The Role of Contact Spots of Friction Pairs of Microprotrusions in The Energy Loading of Braking Devices

D.A. Volchenko[1], H.F. Miralamov[2], V.S. Skrypnyk[1], N.A. Volchenko[3], D.Y. Juravlev[1]

[1] *Ivano-Frankivsk National Technical University of Oil and Gas (Ivano-Frankivsk, Ukraine)*
[2] *Azerbaijan Engineering Academy (Mardakan ave. 30, Baku, AZ1045, Azerbaijan)*
[3] *Kuban State Technological University (Moskovskaya st. 2, bld. A, Krasnodar, 350072, Russia)*

For correspondence:
Skrypnyk Vasily / e-mail: skripnik-vs07@ukr.net

Abstract

The article demonstrates that the presence of temperatures (flash, surface and volume) requires clarification that there is still a steady temperature and a thermal stabilization state of a metal friction element, when the temperature gradient over its thickness remains constant and minimal for some time. Relationships between one and two materials of metal friction linings with impulsive normal forces and current surface-volume temperatures of friction pairs and the allowable temperature of the FK-24A material are established. The introduction of the obtained data on the energy levels of the contact patches of microprotrusions of friction pairs of brakes will significantly improve their quality and significantly reduce the volume of tribological studies.

Keywords: braking devices, friction pairs, microprotrusion contact spots, dynamic and thermal load.

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Əyləc qurğularının enerji yüklənməsində sürtünmə cütü mikroçıxıntılarının kontakt ləkələrinin rolu

D.A. Volçenko[1], H.F. Mirələmov[2], V.S. Skrıpnık[1], N.A. Volçenko[3], D.Y. Juravlev[1]

[1]İvano-Frankivsk Milli Texniki Neft və Qaz Universiteti (Karpatska küç.15, İvano-Frankivsk, 76019, Ukrayna)
[2]Azərbaycan Mühəndislik Akademiyası (Mərdəkan pr. 30, Bakı, AZ1045, Azərbaycan)
[3]Kuban Dövlət Texnologiya Universiteti (Moskovskaya küç. 2, Krasnodar, 350072, Rusiya)

Yazışma üçün:
Skrıpnık Vasiliy / e-mail: skripnik-vs07@ukr.net

Xülasə

Məqalədə göstərilir ki, səth və həcmi temperaturlarının işıltısının mövcudluğu, onun qalınlığı üzərindəki temperatur qradiyenti bir müddət sabit və minimal qaldıqda belə, qərarlaşmış temperatur və metal sürtünmə elementinin termostabilizasiya vəziyyətinin də mövcud olmasının dəqiqləşdirilməsini tələb edir. Metal friksion kündələrin bir və iki materialları ilə impuls normal qüvvə, sürtünmə cütünün cari səth-həcmi temperaturu və ФК-24А materialının buraxıla bilən temperaturu arasında nisbətlər müəyyən edilmişdir. Əyləclərin sürtünmə cütlərinin mikroçıxıntılarının kontakt ləkələrinin enerji səviyyələri haqqında məlumatlar əldə edilmişdir.

Açar sözlər: əyləc qurğusu, sürtünmə cütü, mikroçıxıntıların kontakt ləkəsi, dinamik və istilik yüklənmə.

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Роль пятен контактов микровыступов пар трения в энергонагруженности тормозных устройств

Д.А. Вольченко[1], Г.Ф. Мираламов[2], В.С. Скрыпнык[1], Н.А. Вольченко[3], Д. Ю. Журавлев[1]

[1] Ивано-Франковский национальный технический университет нефти и газа (г. Ивано-Франковск, Украина)
[2] Азербайджанская Инженерная академия (Мардакянский пр. 30, Баку, AZ1045, Азербайджан)
[3] Кубанский государственный технологический университет (ул. Московская, 2, Краснодар, 350072, Россия)

