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Effects of Electrothermal Contact Resistance in Metal-Polymer Friction Pairs of Brakes

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Abstract

The article examines to the electrothermal contact resistance of moving and fixed joints. Movable resistances include the frictional interaction of microprotrusions of friction pairs, on the spots of which at the initial moment of time an electrical contact resistance is formed, which later becomes a thermal contact resistance. For two fixed coaxial cylinders, the task is to determine the magnitude of the contact specific loads depending on the heat flow passing through the second shell, its temperature and the physical and chemical characteristics of the materials. The electro-thermal contact resistance in metal-polymer friction pairs of brakes under cyclic and long-term braking modes with variable dynamic coefficients of mutual overlap is that with discrete contact of microprotrusions under the influence of pulsed specific loads, their electrical contact resistance is formed in the surface layers of the friction pairs and in the volumes of microprotrusions and in the surface layers of friction pairs – their thermal contact resistance.

Keywords: friction pair, contact patch, microprotrusions, polymer and metal element, contact resistance, electrical and thermal resistivity, microprotrusion capacity, computer modeling.

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"Metal-polimer" əyləclərin sürtünmə cütündə elektrotermik kontakt müqavimət effekti

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Xülasə. Məqalədə hərəkətli və hərəkətsiz birləşmələrin elektrotermik kontakt müqaviməti məsələsinə baxılıb. Hərəkətli müqavimətlərə sürtünmə cütləri mikroçıxıntılarının friksion qarşılıqlı təsirləri daxildir və onların ləkələrində ilkin anda elektrik kontakt müqaviməti yaranır, sonradan isə bu, termik kontakt müqavimətinə çevrilir. İki hərəkətsiz koaksial silindr üçün nazik divarlı qabıqdan keçən istilik axınından, onun temperaturundan və materialların fiziki və kimyəvi xüsusiyyətlərindən asılı olaraq kontakt, xüsusi yüklərin qiymətini müəyyən etmək vəzifəsi qoyulur. Qarşılıqlı üst-üstə düşmənin dəyişən dinamik əmsalları ilə tsiklik və uzunmüddətli əyləc rejimləri altında "metal-polimer" əyləclərin sürtünmə cütlərində elektrotermik kontakt müqaviməti ondan ibarətdir ki, sürtünmə cütlərinin üst təbəqələrində impulslu xüsusi yüklərin təsiri altında mikroçıxıntıların diskret kontaktı zamanı, onların elektrik kontakt müqaviməti, mikroçıxıntıların həcmlərində və sürtünmə cütlərinin üst təbəqələrində isə termik kontakt müqaviməti formalaşır.

Açar sözlər: sürtünmə cütü, kontakt ləkəsi, mikroçıxıntılar, polimer və metal element, kontakt müqaviməti, xüsusi elektrik və istilik müqaviməti, mikroçıxıntıların tutumu, kompüter modelləşdirməsi.

Эффекты электротермического контактного сопротивления в парах трения «металл - полимер» тормозов

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Аннотация. В статье рассматривается электротермическое контактное сопротивление подвижных и неподвижных сопряжений. К подвижным сопротивлениям относится фрикционное взаимодействие микровыступов пар трения, на пятнах которых в начальный момент времени формируется электрическое контактное сопротивление, которое в дальнейшем становится термическим контактным сопротивлением. К неподвижным двум коаксиальным цилиндрам ставится задача определения величины контактных удельных нагрузок в зависимости от проходящего через вторую оболочку теплового потока, ее температуры и физико-химических характеристик материалов. Электротермическое контактное сопротивление в парах трения «металл - полимер» тормозов при циклических и длительных режимах торможения при переменных динамических коэффициентах взаимного перекрытия заключается в том, что при дискретном контакте микровыступов под действием импульсных удельных нагрузок в поверхностных слоях пар трения формируется их электрическое контактное сопротивление, а в объемах микровыступов и в поверхностных слоях пар трения – термическое контактное сопротивление.

Ключевые слова: пара трения, пятно контакта, микровыступы, полимерный и металлическкий элемент, сопротивление контакта, удельное электрическое и тепловое сопротивление, емкость микровыступов, компьютерное моделирование.

Introduction

For modern vehicles, during cyclic and long-term braking in the metal-polymer friction pairs of the brakes, electrothermal contact resistance occurs during their frictional interaction. In this case, insignificant electrical flows are observed preceding heat flows of very high density. Under these conditions, issues of contact heat transfer become essential. The need to calculate contact thermal resistance is encountered in reactor engineering, when designing devices for direct energy conversion, in aviation, rocket and space technology, in electronics, etc. The effects of electrothermal contact conductivity are very complex, since they depend on a number of factors of different nature. A significant part of the currently known works on contact heat transfer is of an experimental nature; The calculated relationships found in some studies are often contradictory and not sufficiently theoretically substantiated. In electrothermo-mechanical frictional interaction of contact spots of microprotrusions of friction pairs of brake devices, one of the main operational parameters is the contact resistance of their surfaces. The latter have different characteristics caused by high thermal conditions, the presence of films and without them, the ingress of wear products onto the contact spots of the microprotrusions and into the gaps between them, and mechanical vibrations of the microprotrusions of the friction linings located on the brake band. Based on this, it is necessary to raise the question of determining the transient electrothermal resistance of the contact interaction of microprotrusions of friction pairs of braking devices.

