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PROVIDING STABLE FRICTION PROPERTIES OF DISC BRAKES FOR RAILWAY VEHICLES

Summary. A new approach is developed to ensure the stability of the coefficient of friction at different braking modes for the entire speed range of braking high-speed ground transport. The new approach is a combination of friction materials with individual effort effects on the brake disc. A brake pad design and its performance are confirmed experimentally.

1. INTRODUCTION

The safety of open-cut, mountain, automotive and railway transport depends on stability and level of friction coefficient of friction brake, which in turn depends on the properties of friction materials. Product nomenclature of friction materials includes several hundreds of titles. Consumption friction materials in the world is dozens of thousands tons. There are a number of companies that develop and produce friction materials in the market. The most well-known world producers of this production are Federal-Mogul, Honeywell (the USA), TMD Friction (Germany), Becorit (Germany) and Wabtec (Canada). Currently, despite considerable financial expenditure, there is no frictional material for disc brakes that has fully acceptable operation properties in terms of power intensity, stability of the friction coefficient, wear intensity and cost. In addition, the development of new frictional materials leads to a steep increase in the cost of products.

An important task is to reduce the cost of brake systems, taking into consideration their great consumption at the transport. . Due to this, one of the promising research avenues is the search for new methods to create frictional properties for disc brakes that meet modern requirements.

There are two frictional materials in classic force schemes of disc brakes: material of the pad and material of the disc. The frictional properties of disc brakes are a function of the properties of friction materials and the conditions of their strength load.

The main problem involving disc brakes is the influence of the temperature generated while braking on the friction coefficient of working elements and the stability of its implementation. A solution for this problem is the goal of the researches carried out by V.I. Kolesnikov (analytical solution of heat problem), Jon Barber (issues of heat energy redistribution in case of an ideal thermal contact of friction elements), Przemyslaw Zagrodzki (researches of thermomechanical phenomena that occur while braking in the working elements of braking systems of high-speed vehicles), Banerjee Piyali, Wang Hui-ming (thermal problems solution by numerical methods on the bases of partial differential equations), etc.

2. UNSOLVED PROBLEM DEFINING

The alternative to creating new friction materials is establishing new properties of disc brakes due to a combination of several working materials in the friction unit that does not involve a significant change in brake disc design, its control tools and provides a stably high friction coefficient that is not negatively influenced by factors that are involved while braking. This will allow neutralization of the disadvantages of one material by means of another one and obtaining integrated new properties of disc brake that significantly differ in their parameters from existing analogues and improve braking parameters of a vehicle.

In addition, the efficiency of a vehicle disc brake depends on the loading conditions of its working elements directly when braking that stipulates individual loading of each of them. Therefore, improvements in the technical and economic parameters of braking of vehicle are possible due to creating disc brake, whose force scheme includes a combination of friction materials that are structurally united by brake pads and each of exerts an individual level of pressure on the brake disc. This will allow full usage of potential friction capability of the working material and will create conditions to achieve new operational properties of disc brake directly during the stage of vehicle braking.

Therefore, creating new properties of disc brake due to the use of a combination of friction materials with different properties in force interaction of working elements is a promising research direction.

This article focuses on the development and substantiation of a method of providing stability of the friction coefficient of disc brake with the use of a combination of friction materials in a force scheme. Experimental proof of efficiency of the developed method is provided according to the criterion of stability of the friction coefficient of disc brake elements under extreme conditions of braking. There is a focus on the development of principles of creation of the brake pad of a disc brake that provides implementation of the developed method. Adaptation of the brake pad to the design of a disc brake of rolling stock is performed.

3. PRESENTATION OF THE MAIN RESEARCH MATERIAL

In accordance with modern ideas of external friction of solid bodies, the total force of friction is the force that consists of elementary forces that appear on solitary frictional bonds.

$$F_{T_{\Sigma}} = \sum_i^n F_{T_i} ,$$

where: $F_{T_{\Sigma}}$ - total force of friction; F_{T_i} - elementary force that is formed on solitary frictional bonds.

