ANALYSIS METHOD FOR ASSESSING THE STRENGTH OF FREIGHT WAGON WHEELS

Shokuchkarov Kurbonnazar

Ruzmetov Yadgor

Raximov Rustam

Yo'ldoshov Rustam
Author's Affiliations
Tashkent, Adilxadjayev st, 1-A, Uzbekistan.

The paper analyzes the methods and methods for calculating and testing the strength of wheels used on rolling stock of railways. The purpose of this study is to study the basic requirements of the technical conditions of production, standards for the calculation and testing of railway wheels, compare domestic and foreign calculation standards, and identify their advantages and disadvantages. The paper describes the method of strain measurement, the measurement of residual stresses by the ultrasonic method, and the X-ray method of measurement. It has been determined that the results of an experimental assessment of the stress-strain state of railway wheels, first of all, should be based on the experience of conducting the following type tests: determination of residual stresses; measurement of stresses on the disk surface during fatigue tests; determination of the stress-strain state during long-term braking by the shoes.

Keywords: wagon, railway wheel, axial load, stress state, Sainz criterion, strength, fatigue resistance margin.

INTRODUCTION

Currently, the main directions of rolling stock modernization are: - the use of new materials and structures in the repair and manufacture; – increase in axle load up to 27 tf for new generation locomotives and freight cars; – reduction of tare weight of freight cars by 25%. Widely used domestic wheel designs for freight and passenger cars, locomotives and metro cars, designed and tested for lower axle loads and design speeds, have more than half a century of development history. The used standard wheel designs are characterized by a high weight compared to the closest Western counterparts, or do not meet the requirements of strength and reliability when operating under rolling stock with increased payload. Significant difficulties for the design of wheels are the imperfection of the existing regulatory framework, which is limited in the methods of complex analysis of the strength indicators of railway wheels from the action of various operational factors and the peculiarities of the influence of their production technology. The used methods for assessing the strength of wheels are based to a greater extent on the results of expensive bench or operational tests, rather than on theoretical calculations, which greatly complicates the solution of optimization problems in the design. At the same time, the current standards [1] explicitly indicate the need to develop reliable methods for calculating the stress-strain state of solid-rolled wheel structures under conditions of long-term braking by pads, which in the future may make it possible to abandon full-scale tests. A modern approach to the computational determination of residual process stresses is to carry out finite element analysis in accordance with the methodology of the Association of American Railroads 8-669 standard [2] by solving a non-linear non-stationary heat-strength problem, taking into account high-temperature creep (stress relaxation during tempering), elastic-plastic properties of the material, joint effects of radiative and convective heat transfer. The complexity of the practical use of this technique is associated with the lack of a description of reliable boundary conditions for a given heat treatment mode in the conditions of the manufacturer

MAIN PART

Currently, the requirements of foreign and domestic specifications for the production of solid wheels include the mandatory heat treatment of the rim (hardening and tempering). Various hardening technologies are used - intermittent hardening, hardening in water and oil. Taking into account the classification of railway wheels, it is necessary to designate the residual stresses in the wheel disk, which is comparable to the level of stresses from external loads. The use of full-profile machining allows to increase the endurance limit of the disc up to 25%, and shot blasting by 1.5 times. As a result, in practice there are unreasonable requirements for the introduction of shot blasting for the case of full-profile processing of a disk with sufficient margins for structural fatigue resistance, the absence of a theoretical justification for revising wheel designs in terms of weight reduction when introducing various technologies for processing the surface of a disk or new heat treatment modes [3– 6]. The second problem of assessing the strength of railway wheels can be defined as the determination of loading modes. The operating conditions of the wheels are largely determined by the design of the wheelset, which depends on the type of rolling stock (traction, non-traction). The structure of the loads acting on the wheel, depending on the source of their occurrence and determining the stress-strain state of the wheel, is shown in Figure 1. The permissible load rates under various conditions are given in [7, 8]. the following topical scientific problems in the field of assessing their strength. The first is that the existing methods for calculating the margin of wheel fatigue resistance do not allow taking into account the influence of a combination of factors associated with the peculiarities of the production technology. However, it is known that heat treatment of the rim creates a significant level.

