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Deviation Control Theory and Strategy in Aluminum Hot Rolling

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Abstract

Deviation of rolled strip has a harmful influence on the shape and quality of the products, hence the necessity of deviation control in aluminum hot rolling for rolling quality and work safety. The theoretical basis of the control strategy deviation control was proposed. Wedge-an observed quantity that can exactly describe the deviation condition was found and verified by Marc simulation. Additionally, the observation export wedge model based on the asymmetric deformation model, and the deviation criteria that are suitable for various origins, were set up. Owing to the work above, the deviation control strategy to be applied to a single machine frame is carried out, and deviation control for the tandem rolling is realized.

Key words: *aluminum hot rolling, deviation, control strategy*

1. Introduction

Deviation of rolled strip is a crucial factor in damaging the safety and normal work of a mill, and also a factor of harmful influence on shape and quality of the products. Therefore, deviation control in the hot rolling is essential for rolling quality and work safety. At present, there are over 10 aluminum hot tandem rolling lines built and to be built in our country [1]. The former 20-30m of the aluminum strip at whose head the deviation exists, fails to thread and becomes waste. What’s worse, grievous deviation can even cause the entire abandonment of an aluminum ingot. Assuming that the average coil weight is 15t, and the average cut-off length is 20m, accounting for 50% of the annual energy consumption and 60% of the output, in our country, the economic loss due to the deviation in aluminum hot rolling exceeds 1 billion RMB.

The first research on deviation appeared in 1980, in which Nakajima, et al. gave qualitative explanations for the deviation mechanism caused by the thickness wedge of the strip and the relationship between deviation and rigidity [2]. Afterwards, numerical analysis and experiments were used in studying deviation. The relationship between wedge and lateral bending was roughly analyzed using numerical analysis [3], and the impossibility to reduce wedge and lateral bending simultaneously was declared. The forming process of lateral bending was simulated using finite-element analysis and its soundness was proved by experiments [4]. But because of the excessive simplification of the model and low calculating accuracy, only qualitative analysis was given. Furthermore, the impacts that various origins have on the deviation quantity were analyzed using experiment analysis and some crucial origins were found [5]. After that, ways to reduce deviation from the explicit origins were studied. However, the study in the deviation stemming from the explicit experiment- based origins were not enough, and some force and energy parameters necessarily needed in this study failed to appear, so these studies could not meet the demand that the origins should be found and confirmed on line, hence little guiding significance in the deviation control.

The deviation evolving processes from different origins, wedge, initial deflection, roll tilt, and eccentricity, were simulated [6]. The formula of the deviation law was also fitted. But because of the short rolling time, the deviation evolvement rule in the period when the strip runs out of the rolling area cannot be exactly described. Some other scholars also discussed and explained the deviation phenomenon in actual products. The deviation phenomena in the rolling process in Tangshan Iron and Steel Company get analyzed, and the various origins pointed out [7]. At the same time, the deviation direction is qualitatively studied using the simplified formula.

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2. Research Method

2.1 Theoretical Basis of Deviation Control

In the rolling process, because of the asymmetry of the strip (the strip being partially put, the wedge of the strip, etc) and the asymmetry of the rolling mill (the wedge of the roll gap and the inequality between the two sides of the mill), the rolling forces between the two sides of the rolling mill are different, thus causing the emergence of wedge and deviation. The following rolling process would be affected, the strip snapped, and the rolls damaged [8]. So the direct manifestation of deviation in the rolling process is wedge. Following are the causes of the wedge.

(1) The initial wedge of the rolled strip;
(2) Some origins that contribute to the wedge, such as the asymmetry of the rolling mill and the unevenness of the temperature distribution on the surface of the strip ;

So no matter what the origins are, they can be expressed by a direct form— wedge.

The relationship between wedge and deviation are explained below. In Figure 1, assuming that the necessary and sufficient condition— the strip gets through the mill without deviation and the thickness of the strip gets pressed from *H* to *h* — is the lengths of two sides of the mill stay equal. So, $l_{os} = l_{ds}$.

