Svetlana SAPRONOVA*, Viktor TKACHENKO, Nikolay KRAMAR, Aleksander VORON'KO
East Ukrainian National University named V. Dal
Molodezhnogo blok 20A, 91000 Lugansk, Ukraine
**Corresponding author*. E-mail: doc_Sapronova@mail.ru

REGULARITIES OF SHAPING OF A WHEEL PROFILE AS A RESULT OF DETERIORATION OF THE ROLLING SURFACE IN EXPLOITATION

Summary. In the middle of the 90s the deterioration of wheels flanges and lateral rail surfaces on roads in the countries of CIS from natural process of wear process of surfaces has turned to the sharp problem which has received the status of a «rail plague». On separate roads the lateral deterioration of rails has reached 1 mm times 10^6 tons, by exceeding a level of normative deterioration in some times. Thus the run of wheel pairs between regrinding on flange undercuts was reduced in by 3-5 times [5]. In the article some ways of elimination of deterioration of wheels and rails are considered. The technique of process modeling of parameters changes of deterioration is offered.

ЗАКОНОМЕРНОСТИ ФОРМООБРАЗОВАНИЯ ПРОФИЛЯ КОЛЕСА В ПРОЦЕССЕ ИЗНОСА ПОВЕРХНОСТИ КАТАНИЯ В ЭКСПЛУАТАЦИИ

Резюме. В середине 90-х годов износ гребней колес и боковых поверхностей рельсов на дорогах стран СНГ из естественного процесса изнашивания трущихся поверхностей превратился в острую проблему, получившую статус «рельсовой чумы». На отдельных дорогах боковой износ рельсов достиг 1 мм на 106 т, превысив уровень нормативного износа в несколько раз. При этом пробег колесных пар между обточками по подрезу гребня сократился в 3-5 раз [5]. В статье рассмотрены некоторые способы устранения износа колес и рельсов. Предлагается методика моделирования процесса изменения параметров износа.

1. STATEMENT OF A PROBLEM

The numerous researches of the reasons of increased deterioration of flanges have allowed to define its reasons and to develop some ways of its reduction. In the 70s in USSR the American concept of increase of productivity of railway transportation at the expense of substantial growth of axial loadings in a combination was developed to intensive technologies of process of transportations. Large distribution was received by cargo trains of increased weight. There were usual structures of weight 5 and more than thousands tons, and overweight of freight cars up to 25,75 tons on one axis. The joint operation of ways by cargo and passenger trains has resulted to inconsistent and even to the mutually exclusive requirements in parameters of a way. For example, for maintenance of a safe movement of passenger trains with speeds up to 160 km/h it was required to increase an eminence of an outside rail in an abrupt curve up to 150 mm. With a movement on the same ways of cargo trains the character negotiation varies, the angles of attack of wheels by outside rails were increased. In the 70-90s it used to be the basic reason of increase of intensity of lateral deterioration of rails and undercut of flanges of wheels. Besides, for loaded cars the intensity of lateral deterioration in account on 10^6 tons is more than for the empty ones.

By results of gauging lateral deterioration of rails (at the end the 90s) on several sites was established, that on empty courses the intensity of lateral deterioration in account on 10^6 tons 2-2,2 times is higher, than on the loaded ones [1]. Hence, the reason of increase of lateral deterioration of rails and undercuts of flanges is not the level of lateral forces, but the dynamic factors. These factors are determined by a condition of running parts of the rolling-stock, on which, in particular, the angles of attack of wheels on rails depend.

For reduction of lateral pressure by a rail:

- The eminence of an external rail in a curve is accepted;
- In a design of carriages use elements facilitating negotiation in curves;
- Radius of curves is reduced.

For reduction of speeds of relative sliding of wheel flanges and rails:

- A structure of a wheel is carried out cone-shaped;
- Special polishing of rails for increase of a difference of circles of driving wheels in a curve is made.

