Curvature Analysis of Hot-rolled Steel Thin Plate Produced by Multi-pass Alternate Asymmetric Rolling

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Abstract. In order to study the bending behavior of C45 sheet, after the process of multi-pass hot rolling, several thermo mechanical coupled finite element models (FEM) are established. The effects of different speed ratio, friction coefficient, initial thickness, initial temperature, roll diameter on the bending value are analyzed. In this work, a multi-pass alternate asymmetric rolling (MAAR) process is intended, and a formula is defined for calculating the bending degree of rolled sheet. The values of sheet curvature are predicted by FEM. The results show that MAAR greatly reduced the cumulative value of bending, while the final curvature increases with increasing of the speed ratio and work diameter, fluctuates with ascending of friction coefficient, initial thickness and initial temperature. This study indicates that MAAR, with two work rolls as small as possible, many rolling passes and same pass reduction, can product nearly flat hot-rolled sheet by selecting appropriate blank.

Introduction

Theoretical and experiment studies on asymmetrical rolling plate and strip have been carried out, because asymmetrical rolling offers benefits such as less rolling pressure, less rolling force, less rolling torque, and more accurate dimension in thickness of the product than those obtained by symmetrical rolling. Most investigations concerning the deformation mechanical and frictional aspects have been executed [1, 2, 3]. The asymmetric rolling process also shows a significant effect on the recrystallization, texture formation and plastic anisotropy [4, 5, 6]. Based on the results of asymmetric cold rolling, asymmetric hot rolling can be a good way to improve the uniformity of microstructure and properties of plate and strip [7, 8, 9].

However, during asymmetric hot rolling process the bending of the plate and strip often happens. Both turn-up and turn-down can lead to problems, such as reducing productivity, deterioration of the plate shape. In addition, considerable damage to mill equipment may result, especially when the curvature is severe [10]. Some researchers studied on effects of rolling parameters on the bending behavior of the plate in asymmetric rolling [11, 12]. FU et al concluded that a proper offsetting distance of the top roll can control the plate curvature in snake asymmetric rolling [13, 14].

Previous investigations on turn down warping concentrated on the curvature of thick/thicker aluminum alloy plate or thin/thinner steel plate under one-pass asymmetric rolling. However, the plate and strip, especially the sheet metal, are produced by multi-pass rolling. While, sometimes asymmetrical rolling causes serious bending of the front end of the rolled block so that it cannot enter the roll gap of next pass, the application of multi-pass rolling to prepare plate and sheet metal is an innovation attempt to full play to the advantages of asynchronous rolling. So it is significant to achieve a greater understanding of the relationship between process
parameters and plate curvature. Although multi-pass asymmetric hot rolling aluminum alloy thicker plate has been proposed [15], the study on this aspect is still very limited, and there is hardly any report of multi-pass asymmetric hot rolling for steel plate.

In this work, on the basis of the definition of the alternate asymmetric rolling and the curvature of the rolled sheet, finite element techniques are used to predict the value of plate curvature, and then the relationship between the process parameters and the bending behavior of steel sheet is analyzed. These results of the research have very important role for effective controlling the plate bending in multi-pass asymmetric rolling process.

Alternate Asymmetric Rolling

In this paper, asymmetric rolling originates from the asymmetry due to different rotational speed between top and lower rolls with same diameters. Previous studies have shown that due to low mismatch of velocity of the work rolls, the sheet would almost always bend toward the direction of the bottom roll in one-pass asymmetric rolling. Therefore, a alternate asymmetric rolling process shown as Fig.1 is schemed. According to the schematic diagrams, the faster roll alternates top and bottom rolls. The alternation of the faster roll will lead to opposite directions of the plate bending between two adjacent passes, so reduce or even eliminate the accumulative curvature of the sheet after multi-pass asymmetric rolling.

Numerical Modeling

The purpose of the investigation undertaken is to develop a prediction model for the curvature of the plate after finishing rolling in the asynchronous rolling process. Several coupled thermo-mechanical models of multi-pass asynchronous rolling processes were established in DEFORM™. In this study, effects of different initial thickness, friction condition, initial temperature, speed ratio and work roll diameter on the final curvature of rolled sheet were analyzed. The material of the plate is C45 steel, considered to be rigid-plastic, work hardening and obeying the Von-Mises yield criterion and Levy-Mises flow criterion. Isotropic plasticity is assumed with the flow stress curves obtained from compression of C45 at varying strain rates. The top roll, as well as the bottom roll, is assumed to be rigid. The rolling parameters are shown as Table 1.

