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PHYSICAL FUNDAMENTAL AND ECONOMICAL ISSUES OF A WHEEL-RAIL FRICTION CONTRACT

In this paper it the influence of real surface layers in wheels and rails on their structure and thermophysical properties is shown. These define friction forces between maked dusty bodies. Methods to make the forecast and the technical diagnostic of the level of the cohesion of wheels and rails are given. Influence of the coefficient of the friction in the "wheels - rail" system on expenses of various economic resources on a railway transportation is presented in the report.

The railroad operation practice shows, that adhesion coefficient of a rolling-stock and a rail can vary between 1 and 0,5. In one case it can lead to underusing of the determined capacity. Otherwise, it can lead to cohesion's breaks and wearing out of wheels and rails. Therefore, since the generation of railroads and up to present days it has been an important thing to change the highest and constantly realized adhesion coefficients.

The main research direction has been accumulation of knowledges and clarifying of empiric dependencies of adhesion coefficients from speeds of rolling-stocks for a long time. There were mostly falling characteristics of exploited rolling-stock and rail and also in the requirements to the calculated adhesion coefficients their stability vary one from another. At the same time the experience of exploitation of this rolling-stock shows, that the calculated coefficients differ from one realized by him on 30-40%. More careful selection of the adhesion coefficients calculation results, taking into consideration the weather conditions, allowed Endruce to determine, that higher coefficients were realized in the whole locomotive's speed interval in dry weather, then in wet weather. However, in both cases one can observe a large variation between experimental results under the constant rail's moistening. [1]

According to the Minov's research adhesion coefficients of locomotives can be represented as follows:

$$\Psi = \Psi_0 \cdot \eta_0 \cdot \eta_d = \Psi_0 \cdot \eta_i , \qquad (1)$$

Where:

Ψ_0 - main adhesion coefficient, representing the influence of friction properties of friction covers of rails and wheels;

η_0 and η_d - static and dynamic parts of a coefficient of use of locomotive's adhesion weight.

The whole row of technical measures is nowadays applied for increasing η_i. Among them one should notice the alignment of loads and efforts between wheels and rails, electrical and mechanical adhesion of wheels, choice of propelling characteristics of engines and sizes of wheel pairs, flowing operation of locomotives' starting, improving condition of rails etc. The most perfect locomotives have an adhesion weight use coefficient 0,95 on separate areas. In compare with this coefficient the main adhesion coefficient remains, somewhat unresearched. It is known that it can vary between 0,6-0,1 in dependence of weather conditions.

Insufficient research of rails and wheels' friction properties changes' legitimacy and connected with this absence of reliable stabilization methods lead to growth of the normative trains' measures and the choice of its operating mode is being carried out under average empiric dependencies, not have taken into account the conditions of rail-wheel contact. Therefore, research of physical basis of adhesion and laws, determing deflections of adhesion coefficients from calculated values represents a problem, being actual for railways.

We make an attempt to largely use and develop the results of fundamental researches, carried out at the field of friction, physics, chemistry of surface, applying to the decision of the problem of friction at railroad transport. In connection with this fact the expedience of carrying out special researches on structure, composition and friction properties of surfaces of friction of rolling-stocks' rails and wheels for revealing physical foundations and the laws of rails and wheels' adhesion.

In these researches the well-known analytic, X-rays, structural, spectral and frictional methods of researching were applied. And also specially generated methods for field studies were used: methods on gathering samples of pollution's from friction surfaces and on their processing; on analysis of surface activities along the moistening angle for evaluation of lubricants' distribution along the friction surface; on studying of boarded viscosity of liquid and microgearcy of surfaces and others. Systematical researches were carried out on Moscow, Nothern and October railroads, Selectionaly, the samples were taken on separate areas of railroads in the Middle Asia, Siberia, Vietnam and also on rails of Moscow trams. The studies were carryied out in 1957-1999.