Analysis of literary sources and the state of the problem

I.V. Kragelsky, M.M. Dobychin, V.S. Kombalov [1], analyzing the critical points that characterized the conditions of transition from one type of frictional interaction to another, stated: “Individual sections of a thin surface layer of metal as a result of the occurrence of Here, under electromechanical friction, significant deformations and stresses, as well as high contact temperatures, transform into a special activated unstable state. The latter would later be called “magma plasma” by P.A. Thiessen [2] (fig. 1).

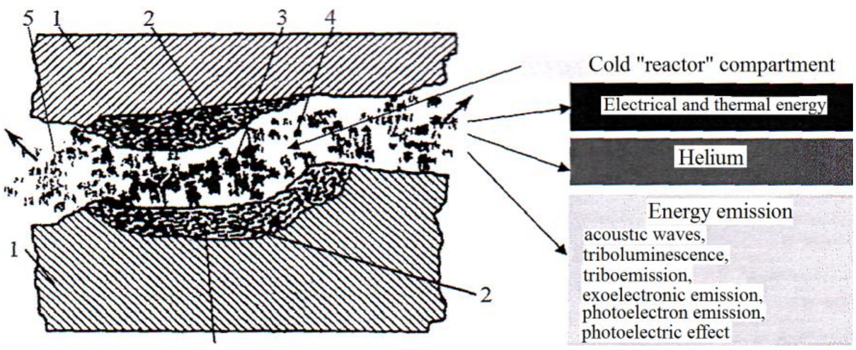

Figure 1 – Magma-plasma model: 1 - initial structure; 2 - molten structure; 3 - plasma; 4 - triboemission electrons; 5 - atoms, photons, phonons, ions, excited molecules, fast electrons

A substance in this state is capable of reacting with the counterbody material and the environment, even with neutral gases." This process is accompanied by mechano-immersion and mechanochemical effects, chemical reactions, gas-discharge phenomena, the synthesis of certain substances, as well as the emergence of particles with high energy, that is, excited molecules, atoms, ions, fast electrons, phonons (sound quanta), photons (electromagnetic radiation quanta).

The listed processes, phenomena and effects take place in metal-to-metal friction pairs. In metal-polymer friction pairs, the exciting factor is the metastable state of the surface layers of the polymer pad when they reach the permissible temperature for its materials. This publication does not pay attention to the transient electrothermal resistance in tribocouplings of friction pairs, depending on the changing value of which the energy load of their surface layers directly depends.

This publication addresses the following issues in relation to the problem under study: the nature of electrothermal contact resistance during frictional interaction of micro-protrusions of friction pairs; capacity of the transition zone of contact resistance of microprotrusions of friction pairs; assessment of thermal contact resistance in fixed joints; features of computer modeling of the energy load of metal-polymer brake friction pairs.

The purpose of the work is to develop a method for determining the electrothermal contact resistance of microprotrusions of friction pairs of brake devices to assess the energy load of their surface layers.

The nature of electrothermal contact resistance during frictional interaction of microprotrusions of friction pairs

During the frictional interaction of microprotrusions of metal-polymer friction pairs of brake devices, the electrothermal contact resistance changes mainly due to a change in the transition resistance. The nature of the transition resistance has not yet been fully clarified. There are several different theories on this issue, but the most widespread are the two main theories of contact resistance - V. Chelkhlin and R. Holm, these theories are based on the slightly different nature of this phenomenon, but nevertheless lead to the same result. In the first case, the occurrence of transition resistance is explained by the resistance of the microprotrusions conducting electric and thermal current, in the second - by the resistance of the contraction of the electric and thermal current lines to the conducting sections of the microprotrusions. With increasing contact specific loads, the microprotrusions are compressed, increasing the actual contact surface and, accordingly, reducing the resistance of the protrusions and the amount of contraction.

In table 1 depending (1)-(9) the following symbols are given:

R_l, R_2 - electrical resistance of polymer and metal microprotrusions, Ohm; ρ - electrical resistivity. (Ohm·mm^2)/м; K - Boltzmann constant, J/К; p_c - contact specific loads, MPa; a, r - radiuses: micro-extrusion areas; cylindrical contact body, mm; HB_1 - Brinell hardness of the polymer micro-protrusion, MPa; d - total film thickness, мм; σ_m - specific tunnel resistance, Ohm·mm^2.

