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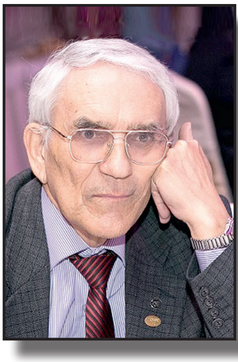
Determining Dependence of the Change in Normal Stresses in Rail on Its Wear Degree



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ABSTRACT

The safety of railway operation is associated with the stress state in rails, depending on the applied load (both vertical and lateral load) and on changes in the rail profile associated with wear.

The objective of this work is to obtain and describe the dependence of the edge stresses in a rail as a function of wear magnitude. The obtained dependence is used to determine the maximum stresses. The technique consists in constructing a spline approximation of a worn rail profile. The proposed approach allows simulating real rail wear (vertical and lateral wearing).

The work has applied in MathCAD environment a practical algorithm for calculating the influence of the degree of rail wear on the increase in the maximum bending stresses and on decrease in permissible loads.

A technique has been developed for simulating the profile and calculating the normal contour stresses during rail bending, considering the wear magnitude. It is applied to the movement of a rail wheelset along the rail track in a straight section of the track. The technique also allows considering horizontal lateral force from the wheel flange during movement of various types of rolling stock in curved track sections. Calculations have been carried out and a nonlinear dependence of the growth of maximum compressive and tensile normal stresses on the degree of wear has been obtained. Three characteristic ranges have been identified and recommendations have been given for reducing the destructive load with regard to rail wear.

<u>Keywords:</u> railway, wear, simulation, stress, load, axis of inertia, chart, calculation, rail, rail side face, rail foot, rail head, unsymmetrical bending.

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Background. The problem of intensive rail side wear which significantly affects safety of train traffic and operating costs of railways, has been continuously one of the priorities for rail networks for more than 30 years [1].

Safety of operation of rail tracks is particularly affected by stresses arising in welded joints, leading to premature onset of limit states, for example, through achieving maximum permissible stresses and cracking conditions.

The occurrence of tensile stresses in the area under the rail head as a result of local bending of vertical and lateral parts of the rail on the railway track is significant and can potentially contribute to accumulation of fatigue damage. Therefore, assessment of the stress state in the rail foot regarding changes in the rail profile due to wear is amidst most pressing problems.

For example, the conference on railway engineering (CORE2012: Global Perspectives; September 10–12, 2012, Brisbane, Australia) comprised the report [2] containing the results of applying FEM model to the analysis of the stress state of a rail under heavy traffic conditions. The constructed FEM model considered the change in the rail profile due to wear. This model was obtained as a result of a rather large-scale and laborious study, based on the solution of the contact problem.

From a practical point of view, it is of interest to solve the problem associated with operation of rails with a fixed degree of wear using technical regulations based on the well-known approach to determining internal forces and stresses in rails. That approach determines bending moments from the train load as in a beam on an elastic foundation, and thus calculates the maximum bending stresses. MathCAD computing environment allows to build a practical, easily implemented, computation algorithm allowing to analyze how a degree of wear affects the increase in maximum bending stresses and, accordingly, the reduction of permissible loads.

All over the world, where railway networks are intensively used for cargo and passenger transportation, they experience problems due to rail wear, that consequently significantly affect traffic safety and cause additional infrastructure maintenance costs. In the Russian Federation alone, JSC Russian Railways spends more than 4 billion rubles annually on prevention and elimination of the consequences of rail wear [3].

Since almost all operating railway tracks have rails with one or another wear magnitude, and the rails can be used to make a continuously welded track, it is relevant to assess the strength depending on the amount of rail head wear.

Safety requirements in Russia are generally established by documents [federal laws] No. 184-FZ [4], No. 16-FZ [5] and are directly regulated by TR TS [Technical Regulation of the Customs Union] 003/2011 [6]. At the same time, GOST [State standard] R57179 [7, Table 1] allows reducing breaking load rate by 2 % when rail wear is of 1 mm, but not more than by 20 % with a maximum rail wear of more than 10 mm. Thus, GOST R57179 stipulates linear dependence of the limit state on the wear magnitude. However, the work [3] notes that the wear process differs significantly from the linear law, and, therefore, accumulation of damage and the onset of the limit state depending on the wear value should also be non-linear.