The researches showed that rails and wheels' friction surfaces were always covered with pollution that have structurally specific properties. Hard bodies, consisted of products of erosion of hard bodies, brought to the friction area, form the main measure (80-95%). There are water and lubricants in smaller quantities. Thickness of surface pollutions' layer (*h*) is not homogeneous on the whole width of friction tracks. The thinnest layers (1.. .20 micron), owning the highest free energy and good water moistening, are situated on the central rails and wheels' friction tracks. The thickest and hardly moistened with water ones are situated outside friction tracks. Friction tracks can be thinner and thicker, situated symmetrically with the rails' axis and unsymmetrically moved into the axis rail line. Their situation is rather stable on the determined rails' area, and they have similar structure and pollution properties

The basis of hard pollutions of central friction tracks is ferum oxides, waterless silicates of aluminum and cremnium. There are combinations of Ca, C, Mg, Pb, Ni, Cu in less quantities. Water is slighdy present (1-5%) with the exception of separate cases (up to

20%) and highly depends on weather conditions. Lubricants in free conditions usually concentrate inside hollows, defects and cracks of surfaces. And there are only tracks of lubricants of surface pollutions and surface projections. Separate drops of lubricants, falling out on rails after passing by of several train's wheel pairs (10-30), do not influence gready on the structure of pollution. Adsorption properties of pollutions and their free surface energy are mainly influenced by correlation between quantity of lubricants and hard bodies, falling out on rails, by measure of crushing into pieces and oxidizing of hard pollutions. Surface pollutions are polydispersional in their structure. The most possible size of particles of pollutions is 0,1-0,2 microns. Big part of pollutions, mostly ferum, is in amorphous condition. The most possible size of particles is less than the thickness of the pollution layer. The difference between the structure of pollutions of friction tracks of rails and wheels hasn't been discovered.

Inside and outside friction tracks much more quantity of pollutions accumulates. There are sand particles and lubricants in higher percentage correlation (20-30%).

The researches of properties of the oils, falling out on the rails and taken from pollution samples, have shown that they had had a viscosity at hard surface 1,5-2 times less than capacious one in the bywall layer. Thin layers of lubrications, put on the preliminarily carefully refined surface of a rail, are very unsteady in the time and especially on projections of a surface. This process of their destruction is quickened with the appearance of water. Lowered limit viscosity and low stability of films on projections assist to fast inculcation of lubricants to pores of pollutions and defects of pollutions.

The process of forming of the structure and properties of surface pollutions of rails and wheels is in dynamic balance between newly given products on one side (particles of metals' consumption, sand and transported goods, products of corrosion, lubricants and dust fallen out on rails, migrations of organic substances etc) and other side between taking out of particles of pollutions and liquids from friction surfaces (by trains' wheels, steams of air and water). Intervals in trains' schedule and other factors can influence on changing of structure and properties of friction surfaces. They can be reasons of a disperse of the experimental data of experiments, carried out on railways. However, it hasn't been observed any essential and strongly expressed deflexions from average values in the structure of the pollutions, taken from rails and wheels for the last 5 years (except for appearance of moisture) of the definite areas of railways.

The classification of sources of pollution of rails and wheels has been offered on the basis of the received experimental data. Definite forces, determing interaction between particles of pollutions and friction surfaces like:

$$F = F_{mol} + F_{em} + F_{cap} + F_p + F_{em} \quad (2)$$

where F - a resulting force;
F_{mol} - a molecular force;
F_{cap} - a capillary force;
F_p - a tensile force;
F_{em} - a component of electro-magnetic influence.

Schematically, the layer of surface pollutions on friction tracks is submitted on *Figure 1*, where *1*-rough surface of a rail or a wheel; *2* - a layer of surface pollutions; *3* - an area of condensation of the main measure of lubricants; *h* - the nominal layer thickness.

At the contact of rails and wheels, surface pollutions, filling in the space between projections, can assist to increasing of the area of the true contact between bodies.

Disperse systems, like considered surface pollutions, are able to change strongly structural reological characteristics in dependence of the presence of liquid phase inside them, approaching to properties of hard bodies, or pastes, or liquids. Thus, surface layers strongly influence on the process of forming of friction contact and on the adhesion of wheels & rails.

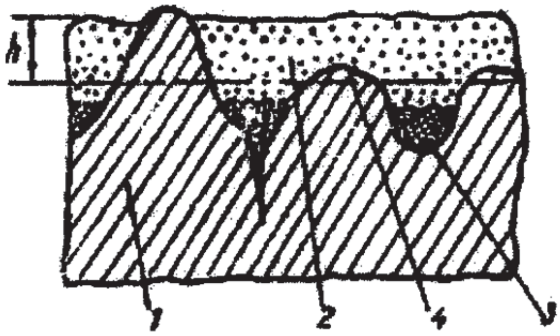

***Fig. 1.** The structure of the surface layer of the tracks of friction of rails and wheels*

There is a distribution of friction coefficient along the width of rails and wheels under the constant moistening at wheels (1 3 4 5) and rails (2 5). At the areas with symmetrical (1 2 3) and unsymmetrical position of friction tracks their considerable variety in width. The highest friction coefficients were realized along the central friction tracks, and what's more that for a wheel and for a rail they were close in values.

