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STUDYING THE LOAD OF COMPOSITE BRAKE PADS UNDER HIGH-TEMPERATURE IMPACT FROM THE ROLLING SURFACE OF WHEELS

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Abstract

The object of the research is the processes of thermal stress, perception and redistribution of loads by the brake composite pad during braking of the car in operation.

In the current conditions, wedge-dual wear of composite brake pads is observed in the braking systems of freight cars, the feature of which is the deterioration of the braking efficiency of freight trains. With this type of wear, both an increase in the load on the brake pad and an «underuse» of the amount of pressure on it can occur.

A comprehensive thermal calculation was carried out for composite brake pads with uniform and wedge-dual wear. The results of the calculation showed that the amount of pressure on an abnormally worn pad is 23.3 % less than that acting on a pad with nominal values.

It has been proven that the change in the pressure force on the composite pad with different values of the wear parameters during braking leads to a change in the braking force that occurs between the wheel and the rail during braking.

The calculation of the strength of the composite brake pad with wedge-dual wear was carried out.

The obtained results will make it possible to develop measures to modernize the elements of the brake lever transmission of freight cars.

The field of practical use of the obtained results is car-building enterprises. The conditions for the practical use of the results are the brake lever transmissions of carriages of cars with a gauge of 1520 mm.

The conducted studies prove the negative impact of wedge-dual wear not only on braking efficiency, but also on the strength of brake pads. This makes it necessary to create measures aimed at its elimination, which will contribute to increasing the level of train traffic safety and significantly reducing the operational costs of maintaining freight cars.

Keywords: car brake pad, wedge-dual pad wear, brake pad strength, thermal stress state of the pad, safety of train movement.

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1. Introduction

Increasing the efficiency of railway transport operation requires the implementation of solutions to increase the safety of its movement [1–3]. At the same time, the greatest attention should be focused on the braking system, as the most responsible in operation [4–6].

In the process of braking a freight train with a friction pad brake, the kinetic energy of the moving train is converted into thermal energy [7–9]. In this regard, in the contact zone of the brake pad and the rolling surface of the wheel, the process of converting the kinetic energy of the movement of the wheel into the energy of the chaotic thermal motion of the molecules of the wheel and the composite brake pad takes place. The contact of the friction node, which causes the action of sliding between the block and the wheel, becomes a source of heat generation [10–12]. The rest of the mass of the wheel and pad absorbs this heat by heat transfer, and from points far from the center of the brake pad and wheel surfaces, the heat is dissipated into the environment by heat transfer. However, modern trends regarding a significant increase in freight train speeds and the use of more effective friction materials for brake composite pads that have reduced thermal conductivity, the thermal intensity of the processes that occur during braking significantly increases [13, 14], which leads to various types of damage and a reduction in the durability of tribotechnical components of the brake and wheels due to structural changes in the material of the brake pads. Thus, the problem of interaction in the «brake pad – wheel» system is currently relevant and important [15–17].

The issues of ensuring the movement of freight trains are quite urgent and depend on many factors, in particular the technical condition and load of their brake components. So, for example, in work [18] an analysis of the stresses occurring in the brake pad and thermal analysis was performed using SolidWorks software. An alternative solution for using a composite based on a modified alkylbenzene resin to increase the friction coefficient is proposed.

In the brake system of cars of freight cars, lever gear triangles work in such a way that during braking of the car, the brake pads are pressed against the wheels at the same time, and the brake lever gear system (BLG) must be balanced with respect to the force load of each pad. But due to the dynamics, which takes into account the interaction of the wheels with the unevenness of the rail path, this balance is disturbed and the pads are worn mostly by their upper edges, which is the main reason for their wedge-dual wear [19].

