Study on setting method of flatness target curve of SUNDWIG 20-high mill considering target crown

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Abstract
The flatness target curve is important in the flatness control theory. The accuracy of flatness target curve is an important factor to determine the load of flatness control means and flatness quality. Aiming at the defect that crown of each pass after rolling cannot be controlled quantitatively in the traditional target curve formulation of cold rolling, a new method considering the target crown was proposed. Specifically, the target crown of each pass can be set by combining the total proportional crown change in hot rolling field to each pass and the instability discrimination model in cold rolling field. The total proportional crown change of incoming material and finished product is allocated to each pass, and the instability discrimination model is applied to ensure the stability of the plate. The purpose of new method is to control of the crown of each pass quantitatively, so that the flatness and thickness of plate can meet the production requirements. Taking SUNDWIG 20-high mill and typical rolling products as an example, the simulation results show that, on the basis of ensuring the flatness and obtaining the minimum available crown after rolling, the model can make the flatness and crown meet the production requirements at the same time and control the crown of each pass after rolling quantitatively by setting the target crown of each pass.

Keywords 20 high-mill; Copper sheet and strip · Support axle group bending deformation · Flatness · Finite element method

1 Introduction
Flatness is the bulking extent of the plate, also represents the residual stress distribution. The flatness target curve refers to the flatness control curve established to consider the rolling or subsequent processing requirements [1]. As a primary machine of rolling thin strip, it is important to study the flatness control theory of 20-high mill. The study about flatness control of 20-high mill is as follows: Zhao [2] improved the unit matrix method for decoupling in the flatness control program of Sendzimir 20-high mill. The study about flatness control of 20-high mill is as follows: Zhao [2] improved the unit matrix method for decoupling in the flatness control program of Sendzimir 20-high mill. The simulation results showed that the improved method improved the quality of flatness. Zhang et al. [3] established the finite element model of Sendzimir rolling mill and explored the influence of the flatness control means on the flatness by simulating the rolling process. Liu et al. [4] used the Contact Element Model to calculate the roll system elastic deformation model of 20-high mill and analyzed the influence of the inner intermediate roll’s axial shift on the flatness. Dai [5] proposed to use polynomial to fit the pressure between rolls to improve the calculation speed of the flatness prediction model. Yuan et al. [6] established an accurate roll-to-roll flattening model by using the boundary integral equation, and combined with the metal plastic deformation model to predict the rolling of extremely thin strip in 20-high mill. Guo [7] established the finite element model of a new 20-high mill and analyzed the influence of ASU and other flatness control means on the flatness, but this model only simply distributed the rolling force equally.

The above scholars have made many achievements in the aspect of flatness control, but the research on the setting method of flatness target curve is less. Flatness target curve is the benchmark of flatness control. Whether setting flatness target curve is reasonable determines the flatness quality and the response speed of flatness control means to a certain extent. The research status of the flatness target curve in the cold rolling field is as follows: Lin et al. [8] conducted rolling experiments on the 1850-mm single-stand cold rolling
The results showed that only when there was a big difference between two methods, there would be a big difference in the flatness of the final product. Liu et al. [9] coupled the metal plastic deformation model with the instability discrimination model and obtained the transverse residual stress distribution when the strip was in critical instability and noncritical instability. The residual stress distribution under this condition was the flatness target curve, and this paper lays a foundation in the flatness target curve theory in China. Sun et al. [10] proposed a converse stepwise independent optimization method for reverse flatness control target. The concrete method was to make each flatness control target independent and avoid the iteration between models to improve the calculation speed. In the process of formulating the flatness target curve, the factors such as the compensation of the transverse temperature distribution and the detection roll deflection change were considered, and the effect was better after the industrial verification. Chen [11] proposed the method of dynamically setting the flatness target curve, which improved the product quality, considering the rolling force and rolling speed fluctuation and plate parameters in the rolling process. Zhao [12] proposed to combine the flatness control ability of the rolling mill with the flatness target curve theory, and in the formulation process, factors such as the installation error compensation of the detection roll and the transverse temperature were considered. Hao et al. [13] studied the influence of balance stress and non-balance stress flatness target curve on cold-rolled aluminum strip by parameter setting method. The results showed that the crown was mainly controlled in the first few passes, and the flatness was mainly controlled in the final passes, and in the final passes, the aluminum strip with the balance stress flatness target curve was smoother. Zhou et al. [14] used ABAQUS software to calculate the residual stress generated during cooling. The results showed that the transverse temperature gradient had a greater effect on the residual stress than the transverse temperature distribution. Usamentiaga et al. [15] fitted the strip lateral temperature distribution into a shape compensation curve, which was then input into the shape control system to modify the preset shape target curve. Neto and Ayhan [16] found that the coil shape interfered with the flatness control and worked out the compensation parameters under different strip roll widths and layers. After inputting the compensation parameters into the flatness control system, the actual shape quality can be improved.

