TRANSPORT PROBLEMS 2009
PROBLEMY TRANSPORTU Volume 4 Issue 4

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LOADING AND DAMAGEABILITY OF WHEELS AND RAILS

Summary. Friction, rolling resistance and durability of rails and wheels at operation, belong to a number of the most important problems of railway transportation because they have strong impact on derailment, energy consumption and restorative maintenance. Various aspects of these problems are insufficiently investigated, have only partial solution. The sources of creep and slipping of a wheel on a rail and ways of its reduction are specified in the work. These approaches alongside with the traditional methods (lubrication, radial steering bogie, etc.) will ensure the reduction both the power and the thermal loading of the contact zone and wear rate of rails and wheels.

НАГРУЖЕННОСТЬ И ПОВРЕЖДАЕМОСТЬ КОЛЁС И РЕЛЬСОВ

Аннотация. Трение, сопротивление качению и долговечность рельсов и колёс при эксплуатации принадлежат к числу наиболее важных проблем железнодорожного транспорта. Они оказывают влияние на сход колёс с рельсов, потребление энергии и профилактико-ремонтные работы. Различные аспекты этих проблем недостаточно исследованы и имеют лишь частичные решения. В работе указаны источники крипа и скольжения колёс по рельсу и пути их уменьшения, которые наряду с традиционными подходами (смазывание, радиально управляемая тележка и т. д.) позволяют уменьшить как силовую и тепловую нагруженность зоны контакта, так и интенсивность изнашивания рельсов и колёс.

1. INTRODUCTION

Increase of axial loads and speeds of the railway traffic leads to the rise of power and thermal loadings of wheels and rails. Spatial vibrations of the rolling stock, magnitude of slipping, rolling resistance, traffic safety, consumed power, damageability of wheels and rails and expenses of the preventive maintenance greatly depend on the constructional features and technical conditions of the rolling stock and railway track. A wheel can slip on the rail along the rolling surface and lateral surface of the rail head. A micro- and macro-slipping of the rolling surface under rolling of the wheel can take place in longitudinal and transversal directions, the wheel can turn about vertical axis and flange of the wheel can slip along the rail lateral surface. Rolling resistance, depending on the radius of curvature of the track and rolling magnitude can vary approximately 10-20 times [1]. Turning of wheels (removal of the metal and “pointed smoothing”) due to worn out flanges makes up about 88 % [2] on the Russian Railways, and cost of technical service of wheelsets can axed 30 c% of that of the carriage [3]. Loading and damageability of a wheel and a rail are especially susceptible to slipping of the wheel along the rail. Revealing the causes of the wheel slipping, finding the ways for its reduction and stabilization of friction forces, together with well-known measures for reduction of loading of the wheel and rail (applications of lubricants, choice of profiles of the working surfaces, etc.) are important tasks of the railway transport. Availability of great number of works on research of wear of wheels and rails [4-9] is indicative of the importance of the problem.

2. SLIPPING OF A WHEEL ALONG THE RAIL ROLLING SURFACE

It is characteristic of the pair wheel-rail great magnitudes of the coefficient of sliding friction (01-08) [10] that, under slipping leads to rise of friction power, and power and thermal loading of contact. Typical graphs of dependence of the coefficient of sliding friction (1) and tractive force (2) under simultaneous rolling and slipping, on the relative speed of slipping, are shown in Fig. 1. Under absence of slipping the wheel is considered as freely rolling and shearing stresses are minimum. With the increase of torque, force and coefficient of friction (cohesion of surfaces) and magnitude of the partial shear of surfaces in the contact zone increase (Fig. 1, zone I). These magnitudes become maximum in the zone II [11, 12] and characteristic types of damage for these zones are: contact fatigue, generate and development of cracks and shelling.

Study of the problem of micro-slipping, called creep, was developed in works of Wellmier, Jonson, Kalker, Sladkovsky and others [13, 14]. At increase of the tractive force (torque) shear of surfaces is spread along the whole contact zone, force of friction reaches the maximum value, partial slipping becomes complete (zone II) and decrease of the coefficient of friction and tractive force begins. Experimental researches carried out on the roller machine, show that further increase of the speed of slipping (zone III) can lead to the sharp increase of the coefficient of friction and its non-stability, friction power and wear rate. At that, the process is accompanied by signs, typical for scuffing: non-stability of the coefficient of friction, typical noise and in especially heavy conditions – appearance of smoke from the contact zone [15].