Table 1 – Determination of transient electrical resistance in metal-polymer friction pairs of brake devices

Parameter name	***Calculated dependence***
Electrical resistance of contacts of microprotrusions:	
total;	$R_{tot} = R_1 + R_2 + R_n$; (1)
transitional;	$R_t = \rho K / p_c$; (2)
transitional taking into account the film.	$R'_{tr} = R_p + R_f$; (3)
Pull resistance:	
microcurrents on the contact spots of microprotrusions, provided $r >> a$;	$R_p = 0{,}5\rho\left(a^{-1} - r^{-1}\right)$; (4)
when contacting metal-polymer stains;	$R_p = 0{,}5\rho a$; (5)
with discrete contact, components (n) given identical areas of contact spots with their actual interaction area $A=1{,}5\pi an$ and the action of contact specific loads, which is $A=\rho_c/HB$ for resistance R_p.	$R_p = 0{,}25(\rho_1 + \rho_2)/a$; (6) $R_p = 0{,}5\rho\sqrt{\pi HB_1 / np_\kappa}$; (7)
Resistance of inhomogeneous films of the same thickness with its reduced specific value (ρ'_{in}) provided that $\rho'_{in} = \sigma_m$ and after transformations taking into account (1) and (3) the expression (7) for transition resistance has the form	$R_{in} = (\rho'_{in} d)/A$; (8) $R_n = 0{,}5\rho/a + \sigma_m/(\pi A)^2$ (9)

The total electrical resistance of the contacts of the microprotrusions is determined by dependence 1. In turn, the contact resistance is determined by dependence 2. In this case, the transition resistance, taking into account the film formed on the contact spots of the microprotrusions, is determined by dependence 3.

R. Holm's theory has become widespread because it more fully reflects the phenomena in the transition zone of contact of microprotrusion spots. The model of the contact surfaces of the microprotrusion spots of friction pairs according to the theory of R. Holm is shown in Fig. 2.

The entire contact surface, the area of which is determined by the Hertz formula, is apparent. Due to its changing roughness in the process of frictional interaction, the contacts come into contact only in separate areas, the total area of which is called the actual area. Both contact surfaces are usually covered with oxide films, which are destroyed when increasing specific contact loads are applied to them.

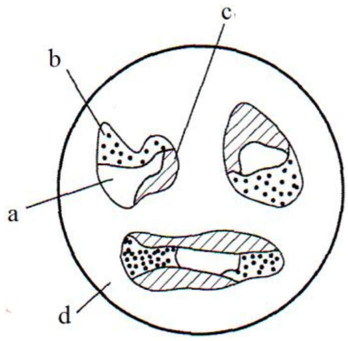

Figure 2 – Model of contact surfaces of micro-protrusions of friction pairs: a – “metal-metal”; b – “polymer-metal”; c – “polymer-polymer”; d – non-contacting spots of microprotrusions

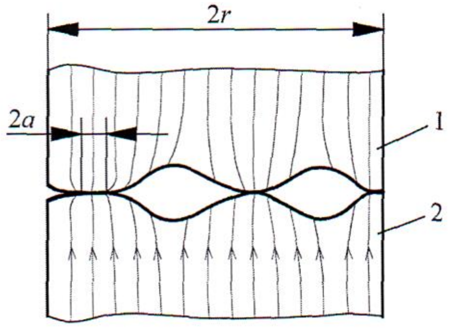

Figure 3 – Lines of electric current contraction in discrete contacts of microprotrusions of the friction pair “polymer (1) – metal (2)”

As a result, areas are formed with contact of clean metal surfaces (areas *a*). Areas with metallic conductivity are also formed as a result of fritting, that is, breakdown of the oxide film under the influence of an electrothermal field. When compressed, stronger sections of the film acquire the properties of semiconductors with high resistivity. Their conductivity is called quasi-metallic (sections *b*). Areas where film destruction did not occur upon contact do not conduct electric current (areas *c*). Other areas of the apparent contact surface are not in contact (areas *d*); they are separated by destruction products of the polymer pad. Remains of destroyed oxides, dust and wear products, accumulating in the depressions of the rough surface, are strengthened and prevent the contacts from approaching each other and the formation of new spots with metallic conductivity, which, in turn, leads to an increase in the transition resistance. The current, passing from one contact to another, is drawn to the conductive areas (Fig. 3), where its density can reach a very high value (up to $1{\cdot}10^5$ A/mm^2).

Electrothermal contact resistance in friction pairs. Let us dwell on the thermal current lines developing on the contact spots of microelements. In Fig. 4, and the “boundary” streamlines are highlighted, separating the region of the main heat flow passing through the actual contact area from the region of additional heat flow passing through the intermediate medium in the gap between the microprotrusions. In a metal-to-metal friction pair, there is equality of heat flux densities and temperatures at the boundaries of different media.

