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A finite element analysis for asymmetric contraction after coiling of hot-rolled steel

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ABSTRACT

Asymmetric contraction during natural cooling is often observed after the coiling of hot-rolled steel, which has significantly large hardenability due to high content of carbon or other alloying elements. In this study, a finite element (FE) model incorporating transformation plasticity was used to analyze the thermo-mechanical and metallurgical behavior of hot-rolled steel during the phase transformation after coiling. The transformation plasticity was caused by a small amount of stress that develops naturally in a hot-rolled coil due to the gravity. The asymmetric contraction behavior of the coil was reproduced successfully using the FE simulation by considering the transformation plasticity. The effect of some selected process variables on the asymmetric contraction was examined through a series of process simulations.

1. Introduction

A hot-rolled steel strip is generally stocked in the form of a hollow cylindrical coil after the hot rolling process. The hot coil is cooled from 500–700 °C to room temperature over a 4–5-day period under natural air cooling conditions as presented by Park et al. (1998) and Saboonchi and Hassanpour (2007). In most hot strip rolling processes, the phase transformation of steel was finished on the run-out table (ROT) before coiling (Han et al., 2002), and the hot coil is normally cooled down but maintaining the cylindrical shape (Park et al., 2009). However, asymmetric contraction occurs in an actual mill during cooling after the coiling of hot-rolled steel, which has significantly large hardenability due to high content of carbon or other alloying elements and shows incomplete phase transformation prior to coiling, as shown in Fig. 1. This asymmetric contraction behavior is closely related to the phase transformation that occurs after coiling, and cannot be described by conventional creep behavior. This shape change in the hot coil causes acute problems in industrial applications, such as serious scratching on the strip surface during uncoiling.

In this study, the concept of the transformation plasticity was adopted to describe this asymmetric contraction behavior occurring during the phase transformation in hot-rolled steel after coiling. The transformation plasticity refers to the permanent deformation that occurs during a phase transformation of ferrous or other alloys under an applied stress, which is even lower than the yield stress of the material (Greenwood and Johnson, 1965; Han and Lee, 2002). Owing to its technological importance, several theoretical models based on continuum mechanics have been proposed to quantify the transformation plasticity phenomenon, one widely accepted description being the contribution of Greenwood and Johnson (1965). In comparison with the previous continuum-based theory, approaches, which consider the microstructural aspects of phase transformation, have also been suggested. Han and Suh (2003) and Han et al. (2004) developed a microstructure-based model using the Kurdjumov–Sachs (KS) orientation relationship between fcc and bcc to interpret the transformation plasticity phenomenon during the displacive transformation under an applied external stress. Recently, Han et al. (2007, 2008) suggested a constitutive equation for the transformation plasticity based on the diffusion mechanism of the migrating interface during the diffusional phase transformation, which can be described as accelerated Coble creep. The constitutive equation for transformation plasticity was incorporated into a general purpose implicit finite element (FE) program. In addition to thermo-elasto-plastic constitutive equations, the phase transformation kinetics was characterized by a Johnson–Mehl–Avrami–Kolmorgorov (JMAK) type equation. The validity of the proposed model was examined by reproducing the asymmetric contraction behavior of the coil. The effect of some selected process variables on the asymmetric

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Fig. 1. An example of asymmetric contraction of hot coil after coiling.

contraction was investigated through a series of process simulations.

2. Model development

2.1. Phase transformation kinetics

High carbon steel (0.82 wt.%C–0.18 wt.%Si–0.40 wt.%Mn–0.15 wt.%Cr), which has a sufficient hardenability to retain a large amount of untransformed austenite at the stage of coiling in hot rolling process, was used. The untransformed austenite in the hot-rolled coil transformed to pearlite during air cooling due to the high carbon content of the steel. The transformation kinetics for the austenite-to-pearlite transformation was characterized using a Johnson–Mehl–Avrami–Kolmorgorov (JMAK) type equation as follows:

$$X = 1 - \exp(-kt^n) \tag{1}$$

where X is the transformed phase fraction, t is the total time for the transformation at a given temperature, respectively. n is the time exponent and k is the parameter depending on the temperature and transformation mechanism.

