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Correlation between sliding bearing wear rate and material characteristics of friction surfaces in heavily loaded construction and road machinery

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Abstract

Based on an investigation of how entropy generation depends on material and tribological characteristics, it was found that the wear rate of a sliding bearing operating under elastic and elastoplastic contact conditions exhibits a nonmonotonic relationship with the surface dislocation density. Specifically, at relatively low dislocation densities, wear intensifies as this parameter increases, whereas in the high-density regime, further growth leads to a reduction in wear. A mathematical model describing entropy generation arising from the interaction between lubricant molecular dipoles and dipoles induced by fluctuations in surface dislocation density has been derived. The results demonstrate that the component of wear associated with this mechanism of entropy production decreases as the dipole moment of the lubricant molecules increases.

An additional analysis focusing on the influence of material parameters on entropy generation shows that bearing wear intensity rises with increasing surface dislocation density. An analytical expression for entropy production due to fluctuations in surface dislocation density has been obtained.

It is also established that, for the crankshaft sliding bearing of the DZk-250 motor grader operating under elastoplastic contact conditions, the wear intensity follows a similar trend: it increases with growing surface dislocation density in the low-value range and decreases when this parameter reaches higher values. Furthermore, an equation describing entropy generation during the interaction between lubricant molecular dipoles and dipoles associated with dislocation density fluctuations has been formulated.

Key words: sliding bearing, entropy, dislocation, oil, contact, wear intensity

Introduction

It is known that friction is a dissipative process that causes destruction and structural changes in the layers of rubbing bodies. The study of these processes is complicated by the lack of information about the physical and chemical properties of the surface layers, which are directly exposed to high deformation rates, significant temperature gradients, and force effects, so creating an adequate model of friction and wear is a challenging task. Studying friction and wear processes for specific systems operating under varying mechanical and thermal conditions is even more difficult.

Let us consider a plain bearing installed in the engine of a motor grader DZk-250 as such a system.

Literature review

In [1], it is shown that the value of the wear intensity of a sliding bearing in elastic and elastoplastic contact is determined by the expression

$$I = C_1 \cdot \alpha_{\Gamma e} \cdot p_a \cdot \tau_0^{\frac{t'}{2}} \cdot \theta^{1-\frac{t'}{2}} \cdot \left(\frac{K' \cdot f}{\sigma_0'} \right), \quad (1)$$

where $C_1 = 0{,}1216^{\frac{2t'}{5}} 2{,}6^{\frac{5}{5}-t'}$ p_a – nominal pressure; τ_0 – shear resistance; $\theta = \frac{1-\mu^2}{E}$ – Kirchhoff elastic constant; μ – Poisson's ratio; K' – coefficient close to three; f – friction coefficient; t' – friction fatigue curve indicator; σ_0' – fatigue fracture stress; $\alpha_{\Gamma e}$ – hysteresis loss coefficient.

The latter value is determined by the ratio of energy loss (dissipation) per unit volume per cycle (period) ΔW_σ to the maximum elastic energy density of the system [2].

$$\alpha_\Gamma = \frac{\Delta W_\sigma}{2\pi W_0}. \quad (2)$$

During plastic deformation, energy dissipation is described by the dissipative function [2]

$$D = \sigma_{ij}^D e_{ij}, \quad (3)$$

where σ_{ij}^D – dissipative stress tensor; e_{ij} – plastic strain rate tensor.

It is evident that the integral value of the dissipative function over a period τ is equal to the energy loss over this period, i.e.

$$\Delta W_\sigma = \int_0^\tau D dt. \quad (4)$$

The value of the maximum elastic energy density is [3]

$$W_0 = \frac{\sigma_0 \cdot e_0}{2}, \quad (5)$$

where σ_0 – maximum stress; e_0 – maximum relative strain.

Then, according to expressions (2), (4) and (5)

$$\alpha_\Gamma = \frac{\int_0^\tau D dt}{\pi \cdot e_0 \cdot \sigma_0}.- \quad (6)$$

Since the dissipative function D and entropy production p_s are related by the relation $D = p_s T$ (where T – тis the temperature), we obtain the expression of the hysteresis loss coefficient through entropy production:

$$\alpha_\Gamma = \frac{\int_0^\tau p_s \cdot T \cdot dt}{\pi \cdot e_0 \cdot \sigma_0}. -- \quad (7)$$

Purpose

The purpose of the study is to establish the relationship between the values that determine the entropy production in the surface layer of the crankshaft sliding bearing of the DZk-250 motor grader and its wear resistance.

Summary of the primary material

Let's consider the role of entropy production in the friction and wear processes of a sliding bearing.