Hardening of a wheel surface with application of steels by hardness up to 340 HB is rather effective. The most effective way to increase the service life of wheel flanges and rails considers application of a flange.

The work conditions of the rolling-stock of iron roads of Ukraine nowadays considerably differ from conditions in the 80s. The heavy long trains became history. But the problem of intensive flanges undercut of wheels has remained and is the reason of significant material losses.

The most widespread method of an estimation of deterioration of surfaces of the wheels driving - relative method under the factor of deterioration:

$$I = N \cdot f \cdot V_{ck}\,, \tag{1}$$

where: N – regular loading in the contact, f – friction factor, $V_{ск}$ – slippage speed.

In (1) the factor of deterioration has the dimension of capacity and is equal to work spent on galling of surfaces in a contact zone in unit of time. Such technique, however, does not allow to estimate two major characteristics of deterioration: absolute size of deterioration and its distribution on a surface of a flange.

The absolute size of deterioration can be submitted as weight of the galling metal of a rim (mass deterioration), or as thickness of a galling layer (hire or undercut). Obviously, the quantitative characteristic of deterioration is connected with abradability or wearing capacity of galling materials. The modern line of increase of hardness of a material of wheels is based on ability of firmer steels to transform work of friction to a thermal energy, instead of spending it for removal of a layer of metal.

Concerning the proportionality of deterioration of forces of friction, the formula allowing to calculate size of volumetric deterioration, similar to the formula offered by Masliev [2], could look as follows:

$$V = \varsigma \cdot N \cdot f \cdot V_{ск} \cdot t\,, \tag{2}$$

where: ς − deterioration factor, that has dimension of $\left[\mathrm{m}^3/\mathrm{J}\right]$ with the dimension of $V\left[\mathrm{m}^3\right]$; t – time of deterioration process.

However, because of the difficulties of determination of deterioration factor ς we should content ourselves with the comparing analysis of deterioration in the regular contact on the surface of the rim rolling in the flange contact.

2. METHODS OF THE MODELING PROCESS OF THE CHANGES IN THE DETERIORATION CHARACTERISTICS

The deterioration of a surface of driving tires is estimated in three parameters: by hire, thickness of a flange and parameter of a steepness of a flange [4].

The technique of modeling of process of change of each parameter of deterioration as a model of a structure of a surface of driving of a wheel during operation.

The value of speeds of slippage $V_{скI}$ и $V_{скII}$ within the limits of the first and the second spots of contacts, factor of coupling f and factor of galling ς are accepted by constant sizes. The distributions of volumetric deterioration within the limits of areas of the first and second contacts will submit to the following laws:

$$\begin{aligned} dv_I &= \varsigma \cdot f \cdot V_{скI}(t) \cdot n_I(x_I, y_I, t) \cdot dx_I \cdot dy_I \cdot dt; \\ dv_{II} &= \varsigma \cdot f \cdot V_{скII}(t) \cdot n_{II}(x_{II}, y_{II}, t) \cdot dx_{II} \cdot dy_{II} \cdot dt, \end{aligned} \tag{3}$$

where: $n_I(x_I, y_I, t)$, $n_{II}(x_{II}, y_{II}, t)$ − functions of distribution of specific pressure on areas of the first and second contacts.

According to the theory of Herz, with an assumption about elasticity of deformations within the limits of a stain of contact, the function $n(x, y)$ looks like this:

$$n(x, y) = n_o \sqrt{1 - \left(\frac{x}{a}\right)^2 - \left(\frac{y}{b}\right)^2}, \tag{4}$$

where: a, b − half-axes of a contact ellipse, n_o − the maximal specific pressure at centre of a stain of contact, x, y – coordinates of a point within the limits of a stain of contact.