According to the literature mentioned above, there are two ways to set the target curve of cold rolling. One is to set the target curve directly by using parameters, and the other is to derive it from the mechanism model. The parameter setting method is more dependent on the guidance of production experience. If the original flatness target curve is still used for new materials and new processes, there may be a large deviation between the actual shape and the target shape, so the parameter setting method has certain limitations. In the method of mechanism model derivation, the principle is that on the principle of ensuring the flatness of each pass is stable, the crown is mainly controlled in the first few passes, the flatness and crown are both considered in the middle passes, and the flatness is mainly controlled in the final passes.

In the field of hot rolling, the setting method of the flatness target curve is based on the plate crown. The Siemens model completes crown distribution according to the entry proportional crown of rough-rolled strip steel, the target proportional crown of finished strip steel, the reduction rate of the proportional crown in each pass, and the exit thickness of each pass [17]. Liu et al. [18] proposed to assign the total proportional crown change to each pass according to the ratio of the reduction ratio of each pass to the total reduction ratio, and then calculated the distribution strategy of target plate crown of each pass. Liu et al. [19] proposed to set a crown distribution strategy based on fining-rolling flatness priority. In the existing crown allocation models, the idea of crown distribution is almost the same, that is, firstly, the range of the wave-starting boundary condition is calculated by Shohe discriminant, and then, the crown is redistributed by the proportional crown or crown distribution model at range.

Whether it is cold rolling or hot rolling, flatness is not the only index to evaluate the strip quality, in addition, also includes the plate section uniformity, that is, the magnitude of the plate crown. Therefore, when setting the shape target curve, the mill, the flatness, and the crown should be considered at the same time. In this paper, from the crown after rolling of view, a new method of setting flatness target curve of cold rolling in 20-high mill is proposed. Combined with the instability discrimination model, the crown of each pass can be controlled quantitatively on the basis of meeting the flatness requirements by reasonably setting the target crown of each pass.

2 Basic model of shape target curve of SUNDWIG 20-high mill

2.1 The roll system elastic deformation model

The main methods to study the roll system elastic deformation model include analytical method, influence function method, finite element method, etc. Taking into account the
calculation time and accuracy, the commonly used method in engineering is the segmentation model method, also known as the influence function method. The position relationship of each roller in the upper roller system is shown in Fig. 1.

The exit thickness [4] is shown as Eq. (1):

\[
h_{\text{out}(i)} = s_0 + f_{S(i)} + f_{T(i)} + \delta_{S(i)} + \delta_{T(i)} + m_{S(i)} + m_{T(i)} + C_{Z(i)} \quad (i = 1, 2, \ldots, N_{SZ})
\]  

where \(h_{\text{out}(i)}\) is the exit thickness of each strip, \(s_0\) is the initial roll gap, \(f_{S(i)}\) is the deformation of the upper work roll, \(f_{T(i)}\) is the deformation of the lower work roll, \(\delta_{S(i)}\) is the flattening of the upper work roll caused by rolling force, \(\delta_{T(i)}\) is the flattening of the lower work roll caused by rolling force, \(m_{S(i)}\) is the upper work roll crown, \(m_{T(i)}\) is the lower work roll crown, \(C_{Z(i)}\) is the crown of the strip.

### 2.2 The metal plastic deformation model

The calculation methods of metal plastic deformation model mainly include strip element method, boundary element method, variational method, strip element variational method, etc. The strip element variational method is widely used in engineering calculation because it combines the advantages of the strip element method and the variational method. Figure 2 is the schematic diagram of strip division. In this paper, the strip element variational method in reference [20] is used to calculate the distribution of the exit and entrance tensile stress of the strip.

