Research Article

Prediction of Exit Thickness and Its Compensation after Snake Rolling of Aluminum Alloy Thick Plate

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Received 29 June 2022; Accepted 2 August 2022; Published 19 August 2022

1. Introduction

In the regular rolling process of aluminum alloy thick plate, there is less plastic deformation at the center of the thick plate than that on the surfaces [1], and this results in bad mechanical properties at the center of the thick plate because of the almost unchanged microstructure of metal.

Then, an asymmetrical rolling process appears and results in a change of stress state inside the thick plate, which can make metal deforms more easily. Cross shear rolling [2], as a typical asymmetrical rolling process, is studied for promoting shear strain at the center of the thick plate, which is originally applied for obtaining a thinner strip by producing more shear strain [3]. If this technology can be applied to the rolling process of the thick plate, researchers suppose that there will be more shear strain appearing inside the plate and this is good for promoting the plastic deformation inside the plate [4]. Due to higher computation speed and easier modelling process, the finite element method is adopted to study the cross shear rolling process [5]. Although cross shear rolling promotes plastic deformation at the center of the thick plate, bending of the thick plate appears at the same time and this leads to the infeasibility of the application of the technology.

For improving the bending of the thick plate, researchers move the low-speed roll along the rolling direction. This novel rolling process is defined as snake rolling and reduces the bending curvature effectively. Research studies on snake rolling partly focus on the microstructure and mechanism properties of metal at the center of the thick plate [6–8]. For obtaining a flat plate after the snake rolling process, a lot of finite element models are established to analyze the influence of rolling conditions on the bending curvature of the thick plate. Through these finite element models, distribution of plastic deformation in thickness direction [9, 10], temperature field [11], curvature of the thick plate, and rolling force [12] were studied deeply under different speed ratios and offset distance, which are the two special rolling parameters of snake rolling. For accurately predicting the curvature of the thick plate after snake rolling, several mathematical models were also developed. Fu et al. [13] predicted the curvature of the thick plate after snake rolling based on the FE model. Aboutorabi et al. [14] represented a theoretical
model to calculate the curvature of the thick plate based on the slab method. Wang et al. [15] and Jiang et al. [16–20] established several analytical models to calculate the curvature of the thick plate and the rolling force of snake rolling. Meng et al. [21] represented a model for calculating the rolling force of snake rolling based on the slab method.

Whereas, asymmetrical rolling leads to irregular shape of deformation, which means the boundaries of the plastic deformation zone can hardly be defined accurately. So, the location of exit thickness appears to be difficult to be figured out. As a key rolling parameter that can seriously affect the accuracy of thickness of the final production, the exit thickness after each rolling process must be predicted accurately. Due to the unknown boundaries of plastic deformation during the snake rolling process, the exit thickness can hardly be predicted. For obtaining accurate exit thickness, the location where exit thickness appears must be figured out.

In this study, three formulas applied for calculating exit thickness are proposed based on different assumptions about the locations that the exit thickness appears. Then, a finite element model of snake rolling with rigid rolls is established for verifying the accuracy of those formulas and researching the influence of speed ratio and offset distance on the exit thickness. Finally, an exit thickness compensation model is established based on the location where the exit thickness appears and the accuracy of this compensation model is verified by the results of simulations.

2. Materials and Methods

2.1. Exit Thickness Calculating Formulas. In the regular rolling process, the exit thickness can be obtained by the difference between the initial thickness and the reduction. While in snake rolling, with the same reduction and initial thickness, the exit thickness is hard to be predicted due to the exit location of the deformation zone is hard to be determined. The first assumption about exit location is shown in Figure 1. By moving the upper work roll along the rolling direction, based on the contact conditions, the lowest point of the upper work roll, and the highest point of the lower work roll, the deformation zone can be divided into three sections.