According to the constant volume theorem, when the broad extension in the rolling process is ignored, the following equation can be given as:

$$\begin{cases} H_{os} \times L_{os} = h_{os} \times l_{os} \\ H_{ds} \times L_{ds} = h_{ds} \times l_{ds} \end{cases} \tag{1}$$

The deformation of Equation (1) can be:

$$\frac{H_{ds} - H_{os}}{H} = \frac{h_{ds} - h_{os}}{h} \tag{2}$$

So $\Delta\beta = \frac{H_{ds} - H_{os}}{H} - \frac{h_{ds} - h_{os}}{h} = 0$

Above is the criterion for running stably without deviation.

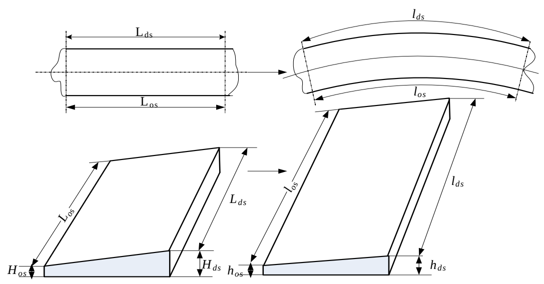


Figure 1. Theory of constant wedge ratio

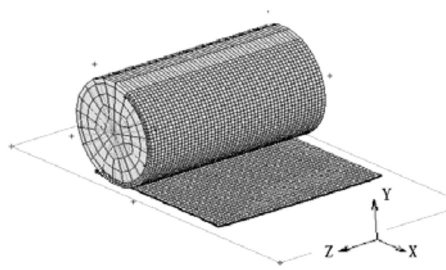


Figure 2. Finite element model

Equation (2) also indicates that when the ratio, the result that the wedge of the strip in the entrance and the exit of the rolling mill divides the average thickness of either side of the work piece, keeps constant, the strip can run without deviation. So Equation (2) can also be given as:

$$\frac{W_g}{H_{av}} = cons\tan t \tag{3}$$

where W_g is wedge ($H_{os} - H_{ds}$), and H_{av} is the average thickness of the board. If the ratio keeps constant, deviation will not appear.

2.2 Verification for the Deviation Control Theory Based on Marc

In order to verify the theory that deviation will not appear under the condition of constant wedge ratio, according to the experimental and production data, the model of rolling process in correspondence with the practice situation is set up using Marc [9].

To save calculation time, 1/2 of the finite element model with symmetry relative to *XOZ* plane is set up. Eight-node hexahedral isoparametric units are adopted in the roller model and the rolled piece model. Figure 2 shows the finite element model of equivalent structure parameters. As can be seen in the figure, the strip has been rolled for a period of *t*. The basic rolling requirements are given in Table 1.

Table1. Basic Rolling Requirements

Parameter	Value
Roller Diameter, (mm)	750
Roller body length, (mm)	1300
Linear velocity, (m/s)	0.81
Initial temperature, (℃)	49
Rolled strip Width, (mm)	1200
1/2of the initial thickness,(mm)	19.5
Initial temperature, (℃)	350
Frictional factor	0.4
Screw-down rate	49%
Spring equivalent stiffness（N/mm）	6.35e9
Front tensile stress（MPa）	8

In this model, *XOZ*-plane is regarded as the horizontal plane *X*-axis is the length wise direction of the system in which the forward direction is the heading direction, and *Z*-axis is the crosswise direction, also the width direction. *YOZ*-plane is the vertical plane in which the forward direction of *Y*-axis directs upward. Lateral asymmetry can be seen as the asymmetry of the parameters relative to the *XOZ*-plane. The deviation of the strip can be seen as the center of the strip departing from the *XOY*-plane.

Below is the simulation analysis for the two models.

