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Original Research Article

Numerical analysis of temperature and residual stresses in hot-rolled steel strip during cooling in coils

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ABSTRACT

The main factors influencing on the level of residual stresses in hot rolled steel strips are related with uneven temperature and microstructure changes during cooling on the run-out table and in a coil. That is why in this work, development of coil cooling model with taking into account the influence of radial stresses on the effective thermal conductivity in the radial direction was performed. In order to assess the influence of the phase transformations in the coil on the level of residual stresses, the different laminar cooling strategies were applied. The results of numerical simulations obtained in this work were validated in industrial conditions. It is shown that the end of phase transformations in the strip coil has a significant influence on the level of residual stresses.

1. Introduction

The production process of hot-rolled steel strip is a complex process which incorporates the five major stages: heating the slab in the reheating furnace, deformation in the roughing and finishing mill, cooling on the run-out table (ROT), and coiling for an easier transportation. To obtain the required quality and properties of steel strip, strictly controlling the temperature and the rolling conditions is essential to produce a high-quality steel strip, free from surface and internal defects. One of important quality parameters of strip which strongly depends on the cooling process is the level of residual stresses. The residual stresses are stresses which remain in the strip after the original causes of the stresses (temperature distribution, mechanical deformation) have been removed [1]. High values of residual stresses lead to deformation (bending and twisting) of strips during laser cutting because the internal equilibrium of residual stresses fields is destroyed. As a result, it is not possible to get strips with straight edges. For this reason, the manufactures of strips are interested in reduction of the level of residual stresses.

The main factors influencing the residual stresses in hot-rolled strip are related with uneven temperature distribution across the width and includes the non-uniform distribution of elastic–plastic deformations [2], stress relaxation during roll-

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ing and cooling [3], and phase transformation occurring during cooling [4].

In the last two decades, several studies have been made for computing of residual stresses in hot-rolled steel strip for enhancing the final product quality [4–8]. Zhou et al. [4] performed a preliminary computational study of residual stresses developed during cooling on the ROT using ABAQUS software. The investigations were continued and results have been published in [5]. It was concluded that the temperature profile along the strip has little effect on residual stresses but transverse temperature gradient plays a pivotal role. In work [6], a three-dimensional FE model was established and later improved [7] to analyze the residual stresses developed during the cooling of hot rolled strip on the ROT. This model was also performed using ABAQUS software. The results showed that temperature drop within the strip edge region resulted to the development of edge waviness. To better control the flatness quality of steel strip, the strip shape compensation control strategy of slight center wave rolling and edge masking were proposed. Cho et al. [8] developed a three-dimensional numerical model to predict the edge wave behavior of hot rolled steel during ROT cooling based on FEM. The effect of the edge mask width and the checkers on the edge wave were examined through a series of process simulations.

In general, it was proved that the optimization of the cooling process allows to reduce the level of residual stresses to avoid strip flatness defects. However, the long computational time of these models does not allow to use them in the control system of the rolling mill. To solve this problem, the model of residual stresses based on fast computing methods was developed [3,9,10]. The proposed model was composed of mechanical and thermal parts that enable the modeling of thermo-mechanical and microstructural phenomena for the entire manufacturing process of strip.

A significant influence on the residual stresses is provided by cooling in a coil. This is due to the fact that cooling in the strip coil is most unevenly along the length and width of the strip. This especially affects the residual stresses in the case when the phase transformation does not have a time to complete at the laminar cooling stage on the ROT. In this case, there are two factors that increase the magnitude and uneven distribution of residual stresses. The first is associated with the generation of heat during the phase transformations in the coil. This can lead to uneven heating of the coil during the initial cooling stage. The second factor is related to the dilatation of the material during the phase transformations, which directly affects the magnitude of the stresses. Thus, in the described situation, the accuracy of the temperature model of the cooling process in the coil must be higher than is usually considered sufficient. In particular, the anisotropy of the thermal conductivity caused by the loose contact of the turns and the features of the strip surface must be taken into account. This question in the existing works is usually solved in a simplified manner [9]. Thermal conductivity in the radial direction is adopted as a part (usually in the range 0.05–0.2) of the thermal conductivity of the base material. In the presence of phase transformations during cooling in a coil, this approximation is insufficient, since the sensitivity of residual stresses to temperature increases.

Hence the objectives of the current work are twofold. The first objective is to develop and experimental validation of the coil cooling model with taking into account the key parameters influencing on the radial thermal conductivity of the coil during cooling. This model is crucial to thoroughly investigate the effect of phase transformation in the coil on the level of residual stresses, which states the second objective of the current work.

2. Numerical models

2.1. *Rods model of residual stresses*

A model to predict the residual stresses formation in hot-rolled strips during laminar cooling, coiling and cooling in the coil was presented in the article [9]. The mechanical part of that model was 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. It was shown that only longitudinal stresses have significant influence in the rolling process. That is why, in this model the profile of strip was presented as a system of rods interconnected at the ends. In addition to the thermal deformation of each rod, all the rods were exposed to the average strain of the strip ε_m that is a result of the changing of the length of the strip in the cooling process. Thus, if in the rod *i* an increment of temperature Δt and the corresponding increment of thermal deformation $\Delta\varepsilon_t$ appeared, the total increment of the deformation $\Delta\varepsilon_i$ of the rod is equal to:

$$\Delta\epsilon_i = \Delta\epsilon_m - \Delta\epsilon_t - \xi_c\Delta\tau \pm \Delta\epsilon_b \quad (1)$$

where $\Delta\tau$ is an increment of time; ξ_c is the rate of creep; $\Delta\varepsilon_b$ is an increment of deformation during coiling and uncoiling processes. The current strain of the rod *i* is:

$$\epsilon_i = \sum_{j=1}^{J} \Delta\epsilon_{ij} \quad (2)$$

where *J* is the number of increments of time, *j* is the current number of step.

The increment of the thermal deformation was determined taking into account phase transformations. This relation can be represented in a general form:

$$\Delta\epsilon_t = f\left(t, \dot{t}, \Delta t\right) \quad (3)$$

where $\dot{t}$ is the cooling rate, *t* is the temperature.

Increment of deformation during coiling and uncoiling processes can be calculated from the equation, which was obtained from geometrical interpretation of bending:

$$\Delta\epsilon_b = \frac{y}{2R_{coil}} \quad (4)$$