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NON-EQUILIBRIUM THERMODYNAMICS WITH THERMAL AND FLUCTUATIONS OF THE VALUES OF STABILITY OF MATERIALS OF PARAMETERS OF FRICTION PAIRS OF BRAKE

Theoretical and experimental studies of the thermal stability of materials and fluctuations in the friction pair parameters of lifting and transport equipment brakes have revealed the following. The working layers of the lining and the metal friction element are located at different charge poles, but their roles are different: the former act as charge accumulators and undergo profound tribokinetic changes, while the latter act as entropic energy accumulators, i.e., as a battery. Stressful conditions for entropic energy flows include steady-state and thermal stabilization temperatures, as well as the destruction of the surface layers of friction lining materials. Entropy changes related to fluctuations in the friction pair parameters of operating brake devices. Based on the calculated dependence obtained, 3D graphical patterns were constructed to determine the linear wear of the lining for the values of the impulse normal forces, friction path, lining working area, and the hardness of its materials.

Key words nonequilibrium thermodynamics, braking device, friction pairs, thermal stability, entropy, fluctuation of parameter values.

Introduction. A significant drawback of small and large friction units in brake systems is their high energy load, which causes a catastrophic change in the dynamic friction coefficient and, consequently, a drop in braking torque. This circumstance impacts the operational safety of lifting and transport equipment. One way to reduce the energy load on large friction pairs is by using forced nanofluid cooling. The stability of the brake friction pair operating parameters is affected by the thermal stability of the materials and the fluctuations in the brake friction pair parameters.

Analysis of literary sources and the state of the problem. In the work [1] attention is paid to the selection and comprehensive study of the tribological efficiency of clutches of samples and parts of automobiles during friction and wear, made of composite alloys based on copper and lead. The work [2] is devoted to the mechanisms of internal and external friction of mating parts of machines and their influence on wear processes, as well as the development on this basis of methods for strengthening the working surfaces of parts and the implementation of self-organization processes and states. Based on the results of research by domestic and foreign scientists, the work [3] presents the patterns of wear capacity of the surface layers of materials of friction pairs. And in works [4] and [5] the stress-strain state in the mating parts of machines is considered. In works [6] and [7] the physical-mechanical and physical-technical processes that occur in materials during the operation of machine parts in various working environments are considered. The work [8] is devoted to a set of measures for increasing the tribological reliability of heavily loaded automotive tribo-clutches. However, no study has established a relationship between thermal stability and fluctuations in parameter values with the entropy of friction pairs in brake assemblies.

The aim of this study is to demonstrate the influence of thermal stability of materials and fluctuations in the operating parameters of friction pairs in brake assemblies.

Thermal stability of surface layers of materials of metal friction elements. During the electrothermomechanical frictional interaction of friction pairs in brake assemblies, heat accumulation Q_1 and heat release Q_2 into the environment occur, which depend on the thermal conductivity coefficient of the metal element λ and the external ambient temperature t_e.

The ratio of Q_1 to the surface temperature t_S is the entropy of the friction coupling. Stress conditions for entropy include steady-state and thermal stabilization temperatures, as well as the destruction of the surface layers of friction lining materials.

The change in entropy consists of two components:

$$dH = dH_1 + dH_2 , \tag{1}$$

where dH_1 is the entropy energy exchange with the environment; dH_2 is the entropy energy generated in the friction pairs and accumulated in the metal friction elements. The change in entropy energy depends on the braking time of the lifting and transport equipment. According to the second law of thermodynamics, entropy energy is never negative.

$$dH \geq 0 \tag{2}$$

The entropy energy can be quasi-equal to zero only if the tribocoupling enters the zone of steady-state surface temperature or the thermal stabilization state of metal friction elements.

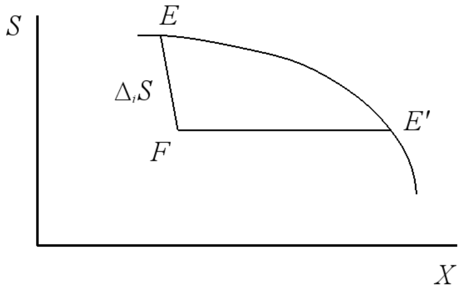

Fig. 1. Change in entropy ΔS associated with fluctuations in the values of the parameters of the operating friction pairs of the friction pairs of the braking devices.