Для переписки:
Скрыпнык Василий / e-mail: skripnik-vs07@ukr.net

Аннотация

В статье показано, что наличие вспышки, поверхностной и объемной температур требует уточнения, так как есть еще установившаяся температура и термостабилизационное состояние металлического фрикционного элемента, когда градиент температуры по ее толщине на некоторое время остается постоянным и минимальным. Установлены соотношения между одним и двумя материалами металлических фрикционных накладок с импульсными нормальными силами и текущими поверхностно-объемными температурами пар трения и допустимой температурой материала ФК-24А. Получены данные об энергетических уровнях пятен контактов микровыступов пар трения тормозов.

Ключевые слова: тормозные устройства, пары трения, пятна контактов микровыступов, динамическая и тепловая нагрузка.

Introduction

Both the rheological characteristics that determine the contact interactions of the spots of microprotrusions of the friction sur-faces of the brakes and the frictional characteristics of friction depend on the energy load of the friction unit. In the process of sliding friction surfaces, heat is generated and its surface-volume temperature rises. With the relative rest of the friction surfaces due to the removal of heat, the surface-volume temperature de-creases.

Heat removal from matte and polished surfaces of metal friction elements also takes place with relative sliding of friction surfaces. The wear resistance of friction surfaces depends on the rheological and frictional characteristics of the friction pairs and, therefore, on the surface-volume temperatures of heating of the friction pairs.

Analysis of literature data and statement of the problem

The paper [1] presents the results of a study of the friction force up to the slip threshold. With the help of a second-order differential equation relating stresses and deformations of bodies under the action of forces, the laws of change in the friction force, as well as the criterion for choosing materials for friction pairs, are established. Only the mechanical component of the friction power was taken into account.

The work [2] is devoted to the study of impulse specific loads in friction pairs of a drawworks band-shoe brake. In the latter, no attention was paid to the displacement of the contact of microprotrusions of friction pairs up to the slip threshold. This parameter significantly affects the static coefficient of mutual overlap of brake friction pairs.

The work [3] is devoted to deformations of contact patches of microprotrusions of friction pairs of a band-shoe brake. However, it did not consider the displacement of contacts of microprotrusions and their influence on the increase in the area of frictional interaction. The change in the free energy of the near-surface layers of metal friction elements is given in [4]. However, this did not take into account the type of contact for the displacement of the contacts of microprotrusions of friction pairs under the action of an external energy impact. The work [5] considers neutral, blocking and ohmic contacts of microprotrusions of brake friction pairs. At the same time, the influence of the energy levels of various types of contacts on their displacement was not established. A significant part of the stresses arising in the process of electro-thermomechanical braking is concentrated in the surface layers of metal friction elements. In microzones of actual touch spots, as shown in [6, 7]. These stresses become proportional to the flash points and cause strong heating in thin layers of the friction surface, leading to the formation of burns, thermal spots and microcracks. During cooling after braking of the friction element, a temperature gradient occurs, causing large thermal stresses. Surface temperature gradients determine the non-uniformity of the thermal field [8], and temperature gradients across the thickness of the metal friction element determine the thermo-stable state [9].

The constant value of the surface temperature gradient is characteristic of the steady temperature, when the amount of heat generated on the friction surface for some time is equal to the amount of heat removed to the environment. With a thermally stable state of a metal element, the temperature gradient over its thickness becomes minimal in magnitude.

The following questions were included in the materials of the article: levels of energy loading of friction pairs of brakes; energy levels of contact patches of microprotrusions of friction pairs under their dynamic loading; the discussion of the results.

The aim of the work is to establish the role of contact spots of microprotrusions in the formation of thermal fields in friction pairs of braking devices.