Ways of constructive changes in the elements of the BLG to avoid such consequences during its operation are proposed in the work [20]. A comparative analysis of the designs of various types of devices for uniform wear of brake pads was carried out. Their disadvantages and advantages are determined. The work also highlights the peculiarities of kinetostatic analysis taking into account dynamic forces in the unsprung part of the cart. The results of the study made it possible to identify the cause of the dual wear of the pads, as well as to determine the possibility of its elimination. At the same time, the work did not determine the thermal stress state of the pads, taking into account the presence of dual wear.

Currently, one of the main documents regulating the operation of rolling stock brakes is [21, 22]. Meanwhile, the corresponding regulatory document does not provide any warnings against wedge-dual wear of composite brake pads in operation. This is due to the fact that this effect has not been sufficiently studied in relation to serial trolleys of 1520 mm track (mod. 18–100) with BLG.

Both domestic and foreign experts have tried to correct the situation that has developed in the car industry regarding the excessive removal of composite brake pads due to this defect by developing special devices. Therefore, some studies were carried out in laboratories for testing components of rolling stock, where they checked the performance of braking systems of trolleys on rolling stands and measured wear parameters and temperature indicators [23].

In the research described in the paper [24], the verification of the regression model of the friction of the pad against the wheel of haul-out locomotives in the industry under conditions of uncertainty, when the number of input parameters is very large, and the output parameters are limited, taking into account the value of the friction coefficient, was studied. However, due to the significant dimensionality of the mathematical model, the obtained initial parameters do not have stable solutions.

In the work [25], the authors analyzed the performance indicators of the quality of cast iron and composite brake pads used on various types of rolling stock. Some negative factors of composite pads are given, their impact on the environment and processes that cause damage to the rolling surfaces of rolling stock wheels are described.

An analysis of the design features of modern rolling stock brakes is given in [26]. The main factors affecting the efficiency of the brakes have been determined. The temperature load on the components of tribotechnical pairs during braking is calculated. However, the work does not take into account how abnormal wear of composite pads affects the rolling surface of the wheels during train braking.

In work [27], to eliminate angular movements of the brake cylinder rod at its maximum exit from the housing, modernization measures are proposed that will limit its displacement. The selection of the optimal parameters of the safety element for the rod of the brake cylinder of the car based on the allowable moment of resistance was carried out. The calculation of the strength of the brake cylinder was carried out using the finite element method, which made it possible to prove that the condition of strength is fulfilled. However, it should be noted that an equally important factor that affects the efficiency of rolling stock braking is the BLG, which depends on the safety of train movement. However, the authors in the paper did not consider how exactly and whether the output value of the brake cylinder rod really changes during the wear of brake pads, especially wedge-dual ones.

In the work [28], based on a review of publications, the authors provide comparative quality indicators and performance characteristics of cast iron brake pads and composite pads. Some disadvantages of the use of composite pads are described, for example, low thermal conductivity, which causes thermal effects on the rolling surfaces of rolling stock wheels. And this leads to an increase in operating costs for the repair of wheel pairs. Another significant shortcoming is the lack of a list and content of ingredients in the rubber mixture of the composite, their chemical composition in the technical conditions for production, standards and technical documentation, which contradicts the current legislation of Ukraine and makes the process of controlling these substances impossible. However, the article does not mention the costs of abnormal wear of composite brake pads, which occurs when driving without braking in rolling stock.

It is almost impossible to solve the actual problem related to wedge-dual wear of composite brake pads in practice, since the BLG design becomes not only very complicated, but also increases its weight and the range of component elements, and this, in turn, leads to an increase in the cost of planned and preventive repairs of cargo cars.

In the production studies carried out by the order of JSC «Ukrzaliznytsia», the development of design and technological documentation for the modernization of freight cars BLG was carried out. However, this research [29] did not carry out statistical studies [30] of the wear of the brake pads of its own fleet of freight cars, which are assigned to private enterprises and, unlike the cars of JSC «Ukrzaliznytsia», have a permanent location and are operated in mild conditions in terms of working blocks per resource.

