

Development of the Theory and Methodology of Controlling the Local Tribological Contact Thermomechanical Loading

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Abstract

Theoretical and experimental studies have been carried out, which confirmed the fact that the contact temperature is the most important factor affecting the entire complex of service properties of the contacting materials. The authors of the paper propose the control of the frictional interaction of the tribological contact by controlling the temperature by forced cooling, which will stabilize the coefficient of engagement of the wheel with the rail.

KEY WORDS: *rail transport, clutch coefficient, temperature, cooling, clutch control*

1. Introduction

Among the existing friction gears (clutches, variators, belt drives, etc.), the most specific operating conditions are the frictional transmission of the locomotive's wheel tractive or braking power.

The specificity of wheels and rails interaction has several aspects. Firstly, the particles of substances of different origin get into the contact of wheel and rail:

- climatic (fallen leaves, moisture, ambient temperature);
- technological (ballast stones, corrosion products, lubricants);
- products of wear of wheels, rails, brake pads;
- transported cargo (oil, coal, cereals, etc.).

Secondly, the frictional conditions of contacting wheels and rails can be actively affected (by abrasive materials supply, friction activators, lubrication). Another feature of the wheel pairs is their multifunctionality. Wheel pairs provide:

- support and direction of the rolling stock while driving along the track;
- transmission of traction (braking) force;
- transmission of traction currents to the ground.

All these functions are realized when the wheels are in contact with the rails, and different functions are realized in different areas of friction surface of both the wheel and the rail. Therefore, the «wheel-rail» system is a combination of two pairs «friction» and «antifriction» [1].

2. Development of the Theory and Methodology of Controlling the Local Tribological Contact Thermomechanical Loading

As known, realization of the tractive (braking) force is accompanied by the wheels slipping relative to the rails. This leads to the fact that part of the locomotive power is spent not on traction, but on warming up and destruction (wear) of surfaces in the contact zone. Therefore, it is more correct to use the concept of transmission efficiency coefficient, first formulated in [2] in addition to the level of cohesion. It offers the following expression for determining the efficiency coefficient:

$$\eta = \frac{W_u}{W_g} = \frac{F_c \cdot V_l}{(F_c \cdot V_l + F_c \cdot V_{sl})} = \frac{1}{1 + \frac{V_{sl}}{V_l}}, \quad (1)$$

where η – transmission efficiency coefficient; W_n – useful power; W_g – general power; F_c – force of wheel and rail cohesion; V_l – locomotive speed; V_{sl} – speed of slipping of the wheel relative to the rail.

One of the fundamental concepts used to describe the process of wheels and rails cohesion is the concept of «cohesion characteristic» - the dependence of the coefficient of cohesion on the relative slipping $\psi = f(|\varepsilon|)$. Considering $\varepsilon = V_{sl}/V_l$ it seems expedient to transform the formula (1) to the following form:

$$\eta = \frac{1}{1 + \varepsilon}. \quad (2)$$

From Fig. 1 it follows that in all cases the use of sand increases the coefficient of cohesion and reduces slip, which leads to an increase in efficiency. But there is a «side effect»— an increase in resistance to movement (up to 12% [3]). However during braking this effect can be considered positive.

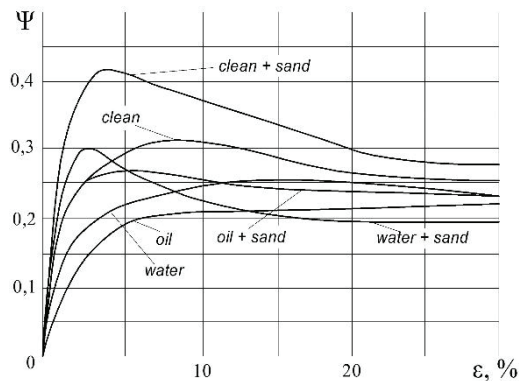


Fig. 1 Cohesion characteristic of contacting wheel and rail under different conditions

Using the formula (2) and dependences presented in Fig. 1, we determine the transmission efficiency for different frictional states. Considering implementation of the locomotive traction force corresponding to the two levels of the coefficient of cohesion: 0,2 and 0,25. The results of the calculations are summarized in Table 1.