The electrification of the surfaces of the polymer lining and the polymer film, carried out due to mass transfer on the working surface of the metal friction element during contact-pulse interaction with each other, is the sum of two effects, kinetic and equilibrium (Fig. 4, *a*). The kinetic effect is caused by the fact that the metal friction element with polymer films on its working surfaces rotates, and the working surface of the polymer lining is stationary. In this case, the kinetic effect causing electrification is associated with the fact that the interacting film of the metal friction element heats up more than the stationary strip of the surface of the polymer lining. To study the “polymer-polymer” friction pair (Fig. 4. *d*), the equilibrium effect is of great importance. This effect occurs at the initial and final stages of the contact-pulse interaction of two polymer contact spots and at the same time the film of the metal friction element is partially worn out.

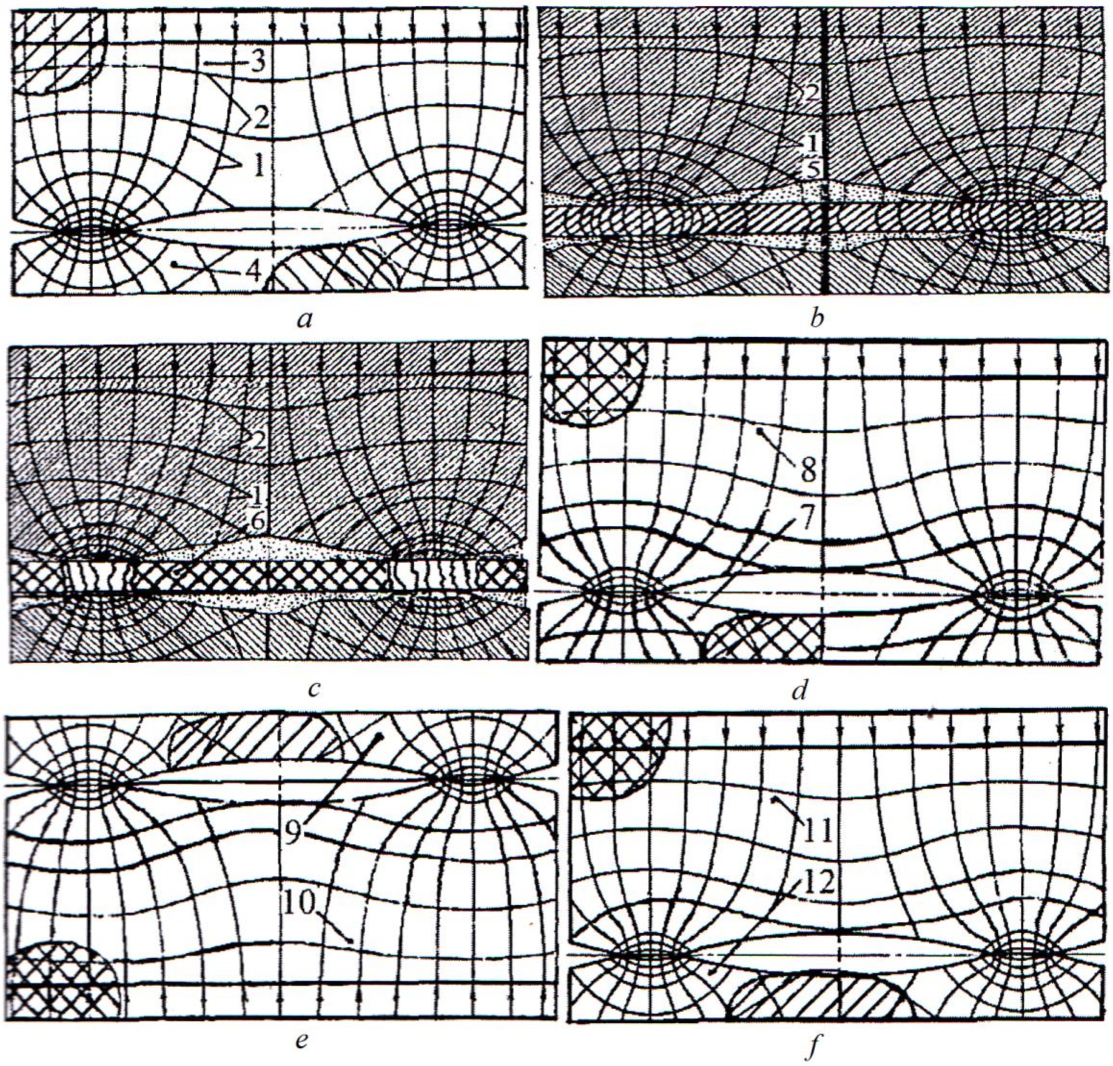

Figure 4 – Thermal current lines (7) and isotherms (2) during frictional interaction of contacts of friction pairs: a – “metal (3) - metal (4)”; b – “metal (3) - metal film (5) - metal (4)”; c – “metal (3) - polymer film (6) - metal (4)”; d – “polymer (7) - polymer (5)”; e – “metal (9) - polymer (10)”; f – “polymer (11) - metal (12)”