In order to extend the JMAK equation for the austenite-to-pearlite transformation into the non-isothermal process, the concept of additivity rule was introduced under the assumption that the cooling curve can be divided into small time intervals within which the kinetics parameters in Eq. (1) are constant (Sheil, 1935). The transformed phase fraction until the i-th time step, X_i, could be expressed as follows:

$$X_i = 1 - \exp(-X_{i-1}^{ex} + \Delta X_i^{ex}), \qquad \Delta X_i^{ex} = nk_i t_i'^{\,n-1}\Delta t, \qquad t_i' = \left(\frac{X_{i-1}^{ex}}{k_i}\right)^{1/n} \tag{2}$$

where t' is the equivalent transformation time needed to transform into the fraction of X_{i-1}^{ex} at the temperature of the i-th step, and Δt is the time step corresponding to the i-th step. The constants of Eq. (2), k and n, were determined by applying an inverse additivity technique into the dilatation data obtained from the continuous heat treatment tests (Han and Park, 2001). Table 1 lists the k and n values of the austenite-to-pearlite transformation for high carbon steel. Here, C_γ is the carbon content in untransformed austenite, AGS (μm) means the prior austenite grain size and T_{eq} (K) is the equilibrium transformation temperature. D_c is the composition and temperature dependent diffusivity of carbon in austenite, and the equation assessed by Årgen (1986) was used at a given temperature as follows:

Table 1
k and n values of Eq. (2) for austenite-to-pearlite transformation of high carbon steel (0.82 wt%C–0.18 wt%Si–0.40 wt%Mn–0.15 wt%Cr).

ln(k)	n
$83.1859 + 12.5562 \ln [\sin((6.2832T)/4(T_{eq}-80))] + 1.3172 \ln(\mathrm{AGS}) + (7.5854 + 1.9038 [\%C_\gamma]^{-3.5964} - 4.4014[\%C_\gamma]^2) \ln[(T_{eq}-T)/T] + (7.6049 - 5.2261 [\%C_\gamma]) \ln D_c$	$7.6049 - 5.2261 [\%C_\gamma]$

$$D_c = 4.53 \times 10^{-7} \left\{1 + y_c(1-y_c)\frac{8339.9}{T}\right\} \times \exp\left\{-\left(\frac{1}{T} - 2.221 \times 10^{-4}\right)(17767 - y_c 26436)\right\} \tag{3}$$

where y_c depends on the mole fraction of carbon, x_c, as $y_c = x_c/(1-x_c)$. The values for C_γ and T_{eq} were calculated by thermodynamic analysis using Thermo-Calc (Sundman et al., 1985).

2.2. Heat transfer

In the thermo-mechanical analysis involving the phase transformation, consideration of the temperature increase caused by the latent heat generated by enthalpy changes during the phase transformation is quite important. The isotropic heat transfer equation is represented as follows:

$$\rho C_P \dot{T} = \nabla \cdot (k \nabla T) + \Delta H \cdot \dot{X} \tag{4}$$

where ρ, C_P and k are the density, heat capacity and thermal conductivity, respectively. ΔH and $\dot{X}$ are the heat evolution due to the phase transformation and transformation rate, respectively. Here, C_P, ΔH and $\dot{X}$ were obtained from thermodynamic and phase transformation analyses. ρ and k were determined as a function of temperature and the chemical composition of the steel using Miettinen's data (Miettien, 1995). The latent heating by the phase transformation was added to the regular thermal constitutive behavior via a user subroutine defining a thermal behavior of a material, UMATHT in ABAQUS (ABAQUS Inc., 2006). The user subroutine, UMATHT, was used with a fully integrated coupled temperature–displacement and heat transfer element. In the user subroutine, the variables to be updated were the internal thermal energy per unit mass, the heat flux and their variations with respect to temperature, and the change in the heat flux with respect to the spatial gradient of temperature.

2.3. Transformation plasticity

The transformation plasticity proposed by Han et al. (2007) was adopted. This model is based on the diffusion mechanism of the migrating interface during the diffusional phase transformation. According to this theory, it was assumed that the overall atomic flux across the phase interface is perpendicular to the interface, and that the migrating atoms are relocated to the nearest atomic sites in the transformed phase. However, when a stress is applied, the migrating atoms may move to positions where they can release the applied stress field, which induces an atomic flux along the phase interface.

Using this concept, Han et al. (2007) derived a constitutive equation describing the transformation plasticity strain rate $\dot{\varepsilon}^{TP}$ as a function of the transformation rate, temperature and applied stress