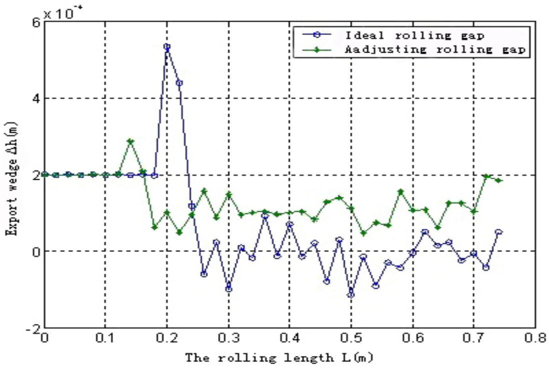


Figure 3. Wedge before and after adjusting the roll

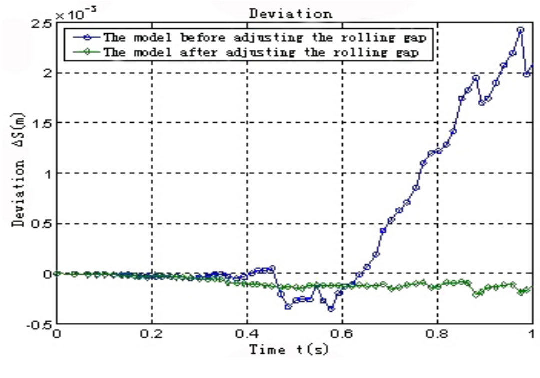


Figure 4. Deviations of a Center Node Before and After Adjusting the Roll

The longest rolling time of the simulation is 1.3s, and the average calculating time for each model is about 50 hours. The length of the rolled aluminum strip is about 1m.

Assuming that the origin of the strip deviation is initial wedge, and $\Delta H = 0.2\text{mm}$, the calculation analysis can be done on the two models respectively:

(1) The rolling model under the condition of ideal rolling gap;

(2) The rolling model that meets theory of constant wedge ratio by adjusting the rolling gap.

According to the constant wedge ratio theory— Equation (2), the wedge after rolling without deviation can be calculated as:

$$\Delta h = \frac{h}{H} \times \Delta H = \frac{10}{19.5} \times 0.2 \approx 0.1\text{mm}$$

Figure 3 is a comparison figure for the wedge paths before and after adjusting the roller. As can be seen in the picture, the rolled piece doesn’t meet the theory of constant wedge ratio before adjusting the roller. Whereas after adjusting the roller, the value of the wedge vibrates near 0.1mm, meeting the constant wedge ratio theory.

Figure 4 is the deviations of a center node during the rolling process. From the figure, we can conclude that the deviation before adjusting the roller, i.e. when the screw-down rate of either side of the mill differing greatly from each other, has an obvious tendency of climbing. But when the strip meets the theory of constant wedge ratio after adjusting the roller, the deviation of the node is inconspicuous.

Figure 5 shows the deviation path in the rolling region. It can be easily summarized from the picture that during the rolling process the model of unadjusted rolling gap evidently deviates on the side with small screw-down rate. But the piece meeting the theory of constant wedge ratio has an inconspicuous deviation.