The exit tensile stress model \(\sigma_{1(i)}(y)\) in reference [21] is shown in Eq. (2):

\[
\sigma_{1(i)}(y) = \frac{T_1}{Bb_i} + \frac{E}{1-\nu^2} \left[ 1 + \frac{h_{1(i)}}{h_i} \right] \left[ \frac{h_{0(i)}}{h_i} - \frac{h_{0(i)}}{h_{0(i)}} \right] + u'(y) - \frac{u_B}{B}\left(1 - \frac{u_B}{B}\right) \quad (i = 1, 2, \ldots, n)
\]

where \(T_1\) is the exit tension (GPa); \(B\) is the width of plate (mm); \(h_{0(i)}\) and \(h_{1(i)}\) represent the average entry (mm) and exit thickness (mm) respectively; \(h_{0(i)}\) and \(h_{1(i)}\) the entry thickness (mm) and exit thickness *(mm) of each element; \(l_{0(i)}\) and \(l_{1(i)}\) represent each element incoming material length (mm) and its mean value respectively; \(u_{1(i)}\) and \(u'_{1(i)}\) are the transverse displacement function of the outlet on the bar element and its derivative respectively, \(E\) and \(\nu\) are the Elastic modulus (GPa) and Poisson’s ratio respectively.

The entry tensile stress model \(\sigma_{0(i)}(y)\) in reference [21] is shown in Eq. (3):

\[
\sigma_{0(i)}(y) = \overline{\sigma_0} + \frac{E}{1-\nu^2} \left[ \frac{h_{0(i)}}{h_i} \right] \left[ 1 + u'(y) \right] \left(1 + \frac{u_B}{B}\right) - \frac{l_{0(i)}}{l_0}
\]

where \(\overline{\sigma_0}\) is the average entry tensile stress (GPa). \(u_1\) and \(u_n\) are the transverse displacement (mm) of element 1 and element \(n\) respectively.

### 2.3 The instability discrimination model

According to the metal plastic deformation model in 2.2, the exit tensile stress distribution of the strip can be obtained. After removing the average exit tensile stress, the residual stress distribution can be obtained, as shown in Eq. (4):

\[
\sigma_s(y) = \sigma_1(y) - \overline{\sigma_1}(y)
\]

where \(\sigma_1(y)\) is the exit tensile stress (GPa); \(\overline{\sigma_1}(y)\) is the average exit tensile stress (Gpa).

The residual stress meets the self-phase equilibrium condition, that is, the integral of residual stress along the width of the plate is 0, as shown in Eq. (5):

\[
\int_{-B/2}^{B/2} \sigma_s(y) dy = 0
\]
Figure 3 shows the strip element discriminant model. After slicing the strip along the width direction, a strip of length $l$ is intercepted. There is equal opposite longitudinal load in the $x$ direction of the two sides, which is namely residual stress $\sigma_x(y)$. The basic principle of the instability discrimination model is as follows: firstly, figure out the residual stress distribution along the width direction of plate; Secondly, based on the theory of small deflection, the classic buckling theory is used to figure out the flatness defect or instability degree, and the result is used to measure whether the strip meets the production requirements. This section use the instability discrimination model established in reference [22] to solve the discrimination factor, with the purpose of determining the energy state of the strip, that is, whether the flatness quality is good or not. In order to judge the energy state of the strip, it is necessary to know its residual stress distribution $\sigma_x^*(y)$ in the critical stable state, which can be expressed by Eq. (6):

$$\sigma_x^*(y) = \xi \sigma_x(y)$$  \hspace{1cm} (6)

where $\xi$ is discriminant factor.