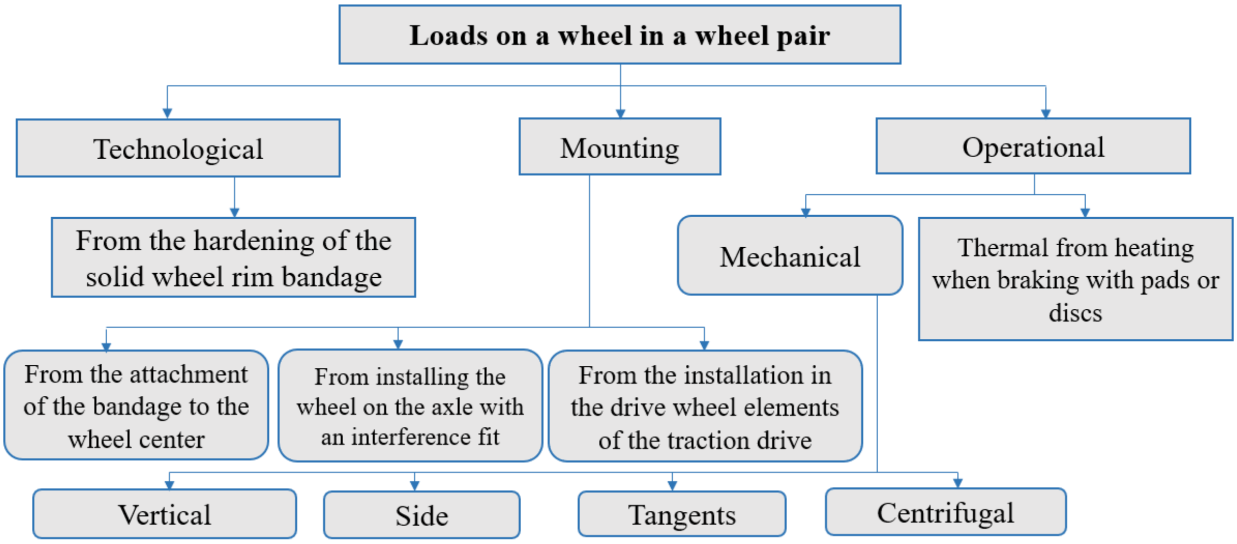

Figure 1 - Loads acting on a railway wheel

Significant thermal loads occur in the wheel during shoe braking. Also, research is required on the thermal load on the disc mounted on the wheel with a disc braking system. The results of an experimental assessment of the stress-strain state of railway wheels, first of all, should be based on the experience of the following type tests:

– Determination of residual stresses;

– Measurement of stresses on the disk surface during fatigue tests;

– Determination of the stress-strain state during long-term braking by the blocks. According to the requirements of regulatory documentation [9–11], residual stresses in solid-rolled railway wheels are determined by strain measurement using a destructive method, or surface and internal residual stresses are determined by non-destructive methods (X-ray, ultrasonic) [12]. The assessment of residual stresses by the method of radial cutting of wheels with subsequent measurement of the convergence of the separated parts of the rim is widely used in acceptance tests. At the same time, this method gives only a qualitative picture of the stress distribution, determining the sign of the circumferential stresses in the rim. The essence of the strain gauge method is to make incisions that lead to an increasing release of internal residual stresses in the wheel rim. The change in the state of internal stresses arising after each of the cuts is fixed by measuring the deformations on the surface of the structural elements using strain gauges. Each wheel is equipped with strain gauges installed in two to four radial sections on the outer and inner sides of the disk and rim. When measuring, two- or three-component sockets of strain gauges are used, depending on the nature and direction of the main stresses (Figure 2). The processing and evaluation of the results of measurements by the destructive method is carried out according to special formulas. Based on the results of measurements, a diagram of the distribution of residual stresses over the section is built, zones of maximum stresses are determined.