In the general case, the acting stresses σ are composed of the stresses σ_o, arising from operational loads, temperature stresses σ_θ and residual stresses σ_{res}:

$$\sigma = \sigma_o + \sigma_\theta + \sigma_{res}. \quad (1)$$

In turn, the residual stresses σ_{res} can be considered as the sum of the residual stresses obtained in the process of manufacturing $\sigma_{res,\ man}$ and during welding $\sigma_{res,\ wel}$:

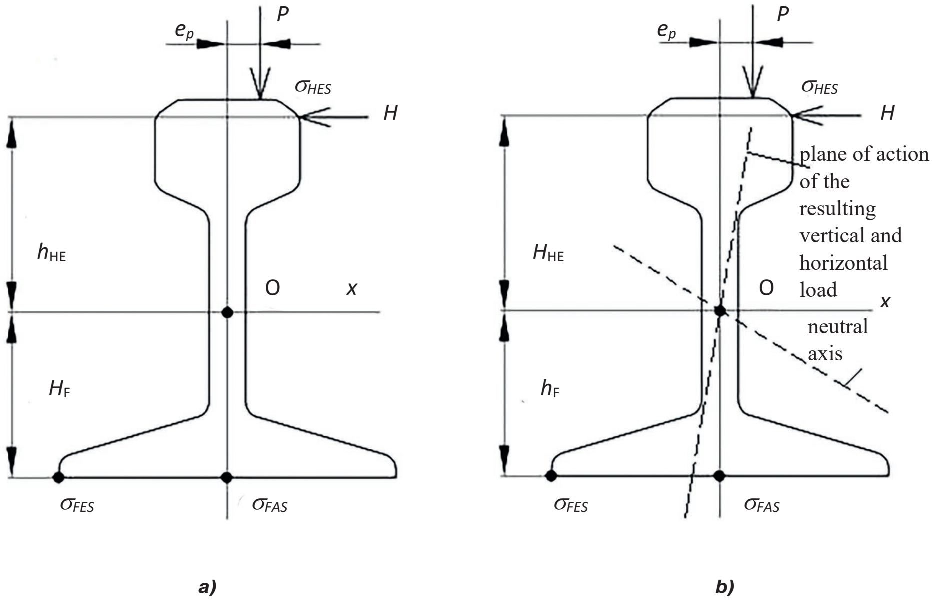
$$\sigma_{res} = \sigma_{res,\ man} + \sigma_{res,\ wel}. \quad (2)$$

All these stresses have large, or lesser impact on performance of rails.

However, the onset of limit states in the rail during operation of the railway track is mainly caused by the increase in stress from loads σ_o due to wear of the rail head. Therefore, in this study we restrict ourselves to considering the change in σ_o depending on the wear magnitude.

Accordingly, the *objective* of this work is to obtain and describe the dependence of stresses in the rail as a function of the wear magnitude.

The research is based on the *methods* of mathematical simulation of the stress-strain state with allowance for nonlinear changes in geometry of the rail cross section associated with rail wear, as in similar works by foreign authors [8–10]. For this, a geometric model of the rail cross section has been developed and a design scheme (loading model) has been used in accordance with regulatory documents [11; 12].



Pic. 1. Scheme of application of forces on the rail (a – vertical and horizontal loads, b –neutral axis position).

The methodology (functional dependencies) and the sequence of calculation of acting forces were adopted in accordance with [13]. This work, to determine the maximum stresses, uses the mathematical apparatus (in the form of analytical dependences) of the influence lines of bending moments in a beam on an elastic foundation, implemented in MathCAD computing environment. At the initial stage, stress calculation is limited to considering wear of the standard profile of the rail cross section in straight sections of the track.

Results.

It is initially assumed that the vertical load *P* from the wheel on the rail does not have a shift relative to the axis of symmetry of the rail section (Pic. 1). However, while wear is growing, the cross section becomes asymmetric, the position of the main axes of inertia changes, and the initial moment from the vertical load should be decomposed into component moments (M_z, M_x, M_y) relative to the new (main) axes of inertia. As a result, a complex stress state arises, characterized by the presence of normal and tangential stresses.

Maximum normal stresses in the foot and head of the rail from bending under *vertical* load are calculated as:

$$\sigma_{max} = M_x / W_x, \quad (3)$$

where W_x is moment of resistance of the cross section of the rail, calculated relative to the neutral axis for the most distant fiber;

M_x is bending moment from vertical load.