Different $\xi$ correspond to different flatness states, as shown in Table 1.

| Discriminant factor | Flatness condition          |
|---------------------|----------------------------|
| $\xi < 1$           | Stable buckling, poor shape|
| $\xi = 1$           | Critical buckling          |
| $\xi > 1$           | No loss of stability, good shape|

3 Optimization of flatness target curve considering target crown

3.1 The instability discrimination model

As mentioned in the introduction, when setting flatness target curve the most basic principle is to ensure the plate of each pass stable. The determination of the flatness target curve should be based on three factors: rolling mill, flatness, and crown. The flatness and the plate section shape have a corresponding relationship. The section shape corresponds to the crown of the plate. Therefore, the overall idea of this paper is as follows:

1. Firstly, according to the incoming crown and the preset target crown value of the final pass, the total crown change is allocated to each pass and calculated to obtain the target crown of each pass;
2. Secondly, flatness prediction model is used to get the exit thickness distribution and residual stress distribution, the residual stress can be calculated by the Instability discrimination model, and then judge whether crown and discriminant factor of each pass meet the requirements. If they does not meet the requirements, then change the flatness control means parameters to calculate again until the requirements are met. And if they meet the requirements, then begin the calculation of next pass;
3. Finally, when all the flatness control means reach the limit value and the ideal crown and flatness after rolling are still not obtained, it is proved that the crown control ability of the rolling mill in this pass has reached the limit under the condition of ensuring the strip stability, then the target crown needs to be reset. The specific process of the flatness target curve formulation
The difference between the incoming proportional crown and the target proportional crown is distributed according to the proportion of the reduction ratio of each pass to the total reduction ratio in the literature [17]. Suppose that there are \( n \) passes in this process, the crown distribution model is shown in Eqs. (7) to (9): 

\[
\varepsilon_i = \frac{h_{f(i)} - h_{b(i)}}{h_{f(i)}} \tag{7}
\]

\[
\Delta C_{p(i)} = \Delta C_p \varepsilon_i \sum_{i=1}^{n} \varepsilon_i \tag{8}
\]

\[
C_{b(i)} = \left( \Delta C_{p(i)} + \frac{C_{f(i)}}{h_{f(i)}} \right) h_{b(i)} \tag{9}
\]

where \( h_{f(i)} \) and \( h_{b(i)} \) represent the thickness before rolling (mm) and after rolling (mm) of each pass; \( \varepsilon_i \) is the reduction rate of each pass; \( \Delta C_{p(i)} \) is proportional crown variation of each pass; \( \Delta C_{b(i)} \) is target crown (mm) after rolling of each pass.

### 4 Results analysis and discussion

#### 4.1 SUNDWIG 20-high mill and rolling parameters of a factory

In this section, SUNDWIG 20-high mill of a factory is taken as the research object. The upper stand can be moved up and down along the column to achieve lift or push down operation, which is more flexible than the push down operation of the Sendzimir mill using rack and pinion drive. The flatness control means of the mill mainly include the following three kinds: the inner intermediate roll axial shift, the support axle group bending deformation, and the roll tilting. The maximum width of the main rolled products is 650 mm, and the thickness is between 0.5 and 1.35 mm.

The roll system of SUNDWIG 20-high mill is shown in Fig. 6. Table 2 shows the parameters of each roll.

#### 4.2 Comparison of traditional ideas and idea in this paper

According to the proposed method in this paper, the three passes 650 mm product are respectively calculated by adopting the traditional “crown first and then flatness” and the new idea in this paper, and the calculation results are compared to verify whether the new idea is reasonable. The product’s
The incoming crown is 13.5 μm, and its elastic modulus and Poisson’s are 115 GPa and 0.34 respectively. Other detailed process parameters and preset values of shape control means are shown in Tables 3 and 4. Besides, the roll crown is 0 and the incoming section shape is assumed to be symmetric about the middle line of the roll system.

Fig. 5 The idea of setting the flatness target curve considering the target crown

Fig. 6 The roll system of SUNDWIG 20-high mill

| Table 2 Material properties of roll system |
|------------------------------------------|
| Name          | Parameters          | Young’s modulus (GPa) | Poisson’s ratio |
|---------------|---------------------|-----------------------|-----------------|
| S roll        | Φ90×810             | 540                   | 0.3             |
| P roll        | Φ90×810             | 210                   |                 |
| J roll        | Φ150×750            | 210                   |                 |
| K roll        | Φ145×750            | 210                   |                 |
| C, D roll     | Φ220×730            | 210                   |                 |

| Table 3 Product parameters |
|-----------------------------|
| Pass number | 1 | 2 | 3  |
|-----------------------------|
| Entrance thickness (mm)    | 0.7 | 0.433 | 0.315 |
| Exit thickness (mm)        | 0.433 | 0.315 | 0.240 |
| Friction coefficients      | 0.05 | 0.05 | 0.05 |
| Exit tension (kN)          | 29.37 | 21.50 | 18.97 |
| Entrance tension (kN)      | 18.15 | 18.57 | 15.43 |
| Deformation resistance (GPa) | 0.320 | 0.365 | 0.392 |
Firstly, the traditional “crown first then flatness” approach as shown in Fig. 5 was used to calculate the actual crown of the final pass after rolling with a critical good flatness, it was 5.11 μm. Then, the target crown of each pass was deduced adversely using Eqs. (7) to (9), and the crown calculation results are shown in Table 5.