Levels of energy loading of friction pairs of brakes

The levels of energy loading of friction pairs of brakes are determined by the flash temperatures, surface and volume, which are characteristic of a thermal field. We believe that it is in the surface layer that, under the action of the flash temperature ϑ_{fl}, thermal fatigue cracks are initiated. These cracks develop further between braking cycles as a result of cooling of the surface layer and the formation of a temperature gradient from ϑ^*, when the thermal stresses under the surface layer reach the highest values. With an increase in the surface-volume temperature, the nature of the transformation of structural components in the material changes, the strength of the grain boundaries decreases, and the oxidation rate increases. All these processes affect the crack initiation mechanism.

Considering that the temperature flash can quickly reach several hundred degrees, these instantaneous temperature rises can bring the material into a state of plasticity, when the frictional resistance drops. Also, since the temperatures at the actual contact spots of microprotrusions do not exist for long (10^{-3}-10^{-6}) s, it is not the properties of the static strength of the surface layer of the materials of the friction pair that are important, but the properties of fatigue strength, given that the crystal lattice of a solid body reacts on impacts through 10^{-5}-10^{-8} s [8]. Therefore, the restructuring of the surface layer under the action of external thermal loads occurs precisely in the process of the formation of the temperature field, and by the time the thermal stabilization state is reached, the surface layer is already under the action of certain residual stresses. The formula proposed in [8] was used to calculate the flash temperature ϑ_{fl} on a single microprotrusion contact spot:

$$\vartheta_{fl} = \frac{\sqrt{2}+1}{\sqrt{2}} \frac{\alpha_2 \sqrt{a_2}\, N_{fr}}{A_r \left[4\lambda_1 \sqrt{a_2} + \alpha_2 \sqrt{\sin d_r / \dot{S}_k - \dot{S}_{k+1}} \right]}, \quad (1)$$

where d_r – average diameter of microprotrusion touch spots; A_r – area of the actual touch spot; λ_1, λ_2 – coefficient of thermal conductivity of materials of micro protrusions of friction pairs; a_2 – coefficient of thermal diffusivity of the friction lining material; $\dot{S}_k - \dot{S}_{k+1}$ - sliding speeds of conjugate friction pairs.

Dependence (1) is valid for Peclet numbers $Pe = Vd_2 / a_2 \geq 20$. Typically, friction units operate at high initial relative speeds, usually at $\mathrm{Pe} \geq 20$. At the end of the sliding stage of the friction surfaces, when the speeds $V = \dot{S}_k - \dot{S}_{k+1}$ become small $\mathrm{Pe} \leq 20$, flash point ϑ_{fl} is small and is less than 5% of the surface-volume temperature ϑ. Based on this, the formula for determining ϑ_{fl} at $\mathrm{Pe} \leq 20$ unsuitable. Taking into account that plastic deformations of microprotrusions take place during heating, the area of the actual spot of their contact is determined by the following approximate dependence

$$A_r = N / HB_2, \quad (2)$$

where N – impulsive normal load on friction surfaces; HB_2 - Brinell hardness of the friction lining material.

The average diameter of a microprotrusion spot for a plastic microcontact is determined by the formula

$$d_r = \sqrt{\frac{8r_1h_{1m}}{\nu}}\left[\frac{N}{A_{c1}b_{01}HB_2}\right]^{0,5\nu_1}, \qquad (3)$$

where r_1, h_{1m} – radius of curvature and maximum height of microprotrusions; b_{01}, v_1 – parameters of the reference curve of microroughnesses; A_{c1} – contour contact area.

So, to calculate the average temperature on the i-th friction contact patch, the dependence has the form

$$\vartheta_{fl} = \frac{\alpha_{\text{hfdi}}\psi_i b_i}{k_{\text{cca}}A_{ai}\lambda_i}\left\{\left\{\frac{1}{3} - \frac{2}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\cdot\exp\left[-\alpha_i\left(\frac{\pi n}{b_i}\right)^2 t\right]\right\}N_{fr} + \frac{a_i}{b_i}W_{fr}\right\}, \qquad (4)$$