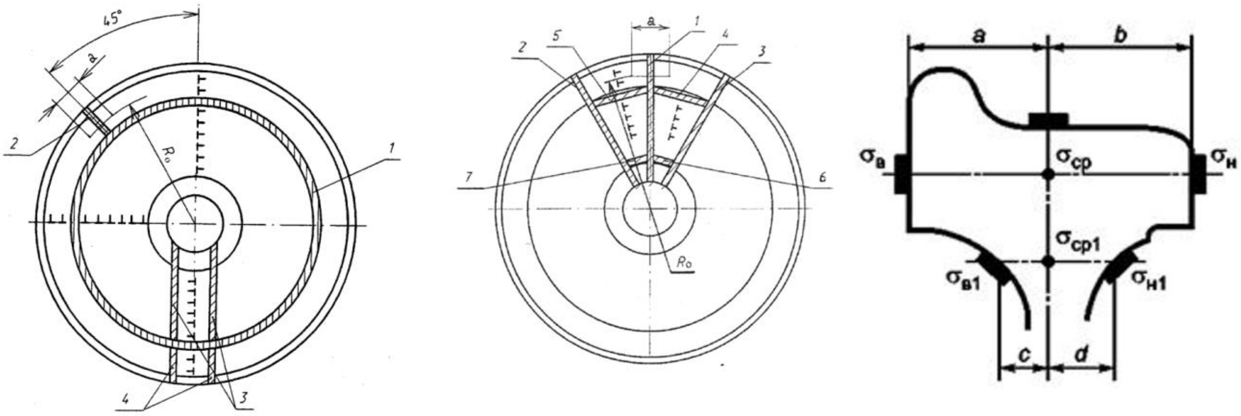

Figure 2 - Measurement of residual stresses by strain gauge

Measurements of residual stresses by the ultrasonic method are carried out using ultrasonic devices with an electroacoustic transducer. The measurement method consists in determining the speed of ultrasound, which uses the effect of acoustoelasticity, which consists in the influence of elastic stress in the metal on the speed of ultrasonic waves. This method is used to measure residual stresses in the wheel rim. To determine the residual stresses, the value of the acoustoelasticity coefficient for a given material must be known, and the possible effect of texture on the measurement results must also be taken into account. The measurement of residual stresses of the wheel by the ultrasonic method is carried out from the side surface of the rim, ensuring the propagation of polarized ultrasonic waves between the side faces of the rim. The X-ray method measures the residual stresses of the surface layer of the wheel, which is substituted for the beam of incident X-rays. The thickness of this layer is equal to half the depth of X-ray penetration into it. Before inspection, the surface must be free from contamination and have a surface roughness not higher than R_z=10. Determination of the stress state of the wheels from the action of mechanical loads is carried out during bench tests for fatigue. There are several schemes of full-scale testing of wheels - bending, bending with rotation and vertical load testing. Fatigue testing schemes for wheels using the bending method (Figure 3, a) and bending with rotation (Figure 3, b) are two alternative methods for determining the endurance limit of the wheel disc according to the requirements of European standards [1, 13]. The test sample is a wheel with a pressed part of the axle, which allows taking into account the effect of mounting stresses on the endurance limit value. Domestic standards also regulate two fatigue test schemes, which, in turn, are not alternative. When qualifying wheel sets, tests are carried out according to the above-described bending with rotation method, but on the basis of 20 million cycles [7, 13].

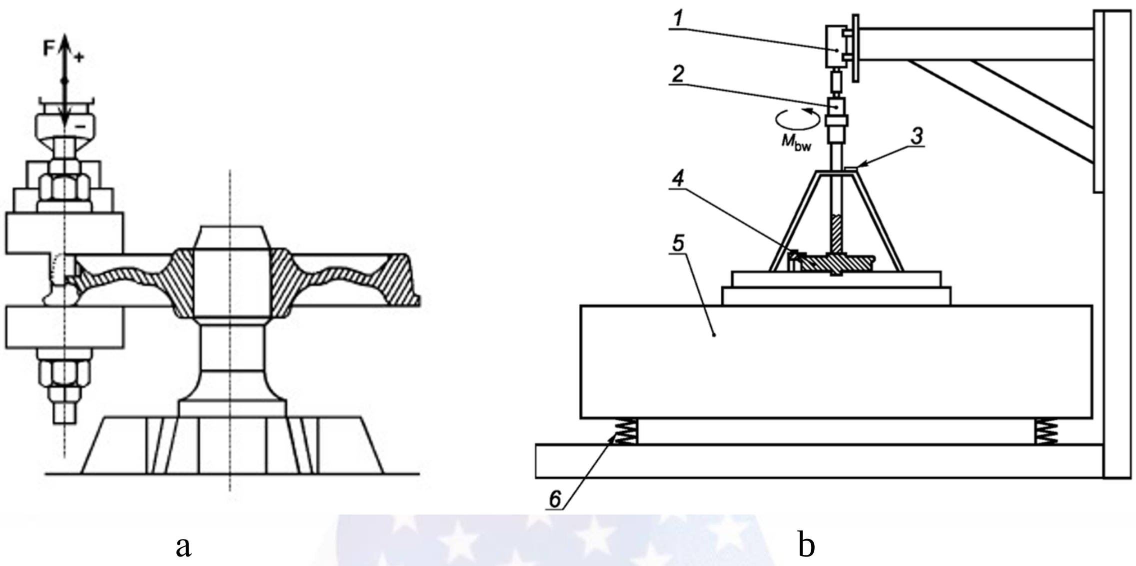

Figure 3 - Schemes of testing wheels for fatigue: a - bending; b - bending with rotation