Metallic and quasi-metallic conductivity areas are not uniformly distributed over the contact area for the case of contact between two microprotrusions, when the average value of the specific loads depends on which branch (running or escaping) of the brake band the friction linings with their approaching and escaping surfaces are located on. When spherical surfaces come into contact, the specific pressure changes according to an elliptical law, decreasing from the center of the contact pad to the periphery, and is equal to zero at the boundaries of the pad (Hertz problem). In accordance with this, the ratio of the number of areas with metallic and quasi-metallic conductivity changes: areas with metallic conductivity predominate in the center, and areas with quasi-metallic conductivity predominate at the periphery. Moreover, on the boundary strip there is a zone consisting only of areas with quasi-metallic conductivity. This is very important when working at high frequencies of mechanical vibrations of microprotrusions located on the working surface of the pads. In this case, the generated electric current shifts to the outer surfaces of the contact spots of microprotrusions covered with oxide films with high resistance, that is, to a zone with quasi-metallic conductivity. Therefore, with an increase in the frequency of mechanical vibrations of the microprotrusions of the linings, the transition resistance of the contact pairs increases especially intensively, starting from 1,1 kHz.

In the general case, the contact resistance of the contacts is determined by the pulling resistance Rc and the resistance of the surface film R_f and is expressed by dependence 3.

Pull resistance R_p due to the roughness of the contact surface and the nature of the contact (microprotrusions). Surface film resistance R_f due to the presence of non-conducting or semi-conducting films on the surfaces of the contact spots.

The resistance to tightening the protrusions with the radius of the contact area (a) is described by dependence 4 and, in its final form, by expression 5.

Subsequently, when contacting metal-polymer spots, dependence 6 was obtained.

And finally, expression 7 is obtained, which describes the resistance to contraction of microcurrents on the contact spots of microprotrusions of friction pairs.

The surface resistance is mainly due to the resistance of the quasi-metallic areas, since the resistance of the metallic areas is relatively small.

After that, the resistance of the films of the contact spots of the microprotrusions was determined using expression 8, and then dependence 9 was obtained to determine the transition resistance. The resulting formula is valid for strong thin films at specific loads up to 1.5 MPa, i.e. until the working surfaces of the linings are destroyed. Under significant specific loads, the surface films are destroyed, the dimensions of the contact metal surfaces increase, and the transition resistance is almost completely determined by the tensile resistance.

Modern research shows that the total conductivity of contacts is much more complex and consists of the following types: metallic, quasi-metallic (semiconductor), cold emission, thermal emission, gas discharge, electrochemical and thermo-emf. However, the main influence on conductivity is exerted by the first two types of conductivity - metallic and quasi-metallic.

It is advisable to present the operating diagram of the electrical contact of the microprojection spots of friction pairs in general form as shown in Fig. 5.

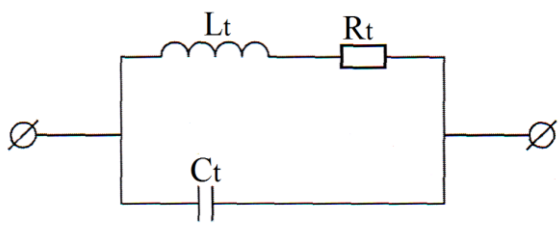

Figure 5 – Equivalent circuit of electrical contact of microprotrusions of friction pairs

The transition zone, like any resistance, has inductance (L_t) and capacitance (C_t), which form the reactance of this zone.

At low frequencies of microcurrents and at their variable magnitude, the influence of reactance is negligible.

Thermal contact resistance in fixed joints. As an example, consider the contact of two coaxial cylinders, the upper one of which is the working surface of the rim of a band-shoe brake pulley, and the lower one is a chamber with liquid for forced cooling of the upper cylinder.

The contacting cylinders are shells loaded with external pulsed specific pressure p_1 caused by the frictional interaction of the microprotrusions of the brake friction pairs. The specific load p_2 acts on the liquid side. The geometric dimensions, mechanical and physical properties of the shell materials are known. In this case, the heat flow is evenly distributed over the outer cylinder (Fig. 6).