In this regard, the purpose of the research is to determine the thermal stress state of composite brake pads under conditions of high-temperature influence from the rolling surface of the wheels.

To achieve this goal, the following tasks are set:

– determine the thermal regimes during braking of the car for pads that have a uniform and wedge-dual type of wear;

– calculate the temperature on the friction surface of the tribotechnical pair «brake pad – wheel» during braking, depending on the type of wear of the composite brake pads;

– investigate the thermally stressed state of the composite brake pad with wedge-dual wear.

2. Materials and methods

The main hypothesis of the study is that the presence of wedge-dual wear of the composite brake pad impairs the efficiency of the train's braking system. At the same time, there may be both an increase in the load on its structure and an «underuse» of the amount of pressure on it, which leads to an increase in the braking distance of the train and, accordingly, wear of the wheel pairs and the upper structure of the track.

Under the conditions of temperature conditions, the maximum pressure K_t^k, kN for composite pads during the thermal regime in the braking process can be found from the expression [31, 32]:

$$K_t^k = \frac{\left[4\Phi(t) - 2.34 v_0 m_v\right] + \sqrt{\left[4\Phi(t) - 2.34 v_0 m_v\right]^2 + 9.36 v_0 m_v \Phi(t)}}{0.023 v_0 m_v}, \quad (1)$$

where

$$\Phi(t) = \frac{F_k \Delta\tau_{\max} \alpha_0}{1 - e^{-1.52\alpha_0\sqrt{t}}}, \quad (2)$$

$$\alpha_0 = 0.004\left(1 + 1.33\sqrt{v_0}\right), \quad (3)$$

$$m_v = 0.44 \frac{3.6 v_0 + 150}{7.2 v_0 + 150}, \quad (4)$$

where v_0 – the initial braking speed, m/s; $\Delta\tau_{\max}$ – the maximum permissible temperature of the composite brake pad during braking, $\Delta\tau_{\max} = 400$ °C; t – the duration of braking, s.

The duration of braking t with the length of the braking distance S_b on the slope with the initial braking speed v_0, which is known according to the standards, is based on the assumption of uniformly decelerated motion [32]:

$$t = \frac{2S_b}{v_0}. \quad (5)$$

At the next stage of the research, the calculation of the jammed state of the wheel pair was carried out under the condition of braking with composite pads [32]:

$$t^k = \frac{2}{2a^k + b^k}(v_0 - v_k) - \frac{150 b^k}{\left(2a^k + b^k\right)^2} \ln\left(\frac{\left(2a^k + b^k\right)v_0 + \left(2a^k + b^k\right)\cdot 150}{\left(2a^k + b^k\right)v_k + \left(2a^k + b^k\right)\cdot 150}\right), \quad (6)$$

$$a^k = \frac{3.6 n_1}{4\gamma q_0}\left[-\frac{0.44 m_1}{1+\gamma} \cdot \frac{v_0 + 150}{2v_0 + 150} \cdot \frac{0.1K_m^k + 20}{0.1K_m^k + 20} K_m^k + q_0\left(\psi_p - \psi_{ck}\right)\right], \quad (7)$$

$$b^k = \frac{3.6 n_1}{4\gamma q_0} \cdot 0.44 m_1 \frac{0.1K_m^k + 20}{0.1K_m^k + 20} K_m^k, \quad (8)$$

where v_K – the circular speed of the wheels in the slip process, km/h; q_0 – axle load of the car, N; n_1 – the number of wheel pairs of a rolling stock unit, $n_1 = 4$; γ – the coefficient of inertia of the rotating masses, $\gamma = 0.08$; ψ_p – the realized coefficient of adhesion of the wheels to the rails on the section with high adhesion, $\psi_P = 0.2$; ψ_{ck} – coefficient of friction of the wheel sliding on the rail during blocking, $\psi_{ck} = 0.05$; m_1 – the number of pads per axle, $m_1 = 2$.