Based on numerous calculations and experiments, the formula for stresses in the edge of the rail foot [FES] was obtained and used in applied calculations [13]:

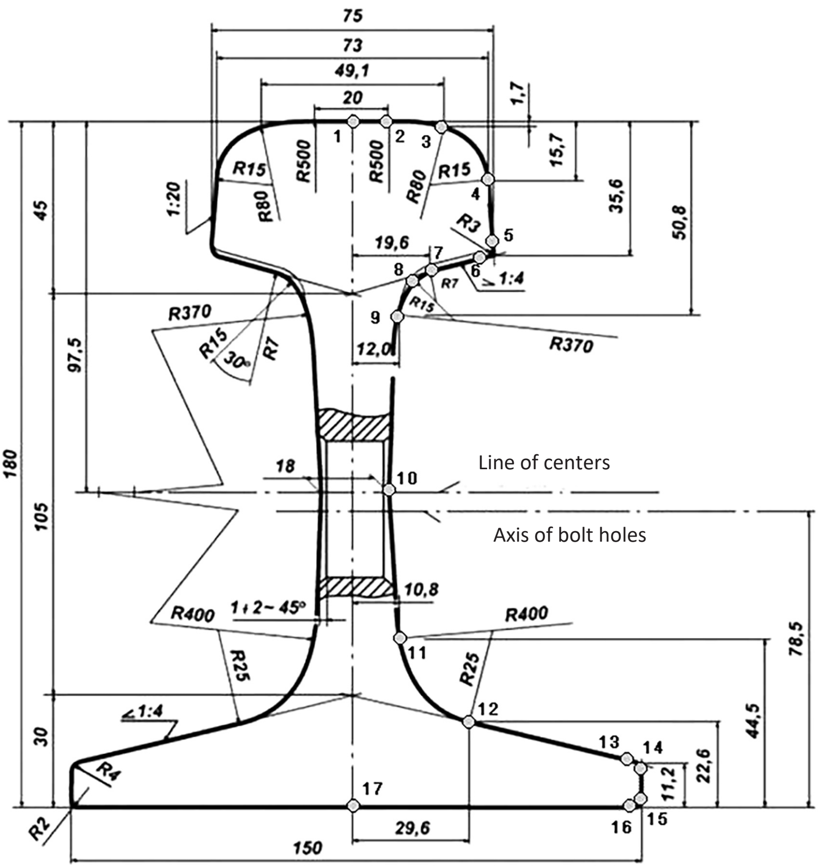
$$\sigma_{FES} = f \cdot \sigma_{FAS}, \quad (4)$$

where *f* is coefficient of transition to edge stresses, depending on the type of vehicle, the radius of the curve, the action of horizontal loads (H in Pic. 1), eccentricity of application of vertical load – e_p; seasonality (summer, winter), etc.

Normal stresses in the cross section arising from each of the bending moments are summed up. Simultaneous action of two bending moments and inequality of the moments of inertia of the section I_x and I_y give rise to a phenomenon known as unsymmetrical bending regarding the neutral axis. Therefore, when calculating the maximum normal stresses, it is necessary to specifically determine the position of the neutral axis and of the fibers which are most distant from this neutral axis.

To build a mathematical model for description of the profile of the rail R65 the chart, presented in Pic. 2 was used, as more informative than that given in GOST R51685-2013 [14]. There are no fundamental difficulties for implementation in this model of other rail profiles and grades.

