Finite Element Analysis of the Deformation Behavior of the Up and Down Roll Differential Diameter Rolling for Medium Plate

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Abstract: In order to realize the rolling technology with different reduction of upper and lower surface in the production of medium and heavy plate, a rolling technology with the same rolling line speed and different diameter of upper and lower rolls was adopted in a factory, and good results were achieved. This technology is different from the previous large roll diameter difference rolling and differential speed rolling. Large roll diameter difference rolling is an asynchronous rolling technology, which uses the difference of upper and lower roll diameter to cause the different linear speed of rolling, so as to achieve the purpose of upper and lower pressure rolling. It is mainly used in the production of section steel, and belongs to the asymmetric rolling condition. Under the condition of asymmetric rolling with unequal roll diameter, a three-dimensional large deformation and asymmetric rolling FEM model is established by using the finite element software. The stress and deformation behavior of the deformation area of the steel plate are analyzed. The fiber length changes along the longitudinal direction at different thickness positions and the shape change of steel plate in the rolling process are obtained. The results show that when the diameter of the upper roll is larger than that of the lower roll, the Mises equivalent stress, equivalent plastic strain and the change of the length of the longitudinal fiber in the deformation area are approximately distributed symmetrically along the center of the two sides, the center value of steel plate is small, and the upper and lower surface values are large; the equivalent stress of the lower surface is larger than the upper surface, and the minimum change of the fiber length appears about 1/3 of the thickness from the lower surface. Under the condition of asymmetric up and down rolling, the head of steel plate tends to down-bending. The maximum distance of the steel plate head buckle Δy is 0.185 m, the bending radius is 6.519m and the bending curvature is 0.153.

1. INTRODUCTION

In the production of medium and heavy plate, in order to realize the rolling technology with different reduction of upper and lower surface, a rolling technology with the same rolling line speed and different diameter of upper and lower rolls was adopted in a factory. In the process of plate rolling, the upper and lower rollers with different diameters are used in the plant. The rolling line speed is the same and the angular speed is different, which lead to the reduction amount of the upper and lower rollers different. This asymmetric rolling technology belongs to the category of asynchronous rolling technology, which has been studied at home and abroad. Yuan Fushun, sun Jiquan, et al. Studied that
if the angular velocity of two rolls is the same, the metal flow distance on the surface of rolled piece on one side of large roll is long in unit time, which makes the rolled piece bend to the side of small roll [1-4]. Hu Yansheng, Cheng Xiaoru and others studied that the unequal linear velocity of the upper and lower work rolls will cause the friction asymmetry on the two work roll surfaces in the deformation zone, which will lead to the formation of rolling state in the deformation zone. The torque difference between the fast roll and the slow roll and the shear stress difference on the exit side of the two roll surfaces are derived [5-9]. but most of them have the same roll diameter and different roll speed, or the speed of the transfer roller table is greater than the speed of the roller[10-13], or different roll diameter and the same roll speed[14-15].Asynchronous rolling with different roll diameter and different roll speed is relatively rare.

In this study, the three-dimensional large deformation elastic-plastic finite element method is used to analyze the deformation behavior of the deformation zone under the condition of asymmetric rolling with different roll diameters. The distribution rules of stress, strain and longitudinal fiber length of steel plate in the deformation zone are obtained when the upper roll diameter is larger than the lower roll diameter.

2. Establishment of 3D finite element model

2.1. Model description
The process of finite element modeling is to deal with the actual model reasonably in order to meet the requirements of finite element solution. Generally, the actual model should be simplified to some extent, but the model should be able to correctly reflect the actual conditions. Due to the symmetry of geometry and load in the width direction of rolling model, 1/2 model is used for modeling. The simulated roll diameter is: the upper roll diameter is 1.1 m, the lower roll diameter is 1.02m, the roll length is 3.5m; the steel plate is 10m long, 3.5m wide and 0.1m thick. The grid size is divided into 0.02m * 0.02m * 0.01 m. There are 440000 units and 490000 nodes in the model.

The coordinate system of the geometric model is three-dimensional rectangular coordinate system. The positive direction of X axis is the direction of steel plate rolling, the negative direction of Y axis is the direction of upper roll pressing, and the Z axis is the direction of steel plate width. The geometric model and coordinate system are shown in Fig.1. See Fig. 2 for the mesh generation of the finite element model.

