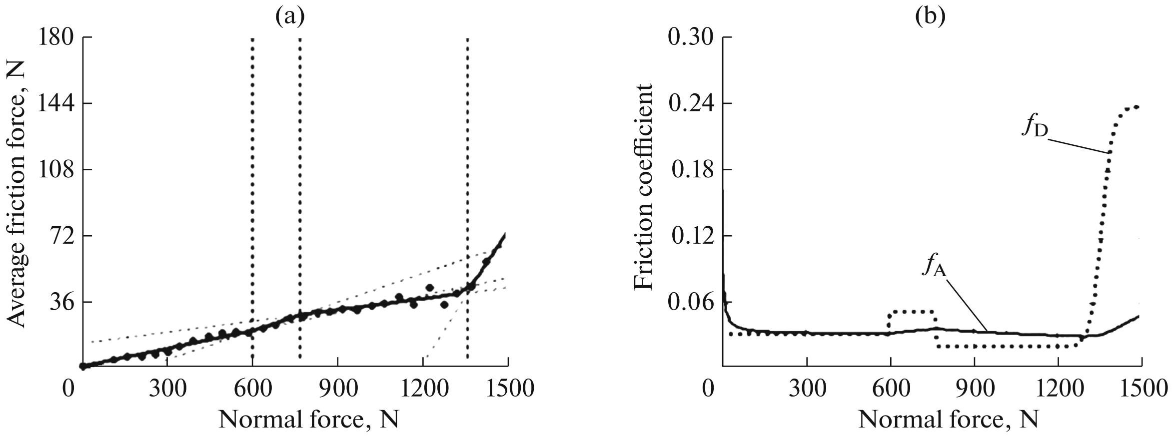

Fig. 1. (a) Average friction force and (b) differential friction coefficient f_D and Amonton friction coefficient f_A vs. the normal force during sliding friction of R6M5 steel on grade 45 steel in Litol-24 with zinc and cadmium powder additives.

EXPERIMENTAL

Lithium-containing Litol-24 grease, into which 3 wt % PR-TsnYu16 zinc powder (particle size was 40–100 μm) and 2 wt % metallic cadmium powder (particle size was 0.3–1.6 μm) were added, was used as a plastic lubricant.

Sliding friction tests of the R6M5 steel–45 steel pair along a circular trajectory was carried out according to the roller–roller scheme for 3 hours in the normal load range 0–1400 N and a rotation speed of 1500 min^{-1} [34–36]. Rollers with 50 mm in diameter and 10 mm in length with a central hole 16 mm in diameter had a contact surface roughness $R_a \leq 1.6$ μm. A 3-mm-thick lubricant layer was applied onto a movable roller made of R6M5 steel.

Experimental results were described using the Amonton–Coulomb law interpreted by Deryagin in terms of the molecular theory of friction [37, 38],

$$F_f = f_D(F_N + F_M), \tag{1}$$

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

We also used the generalized version of the Amonton–Coulomb law, which transmission spectra changes in friction modes [34–36, 39, 40],

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

$$\begin{aligned} f_A = \frac{F_f}{F_N} = f_D\left(1 + \frac{F_M}{F_N}\right) \\ + \frac{\Delta f}{rF_N}\ln(1 + \exp(r(F_N - F_{cr}))), \end{aligned} \tag{3}$$

$$F_f = f_D(F_N - F_{cr}) + F_{fM}, \tag{4}$$

where Δf is the increment of the coefficient of friction when the frictional interaction mode changes, r is the sharpness parameter of the transition from one friction mode to another when critical normal force F_{cr} is reached, F_{cr} is the critical normal force, f_A is the Amonton coefficient of friction, and $F_{fM} = f_D F_M$ is the molecular component of the friction force.

RESULTS AND DISCUSSION

The dependences of the average friction force and the friction coefficient on the normal force during sliding friction of R6M5 steel on grade 45 steel in the medium of modified Litol-24 grease are shown in Fig. 1, and Fig. 2 shows these data in comparison with the results obtained for the friction conditions in the medium of Litol-24 grease without additives.

Under the friction conditions in the medium of Litol-24 grease without additives, the $F_f(F_N)$ dependence consists of two linear sections (see Fig. 2), each of which corresponds to a linear version of the Amonton–Coulomb law. In the normal force F_N range from 0 to 390 N, it is described by the equation [4, 34–36]

$$F_f = 0.12(F_N + 2.5); \tag{5}$$

in the F_N range from 390 to 800 N, by the equation

$$F_f = 0.46(F_N - 390) + 47.1. \tag{6}$$

The molecular component of the friction force F_{fM} in these ranges is ≈0 and 47.1 N, respectively. In the second case, friction processes are more intense.

