Physical Methods for Evaluating the Load of Friction Pairs of Braking Devices (Part I)

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Abstract

Materials of the article apply to the physical methods for estimating the load of friction pairs of brake devices. Methods are expressed by principles influencing the physicochemical properties of materials of friction pairs and their internal and external parameters. Principles include causation, symmetry, reciprocity and equivalence, affinity, superposition (elementary and complex). The principles have been analyzed and it is shown as they extend to the energy fields of fric-tion pairs of brakes. Based on the action of the principles, the following pairs are distinguished: "mechano-thermal", "chemico-thermal" and "electro-magnetic". The materials of this article only pay attention to "mechano-thermal" energy field at electromechanical friction coupling of pairs of friction of brake devices.

Keywords: physical methods; braking devices; friction pair; metal-plate friction element; mechanical and thermal load.

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Əyləc qurğularının friksion cütlərindəki gərginliklərin qiymətləndirilməsinin fiziki metodları (I hissə)

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Annotasiya

Məqalədə əyləc qurğularının friksion cütlərindəki gərginliklərin qiymətləndirilməsinin fiziki metodlarına baxılıb. Metodlar sürtünmə cütü materiallarının fiziki-kimyəvi xüsusiyyətlərinə, onların daxili və xarici parametrlərinə təsir edən prinsiplərə əsaslanıb. Prinsiplərə səbəb-nəticə əlaqəsi, simmetriya, qarşılıqlılıq və ekvivalentlik, affinlik və superpozisiya (elementar və mürəkkəb) daxildir. Təhlil olunub göstərilmişdir ki, bu prinsiplər əyləclərin sürtünmə cütünün enerji sahələrini əhatə edir. Prinsiplərin təsirinə əsasən aşağıdakı cütlər ayırd edilir: "mexano-termik"; "kimyəvi-istilik" və "elektromaqnit". Məqalədə yalnız əyləc qurğularının sürtünmə cütünün elektromexaniki friksion əlaqəsi zamanı "mexano-termik" enerji sahəsinə baxılıb.

Açar sözlər: fiziki metod, əyləc qurğusu, sürtünmə cütü, metal plastin materialdan hazırlanmış friksion element, mexaniki və istilik gərginliyi.

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Физические методы оценки нагрузки фрикционных пар тормозных устройств (часть I)

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Аннотация

В статье рассматриваются физические методы оценки нагрузки фрикционных пар тормозных устройств. Методы основаны на принципах, влияющих на физико-химические свойства материалов пар трения и их внутренние и внешние параметры. Принципы включают причинно-следственную связь, симметрию, взаимность и эквивалентность, аффинность и суперпозицию (элементарную и сложную). Проанализировано и показано, что эти принципы распространяются на энергетические поля пар трения тормозов. На основании действия принципов выделяют следующие пары: «механотермические»; «химико-тепловой»; «электромагнитный». В статье рассматривается только «механотермическое» поле энергии при электромеханической фрикционной связи пар трения тормозных устройств.

Ключевые слова: физические методы, тормозные устройства, пара трения, фрикционный элемент из металлической пластины, механическая и тепловая нагрузка.

Introduction

The application of various general physical principles opens wide possibilities for calculation and analysis of the thermal mode of metal friction elements of disc-drum type and strip-block type of braking devices and becomes a qualitatively new method for solving thermal problems.

The material of the proposed articles is largely focused on the development and implementation of this method, which can be called the physical principle method or, in short, the principle method.

Among the principles that are used in the articles are the principles according to the figure 1. The principles of symmetry, equivalence, superposition (elementary and complex) have long been applied in thermodynamics and heat transfer, although unreasonably not enough. The principle of reciprocity was not used for thermal problems. In contrast, the work [1] paid attention to all principles in the case of a plate of a given thickness in which the temperature sources interact as well as a symmetrical arrangement.