The maximum allowable pressing force is found from the expression [32]:

$$K_m = \frac{(d \cdot q_0 \cdot \psi_k - m_v \cdot c) + \sqrt{(d \cdot q_0 \cdot \psi_k - m_v \cdot c)^2 + 4b \cdot q_0 \cdot \psi_k \cdot m_v \cdot c}}{2b \cdot m_v}, \quad (9)$$

where

$$m_v = a \cdot m_l \frac{v_0 + e}{f \cdot v_0 + e}, \quad (10)$$

$$\psi_k = 0.20 \frac{0.1 q_0 + 100}{0.4 q_0 + 100} \cdot \frac{v_0 + 200}{3v_0 + 200}. \quad (11)$$

To determine the temperature $\Delta\tau_s$ on the surface of the wheel during braking, the following expression was used [32]:

$$\Delta\tau_s = \frac{q_T}{\alpha_0}\left[1 - e^{-\frac{2\alpha_0}{\sqrt{\pi\lambda\gamma c}}\sqrt{t}\left(1-\frac{2}{3}\cdot\frac{t}{t_B}\right)}\right]. \quad (12)$$

The highest temperature during braking is reached in the middle of the braking process [32]:

$$\Delta\tau_{s\max} = \frac{q_T}{\alpha_0}\left[1 - e^{-0.9433\frac{\alpha_0}{\sqrt{\pi\lambda\gamma c}}\sqrt{t_B}}\right]. \quad (13)$$

When the train stops, the temperature on the surface of the wheel is determined [32]:

$$\Delta\tau_{sK} = \frac{q_T}{\alpha_0}\left[1 - e^{-0.667\frac{\alpha_0}{\sqrt{\pi\lambda\gamma c}}\sqrt{t_B}}\right]. \quad (14)$$

Temperature during established braking (at constant speed) [32]:

$$\Delta\tau_{s\infty} = \frac{q_T}{\alpha_0}\left[1 - e^{-2\frac{\alpha_0}{\sqrt{\pi\lambda\gamma c}}\sqrt{t_B}}\right], \quad (15)$$

where q_T – the heat flux density, kcal/(m²·°C); λ – thermal conductivity coefficient, kcal/(m·°C); γ – specific gravity, kN/m^3; c – specific heat capacity, kcal/(kgf °C); t_B – braking time to a complete stop, p.

The values of λ, γ, c are given in the **Table 1** [32].

The heat flux density at the initial moment of braking is determined by the expression:

$$q_T = \frac{\alpha_R \cdot B_b \cdot q_0 \cdot v_0}{17080\pi \cdot R \cdot h_k}, \quad (16)$$

where α_R – the heat flow distribution coefficient in the wheel for a car equipped with composite brake pads, $\alpha_R = 0.95$; h_k – the width of the friction surface of the wheel, $h_k = 0.09$ m.

Table 1
The value of temperature coefficients

Material	Physical characteristics				
	λ	γ	c	$\sqrt{\pi\lambda\gamma c}$	$\alpha = \lambda/\gamma c$
Composite pad	$0.2\cdot10^{-3}$	2200	0.28	0.62	$0.325\cdot10^{-6}$

Since the braking force changes in the process of filling the brake cylinders, as well as when the speed changes, the value of the braking force B_b is calculated based on the length of the actual braking distance S_b. At the same time, the time of preparing the brakes for the action of t_P is also taken into account. Taking this into account, it is possible to write a formula for determining the braking force in the following form [33]:

$$B_b = \frac{108 \cdot v_0}{2(S_b - v_0 t_P)} - w_0 - i_c, \quad (17)$$

where w_0 – the main specific resistance of the train, N/kN.

At the same time, the time t in the expression for thermal mode calculations is taken as reduced by the preparation time t_P, if $t \geq t_P$.