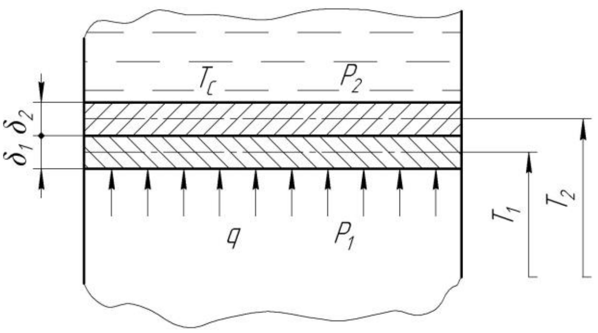

Figure 6 – Cylindrical contact model

In order to determine the specific loads in the contact zone from the condition of maintaining contact under elastic and thermal deformations, an equation for the radial displacements of the shells is compiled. Expressing thermal displacement in terms of temperature, and elastic displacement in terms of specific load, we can obtain the expression

$$p = \gamma\Delta\theta + p^*,$$

where $\Delta\theta = \alpha_1(T_1 - T_{01}) - \frac{r_2}{r_1}\alpha_2(T_2 - T_{02})$ -

- a dimensionless parameter depending on the temperature distribution in the shells and the ratio of their radii and the meaning of excess thermal deformation of the inner shell;

$$\gamma = r_1\left(\frac{r_1^2}{\delta_1 E_1} + \frac{r_2^2}{\delta_2 E_2}\right)^{-1},$$

where γ – constant coefficient, E_1, E_2 – Young's modulus of cylinder materials.

$$p^* = \left(\frac{r_1^2 p_1}{\delta_1 E_1} + \frac{r_2^2 p_2}{\delta_2 E_2}\right)\left(\frac{r_1^2}{\delta_1 E_1} + \frac{r_2^2}{\delta_2 E_2}\right)^{-1} -$$

coefficient reflecting the influence of external specific pressure; α_1 and α_2 – linear expansion coefficients.

After a series of transformations, a criterion equation that characterizes the dependence of the pressure on the contacting cylinders on the heat flow and physical and mechanical properties of the contact:

$$\frac{p}{p_m} = Q\left(\frac{\alpha_{\kappa m}}{\alpha_\kappa} + H\right) + \frac{p^*}{p_m} + N, \qquad (10)$$

where $Q = q\gamma\alpha_1 / p_m\alpha_{\kappa m}$ – dimensionless criterion determined by the magnitude of the thermal load; $N = \gamma\Delta\theta_0 / p_m$ - dimensionless criterion determined by initial conditions; $H = \alpha_{1,2}\alpha_{\kappa m} / \alpha_1\alpha$ – dimensionless criterion, the value of which depends on the cooling conditions of the outer shell; p_m and $\alpha_{\kappa m}$ – maximum values of pressure and thermal conductivity of the contact, corresponding to plastic deformation of the material of one of the shells; α – coolant heat transfer coefficient;

$$\alpha_{1,2} = \alpha_1 - \frac{r_2}{r_1}\alpha_2;$$

$$\Delta\theta_0 = \alpha_{1,2}(T_0 - T_{02}) - \alpha_1\Delta T_0;$$

T_c – coolant temperature; $\Delta T_0 = T_{01} - T_{02}$, where T_{01} and T_{02} – temperatures of the first and second cylinders, corresponding to the absence of thermal stress.

After the thermal load reaches a certain value $Q = Q_1$, at which $p = p_m$, left side of the equation (9) and the first term in brackets turns to one.

Thus, for equation (9) looks like:

$$1 = Q(1 - H) + \frac{p^*}{p_m} + N.$$

In the special case, when decreasing Q, starting from some value $Q = Q_2$, pressure p can become negative, which physically means separation of the shells, i.e., in this case, the value of contact conductivity α_c is determined only by the conductivity of the gas layer. The value of contact conductivity α_c, which is included in dependence (9), can be determined by any of the known methods obtained by plane contacting.

Thus, the presented technique allows, with some assumptions, to determine the value of contact pressure in composite cylindrical structures of fuel elements depending on the heat flow passing through the cladding, the temperature of the cladding and the physical and chemical characteristics of the materials.

Capacity of the transition zone of contact resistance of microprotrusions of friction pairs

The contacting surfaces of microprotrusions always have a certain roughness, so their actual contact occurs only in individual spots. Other microprotrusions, at the moment of touching the surfaces of the spots, are at a distance that is commensurate with the size of the atoms, and form areas with high local capacitance, connected in parallel with the conducting areas located on the surfaces of the microprotrusions. As for the presence of a surface film on the contacts in some spots of microprotrusions at specific loads below the tensile strength of the film, it does not collapse, but contributes to the creation of a semiconductor structure. Some of the films may have insulating properties that contribute to the formation of areas with high local capacitance. The latter is enhanced when wear debris gets between the micro-protrusions, since they are negatively charged. When wear products get on the surface of the microprotrusion spots, the double electrical layer of the metal friction element is strengthened, and, as a result, the potential difference between the microprotrusions of the friction pairs increases. As a result, a decrease in local capacitance between the contact spots of micro-protrusions is observed.

