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Effect of Deformation between Stands on the Strip Shape in Hot Rolling

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Abstract: A theoretical model about the secondary deformation is developed by the combination of analytical and experimental approaches. A system simulation based on the model is completed to predict the strip profile after the interstand deformation. On the other hand, comprehensive experiments and quantitative comparisons are made to calibrate the model for a wide variety of products. As a result, the correction of the model has been verified by the actual rolling data from production mill and it is helpful to improve the strip shape control.

Key words: hot rolling; strip shape; secondary deformation

In hot strip rolling, the secondary deformation of strip, differing from the primary one which is occurred in the gap of work roll, happens between the exit of one stand and the entry of next one. Because of its great influence on the strip profile and flatness, the research on secondary deformation is very important.

Due to entry profile's great influence on strip exit profile in the finishing mill stand, it is very important to estimate the strip profile during secondary deformation and get the right value of entry strip profile [1–4]. Therefore, the research to predict the profile accurately during the secondary deformation is significant to improve the profile and flatness control of hot strip.

1 Theoretical Model

Generally, strip shape can be described by many parameters, such as strip crown, flatness, edge drops, high spots, *etc.*, especially strip crown and flatness are two crucial concepts to reflect the strip shape in empirical applications.

Strip crown is usually defined as the difference between the center gauge and the arithmetic average of edge drop thickness. While flatness defects are usually described by differential strip fiber elongation across the entire width of the strip from center toward both edges because there is simple relationship between the strip flatness and elongation.

It is assumed x as a defined distance from strip center to its real edge. Then strip crown and elongation are respectively expressed as follows:

$$C = H(0) - \frac{1}{2}\left[H(\frac{B}{2} - E_d) + H(-\frac{B}{2} + E_d)\right] \qquad (1)$$

$$\varepsilon = \frac{L(0) - L(\frac{B}{2} - E_d)}{L(0)} \qquad (2)$$

where C is the strip crown; ε the strip elongation; $H(x)$ the thickness of strip profile; $L(x)$ the length of strip fiber line; B the strip whole width; E_d the index distance from strip edge. In general, $E_d = 25, 40, 100\,\text{mm}$.

In this article, the deformation of strip can be classified as two stages: the primary deformation and the secondary deformation.

As shown in **figure 1**, the entry thickness of a strip h_i is reduced to the exit thickness h_{i+1} in finishing mill stand F_i. The strip cross-sectional entry crown, CH_i, becomes exit crown, Ch_i, during the primary deformation in work roll bite of stand F_i. Simultaneously, the strip flatness changes from the entry value εH_i to the exit value εh_i.

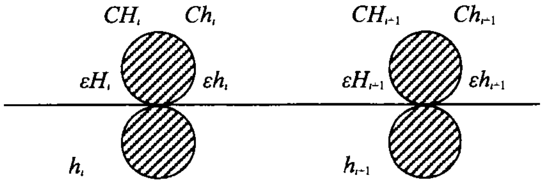

Figure 1 Variables for theoretical model.

During the secondary deformation, The strip cross-sectional crown, Ch_i, becomes the entry crown of next stand F_{i+1}, CH_i. Simultaneously, the strip flatness also changes from value εh_i to εH_{i+1}.

The detail calculating steps are presented as follows.

(1) Initializing the strip crown and flatness. When

the strip is threaded into the mill, the entry crown and flatness of stand F$_1$ is the exit profile crown and flatness of roughing stand:

$$CH_1 = C_{\text{init}} \qquad \varepsilon H_1 = \varepsilon_{\text{init}} \tag{3}$$

where C_{init} is the strip initial crown; $\varepsilon_{\text{init}}$ is the strip initial flatness.

(2) Calculating the strip crown Ch_i of other stands.

At the primary deformation stage, the value of strip crown CH_i becomes Ch_i in the gap of loaded work rolls. The primary deformation is the plastic deformation resulting from the combined actions of rolling force and bending force.

Usually the calculation of strip profile in primary deformation needs taking into account the following factors:

(a) No load profile of work roll;

(b) The initial grinding contour of work roll;

(c) The surfaces wear contour of work roll;

(d) The thermal expansion contour of work roll;

(e) Elastic deflection of work roll;

(f) No load profile of backup roll;

(g)The initial grinding contour of backup roll;

(h) The surfaces wear contour of backup roll;

(i) The thermal expansion contour of backup roll;

(j) The strip entry profile.