In the case of using the modified Litol-24 grease, the dependences of the average friction force F_f and the differential coefficient of friction on the normal

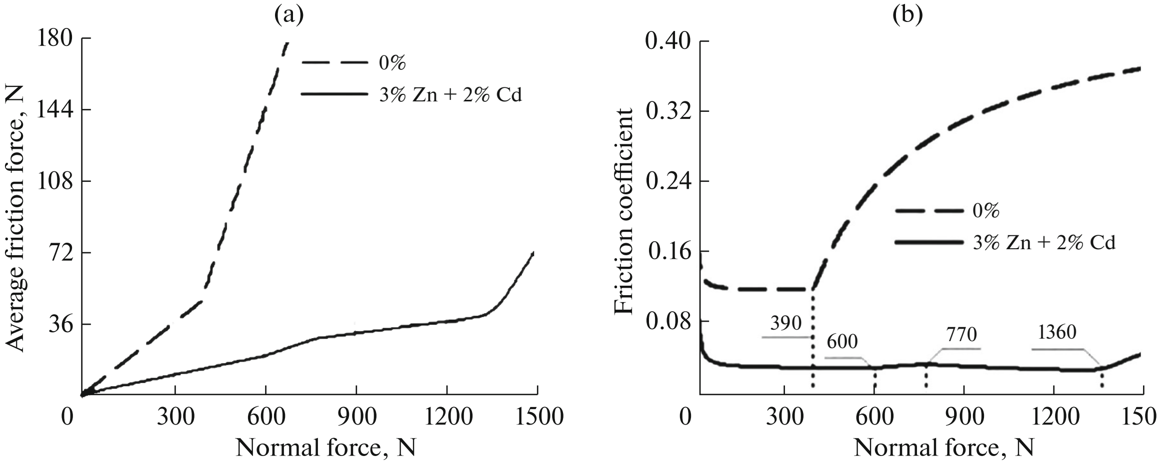

Fig. 2. (a) Average friction force F_f and (b) Amonton friction coefficient f_A vs. the normal force during sliding friction of R6M5 steel on grade 45 steel in pure and modified Litol-24 grease.

force can be described by the following equations (see Fig. 1):

$$F_f(F_N) = 0.032F_N + 0.4 + \left(\frac{0.02}{0.5}\right) \times \ln(1 + \exp(0.5(F_N - 600))) - \left(\frac{0.032}{0.5}\right)\ln(1 + \exp(0.5(F_N - 770))) + \left(\frac{0.22}{0.05}\right)\ln(1 + \exp(0.05(F_N - 1360))), \quad (7)$$

$$f_D = \frac{df_f}{dF_N} = 0.032 + \frac{0.02}{1 + \exp(-0.5(F_N - 600))} - \frac{0.032}{1 + \exp(-0.5(F_N - 770))} + \frac{0.22}{1 + \exp(-0.05(F_N - 1360))}. \quad (8)$$

According to Eq. (3), the normal force dependence of the Amonton coefficient of friction has the form

$$f_A = 0.032 + \frac{0.4}{F_N} + \left(\frac{0.02}{0.5F_N}\right) \times \ln(1 + \exp(0.5(F_N - 600))) - \left(\frac{0.032}{0.5F_N}\right)\ln(1 + \exp(0.5(F_N - 770))) + \left(\frac{0.22}{0.05F_N}\right)\ln(1 + \exp(0.05(F_N - 1360))). \quad (9)$$

In contrast to the $F_f(F_N)$ dependence for friction under the unmodified lubrication conditions, the $F_f(F_N)$ dependence for friction under the lubrication conditions with zinc and cadmium powder additives has four sections, each of which agrees with a linear version of the Amonton–Coulomb law (Eq. (1)). In the range $F_N = 0$–600 N, the dependence is described by the equation

$$F_f = 0.032(F_N + 12.5), \quad (10)$$

in the range $F_N = 600$–770 N, by the equation

$$F_f = 0.052(F_N - 600) + 19.6; \quad (11)$$

in the range $F_N = 770$–1360 N,

$$F_f = 0.02(F_N - 700) + 28.44; \quad (12)$$

at $F_N > 1360$ N,

$$F_f = 0.24(F_N - 1360) + 40.24. \quad (13)$$

As for the case of lubrication without additives, the inflection points of the linear dependences correspond to changes in the frictional interaction mode. The slope of the second section is higher than those of the first and third ones, which indicates more intensive friction processes in them. These processes proceed at the maximum intensity at F_N corresponding to the fourth section with the highest slope (see Figs. 1a, 2a).

As follows from a comparison of Eqs. (10)–(13) and (4), the molecular component of the friction force in the first section is $F_{fM} \approx 0$ N (as in the case of additive-free grease); in the second section, it is 19.6 N; in the third, 28.44 N; and in the fourth, 40.24 N.