When confirming the quality characteristics of the wheels to the requirements of the standard technical specification [11], tests are carried out using a hydraulic pulsator under the action of a vertical cyclic load with an asymmetry factor of 0.1 based on 5 million cycles. At present, we can talk about three main established systems for admitting new wheel designs to operation on the largest railway networks in the world. These include the M-107/M-208 [9], S-660 [14], and S-669 [2] standards of the Association of American Railroads (AAR), the International Union of Railways, UIC) [13], whose analogue is EN 13979–1 [1] of the European Committee of Standardization (CEN), as well as Russian GOST 31373 and NB ZhT TsT 063 [8]. Despite the commonality of goals, each of these regulatory bases has different approaches to assessing the strength and reliability of solid-rolled railway wheels, thereby defining a unique set of objective functions and constraints when solving a complex problem of design optimization. The calculation of the stress state is carried out under the assumption of a linearly elastic behavior of the material with small deformations. This does not take into account the mounting stresses due to the interference between the wheel hub and the axle. The axle is modeled as a hollow one with a hole of 50.8 mm, integrally with the wheel hub (Figure 4). The axle hole is fixed rigidly in all degrees of freedom.

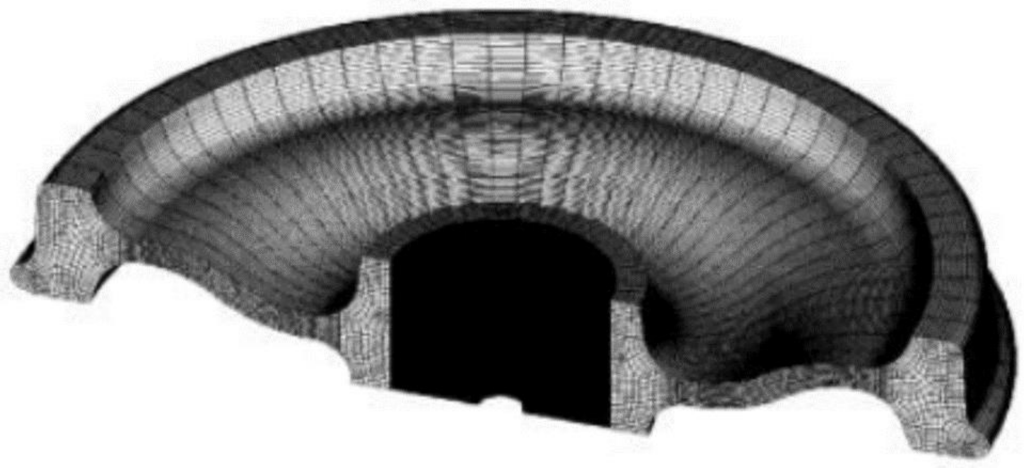

Figure 4 - View of the finite element model of the wheel in accordance with [15]

The wheel design analysis procedure for S-669 locomotives is a modern development of the S-660 standard. The purpose of this analytical assessment is to determine the margin of fatigue resistance of the wheel disk according to the Sainz criterion, as well as the maximum stresses in the wheel rim under the action of a dynamic traction load with a frequency characteristic of the first saddle form of natural oscillations. Evaluation of fatigue resistance is carried out based on the results of three analytical procedures, which give a set of eight options for the stress state for a wheel with a new and worn rim (Table 1):

– determination of residual stresses due to the influence of heat treatment in the production of wheels;

– calculation of mounting stresses from landing with an interference fit of the wheel on the axle. In accordance with the Sainz criterion, the stresses from the action of external loads are variable, and the installation stresses from the interference fit and the residual stresses from heat treatment are static stresses.