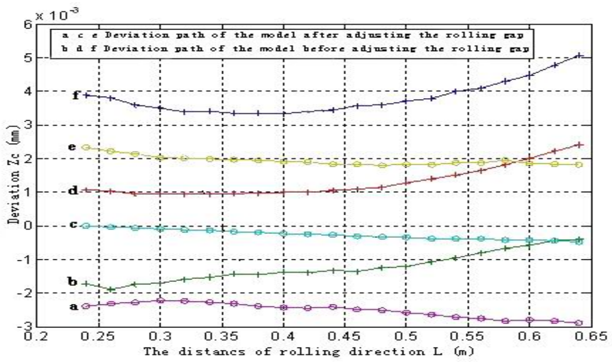


Figure 5. Deviation Path Before and After Adjusting the Roller

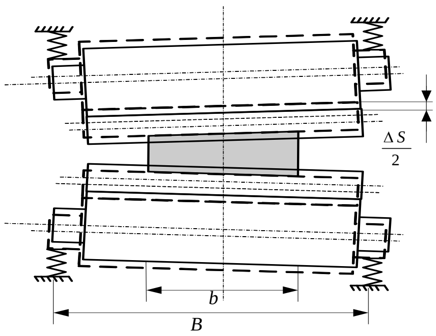


Figure 6. Deformation of the Mill Without Consideration of Roll Deformation

3. Results and Analysis

3.1. Research on the Deviation Control Strategy

Aim: before and after rolling, the errors of wedge rates fall on the allowed band:

$$\Delta\beta = \left| \frac{H_o - H_d}{H} - \frac{h_o - h_d}{h} \right| \leq \Psi \quad (4)$$

where ψ is the allowed error band of the wedge rate.

Assumption: when the deviations are equal, the deviation controlling quantities exerted through lifting and pressing are equal.

(1) Observation model of wedge

The cause of deviation is the growing of origins that lead to wedge. Every rack in the rolling process cannot meet the theory of constant wedge ratio automatically. Whether the theory of constant wedge ratio can be met or not can be determined by comparing the wedges before and after rolling. The model of wedge can be set up according to the asymmetry of the mill [10, 11].

When the observation model of wedge is to be set up, because of the centering device existing in the entrance where the strip enters the finishing mill group, the deviation of the strip should not be considered. According to the rolling force difference, horizontal roll gap difference, and force balance of the rolled piece, the observation model can be set up as:

$$\Delta h = \left(\frac{\Delta P}{K} + \Delta S\right)\frac{b}{B} \quad (5)$$

Where ΔP represents the rolling force difference, ΔS represents the pressed quantity difference, b the width of the work piece, and B the center length of pressing bearing.

Figure 6 shows the deformation of the mill when the roll deformation is not taken into consideration. Where the active lines represent the initial shape and the dotted lines represents the deformation shape.

The observation points required before the strip runs into the finishing mill are measured by contour graph set at the exit of the roughing mill, so the wedge of the strip ΔH can be obtained. Then the strip runs into the first rack, the wedge of the work piece, Δh, having finished getting through F1, can be calculated by the observation model, Equation (5). Following is the explanation for the details.

The target wedge of the strip can be a deformation of Equation (2):

$$\Delta h^* = \frac{h}{H}\Delta H \quad (6)$$

Then the actual wedge at the exit, Δh, can be calculated from Equation (5) and compared with $\Delta h*$. If the two are equal, the deviation is proved to not exist. Otherwise, the deviation exists, waiting to be controlled. In the actual rolling process, due to the influence of various factors, before and after rolling, the strip cannot precisely meet the constant wedge ratio theory. In other words, the actual wedge, ranging in a given interval, cannot precisely be equal to the target one. So when the actual wedge meets Equation (7), it can be considered that the deviation does not exist:

$$\Delta h' = \left|\Delta h^* - \Delta h\right| \le \eta \quad (7)$$

where η is the permitted wedge difference before and after rolling, $\Delta h'$ the actual wedge difference before and after rolling. So Equation (7) can serve as the observation quantity of deviation.

(2) The establishment of deviation criterion

The direct cause of deviation is the failure to meet the constant wedge ratio theory, which leads to the velocity difference at the entrance and exit. So it is the theory of constant wedge ratio that is the deviation criterion. Correspondingly, the ratio of the wedges before and after rolling can be used to show the direction of deviation. If The deviation criterion are given in Table 2. The criteria given above can precisely reflect the deviation condition, providing a basis for deviation control.