Based on expressions (13), (16), the obtained formula for determining the wheel diameter D_k, which provides the necessary heat convection to avoid its overheating during emergency braking, is determined by the expression:

$$D_k = \frac{\alpha_R \cdot b_B \cdot q_0 \cdot v_0}{8540\pi h_k \cdot \Delta\tau_{sK} \cdot \alpha_0}\left(1 - e^{-0.9433\frac{\alpha_0}{\sqrt{\pi\lambda\gamma c}}\sqrt{t_B}}\right). \quad (18)$$

In order to determine the strength of a brake pad with wedge-dual wear, its calculation was carried out.

For this purpose, the lost SolidWorks Simulation complex [34–38], which implements the finite element method, is used.

The Mohr-Coulomb method [39, 40] was used as the calculation method. The calculation was made on the example of a composite brake pad type 2TP-11, which is used in modern brake systems of innovative freight cars.

The creation of a spatial model of the block was carried out in accordance with the album of its drawings in the SolidWorks software complex, as well as for the wheel.

3. Results and discussion

3. 1. Determination of thermal regimes during braking of the car for pads

Formulas (1)–(4) were used to calculate the thermal regimes during braking of the car for pads with uniform and wedge-dual wear.

The calculation was carried out on the example of brake pads with an area of 0.02 m^2 and 0.015 m^2 for a car mileage of 62.4 thousand km (**Fig. 1**).

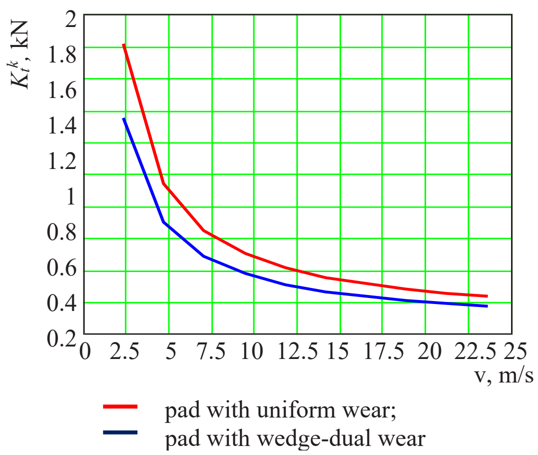

Fig. 1. Dependence of the compression value of the composite brake pad on the speed of movement

Therefore, taking into account the presence of wear of the brake pad, the amount of its pressing against the wheel is reduced by 25.5 % compared to a pad with uniform wear. This is due to a decrease in the useful area of the pad.

To determine the dependence of the time of the stuck state of the wheel pair on the initial braking speed, variational calculations were carried out in accordance with formula (5). The calculation results are shown in **Fig. 2**.

Analyzing this dependence, it can be concluded that the time of the jammed condition of the wheel pair is a directly proportional function to the speed of the train. At the same time, under the condition of the presence of wedge-dual wear, this dependence has a similar configuration, but exceeds the established value by almost 17 %. This again proves the negative effect of the presence of wedge-dual wear of brake pads.

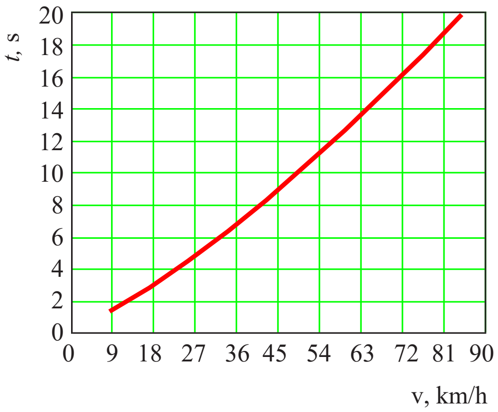

Fig. 2. Dependence of the wheel pair jamming time on initial braking speed

3. 2. Calculation of the temperature on the friction surface of the tribotechnical pair

Under the condition of providing braking, the amount of pressure on a brake pad with wear can be equal to that inherent in a pad with nominal parameters. Due to the smaller area, the temperature load of the pad increases (**Fig. 3**).