As shown in [3], during the movement of dislocations, plastic deformations are created in the surface layer, which causes entropy production

$$p_{s1} = \frac{10 \cdot \gamma \cdot b^4 \cdot \sigma_\tau^2}{3 \cdot k \cdot T^2}, \tag{8}$$

where σ_τ – tangential stress; b – value of the Burgers vector; γ – surface density of dislocations; k – Boltzmann's constant.

According to [4], the second reason for entropy production in the friction layer is the attenuation of surface acoustic waves (Rayleigh waves) on the dislocations of the surface layer. As shown in [4], the Rayleigh wave flux density at a distance z from the surface is determined by the equation

$$J_{vz} = 2\pi \cdot \sigma_s \cdot \sigma_\tau \cdot u_R \cdot n_s \cdot \exp(-2\alpha \cdot z) \tag{9}$$

where α – absorption coefficient; U_R – Rayleigh wave velocity; σ_s – wave scattering cross-section; n_s – concentration of surface inhomogeneities.

In the resulting equation, the surface tangential stress σ_τ depends on the coordinate z, which corresponds to numerous experimental data summarised in [1] and can be represented as

$$\sigma_\tau = \sigma_{\tau 0} + \frac{d\sigma_\tau}{dz}\lambda_R \tag{10}$$

where $\sigma_{\tau 0}$ – is the tangential stress on the friction surface; λ_R – is the length of the Rayleigh wave, which is the interval of localisation of the wave field along the axis z.

Substituting (10) into (9) and taking into account that at large obstacles compared to the wavelength of the wave, the cross-section of the wave scattering σ_s is proportional to the fourth power of its frequency, we can represent (9) in the form

$$j_{Vz} = 2\pi\varsigma\omega^4 u_R n_s \sigma_{\tau 0}\lambda_R \left(\frac{1}{\lambda_R} + \frac{1}{\sigma_{\tau 0}}\frac{d\sigma_\tau}{dz}\right)\exp(-2\alpha z), \tag{11}$$

where ς – is the proportionality coefficient between σ_s and ω^4.

The expression shows that the energy flux density of a bulk wave arising during the scattering of surface Rayleigh waves is proportional to the gradient of the tangential stress value $\frac{d\sigma_\tau}{dz}$, with which it is natural to associate the thermodynamic force. Let us define the thermodynamic force corresponding to the volume wave flux density X_v, corresponding to the volume wave flux density, using the relation

$$X_{Vz} = \frac{1}{\sigma_{\tau 0}}\frac{d\sigma_\tau}{dz} \tag{12}$$

Then, taking into account that the entropy production is equal to the product of the flow density and the corresponding thermodynamic coordinate, we find the entropy production caused by the absorption of elastic waves by dislocations (taking into account the smallness of the second term in the brackets of Equation (11) compared to the first):

$$p_{s2} = 2\pi\varsigma\frac{\omega^4 u_R n_s}{T}\exp(-2\alpha z)\frac{d\sigma_\tau}{dz} \tag{13}$$

We will assume that the average value of entropy production in the wave field localization layer is close to its value at the point $z = \lambda_R / 2$, i.e.

$$\langle p_{s2} \rangle = 2\pi\varsigma\frac{\omega^4 u_R n_s}{T}\exp(-\alpha\lambda_R)\frac{d\sigma_\tau}{dz} \tag{14}$$

The absorption coefficient α in the latter equation is mainly due to dislocations and, according to the Granato-Lücke-Koehler dislocation string model [5], is

$$\alpha = \frac{d_0 \gamma \Delta_0 \eta^2}{2\pi C_\tau \left[\left(\frac{\omega_0^2 - \omega^2}{\omega} \right)^2 + d_0^2 \right]}. \tag{15}$$

where ω_0 – is the natural frequency of oscillations of the dislocation strings; Δ_0 – is a constant of the order of unity; d_0 – is the attenuation coefficient of the dislocation strings; G – is the shear modulus; C_τ – is the shear modulus; - is the propagation speed of transverse acoustic waves (transverse sound velocity); $\eta^2 \approx 2C_\tau^2$.