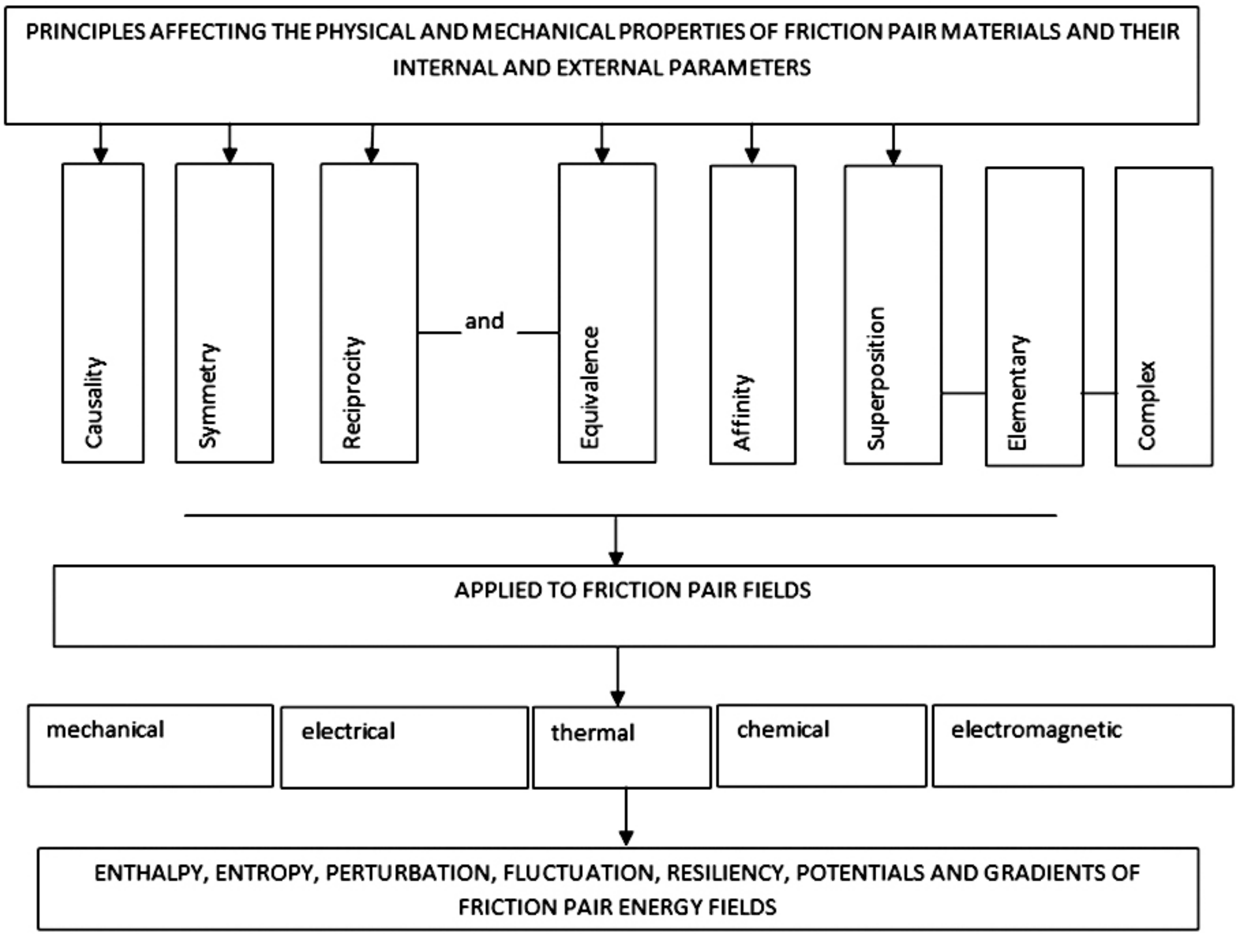


Figure 1. Principles, perturbations, potentials and gradients in metal polymer friction pair energy fields

The analysis of literary sources and the state of the problem. Brief reference to the principles of thermal problems. Causation is the mutual relationship between processes, phenomena and effects where one is the cause of the other. Symmetry is the proportionality of the parts of the product located on either side from the middle of the center.

