Development of an Innovative Technical Solution to Improve the Efficiency of Rolling Stock Friction Brake Elements Operation

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Abstract. Braking system is the most important component of a vehicle. Traffic safety directly depends on its correct function and proper operation. When braking, a large amount of heat is generated, which can lead to overheating of the friction elements and subsequent damage. The authors describe a method for stabilizing the temperature of the brake pad and wheel contact in the article. In this context, it is proposed to use inserts made of expanding agents in the brake pad design. The presence of holes in the pad helps to eliminate wear particles, that reduces the intensity of the pad wear. The design of such a pad and the operation of the proposed brake system are described in the article. The diameter and depth of the brake pad holes are substantiated. The described solution will allow to cool the contact area of the brake pad and the wheel, and, thus, increase the braking efficiency.

Keywords: Brake pad · Friction wear · Expanding agent

1 Introduction

One of the priority development fields of railways is the creation or the improvement of the new design elements of vehicle which will meet the modern needs [1–4]. Traffic safety, the possibility of increase in the speed, and, accordingly, increasing the carrying and traffic capacity of the railway line largely depend on the efficiency of the friction elements of the rolling stock brake system. When braking, the train kinetic energy is converted into other forms of energy, most of which is a heat one. This process is accompanied by an increase in the temperature of the friction elements [5]. In cases of thermal overloads, which mainly occur as a result of long-term braking on down-grade railroads, the generation of stresses and deformations occurs, whose consequences are the appearance of cracks on the rim of a wheel and the final total wheel defect [6, 7]. Effective train braking depends on the coefficient of friction, which is influenced by temperature changes in tribocontact [8–10]. Hence a topical issue in the operation of rolling stock is the development of innovative technical solutions to stabilize temperature conditions in the interaction zone of brake elements.

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2 Analysis of the Problem

When braking, the place of contact between the wheel and the brake pads heats up due to friction forces. The temperature determines thermo-mechanical behavior of the structure. In the braking surface, high temperatures and thermal gradients are produced. This generates stress and deformations in which the consequences are manifested by the appearance of cracks [11, 12].

The authors of papers [13, 14] revealed serious thermal effects on the rolling surface of a wheel during braking (heating up to 700–800 °C). It was found that thermal loads are in inverse relation to the contact area of the brake pad with the wheel. Temperature fields with significant gradients are an unstoppable physical phenomenon of the transformation of mechanical energy into thermal energy. This will lead to a change for the worse in both frictional and strength properties due to structural changes in the materials. With prolonged exposure to high temperatures, thermal crack initiation with their exit to the outer face is possible [5, 6, 15]. Under such conditions of friction, there is a rapid thermal wear of the surfaces of the wheel and brake pad [5, 6]. In this case, the wear rate is determined by the occurrence and development of high temperatures in the friction zone. For brake discs, an increase in the disc temperature leads to axial skewing (umbrella) of the disc, and thermal deformation in the rib area necessarily causes waviness or roughness of the disc friction surface, thereby increasing the pressure on the friction linings and creating local temperature spots on the disc friction surface [16].

The problem of resource saving of shoe brakes with which the rolling stock is equipped is multi-scale. It needs a solution of technical and economic, technological, metallurgical and tribological knowledge associated with the choice of wear-resistant materials and methods of cooling the working surfaces of the brake elements.

There are various ways of implementing thermoregulatory and energy-efficient functions in brake systems. They can be considered within the framework of the following classification.

1. Thermal control based on the heat absorption or release by metallic or non-metallic friction elements of braking devices. In this case, the following items can be used:
    1.1. Chemical reactions to friction lining materials with the heat emission or absorption.
    1.2. The effects of energy emission and absorption when changing the aggregative state of friction elements (melting, evaporation, sublimation, crystallization, etc.).
    1.3. Physical properties of friction elements materials that provide high heat transfer.
2. Thermal regulation based on the heat elimination from the friction pairs of friction elements into the environment.
    2.1. Ventilation and self-ventilation.
    2.2. Heat elimination by special cooling elements.