Analyzing the dependencies shown in **Fig. 4**, it can be concluded that the heating temperature of composite pads of both types with wedge-dual wear increases by 16.8 % compared to uniform wear.

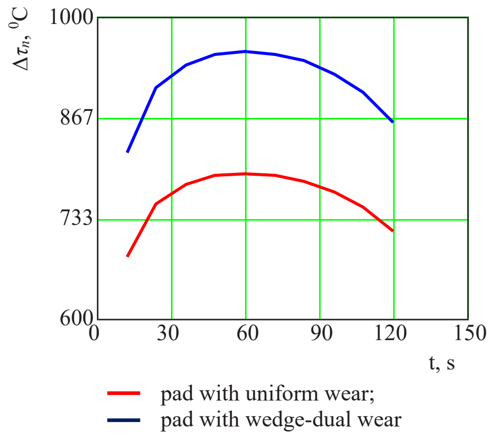

Fig. 3. Change in the heating temperature of the composite pad over time

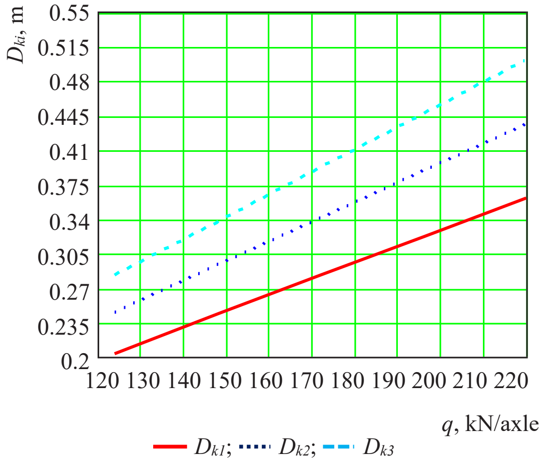

Fig. 4. Dependence of wheel diameter on braking speed and axial load when using evenly worn pads

Let's calculate the diameter of the wheel, which provides the necessary convention of heat to avoid its overheating during emergency braking according to expression (18). The calculation results are shown in **Fig. 4, 5**.

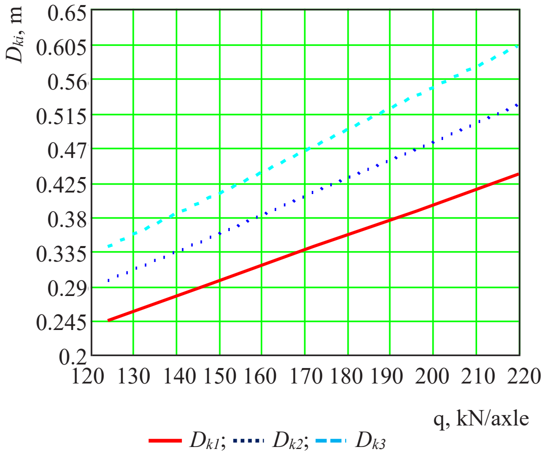

Fig. 5. Dependence of wheel diameter on braking speed and axial load when using wedge-dual worn pads

At the same time, the permissible value of the wheel diameter must have greater values than those calculated for the case of using pads with nominal parameters.

Therefore, when using blocks with wedge-dual wear, the wheel diameter should be increased by 17.5 % over that calculated for the case of using blocks with nominal parameters.

3. 3. Study of the thermal stress state of a composite brake pad with wedge-dual wear

To determine the thermally stressed state of a composite brake pad with wedge-dual wear, it is taken into account that the pad has the following parameters: thickness at the upper end $b_u = 42$ mm; thickness along the demarcation line of planes $b_{dl} = 35$ mm; the thickness at the lower end of $b_l = 13$ mm and the length of the harmful abrasion in the upper part of the pad $l_{ha} = 81$ mm. These parameters are determined on the basis of natural studies.