Table 1
Efficiency of the wheel-rail transmission under various frictional conditions of contact

Frictional conditions	Slipping, %		Efficiency, %	
	0,2	0,25	0,2	0,25
Clean surfaces	0,9	2,5	0,991	0,975
Water	3,5	12,1	0,966	0,892
Oil	6,5	-	0,939	-
Water + sand	0,7	1,5	0,993	0,985

On the basis of the results obtained, it is possible to formulate requirements for frictional interaction in the wheel-rail system: providing a stably high coefficient of cohesion together with ensuring the maximum possible efficiency coefficient and minimizing the magnitude of the resistance to movement, taking into account the movement regimes and parameters (traction, braking, acceleration, etc.). Taking this into account, it is necessary to analyze the methods of active influence on the frictional properties of the «wheel-rail» tribosystem.

Improving the wheel-rail system interaction conditions is achieved by improving the design of locomotives, preventive measures and direct impact on the frictional properties of the surfaces of wheels and rails during their operation.

The mathematical model of tribological contact with intensive heat release in the system «wheel-rail-braking elements» which allows to determine the local surface temperature of the interacting elements depending on various factors was created. It involves the use of the experimentally obtained dependences of the coefficient of friction in rolling with slip (hereinafter friction coefficient) on the temperature in the contact zone $f(\theta)$. The temperature in contact is to be understood as excess of the temperature in contact above the ambient temperature obtained by the relative friction of the roller against the rail.

In this paper, to establish the dependence $f(\theta)$ the original automated measuring and computing complex «Friction machine» designed to study the frictional properties of the wheel-rail contact during rolling with slipping, both in laboratory and field conditions was used.

In the study of rolling with slip, the coefficient of friction can be considered as a function of the following parameters: absolute slip velocity; relative slip; contact temperature.

The temperature in the contact zone is of special interest. In order to test the effect of this factor on the coefficient of friction, two series of experiments were carried out with different values of the linear speed of the «Friction machine»

movement ($V = 0,09 \text{ m/s}$ and $V = 0,18 \text{ m/s}$). The experiments were carried out on a dry, clean rail.

After appropriate processing, the dependences of the coefficient of friction on the temperature in the contact zone (Fig. 2), the absolute slipping speed (Fig. 3), and the relative slip (Fig. 4) are obtained using the same experimental data. The last two quantities are determined by formulas:

$$g = \omega \cdot R - V; \tag{3}$$

$$\varepsilon = \frac{g}{V} \cdot 100, \tag{4}$$

where g – absolute slipping speed; ε , ω , R – relative slip, angular velocity and working roller radius; V – «Friction machine's» linear speed.

In all figures, dots indicate the experimental points obtained at the speed of the friction machine 0,09 m/s, and circles – 0,18 m/s.

As can be seen from Fig. 2, the experimental data shown in the coordinate axes «temperature – coefficient of friction», for the indicated velocities of motion practically match. But the data in the coordinate axes «absolute slipping speed – friction coefficient» (Fig. 3) and «relative slip – coefficient of friction» (Fig. 4) are significantly different.