In Section 1, metal is rolled only by the lower work roll. In Section 2, metal is rolled by both upper and lower work rolls and more shear strain can be obtained in this area. In Section 3, metal is rolled only by the upper work roll and the bending curvature caused in Section 2 can be reduced effectively. So, if the deformation in Section 3 is considered as pure bending deformation and the influence of bending deformation on thickness is ignored, the exit of Section 2 can be defined as exit of the plastic deformation zone. So, the thickness at the exit of Section 2 must be the exit thickness of snake rolling and can be calculated as follows:

\[ h_{SR1} = \mu \left[ H (1 - \varepsilon) + \left( R - \sqrt{R^2 - d^2} \right) \right], \]  

where \( h_{SR1} \) is the exit thickness after snake rolling (mm), \( H \) is the initial thickness (mm), \( \varepsilon \) is the reduction ratio, \( R \) is the roll radius (mm), \( d \) is the offset distance (mm), and \( \mu \) is the coefficient of elastic recovery of the thick plate, which can describe the influence of elastic recovery on the exit thickness, when the rolling force is unloaded [22, 23].

It is notable that behind the exit of Section 2, the upper part of the thick plate is still rolled by the upper work roll. At the entrance of Section 3, the slope of the contact arc between the upper surface of the thick plate and the upper work roll is greater than that between the lower surface of the thick plate and the lower work roll, so that the thickness of the thick plate is still reduced in Section 3. Then, in the second assumption, the location of the exit thickness is where the location of the shortest distance between these two work rolls appears, as shown in Figure 2. While, this shortest distance also is the minimum of thickness.

Connecting the centers of two work rolls, the distance between two work rolls is the shortest distance and can be calculated as follows:

\[ h_{SR2} = \mu \sqrt{\left[ 2R + H (1 - \varepsilon) \right]^2 + d^2} - 2\mu R, \]  

where \( h_{SR2} \) is the exit thickness after snake rolling based on the shortest distance between two rolls (mm).
While at midpoint B, as shown in Figure 2, draw a straight line in the thickness direction, with the two endpoints located at the two work rolls, respectively; the length of this new line is the shortest distance between the two work rolls in the thickness direction and can be calculated as follows:

\[ h_{SR3} = 2\mu R + \mu H (1 - \varepsilon) - 2\mu \sqrt{(R)^2 - \left(\frac{d}{2}\right)^2}, \quad (3) \]

where \( h_{SR3} \) is the exit thickness after snake rolling based on the shortest distance between the two work rolls in the thickness direction (mm).

Notably, the offset distance and exit thickness are positively correlated in all three formulas, which means that the exit thickness increases as the offset distance increases. So, the offset distance can reduce the curvature of the thick plate after snake rolling; meanwhile, it can result in the inaccuracy of reduction ratio and less plastic deformation.

2.2. Finite Element Model. Lacking of experimental equipment for snake rolling, the finite element method is the most effective method for verifying the accuracy of those three formulas. It is notable that when the rolling process is symmetrical, the accuracy of the finite element models can be verified by comparing the results of the rolling force obtained by finite element models and the actual rolling process.

Then, a finite element model with rigid rolls is built. LS/DYNA is chosen for modelling in this study.

Geometry parameters of the finite element model are listed in Table 1.

Temperature can seriously affect the constitutive relation between stress and strain. Considering the high rolling speed and short length of the thick plate, the rolling time of snake rolling is quite short, so the temperature of the thick plate changes in a small range [24] and can hardly influence material properties of the thick plate. Then, the influence of the temperature reduction on material properties is neglected in simulation. The strain rate can be calculated by the rolling velocity and reduction.

Constitutive relation [25–27] is a key content for establishing the relationship between loads and deformation degree and has been researched for a long period. Based on the theory of the elastoplastic body, the constitutive relation of the thick plate is set as a bilinear kinematic model with an elastic modulus of the thick plate being 0.8 GPa and yield strength being 60 MPa and no hardening effect [28].

Considering the large elastic modulus of the two work rolls, the elastic deformation of the work rolls can be ignored. Thus, the work rolls are set as rigid rolls and built as two shells. The initial width and length of the thick plate are 400 mm and 800 mm. The element type of both the plate and work rolls is selected as SOLID164, which has eight nodes. As to the thick plate, the number of elements in the thickness direction is set as 10, which means when the thickness of the thick plate is 50 mm, the length of element in the thickness direction is 5 mm, while when the thickness of the thick plate is 50 mm, the length of element in the thickness direction is 10 mm. The length of element in the length direction is 5 mm, while when the thickness of the thick plate is 50 mm, the length of element in the thickness direction is 8 mm, and the length of element in the width direction is 10 mm.

