Study on Deformation Penetration of Rolling Process by Rolling FEM Model of Wedged Ingot

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Abstract. In order to study the law of deformation penetration in thickness direction of the plate, 3D finite element model of wedged ingot rolling has been developed by means of software ABAQUS, in order to quantitative study the influence of reduction rate on the deformation penetration effect of steel plates, on the same reduction amount of whole wedged ingot and different reduction at different locations of the wedged ingot. Two pass rolling tests of small rolling mill on 120 mm thick wedged plate has been conducted. Finite element calculation and test results show that the center of plate almost no deformation when the reduction rate decreased to a certain extent (<15%) and the center of plate deformation rate increased significantly with the increase of the rate of pass reduction.

1. Introduction
There are typical defects such as center segregation, central porosity, inclusions and crack due to the existence of low plastic microstructure enriched by solute elements in the slab thickness center[1-5]. With the increasing proportion of continuous casting slab in medium plate production, how to further improve the quality of steel plate and extra heavy plate produced by continuous casting slab as raw material has become an important research topic in recent years[6-8]. In order to improve the quality defects of the center from the perspective of steel rolling and analyze the deformation characteristics of the thick plate in the rolling process, it is urgent to study the deformation penetration law of the thickness direction of the steel plate. The finite element software ABAQUS has been used to develop the wedge ingot rolling 3D FEM model in this paper, the wedge ingot different reduction in the length direction has been utilized to research quantitatively rolling reduction effect on penetration of steel plate deformation and critical value of rolling reduction to satisfy the center penetration has been found. The two pass rolling test of wedge shaped ingot has been done by small rolling mill are used to study the deformation penetration of different locations along the thickness direction (different reduction quantities) and the test results are consistent with the finite element calculation.

2. The establishment of finite element model

2.1 Basic assumptions
(1) The speed and diameter of the upper and lower work rolls are equal and two rolls are symmetrical distribution;
(2) The deformation resistance of the ingot is relatively small during the hot rolling process, so the work roll is defined as a rigid body.
(3) Isotropy of the ingot material;
(4) The symmetrical surface of the rolled piece is treated as an adiabatic surface and the heat flux is zero.
(5) The Kulun friction model has been used between the contact surface of the roll and rolled piece.

2.2 Model description
Half of the width and full thickness of the rolled piece and roll are simulated due to the asymmetric structure of the wedge rolling model in the direction of thickness. The coordinate system of the geometric model is a three-dimensional rectangular coordinate system. The direction of X axis is rolling direction of steel plate and the Y axis is the roll direction of a pair of rollers. The Z axis is the width direction of the steel plate. The 1/2 geometric model (left) and the grid division (right) are shown in Fig. 1.

2.3 Calculation parameters
The diameter of the roll is 760mm, the roll length is 550mm, the rotation speed is 2.63rad/s, the speed of biting steel is 1.0m/s, the quality of the single roll is about 4.934 tons, and the friction coefficient between the rolled piece and the roll is 0.35.

The size of the wedged ingot is 400 mm (long) *150 mm (wide) *120 mm (thick). Two pass rolling is used in the rolling simulation calculation, the reduction of each pass is 30mm, the maximum reduction rate of the first pass is 29.2% and the second pass is 41.2%. The heating temperature is 1180°C.

The ingot material is S460ML, the density is 7800Kg/m3, the young's modulus is 1.16GPa, and the Poisson's ratio is 0.36.

3. Calculation results and discussion
3.1 Stress and strain results of various positions
In order to extract the model post processing results, 4 paths have been made along the model. Fig. 2 is a point position on each path, from right to left is path 1, path 2, path 3, and path 4. The specific coordinates of the points on each path are shown in Table 1.
Table 1. Coordinate values of each path point (from the bottom to up)

| Sequence | Path 1 (x, y, z) | Path 2 (x, y, z) | Path 3 (x, y, z) | Path 4 (x, y, z) |
|----------|-----------------|-----------------|-----------------|-----------------|
| 1        | -0.375,0.0,0    | -0.325,0.0,0    | -0.275,0.0,0    | -0.225,0.0,0    |
| 2        | -0.375,0.02,0   | -0.325,0.02,0   | -0.275,0.02,0   | -0.225,0.02,0   |
| 3        | -0.375,0.04,0   | -0.325,0.04,0   | -0.275,0.04,0   | -0.225,0.04,0   |
| 4        | -0.375,0.06,0   | -0.325,0.06,0   | -0.275,0.06,0   | -0.225,0.06,0   |
| 5        | -0.375,0.08,0   | -0.325,0.08,0   | -0.275,0.08,0   | —               |
| 6        | -0.375,0.1,0    | -0.325,0.095,0  | —               | —               |

Fig.3 shows the result of the equivalent plastic strain nephogram (left) and the equivalent stress nephogram (right). Fig.4 is the equivalent plastic strain of each path points and Fig.5 is the equivalent stress of each path points.