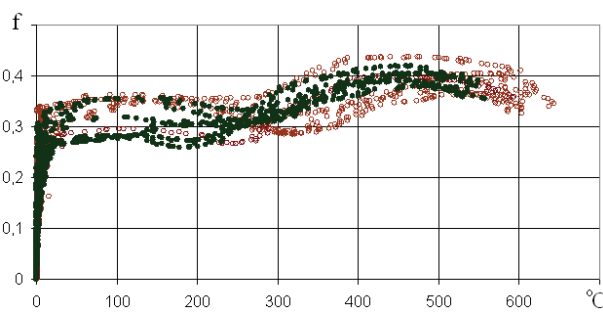


Fig. 2 Dependence of friction coefficient on temperature in contact

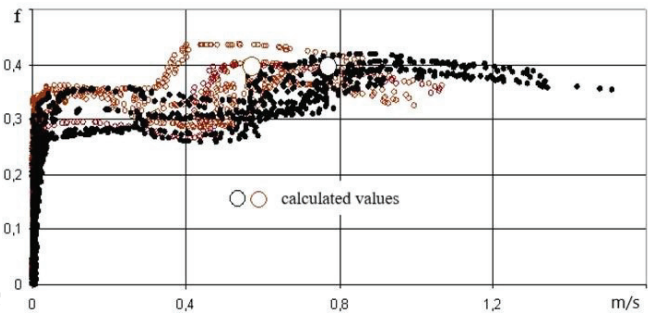


Fig. 3 Dependence of friction coefficient on slipping speed

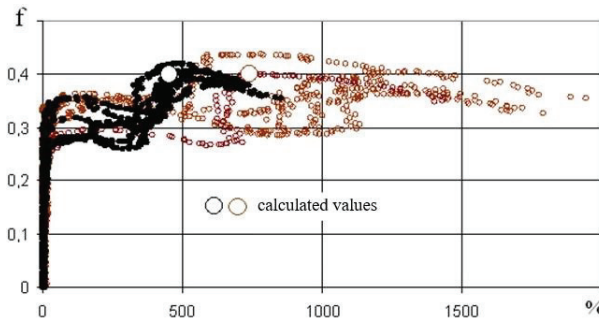


Fig. 4 Dependence of the coefficient on the relative slip

This result allows us to propose that the dependence of the coefficient of friction on temperature is universal (for specific frictional conditions) and does not depend on the parameters of motion. In order to test this assumption with given temperature and friction coefficient, we determine the absolute slip velocity and the relative slip.

We use the formulas obtained in [3] for determining the mean integral temperature on the rail surface and the distribution coefficient of the heat fluxes between the roller and the rail.

$$\theta_{1mi}^* = \frac{4 \cdot a_1 \cdot q}{3 \cdot \lambda_1} \cdot \sqrt{\frac{L_1 \cdot a_1}{\pi \cdot V}}; \tag{5}$$

$$a_1 = \frac{1}{1 + \sqrt{\omega \cdot R / V}}; \tag{6}$$

where θ_{1mi}^* – mean integral temperature on the rail surface; a_1 – the coefficient of distribution of heat flows between the roller and the rail; q – power of the heat source; ω , R , V – have the same meaning as in (3.1); λ_1 – coefficient of thermal conductivity of the rail material; L_1 – the length of the roller contact with the rail.

Using (6) in (5), we obtain equation that relates the mean integral temperature θ_{1mi}^* to the angular velocity ω :

$$\theta_{1mi}^* = \frac{4 \cdot P \cdot f(\omega \cdot R - V)}{3 \cdot \lambda_1 \cdot F} \cdot \sqrt{\frac{L_1 \cdot a_1}{\pi \cdot V}} \cdot \frac{1}{1 + \sqrt{\omega \cdot R / V}}, \quad (7)$$

where P – is the vertical load from the roller to the rail; F – area of contact of the roller with the rail.

From Fig. 2 it follows that the maximum of the f coefficient that equals to 0,4 corresponds to a temperature of $\theta_{1mi}^* = 450^\circ\text{C}$. These values will be used in the calculations.

The values of the remaining values are taken from the experimental conditions and are summarized in Table 2.

Table 2

Calculated values

№	Designation	Value
1.	R , m	0,02
2.	V , m/s	0,09; 0,18
3.	λ_1 , J/kg $^\circ\text{C}$	460
2.	F , m 2	0,0001230
5.	L_1 , m	0,0062583
6.	a_1 , W/m $^\circ\text{C}$	74,4
7.	P , H	240

In this case, in Eq. (7), the unknown is the angular velocity of the roller ω . Using the values from Table 2 in Eq. (7), we solve it for two values of the linear velocity (0,09 and 0,18 m/s) relative to ω . This can be done by one of the numerical methods, for example, by the method of half-division. After finding ω the quantities ϑ and ε are determined by the Eqs. (3, 4). The results of the calculations are shown in Figs. 3 and 4 with large circles.

As can be seen from the figures, the error in determining the calculated absolute slip velocity does not exceed 6%, and the relative slip – 11%.

The peculiarity of the experiments was the fact that the «Friction machine's» operator increased the voltage of the working roll motor before the onset of slippage, but the slipping time was limited to 3-6 seconds to avoid damage to the «Friction Machine». After the operating roller «Friction Machines» has been thrown into skidding, the frictional force can raise, fade or remain unchanged, but the task of this study was not to study the development and termination of skidding.

