Simulation and Experiment of Stainless Steel - Carbon Steel Cladding Rebar Rolling

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Abstract. In this paper, ABAQUS is used to simulate the rolling process of stainless steel (304)-carbon steel (20MnSiV) clad rebar, and the metal flow law is analyzed. It was found that the K1 pass type has a great influence on the stress and strain distribution of the clad steel. The thickness of the stainless steel wall is thinned at the roots of the transverse and longitudinal ribs, and the thickness of the front end of the transverse rib root is thinner than the rear end along the rolling direction. The clad rebar rolling experiment was carried out to verify the simulation results. Then, the steel bars were subjected to tensile and bending tests, and the results showed that they have good mechanical properties. And the metallographic observation of the bonding layer proves that a good metallurgical bond between the two metals is achieved.

1. Introduction

Stainless steel clad rebar, a new type of rebar with a core made of carbon steel and an outer layer of stainless steel. It has good mechanical properties and corrosion resistance, and has broad prospects in areas with corrosion resistance requirements such as seaports, bridges and roads[1-3].

At present, Shen, Szota et al.[4-7] established a finite element model for the rolling process of clad rebar and analyzed the stress-strain relationship during the rolling process. Yanan G, Hong X et al.[8-10] conducted a six-pass simulation study on stainless steel clad rebar in MSC.Marc, and produced round clad rebar with good performance. Wei Y et al.[11,12] studied the influence of the square-elliptical hole system on the deformation law of composite bars.

In this paper, a model of stainless steel-carbon steel clad rebar rolling is established in ABAQUS, and the deformation of the rolled piece in the last two passes of rolling is simulated, namely K1 pass (also known as finished pass) and K2 pass (leader pass). Finally, the law of metal flow is analyzed, and the rolling experiment of clad rebar is carried out.

2. Rolling Model

2.1. Groove design

According to the standard GB/T1499.2-2018[13], the parameters of the K1 groove of the crescent rib rebar with a diameter of 18 mm are obtained. In industrial production, the commonly used K2 groove has three forms: single radius elliptical groove, flat elliptical groove, and hexagonal groove. The simulation uses a flat elliptical groove, the shape and size of which is shown in Fig. 1.
2.2. Rolling model of clad rebar
The rolled piece consists of core carbon steel (20MnSiV) and outer stainless steel (304). According to the size of the $K_3$ groove (preleader pass), the section size of the rolled piece is determined to be 23mm in diameter. The initial wall thickness of stainless steel is set to 1mm, and the length is 120mm. And the diameter of the roll is 350mm. The rolling model is shown in Fig. 2.

Before the last two passes of rolling, the inner and outer materials of the rolled piece have formed stable metallurgical bonding, that is, the interaction constraint is set as "Tie". The roll is set as “rigid” body, and the rolled piece as “deformed” body. The friction coefficient is set to 0.3. In addition, according to the actual situation, the passing time of the last two rolling pieces is very short, so the temperature change is negligible. Therefore, the simulation model is simplified as constant temperature rolling and set to 1100 °C. At this temperature, the physical properties of the rolled piece are shown in Table 1, and the true stress-strain curve sees references\cite{14,15}. 

| Material  | Density /t·mm$^{-3}$ | Young's modulus /MPa | Poisson's ratio |
|-----------|----------------------|-----------------------|-----------------|
| 20MnSiV   | 7.4e-9               | 9.6e4                 | 0.3             |
| 304       | 7.9e-9               | 1.1e5                 | 0.3             |

3. Results and Analysis

3.1. Metal flow in the wide direction
In the post-processing module, view the overall shape of the finished clad rebar. Then, the cross section of it in the $K_2$ and $K_1$ rolling passes is extracted. The equivalent stress and equivalent strain are shown in Fig. 3.

It can be seen from the stress nephogram that stress is symmetrically distributed along the wide direction and gradually decreases from outside to inside. The stress is greatly reduced at the joint surface. This is because the deformation resistance of stainless steel is larger than that of carbon steel. In addition, the outer layer directly contacts the larger-rigidity roll, while the inner carbon steel is deformed after the rolling force is transmitted by the stainless steel.

In the $K_2$ pass, the stress distribution of the stainless steel is relatively uniform, but there are different degrees of mutations in the $K_1$ pass, especially at the transverse ribs. The main reason is that
the metal flow process of the rolled piece is different. When the piece enters the flat elliptical groove, rolling reduction is smaller. Besides, the shape of the groove is smooth and there is no ear generation, which makes the metal flow resistance change smoothly. When entering the threaded groove, the rolled piece has a large deformation along contact side and wide side. And it is squeezed to produce the ear (longitudinal rib). Both cause large stresses at contact sides and longitudinal ribs. At the transverse ribs of rebar, there are "crescent" grooves with sharp shape along the circumferential direction of the pass. When the metal flows inward, it will generate greater stress.