Half-axes a и b, в according to the theory of Herz equal:

$$a = n_a \sqrt[3]{\frac{2}{3}\left(\frac{1-\nu_к^2}{E_к} + \frac{1-\nu_р^2}{E_р}\right)\frac{N}{k_s}}\ ; \quad b = n_b \sqrt[3]{\frac{2}{3}\left(\frac{1-\nu_к^2}{E_к} + \frac{1-\nu_р^2}{E_р}\right)\frac{N}{k_s}}, \tag{5}$$

where: $\nu_к$, $\nu_р$, $E_к$, $E_р$ − factors of Puasson and modules of elasticity of materials of a wheel and rail.

With $\nu_к = \nu_р = \nu$ и $E_к = E_р = E$:

$$a = n_a \sqrt[3]{\frac{4}{3} \cdot \frac{1-\nu^2}{E} \cdot \frac{N}{k_s}}\ ; \qquad b = n_b \sqrt[3]{\frac{4}{3} \cdot \frac{1-\nu^2}{E} \cdot \frac{N}{k_s}}; \tag{6}$$

where: n_a, n_b − factors dependent on the geometrical form of surfaces of contacting ph. The form of surfaces is characterized in factors A and B [3].

Factors A and B:

$$A = \frac{1}{4}[k_s - K]; \qquad B = \frac{1}{4}[k_s + K], \tag{7}$$

where: K − relative curvature of contacting surfaces of a wheel and rail:

$$K = \sqrt{(k_{кx} - k_{кy})^2 + (k_{рx} - k_{рy})^2 + 2(k_{кx} - k_{кy}) \cdot (k_{рx} - k_{рy})}; \tag{8}$$

where: k_s – the given curvature of contacting surfaces of a wheel and rail:

$$k_s = k_{кx} + k_{кy} + k_{рx} + k_{рy}, \tag{9}$$

where: $k_{кx}$, $k_{кy}$, $k_{рx}$, $k_{рy}$ − curvature of contacting surfaces, accordingly, wheel both rail in longitudinal and cross planes of symmetry, return appropriate radiuses of curvature in main sections *А-А*, *Б-Б*, *В-В*, *Г-Г*, *Д-Д* (fig. 1):

$$k_{кxI} = \frac{1}{R_I^x}; \qquad k_{кyI} = \frac{1}{R_I^y}; \qquad k_{рyI} = \frac{1}{R_{рI}^y};$$
$$k_{кxII} = \frac{1}{R_{II}^x}; \qquad k_{кyII} = \frac{1}{R_{II}^y}; \qquad k_{рyII} = \frac{1}{R_{рII}^y}. \tag{10}$$

Curvature of a rail in sections *Г-Г* и *Б-Б* on fig. 1: $k_{рxI} = 0$ and $k_{рxII} = 0$, as $R_{рxI} = \infty$ and $R_{рxII} = \infty$.

The maximal pressure at centre of a stain of contact according to the theory of Herz-Belyaev depends on a normal loading in contact and sizes of contact:

