UDC 621.1.016 – 536
DOI 10.52171/2076-0515_2024_16_02_24_33

Conductive Heat Transfer in Friction Pairs of Brake Devices

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Abstract

Theoretical and experimental studies of conductive heat transfer during the frictional interaction of brake friction pairs based on the gradient theory regarding circular isotherms, which allow the formation of energy loading modes, made it possible to obtain the following results: patterns of changes in the heat flow passing through the thickness of the metal friction element depending on its thermal resistance and volume temperature; the patterns of changes in the thermal resistance of a metal element depending on its thickness and the thermal conductivity coefficients of materials, varying within the range of (20-200) W/(m·ºC), are given; the following total electric microcurrents have been established: contact electrification, frictional mass transfer, sorption-desorption, reverse discharge, depending on the work function of particles from the surfaces of the metal and polymer element; while the latter is considered at different surface-volume temperatures; the different nature of electric and heat flows nevertheless has the same approach to their potential, and as a consequence, to the resistance of microprotrusions of the surfaces of brake friction pairs; isotherm levels corresponding to the surface and subsurface layers of the metal friction element indicate their loading modes; at a minimum temperature gradient – steady; at maximum, conductive heat transfer is intensified.

Keywords: braking device, friction pair, surface and subsurface layer, thermal conductivity coefficient, conductive heat transfer.

Received *27.03.2024*
Revised *11.06.2024*
Accepted *21.06.2024*

For citation:
A.Kh. Janahmadov, D.A. Volchenko, M.Y. Javadov, N.A. Volchenko, V.S. Skrypnyk, D. Yu. Zhuravlev, A.V. Vozniy
[Conductive Heat Transfer in Friction Pairs of Brake Devices]
Herald of the Azerbaijan Engineering Academy, 2024, vol. 16, № 2, pp. 24-33 *(in English)*

Əyləc qurğularının sürtünmə cütündə konduktiv istilik mübadiləsi

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Xülasə

Məqalədə enerji yüklənməsi rejimlərinin formalaşmasına imkan verən dairəvi izotermlərə aid qradient nəzəriyyəsi əsasında əyləclərin sürtünmə cütündə friksion qarşılıqlı təsir zamanı konduktiv istilik mübadiləsinin nəzəri və eksperimental tədqiqatları təqdim olunub. Metal sürtünmə elementinin qalınlığından keçən istilik axınının dəyişmə qanunauyğunluqları onun termik müqavimətindən və həcmi temperaturundan asılı olaraq müəyyən edilib; metal elementin termik müqavimətinin onun qalınlığından və *(20-200)Vt/(m·ºS)* diapazonunda dəyişən materialların istilik keçiricilik əmsallarından asılı olaraq dəyişmə qanunauyğunluqları verilib; aşağıdakı ümumi elektrik mikrocərəyanları verilib: metal və polimer elementin səthlərindən hissəciklərin iş funksiyasından asılı olaraq kontakt elektrikləşdirilməsi, friksion kütlə ötürülməsi, sorbsiya-desorbsiyası, əks boşalması; metal sürtünmə elementinin səth və səthaltı təbəqələrinə uyğun gələn izoterm səviyyələri onların yüklənmə rejimlərini göstərir; konduktiv istilik mübadiləsi minimum temperatur qradientində – sabit qalır; maksimumda – intensivləşir.

Açar sözlər: əyləc qurğusu, sürtünmə cütü, səth və səthaltı təbəqə, istilikkeçiricilik əmsalı, konduktiv istilik mübadiləsi.

Кондуктивный теплообмен в парах трения тормозных устройств

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Аннотация.

В статье приводятся теоретические и экспериментальные исследования кондуктивного теплообмена при фрикционном взаимодействии пар трения тормозов на основе градиентной теории, касающейся круговых изотерм, которые позволяют формировать режимы энергонагруженности. Установлены закономерности изменения теплового потока, проходящего через толщину металлического фрикционного элемента в зависимости от термического сопротивления и объемной температуры; приведены закономерности изменения термического сопротивления металлического элемента от его толщины и коэффициентов теплопроводности материалов в пределах 20-200 Вт/(м·ºС); установлены суммарные электрические микротоки: контактной электризации, фрикционного массопереноса, сорбционно-десорбционный, обратный разрядный в зависимости от выхода частиц с поверхностей металлического и полимерного элемента; уровни изотерм, отвечающие поверхностным и подповерхностным слоям металлического фрикционного элемента указывают на режимы их нагруженности; при минимальном температурном градиенте интесифицируется установившийся; при максимальном – кондуктивный теплообмен.