where α_{hfdi} - heat flow distribution coefficient, determining the share of the heat flux passing through the i-th surface of the contact spots of microprotrusions during friction ψ_i – coefficient taking into account the effective heat absorption of the volume of microprotrusions; b_i – average effective thickness of the i-th microprotrusions of friction pairs; k_{cca} – coefficient characterizing the formation of the constructive contour area of the microprotrusion contact patch; A_{ai} – nominal area of contact of surfaces of spots of microprotrusions; $a_i = \lambda_i/(c_i\rho_i)$ - thermal diffusivity (here λ_i – coefficient of thermal conductivity, c_i – specific mass heat capacity, ρ_i – material density of the i-th part constituting the friction pair); N_{fr} и W_{fr} – power and work of friction.

Friction pairs, consisting of metallic and non-metallic friction elements, washed by air flows in braking devices, are multilayer objects. The latter includes the working layer of the friction pair [8].

The process of formation of the working layer depends on the thermal mode of operation of the rubbing pair. There may be cases when the metal working layer does not have time to form, and then a very intensive spreading of the metal of the metal element of the pair (steel or cast iron) on the surface of the friction lining can occur.

The heat transfer coefficient in the heat exchange process through such a multilayer object as "the environment of the intercontact zone - a metal friction element - washing air" is determined by the dependence of the form:

$$K_1 = \frac{1}{\frac{1}{\alpha_1} + \frac{\delta_1}{\lambda_1} + \frac{1}{\alpha_1}}, \qquad (5)$$

where α_1, α_2 - heat transfer coefficients from: intercontact medium to the working (polished) surface of the metal friction element; its outer (matt) surface to the washing air; δ_1, λ_1 - the thickness of the rim and the coefficient of thermal conductivity of the metallic friction element.

The heat transfer coefficient in the heat exchange process through the "medium of the intercontact zone - the near-surface layer of the friction lining - the body of the friction lining - the base of the brake shoe - the air washing it" is determined by the dependence of the form:

$$K_2 = \frac{1}{\frac{1}{\alpha_1} + \left(\frac{\delta_{sl}}{\lambda_{sl}} + \frac{\delta_l}{\lambda_l} + \frac{\delta_b}{\lambda_b}\right) + \frac{1}{\alpha_3}}, \qquad (6)$$

where α_3 - heat transfer coefficient from the matte surface of the base of the brake pad to the washing air; δ_{sl}, δ_l, δ_b - thickness: the surface layer of the friction lining, the lining itself and the base of the brake shoe; λ_{sl}, λ_l, λ_b - thermal conductivity coefficients: the surface layer of the lining, the lining itself and the base of the brake shoe.

If the stabilization thermal state is

reached by the metal friction element of the brake device, the dependence for determining the heat transfer coefficient through the "washing air - the metal friction element, the medium of the intercontact zone - the surface layer of the friction lining" is determined by the dependence:

$$K_3 = \frac{1}{\frac{1}{\alpha_2} + \frac{\delta_1}{\lambda_1} + \frac{1}{\alpha_1} + \frac{\delta_{sl}}{\lambda_{sl}}}. \quad (7)$$

Dependencies (6) and (7) take into account the thermal resistance of the near-surface layer $\left(\frac{\delta_{sl}}{\lambda_{sl}}\right)$ of the friction lining, the value of which determines the direction of the heat flow.

Based on the values of heat transfer coefficients in friction pairs, we determine the coefficients of heat distribution between their elements during braking:

$$K = \frac{K'_{av}}{\sum K'_{av} + \sum K''_{av}}, \quad (8)$$

where $\sum K'_{av}$ - average value of heat transfer coefficients in the heat-exchange process "medium of the intercontact zone - metal friction element - air washing it" for the period of time from the beginning to the end of braking; $\sum K''_{av}$ - the average value of the heat transfer coefficients in the heat exchange process of the multilayer object "medium of the intercontact zone - near-surface layer of the friction lining - the body of the friction lining - the base of the brake shoe - the air washing it" for a period of time from the beginning to the end of braking.

