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Analysis on Shear Deformation for High Manganese Austenite Steel during Hot Asymmetrical Rolling Process Using Finite Element Method

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Abstract: Based on the rigid-plastic finite element method (FEM), the shear stress field of deformation region for high manganese austenite steel during hot asymmetrical rolling process was analyzed. The influences of rolling parameters, such as the velocity ratio of upper to lower rolls, the initial temperature of workpiece and the reduction rate, on the shear deformation of three nodes in the upper, center and lower layers were discussed. As the rolling parameters change, distinct shear deformation appears in the upper and lower layers, but the shear deformation in the center layer appears only when the velocity ratio is more than 1.00, and the absolute value of the shear stress in this layer is changed with rolling parameters. A mathematical model which reflected the change of the maximal absolute shear stress for the center layer was established, by which the maximal absolute shear stress for the center layer can be easily calculated and the appropriate rolling technology can be designed.

Key words: high manganese austenite steel; hot asymmetrical rolling; shear deformation; finite element method

High manganese austenite steel has many industrial applications due to its high toughness, excellent work-hardening characteristics as well as good abrasion resistance[1,2]. Over the past years, high manganese austenite steel has been widely used in electricity, mining, automotive and other industries. The improvement on mechanical properties of high manganese austenite steel is an important metallurgical theme, both academically and commercially. It is well known that grain refinement is an effective way to enhance mechanical properties of metallic materials from the Hall-Petch relation[3] and has received special attentions[4-7].

Recently, the asymmetrical rolling has been used for grain refinement in the processes of strip cold rolling and subsequent static recrystallization[8-10] since the circumferential velocities of the upper and lower rolls are different[11,12] and the band with large shear deformation can be formed in the rolling deformation zone[13]. The shear deformation characteristic for cold-rolled strip with the materials of Q235 and aluminum have been analyzed using finite element method (FEM) by Hao et al.[14] and Farhat-Nia et al.[15], even for the hot rolled SUS436L stainless steel by Zhu et al.[16] in the symmetrical rolling processes. However, the shear deformation characteristic for hot-rolled strip in asymmetrical rolling process, especially for the high manganese austenite steel, has not been reported till now.

In this paper, based on rigid-plastic FEM, a coupling thermo-mechanical simulation model was established for the shear deformation analysis on hot-rolled strip of high manganese austenite steel in asymmetrical rolling processes. A flow stress model of high manganese austenite steel was regressed and introduced to the finite element (FE) model. The shear stress field was obtained, and the shear stress change for three nodes in the upper, center and lower layers with rolling parameters was discussed. Finally, a mathematical model to calculate the maximal absolute shear stress of the center layer was built in the hot asymmetrical rolling process.

1 Establishment of FE Model

Due to large deformation at high temperature in the hot asymmetrical rolling process, the roll and hot-rolled strip are considered as rigid and rigid-viscoplastic materials, respectively. The width spreading is ignored due to large width-thickness ratio of the strip and two-dimensional FEM is used to establish the analytical model in that process.

1.1 Basic equations

Two main parts are involved in the analytical model: the first is the temperature computation of the strip and the rolls, and the second is the metal flow stress calculation in the roll gap to obtain the distribution of

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strain, stress and strain rate[17]. The FE formulation inside hot-rolled material is expressed as Eq. (1)[18]. The flow stress model (Eq. (2)) for high manganese austenite steel used in the FE model was regressed from the data provided by the stress-strain curves obtained in the uniaxial compression experiments on a Gleeble-3500 simulator.

$$\int_V \sigma \delta \varepsilon \mathrm{d}V + K\int_V \dot{\varepsilon}_v \delta \dot{\varepsilon}_v \mathrm{d}V - \int_{S_F} F_i \delta u_i \mathrm{d}S = 0 \quad (1)$$

$$\sigma = 279\exp\left[-2.29\left(\frac{T+273}{1\,000}\right)+2.92\right]\cdot \left(\frac{\dot{\varepsilon}}{10}\right)^{0.48\left(\frac{T+273}{1\,000}\right)-0.5}\left[1.37\left(\frac{\varepsilon}{0.3}\right)^{0.30}-0.37\left(\frac{\varepsilon}{0.3}\right)\right] \quad (2)$$

where, σ is equivalent stress, MPa; ε is equivalent strain; $\dot{\varepsilon}$ is equivalent strain rate, s^{-1}; T is deformation temperature, °C; F_i is layer tractions; u_i is the velocity field; K is the penalty constant; and $\dot{\varepsilon}_{v'}$ is the volumetric strain rate.

