Simulation study on steel pipe deformation behavior in retained mandrel pipe mill

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Abstract. Continuous rolling technology of seamless steel pipe is the leading technology in the production of steel pipes in recent years. However, due to the complicated pipe rolling process, the rolling parameters must be adjusted according to the rolling conditions after many trials of rolling. This paper focuses on a Φ180mm retained mandrel pipe mill, and the continuous rolling process finite element analysis model of seamless steel pipe is established by using ABAQUS software. The finite element model is validated by the measured wall thickness and pipe diameter data of industrial production, and the model is designed to reveal the evolution of rolling pressure distribution, metal flow, strain, wall thickness and pipe diameter during the continuous rolling process. The simulation results support key structural design of the rolling mill, the determination of rolling process parameters and the optimization of process parameters in engineering commissioning.

1. Introduction

The retained mandrel pipe mill produced by Taiyuan Heavy Industry Co., Ltd. is the first domestically produced three-roller retained mandrel pipe mill with independent intellectual property rights [1]. After the steel pipe enters the continuous rolling pipe mill, the elastoplastic deformation occurs under the double action of the mandrel and the roll. Therefore, the continuous rolling pipe process has the nonlinear characteristics of material and geometry. The metal deformation of the steel pipe during the rolling process is complicated. The traditional calculation method is to approximate the continuous rolling process by using the strip rolling formula, which is complicated in calculation and low in precision.

In the actual steel pipe production process, the rolling process parameters are adjusted according to the rolling conditions after many trials of rolling. Such test methods consume a lot of time and increase production costs. With the development of finite element theory, more and more scholars use finite element simulation technology to analyze and optimize the continuous rolling process of steel pipe [2-6]. In order to obtain better analysis results, three-dimensional elastoplastic large deformation finite element analysis and corresponding dynamic model are required to describe the key factors affecting the quality of continuous rolling mill products [7-11]. Distribution laws of stress and strain, the rolling force and wall thickness, the deformation flow law of metal during the continuous rolling process are obtained.
In this paper, a finite element simulation model for the Φ180 mm dynamic mandrel mill is established in the ABAQUS explicit dynamic analysis platform to deeply analyze the metal flow, equivalent strain, contact pressure and wall thickness during the continuous rolling process. The simulation results support key structural design of the rolling mill, the determination of rolling process parameters and the optimization of process parameters in engineering commissioning.

2. Establishment of finite element model

The model is established through ABAQUS to research on the Φ180mm retained mandrel pipe mill designed and manufactured by Taiyuan Heavy Industry Co., Ltd. To reduce the computation time and ensure computational convergence, the following simplifications and assumptions are made.

(1) The mechanical properties of the material are isotropic.
(2) The deformation of the material is a large elastic-plastic strain.
(3) The material is not compressible. In other words, the total volume of the rolled product does not change during the rolling process.
(4) Temperature changes are ignored during rolling process.

The schematic view of a seamless steel pipe continuous rolling model is shown as Figure 1. It can be seen from Figure 1 that the rolling mill consists of a steel pipe, a mandrel and rolls distributed by 120°. When the rolling mill is working, the steel pipe enters the roll at a speed of 1291 mm/s. After the pipe is bitted into the rolls, the steel pipe is rolled as the rolls rotate.

![Figure 1. Schematic view of seamless steel tube continuous rolling model.](image1)

According to the Φ180mm retained mandrel pipe mill data provided by Taiyuan Heavy Industry Co., Ltd., the main dimensions and speed parameters of the rolls are shown in Table 1:

| Rack number | 1     | 2     | 3     | 4     | 5     |
|-------------|-------|-------|-------|-------|-------|
| Roll diameter/mm | 710   | 710   | 710   | 580   | 580   |
| Roll speed/(rad·s⁻¹) | 6.445 | 9.724 | 9.733 | 17.744| 17.018|

In this model, the rolls and mandrels are rigid bodies, so the material of rolls and mandrels are not need to set. The material of the steel pipe is steel grade 20. The friction model uses Coulomb friction, and the friction coefficient between the steel pipe and the roll is set to 0.3. Due to the lubricating fluid between the rolling piece and the mandrel, the friction factor is set to 0.07 [12].