The model differentiates 17 nodal points (Pic. 2) and determines analytically in

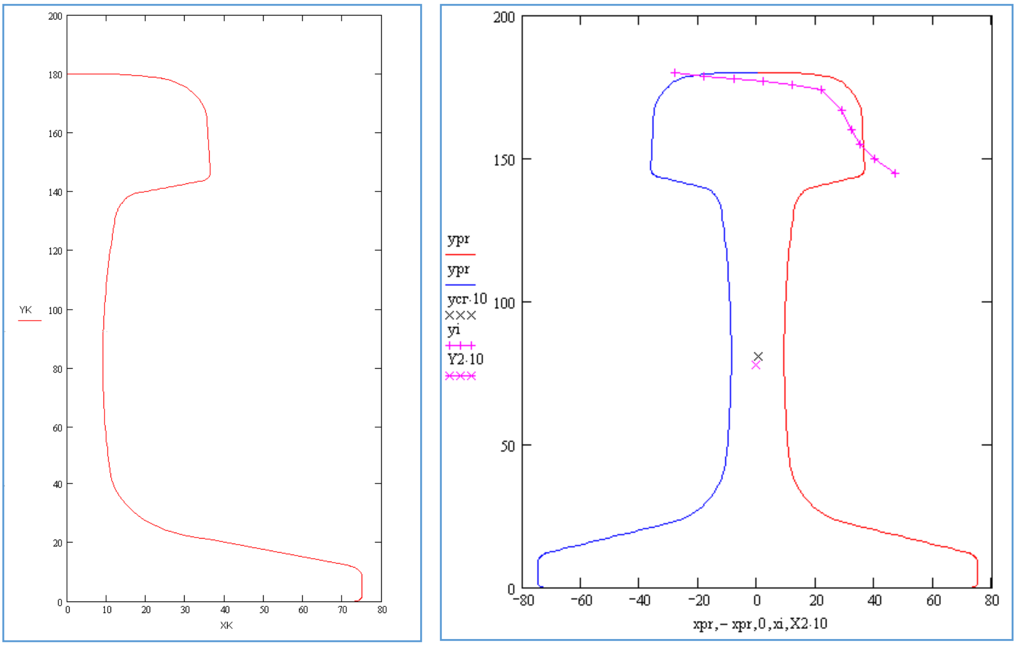


Pic. 2. Geometrical parameters of cross-section of the rail R65 and calculation points.

MathCAD environment their coordinates at the points where the curves and lines meet. To build a profile on the curved sections of the profile, including roundings with small radii, the coordinates of the centers of curvature are analytically found, which are further used to enter the corresponding angular coordinates in order to obtain uniform distribution of *x, y* coordinates along the arcs of these curves. Straight sections (4–5, 6–7, 12–13, and 14–17) are also partitioned (up to 20 points) in order to use them later for numerical integration of the area and of the moments of the cross-sectional area of the rail based on the profile contour represented as a set of points instead of using directly the equations of lines and circles. All this allows to get a set of discrete points describing the rail profile, transmitted as an array of *x, y* coordinates to another MathCAD document for further numerical processing (Pic. 3a).

To determine the corresponding geometric characteristics of the section of a worn rail in the second MathCAD document, parameter values are assigned that describe the calculated profile (pattern) of wear of the rail head. The pattern can be moved vertically and horizontally with a certain step relative to the rail head (Pic. 3b).

The characteristic profile is determined on the basis of previously performed measurements as a kind of a pattern, in this case, as an unchangeable wear profile, the position of which can be changed by setting the displacement coordinates along *x* and *y* axis (*xiv*, *yiv*, see Pic. 3b), for example, with a step of 1,6 and 1,1 mm. With a decrease in reference coordinates *xiv*, *yiv*, the wear profile pattern moves to the left and down relative to the rail cross-section profile. The pattern can also be rotated at some angle relative to its left base point, so that it is possible to adapt this template to the observed wear of the rail. For this, an angle θ is introduced, which can be used to recalculate coordinates according to known dependencies:

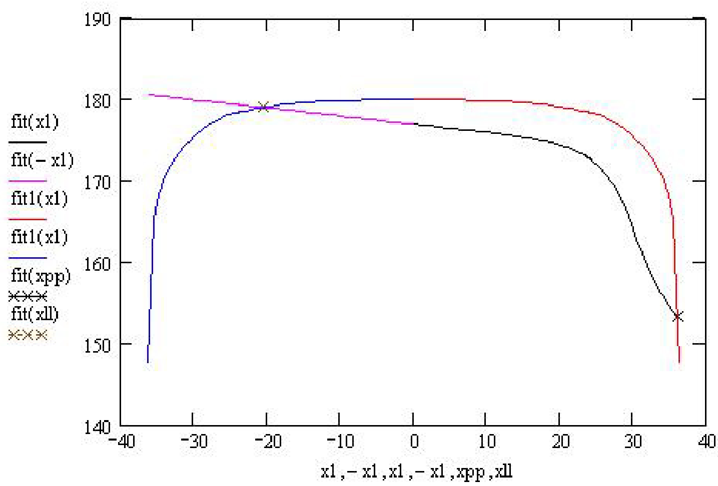


a) b)

Pic. 3. The cross-sectional profile of the rail R65: a) stored as a set of contour points (x, y coordinates); b) the pattern of the wear profile (marked with a curve with crosses).