Substituting this expression into (14), taking into account the value of η^2, and the fact that the Rayleigh wave length $\lambda_R = \frac{2\pi u_R}{\omega}$ and velocity u_R are not much different from the longitudinal wave velocity, $C_t \left(u_R \approx 0{,}9 C_t \right)$, we obtain

$$\langle p_{s2} \rangle = 2\pi\varsigma \frac{\omega^4 u_R n_s}{T} \exp\left\{ -\frac{2 d_0 \gamma \Delta_0 C_\tau C_t}{\left[\left(\frac{\omega_0^2 - \omega^2}{\omega} \right) + d_0^2 \right] \omega} \right\} \frac{d\sigma_\tau}{dz} \tag{16}$$

Substituting expressions (8) and (16) for entropy production into equations (1) and (7) and taking into account that in the stationary mode, none of the values under the sign of the integral is time-dependent, and $\int_0^\tau dt = \frac{2\pi}{\omega}$, we obtain the following equation for the wear rate of a plain bearing under elastic contact:

$$I = \frac{2 C_1 p_\alpha \tau_0^{\frac{t'}{2}} \Theta^{1-\frac{t'}{2}}}{e_0 \sigma_0} \left(\frac{k' f}{\sigma'_0} \right)^{t'} \left[\frac{10 \gamma b^4 \sigma_\tau^2 C_t}{3 k T \omega} + 2\pi\varsigma \omega^3 u_R n_s \exp\left\{ -\frac{2 d_0 \gamma \Delta_0 C_\tau C_t}{\left[\left(\frac{\omega_0^2 - \omega^2}{\omega} \right)^2 + d_0^2 \right] \omega} \right\} \frac{d\sigma_\tau}{dz} \right] \tag{17}$$

The equation shows that under conditions of elastoplastic contact, the wear rate of a sliding bearing increases with an increase in the surface density of dislocations γ at low values and decreases in the region of large values γ. It should be borne in mind that the first term in equation (17) is due to the movement of dislocations, which is possible at their low density, which is possible only at the initial stages of running-in, while the steady-state mode is characterized by higher values of γ and the consolidation of dislocations, and therefore this term in the equation turns to zero.

However, elastic deformation is not the only and by no means the dominant factor that determines the wear process in a plain bearing. According to [6] and [7], the intensity of wear depends to a large extent on the interaction of lubricant molecules with the friction surface. The molecular dipoles that make up such lubricants and are located in the sliding bearing gap are exposed to the electric field created by dislocation fluctuations and interact with the friction surface using electrostatic image forces.

$$\langle p_{s3} \rangle = \sqrt{\frac{2}{3}} K^{3/2} \frac{n_p p_0^{7/6}}{T^{2/3} \ell_0^{6/5} \sqrt{m_p}} \left[\frac{p_0 + 7{,}7 e L^2 \sqrt{\gamma(\xi - 1)}}{1 + \frac{n_p p_0^2}{3 \varepsilon_0 k T}} \right]^{7/6} \tag{18}$$

Within the framework of the model of interaction of molecular dipoles with fluctuating dislocation moments, the physical mechanism of the anti-wear effect of lubricants and additives is the adsorption of lubricant molecules by the surface of the friction unit and blocking of dislocation nuclei by lubricant molecules, which leads to a decrease in the electric fields they create, at least to the quadrupole approximation and a reduction in the interaction between friction surfaces. Based on the analysis of the data presented in [6] and [7], the following expression can be obtained for the average value of entropy production caused by the interaction of molecular dipoles with dislocations in the volume of the friction surface layer:

Now let us determine the total entropy production in the surface friction layer containing the deformed layer and the adsorbed layer by summing the terms p_{s1} ,$\langle p_{s2}\rangle$,$\langle p_{s3}\rangle$, defined by equations (8), (14), and (18), and taking into account the small weight of the term p_{s1} at large values of γ

$$p_s = 2\pi\varsigma\frac{\omega^4 u_R n_s}{T}\exp\left\{-\frac{2d_0\gamma\Delta_0 C_\tau C_t}{\left[\left(\frac{\omega_0^2-\omega^2}{\omega}\right)^2+d_0^2\right]}\right\}\frac{d\sigma_\tau}{dz}+\frac{n_p}{T^{2/3}\sqrt{m_p}}\left[\frac{p_0+7,7eL^2\sqrt{\gamma(\xi-1)}}{1+\frac{n_p p_0^2}{3\varepsilon_0 kT}}\right]^{7/6} \quad (19)$$

In [8], it was shown that entropy production p_s is related to the specific friction force σ_{fr} by the ratio

$$p_s = \frac{\sigma_{fr}u}{hT} \quad (20)$$

where u – relative speed of movement of the tribological surfaces; h – thickness of the surface friction layer.