Table 1 - Initial data for estimating fatigue resistance

Load option	Set result at each node	Terms
1	Normal and shear stresses in load mode	V1+L1, new rim
2	Normal and shear stresses in load mode	V2, new rim
3	Normal and shear stresses in load mode	V1+L1, worn rim
4	Normal and shear stresses in load mode	V2, worn rim
5	Normal stresses	Residual stresses from heat treatment, new rim
6	Normal stresses	Residual stresses from heat treatment, worn rim
7	Normal stresses	Interference fit stresses, new rim
8	Normal stresses	Interference fit stresses, worn rim

Thus, fatigue damage to the wheel structure is predicted in the case when the variable stresses become greater than the static ones for any node of the model.

$$J_2' \leq A\text{-}\propto\left(J_1^M + J_1^R + J_1^P\right) \quad (1)$$

where is the shear stress intensity and is defined as

$$J_2' = \frac{1}{3}\left[\left(S_x - S_y\right)^2 + \left(S_y - S_z\right)^2 + (S_z - S_x)^2 + 6\left(T_{xy}^2 + T_{yz}^2 + T_{xz}^2\right)\right]^{\frac{1}{2}} \quad (2)$$

The amplitude of each nodal voltage component in equation (2) is determined from the following expressions:

$$S_i = \frac{1}{2}\left[\left(S_i^L\right)_{0^\circ} - \left(S_i^L\right)_{180^\circ}\right] \quad (3)$$

$$T_i = \frac{1}{2}\left[\left(T_i^L\right)_{0^\circ} - \left(T_i^L\right)_{180^\circ}\right] \quad (4)$$

2 where 0° and 180° - subscripts show the value of each stress component on the corresponding planes of the model; L - superscript denotes stresses due to applied external loads. - this is the average value of the sum of the normal components of alternating stresses in each node, determined by the formula

$$J_1^M = \frac{1}{2}\left[\left(S_x^L + S_y^L + S_z^L\right)_{0^\circ} + \left(S_x^L + S_y^L + S_z^L\right)_{180^\circ}\right] \quad (5)$$

where are the components of normal stresses at the nodes of the radial plane on which the load acts (at 0°); are the components of normal stresses at the nodes of the radial plane rotated by 180°; - this is the sum of the normal components of residual (static) stresses in each node, due to heat treatment, which is determined from the following expression

$$J_1^R = S_x^R + S_y^R + S_z^R \quad (6)$$

is the sum of the normal components of the mounting (static) stresses due to interference fit in each node:

$$J_1^P = S_x^P + S_y^P + S_z^P \quad (7)$$

In accordance with the criterion equation (8), the Sainz parameter (SP) is calculated at each node of the model for four combinations of load cases presented in Table 2, according to the following formula:

$$SP = J_2' - \left[A - \propto\left(J_1^M + J_1^R + J_1^P\right)\right] \quad (8)$$

where A = 28 ksi (193 MPa) and $\propto = 0.16$ are constants established experimentally.

The fatigue resistance margin is estimated for each load combination by determining the coefficient in each node by which it is necessary to multiply the values of external loads so that the Sainz parameter becomes equal to zero. According to the results of the calculation of the scope of the wheel, taking into account the margin of fatigue resistance for the required need. The results obtained using the Sainz criterion for combined loads turned out to be in the form of contour diagrams on the transverse cross section of the wheel (Figure 5). Negative values of the Sainz parameter (SP < 0) are maintained for stable fatigue resistance criteria, in case of positive signs, restoration of the structure is recommended.

Table 2 - Combination of loads for evaluation by the Sainz criterion

Load Combination				
A	Load case 1	Load case 1	Load case 5	Load case 7
B	Load case 2	Load case 2	Load case 5	Load case 7
C	Load case 3	Load case 3	Load case 6	Load case 8
D	Load case 4	Load case 4	Load case 6	Load case 8

Note: Combinations of load options when calculating stress intensity are shown in the table