Determination of integration interval

xp := 35	Given	fit1(xp) = fit(xp)	xpp := Find(xp)	xpp = 36.048
xl := −30	Given	fit(xl) = fit1(−xl)	xll := Find(xl)	xll = −20.543

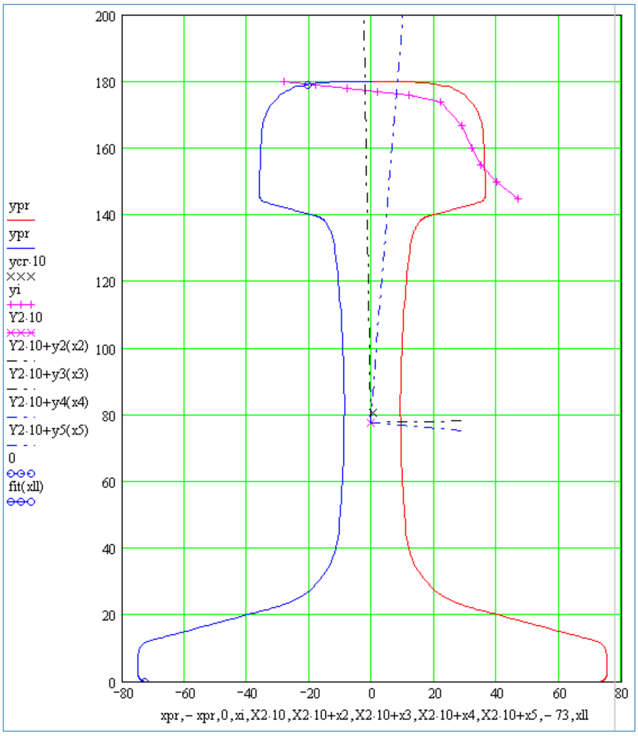


Pic. 4. Determination of integration intervals as intersection points of splines according to the wear profile and the profile of the rail head.

$$x' = x \cdot \cos\theta - y \cdot \sin\theta, \quad (5)$$

$$y' = x \cdot \sin\theta - y \cdot \cos\theta. \quad (6)$$

The value of this angle is calculated by the angle of inclination of the first section of the pattern and is adjusted by setting a coefficient (from 0 to 1) at the beginning of the expression constructed for this angle (0 represents the usual position of the pattern with an angle of



Pic. 5. The main axes of inertia of the profile of the worn rail (tilted to the left); axes oriented with respect to the neutral axis (tilted to the right) and edge points farthest from the neutral axis (marked with circles).

3,173°, 1 means that the left linear part of the pattern is horizontal).

For the wear profile and rail head profile, splines are constructed that enable an analytical description of the curves defined by the set of points, which makes it easier to find the intersection points of these two profiles and to build a numerical integration procedure over the area enclosed between these curves (Pic. 4).

The general algorithm for calculating the normal contour stresses in the cross section of the rail, considering the wear, is as follows.

1. The calculation of coordinates of points characterizing the geometry of the cross section (profile) of the unworn rail (coordinates of the center of gravity, moments of inertia).

Numerical integration for the unworn (new) rail profile was used (for testing the integration technique), although well-known reference data can be used.

2. Calculation of coordinates of points characterizing the geometry of the pattern (*x*, *y* coordinates).

3. Positioning of the pattern location depending on the amount of wear (transmission and rotation), that is, creating a model of a wear pattern.

4. Construction of splines of rail head profile and wear pattern profile.

5. Calculation of the area of the figure corresponding to the captured material of the worn rail head.

This figure is limited by the spline curves of the rail head profile and the profile of the wear pattern (Pic. 5) and hereinafter referred to as the «wear area».

