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Original Research Article

Numerical modeling and experimental identification of residual stresses in hot-rolled strips

A. Milenin [a], R. Kuziak [b], M. Lech-Grega [c], A. Chochorowski [d], S. Witek [a,*], M. Pietrzyk [a]

[a] AGH University of Science and Technology, al. Mickiewicza 30, Krakow 30-059, Poland
[b] Institute for Ferrous Metallurgy, ul. K. Miarki 12, 44-1200 Gliwice, Poland
[c] Institute of Non-Ferrous Metals in Gliwice, Light Metals Division, ul. Pilsudskiego 19, 32-050 Skawina, Poland
[d] ArcelorMittal Poland S.A, Unit in Kraków, ul. Ujastek 1, 30-969 Kraków, Poland

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ABSTRACT

The problem of calculations and experimental validation of residual stresses in hot-rolled strips is considered in the paper. Residual stresses become of practical importance when the laser cutting of strips is applied. The goal of this paper is development and experimental validation of a model of residual stresses in hot-rolled strips based on the elastic–plastic material model. The models of elastic–plastic deformation during cooling of hot rolled strips during laminar cooling and in the coil were developed. Elastic–plastic properties of the material were determined experimentally using tests on GLEEBLE 3800. Industrial testing of residual stress in strips after cooling in coil was performed. For measurement of residual stress in strips the X-ray diffraction method was used.

1. Introduction

Numerical prediction of residual stresses become of practical importance when the laser cutting of strips is applied [1]. High values of residual stresses lead to deformation (bending and twisting) of strips during laser cutting. In consequence, it is not possible to get strips with straight edges. For this reason, beyond the demands regarding product microstructure, properties and dimensions, the manufacturers of strips are interested also in reduction of the level of residual stresses.

Using the experimental methods for measurement of residual stresses for solving this problem is difficult [2]. The measurement of residual stress requires performing an experimental rolling and cannot be used during the design of a technology. Indeed, experimental methods allow estimating only the resulting value of residual stresses, but they cannot monitor the history of the process and cannot find the reasons of formation of these stresses. For these reasons, methods of calculation of residual stresses in strips become important.

Existing research on the calculation of residual stresses in strips can identify significant factors, which influence these stresses [3]. The main factors are:

1. The non-uniform distribution of elastic–plastic deformations in the volume [4];
2. Unloading of the material during cooling [5];

* *Corresponding author*. Tel.: +48 126173866.
E-mail address: switek@agh.edu.pl (S. Witek).
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3. Phase transformation occurring during cooling [6], which affect the temperature of the strip, and also lead to nonlinearity of thermal deformation;
4. Temperature dependence of the elastic–plastic material properties;
5. Stress relaxation phenomenon at high temperatures.

Relaxation affects the residual stresses in three ways:

- When interpreting the results of measurements of elastic–plastic characteristics of the material at high temperatures;
- When evaluating the effect of the amount of deformation during rolling on the residual stresses;
- During the appearance of stresses in the strip in laminar cooling and coiling processes [7].

Thus, some of these factors are taken into account by the research material, while other factors may be the subject of calculation and optimization.

The problem of calculation of residual stresses is generally solved by using the finite element method (FEM) and commercial programs [8]. The following difficulties occurred in such approach:

- Increase of the calculation time, which does not allow to use the model in the control system of the rolling mill;
- Limited accuracy of results.

The latter is connected to the fact that it is difficult to use sufficiently fine mesh when solving three-dimensional boundary problem by FEM. On the other hand, one may assume that only longitudinal stresses have a significant influence in the rolled strips. This allowed to simplify the problem and to solve it using fast computing models.

The present solution is based on rod models of residual stresses in hot rolled profiles, which was proposed in the works [9,10]. In these models profile is considered as a system of rods interconnected at the ends. In such a system only longitudinal stresses may arise. The whole system of rods in the longitudinal direction has a total deformation, which is determined from the equilibrium conditions of the rods. A similar approach is used in the paper [11] to plate distortion prediction model.

Thus, since the conclusion that the longitudinal residual stresses in hot-rolled strips are considerably higher than those in the transverse direction was confirmed, it was possible to develop a model for fast calculation of residual stresses. The goal of this paper is development of such simplified model of residual stresses in hot-rolled strips and experimental validation of this model in the industrial conditions.

2. Thermo-mechanical model of residual stresses in hot-rolled strips

Considered technological process includes:

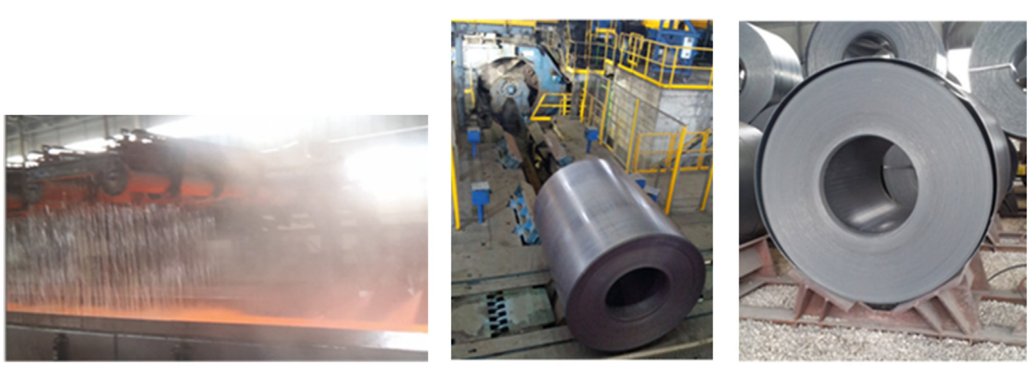
- Rolling in the roughing reversing stand,
- Rolling in the continuous finishing stands,
- Laminar cooling of the strip alternated with air cooling,
- Coiling of the strip and cooling of coils.

The process of formation of residual stresses during laminar cooling (Fig. 1a), coiling of coils (Fig. 1b) and cooling of the strip in the coil (Fig. 1c) has been considered.

2.1. *Assumptions of model*

The proposed numerical model of residual stresses in strips is composed of mechanical and thermal parts. The mechanical model is based on the assumption that all components of the stress tensor except tension along the length of the strip are zero. Verification of this assumption was performed by an experimental study of residual stresses in strips rolled in industrial conditions. The X-ray diffraction method was used for measurement of the residual stresses in strips. Fig. 2 shows the distribution of stresses in longitudinal and transverse direction across the width of the strip near the edge. As can be seen from these results, the deviation of transverse stresses from the zero level is comparable with the error of the stress measurement. This confirms the validity of the assumptions proposed above.

The next assumption concerns the influence of stresses arising during rolling on the total value of residual stresses. It is shown in [7] that an intensive stress relaxation occurs in the finishing rolling at temperature of about 900 °C. It allows



(a) (b) (c)

Fig. 1 – Stages of industrial process which take into account in model: (a) laminar cooling; (b) coiling; (c) cooling in coils.