Reciprocity applies to some heat conductivity problems; this means that if the heat source Is at point 1 causes a temperature change at point 2, Δt=f(τ), then if you move the source to point 2, at point 1, the same temperature change Δt will occur.

It should be emphasized that at reciprocal speeds the changes of temperatures are the same, but the gradients of the temperature are different, so it should be remembered that the transition to a mutual problem is not a transition to an equivalent problem - the temperature fields turn out to be different.

The importance of reciprocity in heat conductivity problems is known [1]. These include with the action of a heat source: in a semi-enclosed body or in an unlimited plate; in a plate covered with a layer of turbulized liquid, and in a plate with a layer of liquid and an adiabatic condition on one boundary; and in a boundary condition of type III on the other boundary. The equivalence, in relation to thermal problems, is that the replacement of any ambiguity condition does not affect the thermal regime of the body in question - all temperatures remain constant.

The principle of equivalence indicates the possibility of equivalent substitution of sources of heat and heat resistance, as well as therma-physical characteristics, geometric shape and body size. It should be reminded that there are two types of heat sources: It – sources of the given temperature and Is – sources of the given intensity of the heat flow. Sources of Is can be both external and internal. It sources can only be external. Therefore, there may be equivalent substitutes as follows:

- external sources of any type (I_t or I_s) are replaced by external sources of another type;
- external sources of type I_t and I_s are replaced by internal sources of type I_s;
- internal sources of type I_s are replaced by external sources of type I_t or I_s.

An equivalent replacement of internal sources with another type of internal source is not possible, as internal sources can only be of one type - I_s.

The substitutions can be complete or partial, but in all cases the principle of equivalence is preserved - the heat mode of the whole body «does not notice» changes of the conditions of unambiguousness.

All equivalent transitions (substitutions) are reversible. For example, if it is shown that it is possible to replace a source of type I_s with a source of It, then the possibility of a reverse transition is shown.

Affinity – a similarity in basic properties or in generality. For example: affinity to an electron, chemical affinity, electrochemical affinity.

Superposition - the resulting effect of several independent effects, is the sum of the effects caused by each effect individually.

The principle of superposition can be elementary and complex. The elementary principle of superposition states the following. If the superposition of the temperature fields in the system is considered, provided that the power of the heat source, the coefficients of the individual parts of the system and its coefficients of heat exchange are temperature-independent, as illustrated [2]. The latter focuses on the conditioned environment and its temperature, as well as on the system's own pointed overheating.

Thus, in this form, the methods of principles cannot be used in friction pairs of brakes and therefore need to be improved.

Problem statement

The use of physical principles for friction pairs of braking devices problem should be resolved and the friction interaction of their mechanical and thermal fields should be considered. The main issues of the article are evaluation of the load of friction pairs of braking devices; mechanical with heat load of the braking friction units. The objective of the work is to justify the use of physical methods for evaluating the load of friction pairs of braking devices.

Evaluation of the load of friction pairs of the braking devices. It is known that the load of the friction pairs of the strip-drum and disc-block type of brakes depends on many subjective and objective factors. For example, for the strip type brake of the drill winch, objective factors are drilling technology, climatic and physiological conditions; subjective factors are the quality of the production of the equipment, the qualification of the maintenance personnel, etc. For drum- and disc-block brakes of means of transport the objective factors are climatic and road conditions; subjective factors are the quality of the overall braking mechanism, drivers' qualification, vehicle driving techniques, etc. Understandably, it is practically impossible to take all these factors into account when mathematically describing the heating processes of the brake unit components.