Ключевые слова: тормозное устройство, пара трения, поверхностный и подповерхностный слой, коэффициент теплопроводности, кондуктивный теплообмен.

Introduction

The energy load of friction pairs during electro-thermo-mechanical friction interaction is influenced by pulsed specific loads, the coefficient of mutual overlap of friction pairs and sliding speeds, not to the same extent as the influence of the surface-volume temperature of the surface and subsurface layers of metal friction elements. The problem of heat transfer from the polished working surface of a metal rotating element to its matte surface is carried out by a flow of electrons using conductive (heat transfer) heat transfer. In the latter, the coefficient of thermal conductivity plays an important role along with the levels of temperature gradients across the layers of thickness of the metal friction element.

Analysis of literary sources and the state of the problem

A characteristic of the level of thermal energy is the surface-volume temperature of the surface and subsurface layers of metal friction elements. It acts as a barometer of the energy load of the elements of metal-polymer brake friction pairs [1-5].

In [1, 2] it is shown that the amount of heat transferred through a vertically located metal flat wall is directly proportional to the temperature difference between the hot (t_1) and cold (t_2) surface of the wall, its area (A) and time (τ), as well as thermal conductivity coefficient (λ) of the wall material and inversely proportional to the thickness (δ) of the wall. However, when estimating the amount of heat during electrothermo-mechanical friction, it is necessary to take into account the zones of discrete contact and electrical resistance of microprotrusions of metal-polymer brake friction pairs. When calculating the thermal regime of solids [6-8], nothing is said about their surface-volume temperature, which is the main operational parameter in metal-polymer friction pairs of braking devices.

The problem of heat transfer from the working polished to matte surface of a metal friction element, the thermal conductivity of which is its main characteristic. So, when determining the heat transfer coefficient (K) of a horizontal element washed by a medium with different heat transfer coefficients (α_1 and α_2), in this case they use a dependence of the form [1]

$$K = 1/\alpha_1 + \delta/\lambda + 1/\alpha_2 ,$$

where $1/\alpha_1$, δ/λ, $1/\alpha_2$ - thermal resistances.

In this case, the thermal conductivity coefficient (λ) of cast iron and steel from which the metal friction element is made is a fixed value. Increase (K) possibility (when α_1=const, α_2=const) only by reducing the thickness (δ) of the friction element. However, the possibilities of reducing (δ) are extremely limited since the thickness negatively affects the strength characteristics of the element.

Thus, the surface-volume temperature of the surface and subsurface layer of materials of friction pairs determines not only their thermal stress, but also the energy state and heat transfer modes according to the theory of gradient temperatures.

Based on the above, an algorithm (Fig. 1) for studying conductive heat transfer is proposed.

The purpose of the work is to estimate the levels of isotherms corresponding to the surface and subsurface layers of metal friction elements based on their temperature gradients during the electrothermo-mechanical interact-tion of microprotrusions of brake friction pairs.

Conductive heat transfer

↓

Coefficient of thermal conductivity

↓

Contact thermal conductivity

↓

Electrical and thermal contact resistance

↓

Intensification of heat transfer due to conductive heat transfer

Figure 1 – Determination of thermodynamic parameters of friction pairs of brake devices during conductive heat transfer

Basic principles of the theory of conductive (heat transfer) heat transfer in friction pairs of brake devices. The process of thermal conductivity, like other types of heat exchange, occurs only under conditions when the surface-volume temperatures of the surface and subsurface layers of metal-polymer friction pairs at different points or tribosystems are not the same. The study of surface-volume temperature comes down to considering thermal conductivity in spatiotemporal changes, i.e., to finding the equation

$$t = t(\mathrm{x, y, z}, \tau). \qquad (1)$$

where x, y, z – coordinates of a point in the interface of friction pairs; τ – braking time.

Equation (1) is a mathematical expression of a non-stationary temperature field that changes over time. The surface-volume temperature at the interface of friction pairs varies from one, two or three coordinates. In accordance with this, one-dimensional, two-dimensional and three-dimensional temperature fields are distinguished. The temperature field can be characterized by a series of isothermal surfaces. An isothermal surface is understood as the geometric location of points with the same temperature. Isothermal surfaces do not intersect and do not break off inside the metal friction element - they can be located both inside and at the interface (Fig. 2 *a*).