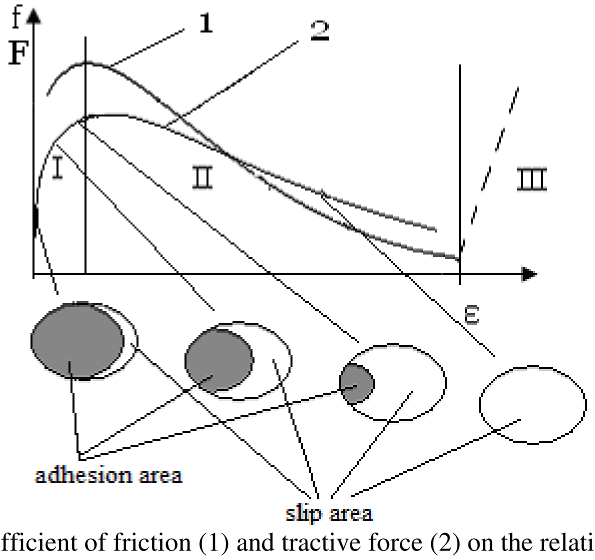

Fig. 1. Dependence of the coefficient of friction (1) and tractive force (2) on the relative speed of slipping

Рис. 1. Зависимость коэффициента трения скольжения при качении со скольжением (1) и силы тяги (2) от относительной скорости скольжения

Stress in the contact zone can reach yielding limit, temperature can exceed 800^0C [3, 16] and operation conditions can influence on the dynamical behavior of the carriage, probability of derailment of the wheel and intactness of the wheel [17]. Slipping of surfaces can lead to decrease of the coefficient of friction and tractive force. Increase of both, the partial slipping within the contact zone and total slipping (leading in some conditions to decrease of the coefficient of friction) leads to rise of the power and thermal loading and wear rate.

It is known that a wheelset performs a winding motion on the straight section of the track. At rolling of the wheelset along curved sections of the track, wheels running along inner rail thread outrun outer once and the wheelset is warped, increasing angle of attack. The only condition of the wheelset's return is slipping of the wheel along the rail rolling surface that is related with well-known negative phenomena.

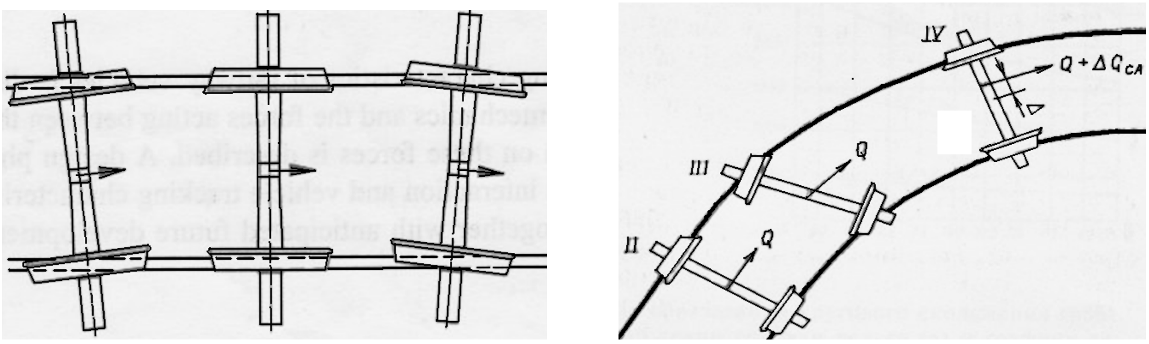

Fig. 2. Wheelset motion on the straight and curved tracks
Рис. 2. Движение колёсной пары по прямой и кривой

Attempts to estimate influence of various parameters on the direction of motion and magnitude of slipping of the wheel are known [18, 19], where calculating vibratory motion of the wheel on the straight section of the track, amplitude of witch depends on the value of transversal excitation is described by equation

$$y''+2i/rl_{w}y=0\,,$$

where: r is average radius of the wheel rolling surface; i-bevel of the wheel rolling surface; l_w-distance between rolling circumferences of the wheel.