6. Calculation of coordinates of the center of gravity of the «wear area».

7. Calculation of axial and centrifugal moments of inertia of the «wear area» relative to its own axes.

8. Calculation of coordinates of the center of gravity of the cross section of a worn rail.

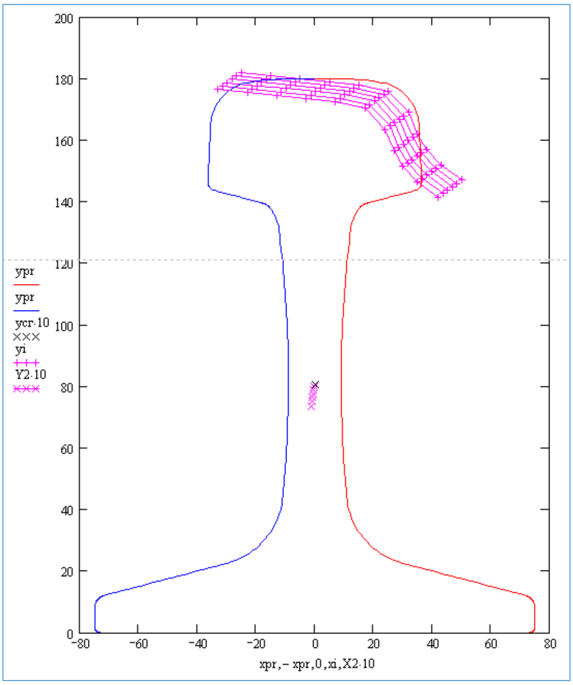
9. Calculation of axial and centrifugal moments of inertia of the cross section of a worn rail.

10. Calculation of main moments of inertia of the cross section of a worn rail.

11. Calculation of the angle of inclination of main axes of inertia of the cross section of a worn rail.

12. Determination of components of the bending moment in main axes of inertia.

13. Determination of the position of the neutral axis.



Pic. 6. The displacement of the wear profile pattern relative to the rail head profile (the crosses in the central part of the rail profile indicate the displacement of the center of gravity of the flat section of the rail, taking into account the wear determined by the pattern's preset positions).

Table 1

Dependence of normal stresses on rail wear

Tensile stresses in the rail foot, σ	Compressive stresses in the rail head, σ	Vertical rail wear, Δh, mm
283,769	-230,369	0
280,282	-226,803	0,5
293,365	-233,093	1,6
308,448	-240,064	2,8
325,486	-247,765	3,9
344,648	-256,248	5
365,881	-265,481	6,2
389,45	-275,542	7,3
415,78	-286,609	8,4
445,029	-298,715	9,6

14. Determination of the points 1 and 2 of the profile of the worn rail and their coordinates which are located as far as possible from the neutral axis (see Pic. 5).

15. Calculation of normal stresses at these points.

This practically exhausts the calculation of the maximum normal stresses for the considered position of the wear pattern. Further, the calculation is repeated from point 3 of the above algorithm for the next position of the wear pattern. The formulas for calculating the corresponding quantities involved in the calculation are well known (one can see any textbook on resistance of materials or the mechanics of a deformable body) and are not given here.

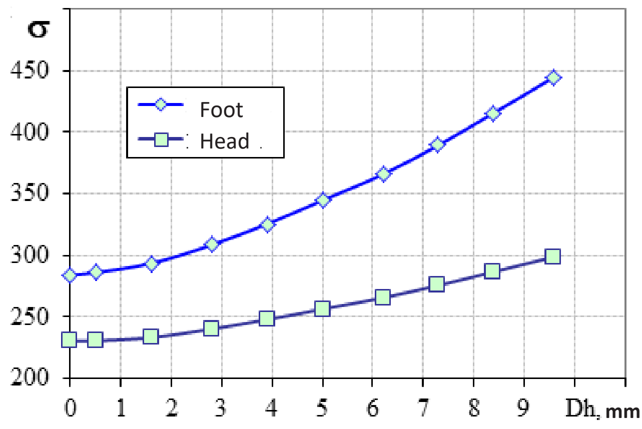
The vertical and horizontal displacements of the pattern for R65 rail were taken equal: with a pitch of 1,6 mm horizontally and 1,1 mm vertically (Pic. 6).

The results obtained are copied to arrays and graphs of stress changes are plotted depending on the position of the pattern that controls the degree of wear. As a result, the calculation results are summarized in Table 1, and in graphical form are presented in Pic. 7.