Elementary force F_{T_i} is stipulated by molecular–mechanical interactions in the microcontacts and consists of the sum of two components: molecular and mechanical [1, 2]. Molecular and mechanical components of the elementary force of friction F_{T_i} are linked to each other and their arithmetical addition, while determining total force of friction, can be used as the first approximation.

$$F_{T_i} = F_{mol} + F_{mech} ,$$

where: F_{T_i} - the force of friction; F_{mol} - molecular component of the force of friction; F_{mech} - mechanical component of the force of friction.

As is known, the force of friction that occurs under the force interaction of two solid bodies depends on their individual properties, conditions of force loading, relative speed of the friction elements and physical and chemical state of the contacting surfaces.

$$F_{T_{\Sigma}} = f(G_1, G_2, W, I, V_r)$$

where: G_1, G_2 - individual properties of the interacting bodies; W - the conditions of force loading; I - physical and chemical state of the contacting surfaces; V_r - relative speed between the friction couple elements.

From the above, it follows that the total force of external friction is always the sum of elementary forces that show resistance to the relative displacement of the elements of friction and have a molecular–mechanical nature. It is known that the molecular–mechanical interaction of friction elements is conditioned by individual properties of the materials that are under conditions of load and the influence of the external environment. Taking into consideration this fact, the authors proposed a new method of creation of frictional properties of the tribotechnical unit of friction the basis of which several frictional materials in the force scheme of their interaction are used.

Fig. 1 shows a principal diagram of this method by the example of a disc brake of the rolling stock. Several frictional materials A, B, C and D interact with a disc. The materials have different individual properties and conditions of loading [3, 4].

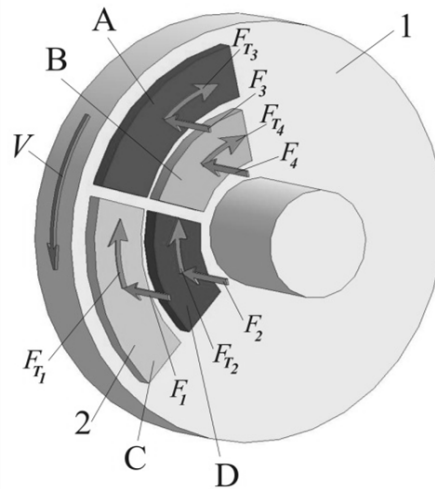


Fig. 1. Principal diagram of a new method of creating frictional properties of the disc brake of the rolling stock: A, B, C, D – the materials that have different frictional properties; 1 – a brake disc; F_1, F_2, F_3, F_4 – optimal forces of loading; $F_{T1}, F_{T2}, F_{T3}, F_{T4}$ – the forces of friction

According to the diagram presented, the integral properties of the disc brake are created on the bases of individual properties of the frictional materials A, B, C and D, the properties of the material of the disc 1, the conditions of their optimal force loading and also the physical and chemical state of the contacting surfaces. In this case, an integral force of friction is equal to the sum of the friction forces, which appear during interactions of each of the frictional materials with the brake disc.

$$F_{T_{\Sigma}} = F_{T_1} + F_{T_2} + F_{T_3} + F_{T_4} .$$

The thermal interaction of working elements of a disc brake that has several friction materials in the force scheme is shown in the differential equation of thermal conductivity (Fourier – Kirchhoff) presented in a cylindrical coordinate system without internal heat sources [5-9] (fig. 2).

$$\frac{\partial T}{\partial \tau} = \mathcal{G} \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{1}{r^2} \frac{\partial^2 T}{\partial \varphi^2} + \frac{\partial^2 T}{\partial z^2} \right), \quad (1)$$

Where: $\mathcal{G} = \lambda / (c_p \cdot \rho)$ – coefficient of temperature conductivity of material, λ – coefficient of thermal conductivity, c_p – specific isobar heat capacity, ρ – specific mass; τ – current value of time when braking; and T – absolute temperature ($T = f(r, \varphi, z, \tau)$, where φ – angle between radius vector r and the X-axis).