Under conditions of turn of the wheel about vertical axis through angle α for traveling a distance from point a to point b, the wheel has to travel additionally greater distance –to point c (fig. 3) that is related with slipping of the wheel.

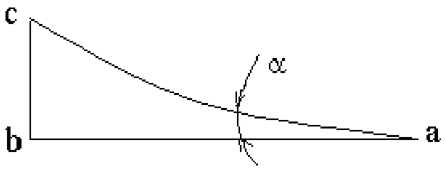

Fig. 3. The additional motion of the wheelset
Рис. 3. Дополнительное перемещение колеса

The graphs characterizing winding motion of the wheelset are given in fig. 4. Graph 1 describes motion of the wheel of radius 350 mm, with the wheel bevel 0,05 for half-width of gauge 750 mm. The number 10 mm is amplitude of transversal vibrations of the wheelset. Graph 2 shows total slipping of wheels of the wheelset obtained by summarizing of transversal displacements of the wheels. Number 170 mm is difference of traveled paths of the wheels at three periods of vibrations. Fig. 3 shows turning of the wheel relative to direction of the motion through angle α ($0{,}49^0$).

Researches have shown linear dependence of slipping and angle of turning of the wheel on the amplitude of winding motion of the wheelset along the straight track.

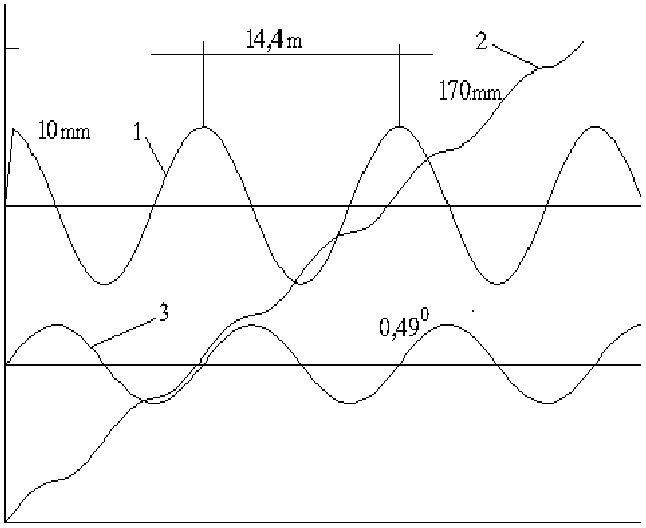

Fig.4. The oscillograms of the wheelset motion
Рис. 4. Осцилограммы движения колёсной пары

3. SLIPPING OF THE WHEEL FLANGE ALONG THE RAIL LATERAL SURFACE

Kinematics and geometric features of contact of the wheels and rails play an important role in their loading and damageability. Slipping of the wheel flange along the rail lateral surface occurs on both, the straight and the curved sections of the track.

Profiles and mutual location of the wheels and rails according to the standard of former USSR are given in fig. 5. For the gauge width of 1520 mm, contact of the wheel and rail is realized mainly along the transitional curve. This leads to: two-point contact or contact along the line; rolling with slipping of surfaces and corresponding negative phenomena.

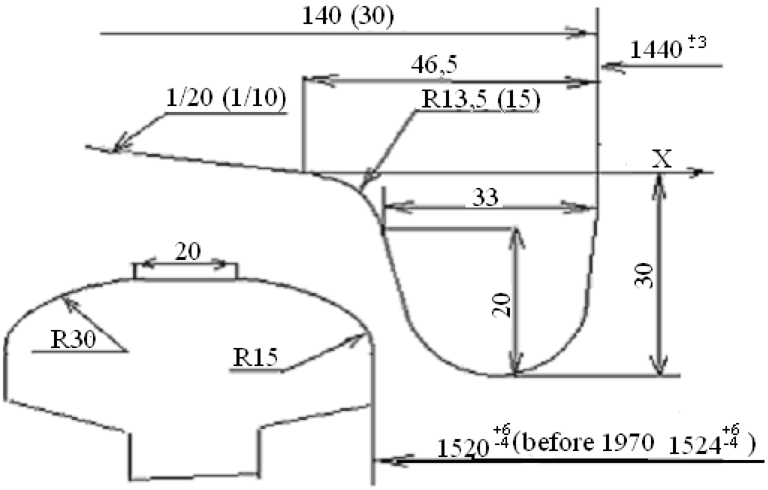

Fig. 5. Profiles and mutual location of the wheels and rails
Рис. 5. Профили и взаимное расположение рельсов и колёс