It has been established that the increase in bulk temperature under conditions of heat transfer to the environment is quasi-proportional to the increase in the work of friction, and at the same time, the increase in volume temperature is always less than the increase in the increase in surface temperature over the same time, and the decrease in volume temperature as a result of heat transfer to the environment occurs according to Newton's exponential law [8].

As a result, the following dependence was obtained for estimating the average bulk temperature at the stage of sliding friction surfaces

$$\vartheta_V(t) = \vartheta_{VO} + \left[\vartheta_V(t_{BS}) - \vartheta_{VO}\right] e^{-K_2(t-t_{BS})} + \\ + K_1 \int_{t_{HC}}^{t} N_T(\tau) e^{-K_2(t-\tau)} d\tau. \quad (9)$$

where ϑ_{VO} - ambient temperature; K_1' and K_2' – constant coefficients depending on the thermophysical properties of materials and the design of the friction unit; N_{fr}(t) – friction power; $\vartheta_V(t_{BS})$ - average bulk temperature of a node at a moment of time t_{BS}, corresponding to the beginning of the slide.

The average bulk temperature at the stage of relative rest will be determined by the dependence

$$\vartheta_V(t) = \vartheta_{VO} + \left[\vartheta_V(t_{BR}) - \vartheta_{VO}\right] e^{-K_2(t-t_{BR})}, \quad (10)$$

where t_{BR} – the time of the beginning of the relative rest stage.

In the process of heating the friction units, the hardness of the materials of the friction elements decreases. In [9], the dependence of the hardness of the surface-bulk temperature was obtained as a result of processing experimental data

$$HB_2 = HB_{20}\left\{m_1 + \frac{m_2}{\left[m_3\left(\vartheta^* + \vartheta''_{VII} - \vartheta'_m\right)\right]^2 + 1}\right\}, \quad (11)$$

where HB_{20} – material hardness at normal temperature; m_1, m_2, m_3 – constant coefficients; ϑ'_m - the value of the surface-volume temperature at which HB (ϑ) maximum.

Energy levels of contact spots of microprotrusions of friction pairs under loading

The friction and wear characteristics of the friction pairs of the friction units of the brake change significantly depending on how the braking energy is absorbed. The latter largely depends on the method of its supply (impulse or continuous) in the process of braking. With the first method, a significant part of the friction work is realized at the initial stage of braking, and with the second method, the friction work is distributed over time more evenly. This determines the nature of the temperature fields, the values of surface and bulk temperatures, and their temperature gradients.

According to the molecular-mechanical theory of friction, implemented through electrothermomechanical frictional interaction, the dynamic coefficient of friction depends on the mechanical properties of the materials of the pair, the microgeometry of the contact spots of the protrusions of the elements of the friction pairs, which regulate the energy levels of the conduction contacts (ohmic, blocking and neutral) and adhesive properties [5, 8, 14].

All electrothermomechanical processes on the microcontact that affect the characteristics listed above also affect friction. During braking, the generated electric currents and the accumulated thermal currents at the friction contact change, occur at the friction contact, structural transformations occur, physico-chemical reactions occur, and the properties of the surface layers of the materials of the friction pair change. The intensity of these processes is influenced by the load (impulse or continuous), sliding speed, temperatures (flash, surface and volume) and washing currents of the environment. Under the conditions of an unsteady friction process, these factors change continuously.