Table. Classic list of boundary conditions

The type of the boundary condition		Dependancies
	I-st	Body surface temperature is known($t_п$)
	II-nd	External heat flux to body (q_v) is specified $-\lambda \frac{\partial t_n}{\partial x}\Big\vert_{x=+0} = q_v.$ (1)
	III-rd	Heat flux from the surrounding medium is directly proportional to the temperature difference between the surrounding and the surface of the body $-\lambda \frac{\partial t_n}{\partial x}\Big\vert_{x=+0} = \alpha(\vartheta - t_{x=+0}).$ (2)
	IV-th	The body is in contact with another body that has different therma-physical characteristics $t_{n1}\big\vert_{x=+0} = t_{n2}\big\vert_{x=-0}.$ (3)

For the complete analytical description of convective and radiative heat exchange of the surfaces of metallic friction elements of the brakes, it is necessary to set systems of equations and unambiguous conditions. Listed in the table four boundary conditions (classical) make up the conditions of one-digit, and the set of initial and boundary conditions is called boundary conditions.

Legend: λ, α - heat conductivity coefficients, heat output; q_v – specific heat flux; indices x=+0 and x=-0 - external and internal surfaces; $\partial t_n/\partial x$ – temperature gradient on body thickness; ϑ – heating temperature.

These initial conditions meet the classical list of boundary conditions

$$t(x, y, z, \theta) = f_3(x, y, z). \quad (4)$$

In general, λ, c, ρ, p, q, α can be functions of coordinates, temperature, and time. On a case-by-case basis, especially in mobile boundary problems where phase transformations occur, boundary conditions may be recorded in a slightly different form, but in principle boundary conditions I - IV types cover all possible cases.

In recent years there have been works in which the question of formalism of boundary conditions I-IV types covers all possible cases.

In recent years, there have been works that have raised the issue of formalism of boundary conditions of types I-IV, especially for non-stationary tasks. For example, in [3] it is shown that non-stationary heat transfer problems should generally be solved as conjugate, i.e. the heat transfer equations should be solved simultaneously for the medium surrounding the body. In [4] it is shown that when solving heat transfer problems, boundary conditions type II correspond better to the physical pattern of phenomena than conditions of type III. For non-stationary modes, the coefficients αq, αm are more fictitious than for stationary modes, where both αq, and αm are formally introduced. In principle, the problems of heat exchange with solids should be solved as related problems, but in some cases boundary conditions of type II and III are justified [5].

Note that non-linear tasks are those in which: λ, c, ρ - temperature function; α, q - temperature functions; ρ is the temperature function; the coordinates of the phase boundaries depend on the temperature (moving boundaries whose position is determined by temperature).

When evaluating the energy load of friction pairs of braking devices, it is necessary to know: the geometric parameters of the friction pairs and their shape; the thermal-physical characteristics of the materials; initial and boundary conditions; the maximum energy loading of the metal friction elements and the heat-exchange capacity thereof, which consists in the joint action of the conductive heat exchange with the radiative and conductive heat exchange from their surfaces, and the acceptable temperature for the polymeric lining materials.

These four conditions are called unambiguity conditions and the set of initial and boundary conditions are called boundary conditions.

The energy intensity of the working surfaces of the pulley rim and drum, as well as the treadmill of the disc friction (solid and self-ventilated) depends on the metal content of the discs. The smaller the latter is, the faster a metal friction element will warm up. The above-mentioned heat exchanges must also interact with the conductive type of heat exchange.

The metallic friction elements of the brakes enter the fixed and thermostatic zones. In the first case, the amount of heat generated by the friction pair is released into the environment. In the second case, the temperature gradient on the thickness of the metal friction element becomes minimal. In addition, the surface layer of the polymeric lining changes its aggregate state. The account of the above elements of the friction pair requires different initial conditions for the temperature zones, which results in variable unambiguity conditions.

Mechanical with heat load of brake friction units

The friction process is inherently dissipative and is characterized by the generation of electrical and thermal currents. Friction heating determines to a large extent the conditions for interaction of friction surface micro projections, the change of their area and the destruction thereof (value of the actual and contour area of the touch, maximum electrical and thermal currents, elastic deformation and its energy levels in the working layers of micro projections which in turn affect the area of actual contact; the values of elementary normal forces and friction forces per unit of actual contact area, etc.). Therefore, studies and tests of mechanical loading of metal-polymeric friction pairs make it possible to assess normal forces, friction forces, dynamic friction coefficient, braking torque developed by friction pairs and wear intensity of their working surfaces in a wide range of changes in the temperature of friction, assuming that they are impulsive in character, obeying wave field theory.

