Numerical Model for Fast Predicting of Residual Stresses in Hot Rolled Profiles

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1. Introduction

The influence of residual stresses in hot rolled products on their geometric dimensions, strength characteristics, material behavior during cutting and welding has been noted by researchers since the middle of the last century [1]. At present, due to the progress in civil and mechanical engineering, the importance of this problem has only increased [2]. For these reasons, beyond the demands regarding product microstructure, properties, and dimensions, the manufacturers of hot rolled profiles are interested also in the reduction of the level of residual stresses.

Cooling conditions after rolling are the main factor affecting the residual stresses. Beyond the thermal expansion, dilatation due to phase transformations is of particular importance. The influence of phase transformations has to be considered in two aspects – the thermal effect of the transformation and the non-linearity of thermal deformation. Moreover, the dependences of Young's modulus, flow stress, and stress relaxation on the temperature have a significant effect. The solution of the boundary value problem of the prediction of residual stresses is usually associated with the three-dimensional coupled thermomechanical problem solved by the FEM. In some cases (for example, if optimization is required), this is unacceptable due to the high costs of calculation. The paper proposes an alternative approach based on simplifying the description of the stress state in the profile.

2. Concept of the numerical model

The work consists of three parts. In the first, a numerical model of residual stresses is proposed. The mechanical part of the model is based on the representation of the profile as a system of bars connected at the ends. Thus, only longitudinal stresses in the profile are taken into account. This avoids solving the mechanical problem by the FEM and significantly speeds up the calculations. An elastic-plastic model of the material, which takes into account both the active load and the unloading when the temperature is equalized over the profile section is used. The thermal problem is solved for the cross-section of the profile using the FEM.

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The second part of the work is devoted to the development of the necessary material models: the dependence of Young's modulus, yield stress, phase transformations, and stress relaxation on temperature. Material model calibration was based on experimental tensile tests performed at different temperatures in the IMZ. Equipment used for testing is Zwick /Roell Z100, tests were performed according to PN-EN ISO 6892-2:2011 standard. To create a model of phase transformations, an approach based on modified Leblond model was used, which significantly accelerates the calculation of the kinetics of phase transformations. This approach improves the quality of the prediction of the phase composition of the material comparing to the JMAK approach. All models were calibrated based on appropriate mechanical and dilatometric tests on a range of steels.

The third part of the work is devoted to validation of the obtained model by comparing the calculation results with the measured residual stresses in the profiles. Practical application of the model to optimize the cooling process of the profiles under production conditions recapitulates the work.

3. Examples of calculations

The first variant of the calculation was made for air cooling of a round profile with a diameter of 50 mm made of steel 20MnCr5. The initial temperature was 970°C (it corresponds to the temperature of the metal in the last rolling pass). The calculated temperature-time curves for the surface and center of the profile are shown in Figure 1,a. The corresponding stress curves are shown in Figure 1,b.

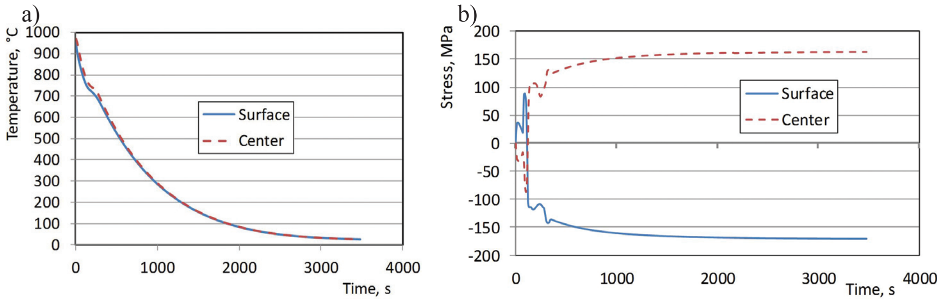

Figure 1. Modeling of the cooling of a round profile: (a) temperature; (b) longitudinal stress.

At the initial stage of cooling, tensile stresses arise on the surface of the profile due to a decrease in the volume of the cooled surface layers of the material. In this case, compressive stresses appear in the inner layers. If only elastic deformations occurred in the material, then when the temperature equalized, the stresses would disappear. However, elastic-plastic deformations occur in the material. The plastic component of thermal deformation changes the physical dimensions of metal volumes. Therefore, with the subsequent equalization of temperature, the signs of stresses change to the opposite. Thus, in a material with an initial zero stress level, after cooling compressive stresses are formed on the surface and tensile stresses in the center.

The influence of the phase transformation is exposed in the nonmonotonicity of the stress-time curves in Figs. 1b. In this calculation, the phase transformation coincides in time with the change in the stress sign. For this reason, the nonmonotonicity of the stress versus time curve occurs both before and after the change in the sign of the stress.

Measurement of residual stresses in this profile was performed in IMZ in laboratory conditions (see Figure 2). Experimental results confirms compressive residual stresses on profile surface and average value of experimental stresses (142 MPa) was very close to calculated value (155 MPa).

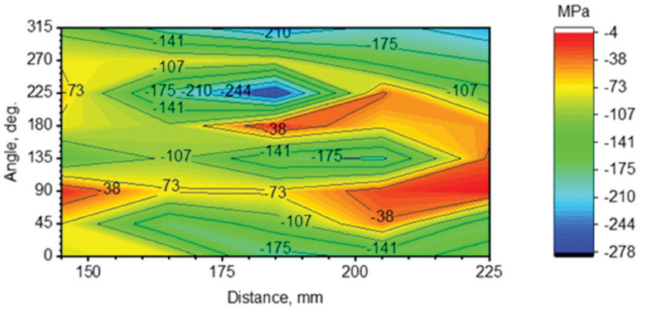

Figure 2. Measurement of longitudinal stress after cooling process.

In the next simulation, the model was verified on the example of an asymmetric profile. Cooling parameters and material model are taken as in the previous calculation. In this case, the classical patterns of the formation of residual stresses are also observed (Figure 3). At the first stages of cooling, the thin parts of the profile cool faster, and tensile stresses arise in them (see Figure 3, a). Next, the process of temperature equalization begins and the stress changes sign (see Figure 3,b).

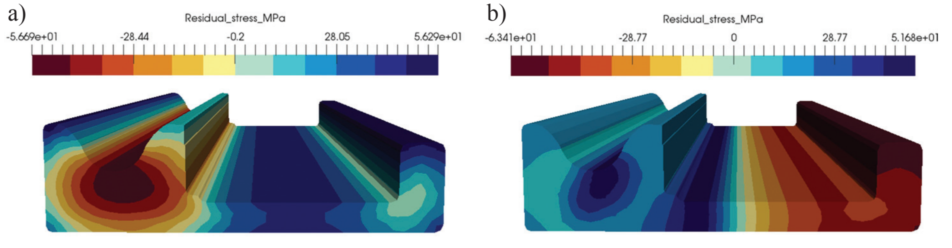

Figure 3. Modeling of the distribution of longitudinal stress on initial stage of cooling (a) and final distribution of residual stresses (b).

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