A typical feature of interaction of the wheel flange surface and lateral surface of the rail head is a comparatively small magnitude of the coefficient of friction (no more then 0,2). But slipping of wheels causes growing thermal and power loadings of the contact superficial layers, generation of vibrations, typical noise and most dangerous type of wear-scuffing [21]. Sliding distance, slip velocity and transversal load depend on the difference of radii contacting circumferences, angle of inclination of the tangent to the flange transitional curve and coordinates of points of contact of the wheel and rail. Dependences of the wheel radius R on the coordinate of the point of contact (x) on the transitional curve; angle of inclination β of the tangent passing through this point and sliding distance L at one revolution of the wheel, correspondingly have the form:

$$R = R_1 + r - \sqrt{r^2 - x^2}\ ; \qquad \beta = \arctan\frac{x}{\sqrt{r^2 - x^2}}\ ; \qquad L = 2R\arccos\frac{R_1}{R};$$

where: R_1 is the wheel radius at the beginning of the transitional curve; r – radius of the wheel transitional curve.

At rolling of the wheel on the rail and contacting of the wheel flange with the rail lateral surface, sliding distance, slip velocity and instantaneous radius of the wheel rotation depend on slipping of the rolling surface. Graphs of dependence of the flange sliding distance on resultant sliding velocity at rolling of the wheel without braking are shown in fig. 6. At slipping of the wheel tread, the instantaneous center of rotation of the wheel (n) coincides with the geometric center of rotation of the wheel, and the flange sliding distance along lateral surface of the rail is maximum. With increase of rolling of the wheel tread, sliding distance (c-d) of the wheel flange (as well as sliding distance of the wheel tread) decreases and instantaneous center of rotation (n) approaches to the rail.

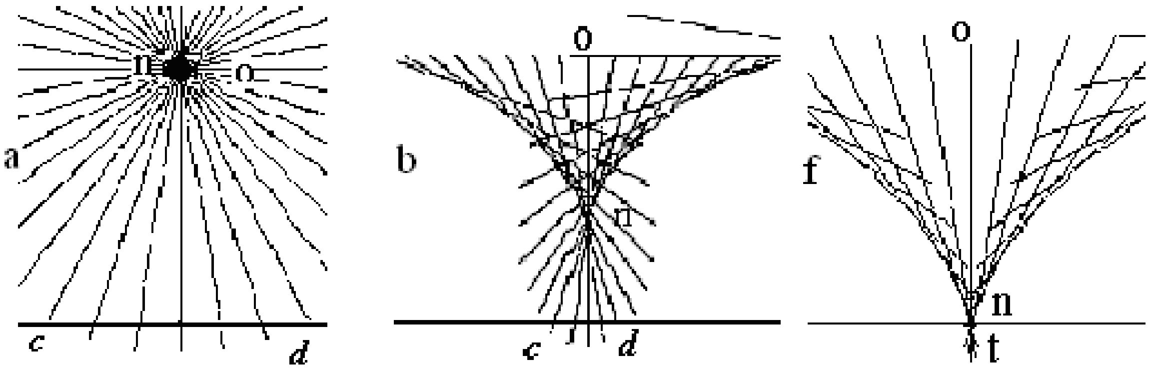

Fig. 6. Influence of the wheel sliding at rolling on the sliding distance and the location of the reduced instantaneous center of rotation: a - total slipping of the wheel tread; b – rolling with slipping of the wheel tread at the wheel spin up; f –rolling without slipping of the wheel tread

Рис. 6. Влияние скольжения колеса при качении на путь трения и положение приведённого мгновенного центра вращения: a - полное скольжение поверхности качения; b – качение с проскальзыванием поверхности качения; f – качение без скольжения поверхности катания

As is seen from graphs, at contacting of the wheel flange with the rail, with decrease of the sliding distance of the wheel tread, sliding distance of the flange along lateral surface of the rail decreases and at pure rolling of the wheel rolling surfaces slipping of the flange reaches minimum value. Dependencies of the wheel radius R, angle of inclination of the tangent β and sliding distance L at one revolution of the wheel, on the coordinate of the contact point (x) on the easement curve, are revealed. Dependences of the sliding distance upon resultant sliding velocity as well as dependences of the sliding distance and location of the instantaneous radius of curvature upon magnitudes of slipping of the rolling surface are given.