The obtained result indicates that, according to the available dependence of friction coefficient on temperature, the remaining parameters of motion can be determined with sufficient accuracy for practical purposes.

According to the data of [4] contact stresses on the track of wheel rolling along the rail can reach up to 600 MPa and higher. In this case, the flash point of interaction of the roughness protrusions of the surfaces of the wheel and rail can reach values corresponding with the melting temperature of the contacting bodies' material.

As the temperature of the steels of wheel and rail increases, the modulus of elasticity and the tensile strength decrease (Fig. 5), and therefore favorable conditions are created for plastic deformation and the process of setting the roughness protrusions of the contacting surfaces [5, 6]. The process of transferring the torque from the wheel to the rail is accompanied by skidding, as a result of which significant temperature gradients arise in the contact zone, contributing to the appearance of favorable conditions for the grasping of the surfaces. Excess heat release leads to a decrease in the strength of the surface layers, the destruction of the binder in the composite materials of the brake pads of locomotives, thermal stresses, dissociation of adsorbed films on the metal [7].

In the work [8], bench tests were carried out and the friction coefficient and tribospectral characteristics were analyzed in the absence and presence of friction modifiers in the friction interaction zone of the model wheel-rail subsystem of friction modifiers (Fig. 6).

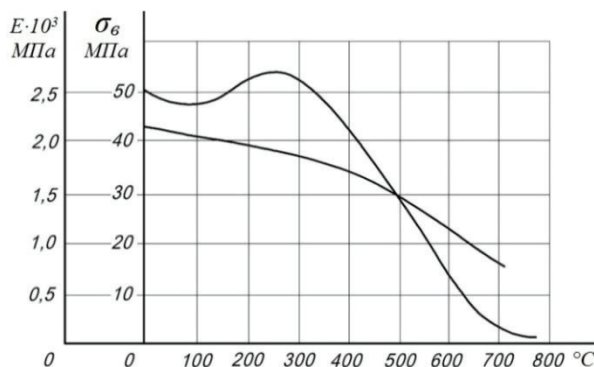


Fig. 5 Temperature impact on the value of tensile strength and modulus of elasticity of steel

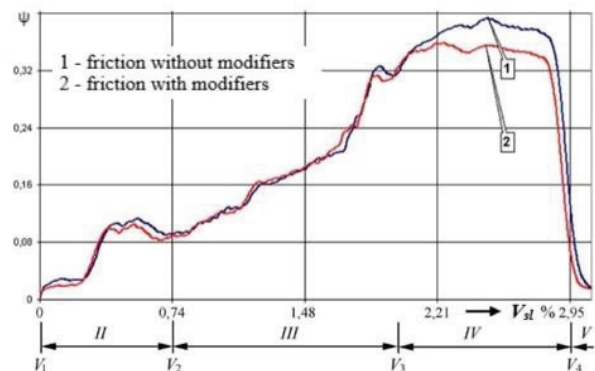


Fig. 6 Curves of changes in cohesion coefficient in time as a function of speed on relative slipping

As can be seen from Fig. 6 zone II is the «starting» of the rolling stock, which is accompanied by the periodic formation of local frictional contact sections with a positive and negative gradient of mechanical properties. Zone III is the realization of the tractive effort of the locomotive, in which the friction surfaces are heated to a favorable temperature, forming connecting bridges, the breaking of which leads to instant increase in traction. Zone IV – effective work and stability of the implementation of tractive effort. Zone V – as a result of plastic deformations of the contacting surfaces and their critical thermal heating, there is a drop in the stability of traction, a decrease in the coefficient of cohesion, and the onset of skidding.

Experimental studies carried out in [9] show that the dependence $f_n = f(\theta)$ (Fig. 7) can be divided into three independent zones within which a different rate of change of the molecular component of the friction coefficient f_n is observed. When the temperature θ varies from 20°C to 200°C (the first zone), the constancy of f_n is observed, which indicates a weak effect of temperature on the state of the contact layer.