In practice, the flatness target curve is usually axisymmetric on both sides of the center of the mill, because there are too many distractions such as vibration and precision of equipments. If asymmetric flatness is desired, it can be adjusted by asymmetric flatness adjustment means in the production process, and the bending deformation of upper roll system A and D support axle group of SUNDWIG 20-high mill is asymmetric flatness adjustment means. Therefore, in the calculation of this paper, the bending deformation function of A and D support axle group does not participate in the optimization process of the parameters of the flatness adjustment means; the inner intermediate roll’s shift is the only one flatness adjustment means.

The data given in Tables 3 to 5 are used to calculate the flatness target curve, and the results are shown in Figs. 8 to 10. Method 1 and method 2 denote the traditional method and the method in this paper. In Figs. 7 to 9, each flatness

| Table 4 | Preset values of flatness control means |
|---------|----------------------------------------|
| Pass number | 1 | 2 | 3 |
| Axial shifting value (mm) | −17.2 | −20.4 | −22.8 |
| Saddle displacement (mm) | 0,0,0,0 | 0,0,0,0 | 0,0,0,0 |

| Table 5 | Setting value of target crown after each pass rolling is proposed in this paper |
|---------|-----------------------------------------------|
| Pass number | 1 | 2 | 3 |
| Setting value of target crown in this paper (μm) | 8.72 | 6.54 | 5.11 |

Fig. 7  Simulation results of the first pass

Fig. 8  Simulation results of the second pass

Fig. 9  Simulation results of the final pass
target curve is symmetric about the plate center line, meeting the principle of self-phase equilibrium of residual stress, that is, the integral of residual stress along the width of the strip is 0. It can be seen that different target curves can be obtained in each pass when different target crown is applied.

In Fig. 7, difference of the crown after rolling difference between two ideas is 0.08 μm in the first pass, and the flatness target curve is almost the same.

In Fig. 8, although the thickness of the second pass is almost the same, after applying the target crown, the exit crown difference is 0.13 μm, and the edge strip element residual stress difference is 0.22 MPa. It proves that target crown can influence flatness to some extent.

In Fig. 9, the crown after rolling is almost the same in the final pass, but the amplitude of residual stress at the edge strip element varies by 0.52 MPa. This is because the thickness distribution in the third pass is different in two ideas, which leads to different reduction magnitude of residual stress of each strip element.

After the optimization of the flatness prediction model, the adjustment value of the flatness control means and the actual crown value of each pass are shown in Tables 6 and 7 respectively. By comparing Tables 5 and 7, the maximum difference between the target crown and the actual crown after rolling is only 0.02 μm, which indicates that the improved method is reasonable. The crown after rolling can be controlled quantitatively by presetting the target crown of each pass under the condition that the flatness is good.

For two different ideas, the common point is that with the increase of passes, the crown after rolling becomes smaller and smaller, and the section shape becomes more uniform in the width direction. Besides, the amplitude of residual stress in the width direction becomes more smaller and smaller, and the plate tends to be straight.

### Table 6 Optimized value of flatness control means

| Pass number | 1    | 2    | 3    |
|-------------|------|------|------|
| Roll axial shift in traditional idea (mm) | −27.4 | −26.4 | −25.2 |
| Roll axial shift in this paper (mm) | −27.2 | −26.0 | −25.6 |

### Table 7 Actual crown value of each pass after rolling

| Pass number | 1    | 2    | 3    |
|-------------|------|------|------|
| The crown in traditional idea (μm) | 8.66 | 6.43 | 5.11 |
| The crown in this paper (μm) | 8.74 | 6.53 | 5.12 |