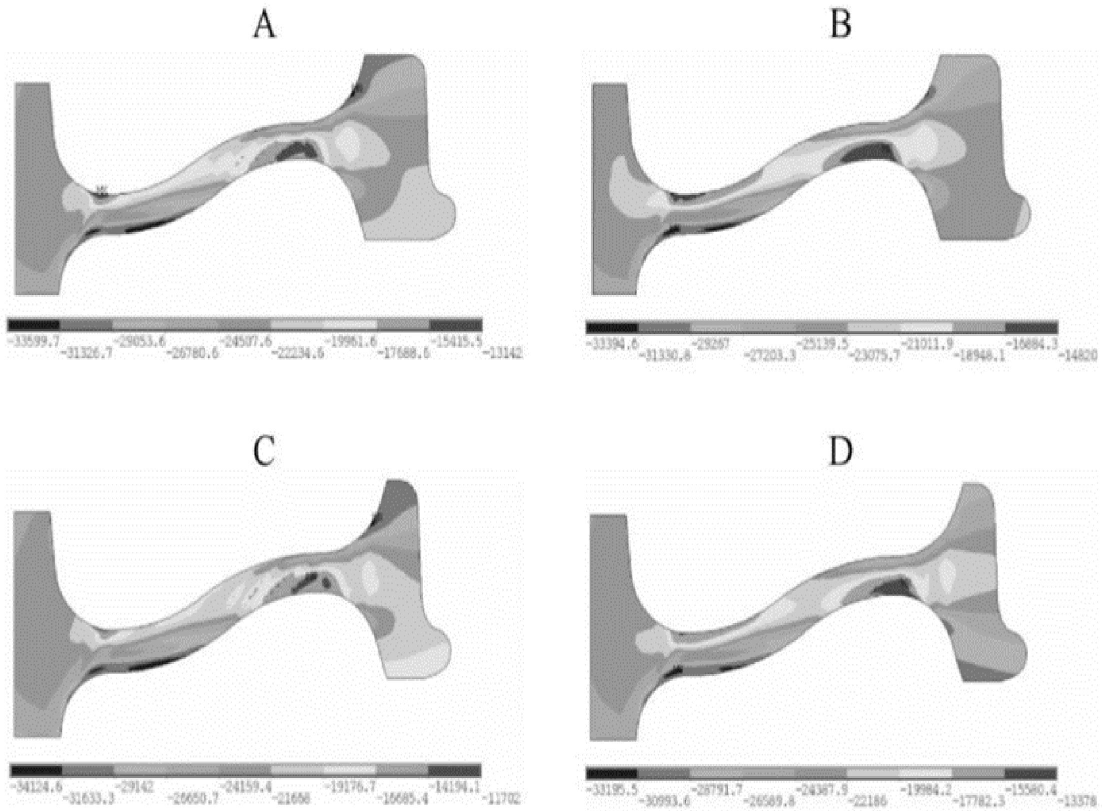

Figure 5 – Distribution of values of the Sainz parameter (psi) in the cross section of the locomotive wheel according to load combination schemes

In contrast to the American approach to assessing the strength of solid-rolled railway wheels, the European and Russian procedures for admitting wheels to operation, in addition to finite element calculations, provide for mandatory bench tests. The factual basis for the admission of a new design of solid-rolled wheels for supervised operation to the European railway network is the satisfaction of the criteria (Table 3) of thermomechanical and mechanical assessments. A graphic representation of this procedure is shown in Figure 6.

Table 3 - Criteria for evaluating the thermomechanical properties of the wheel during bench full-scale tests under conditions of long-term braking

Evaluation criterion	New rim	Worn rim
Maximum lateral deformation of the rim during braking	+3/-1 mm	
Maximum lateral deformation of the rim after completion of the test (permanent deformation)	+1,5/-0,5 mm	
The level of residual stresses in the rim after cooling for steel grades ER6 and ER7 (σrw, - the average value of three measurements; σiw - the value of each measurement)	Σ_{rw}<200 MPa; σ_{iw}=250 MPa	Σ_{rw}<275 MPa; σ_{iw}=300 MPa

In practice, if the thermomechanical properties of the wheels deviate from the specified criteria during bench tests, the second and third stages of evaluation associated with tests on the railway section during long-term braking are usually not carried out. The reason for this is the high cost of the procedure for admitting such wheels to operation in the absence of competitive advantages in terms of resistance to thermal loads, which were identified at the first stage of the thermomechanical assessment. The evaluation of the mechanical properties of the wheels consists of two stages. The first stage consists in carrying out a finite element analysis of the stress state of the wheel structure for three typical loading schemes shown in Figure 7.

