Extending service life of rails in the case of a rail head defect

Rails are subjected to the processes of wear, corrosion and contact and bending fatigue during their lifecycle. As a result of these processes, various types of damage and defects are formed in rails. The residual life of rails depends on the size, position, and orientation of defects. Maximum permissible crack-size values are calculated in this paper using the finite element method. The crack plane orientation relative to the contact surface plane is analysed. The dependence of the stress intensity factor on the crack area is established. This allows continued use of defective rails and safe operation on low-activity railways.

Key words:
railway track, rail defects, finite element method, crack

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1. Introduction

Railway track is an important part of the infrastructure, and its technical condition provides for general safety of traffic. The state of railway components is determined by their carrying capacity. The track superstructure is subjected to very harsh conditions: trains passing, exposure to wind, rain, and temperature changes. However, it is important to maintain, under these conditions, a sufficient strength and stability and ensure economic durability. Being the main bearing element of the railway superstructure, rails have to:
- withstand long-term train wheel load without cracks or other damage
- transfer load from wheels to rail bases, and ensure its distribution over a sufficiently large surface
- direct/guide movement of the wheels of rail vehicles.

In the course of railway operation, rails are subjected to various processes such as rail wear, plastic flow, corrosion, and fatigue, including also the process of contact bending and corrosion fatigue. Due to these processes, various types of damage and defects are formed.

A rail defect is characterized by deviation of its geometric parameters or strength from established specifications, provided that the rail operates in accordance with specified operating conditions. Rail defects include: head checks, shelling, spalling, squats, cracks, rolling contact fatigue, various types of wear, plastic deformations in the form of shelling, spalling, squats, cracks, rolling contact fatigue, etc., if their amplitude exceeds prescribed values. Rail failure is classified as a defect if it brings about the need to stop the train (for example, complete failure with rail damage) or to limit the speed of the train (partial failure, such as running surface defects in track head, etc.) [1].

A frequent rail head defect is a transverse fatigue crack in the form of light or dark spots, due to contact fatigue of metal and various types of wear, plastic deformations in the form of flow of rail heads, corrosion, mechanical damage, etc., if their amplitude exceeds prescribed values. Rail failure is classified as a defect if it brings about the need to stop the train (for example, complete failure with rail damage) or to limit the speed of the train (partial failure, such as running surface defects in track head, etc.) [1].

Figure 1. Representation of a rail head defect [8]
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rail surface using a variety of technical means [10, 11]. The theoretical studies are usually based on the analytic Hertzian solution [12], semi-analytic FASTSIM algorithm [13, 14] and the finite element (FEM) simulations. The FEM simulation of stresses in the wheel rail interaction system is presented in studies [15-17]. An approach for determining a critical size for RCF (Rail Contact Fatigue) initiation from rail surface defects is presented in [18]. The methodology is based on the evaluation of stress of defects at the transient rolling contact, which takes into account the frictional rolling contact model. A prediction of RCF crack initiation life, with identification of crack plane orientation, is presented in [19]. The prediction is based on a dynamic three-dimensional FEM model and a simulation of axle box accelerations.

In this paper, mathematical models are developed for the limit state calculation and assessment of operational life of rails taking into account the head flange surface defects. The mathematical model allows determination of failure rate of the rail with head flange defects by describing the stress field at the crack tip. The following criteria are used for assessing critical K values [4, 20]:
- crack edges are displaced in the direction normal to the crack plane;
- crack edges are displaced in the plane of the crack normal to the crack propagation front;
- crack edges are displaced in the plane of the crack parallel to the crack propagation front.

2. Numerical FEM model for wheel and rail contact interaction

A volumetric finite element model FEM has been developed in the software ANSYS to analyse the stress intensity coefficient in the wheel and rail contact zone. The properties of the materials are completely identical to the properties of rail steel, and to the properties of wagon wheels. All elements are modelled with full geometric similarity to full-scale structures. The capacity of the static structural analysis model is about 400 thousand nodes of 75 thousand tetrahedral elements. The symmetry properties of the model are used to significantly reduce the number of finite elements. In the contact zone, the mesh of elements is noticeably detailed (element size is 0.5 mm) to enable the most accurate display of the analysis results. Such a small value of the element faces in the contact zone allows accurate simulation of the geometry of the real contact spot, as well as improvement of the accuracy of calculation results without significantly increasing the time spent on modelling (Figure 2.).