The mass of the composite brake pad with wedge-dual wear (**Fig. 6**) is 1.94 kg, determined using the options of the SolidWorks Simulation software complex. The resulting mass value is 28.2 % lower than the mass of a typical pad with nominal dimensions.

The calculation scheme of the pad is shown in **Fig. 7**.

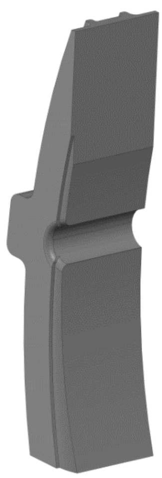

Fig. 6. General view of the spatial model of the composite brake pad type 2TP-11 with wedge-dual wear

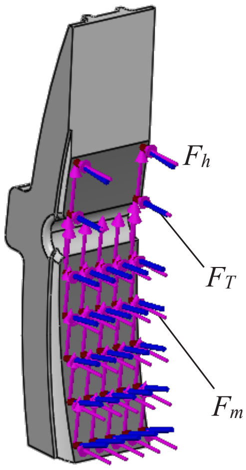

Fig. 7. Calculation diagram of a pad of 2TP-11 type with wedge-dual wear

During its assembly, it was taken into account that the working part of the block is subjected to a horizontal load F_h, the value of which was taken depending on the mode of operation of the air distributor: cargo – 41.69 kN; average – 34.34 kN; empty – 17.5 kN. The model also takes into account the friction force F_{fr}, which was determined by the formula:

$$F_{fr} = F_h \cdot \varphi_{cr}. \tag{19}$$

Spatial isoparametric tetrahedra were used to create the finite element model of the block. The finite-element model of a brake pad with wedge-dual wear has 24048 elements and 5368 nodes. The maximum mesh element size is 12 mm, the minimum is 2.4 mm. Fixation of the model was carried out behind the back in the area of adhesion to the brake pad. At the same time, hard pinching was used. The pad material is a composite that has linear elastic orthotropic properties. At the same time, the compressive strength of the material is assumed to be equal to 15 MPa, and the tensile strength is close to zero. The modulus of elasticity of the pad material is 5 10^3 MPa. Poisson's ratio is 0.37. The coefficient of thermal expansion is equal to $4.0 \cdot 10^{-6}$ K^{-1}.

The results of the calculations are shown in **Fig. 8–10**.

At the same time, the maximum stresses occur in the back of the block and amount to 16.7 MPa (the third main stress), which exceeds the permissible by 10.2 %.

The advantage of this study in comparison with those analyzed in chapter 2 of the article is that the authors first investigated the influence of wedge-dual wear on the thermally stressed state of the brake pad. It is important to say that in the works [21, 23] studies were conducted on the features of dual wear, but wedge-dual, as the most dangerous, was not investigated.

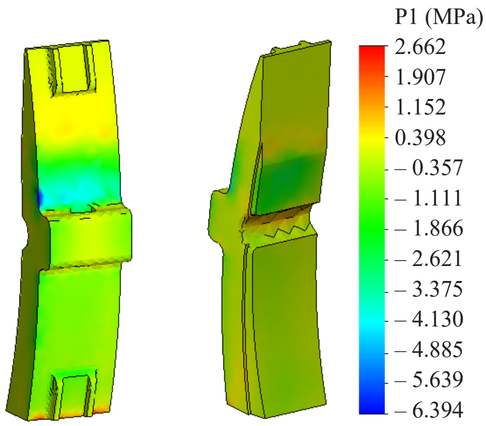

Fig. 8. The first main stress that occurs in a block of 2TP-11 type with wedge-dual wear

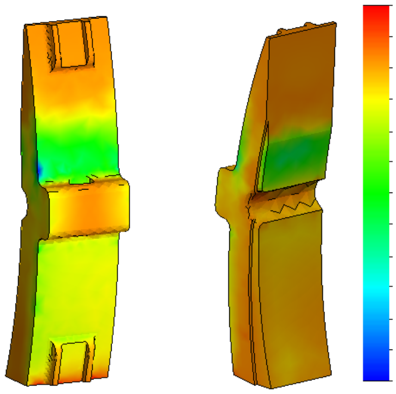

Fig. 9. The second main stress that occurs in a block of 2TP-11 type with wedge-dual wear