The laws of elasticity occurring during contact-impulse interaction of the micro projections of the surfaces of metal-polymeric friction pairs at small deformations thereof reflect the mutually unambiguous relationships between pulsed stress values and deformations. Under the action of dynamic loads, electrical and thermal currents, the surface layers of metal-polymeric friction pairs are subjected to plastic deformations.

It is known that mechanical energy is an ordered form of energy, while internal energy is disorderly. The deformations of micro projections when contacting surfaces of «metal-polymer» friction pair are represented on figure 2.

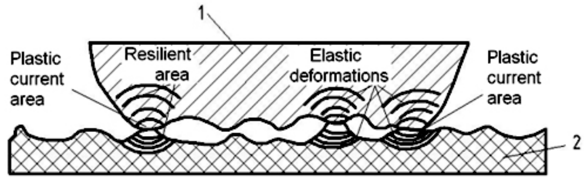


Figure 2. Deformation of micro- projections in contact with friction pair «metal (1) - polymer (2)»

The trajectories of the main tensioning and compressing swirling stresses in the pulley rim with uniform load distribution in the pair of friction «polymer-metal» are given in fig. 3.

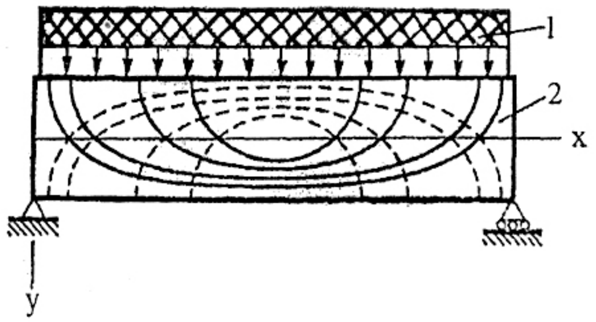


Figure 3. Trajectories of the main tensioning (-) and compressing (-) stresses in the pulley rim with uniform load distribution in the friction pair «polymer (1) - metal (2)»

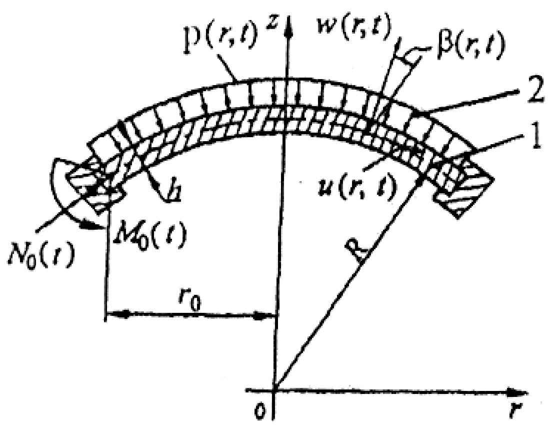


Figure 4. Pulse loading scheme of the friction pair «polymer (1) - metal (2)» in the strip-block type brake

Figure 4 and Figure 5 a, b. show the schemes of the impulse loading of the friction pair «polymer – metal» in the strip-block type brake and the regularity in external and internal parameters changes in its sector. The following legend are used: r - the polar coordinate of the point; h, R - the thickness of the shell and the radius of curvature of its median surface; t, T_{inv} - the time of reciprocal action: normal, dimensional; p, q - the surface loads in the meridian and normal directions; N_0, Q - effort: membrane, transverse; M_0 is a bending moment; u, w is the displacement of the median surface of the shell in the meridian and normal directions; β is the rotation angle of the normal to the median surface.

According to the first variant, the specific load impulse given by the formula $Q(t)=qo\cdot H(t)$, where $q_0=10^5$ Н/м^2, H(t) is the unit Hebryside function, affects the shell.

In the second variant, the shell is affected by the specific load impulse in the form of «steps» given by the formula $Q(t)=q_0[H(t)-H(t-\omega)]$, where ω is time of the specific load pulse.