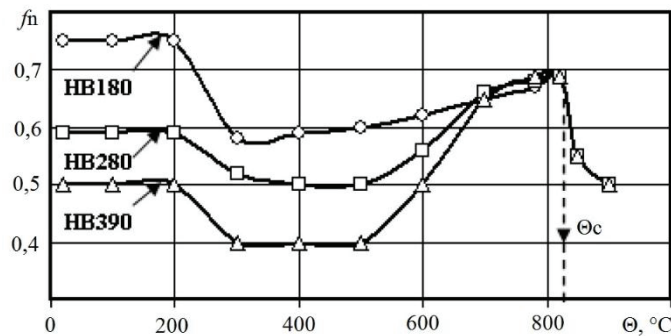


Fig. 7 Effect of heating temperature on the friction coefficient change

In the second zone (from 200°C to 400°C) there is a severe decrease in f_n and a very unstable zone of setting. The main protection against setting is the oxide and other non-metallic films on the friction surface of the materials. In the case of static oxidation, the threshold for the reaction of iron is 350°C, where the term «reaction threshold» is understood to mean the temperature at which a significant rate of formation of thermodynamically stable oxide compounds is observed, but in the process of friction, when oxidation of the activated metal occurs, the reaction threshold may be lower.

With a further increase in temperature to 800°C (third zone), a significant increase in f_n to a temperature θ_c of the structural-phase transformation is observed, which indicates qualitative changes occurring in the contact zone of the surfaces under investigation. This zone is characterized by contact grasping with small plastic deformations.

A further increase in temperature above θ_c significantly reduces the yield stress and sharply increases the ductility of the contacting surfaces, which leads to the destruction of the bridge junctions between the protuberances of the rough surfaces, so that when the locomotive moves, metal particles are extracted from the surface of the wheel or rail and metal particles are transferred from one surface to another.

Analysis of the obtained temperature curves of the friction characteristics and physical and mechanical properties of steels shows that at a temperature of 350°C the tangential stresses and friction coefficient decrease, but with an increase in this temperature, the diffusion mobility of the atoms and the propensity of the steels to grasp increase.

According to the results of the research on the «Friction Machine» in the range of speeds of 0,1-0,9 m/s in the «shaft-partial bearing» scheme, it is established that the influence of the slipping speed on the coefficient of friction and wear is very insignificant until there is an essential temperature changes in the frictional zone on slipping contacts [10].

With an increase in the slipping velocity of more than 1 m/s, an increase in the friction coefficient is observed. In the case of maintaining an artificial temperature constant slipping contact, an increase in the friction coefficient is observed, and then its stabilization. If, on the other hand, the temperature is kept constant on the surface and in the volume, then when the speed increases, the maximum of the friction coefficient practically does not change at a constant load, and the wear rate remains unchanged.

According to research by Luzhnov Y.M. when the surface temperature in a local contact exceeds 450°C, the mechanical properties of the interacting surfaces significantly deteriorate, which leads to a decrease in the frictional force and their intensive wear [11].

Thus, the theoretical and experimental studies confirmed the fact that it is precisely the contact temperature that is the most important factor affecting the entire complex of service properties of the contacting materials.

The authors of the paper suggest controlling the process of frictional interaction of a tribological contact by controlling the temperature by forced cooling, which will allow stabilizing the coefficient of cohesion. On the basis of numerical experiments and bench tests it is established that controlling the temperature in the zone of tribological contact creates the conditions for controlling the process of cohesion the wheel to the rail, and the forced provision of constant temperature in the contact leads to stabilization of the coefficient of cohesion at the maximum level [12].

3. Conclusions

On the basis of the analysis of theoretical and experimental studies of friction contact, it can be stated that control of the mechanical component is not sufficient to achieve consistently high traction qualities of the rolling stock. Therefore,

it is proposed to control the clutch of the tribological «wheel-rail» system by controlling and regulating the local-mechanical temperature component in the range from 250 to 450°C, depending on the frictional conditions of contact.

Based on the results obtained, an algorithm for controlling the thermomechanical loading of a local tribological contact was developed, consisting in cleaning and cooling the contacting surfaces with a two-phase flow of dry ice granules and forced cooling with compressed air using a Ranque-Hilsch tube to achieve a stable contact temperature.

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