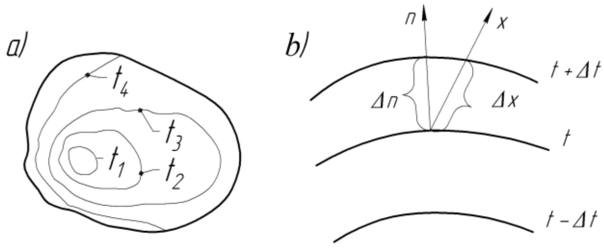

Figure 2 a, b – Isotherms in a metal friction element (a) and their levels when determining the temperature gradient (b)

By the location of isotherms in a metal friction element, you can estimate the intensity of temperature changes in different directions; the more often the isotherms are located, the more intense the temperature changes. In Fig. 2 *b* shows isotherms whose temperatures differ by Δt, and the normal distance between them is Δn. The temperature in the body of the metal friction element changes only in directions intersecting the isothermal surfaces. In this case, the greatest temperature difference per unit length occurs in the direction of the normal to the isothermal surface. The ratio $\Delta t/\Delta n$ characterizes the intensity of temperature changes between isotherms.

The derivative of temperature normal to an isothermal surface is called the temperature gradient. Temperature gradient is a vector quantity directed normal to the isotherm in the direction of increasing temperature:

$$grad\, t = \lim_{\Delta n \to 0} \frac{\Delta t}{\Delta n} = n_0 \frac{\partial t}{\partial n}, \tag{2}$$

where n_0 – unit vector, normal to the isothermal surface and directed towards increasing temperature; $\frac{\partial t}{\partial n}$ – normal derivative of temperature.

The value $\frac{\partial t}{\partial n}$ in the decreasing direction is negative. Vector projections *grad t* to coordinates axes *ox*, *oy*, *oz* will be equal.

$$\left.\begin{aligned} (grad\, t)_x &= \frac{\partial t}{\partial n}\cos(n^\frown, x) = \frac{\partial t}{\partial x} \\ (grad\, t)_y &= \frac{\partial t}{\partial n}\cos(n^\frown, y) = \frac{\partial t}{\partial y} \\ (grad\, t)_z &= \frac{\partial t}{\partial n}\cos(n^\frown, z) = \frac{\partial t}{\partial z} \end{aligned}\right\} \tag{3}$$

The basic law of thermal conductivity is the hypothesis proposed by J. Fourier about the proportionality of heat flow to the temperature gradient. According to this hypothesis, the amount of heat δQ_1 passing through an isothermal surface element *d*H over a period of time *dτ*, proportional to temperature gradient $\frac{\partial t}{\partial n}$:

$$\delta Q = -\lambda \frac{\partial t}{\partial n} dH \cdot dt \ (J), \tag{4}$$

where λ – proportionality coefficient, which is further called the thermal conductivity coefficient, W/(m·ºC).

The minus sign in equation (4) reflects the opposite directions of the heat flow and temperature gradient vectors.

The amount of transferred heat passing per unit time through a unit area of an isothermal surface is called heat flux density:

$$q = \delta Q / dHdt = -\lambda \frac{dt}{dn} \ (\text{W/m}^2) \tag{5}$$

Formulas (4) and (5) are the mathematical expression of Fourier's law. From equation (5) it is clear that the thermal conductivity coefficient is numerically equal to the amount of heat that passes per unit time through a unit surface with a temperature gradient equal to unity:

$$\lambda = \frac{|q|}{|grad\, t|}, \ (\text{W/(m·ºC)}) \tag{6}$$

The thermal conductivity coefficient is an important thermophysical characteristic of a substance, determining its ability to conduct heat through direct contact of the structural particles of the substance. The value of λ depends on the nature of the substance, its structure, temperature and a number of other factors. The metals of the friction elements (steel, cast iron) have the highest thermal conductivity coefficient, and the lowest is the gases that form when the binding components burn out from the surface and subsurface layers of the polymer lining.

An analysis of the dependence of the thermal conductivity coefficient on temperature shows that for most solids, liquids and gases at moderate temperatures the dependence can be approximately estimated by a linear function.

$$\lambda = \lambda_0 (1 \pm bt) \tag{7}$$

where λ_0 – thermal conductivity coefficient of the material at *t*=0 ºC; *b* – experimental constant.