The staff of the open joint-stock company «Heat-resistant products and engineering development» proposes to improve the railway brake pad design [17] to reduce temperature differences by placing a flat element made of material having lower coefficient of linear thermal expansion than polymer friction material in the surface layer of the back of the pad. This solution makes it possible to reduce the temperature stresses in the surface layer of the pad during periodic heating and cooling due to unequal expansion of its individual areas. This reduces the possibility of the surface layer cracking and maintains the integrity of the back of the pad, which is especially important for pads reinforced with only a metal frame or a shortened metal rear part. In the latter case, the flat element is placed in the unreinforced back of the pad. Better interaction of the pad with the brake block holder and better distribution of pressure on the pad during frictional contact provides maintaining the integrity of the pad back during operation, as a result of which the pad operational factors are improved.

In the patent RU2319871 "Brake pad of a railway vehicle (options)", a structure that contains a metal frame and a composite friction element fixed on it is proposed. The composite friction element is made of two longitudinal layers differing in thermal conductivity. The less heat-conducting layer is made of a composite friction material that has greater adhesion to metal and strength compared to the layer located on the pad working surface. The thickness of the heat-conducting layer is less than the minimum pad thickness allowed for operation, but not more than the thickness from the back surface of the pad to the protruding parts of the metal frame (Fig. 1, a).

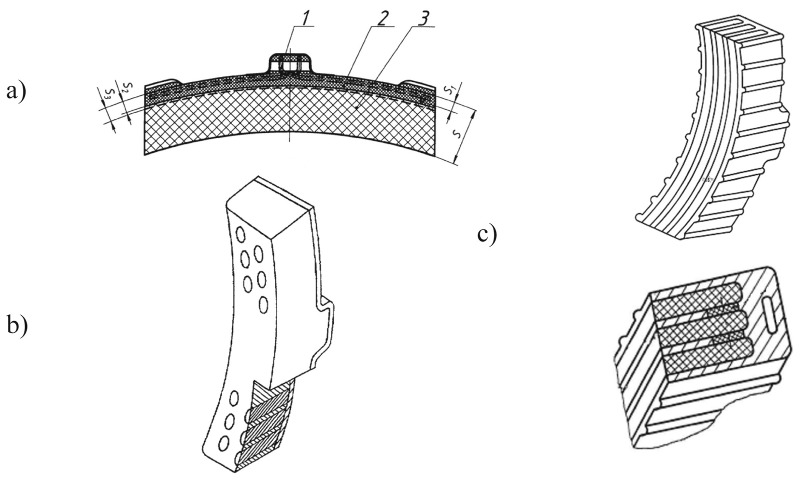

Fig. 1. Analysis of the brake pad designs with improved operational and frictional properties: a) a brake pad of a railway vehicle with a metal frame of reduced thermal conductivity: 1 – is a metal mesh-wire frame, 2 – is a longitudinal less heat-conducting layer of a composite friction element located on the back surface of the pad, 3 – is a longitudinal more heat-conducting layer of the composite friction element, located on the working surface of the pad (working layer); S – is a pad thickness S1 – is a thickness from the back surface of the pad to the protruding parts of the metal frame; S2 – is a thickness of the less heat-conducting layer of the composite friction element; S3 – is the minimum pad thickness allowed for operation; b) bimetallic brake pad; c) binary brake pad.

There is a bimetallic brake pad (Fig. 1, b) [18], which contains an arcuate curved metal bar made by cast iron casting and a steel plate from which steel cylindrical filling pieces extend into the cast iron bar. The filling pieces are located radially, in two parallel rows, unfolded relative to the longitudinal axis of the pad in one direction. The filling pieces are made of a material with a higher abrasiveness than the material of the bar.

The authors of the patent of Ukraine 75974 “Brake pad” proposed a brake pad made of two materials of different thermal conductivity. The body of the pad is made of a material with high thermal conductivity, for example, of cast iron in the form of a box with back and side walls and longitudinal partitions in the middle, and the cavities between them are filled with a composite material. In addition, transverse heat sinking fins of the cooling system are made on the outer surfaces of the body side walls, and fastening holes filled with a composite material are made near the back wall perpendicular to the side walls and partitions (Fig. 1, c). That is, such a pad, due to its design features, with the same resistance against wear, will be able to remove the remaining heat from the contact zone of the pad and the wheel rolling surface. Thus it will ensure the elimination of undesirable effects arising from the use of composite brake pads, and the creation of effective conditions for the operation of railway brake systems while maintaining high resistance against wear of the brake pads used in them.