The value Ch_i can be expressed as

$$Ch_i = M_{CH_i} \cdot CH_i + M_{\text{RF}_i} \cdot F_{\text{R},i} + M_{\text{BFi}} \cdot F_{\text{B},i} + M_{\text{CW}_i} \cdot C_{\text{W},i} + M_{\text{CB}_i} \cdot C_{\text{B},i}$$

where i is the finishing mill stand index; M_{CH_i} the entry crown modules; M_{RF_i} the rolling force modules; M_{BFi} the bending force modules; M_{CW_i} the no load work roll profile modules; M_{CB_i} the no load backup roll profile module; CH_i the entry crown of stand F$_i$; $F_{\text{B},i}$ the bending force of stand F$_i$; $F_{\text{R},i}$ the rolling force of stand F$_i$; $C_{\text{W},i}$ the no load work roll crown of stand F$_i$; $C_{\text{B},i}$ the no load backup roll crown of stand F$_i$.

The modules in formulations were elaborated using the analysis from sophisticated off-line models such as infinite element method model.

(3) Calculating the exit elongation of stand F$_{i+1}$.

Taking into account the strip edge widening, the strip elongation is calculated as follows:

$$\varepsilon h_i = \delta_i \cdot \left(\varepsilon H_i + \frac{CH_i}{h_i} - \frac{Ch_i}{h_{i+1}} \right),$$

$$\delta_i = \begin{cases} 0 & , \quad B/h_{i+1} \le K_{\delta 1} \\ \dfrac{B/h_{i+1} - K_{\delta 1}}{K_{\delta 2}} & , \quad K_{\delta 1} < B/h_{i+1} < K_{\delta 2} \\ 1 & , \quad K_{\delta 2} \le B/h_{i+1} \end{cases} \tag{4}$$

where δ_i is the differential widening coefficient; $K_{\delta 1}$ the minimal width/thickness ratio limit; $K_{\delta 2}$ the maximal width/thickness ratio limit; h_i the thickness of stand F$_i$; h_{i+1} the thickness of stand F$_{i+1}$.

(4) Calculating the flatness threshold.

According to the computed elongation, the limit flatness threshold by wavy edges threshold and center buckle threshold will be:

$$\varepsilon_0 = \begin{cases} \varepsilon_{\text{E},i} & , \quad \varepsilon h_i \le \varepsilon_{\text{E},i} \\ \varepsilon h_i & , \quad \varepsilon_{\text{E},i} < \varepsilon h_i < \varepsilon_{\text{C},i} \\ \varepsilon_{\text{C},i} & , \quad \varepsilon h_i \le \varepsilon_{\text{C},i} \end{cases} \tag{5}$$

and

$$\varepsilon_{\text{C},i} = K_{\text{C}} \left(\frac{h_{i+1}}{B} \right)^{\alpha_{\text{C}}} \qquad \varepsilon_{\text{E},i} = K_{\text{E}} \left(\frac{h_{i+1}}{B} \right)^{\alpha_{\text{E}}} \tag{6}$$

where ε_0 is the flatness threshold; $\varepsilon_{\text{E},i}$ the wavy edges threshold; $\varepsilon_{\text{C},i}$ the center buckle threshold; K_{E} the wavy edges threshold coefficient; K_{C} the center buckle threshold coefficient; α_{E} the wavy edges threshold exponent coefficient; α_{C} the center buckle threshold exponent coefficient.

(5) Calculating the strip flatness εH_{i+1} and crown CH_{i+1} during the secondary deformation.

At the stage of secondary deformation, owing to the fact that the strip entry profile and the work roll profile are not congruent, strain heterogeneity is generated at the exit of roll bite. Because there is a distance between one stand and the next stand, the strain heterogeneity has a chance to be absorbed by means of the secondary deformation. A fiber of strip tightened much more than other fibers will be elongated during the process of the secondary deformation. And a fiber looser than other fibers will be tightened during the same process. Thus the strain heterogeneity will tend to become accordance. Strip flatness defect will be modified in some degree, so does strip crown. As a result, the value of strip flatness will change from εh_i to εH_{i+1}, simultaneously the value of strip crown from Ch_i to CH_{i+1}:

$$\varepsilon H_{i+1} = \alpha \cdot (\varepsilon h_i - \varepsilon_0)$$

$$CH_{i+1} = Ch_i + \beta \cdot h_{i+1} \cdot (\varepsilon H_{i+1} - \varepsilon h_i)$$

where α is the flatness coefficient; β the crown coefficient.