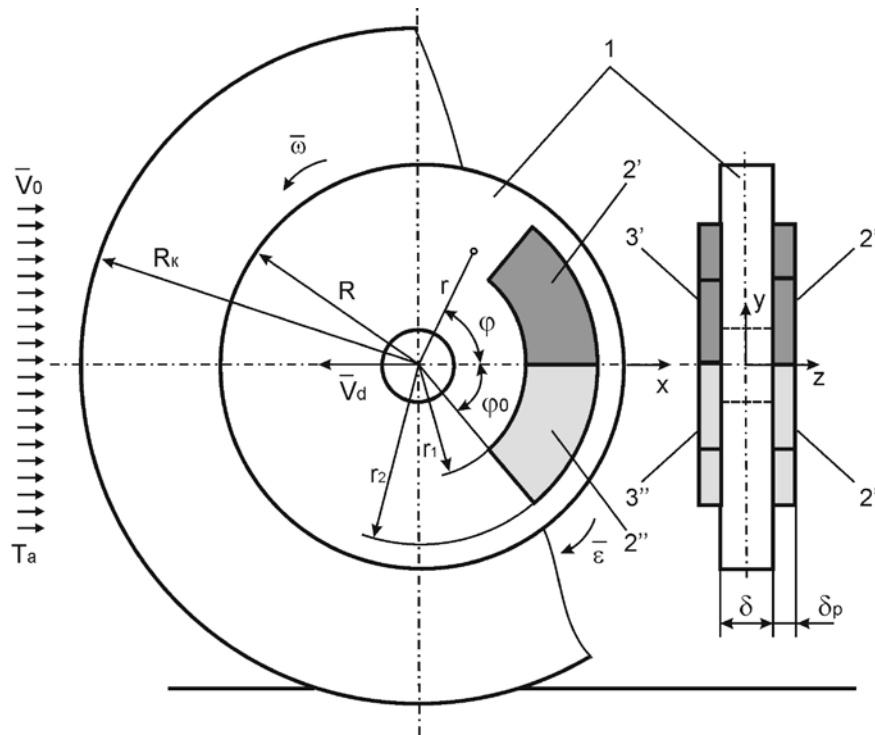


Fig. 2. Design model of disc brake of rolling stock: 1 – brake disc; 2, 3 – brake pads. R, R_k – radius of the brake disc and wheel; δ, δ_p – thickness of the brake disc and lining; V_0 – speed of countercurrent air; T_a – average temperature of air; V_d – current speed of locomotive; ω – rotational speed of the brake disc; ε – angular acceleration (deceleration) of the brake disc

The model allows defining the temperature field of brake surfaces and heat flows that move through the mentioned surfaces.

Equations (1) are added by the following boundary conditions:

For the side and frontal surfaces of the brake disc, the third type of boundary conditions (without internal heat sources):

$$\pm \lambda \left(\frac{\partial T}{\partial z} \right) = \alpha_z (T - T_a), \quad z = \pm \delta / 2, \quad (2)$$

where α_z – coefficient of heat dissipation.

On the side (cylindrical) surface of the brake disc:

$$\pm \lambda \left(\frac{\partial T}{\partial r} \right) = \alpha_r (T - T_a), \quad r = R, \quad (3)$$

where α_r – coefficient of heat dissipation.

For surfaces of the sliding contact zone of a brake disc with linings – the fourth type of boundary conditions with a surface heat source.

$$\left. \begin{aligned} -\lambda_1 \left(\frac{\partial T_1}{\partial z} \right) &= \alpha_{em} q - \frac{1}{R_c} (T_1 - T_2), \\ \lambda_2 \left(\frac{\partial T_2}{\partial z} \right) &= (1 - \alpha_{em}) q + \frac{1}{R_c} (T_1 - T_2), \end{aligned} \right\} z = \pm \delta / 2, \quad (4)$$

where: q – specific heat flow; R_c – contact thermal resistance [10-14]; α_{em} – coefficient of friction energy distribution. Index “1” – brake disc, index “2” – brake lining.

Specific heat flow generated when braking by one of the types of friction materials:

$$q(\varphi, r, \tau) = \frac{\alpha_{em}}{n_k} \frac{m R_k^2 \cdot \varepsilon}{\iint_s r(\varphi) ds} r(\varphi) (\omega^* - |\varepsilon| \cdot \tau),$$

where: m – mass of the vehicle; n_k – number of types of the friction material; n_n – number of brake linings made of one material; r – radius vector that spines contact zone of the disc with lining S ; ω^* – disc rotational speed (ε - angular acceleration of the brake disc); $\tau \in [0; \tau_\kappa]$, $\tau_\kappa = (V^* - V_\kappa) / a^*$ – braking time.