For pure metals, the value of λ varies from 500 to 10 W/(m·ºC). With increasing temperature, the coefficient λ for most metals decreases. The thermal conductivity coefficient of metals can change sharply due to the amount of impurities. Unlike pure metals, the thermal conductivity coefficient of alloys increases with increasing temperature, which can be explained by an increase in structural inhomogeneities, which lead to electron scattering. The coefficient λ for a mixture of metals does not change in proportion to the number of components included in the mixture. It also depends on the type of thermal and mechanical treatment of the metal.

Liquids (except molten metals) have a small coefficient λ (0.09 ÷ 0.07) W/(m·ºC). For most liquids (except water and glycerin), the thermal conductivity coefficient decreases with increasing temperature. Liquid metals have significantly higher thermal conductivity (λ = 7 – 90 (W/(m·ºC)). Gases and vapors conduct heat poorly by thermal conductivity (λ = 0.006 ÷ 0.6 (W/m·ºC)). Coefficient λ for gases increases with increasing temperature.

Interfaces are boundary isotherms in friction pairs that resist heat flow. The latter divided by the difference in surface-volume temperatures of the surface and subsurface layers of friction pairs, i.e., between the interfaces is called the contact thermal conductivity of the connection. Since the hard surfaces of metal-polymer friction pairs are never absolutely smooth, they come into contact only in certain areas of microprotrusions, and the volume of voids between which is usually filled with washing air or wear products. Heat transfer through the interface is carried out mainly by thermal conduction through the layer of media filling the voids and through the protruding microprotrusions of the surfaces in direct contact with each other. The layer of the medium is very thin and therefore convective heat transfer does not take place, and heat transfer by radiation through the gaps at normal surface-volume temperatures below those permissible for polymer overlay materials is negligible. Contact thermal conductivity is essentially determined by two resistances: the resistance of the medium layer and the resistance of the areas in direct contact with each other.

Contact thermal and electrical resistance of layers of friction pairs of brakes. The problem of heat transfers from a metal friction element during electrothermo-mechanical friction of brake device interfaces to the air washing them when the vehicle is moving is the most important problem of reducing the energy load of friction pairs of brake devices. The thermal conductivity of the friction element material is its main characteristic and is related to the heat flow

$$q = \frac{\lambda \Delta t}{\delta},$$

where λ is the thermal conductivity coefficient, W/(m·°C); Δt – temperature jump due to contact thermal resistance in the interface, °C; δ – thickness of surface layers of mating friction pairs, *m*.

The heat flow can be expressed as follows

$$q = \frac{R_c}{\Delta t}, \tag{8}$$

where R_r – thermal resistance along the thickness of the surface layers of the interface, $\frac{(\mathrm{W}\cdot\ {}^\circ\mathrm{C})}{\mathrm{mm}^2}$.

According to the graphical dependence of the form $q=\mu_1(\lambda/q,\ t)$ (Fig. 3) for the friction belt of a self-ventilated disc, it is clear that with an increase in heat flow in the brake friction pairs, an increase in thermal resistance is observed, and as a consequence, an increase in the surface-volume temperature in the interface. As for the graphical dependence of the form $q=\mu_1(\lambda/q,\ t)$ (Fig. 4 *a*, *b*) regarding the friction belt of the disk, it follows that with an increase in its thickness it is necessary to increase the thermal conductivity coefficient of the material. Electric charges are: alternating, constant, conductivity, displacement, convection. The creators of electric charges are those arising during the electrothermomechanical frictional interaction of a metal-polymer friction pair with an electric potential. The latter are described by passing through contact spots of different microcurrent strengths. The electric flow is similar to the heat flow as they pass through the layers of the metal friction element, increasing its surface-volume temperature and volumetric thickness. In this case, the electric flows are directed perpendicular to the mating surface of the friction pairs.

In table shows the names and directions of the components of the total electric current that occurs on the microsurfaces of the contact spots during sliding friction in various zones of the thermal state of their metal friction element.