The following boundary conditions were used. Rigid contact is modelled along the area of the rail foot. The contact surface of the wheel and the axle moves with two-point contact in the vertical and horizontal direction. Symmetric boundary conditions are also used. Other elements are not fixed. The simulation took into account lateral displacement of the wheel relative to the rail, which is considered as the distance between the axis of symmetry of the rail section and the plane of the wheel rolling circle. The transverse offset is zero if the wheel’s rolling circle line is on the rail’s axis of symmetry. The following parameters were used in the simulation: the rail profile R65 of rail steel R350HT according to the standard GOST R 51685-2013, the freight wagon wheel according to the standard GOST10791-2011 [21] with a diameter of 950 mm. Elastic properties of material are $E = 210\text{GPa}$ and $v = 0.3$. The axial load capacity amounts to 27 tons/axle, the lateral force is 10 tons, wheel axle is in vertical position, the rail inclination axis is 1/20, and the contact surfaces correspond to the specified profiles.

The stress fields arising from this wheel-rail interaction are shown in Figure 3. As can be seen, the maximum stresses occur in the contact zone of the wheel and the lateral flange of the rail. It is obvious that the greatest SIF will be observed when the crack is located in the zone of maximum equivalent stresses (Figure 3).
3. Analysis of influence of crack size and orientation on stress intensity factor

Two cases of crack orientation are selected for the numerical simulation and analysis: the parallel and the perpendicular position to the rolling surface. Ten variants of crack size, with different values of length, width and thickness, are calculated for the two cases.

The model mesh for Case 1, in which the crack is perpendicular to the wheel and rail head contact, is shown in Figure 4. In the crack area, the grid becomes thicker and reaches the component size of 0.1 mm. The crack itself is elliptical in shape with a thickness of 0.01 mm in the rail. The results of estimation of stress intensity coefficients at different geometrical parameters of elliptic crack are presented in Figures 5-ab. In the initial data studied, the maximum value of SIF is achieved when the load causes the edge of the crack to shift in the direction normal to the crack plane. The results of SIF calculation for all Case 1 variants are presented in Table 1.

An approximation of the dependence of the stress intensity coefficient on the crack area is presented in Figure 6. The figure shows the most intensive SIF development up to about 1 mm² in area. After that, the increase of the SIF is almost linearly proportional to the increase in crack area.

According to relevant standards [21], maximum permissible values of K for rails produced in various countries are shown in Table 2.
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Thus, when the K value is close to the endurance limit of the rail, the amplitude of crack growth increases significantly, up to destruction of the rail. Based on mathematical modelling, the critical area of the crack - the maximum area of the beam - can be determined, after which the crack growth will be accelerated, leading to further destruction of the rail. For the elliptical crack perpendicular to the plane of contact between the wheel and rail, the maximum allowable value of this area is 0.2 mm². The influence of geometric parameters of the crack and its location relative to the reaction under contact of wheel and rail was evaluated in this paper. Figure 6 shows that the maximal admissible area of cracks can be increased by reducing the loading. This fact can be used for extending the service life of the rails, through their recycling, on the low-activity and smaller

Table 1. Results of modelling crack SIF at two-point contact of wheel and rail for crack that is parallel to contact surface

| Crack size [mm] | | KI [MPa m⁰.⁵] | KII [MPa m⁰.⁵] | KIII [MPa m⁰.⁵] | Area [mm²] | The max value [MPa m⁰.⁵] |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Length Width Thickness | | | | | | |
| 0.1 0.1 0.01 | 28.5 | 2.7 | 3.5 | 0.032 | 28.5 |
| 0.1 0.25 0.01 | 38 | 3.1 | 2 | 0.078 | 38 |
| 0.25 0.25 0.01 | 44.1 | 5.9 | 2.8 | 0.196 | 44.1 |
| 0.25 0.5 0.01 | 56.7 | 6.7 | 2 | 0.392 | 56.7 |
| 0.5 0.25 0.01 | 58.2 | 9.3 | 6.4 | 0.392 | 58.2 |
| 0.5 0.5 0.01 | 64 | 12.1 | 5.4 | 0.786 | 64 |
| 0.5 1 0.01 | 80.5 | 14.6 | 3.9 | 1.57 | 80.5 |
| 1 0.5 0.01 | 83.4 | 20.7 | 14.1 | 1.57 | 83.4 |
| 1 1 0.01 | 94.1 | 26.9 | 12.2 | 3.142 | 94.1 |
| 2 1 0.01 | 123 | 27.8 | 25.7 | 6.284 | 123 |