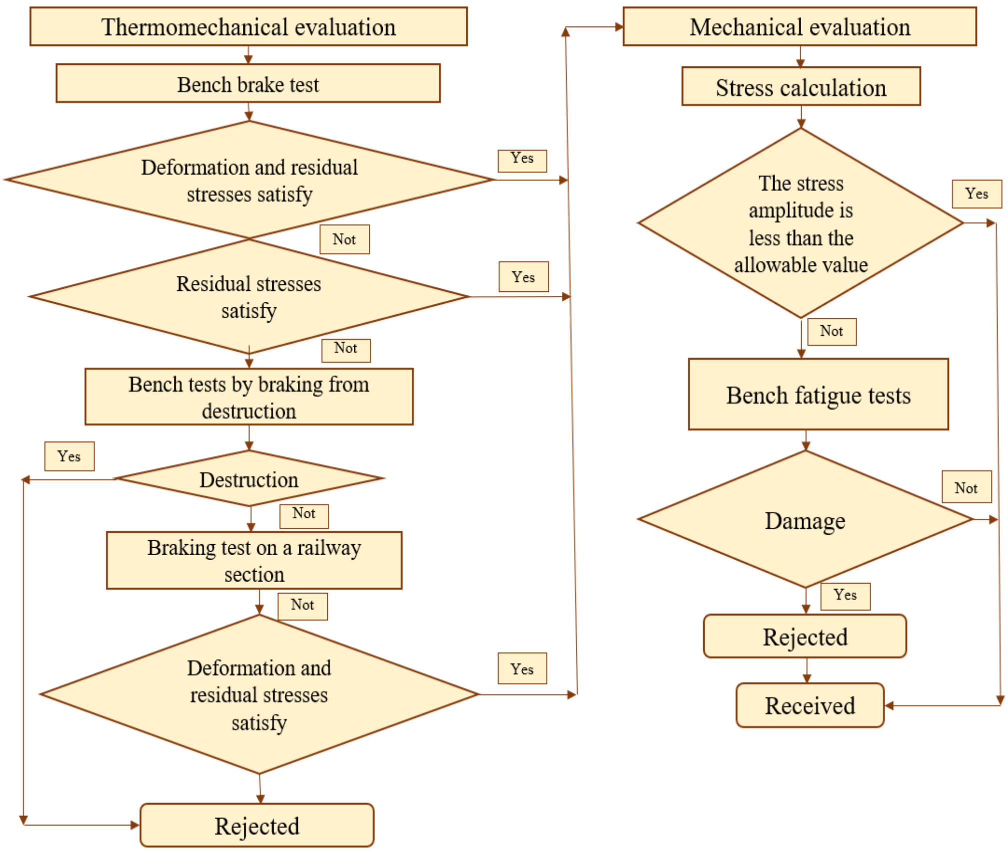

Figure 6 - The procedure for the admission of solid-rolled wheels for operation on the network of European railways according to [1]

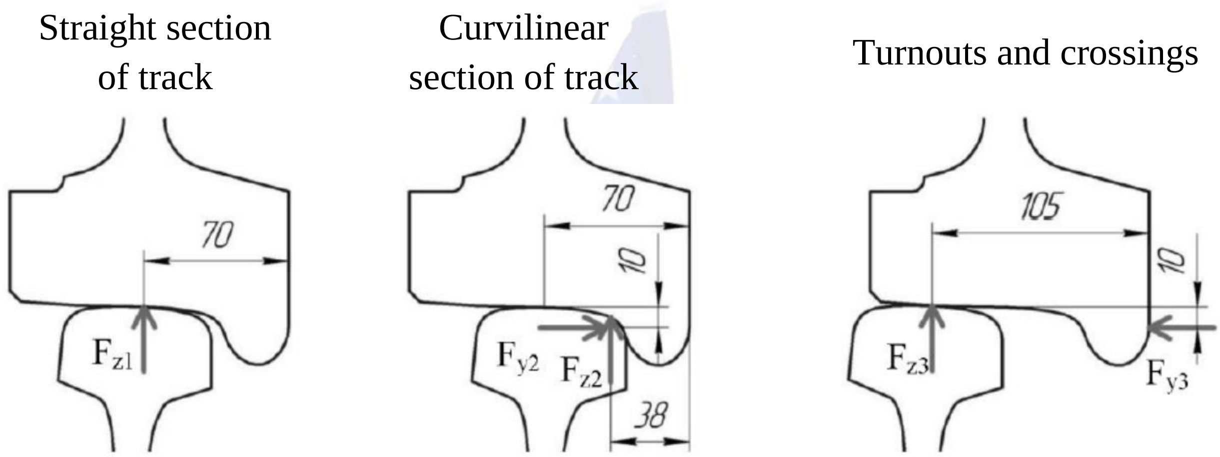

Figure 7 - Scheme of the application of forces during the calculation of stresses according to [1, 14]

The values of loads on the wheel when interacting with the rail are determined in proportion to half of the static load on the axle of the wheelset (P) according to the following formulas:

$F_{z1}=1.25P$

$F_{y1}=0$

- curved section of the track (the flange of the wheel rim touches the rail)