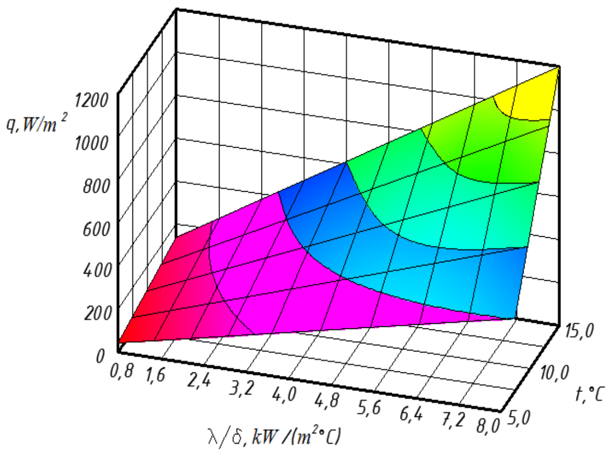

Figure 3 – Regularities of changes in the heat flow q penetrating the friction belt of the brake disc during frictional interaction of the friction pair “lining-disc” of the brake, depending on the parameter λ/δ and the volumetric temperature in the body of the disc

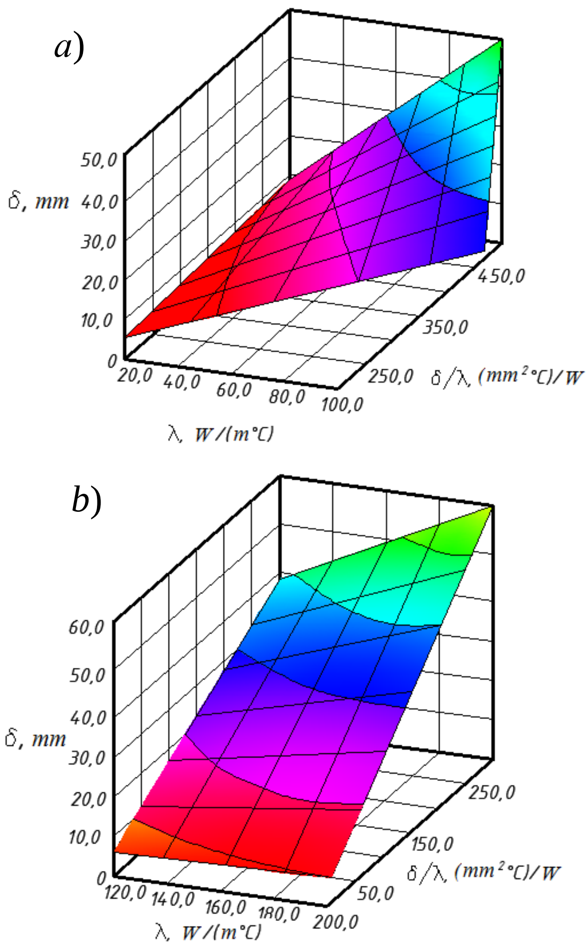

Figure 4 a, *b* – Patterns of changes in thermal resistance (δ/λ) of brake discs depending on their thickness (δ) and thermal conductivity coefficients of materials (λ), varying within: a – (20…100) W/(m·°C); b – (120…200) W /(m·°C) δ, mm

The following notations are used: $\sum_{1}^{n} I_c$ – total current arising due to contact electrification; $\sum_{1}^{n} I_м$ – total current generated by the movement of charged particles of frictional mass transfer; $\sum_{1}^{n} I_d$ – total current due to sorption-desorption processes in the surface layers of the contact. $\sum_{1}^{n} I_S$ – total current arising upon contact of interacting surfaces; $\sum_{1}^{n} I_T$ – the total reverse discharge current that occurs when the friction contact is destroyed (total pulse current); W – work function of electrons leaving the polymer (index «*p*») and metal (index «*m*») surfaces of friction elements.

Table – Changes in the directions of current components during electrification and its total value during the interaction of the surfaces of friction pairs of braking devices in different energy-load zones of their metal friction elements