The thick plate moves towards the work rolls with an initial velocity of 0.4 m/s. The speed of the upper work roll is set as 4.8 rad/s based on the practical rolling process. Then, the speed of the lower work roll can be calculated according to the speed ratios listed in Table 1.

The friction coefficient is calculated based on the viscous-sliding friction model [29], as follows:

\[ \mu = 0.44 \times (1 + 4e^{-0.036}) \times 0.0185 + 0.000269T, \quad (4) \]

where \( v \) is the linear velocity of work roll, (m/s) and \( T \) is the temperature of the thick plate (°C).

The values of the friction coefficient calculated by formula (4) are 0.3297, 0.3294, and 0.3290 when the speed ratios are 1, 1.05, and 1.1.

The explicit algorithm is adopted in this finite element model.

Figure 3 shows the finite element model. In Figure 3, \( d \) is the offset distance of two rolls in the rolling direction.

3. Results and Discussion

3.1. Verification of FEM. For verifying the accuracy of finite element models, the rolling force data obtained from industrial rolling production are compared to the results of finite element models. The rolling equipment is shown in Figure 4 and the rolling conditions and the rolling force are listed in Table 2.

Rolling parameters are obtained from the actual continuous rolling process of three aluminum alloy thick plates. Considering that the initial thickness of the snake rolling process applied in this study is set as 50 mm and 300 mm, so in the actual continuous rolling process, only the rolling force with the initial thickness being close to 50 mm and 300 mm are compared to the results of finite element models.

Through the comparisons of six groups of rolling force data, it can be found that the deviations are all negative and when the initial thickness is close to 50 mm, the absolute values of deviations are larger. This is because when finite element models are established, considering the small range of temperature reduction of the thick plate, the elastic modulus and yield strength of the thick plate are set as constant values which means the temperature has no influence on the rolling force calculated by finite element model. In fact, with the number of rolling pass increasing,
temperature of the thick plate decreases and deformation resistance increases. A larger rolling force is needed. So, the deviations of rolling force when the initial thickness is close to 50 mm are larger. But all deviations between the results of the finite element model and the actual rolling force are in an acceptable range, so the finite element model can be considered a highly accurate model.

3.2. Calculation of Exit Thickness. The thick plates after the snake rolling process are curved, so the exit thickness cannot be measured directly. In this study, the exit thickness of the thick plate is obtained by calculating the difference between the curvature radii of the upper and lower surfaces of the thick plate. The exit thickness calculated by different formulas and finite element models is shown in Figure 5.

It can be observed that first, exit thickness with different speed ratios are almost equal. This indicates the speed ratio can hardly affect exit thickness. Then, exit thickness calculated through formulas (2) and (3) are much closer to the results of simulations. The difference between the finite element model and formulas when the offset distance is 0 mm is caused by the elastic recovery of the thick plate. This consistency of exit thickness indicates the location where exit thickness appears is chosen correctly in formulas (2) and (3), and the exit of the deformation zone appears at the location where the shortest distance between upper and lower work rolls appears. It is significant for calculating the rolling force and the shape of the thick plate because only if the contact arc between the two work rolls and the thick plate is determined, the accurate upper and lower limits of the rolling force integral can be calculated.

When offset distance is set to 60 mm, exit thickness is almost equal to entrance thickness, so the snake rolling process turns into an approximate bending process. The most important objective of the rolling process is to decrease the thickness of the thick plate, so too large offset distance is not allowed. When the offset distance is in the range of 0–40 mm, formula (2) has higher accuracy than formula (3) and can be applied to calculate the exit thickness of the thick plate in the actual snake rolling process.

3.3. Plastic Deformation in Deformation Zone with Great Offset Distance and Speed Ratio, Respectively. The reduction can directly affect plastic deformation inside the thick plate. According to the data on the exit thickness of the thick plate, after snake rolling, it can be found that exit thickness increases along with offset distance increasing. This means decreasing of reduction. So, it is necessary to research the plastic deformation inside the plate. Besides, the speed ratio has no influence on exit thickness, but it can lead to inhomogeneous distribution of plastic deformation because the thick plate is bent after snake rolling.

