Simulation Research on Influence of Temperature Distribution on Deformation Permeability in Plate

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Abstract. During the plate rolling process, the deformation permeability to the inside is one of the important factors that determine the quality of the final product. The permeability capacity that determines the deformation is not only related to the inlet thickness and reduction, but also closely related to the plate temperature distribution. Based on the finite element method, the steel plate thickness, reduction and initial temperature distribution are taken as the initial conditions of the simulation, and the thermo-mechanical coupling finite element simulation is carried out for different steel grades in the paper. After the rolling is completed, the equivalent strains of different nodes are extracted in the thickness direction to obtain the influence law of the temperature gradient distribution on the deformation permeability, which provides reference for the formulation and adjustment of the production process of the plate.

1. Introduction

The production of medium and heavy plate is mostly based on continuous casting billet. In the production process of continuous casting billet, the solidification of molten steel proceeds from the outside to the center, and the solute elements are easily concentrated toward the center, which causes the center segregation and center inclusion of the slab, most of the internal defects in the plate are concentrated in this area. How to improve the central defects in the plate rolling process, and improve the mechanical properties of the plate is an important issue in the production of plate. Under the condition that the quality of the continuous casting slab is constant, the general idea of improving the central defect in the rolling process is to press some of the central defects in the plate by increasing the compression ratio of the deformation of the plate and allowing the deformation to penetrate into the core as much as possible, ultimately improve the performance of plate products.
The plate rolling process is a typical non-uniform deformation process, which is greatly affected by the outer end. Generally, the high-direction compression cannot penetrate deep into the slab, the deformation of the slab core is small, and the surface deformation is large, it has a double drum shape along the section high. In order to meet the requirements of the relevant standards for the microstructure and mechanical properties of the plate, it is necessary to ensure that the core of the plate has sufficient deformation in the rolling process, so that the internal defects of the slab can be pressed together, and fine grains are obtained in the core [1-3]. The traditional rolling process of thick plates usually adopts the method of increasing the reduction ratio of the plate. However, due to the limitation of the rolling mill capacity, the rolling reduction ratio cannot be excessively increased, and the plate with good mechanical properties of the core cannot be obtained.

In the conventional plate production line, a cooling device can be added near the rolling mill, as shown in Fig.1. In addition to the rapid cooling of the intermediate billet and the improvement of the rolling rhythm, the cooling device can also generate a certain temperature gradient on the surface and the core of the plate. Studies have shown that temperature gradient rolling (TGR) or differential temperature rolling (DTR) is another process for controlling austenite microstructures. The intermediate cooling can be used to more effectively refine the structure of the central region of the plate.

Due to the complex deformation of the plate during the rolling process, different cooling processes and reduction rates are difficult to directly calculate the core deformation of the plate. In this paper, the influence of finite element method on the plate deformation under different temperature gradients is studied. It is of practical significance to develop a reasonable differential temperature rolling process and improve the internal deformation of the plate.

2. Numerical simulation of differential temperature rolling

In order to obtain the influence of temperature gradient distribution on the deformation and permeability of plate rolling, the finite element software ABAQUS was used to model the thermo-mechanical coupling of conventional rolling and different temperature gradient rolling processes, compare and analyze metal flow and internal stress and strain distribution during rolling. In order to analyze the influence degree of different steel grades, initial thickness and reduction ratio on deformation and permeability, the following experimental scheme was established to simulate the differential temperature rolling process: the inlet thickness is 100mm, 250mm, the reduction rate is 10%, 20% and 30%, the initial temperature is 1000°C, the differential temperature condition is no differential temperature, 100°C differential temperature and 200°C differential temperature. The steel grade is carbon steel Q235 and pipeline steel X80.
Table 1 Rolling schedules

| scheme | steel grade | Inlet thickness (mm) | Reduction rate | Temperature difference (℃) |
|--------|-------------|----------------------|----------------|---------------------------|
| 1      | Q235        | 100                  | 10%, 20%, 30% | 0, 100℃, 200             |
| 2      | Q235        | 50, 100, 250         | 30%           | 0, 100℃, 200             |
| 3      | X80         | 50, 100, 250         | 30%           | 0, 100℃, 200             |

Since it is only necessary to analyze the deformation of the thickness direction of the rolled piece under different differential temperature conditions, a two-dimensional model of the rolling stock and the roll can be established in the ABAQUS. To simulate the different rolling conditions in Table 1, considering that the object studied in this paper is the hot rolling deformation process, the elastic deformation of the roll is small. To speed up the calculation, the roll is set as a rigid roll, and the roll diameter of the upper and lower rolls is 1000 mm, the speed is 25r/min, and the material of the rolling stock is Q235 and X80 steel. In ABAQUS, the contact conditions of the rollers and rolling stocks were established, the friction coefficient and temperature boundary conditions were set, and the boundary conditions such as roll rotation, initial speed and temperature of the rolling stock were established according to the actual production conditions [4-6].

The material of the rolled piece is carbon structural steel Q235 and pipeline steel X80, the density is set to 7800 kg/m³, and the Poisson's ratio is 0.3. By using the Johnson-Cook constitutive equation to describe the stress state of the material, the effect of work hardening and the temperature softening effect. As shown in Eq. (1).

\[
\sigma = (A + B\varepsilon_p^n)[1 + C \ln(\varepsilon_p/\varepsilon_0)][1 - (T/T_m)]
\]

in the formula, \(\sigma\) is the plastic stress of the material, \(\varepsilon_p\) is the equivalent plastic strain, \(\dot{\varepsilon}/\dot{\varepsilon}_0\) is the relative strain rate, \(\varepsilon_0\) is subjected to a static compression test with a strain rate of \(1/s\), \(T\) is the ambient temperature and \(T_m\) is the melting point of the material.