2.2. Basic assumptions
1) The model is symmetrical in the width direction, that is, the geometric model and boundary conditions are symmetrical along the Z axis at the coordinate origin;
2) In the hot rolling process, the deformation resistance of the strip is small, so the work roll is defined as a rigid body;
3) Material is isotropic;
4) Coulomb friction model is adopted for the contact surface between steel plate and roller;
5) The material obeys von Mises yield criterion;
6) The behavior in the plastic zone obeys the flow criterion and hardening law.

2.3. Process and physical parameters for calculation
The roll rotation speed is 2.73rad/s for the upper roll and 2.94rad/s for the lower roll; the steel biting speed is 1.5m/s, the roll mass is about 124t, the original thickness of the rolled piece is 0.1m, and the one pass reduction is 0.03m. The friction coefficient between rolling piece and roll is 0.35.

The selected steel is Q345, the density is 7800 Kg/m$^3$, the young's modulus is 8.38GPa, the Poisson's ratio is 0.36, when the strain rate is 1s$^{-1}$, the rolling temperature is 1000 $^\circ$C, and the deformation resistance is 104 Mpa.

3. Calculation results and discussion

3.1. Analysis of stress and deformation
Fig. 3 shows the Mises equivalent stress nephogram of steel plate during rolling; Fig. 4 shows the strain distribution nephogram of steel plate during rolling. Fig. 5 shows the Mises equivalent stress of each node along the thickness direction of the steel plate in the deformation area; Fig. 6 shows the equivalent plastic strain of each node along the thickness direction of the steel plate in the deformation area.

It can be seen from Fig. 3 and Fig. 5 that the distribution of equivalent stress along the thickness direction of steel plate is similar between difference-diameter rolling and normal symmetrical rolling, that is, the equivalent stress value at the center of steel plate is the smallest, while the equivalent stress value near the upper and lower surfaces of steel plate is the largest. However, due to the existence of additional shear stress in asymmetric rolling, the neutral plane with zero shear stress deviates from the geometric neutral plane, so the equivalent stress distribution along the thickness direction is not completely symmetrical, and the lower surface stress is greater than the upper surface stress.

From Fig. 5, it can be seen that the equivalent stress of the central node in the deformation area is smaller than that of the nodes near the upper and lower surfaces, mainly because of the low deformation temperature and the small degree of deformation in the central node, resulting in the low deformation resistance of the central node. Moreover, due to the existence of boundary friction, the joints on the steel plate surface are all subjected to three directions of compressive stress, which is not conducive to the development of plastic deformation, and the deformation resistance is large, so the equivalent stress value of near edge joints is relatively large.
It can be seen from Fig. 4 and Fig. 6 that the equivalent plastic strain value in the thickness direction of the steel plate is basically symmetrically distributed in the upper and lower geometric neutral planes along the thickness direction of the steel plate. The plastic strain in the center of the steel plate is the smallest, while the plastic strain near the upper and lower surface of the steel plate is the largest. This is because in the rolling process, the stress on the center of the steel plate is relatively small compared with the upper and lower surfaces, so the deformation degree is relatively small.
3.2. Analysis of longitudinal fiber length change

Fig. 7 shows the displacement difference of each node in X direction (along the longitudinal direction of the plate) in the thickness of the plate. In the deformation area, each node along the thickness direction of the steel plate has been extracted the x-direction displacement and the minimum displacement value has been found. In order to get the figure 7, the minimum value has been subtracted from the x-direction displacement of other nodes. This figure can show the change of fiber length along the longitudinal direction at different thickness of the plate.

It can be seen from Fig. 7 that the fiber length along the longitudinal direction changes in different thickness positions of the plate, which is basically distributed symmetrically along both sides of the central part, with the smallest central part and the largest upper and lower surfaces. However, due to differential-diameter rolling, the minimum fiber length change is not in the center of the steel plate, but in the position about 1/3 of the thickness from the lower surface.