According to the results obtained, the Litol-24 grease with zinc and cadmium powder additives provides the best tribotechnical characteristics for sliding friction of R6M5 steel on grade 45 steel over almost the entire normal force F_N range (from 0 to 1400 N): the average friction force F_f decreases by about 5 times, and the Amonton coefficient of friction, by 4–9 times. When the load increases (especially at $F_N > 390$ N), the antifriction effect of the additives increases.

The experimentally obtained dependences of the Amonton friction coefficient f_A on the normal force F_N (see Fig. 2b) for the modified and unmodified lubricants correspond to the generalized Kostetskii scheme of the normal pressure dependence of the Amonton friction coefficient [41]. This fact is confirmed by Eq. (3) proposed in [34–36, 40], which analytically describes the fundamental dependence of Amonton friction coefficient f_A on normal force F_N (pressure).

The generalized scheme has three characteristic sections. For both lubricants under study, run-in section I is located at low loads (pressures) $F_N = 0–50$ N and corresponds to the adaptability of the friction surfaces. The run-in process is approximately the same in the case of friction under the conditions of Litol-24 lubricant both without and with additives. In this section, we have $F_{fM} \approx 0$ N, which is due to rough friction surfaces and the small actual contact area in the tribounit.

Stationary section II corresponds to the medium pressure range and the normal mode of operation of the friction unit under oxidative wear conditions. The coefficient of friction in this section is stable and can be characterized by an average value. The permissible (minimum) wear is achieved due to the formation of strong secondary structures on the friction surfaces. In the case of using the modified lubricant, this section is larger and corresponds to $F_N = 50–1360$ N; when Litol-24 without additives is used, the friction process is stationary only in the load range $F_N = 50–390$ N. This finding indicates that the addition of zinc and cadmium powders to Litol-24 increases the bearing capacity of the lubricating layer.

The increase in the stationary section during friction under the conditions of the modified Litol-24 grease is also associated with the appearance of two additional sections in the $F_f(F_N)$ dependence corresponding to loads $F_N = 600–770$ N and $F_N = 770–1360$ N, at which the friction process proceeds less intensely and the ratio of friction forces F_N to F_M in the formation of sliding friction force (according to Eq. (1)) shifts toward the molecular component (with the introduction of additives, F_{fM} increases from 0 to 40.24 N). This fact indicates that, at $F_N = 600–1360$ N, zinc and cadmium particles promote more intensive smoothing of the rubbing surfaces and an increase in the contact area.

Damage section III is located in the range of heavy loads and corresponds to intense wear. When friction occurs under the modified lubrication conditions, the length of this section is noticeably smaller as compared to friction using Litol-24 lubricant without additives due to a shift to the range of high pressures (from $F_N >$ 390 N to $F_N >$ 1360 N), and it is less pronounced. The coefficient of friction in this section for the lubricant with zinc and cadmium powder additives is ~6 times lower, and it increases less intensely than in the case of Litol-24 without additives. This fact is caused by the formation of an antifriction layer with a lower shear strength on the friction surfaces.

CONCLUSIONS

(1) The composite Litol-24 grease containing 3 wt % zinc powder and 2 wt % cadmium powder improves the sliding friction characteristics in the R6M5 steel–45 steel pair in the load range from 50 to 1400 N as compared to Litol-24 grease without additives: in particular, the average friction force decreases by about 5 times, and the Amonton coefficient of friction decreases by 4–9 times; the best tribotechnical characteristics were achieved at a load of 390–1335 N.

(2) The dependence of the friction force on the normal force (load) in both cases has a piecewise linear form; however, this dependence consists of four sections in the case of sliding friction under the modified Litol-24 grease conditions and of two sections in the case of Litol-24 grease without additives. In each of these sections, a simple linear version of the Amonton–Coulomb law is obeyed. The generalized version of the Amonton–Coulomb law, which takes into account a change in the frictional interaction conditions, is obeyed in both cases.

(3) The stationary friction mode for the modified grease is longer: the addition of zinc and cadmium powders shifts the stationary section of the dependence of the Amonton coefficient of friction f_A on the normal force F_N to high loads, from 390 N (in the case of grease without additives) to 1360 N, due to the increased bearing capacity of the lubricating layer and a less intensive friction process. In the load range $F_N = 600–1360$ N, zinc and cadmium particles provide the most intense smoothing of the rubbing surfaces and increase the contact area.

(4) The damage section length in the case of the modified grease is noticeably smaller (at the chosen loads it is shifted from $F_N >$ 390 to $F_N >$ 1360 N), and it is less pronounced due to the formation of an antifriction layer with a low shear strength on the friction surfaces.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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