The lowest friction coefficient were received along the sides of friction tracks, where there were more lubricants and hard materials, friction characteristics change strongly in dependence of humidity values of the mils and practically remain unchangeable on the sides (*Figure* 2)

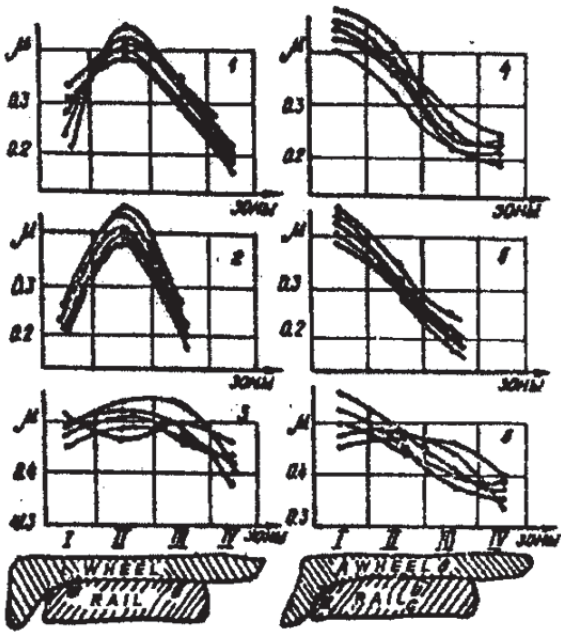

***Fig. 2.** The character of changing of friction coefficient along the width of the tracks of friction of rails and wheels. a,b- contact areas; I, II, III and I_V - areas on friction surface, where measuring were carried out. Represented per 6 series of changing of friction.*

Structural and rheological properties of layers are mainly connected with the quantity of liquid, presented on friction surfaces. Detected facts in the research work allow forming the physical model of friction interaction of rails and wheels in a view of a schematic, represented, where there are: hard bodies in contact, dividing their disperse layer, environment.

In general, friction force F_t between the wheel, rolling along the surface of the rail, covered with the layer of surface disperse pollutions, forms of the elements:

$$F_t = F_{tt} + F_{disp} + F_{def}, \quad (3)$$

where F_{tt} - an element of the friction force forming on benches of roughnesses of hard bodies

F_{disp} - an element of the friction force forming in disperse environment;

F_{dcf} - a deformational element of softer material.

In developed view this expression will looks like:

$$F_t = (A_c + A_r)\cdot\tau_{tt} + [A_a - (A_c + A_r)]\cdot\tau_{disp} + F_{def}. \quad (4)$$

where A_n - nominal square of the contact;

A_c and A_r - contours of true squares of the contact of hard bodies.

τ_{tt} - specific force of hard bodies' friction;

τ_{disp} - specific force of the disperse layer of surface pollutions.

Taking into account the fact, that true and contour surfaces of hard bodies' contact are very small in compare with the rest of the square fulfilled with the disperse pollutions, than even inconsiderable changes of mechanical properties of the last one (for example, connected with the influence of environment, *figure 3* will considerably affect on the result friction force between rails and wheels).

Taking into account the facts, found out within this work, the classification of rails' moistening has been offered and it takes into consideration lows of changing of friction characteristics of tracks of adhesion of rails and wheels. According to this classification four (*4*), different areas of moistening of rails with typical friction properties of the track of rolling of a wheel along of a rail are determined under positive temperatures (*Figure 3*).

The first one is an area of foregoing of the appearance of capillary condensation of liquid in surface pollutions. The second one - from the moment of the appearance of capillary condensation and to closing of pores with water in surface pollutions (to the dew-point). The third one - from the moment of the appearance of dew-point and to the quantity of water on friction surfaces corresponding to the thickness of the layer 0.12 mm.

