Accounting Method for Residual Technological Stresses in Modeling the Stress-Deformed State of a Railway Wheel Disk. Report 1

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Abstract—The work is devoted to the development of a method for accounting residual technological stresses in wheel disks, which will provide both the versatility of the approach and the accuracy of calculations. The analysis of stresses in the wheel disk from the action of assembly (interference between the hub and the axle) and operational loads is carried out based on the results of finite element modeling. Adequacy verification of the used model was made by comparing the calculated information with the experimental data of JSC “VNIIZHT”. The analysis of calculated and experimental values of radial stresses was carried out for the most loaded (critical) zones of the disk during operation—the zones of its interface with the rim and the hub. It was found that by setting the interference fit value to be greater than the actual one, it is possible to obtain the formation of additional stresses in the wheel, which, with a sufficient degree of accuracy, reflect the effect of residual technological stresses on its stress–strain state. On the example of calculating a wheel with a flat-conical disk (GOST 10791–2011), it is shown that an increase in the interference fit value by 60% (from 0.25 to 0.4 mm per diameter) makes it possible to adequately predict the magnitude of stresses in the most critical disk elements. The maximum relative deviations of the calculated values of radial stresses from the experimental ones, both along the outer and inner sides of the wheel, do not exceed 14%. Despite the simplicity of implementation, the proposed method provides an increase in the accuracy of predicting the strength characteristics of wheels, as well as the possibility of using it for various standard wheel sizes.

Keywords: railway wheel, stress-strain state, operational loads, finite element modeling, stresses in disk, residual stresses, interference between hub and axle, wheel disc

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INTRODUCTION

An increase in the service life of railway wheels is a relevant fundamental and practical problem [1–26]. Effectiveness of its solution mainly depends on the accuracy of prediction of the stress–strain state (SSS) of the wheel discs under operational loads [4, 12–26]. One of essential aspects is the demand to consider residual stresses, which arise in stamped-rolled wheels at various stages of their production and inevitably induce corresponding changes of the SSS of wheel discs, the strength of which affects significantly the operational life of the wheel [12, 13, 21, 24, 25].

Under contemporary conditions, analysis of the SSS of wheels at different loading schemes is carried out in the systems of computer-assisted finite-element modeling according to the special procedures mentioned by corresponding regulatory documents [14–25]. In this case, the types of both mechanical and thermal loads employed in various procedures are generally similar; however, their values can differ notably [24]. This fact can be rationalized by specific operating conditions of wheels (surface relief, operational characteristics of railway line, and others), which are intrinsic for different regions of the world [27]. However, such an important factor as residual technological stresses, which always arise in stamped-rolled wheels, regardless of the technology of their production, are not always assumed [21, 24, 25].

It should be noted that the calculation of residual stresses in disc is quite a difficult problem, because primary field of residual stresses arises in wheel during its cooling after press-rolling train. Then, it changes upon subsequent operations of thermal and mechanical treatment procedures of wheel and occasionally strengthening treatment of wheel by shot. In this case, it is known from the experience of wheel production that there is irreversible change of wheel sizes during the mentioned operations. These changes would differ even in the wheel within one batch, which is related to
the technologically allowable variation of sizes of rough wheels within tolerances.

During the calculation of the field of residual technological stresses in the finished wheel, assumption of a large number of factors, which govern the demand of multiple-stage modeling of the physical processes in metal, is necessary [21, 24, 28–30]. In this case, several mathematical models and a large set of material’s characteristics should be used, which are necessary for modeling of interface transformation, elastoplastic strain, and heat and mass transfer. The corresponding base of experimental information for the correct specification of initial and boundary conditions for the solution of boundary problems, as well as for evaluation of the validity of the results of modeling of mentioned technological operations, is also necessary.

These facts complicate the interpretation and compatibility of the results obtained at various stages of modeling and also significantly complicate the refinement of the whole model. Therefore, this approach obviously did not become widespread in engineering practice and corresponding regulatory documentation. Therefore, the aim of this work is to develop the method for the assumption of residual technological stresses in the discs of railway wheels, which provides a versatility of the approach and accuracy of calculations upon modeling of the SSS of the discs of railway wheels.

**PROCEDURE OF STUDY**

It is known [13, 31, 32] that residual technological stresses induce the stresses in the surface layers of disc, which can differ significantly by the magnitude and sign depending on the type and modes of finishing works. The finite-element modeling of the SSS of wheels at each stage of finishing works is quite difficult as was mentioned above.

Before operation, wheels are pressed in the axle with interference. This operation induces additional stresses of different signs and magnitudes, which are given in Fig. 1. In this case, modeling of the SSS of the wheels with the assumption of interference between the hub and axle is not difficult.

Analysis of existing data [13, 31, 32] allows one to state that additional stresses arising from the interference between the hub and axle could be similar to residual technological stresses in the discs of railway wheels. Thus, it can be suggested that one can expect the appearance of additional stresses in wheels, which could reflect to a sufficient accuracy the effect of residual technological stresses on the SSS of the wheel disc by setting the interference value slightly higher than necessary upon modeling.

In order to verify this hypothesis, the construction of wheel with the diameter of 957 mm with flat-conical disc [33], which is employed most frequently on the railroads of CIS countries and characteristics of which are studied in most detail at the moment, was chosen.