Entropy S is represented as a function of the thermodynamic variable X. The initial equilibrium state is denoted by E, when the amount of heat generated in the friction pair interface is equal to the amount of heat released into the environment. A steady-state temperature is reached at the interface for a short period of time. A fluctuation that results in a decrease in entropy moves the tribosystem to point F. The entropy change ΔS associated with the fluctuation is calculated from the entropy production $\Delta_i S$ during the relaxation of the system back to the steady state. In the case of the classical formalism, in which $d_i S$ is not used, the entropy change is calculated by identifying an equilibrium state E′ with the same entropy as state F and then reversibly moving along the equilibrium trajectory $E'E$.

Research has shown that the generated entropy energy currents in friction pairs of small and large brake devices significantly affect the linear wear of the friction lining.

The linear wear of the working surface of the friction lining in a friction pair was determined by a dependence of the type:

$$I_h = \frac{K_u S_f N}{HB_2 A}, \tag{3}$$

where K_U is the proportionality coefficient, $K_U = 0.232$; S_f is the friction path; N is the impulse normal force; HB_2 is the hardness of the lining material;

A is the working surface area of the friction lining.

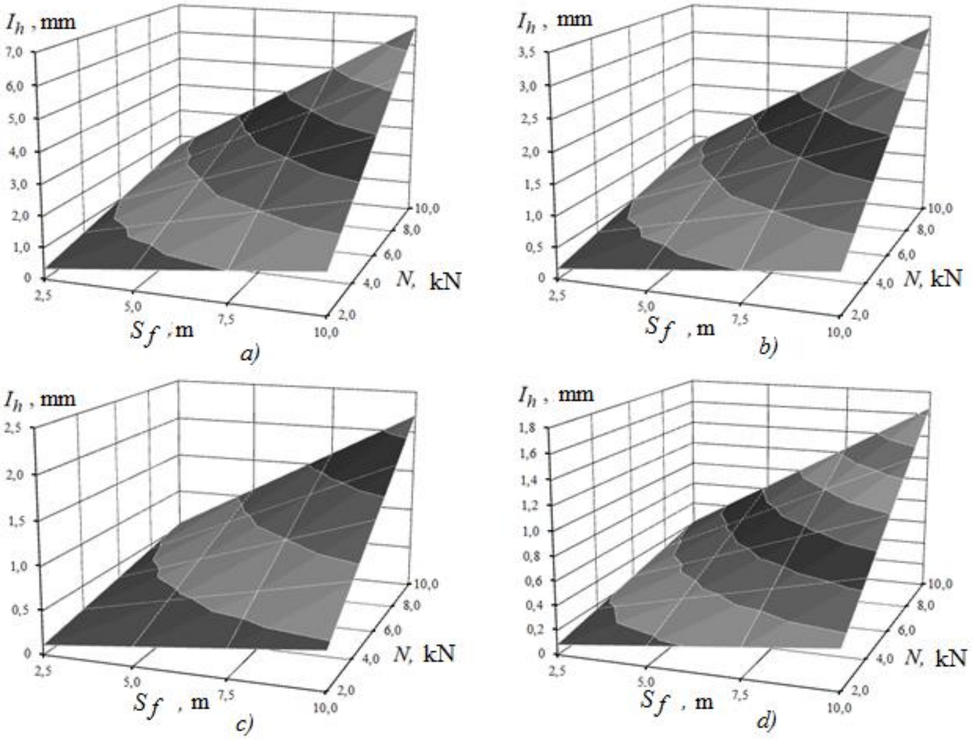

Fig. 2. Dependence of the linear wear (I_h) of the friction lining working surface with an area of its working surface $A = 0.07$ m^2 on the friction path (S_f) and the impulse normal forces (N) in the brake friction pair for different values of lining material hardness: a – $HB_2 = 50$ MPa; b – $HB_2 = 1000$ MPa; c – $HB_2 = 150$ MPa; d – $HB_2 = 200$ MPa

In [9 - 12], the thermal stabilization state of a metal friction element (pulley or drum rim) was investigated based on the conditions of its occurrence and prevention. In this case, the metastable state of the surface of friction linings, located at a temperature higher than the permissible value for their materials, as well as the thermal interaction of the metal friction element with a reinforcing projection or flange, were considered. In this case, the condition of thermal equilibrium was not taken into account, which, as is known, requires, along with constancy of temperature, also the constancy of the sum $\mu + U$ along the medium, where μ is the chemical potential of the particles, and U is their energy in an external electric field. In this case, we are talking about equilibrium with respect to electrons, so that μ must be understood as their chemical potential, and $U = -e\varphi$, where φ is the potential of the electric field. Accordingly, the electric current

j_1 and the dissipative energy flow q turn simultaneously into zero only under the conditions ϑ_1 = const, $\mu - e\varphi$ = const, that is, when $\nabla\vartheta_1 = 0,\ \nabla\mu + eE = 0$.