The processes of electrothermomechanical friction are carried out on the actual contact area, consisting of many discrete contacts with different electrothermal resistance, and, as a result, with different energy activity, accompanied by microcapacitors and microthermobatteries with their instantaneous switching when the areas of contact spots of microprotrusions change, subject to the conditions at the first stage of frictional interaction ($A_f < A_n$), based on the fact that the actual contact area (A_f) small compared to nominal (A_n) and at the same time, the components of the generated electric currents are summed, and under the condition $A_n = A_f$ the triboEMF is fixed in conjunction with the variable gradients of the mechanical properties of its materials. The rate of penetration of interacting pulses of electric and thermal currents affects the intensity of wear of microprotrusions during repolarization, and the magnitudes of thermal currents on the surfaces of the contact spots of microprotrusions are determined using the hypothesis of summation of temperatures on the surface, taking into account the generated electric currents

$$t_{GEN} = t_S + \Delta t_{S1}, \quad (12)$$

where t_S – surface temperature; Δt_{S1} – surface temperature that develops from the action of generated electric currents.

When analyzing the actual and contour contact area, it was found that they are continuously changing, since the mechanical properties of the materials of their surface and near-surface layers change under the influence of temperature deformations and stresses and are subject to wear. The contour contact areas are unevenly distributed over the surface, their distribution and migration also depend on the load and wear.

It is known that the surface temperature of friction pairs is an integral factor reflecting the effect of the heat flux intensity on the friction contact q (specific friction power N_T), those joint effect of specific load (p), sliding speed (V) & dynamic coefficient of friction (f):

$$N = q_t = fpV. \qquad (13)$$

Based on the foregoing, let's move on to the analysis of experimental data obtained in the laboratory.

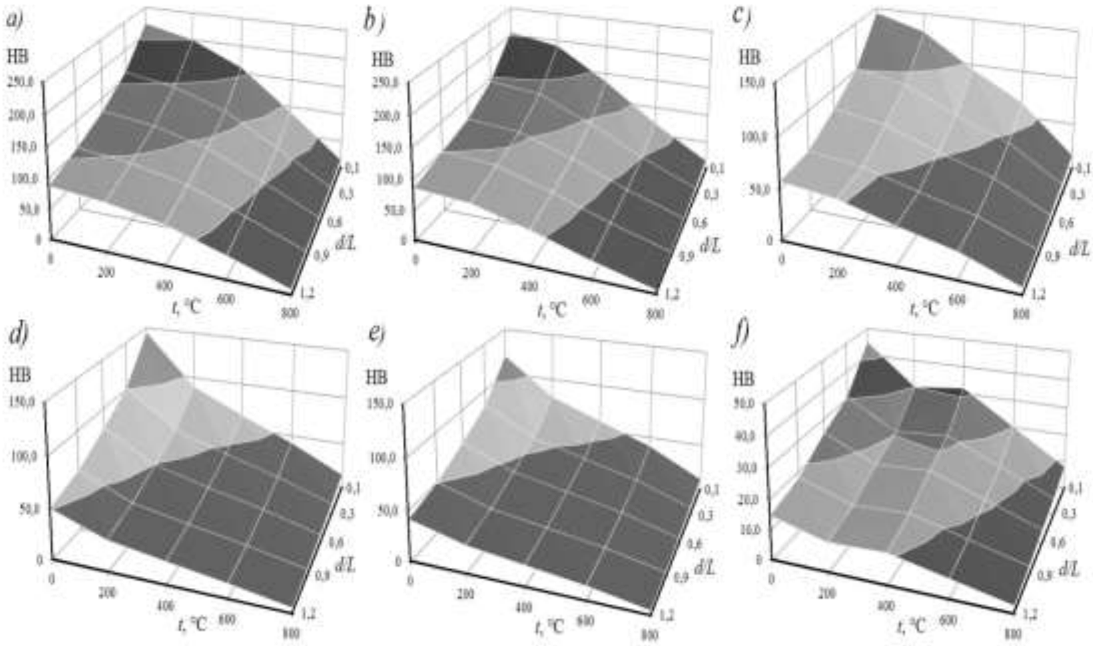

Figure 1 a, b, c, d, e, f. – Patterns of changes in the hardness of HB of various materials used in friction units, on temperature t and the relative value d/L (d, L are the diameter and friction path of the contact patch): a - steel 30KhGSA; b - cast iron ChNMKh; c – FPM brand FMK-845; d – FMK-11; e - FPM brand MVK-50A; f - retinax FK-16L