$$n_o = \frac{3}{2} \cdot \frac{N}{\pi \cdot a \cdot b}. \tag{11}$$

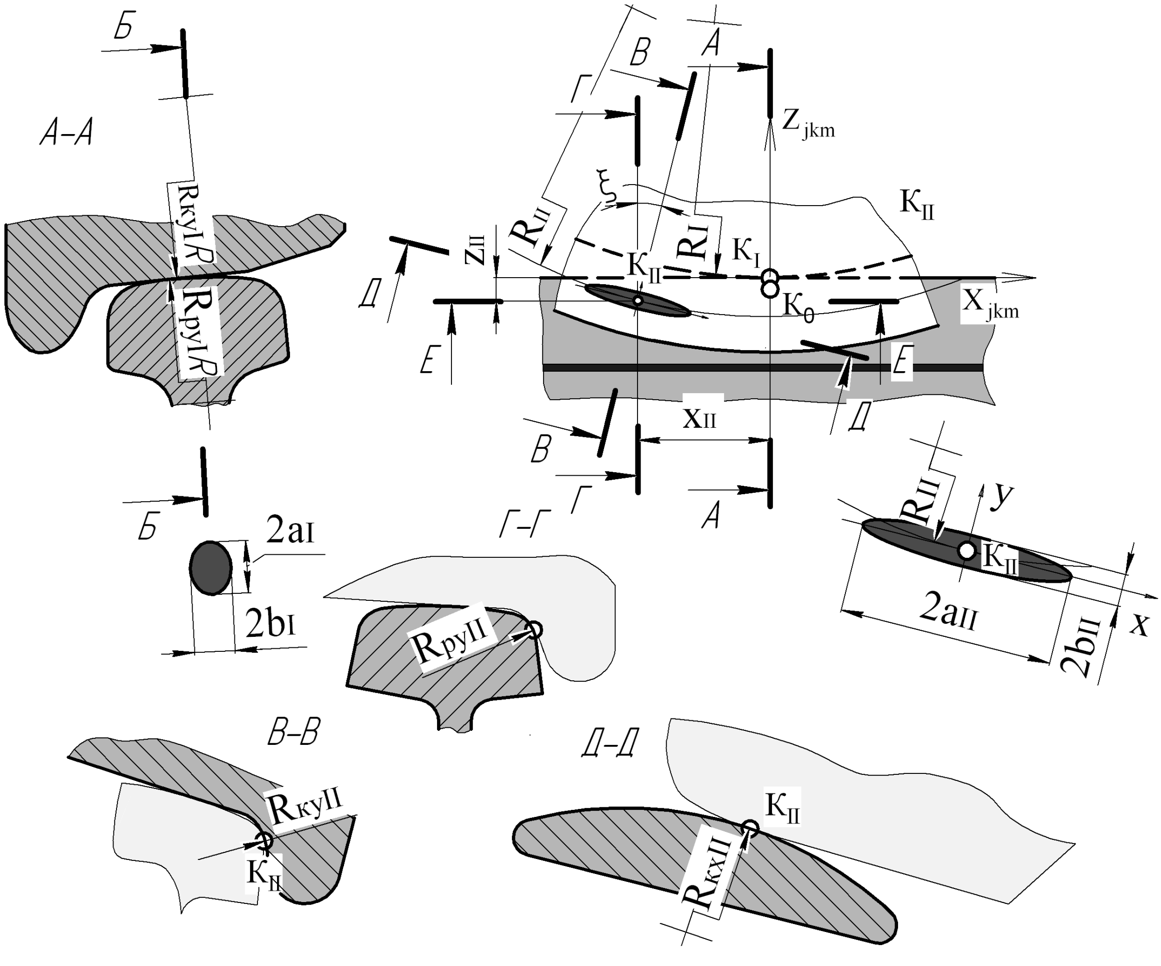

Fig. 1. The circuit of contacting of a tire surface with a surface of a rail
Рис. 1. Схема контактирования поверхности бандажа с поверхностью рельса

The volumetric deterioration of a tire surface in a contact zone can be defined by integration:

$$V = \varsigma \cdot f \cdot \int_t \iint_S V_{ск}(t) \cdot n(x,y,t) \cdot dx \cdot dy \cdot dt = \\ = \varsigma \cdot f \cdot \int_t V_{ск}(t) \cdot \int_{-b}^{b} \left(\int_{\varphi_2(y)}^{\varphi_2(y)} n(x,y,t) \cdot dx \right) \cdot dy \cdot dt \, , \tag{12}$$

where: S − area of an ellipse of contacting of a flange with a rail (area of integration); $\varphi_1(x)$, $\varphi_2(x)$ − functions, describing borders of a stain of contact:

$$\varphi_1(y) = \frac{a}{b} \cdot \sqrt{b^2 - y^2} \, ; \qquad \varphi_2(y) = -\frac{a}{b} \cdot \sqrt{b^2 - y^2} \, . \tag{13}$$