The expression for j_1 and q' is written in the form of the following relations that satisfy the specified condition

$$E + \frac{1}{e}\nabla\mu = \frac{1}{\sigma} j_1 + \alpha\nabla\vartheta_1, \qquad (4)$$

$$q' = q - \left(\varphi - \frac{\mu}{e}\right) j_1 = \alpha\vartheta j_1 - \chi\nabla\vartheta_1, \qquad (5)$$

where σ is the electrical conductivity of the medium; χ is the thermal conductivity; α is the thermoelectric coefficient; the relationship between the coefficients in (4) and j_1 and (5) is a consequence of Onsager's principle [9-10]. The quantity $(\varphi - \mu/e)\, j_1$, minus the total energy flux, represents the convective energy flux density. The latter must be taken into account when assessing the thermal stabilization state of a metal friction element in braking devices.

The phenomenon of fluctuations in the mating surfaces of brake friction pairs. When electrons and ions are exchanged between the working surfaces of metal-polymer friction pairs in brake assemblies, their quantity (per unit volume) deviates from the average value, causing fluctuations in the properties of the tribosystem. Due to the chaotic motion of particles, this variability in the number of molecules in equal parts of the total volume of the tribosystem is constantly changing. Therefore, all static quantities, such as density, the concentration of liquid islands formed on the lining surface after the resinous binders burn out, pulsed specific loads, above-permissible surface-volume temperatures, etc., are subject to spontaneous, random deviations from a certain average value, which is typically used. These deviations are called fluctuations and explain such variable operating parameters of brake assemblies: friction force, pulsed normal force, surface-volume temperature, dynamic friction coefficient, etc.

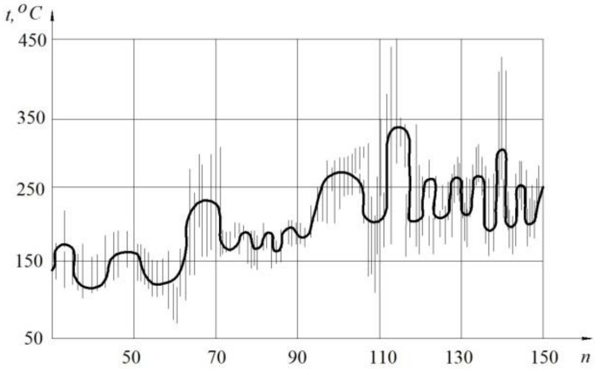

Fig. 3. Patterns of change in surface-volume temperatures of metal-polymer friction pairs depending on the number of braking operations on a mountain route of a LAZ family bus under a fluctuation phenomenon

The practical significance of fluctuations is extremely significant. They determine the gradual nature of changes. Without them, processes such as the crystallization of the surface working layers of metal friction elements and their attainment of isothermal stabilization, among many others, would proceed completely differently.

Naturally, the value of fluctuations is especially large for tribosystems of negligible size with thermoelectric generators and thermoelectric refrigerators formed in them [12].

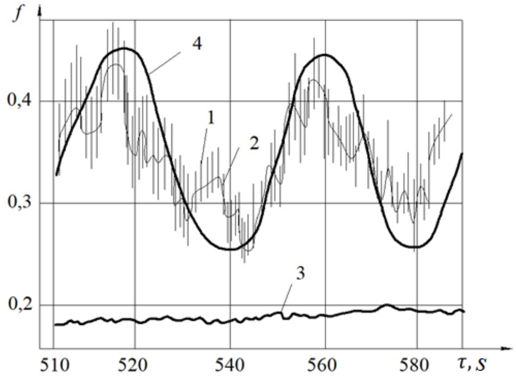

Fig. 4. Patterns of change in the static (3) and fluctuating (2) dynamic coefficient of friction and its harmonic expression (1)

Let's analyze the patterns of change in the surface-volume temperature (Fig. 3) and the dynamic and static friction coefficients (Fig. 4) of metal-polymer friction pairs due to frictional interaction and fluctuation phenomena:

- as the friction lining materials approach their permissible temperature, the physicochemical transformations that affect their surface layers lead to an increase in fluctuation phenomena;
- as the dynamic friction coefficient increases, fluctuations increase significantly due to the sharp change in the pulsed normal forces due to the local nature of their frictional interaction.