Table 2. The Establishment of Deviation Criterion

If wedge exists, the direction of deviation	Criterion1: $H_{os} \ge H_{ds}$	Criterion2: $H_{os} \le H_{ds}$
No deviation	$\left\|\Delta h^* - \Delta h\right\| \le \eta$	$\left\|\Delta h^* - \Delta h\right\| \le \eta$
The strip deviates to the **os** side	$\Delta h^* + \eta < \Delta h$	$\Delta h^* > \Delta h + \eta$
The strip deviates to the **ds** side	$\Delta h^* > \Delta h + \eta$	$\Delta h^* + \eta < \Delta h$

3.2. Practice of the deviation regulation and control

The regulated quantity is small compared to the absolute reduction, hence only once regulation added in every regulating process.

In the regulating process, firstly, calculate the target wedge Δh^* at the measuring point, and then calculate the actual exit wedge Δh when the measuring point reaches the mill. Then compare the two values calculate and the wedge difference $\Delta h'$ if the two are not equal. Choose the side in need of regulation and add $\Delta h'$ on it. Apparently, because of the jumping and roll deformation, the regulation result may not be satisfying.

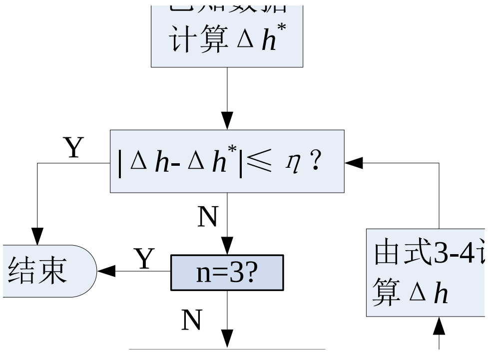


Figure 7. Regulation Quantity Adding Subprogram

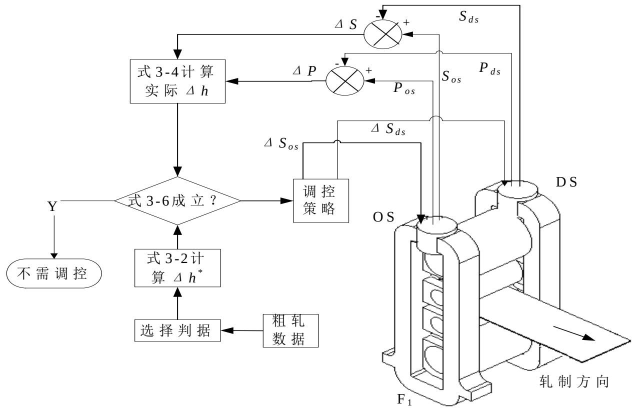


Figure 8. Deviation Control System

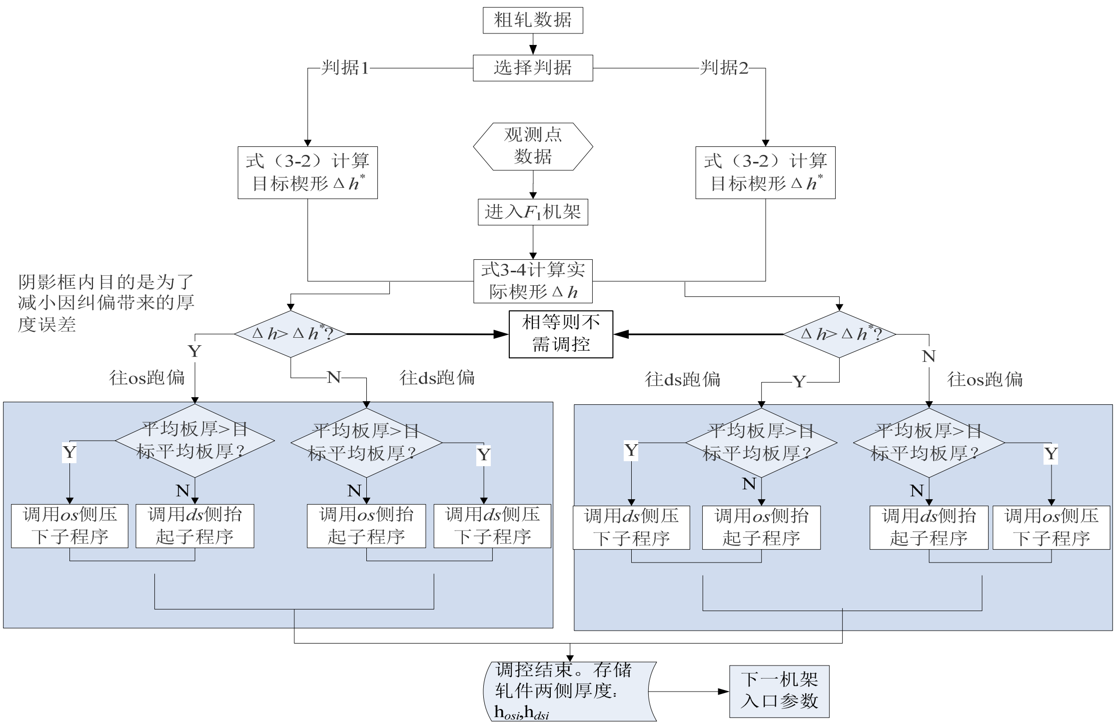


Figure 9. Deviation Control Procedure of F_i

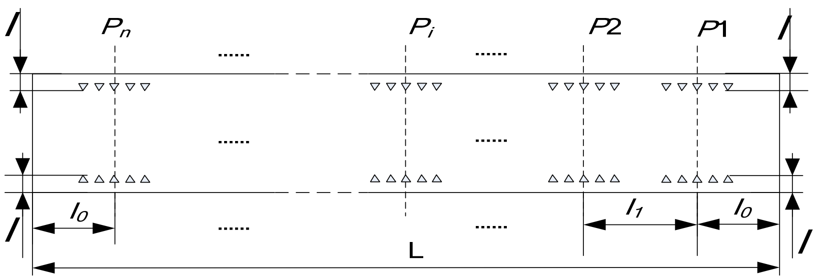
To meet the constant wedge ratio theory, the given process can be repeated. But it can only be repeated for 3 times because the process is quick and the next observation point follows, as can be seen in Figure 7.The deviation control system, set up according to the given deviation determine criterion and control strategy, is shown in Figure 8. And the detail of procedure is given in Figure 9.