4. DAMAGEABILITY OF WHEELS AND RAILS

Wide spectrum of tribotechnical and dynamical phenomena accompanying interaction of the wheels and rails and availability of some insufficiently studied aspects of this interaction makes it difficult to solve the problems of their durability. Winding motion of the wheelset along straight track, unevenness of tractive force and braking forces lead to rising the shearing stresses on the rolling surfaces. At that, the main type of their failure is the fatigue wear. At slipping of the rolling surfaces and also in curve sections of the track, at slipping of the wheel flange along the rail lateral surface, typical type of damage is adhesive wear and scuffing. Thus damageability of wheels is similar by character to damageability of rails: fatigue wear of the rolling surfaces prevails on the straight sections of the track and wear of flanges and lateral surfaces of the rails heads - on the carved once.

The graphs given in fig. 7 shows: quantity of removed wheelsets (N_{rem}) (1) from electric locomotives according to months, because of utmost wear of flanges in Tbilisi Locomotive Depot (2001); quantity of re-turned wheelsets (N_{rt}) (2) due to wear of flanges on the Ulan-Bator Railways (former SU) [22] (1988-1989) and quantity of derailed empty carriages (N_{der}) (3) [23] according to months on Russian Railways (1999-2001). As is seen from graphs, removal of wheelsets and their re-turning due to wear of flanges is especially high from June to November. Precipitation and cold weather prevail from December to May, when atmospheric moisture appears on the rails. This favors: the improvement of conditions of heat irradiation from the contact zone; lessening of thickness of the heated layer predisposed to failure; diminution of the coefficient of friction and its stabilization; decrease of quantities of removed and re-turned wheelsets due to wear and derailments of carriages.