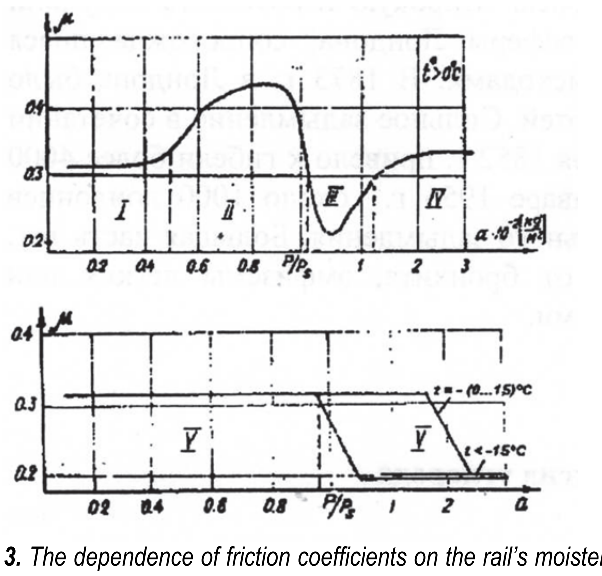

Fig. 3. *The dependence of friction coefficients on the rail's moistening*

The forth one - under large moistening of the surfaces of friction. Average friction characteristics are realized in I and IV areas, high ones - in II area and low ones - in in area. The increase of friction properties is caused by increasing of structural and reological characteristics of the layer of surface pollutions at the expense of kapilar forces' activities, and the decrease -by realization of quasi and hydrodynamic mode of friction. There are two another areas of moistening of surfaces under sub zero temperatures. The fifth area is characterized by average friction properties independently of air temperature and appears when there is no ice in the contact area of rails and wheels and the board mode of friction is realized. The sixth one - by decreased friction characteristics. It can be found under the appearance of ice in the contact area of rails and wheels and under the condition of realization of quasi and hydrodynamic mode of friction. The sixth area prevails with the decrease of temperatures (from -20C and less).

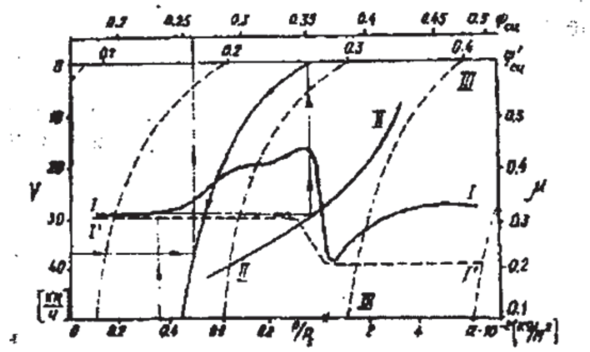

Fig.4. *The abacus for the determination of possible adhesion coefficient*

Generalization of factors determine friction properties of rails and wheels, friction laws of a railway and specialties of locomotives' adhesion, has afforded the ground to build up the abacus (*Figure 4*), which allowed to judge on the most possible realized adhesion coefficients of locomotives, connected with changing weather conditions. The abacus includes: I-I and I'-I' are dependencies between the grade of moistening of friction tracks and of rails (P/Ps and *a*) and (between) friction coefficients μ, measured with the roll tribometer on the central part of friction tracks; II and II - the dependence between the friction coefficient μ and the adhesion coefficient in the moment of motion starts ($\psi'_{сц}$ - without and $\psi_{сц}$ - with sand giving for adhesion's improvement); III-III - the dependence of locomotives' adhesion coefficients ($\psi'_{сц}$ and $\psi_{сц}$) at the speed *V*. The dependence – I-I for positive temperatures. The dependence I'-I' - for subzero temperatures. The dependence II-II is given as an example for the VL-60 locomotive. The abacus allows gaining the data on the most possible adhesion coefficients for realization of for the type of locomotives and motion speed and only for one controlled parameter - value of railways' moistening.

As it is known, external arid internal friction always converts mechanical energy into heat. At unlubricated friction the conversion may be as great as 98%.

Because of this, the processes of physical-chemical mechanics running under conditions of friction depend significantly on the heat and temperature conditions generated by friction.

Thus the well-known Kragelsii's triad, viz. the interaction of solid surfaces, a change in the properties of the materials in contact, and finally the failure of the surfaces (i.e., wear), must take proper account of these heat and temperature factors.

As it follows from the molecular-mechanical theory of friction and fatigue theory of wear [9], friction-wear characteristics and mechanical properties of rubbing materials are related to each other by different non-linear functional dependences which vary considerably with friction conditions and, primarily, with heat and temperature.