Fluctuations make it impossible to measure any quantity with a very high degree of accuracy. Therefore, to detect and measure each of the current families during electrothermomechanical friction in the interfaces of friction units, the current strength must be greater than the fluctuation.

Brownian motion is a classic example of fluctuation formation, i.e., the emergence of entropy-decreasing processes in equilibrium tribosystems. It arises because the sum of momenta from the impacts of air molecules washing over the microprotrusions of friction pairs on the surface of particles is not zero and at each moment chaotically changes in both magnitude and sign, causing particles to move upwards, contrary to gravity and in contradiction with the second law (in its non-static formulations, since Brownian motion occurs in a medium where isothermal equilibrium has already been established). Such contradictions between facts and theory disappear with a static interpretation of the second law of thermodynamics.

Since the number of particles in real tribosystems is very large, both the fluctuations themselves and the deviations they cause from the process's thermodynamically consistent course will be negligible. Therefore, for ordinary systems, the most probable direction of the process coincides with its actual direction. In other words, the event takes on the character of inevitability. Consequently, the cause lies in the number of particles in ordinary systems. Phenomena occurring at the interface between micro- and macrosystems (highly dispersed systems) are largely reversible.

However, for systems consisting of only a few particles, thermodynamic concepts, being static, lose their meaning. For example, one cannot speak of pulsed specific loads in a friction pair, or of the entropy of the surface and subsurface layers of a polymer overlay of a single molecule. For such "systems," the distinction between order and disorder, and, consequently, between work and heat, disappears. For this reason, the law of increasing entropy also loses its meaning. As the number of particles increases, i.e., the transition to ordinary systems, the "most probable" becomes "certain." In other words, for microsystems, the statistical nature of the second law comes to the fore, while for ordinary systems, it has a different formulation.

Discussion of results. Theoretical and experimental studies of the thermal stability of materials and fluctuations in the friction pair parameters of lifting and transport machine brakes have revealed the following.

- the working layers of the lining and the metal friction element are located at different charge poles, but their roles are different: the former are charge accumulators and undergo profound tribokinetic changes, while the latter are entropic energy accumulators, i.e., an accumulator.
- stressful situations for entropic energy flows include steady-state and thermal stabilization temperatures, as well as the destruction of the surface layers of friction lining materials.
- entropy changes related to fluctuations in the parameter values of operating brake friction pairs.
- based on the obtained calculated dependence, 3D graphical patterns were constructed to determine the linear wear of the lining for the parameters of pulsed normal forces, friction path, lining working area, and the hardness of its materials.

Conclusions. Thus, a relationship has been established between thermal stability and parameter fluctuations with the entropy of brake friction pairs.

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НЕРІВНОВАЖНА ТЕРМОДИНАМІКА ПРИ ТЕРМІЧНІЙ І ФЛУКТУАЦІЙ ЗНАЧЕНЬ СТІЙКОСТІ МАТЕРІАЛІВ ПАРАМЕТРІВ ПАР ТЕРТЯ ГАЛЬМ

Теоретичні та експериментальні дослідження термічної стійкості матеріалів та флуктуації значень параметрів пар тертя гальм підйомно-транспортних машин дозволили встановити таке. Робочі шари накладки та металевого фрикційного елемента знаходяться на різних зарядних полюсах, але їхня роль неоднакова: перші є накопичувачами зарядів і в них відбуваються глибокі трибокінетичні зміни, а другі є накопичувачами ентропійної енергії, тобто акумулятором. Стресовою ситуацією для потоків ентропійної енергії є термостабілізаційна температури, що встановилася і деструкція поверхневих шарів матеріалів фрикційних накладок. Зміна ентропії щодо флуктуацій значень параметрів експлуатованих пар тертя гальмівних пристроїв. На підставі отриманої розрахункової залежності визначення лінійного зносу накладки при значеннях параметрів імпульсних нормальних зусиль, шляху тертя, робочої площі накладки і твердості її матеріалів були побудовані графічні закономірності у форматі 3D.

Ключові слова: нерівноважна термодинаміка, гальмовий пристрій, пари тертя, термічна стійкість, ентропія, флуктуація значень параметрів.

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