### Table 8 Setting values of target crown of each pass in this paper

| Pass number | 1    | 2    | 3    |
|-------------|------|------|------|
| The crown in simulation 1 (μm) | 8.63 | 6.43 | 5.00 |
| The crown in simulation 2 (μm) | 9.02 | 6.91 | 5.50 |
| The crown in simulation 3 (μm) | 9.41 | 7.39 | 6.00 |

### 4.3 Calculation of flatness target curve with different target crown

According to the results in 4.2, as long as the target crown of the final pass is reasonably set, then the flatness target curve can be obtained. The best operation is to control the plate as “flat” and “straight”, that is, the crown after rolling is 0, and the residual stress distribution is relatively uniform. But the flatness and thickness of the plate are two contradictory existence, if blindly eliminate one will make the other one poor. Therefore, it is necessary to find a “balance point” between them, where they both meet the products requirements.

In this section, firstly, make sure what the minimum crown of the final pass is. Taking the data in Tables 3 and 4 as an example, the target crown of the third pass is set as $C_3 = 0$ μm. According to Eqs. (6) to (8), $C_2 = 1.62$ μm and $C_1 = 4.78$ μm can be obtained. Combined with the instability discrimination model, the actual crown value of three passes is calculated as $C_1 = 8.66$ μm, $C_2 = 6.16$ μm, $C_3 = 4.55$ μm. Secondly, for comparison, the target crown of the final pass in each simulation condition were set as 5.00 μm, 5.50 μm, and 6.00 μm respectively, and the target crown of other passes can be deduced adversely by using Eqs. (7) to (9). The setting values of target crown of each pass are shown in Table 8.

The simulation results are shown in Figs. 10–12. In Fig. 10, as the setting values of target crown of final pass increase from 5.00 to 6 μm, the crown changes from 8.66 to 9.42 μm. The residual stress in the middle of the plate is from −0.415 to 0.947 MPa, and it changes from 5.938 to 5.261 MPa in the edge.

In Fig. 11, as the setting values of target crown of final pass increase from 5.00 to 6 μm, the crown changes from 6.43 to 7.28 μm. The residual stress in the middle of the plate is from 0.053 to 0.963 MPa, and it changes from 5.938 to 5.261 MPa in the edge.

In Fig. 12, as the setting values of target crown of final pass increase from 5.00 to 6 μm, the crown changes from 5.00 to 5.49 μm. The residual stress in the middle of the plate is from 0.129 to 0.047 MPa, and it changes from 3.143 to 3.612 MPa in the edge. The residual stress at 1/4 plate decreases, the rib wave trend of the final pass is...
aggravated, but the flatness change of the middle plate is small.

The optimal value of the flatness control means and the actual crown value of each pass with the flatness prediction model optimization are shown in Tables 9 and 10 respectively. In Table 10, when the final pass target of simulation 2 is 5.50 μm, and strip is stable in the third pass, the actual crown after rolling is obtained to be 5.33 μm. However, in the simulation 3, when the final pass target crown is 6.00 μm and strip is stable in the second pass, the actual crown after rolling is calculated to be 7.28 μm, and it leads to the difference of 0.17 μm between the final pass crown and target crown in simulation 2, and 0.51 μm between the final pass crown and target crown in simulation 3. However, in the simulation 1, the crown of each pass can be controlled quantitatively.

Table 9 Optimized value of flatness control means

| Pass number | 1    | 2    | 3    |
|-------------|------|------|------|
| Simulation 1 (mm) | −27.4 | −25.6 | −26.0 |
| Simulation 2 (mm) | −26.6 | −25.4 | −25.0 |
| Simulation 3 (mm) | −25.6 | −24.8 | −25.0 |

Table 10 Actual crown value of each pass after rolling

| Pass number | 1    | 2    | 3    |
|-------------|------|------|------|
| Simulation 1 (μm) | 8.66 | 6.43 | 5.00 |
| Simulation 2 (μm) | 9.00 | 6.91 | 5.33* |
| Simulation 3 (μm) | 9.42 | 7.28* | 5.49 |

The font marked with “*” in the table refers to the crown value obtained when the strip is close to instability in the current pass.
5 Conclusions

(1) In this paper, combining the characteristics of cold rolling and hot rolling, the rolling mill, the flatness and the crown, that is, combining the roll system elastic deformation model, the metal plastic deformation model and the instability identification model can obtain the method of setting the flatness target curve considering the target crown.