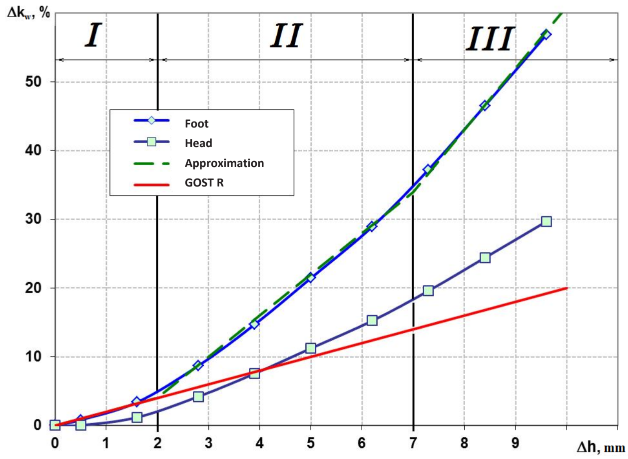
Note. The initial value of $M = 10^5$ is taken as the base value of the bending moment with respect to x axis. Thus, to obtain real stresses for a specific load, a correction factor should be used that takes into account the difference between the considered value and the base one.

Pic. 7 shows the dependences of changes in the normal contour stresses by absolute value in the cross section of a worn rail for the foot (point 1) and head (point 2) at a load $P = const$. The analysis of dependencies allows us to conclude that:

1) regardless of the sign (compressive or tensile), the magnitude of stresses grows nonlinearly as wear increases;



Pic. 7. The dependence of the contour stresses on the degree of wear (absolute values of stresses are shown).



Pic. 8. The dependence of the coefficient of increase in stress on the degree of wear.

2) the growth rate of stresses in the foot is greater than in the rail head.

GOST R57179 establishes a decrease in the value of the breaking load from the wear magnitude in the form of a linear dependence in the dimensionless form (or in %). Therefore, it seems appropriate to determine in a similar way the coefficient of increase in stress from wear as the value of Δk_w and:

$$\Delta k_w = \frac{\sigma_W - \sigma_O}{\sigma_O}, \quad (7)$$

where σ_w – normal stresses taking into account rail wear;

σ_o – normal (operating) stresses without considering wear.

In accordance with formula (7), the dependences presented in Pic. 7 are recounted and shown in dimensionless form in Pic. 8. For the analysis, a linear graph is additionally presented (shown by a red solid line), corresponding to GOST R57179.

The analysis shows that the coefficient of increase in stress due to wear Δk_w in the rail foot is greater than in the rail head. Therefore, further consideration is necessary on the basis of the dependence $\Delta k_w = f(\Delta h)$ for the rail foot, where Δh is vertical rail wear.

A result, it can be stated that the graph according to GOST R and the changes in stresses in the foot till the wear of 2 mm practically coincide, i.e. in the wear range 0–2 mm GOST R57179 correctly reflects the onset of the limit state. This range is highlighted in Pic. 8 and is denoted by the number I. At wear values of more than 2 mm, a significant increase in stresses is observed, therefore, two ranges – II and III – are shown (shown by dashed lines). Within the second range, the magnitude of wear varies from 2 to 7 mm, and the decrease in breaking load should be 6 % per 1 mm of wear. Within the third range, the wear magnitude varies from 7 mm to the maximum of 10 mm established by GOST, while the decrease in breaking load should be of 9 % per 1 mm of wear.

Thus, GOST R57179 reflects the correct trend aimed at reducing the breaking load depending on the wear magnitude but gives it a less rigorous assessment than it should be to ensure safe operation of the track.

Conclusions.

1. The analysis of the stress state under the conditions of transportation of heavy-haul trains, associated with a change in the rail profile during the wear process, is an urgent task for all countries with developed rail networks. To solve the problem, various models are developed and large-scale and labor-intensive studies are conducted. The originality of the model developed in Russian University of Transport is that, with the assumptions and simplifications made, the suggested model can determine regularity of the change in the normal contour stresses and the coefficient Δk_w of stress increase depending on wear Δh, which is non-linear.

2. Regardless of the type of rails (R50, R65, R75, R75, UIC54 (54E1), UIC60 (60E1), etc.), applicability of the calculated mathematical model is universal for all types of rails manufactured in the world. In particular, in Russia, GOST R57179 normalizes the value of the breaking load of 2 % per every millimeter of rail wear. As a result of the simulation, it was found that it is necessary to distinguish three ranges ranging from 0 mm to a maximum value of 10 mm:

- from 0 mm to 2 mm, decrease should be 2 % per 1 mm of wear;
- from 2 mm to 7 mm, decrease should be 6 % per 1 mm of wear;
- from 7 mm to 10 mm, decrease should be 9 % per 1 mm of wear.