Distribution of volume of a material worn in unit of time, on a surface of a flange in radial section *A-A* (fig. 1) is defined by integration:

$$V(y) = \varsigma \cdot f \cdot V_{ск} \cdot \left(\int_{\varphi_2(y)}^{\varphi_2(y)} n(x,y) \cdot dx \right) \tag{14}$$

or, counting on (4):

$$V(y) = \varsigma \cdot f \cdot V_{ск} \cdot \left[\int_{\varphi_2(y)}^{\varphi_1(y)} \left(n_o \sqrt{1 - \left(\frac{x}{a}\right)^2 - \left(\frac{y}{b}\right)^2} \cdot dx \right) \right] . \tag{15}$$

$$\int_{\varphi_2(y)}^{\varphi_1(y)} \left(n_o \cdot \sqrt{1 - \left(\frac{x}{a}\right)^2 - \left(\frac{y}{b}\right)^2} \cdot dx \right) = n_o \cdot \int_{\varphi_1(y)}^{\varphi_2(y)} \sqrt{1 - \left(\frac{x}{a}\right)^2 - \left(\frac{y}{b}\right)^2} \cdot dx \, . \tag{16}$$

Let's calculate uncertain integral, previously by simplifying its kind:

$$I = \int \sqrt{1 - \left(\frac{x}{a}\right)^2 - \left(\frac{y}{b}\right)^2} \cdot dx = \int \sqrt{A - B \cdot x^2} \cdot dx \, , \tag{17}$$

where:

$$A = 1 - \left(\frac{y}{b}\right)^2 ; \qquad B = \frac{1}{a^2} \, . \tag{18}$$

Then:

$$I = \int \sqrt{A - B \cdot x^2} \cdot dx = \sqrt{A} \cdot \int \frac{\sqrt{1 - \left(\sqrt{\frac{B}{A}}\right)^2} \cdot d\left(\sqrt{\frac{B}{A}} \cdot x\right)}{\sqrt{\frac{B}{A}}} \, . \tag{19}$$

Changing $\sqrt{\frac{B}{A}} \cdot x = y$, we get:

$$I = \frac{A}{\sqrt{B}} \cdot \int \sqrt{1 - y^2} \cdot dy \, . \tag{20}$$

After changing $y = \sin t; \quad dy = \cos t \cdot dt$, we get:

$$I = \frac{A}{\sqrt{B}} \cdot \int \sqrt{1 - \sin^2 t} \cdot \cos t \cdot dt = \frac{A}{\sqrt{B}} \cdot \int \cos^2 t \cdot dt =$$
$$= \frac{A}{\sqrt{B}} \cdot \int \frac{1 + \cos 2t}{2} \cdot dt = \frac{A}{2 \cdot \sqrt{B}} \cdot \int (1 + \cos 2t) \cdot dt = \tag{21}$$
$$= \frac{A}{2 \cdot \sqrt{B}} \cdot \left(t + \frac{1}{2} \cdot \sin 2t \right).$$

Counting that

$$t = \arcsin y = \arcsin\left(\sqrt{\frac{B}{A}} \cdot x \right); \quad \sin 2t = \frac{2 \cdot \sqrt{B}}{A} \cdot x \cdot \sqrt{A - B \cdot x^2}, \tag{22}$$

we get:

$$I = \frac{A}{2 \cdot \sqrt{B}} \cdot \left[\arcsin\left(\sqrt{\frac{B}{A}} \cdot x \right) + \frac{\sqrt{B}}{A} \cdot x \cdot \sqrt{A - B \cdot x^2} \right]. \tag{23}$$

Definite integral

$$I = \int_{\varphi_1(y)}^{\varphi_2(y)} \sqrt{1 - \left(\frac{x}{a}\right)^2 - \left(\frac{y}{b}\right)^2} \cdot dx =$$
$$= \frac{A}{2 \cdot \sqrt{B}} \cdot \left[\arcsin\left(\sqrt{\frac{B}{A}} \cdot x \right) + \frac{\sqrt{B}}{A} \cdot x \cdot \sqrt{A - B \cdot x^2} \right]_{\varphi_1(y)}^{\varphi_2(y)}. \tag{24}$$