To define coefficients of heat dissipation, the following criteria equations are used, respectively:

$$\left. \begin{aligned} Nu_z &= 0,135 \cdot [(0,5 \cdot Re_\omega^2 + Re_a^2 + Gr) \cdot Pr]^{0,33}, \\ Nu_r &= 0,037 \cdot (Re_a^{0,8} + Re_\omega^{0,4}) \cdot Pr^{0,33}, \end{aligned} \right\}$$

where Re_ω , Re_a – Reynolds numbers that are defined by blowing of a counter current air flow.

The mathematical model of the temperature field of brake disc surfaces is obtained using the above-mentioned equations.

$$\begin{aligned} T^*(r^*, z^*, \Theta) &= q \cdot \sqrt{\frac{\delta}{2R}} \cdot \frac{\sqrt{A+B}}{\pi \sqrt{A+B} \cdot (\pi - 2\varphi_0)} \times \\ &\times \left[\frac{2\varphi_0}{\sqrt{A+B}} \cdot \exp\left(-\sqrt{\frac{2A \cdot R}{\delta}} \cdot (1 - r^*)\right) + \right. \\ &+ \frac{1}{P} \cdot \sqrt{\frac{\delta}{R \cdot r^*}} \cdot \sum_{\alpha_{em}=-\infty}^{\infty} \frac{\sin(2\alpha_{em} \cdot \varphi_0)}{\alpha_{em}} \cdot \exp\left(2P \cdot R \cdot \frac{\sqrt{\alpha_{em}}}{\delta} \cdot (r^* - 1)\right) \times \\ &\left. \times \cos\left(2\alpha_{em} \cdot \Theta + \frac{\pi}{4} - P \cdot \frac{2R \cdot \sqrt{\alpha_{em}}}{\delta} \cdot (r^* - 1)\right) \right], \end{aligned}$$

where: $T^* = (T - T_a) / T_a$, – dimensionless temperature; $r^* = r / R$; $z^* = 2z / \delta$ – dimensionless coordinates; $\tau^* = \omega \cdot \tau$ – dimensionless time; $\Theta = \varphi - \tau^*$; $P = \omega \cdot c_p \cdot \rho \cdot \delta^2 / (4\lambda)$; here, c_p and ρ – are the specific isobar thermal capacity and the specific weight of material of the brake disc; $A = \alpha_z \cdot \delta / (2\lambda)$; $B = \alpha_r \cdot R / \lambda$.

The following correspondence is obtained to calculate the friction coefficient in the case of the simultaneous use of two different friction materials:

$$f = \frac{1}{N \cdot R_m} \int_{r_1}^{r_2} \int_0^{\varphi_0} dM = \frac{1}{3N \cdot R_m} (\varphi_2^2 - \varphi_1^2) (r_2^3 - r_1^3) \left(f_m \cdot P_n + \frac{0,84\nu \cdot (\nu - 1) \cdot h^{0,5} \cdot k \cdot N^{\frac{2\nu+1}{2\nu}} \cdot 2^{\frac{2\nu+1}{2\nu}}}{\pi \cdot R_h^{0,5} \cdot HB^{0,5/\nu} \cdot b^{0,5/\nu}} \right),$$

where: f_m – molecular component of the friction coefficient; N – normal force of lining pressure to brake disc; HB – hardness of the material; R_h – radius of curvature of microroughnesses; R_m – average radius of friction of brake lining; k – coefficient that depends on the geometrical and mechanical properties of surfaces; h – convergence of contacting surfaces of the brake disc and lining; b , ν – parameters of the bearing area curve.

The mathematical models, considered above, together allow defining the total value of the friction coefficient of friction brake of railway rolling stock that is obtained as an integrated value of the combined effect of several friction materials with different properties and loading conditions that are located at the pad of the disc brake at the same time.