Table 2. Rail steel fatigue limit of full-profile rails and cyclic crack resistance values after cyclic test results

| Country of manufacture | Fatigue limit [MPa] | Crack resistance [MPa m⁰.⁵] |
|------------------------|---------------------|-----------------------------|
| Russia, NKMK (T1)      | 400                 | 41-59                       |
| Russia, NTMK (T1)      | 407                 | 46-56                       |
| France                 | 477                 | -                           |
| Japan, NS              | 430                 | 26-38                       |
| Canada                 | 453                 | -                           |
| Austria                | 423                 | 25-36                       |
| Italy                  | 366                 | 25-29                       |
| Poland                 | 367                 | 29-31                       |

Figure 6. Dependence of stress intensity coefficient on crack area

Table 3. Results of modelling crack development at two-point contact of wheel and rail for crack that is perpendicular to contact surface

| Crack size [mm] | | KI [MPa m⁰.⁵] | KII [MPa m⁰.⁵] | KIII [MPa m⁰.⁵] | Area [mm²] | The max value [MPa m⁰.⁵] |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Length Width Thickness | | | | | | |
| 0.1 0.1 0.01 | 6.7 | 2 | 1.5 | 0.032 | 6.7 |
| 0.1 0.25 0.01 | 8.8 | 2.5 | 1.1 | 0.078 | 8.8 |
| 0.25 0.1 0.01 | 8.8 | 2.2 | 2.1 | 0.078 | 8.8 |
| 0.25 0.25 0.01 | 12.5 | 3.5 | 2.2 | 0.196 | 12.5 |
| 0.25 0.5 0.01 | 15.5 | 4.1 | 1.8 | 0.392 | 15.5 |
| 0.5 0.5 0.01 | 24.4 | 5.8 | 3.3 | 0.786 | 24.4 |
| 0.75 0.5 0.01 | 36.1 | 8.2 | 4.6 | 1.178 | 36.1 |
| 0.75 0.75 0.01 | 42.7 | 6.5 | 4.4 | 1.768 | 42.7 |
| 0.75 1 0.01 | 47 | 10 | 4 | 2.356 | 47 |
traffic-load railways. The model mesh for Case 2, in which the crack is parallel to the wheel and rail head contact, is shown in Figure 7. In the cracked area, the mesh is densified to a component size of 0.1 mm. The crack itself is a bundle of elliptical shapes with a track thickness of 0.01 mm.

The results of estimation of stress intensity coefficients at different geometrical parameters of elliptic crack are shown in Figure 8. The maximum value of SIF loading cracking modes occurs in the load situation in which the edges of the crack are shifted in the direction normal to the plane of the crack.

Unlike Case 1, a maximum crack size of 0.75 x 1.0 mm is selected. Calculation results for ten crack size variants are presented in Table 3. The calculation results show that the critical SIF value reached is not possible when the crack is parallel to the wheel-rail contact plane, compared
to the crack perpendicular to the wheel-rail contact reaction plane. The maximum allowable crack area increases from 0.2 mm² to about 2 mm². Thus, the development of a crack parallel to the contact reaction plane is extremely unlikely.

4. Conclusion

The FEM simulation model of double contact interaction between the rail and wheel is developed. The model takes into account concentration of internal tensions due to cracks of different size and orientation. The stress field at the crack tip is estimated utilizing the stress intensity factor that is used to measure the stress concentration point near the crack. The relationship between the stress intensity coefficient and the crack area is analysed: the maximum allowable crack area of the elliptical crack perpendicular to the wheel-rail contact reaction plane is 0.1 mm². The crack orientation parallel to the plane of the wheel-rail contact interaction is analysed. The results show that the cracks parallel to the contact reaction plane have much lower influence on SIF than perpendicular ones.

The service life of the rails with cracks can be significantly extended through their recycling and use on the low-activity and smaller traffic-load railways.

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