On the other hand, it can be seen from the strain nephogram that strain is also symmetrically distributed along the wide direction. The strain on the carbon steel side is higher than that on the stainless steel side, and the strain at the center of the carbon steel is the largest. Furthermore, the strain along the wide direction is higher than the contact direction. This is because plastic strain is the flow and accumulation of metal. When subjected to a rolling force, the metal flows mainly from both ends toward the center while partially flowing toward the wide side. In addition, because the rolling reduction of $K_1$ pass is larger than $K_2$ pass, the strain becomes larger. In both passes, the strain of the stainless steel is not evenly distributed. The strain at the arc segment of $K_2$ pass and the rib of $K_1$ pass is larger, and the stainless steel wall thickness is also thinned.

As seen from the cross section, the stainless steel wall thickness is significantly thinned at the root of transverse ribs and longitudinal ribs, which indicates that stainless steel layer is most likely to break. This is consistent with the actual production of clad rebar.

![The shape of the finished clad rebar.](image)

![$K_2$ pass.](image)

![minor diameter position of $K_1$ pass.](image)
3.2. Metal flow in the extension direction
The section at transverse rib is extracted along the extension direction for analysis, as shown in Fig. 4.

It can be seen from the stress nephogram that the stress of stainless steel is higher than that of carbon steel. The location with the least stress is at the center of carbon steel, and the location with the greatest stress is at ribs. In addition, the strain of carbon steel is higher than that of stainless steel. The position with the largest strain is located in the center of carbon steel, and the strain at the root of transverse ribs is higher. Besides, in terms of stainless steel wall thickness, it is evenly distributed at minor diameters. But the thickness shows a significant thinning at the roots on both sides of transverse ribs, and along the rolling direction, the front end root thickness is thinner than the rear end.

4. Rolling Experiments and Results

4.1. Experimental blank and rolling process
In the experiment, the stainless steel-carbon steel composite billet is 1.5 m long and consists of 304 austenitic stainless steel tube and 20MnSiV carbon steel rod. The outer diameter of the stainless steel tube is 159 mm, the wall thickness is 5 mm, and the carbon steel rod diameter is 149 mm. After smoothing the two metal surfaces, the carbon steel rod is inserted into the stainless steel tube. Then, the two ends are welded and sealed under vacuum. Finally, the billet is heated to 1200 °C and held for 1 h, then placed in a rolling mill for rolling, as shown in Fig. 5.

(a) composite billet; (b) rolling; (c) the finished clad rebar.

Figure 5. Billet and cladding rebar rolling.

4.2. Section of the clad rebar
The clad rebar is cut along the width and extension directions, as shown in Fig. 6.
The wall thickness of the stainless steel is evenly distributed at the minor diameter, but is significantly thinned at the root of the transverse rib. And the thickness of the front end of the transverse rib root is thinner than the back end along the rolling direction, which is consistent with the simulation analysis results.

(a) wide direction;(b) extension direction with steps.

Figure 6. Sections of the finished clad rebar.

4.3. Mechanical properties and metallographic observation

4.3.1. Tensile test. According to the standard GB/T36707-2018\[16\], the clad rebar samples were prepared and tested in a universal material testing machine. The results are shown in Fig. 7.

During the experiment, the outer stainless steel and the inner carbon steel did not separate. After measurement, the average elongation of steel bars is about 30.1%, the average yield strength and tensile strength are 495 MPa and 670 MPa, and the yield ratio is 1.35, which all meet the national standard (16%, 400 MPa, 540 MPa, 1.25).

4.3.2. Bending test. The positive and negative bending experiments were carried out on the clad rebar according to the standard. As shown in Fig. 8, the stainless steel layer did not show cracking and detachment.

(a) positive bending;(b) negative bending.

Figure 8. Bending specimens.

4.3.3. Metallographic observation. The joint surface of clad rebar was observed under a metallographic microscope, as shown in Fig. 9. A transition zone of a certain length appears at the bonding layer, which
is the result of interdiffusion of elements in the two metals. The number of pearlites in the region is reduced because the diffusion of C element into the stainless steel layer leads to decarburization. The degree of elemental diffusion of the two metals affects the strength of the metallurgical bond. The length of the transition zone reaches about 40 μm.

Figure 9. Metallographic picture of the clad rebar joint surface.

5. Conclusion
(1) By simulating the rolling process of 18mm diameter stainless steel-carbon steel clad rebar, it is found that the stress and strain distribution of K1 pass is uneven because the groove shape is complicated. The maximum change is at the root of the horizontal and longitudinal ribs, and the thickness of the stainless steel is thinned. On the other hand, the thickness of the front end of the transverse rib root in the rolling direction is thinner than the rear end.

(2) The clad rebar is rolled by a rolling mill. The average elongation of the measured steel bars is about 30.1%, the average yield strength and tensile strength are 495 MPa and 670 MPa, and the yield ratio reaches 1.35, which meets the national standard. At the same time, the positive and negative bending experiments were carried out, and the surface of the stainless steel layer did not break and detach.

(3) The metallographic observation of the clad rebar joint surface was carried out, and the length of the transition zone reached about 40 μm, which proved that the two metals achieved good metallurgical bonding.

(4) In order to ensure that the rebar has a relatively uniform cladding thickness and prevent the occurrence of excessively thin positions, it should be treated for the sharp part of the groove, such as rounding. Besides, the initial thickness of stainless steel and the reduction of each pass should be reasonably set.

Acknowledgments
This work was financially supported by Hunan Province Strategic Emerging Industry Project.

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