The productivity of the creation of integral frictional properties of the disc brake on the bases of individual properties of the system elements and the conditions of their optimal loading is confirmed

experimentally. Experimental testing is performed on the special stand that reproduced a force interaction of the elements of the disc brake in real time, of the acting forces and the velocity of relative motion. A disc brake of the tram is the base of the stand [15].

Frequency of rotation, force of pressing, force of friction and the temperature in the zone of contact of the working elements were controlled while carrying out the experiments. The materials, whose characteristics are different in temperature effect – carbon and iron – were used as experimental materials.

Carbon and iron together with the material of the disc created the compositions “carbon – steel”, “iron – steel” and “carbon – steel – iron”. Force of pressing of friction elements – $0,5 \text{ N/mm}^2$ and angular speed – $37,7 \text{ rad/sec}$. The results of the experiment are shown in fig. 3.

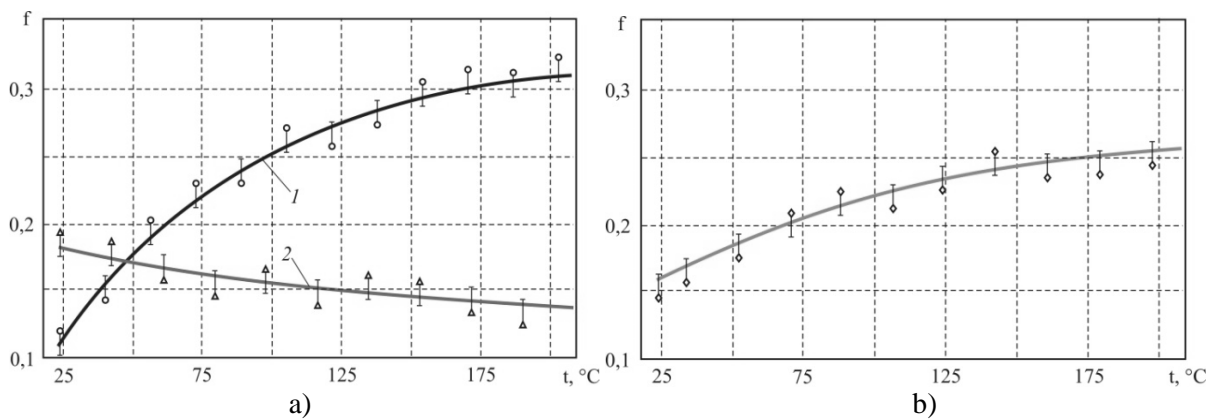


Fig. 3. Dependencies of the friction coefficient on the mean temperature of the contact surface of the elements of the disc brake: a) 1 – the combination “carbon – steel”; 2 – the combination “iron – steel”; b) area of values for the combination “carbon – steel – iron”

The results obtained confirmed the possibility to create new frictional properties of the disc brake on the bases of a combination of individual properties of the elements of the tribocompound and the conditions of their loading.

The friction coefficient in the case of interaction of the combination “carbon – steel” and “iron – steel” has opposite tendencies in terms of the change because of the temperature increase (the higher the temperature, the higher the friction coefficient of carbon and the lower the friction coefficient of iron). But in the process of interaction of the same elements in the combination “carbon – steel – iron,” there is a precise tendency of an increase in the friction coefficient with an increase in temperature with a further decrease of its effect. The combination of the materials “carbon – steel – iron” has more stable frictional properties than in the case of the use of “iron - steel” or “carbon – steel”.

These results confirm the possibility of creation of frictional properties of the disc brake on the bases of a combination of individual properties of the elements of the tribocombination and the conditions of their loading.

4. PRACTICAL IMPLEMENTATION OF THE METHOD

The implementation of the proposed method of creation of frictional properties of the disc brake presupposes the change of the block design. In this case, there are the following demands to the brake pad:

- presence of at least two platforms that are connected with each other kinematically;
- working materials with different properties placed on each platform;
- individual level of loading of each working material;
- autocompensation of wear of the working materials.

The design diagram (fig. 4) meets the above-mentioned demands.

Hinges 3 and 4 ensure the distribution of loads from pads 1 and 2 to the brake disc. Individual loading of brake pads 1 and 2 is ensured due to different lengths of arms C and D. The brake pad that is created on the bases of the given diagram is shown in fig. 5. The design of the brake pad is covered by the Patent of Ukraine.