Figure 6 shows the contour of equivalent plastic strain when the offset distance is too large. It can be observed that the plate bends to the side of a high-speed roll and there is no plastic strain at the lower surface of the thick plate. This indicates with large offset distance, the rolling process becomes a pure bending process. With the rolling process not being established effectively, the speed ratio will have no influence on promoting the plastic strain of metal at the lower surface of the thick plate. Plastic strain at the upper surface is caused by the elongation of metal. Then, considering that in the actual rolling process, there are various equipment beneath the mill, bending to the high-speed roll that should be avoided both for keeping the equipment safe and promoting the plastic deformation inside the plate.

Figure 7 shows the contour of equivalent plastic strain with a large speed ratio. It can be observed contrary to the results under the large offset distance, where plastic deformation mainly appears close to the lower work roll. It is also notable that in the red circle shown in Figure 7, plastic deformation on the lower surface side appears about 24 mm earlier than that on the upper surface side. This indicates that in the snake rolling process, deformation on the upper and lower surface sides does not start synchronously and can result in asymmetrical distribution of contact arcs and rolling force at upper and lower work rolls.

Figure 8 shows the distribution in thickness direction of equivalent plastic strain inside the plate with different rolling conditions. It can be observed that when offset distance is 20 mm, under the combined influence of speed ratio and offset distance, equivalent plastic strain at the side of high roller speed increases, and at another side, equivalent plastic strain...
decreases compared to the regular rolling process. Then, it is obvious that when offset distance increases from 20 mm to 60 mm, the equivalent plastic strain distributed in the whole thickness direction declines. The advantage that promotes the plastic deformation inside the thick plate of snake rolling is not observed. The degree of plastic deformation inside the thick plate mainly depends on the reduction of thickness. Less reduction leads to less plastic deformation. So, the decreasing of equivalent plastic strain indicates that the exit thickness must increase after snake rolling. The increase of exit thickness seriously affects the predicting accuracy of the

<table>
<thead>
<tr>
<th>Rolling parameters</th>
<th>Rolling force verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial thickness/width/mm</td>
<td>Reduction/mm</td>
</tr>
<tr>
<td>323.8/1331.6</td>
<td>45.54</td>
</tr>
<tr>
<td>313.7/1339.8</td>
<td>45.53</td>
</tr>
<tr>
<td>308.6/1367.0</td>
<td>45.52</td>
</tr>
<tr>
<td>57.7/1351.3</td>
<td>18.45</td>
</tr>
<tr>
<td>56.2/1349.7</td>
<td>17.5</td>
</tr>
<tr>
<td>59.1/1379.4</td>
<td>18.68</td>
</tr>
</tbody>
</table>

Figure 5: Exit thickness calculated by different formulas and simulation after snake rolling with the initial thickness being (a) 50 mm and (b) 100 mm.

Figure 6: Distribution of equivalent plastic strain inside the plate with offset distance being 60 mm.

Figure 7: Distribution of equivalent plastic strain inside the plate with speed ratio being 1.1.
rolling mathematic model and the probability that shape defects appear increasing greatly. It is of great importance to research the exit thickness after the snake rolling process to accurately set up the rolling schedule.

The reductions of equivalent plastic strain with an initial thickness being 50 mm are greater than the reductions with an initial thickness being 100 mm; this indicates that the influence of offset distance on the distribution of equivalent plastic strain can be affected by the initial thickness. When the initial thickness increases, the same offset distance results in more reduction.

3.4. Compensating Model of Exit Thickness. Based on exit thickness calculating formulas and finite element model, it is known that offset distance can reduce the real reduction of the snake rolling process. Then, the compensating model is necessary for obtaining accurate exit thickness.

Because of the higher accuracy of formula (3), it can be applied in the establishment of the compensating model which is based on the assumption that the exit thickness appears at the location of the midpoint B, shown in Figure 2, and is equal to the length of the straight line that includes midpoint B in the thickness direction, with the two endpoints locating at two rolls, respectively. If this distance is the preset exit thickness, the compensating value of true reduction in the vertical direction between the two work rolls can be calculated as follows:

\[
\Delta = 2R + h_{\text{pre}} - \sqrt{\left(2R + h_{\text{pre}}\right)^2 - d^2}, \quad (5)
\]

\[
h_{\text{pre}} = H(1 - \varepsilon). \quad (6)
\]

**Figure 8:** Distribution in thickness direction of equivalent plastic strain inside the plate with speed ratio being 1.05: (a) initial thickness is 50 mm; (b) initial thickness is 100 mm.