![Figure 2. Overall mesh model.](image2)
Due to the small deformation and simple shape of the mandrel, the analytical rigid body is used. The roll adopts the discrete rigid body, and the unit type is the rigid body unit R3D4. The steel pipe adopts the deformable analysis unit C3D8R, and the hexahedral mesh with better calculation effect is used for division. The overall mesh model is shown in Figure 2.

3. Simulation result analysis

3.1. Cross-section metal flow and its evolution during continuous rolling
Taking the first frame as an example, Figure 3 shows the longitudinal and lateral metal flow of the steel pipe under the action of the rolls and the mandrel. The longitudinal metal flow is shown in Figure 3(a). After the steel pipe enters the roll, the longitudinal direction of the steel pipe is gradually compressed, and the inner wall of pipe has not been compressed to contact the mandrel. At this time, the flattening deformation occurs, the radial diameter of steel pipe decreases, and the wall thickness of steel pipe slightly increases. When the steel pipe is compressed to contact the mandrel, the steel pipe undergoes a wall-reducing deformation by the action of the roll and the mandrel, the metal extends in a large amount, and the axial length of the steel pipe increases. The lateral metal flow is shown in Figure 3(b). The metal is pressed by the roll and the mandrel at the top area, and the metal flows to three open areas with a distribution of 120° to form a flanged structure. While the wall thickness of the top area decreases, the wall thickness of the open area increases, and even metal overflow occurs.

![Figure 3. Schematic diagram of metal flow in the deformation zone of steel pipe continuous rolling.](image)

3.2. Cross-section geometry and its evolution during continuous rolling
A schematic diagram of the equivalent strain of the exit section of each mill stand is shown in Figure 4. Taking the first mill stand as an example, the deformation process is 0.461s to 0.763s. At this time, the equivalent strain of steel pipe in the top area is the largest as 1.063. The equivalent strain of steel pipe in the open area is the smallest as 0.5004. The reason is that the metal is longitudinally extended in the
contact between steel pipe and roll, which causes a large additional tensile stress. In this case, if the additional tensile stress is too large, the quality of the steel pipe will be affected, and even leads to the occurrence of pipe cracking.

Analysis of the maximum strain of each mill stand shows that the maximum strains from the first mill stand to the third mill stand are 1.063, 1.852 and 2.578 respectively, and the strain increment is large. The maximum strains from the fourth mill stand to the fifth mill stand are 2.758 and 2.870, the strain increment is small. The strain increment from first mill stand to the third mill stand is large because they are the main mill stands for pipe rolling, and the fourth mill stand and fifth mill stand mainly play the role in controlling the roundness.

Figure 4. Equivalent strain diagram of the exit section of each stand.
3.3. Rolling pressure and its evolution in rolling zone during continuous rolling

The contact pressure between the roll and the steel pipe reflects the stress distribution during the rolling process. The excessive contact pressure or uneven distribution on the roll causes the roller to wear excessively, which will reduce the roll life. Figure 5 is a contact pressure distribution graph of each mill stand. It can be seen from the graph that the force area of the first mill stand roll is the largest, and the contact pressure is the largest in the top area which gradually decreases toward the periphery. The force condition of the second mill stand roll is similar to that of the first mill stand, except that the area of the force is smaller than that of the first mill stand roll. Starting from the third mill stand, the maximum contact pressure of the roll shifts from the top area to the side area, and the maximum contact pressures of the fourth mill stand roll and fifth mill stand roll have been completely moved to the side area.

![Figure 5. Roll contact pressure distribution graph.](image)

3.4. Total rolling force and its evolution on the roll during continuous rolling

The variation of rolling force curve is shown in Figure 6. Taking the first mill stand as an example, the rolling force gradually increases after the steel pipe enters the first mill stand roll. When the pipe enters the second mill stand, the rolling force and the second mill stand roll conflicts, which causes the advancement speed of the pipe to decrease in a short time. The fluctuation is generated in the first mill stand, and the rolling force fluctuates. As the second mill stand bites the steel pipe, the pipe enters a steady rolling state, and the rolling force is stable again. In the steady-state rolling stage, the simulation results of rolling force gradually reduce from the first to the fifth mill stand, which is consistent with the actual rolling curve.