To support the aforesaid, we consider the typical dependences of the friction coefficient and wear rate for different materials on the surface temperature θ at unlubricated friction (Fig.5). These values are obtained under standard model testing on frictional heat resistance using friction machines. The tests are generally performed at fixed nominal pressure p_a with a stepwise change (traditionally, an increase) in sliding velocity v, i.e., at a stepwise change in specific friction power [$p_a v$]. The figure shows that there is no linear dependence between the given [$p_a v$]and real [$f p_a v$] friction powers. Since the surface temperature is functionally related to the real specific friction power, then, in most cases, dependency of f(θ) and I(θ) are also non-linear.

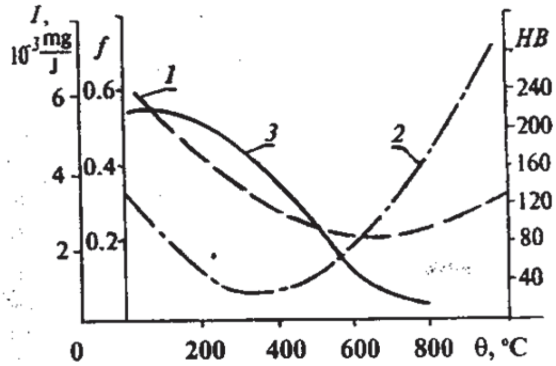

Fig.5. *Effect of the surface temperatutre θ on friction coefficient f(1), wear rate I(2) for steel – cast iron pair, and hardness HB(3).*

The experimental studies indicate that the increase or decrease in pressure p_a results in a fan of curves f(θ, p_a) and I(θ, p_a)

In this case the friction coefficient drops with increasing p_a and increases with its reduction. The same experiments show that increase or decrease in the sliding velocity v does not give rise to the fan of curves but only elongates or shortens the curves of frictional heat resistance without disturbing their behavior. The experiments agree well with the molecular-mechanical theory of friction [16]. Therefore, the friction surface temperature has more dramatic effect on the friction coefficient and wear rate than pressure and sliding velocity do.

Strength properties of materials depend very strongly on temperature, but the influence of load and loading rate (number of cycles) is considerably less. It is seen (fig.5) that within certain temperature ranges the material hardness can decrease many-fold and become minimal as the melting point is approached.

At such temperatures the friction contact becomes plastic and actual contact area A_r increases sharply even at moderate load pa making a close approach to the contour area A_c and then to nominal one A_a.

Naturally, the stages of interaction, change and failure (wear) are profoundly altered under these conditions resulting in the variation of the friction coefficient and wear rate. In this connection it should be noted that the temperature gradient along the normal to the friction surface $\delta\theta^*/\delta z$ (z is the coordinate along the normal to the friction surface) is the most important characteristic of the temperature conditions for friction and wear. As was first shown by Chichinadze [8, 10], the temperature gradient influences the gradient of mechanical properties and. as a result, friction coefficient and wear.

Based on study of friction contact as a viscoplastic "third" body, Kragelskii and Troyanovskaya have derived the fundamental dependences of friction coefficient and wear rate on temperature [9]:

$$f = A_1\theta^{m_1-k_1} + C_1\left(\frac{\delta\theta}{\delta z}\right)^{l_1-k_1}. \quad (5)$$

$$I = A_2\theta^{m_2-k_2} + C_2\left(\frac{\delta\theta}{\delta z}\right)^{l_2-k_2}. \quad (6)$$

Analysis of the relationships shows that in the general case, as the temperature increases, the functions /and / may decrease, increase, or pass a maximum or minimum depending on coefficients $c_{1,2}$, $a_{1,2}$, $m_{1,2}$, $k_{1,2}$, $l_{1,2}$.

Under conditions of liquid friction (hydrodynamic or elastohydrodynamic lubrication) the temperature effect is related to the permissible operating temperature which should not exceed the critical bulk temperature of decomposition and ignition of the lubricant to guard against the spontaneous transition first to boundary lubrication and then to unlubricated friction with all the negative consequences, namely, a sharp increase of the friction coefficient and then the temperature, appearance of scoring, severe wear, and even seizure in the friction unit (Fig.6, 7).