A wide variety of brake element designs does not solve the problem of significant heating at the contact of the brake elements. An integrated approach is needed to reduce the heating of the brake elements. It is necessary not only to cool the contact, but also to remove heat from the contact through the use of heat-absorbing elements. In the studies of the article authors, the task of stabilizing the temperature in contact of tribological elements through the use of several structural elements is posed. Depending on the type of operation and the type of pads, these solutions can be used either together or separately.

3 Problem Solution Elaboration

To solve the problem of temperature stabilization in the tribological elements of the brake system, several technical solutions have been developed. These technical solutions can be used both together and separately. The maximum temperature stabilization effect will be achieved using all three technical solutions.

1. Let us consider the issue of stabilizing the temperature of the frictional contact of the brake elements. To cool the tribopairs, it is proposed to use inserts made of expanding agents which form an active gaseous medium in the pads when the temperature rises.

In this case, when the railway rolling stock is braking, the pads are pressed against the wheel or disc. The temperature in the tribopair rises. Under the influence of temperature, the process of thermal decomposition of the pad expanding agents begins in the pad, that leads to the release of a significant amount of gas products at a high rate [19]. One of the main decomposition products is nitrogen gas, which interacts with thin surface layers of friction units. This has a positive effect on the frictional properties of the friction pair, increases the adhesive coefficient and sharply strengthens and stabilizes the surface of materials, thereby increasing their durability and wear resistance.

2. Cast iron microparticles formed in the process of wear in the brake pad and the wheel friction zone are relatively large. This also leads to an increase in the intensity of wear in the contact zone of the brake elements, and their movement in the friction zone during motion reduces the coefficient of the brake pad friction on the wheel rolling surface. This affects a decrease in the effectiveness of mechanical braking and an increase in the braking distance, and reduces traffic safety.

Elimination of solid microparticles in contact and increasing resource saving when using the brake system is proposed by introducing new elements into brake system design. These elements ensure the accumulation of compressed air and cleaning the contact with it.

The proposed braking system works in the following way.

Before the train departs, the brake is charged. For this purpose the handle of the brake valve 4 is put into the release position (Fig. 2). In this case, the brake cylinder 1 through the brake control valve 2 and the one-way valve 3 is connected to the bellows 4, in which compressed air is accumulated. The one-way valve 3 allows the compressed air to move in only one direction from the brake cylinder into the bellows and prevents the air from moving in the opposite direction.

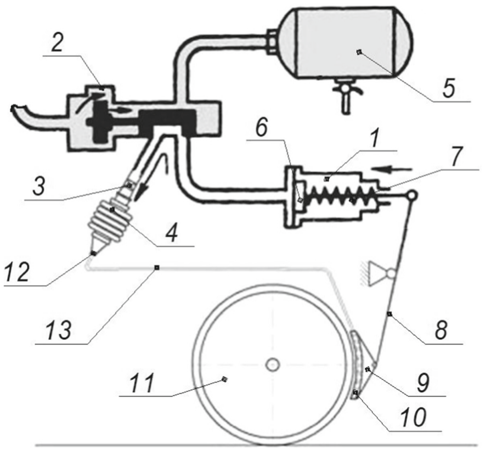

Fig. 2. The braking system of the locomotive with air storage and contact cooling elements.

To brake the train the brake control valve 6 comes into action and disconnects the brake cylinder 1 from the bellows 4 and combines it with a control reservoir 5 filled with compressed air. When compressed air is supplied to the brake cylinder 1, the piston 6 with the push rod 7 moves to the right, and the brake beams 8 at the same time presses the brake shoe 9 with the brake pad 10 to the wheel 11. Then the control valve 12 of the bellows 4 is activated, and the compressed and accumulated air is fed under pressure into the holes 13 (Fig. 3) of the brake pad 10 through the rubber supply line

14. This helps to cool the "brake pad – wheel" contact and to carry the grit along the grooved channels 15 into the environment (Fig. 3).

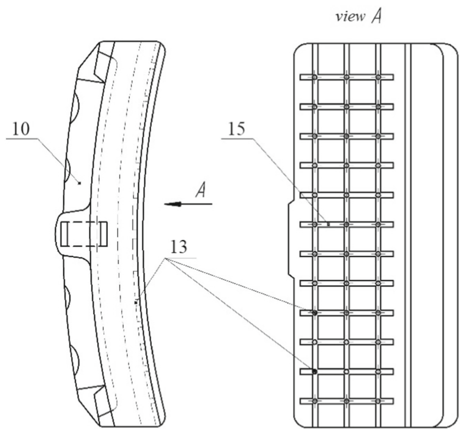

Fig. 3. Brake pad with cooling holes.