Although there is no unambiguous relationship between the friction force and the wear rate, a correlation was established in [9], which, taking into account Equation (20), can be used to obtain the following equation for the wear rate:

$$I = n_s R_\delta\sqrt{\Delta A_\tau}\left[I+\left[\begin{gathered}2\pi\varsigma\frac{\omega^4 C_1 n_s}{T}\exp\left\{-\frac{2d_0\gamma\Delta_0 C_\tau C_t}{\left[\left(\frac{\omega_0^2-\omega^2}{\omega}\right)^2+d_0^2\right]\omega}\right\}\frac{d\sigma_\tau}{dz}+\\ +\frac{n_p}{T^{2/3}\sqrt{m_p}}\left[\frac{7,7eL^2\sqrt{\gamma(\xi-1)}}{1+\frac{n_p p_0^2}{3\varepsilon kT}}\right]^{7/6}\end{gathered}\right]\frac{2\pi h}{\langle\sigma_\tau\rangle\Lambda\omega}-\frac{\sigma_R}{\langle\sigma_\tau\rangle}\right], \quad (21)$$

where n_s – is the surface density of contact spots; R_δ – is the average profile deviation; ΔA_r – is the area of a single contact; σ_R – is the real tensile strength; $\langle\sigma_\tau\rangle$ – is the average value of tangential stresses; m_p – is the mass of the molecular dipole.

Let us analyze the results obtained. First of all, it should be noted that the conclusions drawn from the analysis of the above models are fully relevant to the operating conditions of sliding bearings, i.e., they relate to the transitional between hydrodynamic and boundary friction regimes, when the thickness of the lubricating layer is large enough to allow for the movement of molecular dipoles of the lubricant in it. As can be seen from Equation (21), the wear rate depends most strongly on the surface concentration of material inhomogeneities whose dimensions exceed the Rayleigh wavelength (they do not include dislocations whose line lengths are usually less than the wavelength), the area of contact spots, and the surface density of dislocations. The effect of the dislocation density on the wear rate is manifested in a decrease in the wear rate with increasing dislocation density, since the exponential decline is much greater than the increase according to the law of $\gamma^{7/12}$. A similar dependence is observed in the wear model described by equation (18). The physical reason for this increase is associated with crystal hardening and increasing dislocation density. The dependence of the wear intensity on the tangential stress gradient σ_τ corresponds to the gradient rule of I.V. Kragelsky [1], according to which the condition must be met in the tribunal $grad \quad \sigma_\tau > 0$. This condition follows from equation (16), which is part of the structure of equation (21), as a consequence of the non-negative value of entropy production. Equation (21) implies a decrease in the wear intensity with an increase in the dipole moment of the lubricant molecules, which is inherently associated with blocking fluctuating dislocation dipoles by molecular dipoles.

Conclusions

1. Entropy production in friction contact is caused by the movement of dislocations (at their relatively small concentration of the order of $10^{14}-10^{15}м^{-2}$) and the attenuation of elastic waves on dislocations, the latter mechanism playing a more significant role in the steady-state friction regime. The non-negativity of entropy

production caused by the latter factor implies the necessity of a positive tangential stress gradient in the friction layer, which coincides with the well-known ‘gradient rule’ of I.V. Kragelsky.

2. Based on the analysis of the dependence of entropy production on material and tribotechnical parameters, it was found that the intensity of sliding bearing wear in elastic and elastic-plastic contact increases with the increase in the surface density of dislocations γ at low values (of the order of $10^{14} - 10^{15} м^{-2}$) and decreases with an increase γ in the region of large values of this value.

3. The equation for the entropy production in the process of interaction of molecular dipoles of the lubricant with dipoles caused by fluctuations in the surface density of dislocations is obtained. It is shown that the wear intensity caused by this component of entropy production decreases with an increase in the dipole moment of the lubricant molecules.

Further studies of the wear intensity of sliding bearings are advisable to determine other entropy production components that affect the friction and wear processes of crankshaft sliding bearings of a motor grader DZk-250.

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Щукін О.В., Орел О.В., Холодов А.П., Кравець А.М., Федоряченко С.О. Взаємозв'язок між інтенсивністю зношування підшипника ковзання та матеріальними характеристиками поверхонь тертя у важконавантажених механізмах будівельних і дорожніх машин.

Запропоновано рівняння для опису процесу утворення ентропії під час взаємодії молекулярних диполів мастильного матеріалу з диполями, викликаними флуктуаціями поверхневої густини дислокацій. Встановлено, що збільшення дипольного моменту молекул мастила сприяє зниженню інтенсивності зношування, пов'язаної з цією складовою ентропійного виробництва.

Досліджено, що інтенсивність зношування підшипника ковзання колінчастого валу автогрейдера ДЗк-250 у режимі пружно-пластичного контакту залежить від поверхневої густини дислокацій: вона зростає за низьких значень густини та зменшується у разі її високих значень.

Ключові слова: підшипник ковзання, ентропія, дислокація, мастило, контакт, інтенсивність зношування