(2) Combined with the instability discrimination model, the minimum roll crown of a specific type of mill can be determined, and the final pass target crown can be selected according to the minimum roll crown. The simulation results show that by setting the target crown of the final pass reasonably, the crown of each pass after rolling can be controlled quantitatively on the basis of ensuring the stable strip, and the comprehensive control of the flatness and crown of the strip can be achieved.

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Declarations

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References

1. Yu HX, Liu HM, Xu YH, Wang DC (2019) Interpretation of national standards for cold rolled strip shape detection and control system. Iron & Steel 54(10):52–57

2. Zhao H (2012) Research on flatness control system for a Sendzimir mill. Northeastern University

3. Zhang QD, Dai C, Wen J, Zhang XF, Qin J (2013) Simulation and analysis on shape control behavior of 20-h Sendzimir mill. Steel Rolling 30(03):1–6

4. Liu YF, Huang Y, Zhao XH, Sun YB, Yan D (2013) Analysis on characteristics of traversing influence of the first intermediate roll in Sendzimir twenty-roller Mill, Heavy. Machinery 1:2–6

5. Dai SN (2014) The research based on theory of twenty-high roll mill rapid analysis model of shape. Yanshan University

6. Yuan ZW, Ren ZK, Xiao H, Yu C (2017) Plate shape control of ultra thin strip rolling for 20-high mill. J Cent South Univ (Science and Technology) 48(04):860–866

7. Guo ZY (2017) Simulation analysis of plate profile control of the new-type twenty-high rolling mill. Yanshan University

8. Liu ZB, Duan ZY, Lian JC, Xue FC, Luo DX, Tian M (1997) Analysis and selection method of standard profile curve of cold rolling mill. J Iron Steel Res 9(3):60–63

9. Liu HM, Ding KR, Li XD, Jiang GB (2008) Theoretical computational model of shape standard curve. J Mech Eng 44(8):137–142

10. Sun YB, Liu HM, Wang DC, Peng Y (2011) Flatness pre-set control method based on thickness standard curve. J Yanshan Univ 35(1):29–34

11. Chen J (2013) Research and application of target flatness setting technology for cold rolling mill. Worldsteel 13(3):49–53

12. Zhao ZX (2014) Research on the shape target curve setting model. Yanshan University

13. Hao CG, Ma YY, Cao SQ, Zhao QS, Huang SY, Su LP (2017) Effects of two different target curves on true flatness for cold-rolled strip. Aluminium Fabrication 5:17–20

14. Zhou ZQ, Lam Y, Thomson PF, Yuen DDW (2007) Numerical Analysis of the Flatness of Thin, Rolled Steel Strip on the Runout Table.Proc Inst Mech Eng B J Eng Manuf 221(2):241–254

15. Usamentiaga R, Garcia DF, González D (2006) Compensation for uneven temperature in flatness control systems for steel strips. Tampa, Florida, USA. (1):521–527

16. Neto LS, Ayhan T (2011) Coil build up compensation during cold rolling to improve off-line flatness. Light Metals 2011:621–624

17. Kong XW, Xu JZ, Shi J (2002) Profile and flat control system of hot rolled strip. J Journal of Northeastern University (Natural Science) 23(7):683–686

18. Liu LZ, Liu C, Liu XH, Wang GD (2001) New crown setup model of CVC hot strip mill. J Northeast Univ (Natural Science) 21(1):95–98

19. Liu DZ, He AR, Shao J, Chen CC (1999) Strategy of crown distribution based on flatness priority in finishing rolling. J Cent South Univ (Science and Technology) 51(11):3253–3259

20. Zheng ZZ, Peng Y, Liu HM (1999) A new strip element variation method for analysing lateral flow of metal and transverse distribution of front tension stress of cold rolled strip. J Iron Steel Res 11(5):21–25

21. Liu HM (1988) Theoretical and experimental studies on the transverse distribution of the rolling pressure, frictional stress and tension in 4-high cold strip rolling mill. Yanshan University

22. Liu HM, Peng Y, Chu YP (2002) Strip element method for shape discrimination of strip rolling. J Yanshan Univ 26(2):95–98

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