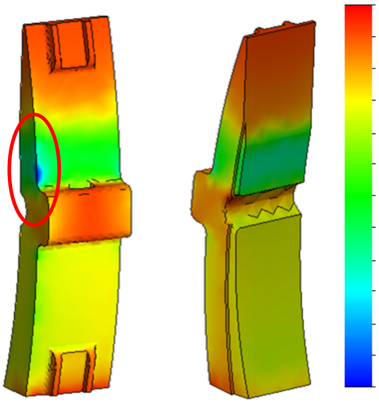

Fig. 10. The third main stress that occurs in a block of 2TP-11 type with wedge-dual wear

A drawback of this study is the calculation of only one type of brake pads used in rolling stock. In addition, the work does not show graphical dependencies regarding the collected statistical data on pad wear.

The limitation of this study is that the creep, i.e., elastic slippage of the wheel pair, was not taken into account during the calculations. Also, the limitation of the study is that it is valid only for composite pads.

The further direction of this research is the development of measures to modernize the elements of the brake lever transmission of the carriage of the freight car to eliminate such a negative phenomenon as wedge-dual wear of the pads. One of the important stages of the work is the performance of field tests of the modernized transmission, which will allow to confirm the proposed modernization measures. Equally important issues are the introduction of innovative materials for the production of brake pads for modern rolling stock [41–43].

The conducted studies prove the negative impact of wedge-dual wear not only on the braking efficiency, but also on the strength of the brake pads, which was not paid attention to at all before [44–46].

4. Conclusions

1. A complex thermal calculation was performed for composite brake pads with different values of parameters, including for a pad with wedge-dual wear, which had an area of 0.015 m^2, which is 25 % less than the nominal one. The results of the comparative calculation prove that the amount of pressure on an abnormally worn pad is 25.5 % less than that acting on a pad with nominal values.

In case of inoperability of devices for uniform pad wear, which leads to mass occurrence of wedge-dual wear of pads in freight cars under operating conditions, calculations have established that when using such pads, the wheel diameter should be increased by 17.5 % over the existing one, which is impossible in practice. It is provided that the calculated values for the case of using pads are compared with the nominal values of the parameters.

2. It was established that different wheel diameters depending on the speed of movement and the axial load of the car provide the necessary heat convention to prevent overheating of the tribotechnical pair «brake pad – wheel» during emergency braking. However, if there will be a change in the amount of pressure on the composite pad during braking, then the braking force will change. In this regard, the heating temperature of the composite pad will increase significantly over time. To study the change in braking force, which affects the heating temperature of a composite brake pad, calculations were performed for pads with different parameter values. The results of the obtained calculations prove that the heating temperature during braking for 2TP-11 pads with wedge-dual wear will be 16.8 % higher than for pads with nominal parameter values.

3. The thermally stressed state of a composite brake pad with wedge-dual wear was studied. The maximum stresses occur in the back of the block and amount to 16.7 MPa (the third main stress), which exceeds the permissible by 10.2 %. This is explained by the fact that the useful area of the pad decreases, and accordingly, its load increases.

The peculiarity of the obtained results is that they prove the negative impact of wedge-dual wear not only on the braking efficiency, but also on the strength of the brake pads. A distinctive feature of the obtained result from the known results is that it takes into account the influence of wedge-dual wear on the thermally stressed state of the brake pad. This issue was not paid attention to before.

This necessitates the creation of measures aimed at eliminating wedge-dual wear of brake pads, which will contribute to increasing the safety of train traffic and significantly reducing the operational costs of maintaining freight cars.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Data will be made available on reasonable request.

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