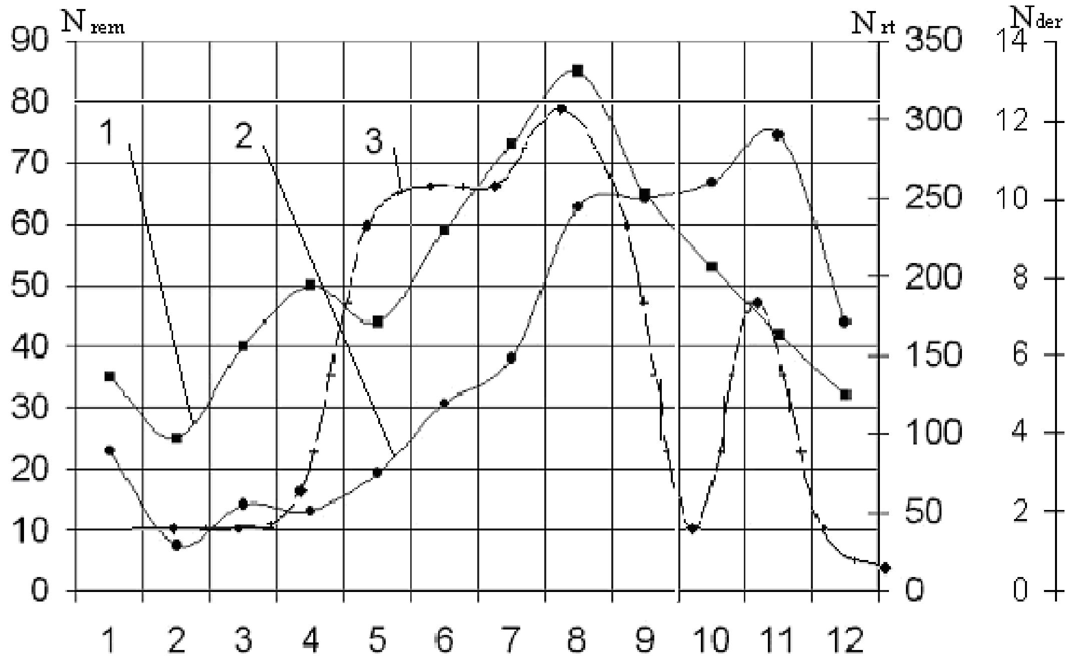

Fig. 7. Graphs showing: quantity of removed wheelsets (N_{rem}) (1) from electric locomotives according to months, because of utmost wear of flanges in Tbilisi Locomotive Depot (2001); quantity of re-turned wheelsets (N_{rt}) (2) due to wear of flanges on the Ulan-Bator Railways (former SU) [22] (1988-1989) and quantity of derailed empty carriages (N_{der}) (3) [23] according to months on Russian Railways (1999-2001)

Рис. 7. Графики показывающие количество снятых с электровозов колёсных пар (N_{rem}) (1) по месяцам из-за предельного износа гребней в 2001 г. в Тбилисском локомотивном депо, переточенных (N_{rt}) из-за износа рёбер (2) в Улан-Баторской железной дороге (1988 – 89 гг. бывшая СССР) и количества сошедших с рельсов порожных вагонов (N_{der}) (3) по месяцам в 1999 – 2001 гг. на Российских железных дорогах

5. LUBRICATION OF THE RAILS AND WHEELS

Important means of reduction of the friction power and rise of stability of the rails and wheels against exploitation influence are availability of the third body in the contact zone and creation of favorable conditions for heat irradiation from the contact zone. Practice has shown a significant influence of conditions of heat irradiation from the contact zone on the wear rate and quantity of derailments of wheels. Wear rate of the wheel flanges and quantity of derailment of wheels rise in the summer period. In spite of low lubrication ability due to high thermal heat capacity and evaporation power, water favors heat absorption in the contact zone, convective heat-exchange; it prevents from heat diffusion into the depths of the material and rise of the heat loading. Water decreases coefficient of friction between the flange and lateral surface of the rail, noise and wear rate [24]. Influence of atmospheric phenomena on variation of the coefficient of friction for carriage wheels can be expressed by formula of Bosh: $\mu = \mu_0 / 1 + 0,03V$, where coefficient μ_0 can vary in the range 0,31-0,14 depending on weather conditions. It is known about rise of the wear rate of flanges in the summer period [8] that is stipulated by decrease of coefficient of friction and thermal loading of the contact zone.

At present for lubrication of the rails and wheels frequently are used liquid lubricants on the base of oil products. Shortcomings disadvantages of traditional lubricants are: low heat resistance, contamination of the environment (for preventing of which bio-degrading lubricants are used), high cost and non-stability of the friction forces under trying conditions of operation. When getting on the rolling surface, lubricant sharply decreases the friction force (that leads to sliding). Traditional lubricants can burnout partially under trying conditions, failing and aggravating the process by educing additional heat and increasing contact temperature. This can restrict a range of rational application of similar lubricants. The enumerated shortcomings are partially eliminated in friction modifiers on the basis of water, containing heat resistant additives, used lately. They are characterized by high heat absorbing properties and steadiness against exploitation influences. Thermal and physical properties of water, air and lubricants are given in the tab. 1.

Tab. 1

Thermal and physical properties of water, air and lubricants

Surroundings	Coefficient of heat irradiation (metal wall) W/(m^2·C)	Specific thermal heat capacity J/(kg·C)	Heat conductivity W/(m·C)
Stagnant Water	350. . .580	4,19	0,58
Running Water	350+2100√v*	-	-
Boiling water	3500. . . 5800	-	-
Air	5,6 + 4√v* ≈13,6. . .21,6	1,009	0,034
Liquid and consistent lubricants	350-700	2,3	0,13-0,15

v* - speed (m/s)

As is seen from the Table thermal and physical characteristics of water prevail that of liquid and consistent lubricants and air. A model of interaction of contacting bodies with the use of traditional lubricant and friction modifier is shown in fig. 8. Under trying conditions of friction the lubricant can burn out partially in the contact zone that can be reflected on quality of lubricant and temperature of discrete points of contact: $t = t_l + \Delta t_2 + \Delta t_3 + \Delta t_4$, where t is temperature on the discrete point of contact, t_l – temperature of surrounds; Δt_2 – increment of average temperature of bodies; Δt_3 - increment of temperature on the micro asperity (temperature of flashing up); Δt_4 - increment of temperature from burning out of lubricant. In similar conditions, water contained in friction modifier can evaporate, absorbing and the heat and modifying additives precipitating on the surface can play a role of the third body.