Inserting into (24) limits of integration (13) and counting the changes (18), we get the equation:

$$I = \frac{a \cdot \sqrt{b^2 - y^2} \cdot \left(1 + 1{,}57 \cdot b \cdot \sqrt{b^2 - y^2}\right)}{b^3}. \tag{25}$$

Based on the equation (12), we can write down the function of distribution of undercut of a flange along an axis Y of the contact area (fig. 1):

$$\lambda(y) = \varsigma \cdot f \cdot V_{ск} \cdot n_o \cdot \frac{a \cdot \sqrt{b^2 - y^2} \cdot \left(1 + 1{,}57 \cdot b \cdot \sqrt{b^2 - y^2}\right)}{b^3} \cdot t, \tag{26}$$

or, counting (11):

$$\lambda(y) = \frac{3}{2 \cdot \pi} \cdot \varsigma \cdot f \cdot V_{ск} \cdot N \cdot \left[\frac{\sqrt{b^2 - y^2} \cdot \left(1 + 1{,}57 \cdot b \cdot \sqrt{b^2 - y^2}\right)}{b^4} \right] \cdot t. \tag{27}$$

To get the distribution of deterioration of a flange, given in radical distance r (fig. 2) we need to be sure that:

$$r = z_{II} - y \cdot \sin \gamma_{II},$$

where:

$$y = \frac{z_{II} - r}{\sin \gamma_{II}}. \tag{28}$$

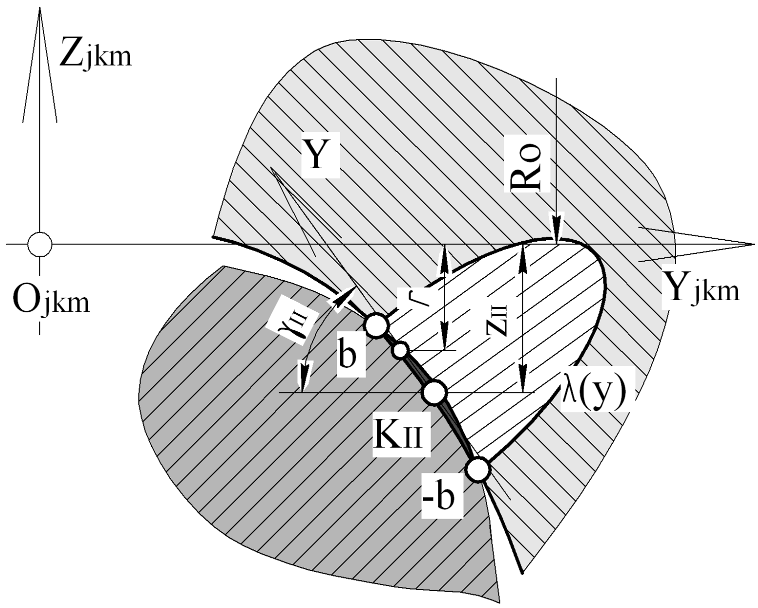

Fig. 2. Distribution of deterioration of a flange depending on Y axis of the contact area
Рис. 2. Распределение износа гребня в зависимости от координаты Y контактной зоны

The received function of distribution of horizontal deterioration (undercut) of a flange on a wheel structure, allows to simulate the shaping process of wheel structures on the determined dynamic models of a movement of vehicle.

3. CONCLUSIONS

1. The method of geometrical shaping modeling of the wornout structures of wheels and rails is based on an assumption that the deterioration of cooperating wheels and rails is proportional to a degree of mutual penetration of contours of researched structures and factor of relative deterioration of a wheel and rail.
2. Modeling of relative intensity of the undercut of flanges, is based on a power method of an estimation of mass deterioration. The method allows to receive a ratio of hire and undercut in the modeling process of a structure on the determined dynamic models of a movement of vehicle.

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