Figures 5 a, b illustrate the systematized and unsystematic (but which can be reduced to systematized) sinusoidal curves generated by the impulse loading of the metal-polymeric friction pair of the brake.

The impulse application of the load to the micro projections of the surfaces of the friction of metal-polymeric pairs at the initial braking moment causes the generation of pulsed electrical currents.

The sinusoidal electric impulse and its characteristics are illustrated in figure 6. The following symbols are used: A' amplitude; t_H – pulse duration; t_{Ha} – pulse duration of $0.5.A'$. The electric impulse is characterized by the short-term deflection of the electric voltage or current force from some constant value.

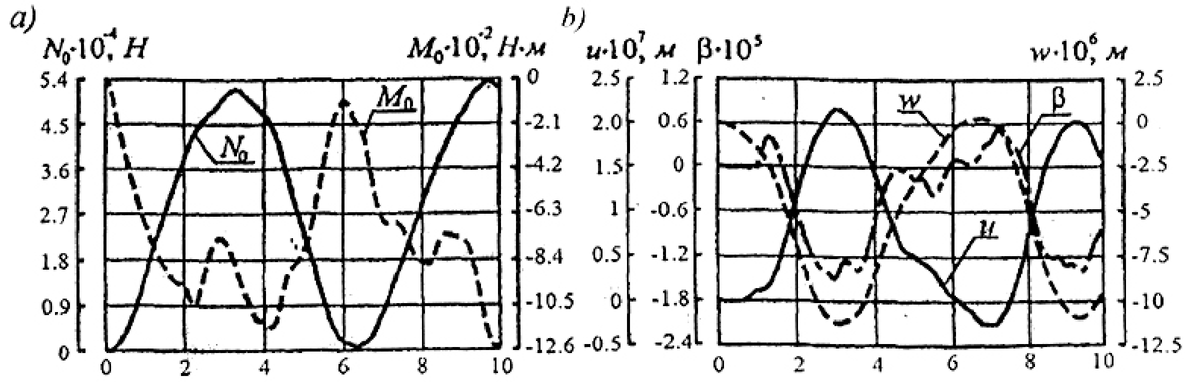


Figure 5 a, b. Regularity of change in the shell sector: a - membrane force (N_0) and bending moment (M_0) from the value of the dimensional time; b - shifting of the median surface in meridian (u) and normal (w) directions at the angle of rotation (β) normal to the median surface in the plane of the meridian from the dimensional time

The empirical dependence of current impulse determination on time is assigned to Figure 6 (where *e* is the base of the natural logarithm). The current impulse is expressed in amperseconds in the case of an random time current flow. It should be stated that the electric impulse and electromagnetic flat wave are described by the same law, the sinusoid.

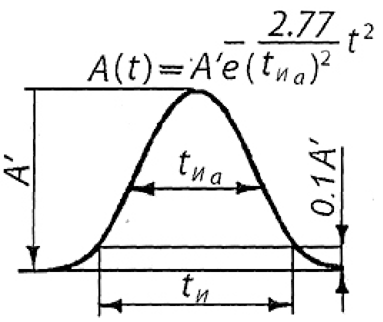


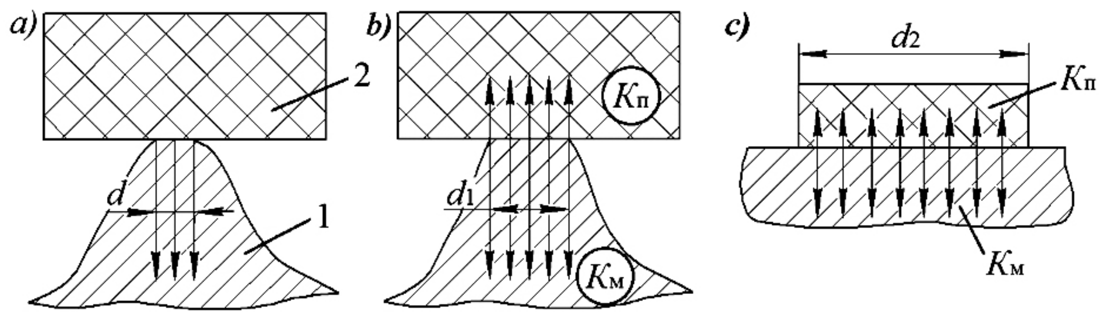
Figure 6. Sinusoidal electric pulse and its characteristics