In general, the transition capacitance at alternating current of two rough contact spots of microprotrusions will be equal to the sum of the capacitances of each protrusion

$$C_{tc} = C'_{cf} + C''_{cu} + C_{cn} = \sum_{i=1}^{n'} C'_{ci} + \sum_{i=1}^{n''} C''_{ui} + \sum_{i=1}^{n} C_{ni}, \quad (11)$$

where C_{tc} – transition capacitance of two contacts; C'_{cf} – capacity of contacting protrusions with destroyed surface film; C''_{cu} – capacity of contacting protrusions with unbroken surface film; C_{cn} – capacity of non-contacting protrusions.

The contact diagram of two rough surfaces of microprotrusions is shown in Fig. 7. The capacitance value of a capacitor with a dielectric (polymer pad) and the electrical charge accumulated in it are determined by several polarization mechanisms, which are different for different dielectrics and can occur simultaneously for the same material.

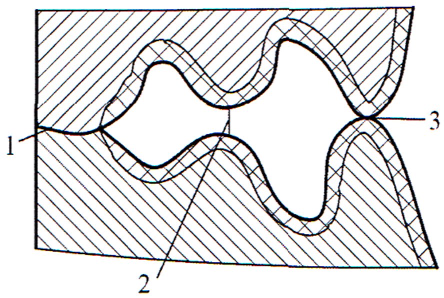

Figure 7 – Scheme of contact of microprotrusions of metal-polymer friction pairs: 1, 3 – contact zone with destroyed and undamaged film (metal contact zone); 2 – no contact zone

The equivalent circuit of a dielectric, in which various polarization mechanisms exist, can be represented as a series of capacitors connected in parallel to a voltage source U, as shown in Fig. 8.

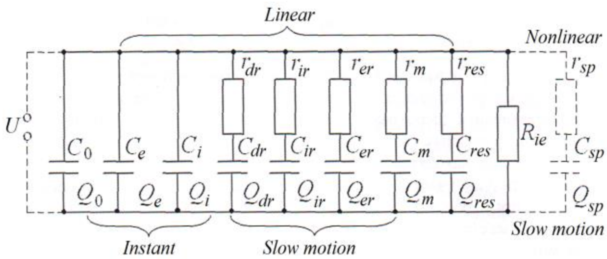

Figure 8 – Equivalent electrical circuit of a polymer pad

Capacitance C_0 and charge Q_0 correspond to the self-field of the electrodes if there is no dielectric (vacuum) in the space between them. All other values of C and Q correspond to various polarization mechanisms: electronic, ionic, dipole-relaxation, ion-relaxation, electron-relaxation, migration, resonance, and spontaneous, r means resistances, equivalent energy losses for these polarization mechanisms.

The capacitances of the equivalent circuit capacitors (Fig. 8) are shunted by insulation resistance R_{in}, representing the resistance of micro-protrusions of the polymer pad to the through electrical conductivity current.

Features of computer modeling of the energy load of metal-polymer brake friction pairs

The design micro- and milligeometric parameters of a friction connection influence all the main characteristics of the thermal regime of electrothermomechanical friction: patterns of heat flow distribution, surface temperature, temperature gradients and volumetric temperature distribution in friction interaction bodies.

The design influences the general patterns of generation and accumulation of electric and thermal currents through the dynamic coefficient of friction, and through the compliance of friction elements - the uniformity of the distribution of accumulated heat in the surface layers of friction pairs within the nominal contact area.

The initial assumptions of the model are as follows: the materials of the microprotrusion contact patch are homogeneous and isotropic; the contact is discrete in nature and occurs along the vertices of individual microprotrusions of roughness, the deformation of the microprotrusions is elastic in nature and is described by the Hertz dependence for the contact of two curvilinear smooth bodies with an initial contact at a point; the dimensions of individual contact spots are small compared to the dimensions of the interaction zone and the radii of curvature of the microprotrusions at the point of contact; in the contact zone only impulse normal forces and friction forces act; the distribution of contact spots over the surface of friction pairs is uniform.

Table 2 – Mechanical and electrical characteristics of the contact patch of two spherical microprotrusions of metal-polymer friction pairs

<table>
<tr><th colspan="3">Parameter name</th><th>Calculated dependence</th></tr>
<tr><td colspan="3">Radius of a single contact patch</td><td>$a = \left(0{,}75Nr / E\right)^{2/3}$; (12)</td></tr>
<tr><td colspan="3">Deformation of contacting microprotrusions</td><td>$\delta = \frac{a^2}{r} = \left[\left(0{,}56N^2 / \left(rE^2\right)\right)\right]^{0,25}$ (13)</td></tr>
<tr><td rowspan="2">Specific load on the contact patch of microprotrusions</td><td colspan="2">maximum</td><td>$P_1 = \left(\frac{6NE^2}{\pi^2 a^2}\right) = 1{,}5N / \left(\pi a^2\right)$; (14)</td></tr>
<tr><td colspan="2">average</td><td>$P_2 = 0{,}66P_1 = N / \left(\pi a^2\right)$; (15)</td></tr>
<tr><td colspan="3">Reduced Young's modulus</td><td>$1/E = \left(1-\mu_1^2\right)/E_1 + \left(1-\mu_2^2\right)/E_2$;(16)</td></tr>
<tr><td rowspan="3">Average penetration depth of elements into the body</td><td>polymer</td><td rowspan="2">warmth</td><td>$b_1 = 1{,}73\sqrt{a_1\tau}$; (17)</td></tr>
<tr><td rowspan="2">metal</td><td>$b_2 = 1{,}73\sqrt{a_2\tau}$; (18)</td></tr>
<tr><td>current</td><td>$b_3 = 0{,}05\sqrt{\rho/\left(\nu\mu_3\right)}$; (19)</td></tr>
<tr><td colspan="3">Current strength</td><td>$I = \sqrt{\frac{t_{\max} \cdot \alpha_T \cdot l_c}{R_c \cdot \rho}}$. (20)</td></tr>
</table>