2 Result Analysis

In order to ensure the accuracy of calculating model, comprehensive experiments were completed in WISCO hot mill to test the reliability of the model.

F_{10} is assumed an entry index of F_1 finishing mill stand, and F_{11} is an exit index of stand F_1. F_{20} is an entry index of stand F_2 and F_{21} is an exit index of stand F_2, *etc.*

During hot strip rolling, operators suddenly stop the process of rolling and keep the strip in the state of procedure in deformation. Then the relevant sections of strip, which remain the real profiles of all stands, are extracted from the mill and are measured by some gage-testing equipment to obtain the transverse thickness profile.

On the base of these actual rolling data, the model can be calibrated for a broad product range throughout relatively large amount of comparison analysis. During model calibration, a set of customized constants and coefficients is developed. It is only after the accuracy of the model was confirmed for a wide variety of the rolled products that it will be utilized in guarding the rolling process.

The calculated result of second deformation is illustrated in **figure 2** in condition of 1 000 mm×2.95 mm (width×thickness).

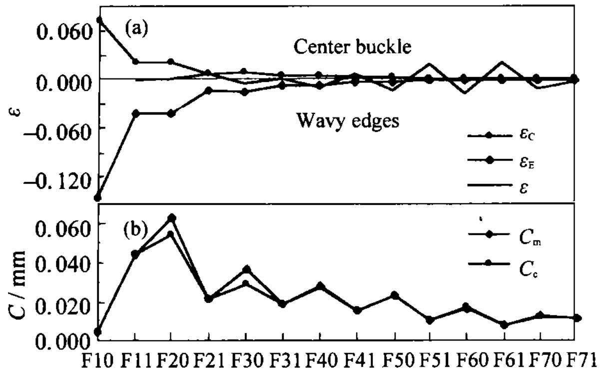

Figure 2 The calculated results in condition of 1 000 mm×2.95 mm, (a) calculated elongation; (b) comparison of measured and calculated crown.

Figure 2(a) shows the calculated result of flatness. Respectively, ε_c and ε_e are the thresholds of center buckle and wavy edges.

Figure 2(b) shows the calculated result of strip crown. C_m is a measured crown and C_c is the calculated crown of the same strip profile.

Figure 3 shows another calculated result of second deformation in condition of 1 340 mm×5.10 mm (width×thickness).

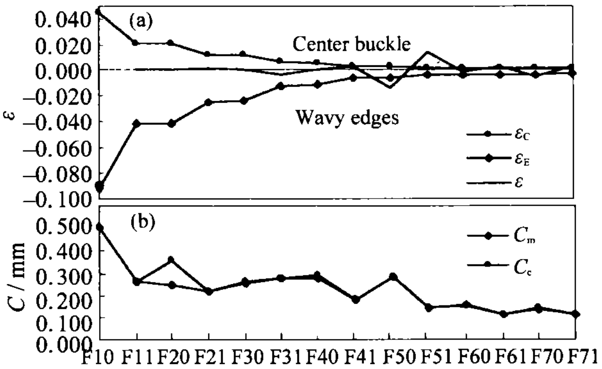

Figure 3 The calculated results in condition of 1 340 mm×5.10 mm, (a) calculated elongation; (b) comparison of measured and calculated crown.

From the comparisons, it can be seen that the model in this article provides a satisfactory agreement with measured results.

3 Conclusions

(1) The phenomenon of secondary deformation occurring between stands in hot strip mill is presented and analyzed. Then a theoretical model is developed to calculate the strip crown and flatness in the secondary deformation.

(2) The strip profile and flatness analysis algorithms provide a satisfactory, qualitative model, which agrees with measured results.

(3) Comprehensive experiments and quantitative comparisons verify the accuracy of the model when it is applied to different conditions.

(4) The model of secondary deformation has contributed to the theory and application in the field of the profile and flatness control of hot strip. At the same time, the work is helpful for cold strip shape control.

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