Table 2 Different steel grade parameters

| Steel grade | A(MPa) | B(MPa) | C     | m    | n    |
|-------------|--------|--------|-------|------|------|
| Q235        | 244.8  | 400.0  | 0.0391| 0.757| 0.36 |
| X80         | 612.0  | 1658.4 | 0.0925| 1.1  | 0.934|

The traditional Johnson-Cook model derives the parameters by fitting the curves. The values of the parameters are shown in Table 2. In the ABAQUS software, the plastic stress and strain parameters of the material represented by the Johnson-Cook constitutive equation are set. The finite element model of the simulation process is established and the appropriate elements are divided into the rolling stock. After the calculation, the stress and strain distribution of the rolled stock are analyzed in the post-processing module.

3. Initial temperature setting

For hot-rolled plate, since the amount of heat dissipation in the length and width directions is much smaller than the amount of heat dissipation in the thickness direction, the heat conduction in the length and width directions can be neglected in the simplified calculation, the heat transfer process is considered as a one-dimensional heat transfer process along the thickness of the plate [7]. The heat conduction differential equation containing the internal heat source can be expressed by the Eq. (2).
\[
\frac{\partial^2 T}{\partial y^2} + \frac{q}{k} = \frac{1}{\alpha} \frac{\partial T}{\partial t}
\]  

(2)

In the formula, \( \alpha = k / (\rho c) \) is the temperature coefficient, \( \rho \) is the material density, \( c \) is specific heat, \( k \) is the thermal conductivity.

For the third type of temperature boundary condition that gives the surface heat transfer coefficient and the temperature of the surrounding medium, see Eq. (3).

\[
k \frac{\partial T}{\partial y} + h(T - T_e) = 0
\]

(3)

In the formula, \( h \) is the heat transfer coefficient between the surface of the steel plate and the environment, \( T_e \) is the ambient temperature.

It can be seen from the temperature partial differential equation that the temperature drop of the plate mainly occurs between the outer surface and the environment. Inside the steel sheet, heat is conducted from a high temperature to a low temperature due to a temperature gradient in the thickness direction. In the thickness direction of the plate, the temperature distribution can be expressed by an elliptic equation, the surface temperature changes drastically, and the temperature of the core changes gently. In order to set the initial temperature, a parabolic approximation is applied to the temperature distribution, and the parabolic equation used is expressed by the Eq. (4).

\[
y = T_0 - ax^2
\]

(4)

In the formula, \( T_0 \) is the steel plate center temperature, \( a \) is the difference between the center and the surface temperature.

The finite element pre-processing module is used to divide the thickness direction of the plate into 10 elements, that is, the half thickness direction is 5 elements and 6 nodes, and the center temperature of the steel plate is set to 1000°C, then the Eq. (4) is used to calculate the different temperature conditions of the plate, the temperature distribution from the inside to the surface of each node is shown in Table 3, where \( T_0 \) is the center temperature and \( T_e \) is the surface temperature.

| Differential temperature (°C) | T0 (°C) | T1 (°C) | T2 (°C) | T3 (°C) | T4 (°C) | T5 (°C) |
|------------------------------|--------|--------|--------|--------|--------|--------|
| 50                           | 1000   | 998    | 992    | 982    | 968    | 950    |
| 100                          | 1000   | 996    | 984    | 964    | 936    | 900    |
| 200                          | 1000   | 992    | 968    | 928    | 872    | 800    |

4. Simulation result analysis

The finite element software ABAQUS was used to simulate the rolling schedule of Table 1 according to the initial temperature conditions. After the calculation was completed, the strain value of the thickness direction node was extracted from the post-processing module, and the influence of different conditions on the deformation penetration was analyzed.
As the inlet thickness increases, the deformation permeability of X80 is worse. Figure 2 shows the simulation results of the Q235 in the initial thickness of 100mm, the reduction rate is 10%, 20% and 30%, and the differential temperature conditions are no temperature difference, temperature difference 100 °C and temperature difference 200 °C, the equivalent strain distribution values of different nodes are taken in the thickness direction.

It can be seen from Fig. 3 and Fig. 4 that the entrance thickness of the plate has a great influence on the deformation penetration. Under the same reduction ratio, the greater the entrance thickness of the plate, the more difficult the deformation is to penetrate into the core, when rolling through large differential temperature conditions, the ability of deformation to penetrate into the interior is limited. As the plate becomes thinner, the ability of differential temperature rolling to increase the deformation of the core is gradually manifested. In the actual production of the differential temperature rolling process, the influence of the initial thickness on the core deformation should be considered, and a suitable rolling process should be selected. For the comparison of the calculation results of Q235B and X80 with different thicknesses, the deformation permeability of X80 is worse with the increase of inlet thickness.
Under the same reduction ratio, differential temperature rolling has similar effects on deformation and penetration of two steel grades.

5. Conclusion
Aiming at the plate hot rolling process, the ABAQUS finite element software was used to establish a simulation model for the rolling process of different materials, and the actual engineering model was transformed into a numerical model. Through the thermal coupling simulation calculation, the metal flow law during the plate rolling process is obtained.

Taking the plate thickness, the initial temperature distribution and the reduction as the initial conditions of the simulation, the simulation calculations were carried out for the rolling process of Q235 and X80, and the effects of different temperature distribution and different reduction ratios on the internal deformation and penetration of the plate were obtained.

The simulation results of finite element software were extracted and the effects of different reduction conditions on deformation penetration were analyzed. Suitable initial thickness and large reduction ratio conditions are more conducive to the penetration of deformation into the interior during differential temperature rolling. The simulation results provide theoretical basis and reference for the formulation and adjustment of plate production process.

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