The initial data for the calculation are the characteristics of the microgeometry of the surfaces - the maximum height of the protrusions above the center line of the profile R_p and the maximum radius of curvature of the protrusions r_{max}; physical and mechanical characteristics of the material – elastic modulus (Young's modulus) E, Poisson's ratio μ, electrical resistivity of the material ρ; operational characteristics, impulse normal force, compressive contact [5].

In table 2 presents the main dependencies for calculating the characteristics of a single contact of two spherical microprotrusions of the contact patch. In dependencies (11)-(19) the following symbols are used: N – impulse normal force, кN; E – reduced modulus of elasticity of materials of contacting microprotrusions, MPa; a_1 a_2 – thermal diffusivity coefficients of materials of contacting microprotrusions, m^2/s; τ – friction interaction time, c; μ_1, μ_2 – Poisson's ratios of materials of contacting microprotrusions; ν – vibration frequency of microprotrusions, s^{-1}; μ_3 – relative magnetic permeability of microprotrusion materials; t_{max} – maximum temperature at the contact patch of microprotrusions, °C; α_m – external heat transfer coefficient, W/(m^2 ·°C); R_c - thermal contact resistance, °C/W; l_c - contact length, mm.

The computer model is practically implemented in the form of a Windows application, written in C++ using the Borland class library. The software model is included in the main calculation module, which includes the assessment of external and internal parameters of metal-polymer friction pairs at the macro, micro and nano levels [8].

In addition to the main one, there is an additional module responsible for the convenience of data presentation and user interface. The result of the work is the operational characteristics of the contact, presented in table form. For greater clarity, based on the proposed formulas, it is possible to construct graphs of the dependences of the contact characteristics on external factors, which are the currents of the washing air and mixture components.

Within the computer model, the contact characteristics are calculated as follows. A pair of random numbers is generated, distributed according to a given law, corresponding to the height and radius of the protrusion of the rough surface. The logic of the program is illustrated by the block diagram of the main calculation module for the parameters of mechanical, electric and thermal fields (Fig. 9).

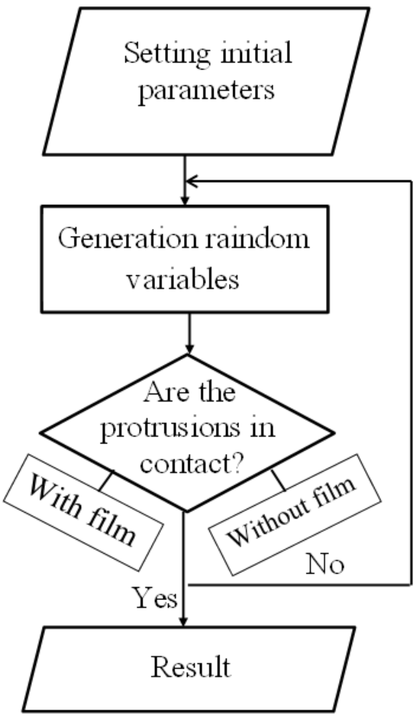

Figure 9 – Block diagram of the main calculation module

The program is connected to an MS Access database consisting of two tables, each of which includes 33 fields. The first table contains the values of the initial intermediate data, and the second table contains the values of the results. Tables are used to construct graphs [9-12].

In this case, the first field of each table is reserved for the verified initial combination of initial parameters and is used only at the beginning of work and for reading only. First of all, the program reads the initial combination of initial parameters from the database and supplements the initial data fields with these values. Then the user edits them, performs calculations, after which a table of values is filled in and a graph is built from it [9].

The adequacy of the model was checked by comparing the modeling results with data from the works of other authors obtained on the basis of analytical models for some special cases [4-6].

Conclusion

Thus, a method has been proposed for determining the contact electrical thermal resistance during frictional interaction of the contact spots of microprotrusions of friction pairs of brake devices for a more accurate assessment of the energy load of their surface layers.

Conflict of interests

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

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