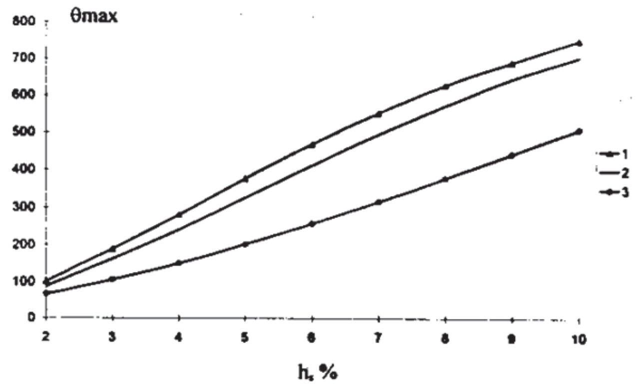

Fig.6. *Function of maximum of temperature- θ_{max} in zone of contact from sliding – h,%. (Conditions R=650m, 1,2 – different slims, 3 – metal, v = 20 m/s).*

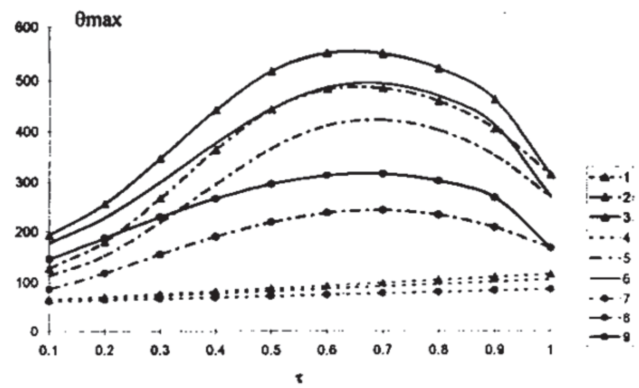

Fig.7. *Functions of temperature- θ_{max} (3,6,9), $\theta_{average}$ (2,5,8) in volume (1,4,7) in zone of contact from time of friction contact - τ. (Conditions R=650m, 1,2,3,4,5,6 – different slims, 7,8,9 – metal, v = 20 m/s, h_s = 7%).*

In heavy-heated friction units the contact temperature can be very high (above 700 °C) resulting in melting of metals and decomposition of non-metallic materials. The effective strain and temperature of the surface layers decrease in depth and the temperature gradient may be as great as 800 -1000 °C/mm under these conditions (Fig.6, 7).

In practice there are occasions when the temperature gradient alone causes such temperature stresses in the surface layers that friction occurs at plastic contact, even though the bulk temperature is small and nominal pressure can set up only elastic deformation. The temperature stresses of this kind promote cracking and result in severe wear. Thus, in addition to the total weakening effect, the high temperatures and temperature gradients cause surface stresses that considerably exceed the stresses induced by friction in some components (e.g. drums, discs, bushings, etc.). The rubbing materials, being under the action of high stresses, tend to have a reduced friction and increased wear. The stresses in the surface layer depend on the material properties, macro- and microgeometry of the contact region. They commonly dominate over the stresses in the bulk of the friction unit which depends mostly on the temperature gradients rather than mechanical parameters.

Chemical and structural transformations in the materials arise from an interaction of the materials with each other and with the environment, as well as from the temperature action.

The bulk temperatures in friction pairs differ considerably with the operating conditions. Under conditions of single heat-pulse friction, when the initial temperature of the friction unit remains unchanged, as a first approximation the bulk temperatures depend on the amount of heat and rate of its generation. The temperature gradient in these units is proportional to the thickness of their elements and may reach as much as 1000 °C per 1 mm of thickness under heavy-duty conditions. A different situation arises with intermittent and prolonged steady-state regimes of friction. In this case residual stresses together with heat transfer into other elements and environment should be taken into account (initial temperature increases reaching the steady-state limit typical for the given conditions). The stresses can be reduced by increasing the total actual contact area and single spot area as well as by uniform distribution of the contact spots over the running surface. It is desirable that the macroscopic thermal deformations of one element are compensated by similar response of the other.

1. ECONOMICAL ISSUES

The consumer properties of any production can be rated in the cost or power form. Last form of an estimation is rather effective and is carried easily out for vehicles. However it can be applied and for other executions. At a power estimation of consumer properties of production as the aggregated index of a technological level of production operating ratio of power resources - η is offered which essentially depends on energy losses in friction units.

$$\eta = \frac{W_k}{W_k + W_{dis}} = \frac{W_k}{W_k + W_f + \Delta W_{dis}}, \tag{7}$$

where W_k - aggregated power index of the consumer requirements to production;

W_f - costs of energy of overcoming of activity of friction forces in a tribotechnical system;

W_{dis} - components of power resources without the registration W_k and W_f.