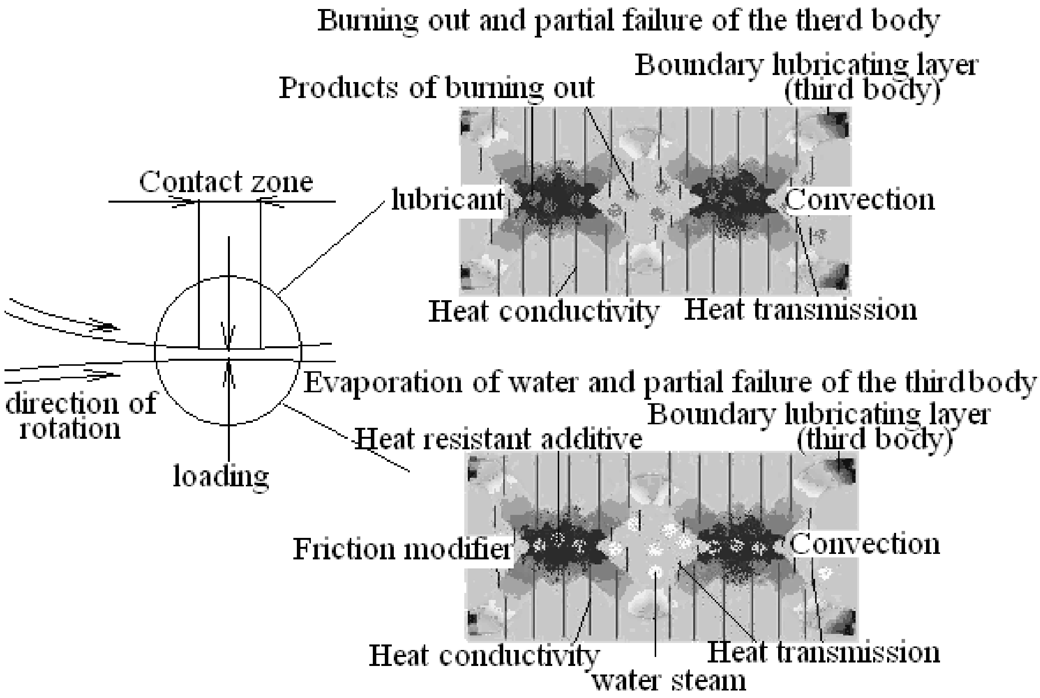

Fig. 8. Interaction model of contacting bodies
Рис. 8. Модель взаимодействия контактирующих тел

Researches have shown influence of various factors on the magnitude of the wheel slipping on the rail. It is shown, that burning ability of traditional lubricants can be reflected on thermal loading of the contact. Researches have shown as well as inevitability of creep or slipping at rolling of the wheel along the rail. At that, magnitudes of the coefficient of friction 0, 25-0, 4 for rolling surfaces and no greater than 0,2 for lateral surfaces of the rail head and wheel flange, are assumed acceptable [10]. But such high magnitudes of the coefficient of friction on the rolling surface, on lateral surfaces of the rail head (gauge) and the wheel flange, as well as controlling by friction with the use of various lubricants and lubricating devices makes it difficult to eliminate extreme conditions and to solve the problems of durability and safety of traffic. For reduction of the contact loading it is necessary to decrease slipping of the wheel on the rail that is achieved by: choice of profiles of wheels and rails; rising of outer lines in curves, and etc. But profiles of wheels and rails, as far as they wear out under exploitation, rapidly vary that also makes it difficult to achieve the mapped aims. Along with above-mentioned methods the elaboration of new constructional approaches of wheelsets and bogies will allow us to reduce the sliding distance and speed of slipping of the wheel along the rail loading and damageability of wheels and rails.

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Received 27.03.2009; accepted in revised form 10.12.2009