Fig. 8 shows the Y-direction displacement of the steel plate during rolling; Fig. 9 shows the shape of the steel plate during the rolling process. It can be seen from Fig. 8 that the closer to the head of the steel plate, the greater the displacement in Y direction, and the Y direction displacement of the steel plate is along the negative direction of Y axis.
3.3. Analysis of steel plate warpage

![Displacement of steel plate](image)

**Fig. 8** Y-direction displacement of steel plate

![Shape of the plate during rolling](image)

**Fig. 9** Shape of the plate during rolling

It can be seen from Fig. 8 that during differential-diameter rolling of steel plate, due to the difference between the upper and lower roll diameters, under the premise of the same rolling line speed, the angular velocity and reduction of the upper and lower rolls are different. In this case of asymmetric rolling condition, the head of the plate has a downward trend. Δy is the maximum distance of the steel plate head buckle. In order to determine the distance, the value is taken along the width center line of the steel plate lower surface. The value starts from the deformation area and ends at the head of the steel plate, and the deformation distance along the length direction of the steel plate is obtained, as shown in Fig. 10. It can be seen from Fig. 10 that the steel plate starts from the deformation zone under the roller, and along the length direction of the steel plate, the maximum distance Δy of buckle down reaches 0.185 m.

![Deformation distance of buckle down](image)

**Fig. 10** Deformation distance of buckle down of steel plate

At present, there is no uniform standard to measure the buckling or warping. In this study, the bending curvature (the reciprocal of the bending radius of the slab head) is taken as the warping index.
Three points on the lower surface of the head of the steel plate are selected, at a certain distance from each other and the horizontal and vertical positions (x0, y0) (x1, y1) (x2, y2) after rolling are extracted, and the bending radius is calculated by formula (1)- (3):

\[
(x_0 - x_n)^2 + (y_0 - y_n)^2 = \rho^2 \quad (1)
\]
\[
(x_1 - x_n)^2 + (y_1 - y_n)^2 = \rho^2 \quad (2)
\]
\[
(x_2 - x_n)^2 + (y_2 - y_n)^2 = \rho^2 \quad (3)
\]

In the formula: The three selected points of the center of the circle are taken as the abscissa and ordinate of \(x_n, y_n\). By substituting the coordinate values of three points into equation (1)- (3), the ternary quadratic equation of Formula can be solved, and \(x_n, y_n\) can be obtained, then the bending radius \(\rho\) is obtained and its reciprocal is taken, so that the bending curvature is \(\frac{1}{\rho}\).

Due to the large distortion of the finite element mesh shape at the head of the steel plate after rolling, in order to avoid the head effect, the first node is selected from the center line of the width of the bottom surface of the second row from the head, and each point is 0.5m apart. The coordinates of the three points after bending deformation of the steel plate are respectively: \(x_0, y_0 (2.969, -0.729)\), \(x_1, y_1 (2.447, -0.510)\), \(x_2, y_2 (1.821, -0.313)\), which are brought into the formula (1) obtained \(x_n, y_n\) is \((-1.425, -5.545)\), the bending radius is 6.519m, and the bending curvature is 0.153.

4. Conclusion
The results of FEM model calculation of asymmetric rolling show that:
1) The equivalent stress is distributed in an incomplete symmetry along the thickness direction of the plate. The equivalent stress of the node in the center of the deformation area is the smallest, the equivalent stress of the node near the surface is the largest, and the stress of the lower surface is greater than that of the upper surface. The equivalent plastic strain is distributed symmetrically along the thickness direction. The plastic strain at the center of the steel plate is the smallest, and which at the upper and lower surfaces is the largest;
2) The fiber length changes along the longitudinal direction in different thickness positions of the steel plate, which is nearly symmetrical along both sides of the central part, the smallest in the central part, the largest in the upper and lower surfaces, and the smallest change in fiber length occurs at the position about 1/3 of the thickness from the lower surface;
3) when the diameter of upper roll is larger than that of lower roll, the head of steel plate tends to buckle down. The maximum distance of the steel plate head buckle \(\Delta y\) is 0.185 m. obtained \(x_n, y_n\) is \((-1.425, -5.545)\), the bending radius is 6.519m, and the bending curvature (reciprocal of bending radius of slab head) is 0.153.

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