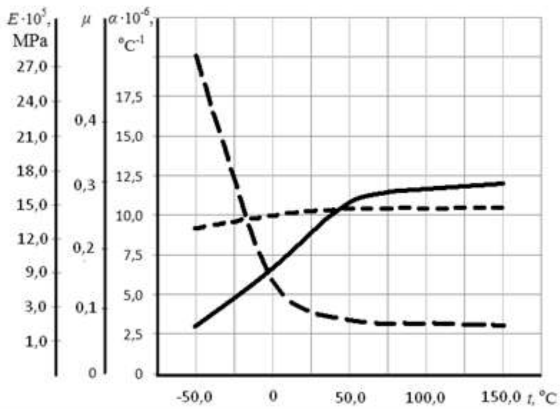

Figure 2 – Experimental dependences of the modulus of elasticity E( ), Poisson's ratio μ ( ) and linear expansion coefficient α ( ) steel 30HGSA on temperature t.

The discussion of the results

On fig. 2 shows the experimental graphical dependences of the modulus of elasticity (E), Poisson's ratio (μ) and linear expansion coefficient (α) steel 30HGSA from temperature (t) from which it follows that the specified parameters in the temperature range (50.0-10.0)ºC are constant. This is due to the fact that in the noted range of surface temperatures, a steady thermal state of friction pairs usually sets in.

As experimental studies and theoretical analysis show, the greatest influence on the change in the friction properties of materials during braking is exerted by the surface temperature at the friction contact. Indeed, temperature significantly affects the mechanical properties of friction pair materials (Fig. 1 *a*, *b*, *c*, *d*, *e*, *f*). Especially, the change in the hardness of HB metal friction elements is not noticeable (рис.1 *a*, *b*) from temperature (in the interval from 300 to 500 ºC) and relative to the value *d*/*L* (*d*, *L* – diameter and friction path of the contact patch). As for friction lining materials (рис.1 *c*, *d*, *e*, *f*), then in their surface layers in the above temperature range, the phenomenon of tribocracking took place, significantly reducing the hardness of the surface layers of the overlays.

It has been established that the ratio of the hardness of steel according to Brinell to the same parameter for cast iron (Fig. 2) is inversely proportional to the ratio of the acting impulse normal forces on cast iron and steel and is expressed by the equality

$$H_s/H_{ci} = N_s/N_{ci}. \qquad (14)$$

At the same time, the ratio of the current Brinell hardness value of cast iron or steel to the permissible value is proportional to the ratio of the current value of the surface-volume temperature of the friction lining (FK-24A material) and is expressed by the equation

$$H_{st}/H_{fl} = t_{st}/t_{fl} \qquad (15)$$

Substituting into relation (14) we got 1.6 = 1.65, and into the second (15) we have 0,376 = 0,375.

Theoretical and experimental studies of the energy loading of friction pairs of various types of braking devices with the separation of microprotrusion contact spots from them made it possible to establish the following: the presence of temperatures (flash, surface and volume) requires clarification that there is still a steady temperature and a thermal stabilization state of a metal friction element, when the temperature gradient over its thickness remains constant and minimal for some time; electrical and thermal processes on the contact patches of microprotrusions showed that the totality of temperatures and their gradients, depending on the work and friction power;
the ratio of the hardness of steel according to Brinell to the same parameter for cast iron is inversely proportional to the ratio of the acting impulse normal forces on cast iron and steel is expressed by the equality $H_s/H_{ci} = N_s/N_{ci}$; at the same time, the ratio of the current Brinell hardness value of cast iron or steel to its allowable value is proportional to the ratio of the current value of the surface-volume temperature to the value of the allowable surface temperature of the friction lining (FK-24A material) and is expressed by the equation $H_{st}/H_{fl} = t_{st}/t_{fl}$; the introduction of the obtained data on the energy levels of spots of contacts of microprotrusions of friction pairs of brakes in the form of data will significantly improve their quality and significantly reduce the volume of tribotechnical studies.