		Components of electrification current: I_c	$I_м$	I_d	I_T	I_p	Total electrification current, $\sum_{1}^{n} I_f$
		Signs of generated currents					
		at $W_m > W_p$					
Before	Stabilization thermal state of metals friction elements	+	-	0	+	+	$\sum_{1}^{n} I_{f+} = \sum_{1}^{n} I_c - \sum_{1}^{n} I_м + \sum_{1}^{n} I_T + \sum_{1}^{n} I_p$; (1)
		at $W_p > W_m$					
After		-	+	0	-	+	$\sum_{1}^{n} I_{f-} = \sum_{1}^{n} I_c + \sum_{1}^{n} I_м - \sum_{1}^{n} I_T + \sum_{1}^{n} I_p$; (2)
		at $W_m > W_p$					
In the zone		+	-	±	+	-	$\sum_{1}^{n} I_{f+} = \sum_{1}^{n} I_c - \sum_{1}^{n} I_м \pm \sum_{1}^{n} I_d + \sum_{1}^{n} I_T + \sum_{1}^{n} I_p$; (3)
		at $W_p > W_m$					
		-	+	±	+	+	$\sum_{1}^{n} I_{ф-} = -\sum_{1}^{n} I_к + \sum_{1}^{n} I_м \pm \sum_{1}^{n} I_д + \sum_{1}^{n} I_T + \sum_{1}^{n} I_p$; (4)
		at $W_m > W_p$					
		+	-	∓	+	-	$\sum_{1}^{n} I_{f+} = \sum_{1}^{n} I_c - \sum_{1}^{n} I_м \mp \sum_{1}^{n} I_d + \sum_{1}^{n} I_T + \sum_{1}^{n} I_p$; (5)
		at $W_p > W_m$					
		-	+	∓	+	-	$\sum_{1}^{n} I_{f+} = -\sum_{1}^{n} I_c + \sum_{1}^{n} I_м \mp \sum_{1}^{n} I_d + \sum_{1}^{n} I_T - \sum_{1}^{n} I_p$; (6)

Let us consider the law of change in the total electrification current in the zones of the thermal state (see Table) of the metal friction element of the braking state under two conditions: $W_m > W_p$ and $W_p < W_m$. In the area of the pre-stabilization device under two conditions: $W_m > W_p$ and $W_m < W_p$. In the zone of the pre-stabilization thermal state of the metal friction element, the total electrification current will be greatest in the case of a friction pair approaching in this zone, provided that $W_p > W_m$. In this case, the total currents $\sum_{t}^{n} I_c$ and $\sum_{t}^{n} I_м$ will be greater than under the condition $W_m > W_p$.

This circumstance indicates that during braking there is an intensive accumulation of thermal energy in the metal friction element, and the intensity of convective heat transfer from its matte surfaces and radiation heat transfer is low.

The most interesting phenomenon occurs in the zone of the thermal state of the metal friction element in the case of intensification of adsorption-desorption processes occurring in the near-surface layers of the metal friction element in the case of intensification of adsorption-desorption processes occurring in the near-surface layers of the lining material under the condition $W_m > W_p$. In this case, the total currents $\sum_1^n I_c$ and $\sum_1^n I_p$ will be greater than under the condition $W_p > W_m$. Burnout of the connecting components of friction materials causes smoke on their surfaces and leads to the formation of liquid fractions on them, which causes the inversion of heat flow from the matte surfaces of the metal friction element to its polished (working) surface. This circumstance contributes to the emergence of a stabilizing thermal state of the metal friction element, despite the intense radiation heat transfer from its polished surface. The duration of the stabilization state largely depends on the time and temperature of completion of sorption-desorption processes in the surface layers. The value of the latter in a zone with a temperature exceeding the temperature of the stabilization thermal state of the metal friction element will be minimal, provided $W_m > W_p$.

Thus, the levels of isotherms corresponding to the layered structure of the entire thickness of the metal friction element indicate the modes of their energy loading; at a minimum temperature gradient – steady; at maximum, conductive heat transfer is intensified.

Theoretical and experimental studies of conductive heat transfer during frictional interaction of brake friction pairs based on the gradient theory regarding circular isotherms, which allow the formation of energy load modes and made it possible to obtain the following results: patterns of changes in the heat flow passing through the thickness of the metal friction element have been established depending on its thermal resistance and volumetric temperature; the patterns of changes in the thermal resistance of a metal element depending on its thickness and thermal conductivity coefficients of materials, varying within the range of (20-200) W/(m·ºC); the following total electric microcurrents have been established: contact electrification, frictional mass transfer, sorption-desorption, reverse discharge, depending on the work function of particles from the surfaces of the metal and polymer element; while the latter is considered at different surface-volume temperatures; the different nature of electric and heat flows nevertheless has the same approach to their potential and, as a consequence, to the resistance of microprotrusions of the surfaces of brake friction pairs; isotherm levels corresponding to the surface and subsurface layers of the metal friction element indicate their loading modes; at a minimum temperature gradient – steady; at maximum, conductive heat transfer is intensified.

Conclusion

The levels of isotherms corresponding to the surface and subsurface layers along the thickness of metal friction elements were assessed based on their temperature gradients during the electrothermomechanical interaction of microprotrusions of brake friction pairs.

Conflict of Interests

The authors declare there is no conflict of interests related to the publication of this article.

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