The presence of hinges 3 and 4 in the pad ensures autocompensation of different intensities of wear of the frictional materials A and B.

It is advisable to use a brake pad (fig. 5) for the wheel pairs with one and two brake discs. For wheel pairs with three brake discs and brake discs that are fastened on the hub of the wheel, it is possible to use traditional brake pads on which the frictional material A or B is fastened. The arrangement of these pads on the wheel pairs is shown in fig. 6.

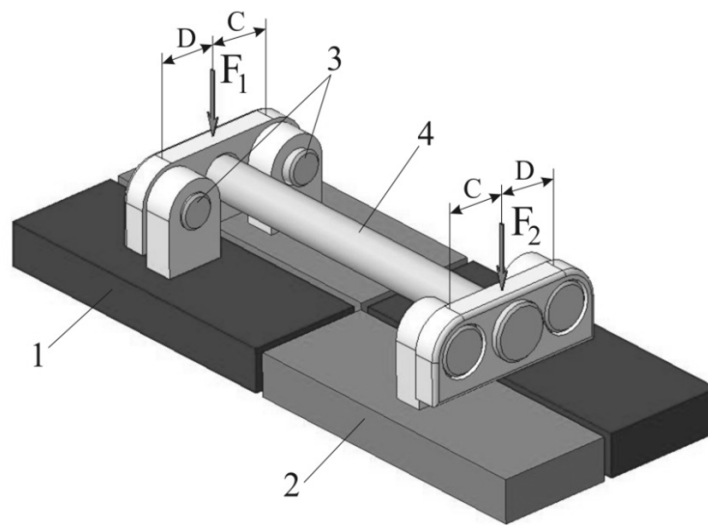


Fig. 4. The diagram of the brake pad of the disc brake: 1 – pad with the frictional material A; 2 – pad with the frictional material B; F_1 , F_2 – the forces of loading of brake pads; 3, 4 – hinges

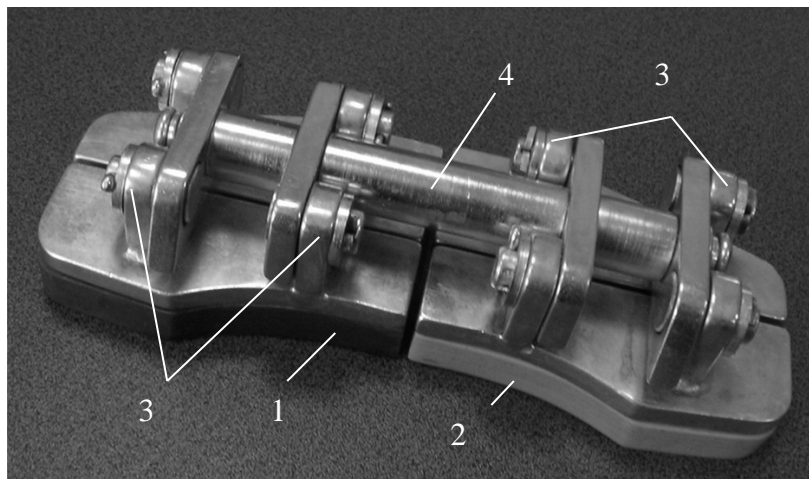


Fig. 5. The design of a new brake pad: 1 – the segment on which the frictional material A is placed; 2 – the segment on which the frictional material B is placed; 3 – hinges; 4 – attachment fitting

The method of creation of the frictional properties of the friction unit is easier in the design of the shoe-type brake of the rolling stock. In this case, brake pads with different frictional materials are placed along different sides of the wheel. Optimal pressure of the brake pad on the wheel is achieved due to variation of the contact area.