At present, there is no uniform method to describe the curvature of rolled sheet. In this work, the curvature $k$ is calculated according to strict mathematical definition described by the follow equations:

$$ y = a + bx + cx^2 $$

$$ k = \frac{y''}{\left(1 + y''^2\right)^{\frac{3}{2}}} \bigg|_{\text{max}} $$
Table 1. Rolling parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work piece width, ( /\text{mm} )</td>
<td>40</td>
</tr>
<tr>
<td>Work piece length, ( /\text{mm} )</td>
<td>80</td>
</tr>
<tr>
<td>Initial thickness, ( H /\text{mm} )</td>
<td>4-8</td>
</tr>
<tr>
<td>Final thickness, ( /\text{mm} )</td>
<td>1.0</td>
</tr>
<tr>
<td>Work roll diameter, ( D /\text{mm} )</td>
<td>100-160</td>
</tr>
<tr>
<td>Work roll length, ( /\text{mm} )</td>
<td>200</td>
</tr>
<tr>
<td>Rotation speed of faster roll, ( N_1 /\text{rpm} )</td>
<td>20-65</td>
</tr>
<tr>
<td>Rotation speed of slower roll, ( N_2 /\text{rpm} )</td>
<td>20-50</td>
</tr>
<tr>
<td>Speed ratio, ( I = \frac{N_1}{N_2} )</td>
<td>1.0-1.5</td>
</tr>
<tr>
<td>Initial temperature, ( T /{\degree}\text{C} )</td>
<td>900-1200</td>
</tr>
<tr>
<td>Friction coefficient, ( F )</td>
<td>0.2-0.7</td>
</tr>
<tr>
<td>Nonmember of pass, ( n )</td>
<td>2-3</td>
</tr>
</tbody>
</table>

Where, formula (1) was a quadratic regressive equation of the sheet shape after final rolling, which was established according to this coordinate value of tracking points shown as Fig.2. Formula (2) indicated that the maximum value of curvature equation was used to measure the degree of sheet bending.

Numerical experiment was conducted on multi-pass alternate asymmetric rolling by selecting top or bottom roll as faster roll in turn. Finite element predictions of curvature for various factors are shown in Figs.3-7.

Results and Discussion

Effect of Speed Ratio on Sheet Curvature

Fig.3 shows the effect of speed ratio on final curvature. It’s quite clear that the superposed bending value after two passes rolling is highly correlated with the speed ratio. The final curvature value is zero only when speed ratio is 1.0, namely, the speed of two work rolls is same. While it increases observably with ascending speed ratio when speed ratio is greater than 1.0. As the rotational speed of slower roll is stable at 20rpm, the speed of faster roll increases with ascending speed ratio. It leads to the metal flow on the side of fast roll is faster increasingly than on the side of the fast roller, thus the metal bends to the slow roll more seriously. While, it is interesting that the curvature will keep steady when speed ratio is reached or over 1.3 on the whole. This variation of curvature above may have something to do with the deformation of the metal.
Effect of Initial Temperature, Friction Coefficient and Roll Diameter on Sheet Curvature

Figs. 4, 5 and 6 reveal distinctly this changes in curvature for initial temperature, friction coefficient and roller diameter respectively. As shown in Fig. 4, the curvature is only a slight change with increasing in beginning rolling, although it’s value is relatively high. Similarly, the curvature value firstly increases and then decreases slightly as friction coefficient of multi-pass asymmetric rolling increases, shown as Fig. 5. Therefore, a larger shear friction factor can improve the sheet shape despite inevitable increase of rolling load in hot asymmetric rolling, as well as in cold asymmetric rolling described in literature [10]. It’s quite clear that the value of final curvature ascends with increasing of work roll diameter, and it is more likely to obtain flat sheet by multi-pass alternate asymmetric rolling with smaller work rolls, shown as Fig. 6.

It can be seen in Figs. 3, 4, 5, and 6 that under the same process condition, the bending of sheet rolled by multi passes with equal reductions is less than with decreasing reductions. According to the survey, the bending of plate in one-pass rolling with small plate thickness or reduction is smaller than with large plate thickness or reduction [14]. So, it is certain that each time bending of metal is small and opposite direction in multi-pass alternate asymmetric rolling with same pass reduction, the final curvature superimposed by pass bending is naturally small.

Effect of Initial Thickness on Sheet Curvature

Fig. 7 presents the effect of initial thickness on final curvature of the rolled sheet in multi-pass rolling process with same pass reduction. Being different from the previous research results [14-15], the change of final curvature is not a single increment or decrement in this work. When the number of rolling passes is fixed, this blanks with
thickness 4, 5, and 8mm, rather than 6 and 7mm, are advantageous to the production of 1mm sheet. Analogously, the favorable number of rolling pass is 3, not the 2, at same blank.

![Figure 7. Final curvature for initial thickness.](image)

**Conclusions**

This work based on pure numerical simulations was carried out to investigate the influences of speed ratio, frictional condition, initial temperature, roll diameter and initial thickness on the final curvature of sheet with thickness 1.0mm after multi-pass alternate asynchronous hot rolling. According to a series of analytical results, the following conclusions have been drawn:

1) In multi-pass asymmetric rolling process, the final curvature of the rolled sheet is greatly reduced by changing the fast roll alternately between top roll and bottom roll.

2) As expected, with the increase of speed ratio from 1 to 1.5, the bending curvature of the sheet after finishing rolling increases rapidly and then tends to be stable at about 3.5 m$^{-1}$.

3) As well as the initial temperature of metal, the friction condition has little effect on the final bending. It is unexpected to get a smaller final curvature of hot rolled sheet by multi-pass alternate asynchronous process with a high value of friction coefficient.

4) It is an effective method to produce nearly flat sheet by two as small as possible using work rolls.

5) For rolling a product with given thickness, it is necessary to select the appropriate blank and number of rolling passes.

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