These decreases can be used both for rails without welds (old and worn-out rails), and for those with welded joints, made, for example, by thermite welding.

3. The values of the coefficient of increase in stress can be used as a correction coefficient Δk_w (considering wear) in the practical calculation of normal stresses in the rail of any type.

REFERENCES

1. Grechneva, M. V., Medvedev, S. I., Nezhivlyak, A. E. Reducing lateral wear of railway rails using plasma surface hardening [*Snizhenie bokovogo iznosa zheleznodorozhnykh relsov pri pomoshchi plazmennofo poverkhnostnogo uprocheniya*]. *Vestnik ISTU*, 2010, Iss. 6, pp. 29–34.

2. Ranjha, S. A., Ding, K., Mutton, P. J., Kapoor, A. Mechanical state of the rail underhead region under heavy haul operations. CORE2012: Global Perspectives; Conference on railway engineering, 10–12 September 2012, Brisbane, Australia.

3. Pokatsky, V. A., Tarasov, A. V. Assessment of intensity of lateral wear of various types of rails [*Otsenka intensivnosti bokovogo iznosa razlichnykh tipov relsov*]. *Bulletin of the Samara Scientific Center of the Russian Academy of Sciences*, 2011, Iss. 3, pp. 1187–1188.

4. Federal Law of December 27, 2002 No. 184-FZ «On Technical Regulation» [*Federalniy zakon ot 27 dekabrya 2002 goda No. 184-FZ «O tekhnicheskom regulirovanii»*].

5. Federal Law of February 9, 2007 No. 16-FZ «On Transport Security» [*Federalniy zakon ot 9 fevralya 2007 No. 16-FZ «O transportnoi bezopasnosti»*].

6. Technical regulations of the Customs Union «On safety of railway transport infrastructure» (TR TS003/2011) [*Tekhnicheskiy reglament TS «O bezopasnosti infrastruktury zheleznodorozhnogo transporta» (TR TS003/2011*].

7. GOST R57179-2016. Thermite rail welding. Testing and quality control procedure [*GOST R57179-2016 «Svarka relsov termitnaya. Metodika ispytanii i kontrolya kachestva»*].

8. Jeong, D. Y., Tang, Y. H., Orringer, O. Estimation of rail wear limits based on rail strength investigations. Volpe center final report, 1998. DOT/FRA/ORD-98/07. [Electronic resource]: https://www.fra.dot.gov/Elib/Document/2935. Last accessed 11.09.2019.

9. Jeong, D. Y. Analytical modeling of rail defects and its applications to rail defect management. Volpe center technical report for the UIC/WEC joint research project on rail defect management, 2003. [Electronic resource]: https://rosap.ntl.bts.gov/view/dot/8995/dot_8995_DS1.pdf. Last accessed 11.09.2019.

10. Lyons, M. L., Jeong, D. Y., Gordon, J. E. Fracture mechanics approach to estimate rail wears limits. Proceedings of the 2009 ASME rail transportation division, Fall technical conference RTDF 2009. October 20–22, 2009, Fort Worth, Texas, USA. [Electronic resource]: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.818.8345&rep=rep1&type=pdf. Last accessed 11.09.2019.

11. Rules for calculation of the strength of the track superstructure [*Pravila proizvodstva raschehtov verkhnego stroeniya zheleznodorozhnogo puti na prochnost'*]. Moscow, Transzheldorizdat publ., 1954, 70 p.

12. Rules for calculating track regarding strength and reliability depending on the class of lines (1st edition) [*Pravila rascheta puti na prochnost' i nadezhnost' v zavisimosti ot klassa linii (1-ya redaktsiya)*]. MPS VNIIZhT. Moscow, 1999, 96 p.

13. Karpushchenko, N. I., Bondarenko, A. N., Ivanova, L. I. Calculation of the railway track for strength and stability: Study guide [*Raschet zheleznodorozhnogo puti na prochnost i ustoichivost: Ucheb. posobie*]. Novosibirsk, Publishing House SGUPS, 2002, 62 p.

14. GOST R51685-2013 «Railway rails. General specifications» [*GOST R51685-2013 «Relsy zheleznodorozhnie. Obshchie tekhnicheskie usloviya»*]. ●