$F_{z2}=1.25P$

– for non-motorized wheelset

$F_{y2}=0.6P$

– for motorized wheelset

$F_{y2}=0.7P$

- turnouts and crossing of tracks (interaction of the inner side of the wheel rim flange with the counter rail):

$F_{z1}=1.25P$

– for non-motorized wheelset

$F_{y2}=0.6$ Fy2=0.36P

– for motorized wheelset

$F_{y2}=0.6$ Fy2=0.42P

ВЫВОДЫ

Thus, the margin of wheel fatigue resistance in s [1, 13] is important for evaluating stress cycles that have a degree of compliance with overestimation of various load patterns, and not for a load that changes cyclically depending on the rotational speed at a given contact voltage frequency. Interaction of wheels with rails, which is typical when performing calculations according to the methods [2] and [7]. Considering the domestic calculation and experimental method for estimating the wheel fatigue resistance margin, we can note that it is comparable with the standard 8–669. However, the absence of a description of the parameters in it for calculating the level of residual stresses of solid-rolled wheels, as well as thermal stresses caused by heating of the rim during friction with brake pads, can lead to an incorrect assessment of the value and position of the minimum fatigue resistance margin, in the case when there is no experimental possibility of them. definitions.

LIST OF USED SOURCES

1. EN 13979-1:2003+A2. Railway applications – Wheelsets and bogies – Monobloc wheels – Technical approval procedure – Part 1: Forged and rolled wheels [Text]. - European committee for standardization, 2011. - 50 p.
2. Standard S-669. Analytic Evolution of Locomotive Wheel Designs [Text]. – AAR Manual of Standards and Recommended Practices. Wheels and Axles, 2011. - P. 125-142.
3. Kanaev, A. T., Bogomolov, A. V., Kanaev, A. A. Improving the wear resistance and strength of wheel steel by plasma hardening // Science and Technology of Kazakhstan. - No. 2. - 2018. - P. 37–44.
4. Kiselev, S. N. Control of the parameters of heat treatment of wagon wheels based on computer simulation [Text] / S. N. Kiselev, A. S. Kiselev, I. A. Martyanova, A. N. Neklyudov // Control. Diagnostics. - 2002. - No. 12. - S. 19–23.
5. Kuhlman, C. The significance of material properties on stresses developed during quenching of railroad wheels [Text] / C. Kuhlman, H. Sehitoglu // Proceeding of the 1988 Joint ASME IEEE Railroad Conference. - Pittsburgh (Pennsylvania, USA), 1988. - P. 55–63.
6. Vainoryute, V. V., Dychko, I. N., Bogomolov, A. V. Development of technology for obtaining blanks for railway wheels on the basis of Prommashkomplekt LLP // Science and Technology of Kazakhstan. - No. 1. - 2018. - S. 41-51.
7. GOST 32.83–97. Wheels with disk and spoke centers of traction rolling stock [Text]. - M. : MPS of Russia, 1997. - 49 p.
8. GOST 10791–2011. Wheels are solid. Specifications [Text]. - Input. 2011–07–01. - M. : Standartinform, 2011. - 27 p.
9. Specification M - 107 / M - 208. Wheels, Carbon Steel. – Manual of Standards and Recommended Practices. Wheels and Axles, 2011—P. 21–60.
10. EN 13262:2004 +A2. Railway applications - Wheelsets and bogies - Wheels - Product requirements [Text]. - European committee for standardization, 2011. - 47 p.
11. GOST R 54093–2010. Wheels of railway rolling stock. Methods for determining residual stresses [Text]. - Input. 2011–07–01. - M. : Standartinform, 2011. - 15 p.
12. Mussina, Zh., Abisheva, M. Magnetic non-destructive examination methods // Science and Technology of Kazakhstan. – No. 3–4. - 2016. - S. 116-119.

13. UIC 510-5. Technical approval of monobloc wheels Application document for standard EN 13979-1. 2nd edition [Text]. - International Union of Railways (UIC), 2007. - 67 p.
14. Standard S-660. Wheel Designs, Locomotive and Freight Car – Analytic Evaluation [Text]. – AAR Manual of Standards and Recommended Practices. Wheels and Axles, 2009—P. 103–108.
15. McKeigan, P. C. Fatigue Performance of AAR Grade B Wheel Sleel at Ambient and Elevated Temperatures [Text] / P. C. McKeigan, F. J. McMaster, and J. E. Gordon // ASME Paper IMECE2002-33240, 2002.