**Figure 9:** Exit thickness with different offset distance after compensating.

<table>
<thead>
<tr>
<th>Entrance thickness/mm</th>
<th>Diameter of work roll and reduction rate and speed ratio</th>
<th>Offset distance/mm</th>
<th>Exit thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>300 mm 10% 1.05</td>
<td>20 40 60</td>
<td>90.4 90.8 91.0</td>
</tr>
<tr>
<td>100</td>
<td></td>
<td>20 40 60</td>
<td>45.0 45.3 45.6</td>
</tr>
</tbody>
</table>

**Table 3:** Compensation value for the initial finite element model.
For ensuring that $\Delta$ can be calculated, the offset distance has an upper limit.

According to formulas (5) and (6), the finite element model is reestablished and compensation values are listed in Table 3. Considering that speed ratio can hardly influence the exit thickness, the speed ratio is set to 1.05.

Figure 9 shows the exit thickness with different offset distance.

It can be observed that exit thickness after compensating is much close to the preset value and the maximum error only reach 0.4%, so that the compensating model has high accuracy and can be applied in the actual snake rolling process.

It is notable that although with the compensating model, the exit thickness can be accurately calculated, the offset distance must be limited. Because if the offset distance is too large, after compensating the exit thickness of the plate, the distance in the vertical direction between upper and lower work rolls will be too small to make the biting process work successfully according to rolling theory.

Figure 10 shows the distribution of equivalent plastic strain in thickness direction with different initial thicknesses.

It can be observed that after compensating the exit thickness, equivalent plastic strain in most locations increases. Compared to the regular rolling process, plastic deformation in the center of the thick plate is larger with same exit thickness. This indicates that the snake rolling can effectively promote the plastic deformation inside the plate only when the exit thickness keeps equal to the results of the regular rolling process.

4. Conclusions

In this study, three formulas for calculating exit thickness based on different assumptions and the compensating model of exit thickness based on the influence of offset distance on exit thickness are proposed and verified by a finite element model. Then, the plastic deformation inside the plate is researched. The conclusions are presented as follows:

1. Through comparing the results of three formulas applied for calculating exit thickness based on different assumptions about the location of exit thickness appearing and simulations of snake rolling, the maximum errors between the results of simulations and the three formulas are, respectively, 15.7%, 0.9%, and 2.6% when the initial thickness of the thick plate is 50 mm, and then when the initial thickness of the thick plate is 100 mm, the maximum errors are 7.5%, −0.7%, and 0.8%. So, formula (2) is based on the assumption that the exit thickness located in the line between the centers of two rolls has high accuracy. Exit thickness and offset distance are positively correlated. So, greater offset distance can lead to decreasing of actual reduction and has a negative influence on promoting plastic deformation inside the plate.

2. Offset distance leads to asymmetrical distribution of plastic strain in the thickness direction. There is more plastic deformation at the side of the low-speed roll. If the offset distance is too great, the plate will be purely bent and the rolling process will not be established effectively. While too great, speed ratio can lead to the bending of the thick plate in the opposite direction. For taking better advantage of snake rolling, both offset distance and speed ratio should be in the proper range.

3. Due to decreasing of exit thickness caused by an offset distance, a compensating model based on the locations of exit thickness appearing is proposed. According to
the rolling parameters applied in the snake rolling process, this compensating model can offer a corrected relative location of two work rolls in the vertical direction. Through comparing with the results of simulations, the maximum error between the results of the compensating model and the preset value is only 0.4%, so the accuracy of the compensating model is verified. This compensating model is of great importance because it can guarantee the accuracy of the rolling schedule which is set before the rolling process starts.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported by the Fundamental Research Funds for the Central Universities of China (FRF-GF-20-24B and FRF-MP-19-014) and Innovation Group Project of Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai) (311021013).

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