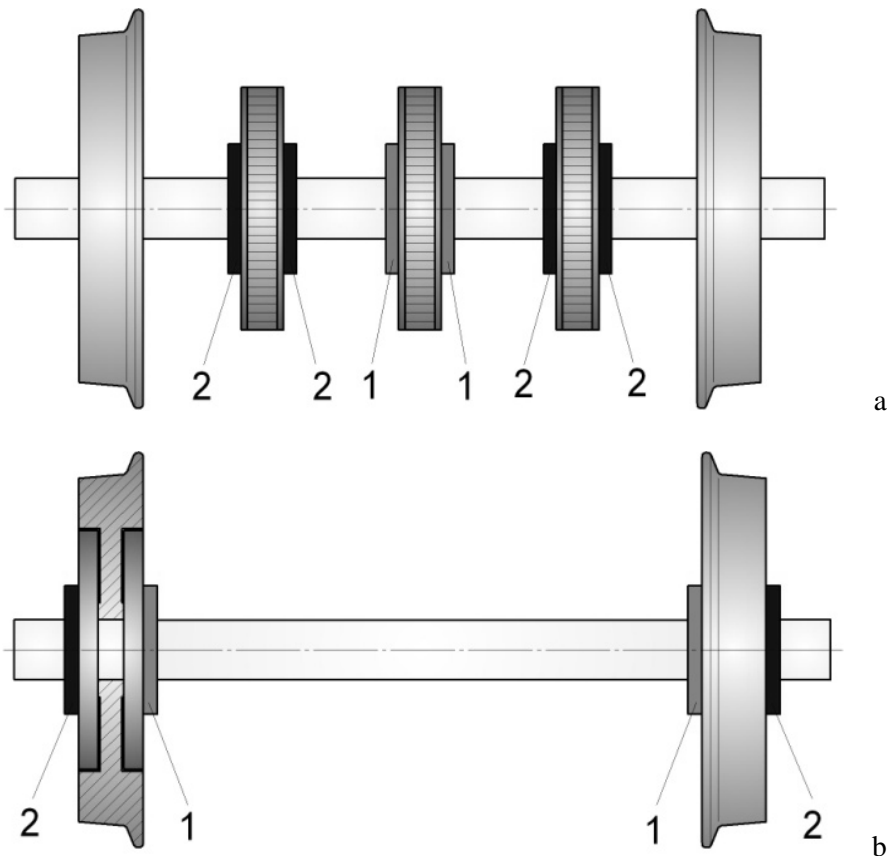


Fig. 6. The diagram of arrangement of the brake pads on the wheel pairs with three brake discs (a) and with the discs on the hub of the wheel (b): 1 – brake pad with the frictional material A; 2 – brake pad with the frictional material B

5. CONCLUSIONS

1. The method of providing stability of the friction coefficient of the disc brake of a vehicle designed for exploitation in extreme conditions has been proposed. The method is based on the use of several frictional materials in the force scheme of their interaction with individual conditions of loading for each of them. Advisability of the method has been confirmed experimentally on the bases of stand testing.
2. A mathematical model of thermal interaction of working elements (which are presented by several friction materials) of a disc brake has been developed. The model is based on the Fourier–Kirchhoff equation that is presented in a cylindrical coordinates system and without internal heat sources.

There is an estimation of integrated friction coefficient of disc brake that has been obtained as a result of force interaction of several friction materials that have different friction properties and individual loading level.

3. The design of the brake pads that differs from the analogues in the use of two materials with different frictional properties has been developed.

The design of the brake block ensures:

- autocompensation of wear intensity of one frictional material relative to the other;
- individual level of loading of each frictional material.

4. A combination of several frictional materials in the force scheme of the disc brake allows achieving the required operation properties of the disc brake due to design measures.