The strong temperature oscillations in the initial friction period are related to the unburdening of electrical currents on the micro projections of the surfaces with the continuous attenuation thereof towards the end is also connected with the migration of «the hot spots», which rise on the friction surfaces as a result of contact discreteness. Judging by the wave frequency of temperature changes in the areas of thermocouples arranged at different points of the surface layer of the lining, the movement of «the hot spots» obeys some aperiodic regularity, due to the uneven distribution of normal forces on the surface of the friction contact, and as a consequence of the specific loads, as well as wear. Typical increase of temperature difference with increase of hardness of material of the surface layer of the lining is connected, obviously, with the change of sizes of the «hot spots» and more uneven distribution of them on the surfaces of friction micro projections.

Figures 7 a, b, show the proposed calculation models for estimating the characteristics of the interaction of the contact spots with different diameters of the «metal-polymer» friction pairs of the generation of electric and thermal currents.

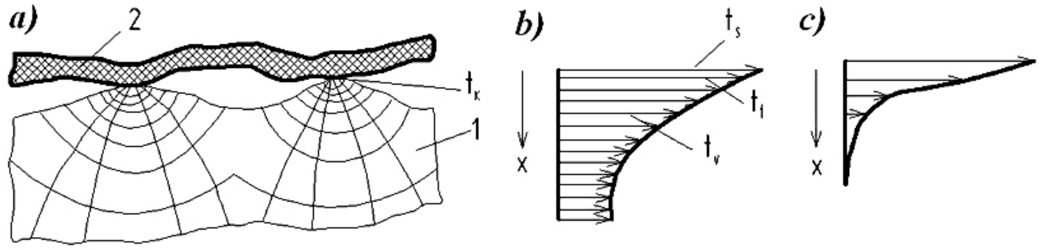
Figure 7 b, introduces legend $K_м$, $K_п$, which mean the coefficients of heat flux distribution respectively in the metal and polymer friction elements [6]. It should be noted that with the increase of the area and the contact spots of the micro-projections, the growth of charged particles on their surfaces is observed.

We analyze the heat-loading capacity of the surface and surface layers of the friction elements of metal- polymer pairs.

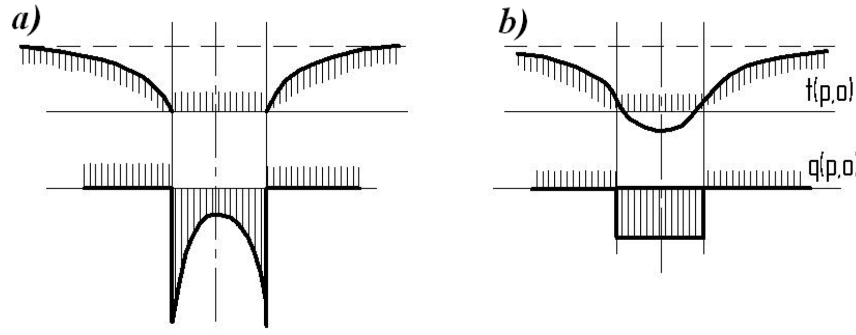


Figures 7 a, b, c In Calculation models for estimating the interaction characteristics of contact spots with different diameters (d, d_1, d_2) of the pair «metal (1) - polymer (2)» at the generation of: a - impulse electric currents; b, c - impulse temperature currents: flashes; surface

According to the classical theory [5, 6, 7] in close proximity to the contact points of the friction pair «metal (1) - polymer (2)» (Figure 8 a) separate semispherical isothermal surfaces are formed, fusing into a common surface at some depth. The arrangement of isothermal surfaces is characterized by the magnitude of the temperature gradient. In general, the temperature field in the metallic and polymeric friction elements related to the surface and subsurface layers, respectively, is presented in Figure 8 b, c.