To release the brake, the brake valve handle is put in the release position. The supply line is combined with the brake line, as a result of what the pressure rises in it and the brake control valve 2 connects the brake cylinder 1 to the bellows 4 through the one-way valve 3, and connects the line to the control reservoir 5. In this case, compressed air accumulates in the bellows 4. If the emergency braking valve (conductor valve) is opened on the wagon, brakes are automatically activated.

3. It is proposed to use compressed air from the locomotive sanding system to supply cooled air into the contact of the brake pad with the wheel. For this, the nozzle of the sanding system must be equipped with a vortex tube, the design of which is based on the Ranque effect [20]. In this case, the nozzle of the sanding system has three holes: the first one is for cooled air, the second one is for hot air, and the third one is with abrasive material. The outlet for the cooled air is combined with the brake pad holes through the pipeline, while ensuring both the transfer of solid microparticles from the contact and its cooling. Hot air should be used when hauling on dirty rails.

4 Result of Research

During braking, the temperature of the brake pad changes from T_1 to T_2 depending on the time t (Fig. 4). In the absence of contact cooling, the dependence of temperature T on time t has a linear increasing character. When compressed air is supplied to the holes of the brake pad, the curve of the dependence of the brake pad temperature T on the of brake pad pressing time t changes (Fig. 4). An increase in the diameters d of the holes to a certain value leads to a decrease in the temperature T in the contact. It is advisable to make holes from 2 mm to 8 mm, a further increase in the diameter of holes will not affect the temperature characteristics of the brake pad.

When compressed air is supplied, a backpressure force Q arises between the brake pad and the wheel. It is necessary that the backpressure force Q does not impair the braking performance of the rolling stock. To do this, it is necessary to control the diameters d and depth h of holes (Fig. 5). The studies (Fig. 5) show that at a hole depth of $h > 0.5$ mm, regardless of the diameter d, the value of Q is much less than the pressing force of the pads and, accordingly, does not affect the braking characteristics of the rolling stock.

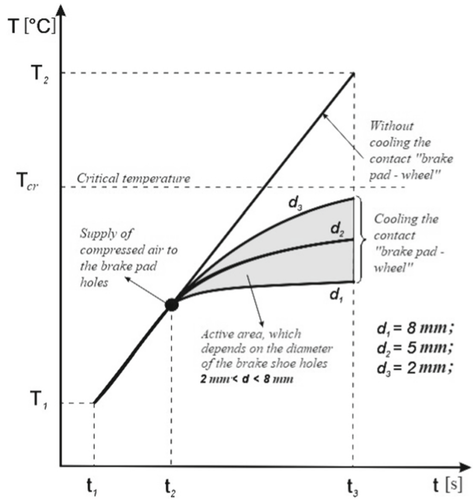

Fig. 4. Brake pad temperature plot against the time of pressing the pads.

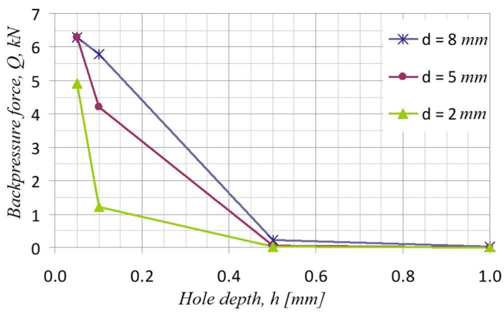

Fig. 5. The backpressure force Q plot against the depth h of the brake pad holes.

The amount of the brake pad wear ΔH in thickness for the case of emergency braking for the time t_s until a complete stop is determined by the formula [8]:

$$\Delta H = \frac{4}{3}\frac{\alpha_p^2 B_b^2 \Delta h v_0^2 t_s}{A^2\left(\chi F_p\right)^2(\Delta\tau_{\max} - \Delta\tau_{av})^2\pi\lambda\gamma c}, \quad (1)$$

where a_p- is a heat flow distribution coefficient, which shows how much of the heat generated by friction has entered the pad; B_b- is a braking force; $\Delta h-$ is an average breaking height of actual contact protrusions; υ_o- is an initial braking speed; $A-$ is a mechanical equivalent of thermal work; $\chi-$ is the coefficient of the actual contact area; F_p- is a geometric area of the pad and wheel contact; $\Delta\tau_{\max}-$ is an increase in temperature and the value at which the destruction of the roughness protrusions occurs (it depends on the pad material and is constant); $\Delta\tau_{av}-$ is an average increasing temperature in the working surface of the pad friction; $\gamma-$ is the specific gravity of the heating wheel; $c-$ is the specific heat.