The samples with height of 12 mm and diameter of 8 mm were machined from the forged billet of high manganese austenite steel with following compositions (mass%): C 0.30, Si 0.45, Mn 21.16, Al 4.11, V 0.12, N 0.02 and Fe balance. The experiments were operated in the temperature range of 900−1 100 °C at an interval of 50 °C and in the strain rate range of 0.1−10 s^{-1}. The stress-strain curves of tested steels are shown in Fig. 1.

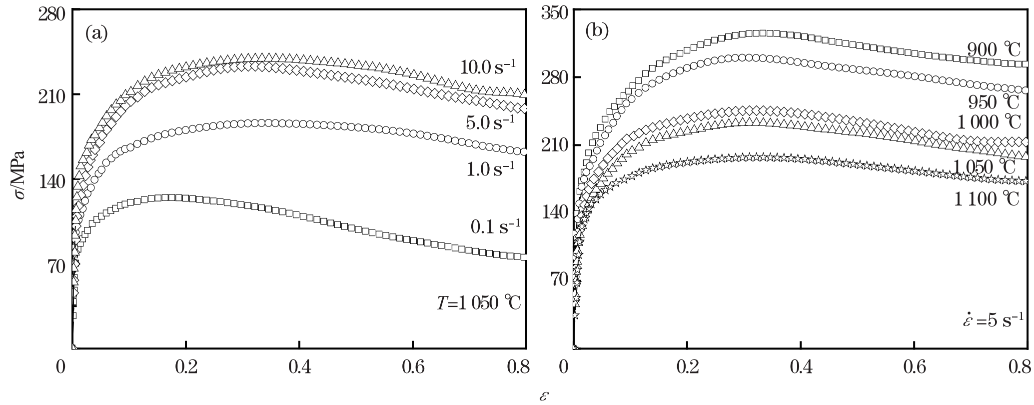

Fig. 1 Stress-strain curves of the tested steel at 1 050 °C with different strain rates (a) and at 5 s^{-1} with different deformation temperatures (b)

1.2 Parameters and FE models

Two work rolls with diameter of 160 mm and workpieces with thicknesses of 2.85, 2.68, 2.50, 2.35 and 2.22 mm are used in the rolling process. The thickness of the final strip is 2.00 mm, and the corresponding reduction rate (η) is 30%, 25%, 20%, 15% and 10 %, respectively. Different initial temperatures (T_i) of workpieces are considered as 950, 1 000, 1 050 and 1 100 °C. The velocity of upper roll is 0.20 m·s^{-1} and that of lower roll is designed as 0.20, 0.21, 0.22, 0.23 and 0.24 m·s^{-1} according to different velocity ratios (R_v) 1.00, 1.05, 1.10, 1.15 and 1.20 calculated by Eq. (3). The conversion efficiency of plastic work into heat is assumed to be about 0.95[10]. The workpiece with length (L) of 50 mm calculated by Eq. (4) is meshed as 10 elements in thickness and 200 elements in length.

$$R_v = \omega_l / \omega_u \quad (3)$$

$$L \geq 3\sqrt{R\Delta h_{max}} \quad (4)$$

where, ω_l and ω_u are the angular velocities of lower and upper rolls; R is the radius of the rolls; and Δh_{max} is the maximum thickness reduction.

The specific heat capacity (c), thermal expansion coefficient (λ) and thermal conductivity (h) of high manganese austenite steel adopted in this work were obtained by specific heat capacity tester (BRR), expansion coefficient tester (PCY-III) and high temperature thermal conductivity tester (DRXJ-II) respectively, as listed in Table 1.

Table 1 Thermophysical parameters of tested steel

T/°C	h/ (W·m^{-1}·K^{-1})	λ/ (10^{-6}K^{-1})	c/ (J·kg^{-1}·K^{-1})	ρ/ (kg·m^{-3})
20	16.1	12.0	501	
100	16.6	12.3	503	
300	17.8	15.7	506	
500	18.5	17.5	509	7 850
700	19.2	18.2	513	
900	20.2	19.2	515	
1 100	20.9	19.3	517	

The FE model for hot asymmetrical rolling was based on commercial software MSC.Marc, as shown in Fig. 2. The displacement constraint in y direction ($U_y = 0$) is applied on the nodes in the tail of the billet to prevent the billet from swinging due to asymmetrical rolling. 11 nodes named $n1$, … , $n11$ from up to down along the vertical line in the middle cross section are chosen as the analytical objects.