From the nephogram of Fig.3, it can be found that the equivalent stress or strain is small to large from the left to the right after the wedge ingot is rolled, that is to say the equivalent plastic strain and stress increase with the increase of the reduction whether it's the side or the heart.

It can be found from Fig.4 that the equivalent plastic strain of every point of 4 paths is small on both sides and large in the middle, that is, the equivalent plastic strain in the middle of the plate is larger than that on the edge of the plate. The order of the equivalent plastic strain of the 4 paths is the path 1> path 2> path 3> path 4. In Fig.5, the equivalent stress of path 1 and path 2 also presents a trend of small on both sides and middle large, that is, the equivalent stress in the middle of the plate is greater than the edge of the plate. However, the equivalent stress of path 3 and path 4 is the opposite.

![Figure 3. Equivalent plastic strain a) and equivalent stress nephogram b) ](image)

![Figure 4. Equivalent plastic strain of each path point.](image)

![Figure 5. Equivalent stress of each path point.](image)
3.2 Deformation rate of various positions
The difference of Y distance between two points before and after deformation divided by the distance between each point before deformation (20mm), and the corresponding deformation rate can be obtained.

From table 2, it can be seen that the deformation rates on the upper and lower surfaces are all large and the deformation rates of the center position are small along each path. The change of the deformation rate at the side of plate is not very large with the reduction of the rate of the pass reduction, but the deformation rate of plate center is obviously reduced. It can be indicated that the pass reduction rate has a great influence on the deformation of the plate center. It can be seen that when the reduction rate is 46.63%, the center deformation rate is 24.33%; when the reduction rate is reduced to 15.19%, the center deformation rate is about 5.02%.

| Pass reduction rate (%) | Path 1 | Path 2 | Path 3 | Path 4 |
|-------------------------|--------|--------|--------|--------|
|                         | 46.63  | 39.62  | 28.03  | 15.19  |
| Deformation rate (%)    | 55.67  | 76.25  | 37.15  | 42.01  |
| in the direction of thickness | 27.11  | 23.68  | 20.4   | 5.02   |
|                         | 24.33  | 19.19  | 17.22  | 2.42   |
|                         | 32.5   | 27.77  | 37.27  |        |
|                         | 77.24  | 55.33  |        |        |

4. Wedge rolling test

4.1 Purpose of test
In order to study the deformation penetration of steel plate thickness in the process of rolling and verify the reliability of the wedge-shaped ingot rolling model, the rolling deformation experiment of the wedge ingot small rolling mill has been designed to study the deformation penetration along different positions of the thickness.

4.2 Test method
The test material is a S460 slab with a size of 400 mm (long) * 150 mm (wide) * 120 mm (thick). Two wedge samples are cut along the diagonal direction in accordance with Fig. 6, and slotted marks are made on one side of the wedge sample, the width of the slot is 2 mm, and the depth of the slot is 10 mm. After slotting, the wedged ingot is divided into 6 equal parts in thickness direction and 8 in length direction.

Two pass rolling experiments are used in the rolling stage, The heating temperature is 1180℃, and the soaking time is 110 min. Rolling and quenching has been made after the steel plate is out of the furnace.

Figure 6. Cutting and rolling results of wedged ingot
Table 3. Deformation of thickness direction under different pass reduction rate

| Pass reduction rate (%) | deformation rate (%) | Pass reduction rate (%) | deformation rate (%) | Pass reduction rate (%) | deformation rate (%) | Pass reduction rate (%) | deformation rate (%) |
|-------------------------|----------------------|-------------------------|----------------------|-------------------------|----------------------|-------------------------|----------------------|
| 44.54                   | 55.73                | 26.73                   | 23.39                | 38.90                   | 19.26                | 31.31                   | 17.89                |
|                         | 79.15                | 22.95                   | 28.61                | 38.08                   | 14.29                | 79.67                   | 8.01                 |
|                         | 28.61                | 37.39                   | 14.29                | 40.07                   |                      |                        |                      |

Figure 7. The effect of pass reduction rate on the central deformation

4.3 Analysis of experimental results

Table 3 is the deformation of the thickness direction of the wedged ingot under the varied pass reduction rate. Fig. 7 is the effect of the pass reduction rate on the central deformation. It can be seen from table 3 the deformation of the upper and lower surface is larger and the core position of deformation is smaller in different pass reduction rate, the central deformation rate decreased when the pass reduction rate is further reduced. It can be seen from Fig. 7 that when the reduction rate is 44.54%, the central deformation rate is 23.39%; when the reduction rate is reduced to 14.29%, the central deformation rate is about 5.4%. The results of the rolling test of the wedged ingot are in good agreement with the results of the finite element calculation.

5. Conclusion

The calculation and rolling test results show that: Deformation of the upper and lower surface of plate is larger than that of the central in different pass reduction; When the reduction rate decreased to a certain extent (<15%), almost no deformation happened in the center of plate; with the increase of the pass reduction rate, edge deformation rate is not increased significantly, while the central deformation rate obviously improved.

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