Analysis of the SSS of wheel was carried out through finite-element modeling in the DEFORM 3D system. In this case, the 3D problem was solved for 1/2 of wheel. Accuracy of modeling of the geometry of wheel and assumption of nonuniform stress distribution in wheel upon its loading were provided by refinement of the grid of finite elements in the range of 1.5—
4.5 mm in the zones of circumference arcs of disc, as well as the arcs of coupling of disc with the rim and hub. Calculations showed that subsequent refinement of grid is unreasonable, because this improves the results by less than 5 MPa with a significant increase in the computational time.

The wheel material was chosen from the DEFORM 3D library and corresponded to high-carbon steel, with the Young’s modulus of 210 GPa and the Poisson’s ratio of 0.3. The type of object is elastic.

The finite-element modeling procedure was adapted to the conditions of experimental studies of the SSS of the wheel in AO “Research Institute of Railway Transport” (VNIIZhT) on a special test machine [16]. Following was considered:

— rigid closing of hub;
— interference upon pressing of wheel in the axle;
— machining of the rim up to the thickness of 22 mm.

The interference value between the hub and axle was 0.25 mm per diameter [34].

Verification of the validity of the employed finite-element model was performed through the comparison of the calculated information with the experimental data from AO VNIIZhT in the case of the application of vertical load of 800 kN to the wheel flange. In this case, the radial stress values in the disc along outer and inner surfaces of the wheel were compared (Fig. 1).

RESULTS

Comparison of calculated and experimental values of radial stresses (Table 1) was performed for the most loaded (critical) disc zones upon operation. These represent the zones of its coupling with rim and hub. To obtain more unbiased and detailed information, the stress values were recorded from the outer and inner sides of wheel at four points, with two points per each critical zone of disc (Fig. 2).

Analysis of the modeling results (Table 1) showed that the calculated stress values fundamentally (stress sign) agree with the experimental data. However, Table 1 shows that the maximum deviations are quite notable and provide deflated estimate of stresses in the critical zones of disc.

A series of analogous calculations with various interference values established that setting the interference value of 0.4 mm per diameter for this type of wheel and loading conditions (that is, 60% higher than required) provide a good agreement of calculated and experimental values of stresses not only at qualitative,

| Point no. | Experimental stress value, $\sigma_e$, MPa | Calculated stress value, $\sigma_t$, MPa | Relative deviation, $\Delta = \frac{|\sigma_e - \sigma_t|}{\sigma_e} \times 100\%$ |
|-----------|------------------------------------------|----------------------------------------|----------------------------------|
| 1         | -472                                     | -471                                   | 0.2                              |
| 2         | -802                                     | -804                                   | -0.2                             |
| 3         | 345                                      | 285                                    | 17.4                             |
| 4         | -11                                      | -11.2                                  | -1.8                             |
| 5         | -318                                     | -280                                   | 11.9                             |
| 6         | 375                                      | 373                                    | 0.5                              |
| 7         | -250                                     | -228                                   | 8.8                              |
| 8         | 30.4                                     | 22.6                                   | 25.7                             |

Table 1. Results of comparing the calculated values of radial stresses in the disk, obtained from vertical load on the flange and interference fit of 0.25 mm, with experimental data

| Point no. | Experimental stress value, $\sigma_e$, MPa | Calculated stress value, $\sigma_t$, MPa | Relative deviation, $\Delta = \frac{|\sigma_e - \sigma_t|}{\sigma_e} \times 100\%$ |
|-----------|------------------------------------------|----------------------------------------|----------------------------------|
| 1         | -472                                     | -483                                   | -2.3                             |
| 2         | -802                                     | -820                                   | -2.2                             |
| 3         | 345                                      | 296                                    | 14.2                             |
| 4         | -11                                      | -12.2                                  | -10.9                            |
| 5         | -318                                     | -334                                   | -5.0                              |
| 6         | 375                                      | 386                                    | -2.9                              |
| 7         | -250                                     | -256                                   | -2.4                              |
| 8         | 30.4                                     | 34.3                                   | -12.8                            |

Table 2. Results of comparing the calculated values of radial stresses in the disk, obtained from vertical load on the flange and interference fit of 0.4 mm, with experimental data
but also at quantitative level (Fig. 3, Table 2). In addition, comparison of Tables 1 and 2 shows that there is upper estimate of stresses in the critical zones of disc, which is certainly a positive result.

Thus, setting the higher interference value between the hub and axle upon modeling provides additional stresses in the wheel, which reflect to a sufficient degree of accuracy the effect of residual technological stresses on the SSS of wheel disc.

CONCLUSIONS

The method of the assumption of residual technological stresses has been developed from modeling of the SSS of the discs of railway wheels. The method idea involves the specification of the larger intere-
ence value between the hub and axle than real value. This results in additional stresses in wheel, which reflect to a sufficient accuracy the effect of residual technological stresses on the SSS of the wheel disc.

Example calculation of the SSS of the wheel with flat-conical disc (GOST 10791–2011) has shown that an increase in the interference value between the hub and axle by 60% (from 0.25 to 0.4 mm per diameter) could adequately predict the stress values in the most loaded disc zones upon operation. The maximum relative deviations of the calculated values of radial stresses from experiments results both along outer and inner sides of wheel are less than 14%.

Practical implementation of the suggested method is sufficiently simple and does not require large-scale theoretical and experimental studies. In this case, the method increases the accuracy of prediction of strength characteristics of wheels, as well as the versatility of the approach, more specifically, the possibility of its use for various typical sizes of wheels.

CONFLICT OF INTEREST
The authors declare that they have no conflicts of interest.

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