![Figure 6. Variation of rolling force curve.](image)

The comparison between the simulated rolling force data and the actual data is shown in Table 2. There are some errors between the simulated rolling force results and the actual production data...
because the inconsistent second flow of metal in the finite element simulation process causes the tension before and after rolling. In the actual production, the on-site process personnel will adjust the set value of the roll gap according to the actual rolling condition, resulting in an error between the actual rolling force and the simulated rolling force. The maximum relative error between the simulation force and the actual rolling force is 15.02%, and the minimum is only 1.42%. The comparison results explain the rationality and reliability of the simulation model and its calculation results.

Figure 7. The wall thickness of the outlet section of each stand in the range of 0°～90°.
Table 2. Comparison of rolling force simulation data and actual data.

| Rack number | Measured rolling force average /KN | Simulated rolling force average /KN | Absolute error /KN | Relative error /% |
|------------|-----------------------------------|------------------------------------|-------------------|------------------|
| 1          | 2109                              | 1956                               | 153               | 7.25             |
| 2          | 1957                              | 1835                               | 122               | 6.23             |
| 3          | 1125                              | 956                                | 169               | 15.02            |
| 4          | 532                               | 506                                | 26                | 4.89             |
| 5          | 424                               | 418                                | 6                 | 1.42             |

3.5. Wall thickness, diameter and evolution of steel pipe during continuous rolling

According to the simulation model, the coordinates of the corresponding points on the inner and outer surfaces of the cross section are extracted. Then, the cubic spline interpolation curves of the inner and outer surfaces are fitted, and the corresponding wall thickness of each point is obtained. Since the deformation of the steel pipe during the continuous rolling process is relatively symmetrical, a 90° point space is selected. In order to divide the grid, the tube blank is divided into 33 parts in the circumferential direction of the section 0°~90°, and 33 coordinate points of the inner and outer surfaces can be extracted. The wall thickness extraction results of the exit sections of each stand are shown in Figure 7. The thickness of the pipe from the initial rolling size to the outlet of the third frame is reduced from 8.1 mm to 6.3 mm, which is close to the final required wall thickness, and the outer diameter is reduced from 226 mm to 193.8 mm. It shows that the main deformation of the continuous rolling process has been basically completed from the first to third mill stands, and the fourth and fifth mill stands mainly play the role of pipe finishing. Finally, the calculated roundness of the steel pipe exiting from the fifth mill stand is with high precision, and the wall thickness is relatively uniform. The simulated wall thickness is about 5.78 mm, and the actual production wall thickness is 5.65 mm provided by Taiyuan Heavy Industry Co., Ltd, which error is 2.30%. The simulated diameter is 193.38 mm, and the actual production diameter is 192.91 mm, which error is 0.45%.

4. Conclusions

The research object of this paper is Φ180mm retained mandrel pipe mill independently developed by a domestic steel plant, and a finite element simulation model is established in the ABAQUS explicit dynamic analysis platform. Conclusions are obtained as follows:

(1) During the continuous rolling process, the longitudinal deformation zone of the metal can be divided into a reduced diameter zone and a reduced wall zone. In the reduced diameter zone, the inner wall of the rolled piece is not in contact with the mandrel, and the diameter reduction mainly occurs. The reduced wall section is subjected to wall reduction deformation under the joint action of the roll and the mandrel, and the wall thickness is reduced.

(2) The transverse deformation zone of the continuous rolling metal can be divided into a hole top zone, a side wall zone and an opening zone. The contact pressure of the top three rows of the first mandrel of the limiting mandrel mill is the largest, and the metal mainly flows from the hole top zone to the opening zone. In the main deformation frame, the contact pressure of the sidewall of the fourth and fifth stand rolls is the largest, and the metal flow is reduced, which indicates that the fourth and fifth stands mainly play the role of pipe rounding and finishing.

(3) The variation of rolling force and wall thickness of steel pipe during continuous rolling are analysed, and the simulation process is verified by comparing the simulation results with the actual data.
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