Conclusions

The role of contacts of microprotrusions of brake friction pairs in the formation of their energy loading has been proved.

REFERENCES

1. **Kapralova N. F.** Choice of materials for friction pairs. *Higher Educational Head, Mechanical Engineering,* No. 12. M. Pp. 29-34 *(in English)*

2. **Volchenko N.A., Volchenko D.A., Juravlev D.Yu., Stefanik V.** Band-shoe brake devices, 2013. - 441p. *(in English)*

3. **Janahmadov A.Kh., Volchenko D.A., Juravlev D.Y.** [and others]. Design and verification calculation of friction units of band-shoe brakes of drilling winches. Baku: *Apostrophe,* 2016. – 312 p. *(in English)*

4. **Landau L.D., Livshits E.M.** Theory of elasticity. M.: *Nauka*, 1987. – 248 p. *(in English)*

5. **Janahmadov A.Kh., Volchenko D.A., Juravlev D.Y.** [and others]. Disc and disc-shoe brakes in mechanical engineering. Volume 2. Baku: *Apostrophe-A*, 2021. - 392 p *(in Russian)*

6. **Janahmadov A.Kh., Volchenko D.A., Volchenko N.A.** [and others]. Tribology: friction, wear and lubrication. Baku*: "Apostrophe - A",* 2019. - 640 p *(in Russian)*

7. **Kindrachuk M.V., Volchenko D.A., Volchenko N.A., Stebeletskaya N.M., Voznyi A.V.** Influence of hydrogen on the wear resistance of materials in the friction couples of braking units. *Mater. sci.* 2017, 53, 282-288 *(in English)*

8. **Kragelsky I.V.** Friction and wear. M.: *Mashinostroenie,* 1986. - 430 p. *(in English)*

9. **Michelich, J.L., Troiano A.R.** Delayed failure in hydrogenated facecentred cubic alloy in nickel. Nature 1963, pp. 996-997 *(in English)*

10 **Warren S.C., Voitchovsky K., Dotan H., Leroy S.M., Cornuz M., Stellacci F., Hebert C., Rothschild A., Grätzel M.** Identifying champion nanostructures for solar water-splitting. *Nat. mater.* 2013, 12, 842-849 *(in English)*

11. **Felton J., Blundo E., Ling S., Glover J., Kudrynskyi Z.R., Makarovsky O., Kovalyuk Z.D., Besley E., Walker G., Polimeni A.** et al. The interaction of hydrogen with the Van der Waals crystal γ-InSe. *Molecules* 2020, 25, 2526 *(in English)*

12. **Mudd G.W., Svatek, S.A., Hague L., Makarovsky O., Kudrynskyi Z.R., Mellor C.J., Beton P.H., Eaves L., Novoselov K.S., Kovalyuk Z.D.** et al. High broad-band photoresponsivity of mechanically formed InSe-graphene Van der Waals heterostructures. Adv. mater. 2015, 27, 3760-3766 *(in English)*

13. **Jamrozik A., Tutak W., Grab-Rogalski K.** Combusting stability, performance and emission characteristics of a CI engine fueled with diesel/n-butanol blends. *Energies*, 2021, 14.2817 *(in English)*

14. **Chichinadze A.V., Berliner E.M., Brown E.D.** et al. Friction wear and lubrication (tribology and tribotechnics). M.: *Mashinostroenie*, 2003. - 576 p *(in English)*

15. **Janahmadov A.Kh., Volchenko D.A., Juravlev D.Y. Shasherina S.A., Romaniv N.N.** Ocenka energeticheskih urovnej kontaktov i tribologicheskih svojstv materialov par treniya. *Herald of the Azerbaijan Engineering Academy,* 2021, T.13, №4, c. 14-21 *(in Russian)*