References

1. Хебда, М. & Чичинадзе, А.В. (ред.). *Справочник по триботехнике. Т.1. Теоретические основы*. Москва: Машиностроение, 2000. 411 с. [In Russian: Khebda, M. & Chichinadze, A.V. (eds.) *Reference book on tribotechnology*. Vol. 1. *Theoretical foundations*. Moscow: Engineering industry].
2. Гаркунов, Д.Н. & Мельников, Э.Л. & Гаврилюк, В.С. *Триботехника*. Москва: КНОРУС, 2013. 408 с. [In Russian: Garkunov, D. & Melnikov, E. & Gavriluyuk, V. *Tribotechnology*. Moscow: KNORUS. 408 p.].
3. Osenin, Yu. & Sosnov, I. & Sergienko, O. Creation method of frictional properties of the disc brake. In: *Europe's braking conference & exhibition "EuroBrake 2013"*. Dresden, 17-19 June 2013. P. 238–244.
4. Старченко, В.Н. & Гурин, В.А. & Быкадоров, В.П. & Шапран, Е.Н. Фрикционные материалы на базе углерод-углеродных и углерод-асбестовых волокон для тормозных устройств. *Железные дороги мира*. 2006. No. 2. P. 38-42. [In Russian: Starchenko, V.N. & Gurin, V.A. & Bykadorov, V.P. & Shapran, E.N. Frictional materials on the basis of carbon – asbestos fibres for brake devices. *Railways of the world*].
5. Недопекин, Ф.Е. *Тепломассоперенос*. Донецк: ДонНУ. 2007. 174 с. [In Russian: Nedoypokin, F.E. *Heat and mass transfer*. Donetsk: National University (Ukraine). 2007. 174 p.].
6. Carslaw, H.S. & Jaeger, J.C. *Conduction of heat in solids*. Oxford University Press. 1986. 520 p.
7. Wong, H.Y. *Heat transfer for engineers*. Longman Group United Kingdom. 1977. 248 p.
8. Ehlers, H.-R. & et. al. Potential and limits of opportunities of the block brake. *GlaserAnnalen*. 2002. No. 6/7. P. 290-300.
9. Coulson, J.M. & Richardson, J.F. & Backhurst, J.R. & Harker, J.H. *Chemical Engineering. Fluid Flow, Heat Transfer and Mass Transfer*. Butterworth-Heinemann. 6th edition. 1999. Vol. 1. 895 p.
10. Меснянкин, С.Ю. & Викулов А.Г. & Викулов Д.Г. Проблемы теплового контактирования твердых тел: современное понимание. *Успехи физических наук*. Москва: Государственный университет аэрокосмического технологий. 2009. Т. 179. № 9. С. 945–970. [In Russian: Mesnyankin, S.Yu. & Vikulov, A.G. & Vikulov, D.G. Solid-solid thermal contact problems: current understanding. *Successes of physical sciences*. Moscow: State University of Aerospace Technologies. 2009. Vol. 179. No. 9. P. 944 - 970].
11. Kreith, F. Convective Heat Transfer in Rotating Systems. In: *Advances in Heat Transfer*. Academic Press. 1968. Vol. 5. P. 129-246.
12. Dorfman, L. A. *Hydrodynamic Resistance and the Heat Loss of Rotating Solids*. Edinburgh: Oliver and Boyd. 1963.
13. Білобородова, І.М. Оцінка здатності гальмівного диска локомотива розсіювати тепло. *Вісник Східноукраїнського нац. ун-ту ім. В. Даля*. 2008. № 8 (126). Ч. 2. С. 190-197. [In Ukrainian: Biloborodova, I.M. Evaluation of the ability of the locomotive brake discs dissipate heat. *Volodymyr Dahl East Ukrainian National University*. 2008. No. 8 (126). Part 2. P. 190-197].
14. Білобородова, І.М. Застосування механічного гальмування на залізничному рухомому складі. *Вісник Східноукраїнського нац. ун-ту ім. В. Даля*. 2008. № 7 (125). Ч. 1. С. 249-252. [In Ukrainian: Biloborodova, I.M. The use of a mechanical brake on rail rolling stock. *Volodymyr Dahl East Ukrainian National University*. 2008. No. 7 (125). Part. 1. P. 249-252].
15. Осенін, Ю.Ю. & Сергієнко, О.В. & Соснов, І.І. & Бугаєнко, В.В. & Погребнова, Н.Є. *Стенд для дослідження взаємодії робочих елементів дискового гальма*. Патент на корисну модель No 79205; Заявл. 15.11.2012; Дата опубл. 10.04.2013, Бюл. № 7. [In Ukrainian: Osenin, Yu. Yu. & Sergienko, O.V. & Sosnov, I.I. & Bugaenko, V.V. & Pogrebnova, N.E. *Disc brakes*. Patent on the useful model No. 79205. *Volodymyr Dahl East Ukrainian National University*. Publ. 10.04.2013. Bull. 7].