Figures 8 a, b, In the temperature field of the surface layer of the metal (1) element (a) during friction and envelope changes in temperature in it (b) and in the surficial layer of the polymer (2) element (в): tf, tk, ts, tv – temperature: friction, occurring in the deformation zone of the microregions of the working surface; contact, formed at points of contact; surface, formed at macro-sectors of friction surfaces; bulk, occurring in the body of the friction element below the deformation zone.



Figures 9 a, b Temperature distribution (t) and heat flux (q) on the contact spot at: a – t=const; б – q=const

The latter shows the following temperatures in the interaction area: t_f – friction, occurring in the deformation zone of the microregions of the working surface; t_k – contact, occurring in the contact points; t_s – surface, occurs on the macro-regions of friction surfaces; t_v – bulk, occurs in the body of the friction element below the deformation zone.

Figures 9 a. b show the temperature distribution (t) and current heat (q) on the contact spot at: a - t = const ; b — q - const. However, such an ideal temperature (t) and heat current (q) on the contact spot in friction pairs is impossible due to the inversion of currents between the interacting zones.

In braking devices having a non-massive metallic friction element (vehicles, some tiering machines, etc.), until the friction linings have reached the permissible temperature, a counter-body performs the role of a thermoelectric generator (metal friction element) and thermoelectric refrigerator - surface layers of friction linings. When the temperature is exceeded, the picture is reversed. In the strip-block brake of the drill winch the metal friction element is massive, it is a thermoelectric generator. The heat state of the surface layers of the friction linings of the tape differs.

Theoretical and experimental studies have shown that the energy levels of the surface and surficial layers and the mechanical characteristics of the materials are significantly affected by their heating speed and forced cooling as well as their cycling. The latter causes a significant change in the nature of structural transformations in surface and surficial layers and, as a result, contributes to changes in the physical and mechanical properties of their materials [8].

When the rim of a pulley made of steel of 35HNL with different temperature gradients on its working surface and thickness is heated, phase transformations occur in the material of the surficial layer of the rim, leading to the formation of austenite in it. This reduces the volume of the surface rim layer due to the uneven heating of the surficial rim layer, while the volume of all the lower rim layers has increased due to the linear expansion caused by their heating. As a result, the outer austenitic uneven layer compresses the internal volume of the rim layers, and in the first, compressive stresses develop, contributing to the occurrence of cross-sectional cracks on the rim working surface at the most thin cross-sections.

Thus, from the comparison of gradients of the mechanical properties of the surface and surficial layers of the pulley rim materials (strength, elasticity, stresses of various kinds)' and temperature gradients, special requirements for permissible heating rates and forced cooling have to be formulated for the development phases in the above-mentioned layers. It is important to note that the type of breakage of the contact surfaces of metal-polymer friction pairs is determined by the gradients of the mechanical properties of the materials, the temperature gradients on the working surface of the pulley rim and the thickness thereof, metastability of friction linings surfaces and the external environment surrounding their working surfaces.

Conclusion

The use of the physical components for friction pairs of braking devices will allow:

- to systematize and present in a drawing the principles, perturbations, potentials and gradients in the energy fields of metal-polymer friction pairs;
- systematize the sequence of processes, effects and phenomena of electrothermomechanic friction;
- consider not only the friction interaction fields separately, but also examine them in pairs to determine the influence of one on the other;

- the following unambiguous conditions have been introduced for the solution of thermal problems in order to evaluate the energy load of different types of friction units:

- the geometric parameters of the friction pairs and their shape;

- the thermaphysical characteristics of the materials;

- initial and boundary conditions;

- is the maximum energy loading of the metal friction elements and the heat exchange capacity thereof, which consists in the combined effect of the conductive heat exchange with the radiative and convective heat exchange from the surfaces thereof, and the tolerable temperature for the polymeric lining materials;

- the initial conditions for the metal friction element should be variables that would correspond to its fixed and thermostatic state.

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