Operating ratio of power resources is determined by spent technical policy, and consequently, directions volumes of the investments in production. The results of technical policy are mirrored in energy losses in friction units, that affect on reduction of all kinds of resources and components of operational costs.

The factor of elasticity – $E_{\eta/Wf}$ of a function η on argument W_f characterizes, on how many percents will change at increase W_f on 1 % and will be at realization of a ecology-economic estimation of technologies:

$$E_{\eta/W_f} = \frac{d\eta}{dW_f}\frac{W_f}{\eta} = \frac{-Wf}{(W_k + \Delta W_{dis}) + W_f}. \tag{8}$$

As it follows from the obtained expression

$$0 \ge E_{\eta/W_f} \ge (-1). \tag{9}$$

If the influence of friction costs on operating ratio of power resources is necessary for reducing up to a tolerance level δ_d, the friction losses should not exceed

$$W_f \le \frac{(W_k + \Delta W_{dis})\delta_d}{1-\delta_d}. \tag{10}$$

The estimation of an economic efficiency and a level of using of resources is offered on following algorithm, taking into account intercoupling of tribotechnical measures and indexes of an economic efficiency of production r_k.

1. All tribotechnical measures presenting to change of interactions, for example a couple of a wheel - rail, are valued in four phases:
   a) The change of a friction factor $f_δ$ is determined from character and volumes of spent measures. The change is valued in percentage terms to values of an index before input in operational practice of the considered tribotechnical solutions, δf_T;
   b) Taking into account, that the value of energy losses depends linearly on a friction factor at constant slip, the change of energy losses in percentage terms is determined to initial value as W_f = $f_δ$;
   c) The change of operating ratio of power resources is determined on the basis of an index of its elasticity on change of costs of energy on overcoming of activity of friction forces in a tribotechnical couple;
   $$\delta\eta = \delta W_f E_\eta / W_f. \tag{11}$$
   d) The change of indexes of economic efficiency r_k is determined on change of operating ratio of power resources:
   $$\delta r_k = \delta\eta E_r / \eta. \tag{12}$$
2. The second part of algorithm actuates a definition of absolute values of change using of resources and an index of an economic efficiency and level of ecological cleanness of the technology.
3. The final part contains a definition of the best version of measures under the multicriteria approach or formation of volumes and character of measures on preset limitations.

CONCLUSION

Based on the research performed earlier, it can be concluded that

- friction coefficient and wear rate of wheels and rails depend mainly on the temperature and properties of the thin surface layer of rubbing bodies over a wide temperature range. The temperatures are realistic for railway transport and have their proper maxima and minima. Bulk mechanical properties and temperatures give no more than a correction to the real processes running in the contact zone;
- employment of heat friction dynamics with consideration for revealed physical-chemical concepts of the interaction and the laws defining a change in friction characteristics of friction tracks will provide insight into the nature of the catastrophic wear of wheel and rail and suggest some efficient ways for preventing such wear.
- aggregate indicator branch technologies level - indicator of use power resources - was used for estimation. This indicator makes it possible to define investment support for every per-

centage of reduction of power expenses connected with tribology losses.

The carried out researches have shown, that:

- more full use of natural friction properties of their surfaces and knowledges about the origin of their interaction can assist to the increase of the efficiency of work of friction pair wheel-rail;
- there are possibilities and limitations for realization by the lowest costs ways of more high and stable adhesion coefficients of rails and wheels and rolling-stocks;
- it is rational to evaluate the exploited facilities according to their increase of friction of rails and wheels from new points of view and to develop new and more perfect methods of influence on their friction surfaces;
- the ways to giving prognosis and to operative determination of the level of adhesion of rails and wheels.

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Fizyczne i ekonomiczne zagadnienia kontaktu tarcia koła i szyny

W pracy przedstawiono wpływ rzeczywistych warstw powierzchniowych kół i szyn na ich strukturę i właściwości termofizyczne. Określono siłę tarcia między współpracującymi ciałami. Przedstawiono sposoby prognozowania i diagnostyki technicznej poziomu kohezji kół i szyn. Przedstawiono również wpływ współczynnika tarcia w systemie "koło - szyna" na koszty różnych podmiotów gospodarczych na transporcie kolejowym.

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