It can be seen from the formula (1) that the presence of holes and grooves contributes to the effective removal of the third body (wear cast iron microparticles) from the friction zone, that makes it possible to reduce the average destructible height of the protrusions of the actual contact during braking, thereby reducing the wear rate of the pad and increasing its friction coefficient, that improves braking efficiency.

The average increase in the temperature of the working surface of the pad friction is determined by the formula:

$$\Delta\tau = \frac{1}{t_b}\int_0^{t_b} \Delta\tau_s dt, \quad (2)$$

where $\Delta\tau_s-$ is the excess temperature of a surface on which heat is generated.

The change in temperature $\partial(\Delta\tau_s)$ up to time t is caused by the amount of heat generated per surface unit:

$$\partial(\Delta\tau_s) = \frac{q(t)}{\sqrt{\pi\lambda\gamma c}\sqrt{t_1 - t}}dt. \quad (3)$$

We have while taking into account the transfer of heat from the friction surface into the environment:

$$q(t) = q_a\left(1 - \frac{t}{t_r}\right) - \alpha \cdot \Delta\tau_s, \quad (4)$$

where q_a- is the amount of heat released per surface unit per time unit (heat flux density) at the beginning of the temperature rise process; $\alpha-$ is the coefficient of heat transfer from the friction surface into the environment.

The heat transfer coefficient from a heated surface into the environment is defined as the sum of the convection α_c and radiation α_r heat transfer coefficients:

$$\alpha = \alpha_c + \alpha_r. \quad (5)$$

The radiation heat transfer coefficient α_r depends on the given measure of the colour scheme tone (dark or light) of the emitting pad surface, the absolute pad temperature and the environment temperature. In the modified pad design, the radiation heat transfer coefficient α_r is not considered, since it does not significantly affect the wear of the pad, since there is little heat removal from the friction zone of the rolling surface of the wheel and pad into the environment.

The convection heat transfer coefficient α_c is calculated depending on the Reynolds and Prandtl numbers [8].

The presence of grooves in the proposed pad design reduces the intensity of their wear ΔH, especially at high motion speeds, by stabilizing the temperature regime by increasing the efficiency of heat removal from the friction zone into the environment. During braking, the cold air blown under the pad heats up and is efficiently released into the environment. As a result, the coefficient α_c increases, that reduces the average friction temperature of the pad working surface $\Delta\tau_{av}$. So the time to reach the maximum temperature $\Delta\tau_{\max}$, at which the destruction of the protrusions of the actual contact occurs, increases according to the formula (1). In a typical pad, the heating intensity increases when increasing the initial braking speed.

5 Discussion of Results

When braking, the train kinetic energy is converted into other forms of energy, most of which is a heat one. This process is accompanied by an increase in the friction elements' temperature, which affects the braking efficiency and the wear resistance of the brake elements. The problem of resource saving of shoe brakes with which the rolling stock is equipped is multi-scale. It needs a solution of technical and economic, technological, metallurgical and tribological knowledge associated with the choice of wear-resistant materials and methods of cooling the working surfaces of the brake elements. In research, innovative technical solutions to stabilize temperature conditions in the interaction zone of brake elements developed.

To cool the tribopairs, it is proposed to use inserts made of expanding agents which form an active gaseous medium in the pads when the temperature rises. One of the main decomposition products is nitrogen gas, which interacts with thin surface layers of friction units. This has a positive effect on the frictional properties of the friction pair, increases the adhesive coefficient and sharply strengthens and stabilizes the surface of materials, thereby increasing their durability and wear resistance.

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6 Conclusion

In the process of research, innovative technical solutions have been developed to improve the conditions for the interaction of tribological elements of the brake system.

These solutions can be effectively used both together and separately. These studies were carried out at an inventive level. According to the calculated data, the presented technical solutions will stabilize the temperature at the contact of the brake elements, remove wear elements. The most efficient brake pad air hole is 2–8 mm.

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