The strategy given above calculates the target wedge referring to the initial rolled strip data. Control is conducted according to the theory of constant wedge ratio and founded deviation decision criterion. Because of the high rolling speed, the precondition of the application of this strategy is quick response and accurate depressing.

3.3 Practice of the deviation control strategy in tandem rolling

(1) Distribution of strip observation points

Because of the high speed in the rolling process, the deviation control implementing system delays. So the simultaneous control could not be realized. The observation points are distributed uniformly on the strip, as is shown Figure 10.



$$l_1 = \frac{L-2l_0}{n-1}$$

Figure 10. Distribution of Observation Points

The edges of the strip become thinner and thinner, so the observation points should be located *l mm* away from the edge (generally *l* is located in 30～40mm). Average value should be calculated every 5 points. The total number of the observation points is determined by the initial length *L*. l_0 is determined by the rolling length after the strip runs into the mill and before it runs out, keeping stable.

(2) Practice in Tandem Rolling

The observation points 1, 2…I are marked P_1,P_2,…P_i respectively. To explain the deviation control in tandem rolling, P_i is taken as an example. The thicknesses of the two sides of the strip are H_{os}, H_{ds}, when the following equation is met, the deviation control can be taken into practice.

$$\begin{cases} h_{i-1} = H_i \\ h_{os}^i = H_{os}^i \\ h_{ds}^i = H_{ds}^i \end{cases} \quad (8)$$

where *h* is the exit thickness: *H* is the entrance thickness; *os* is operating side; *ds* is driving side.

4. Conclusion

The origins of deviation in the rolling process flourish. A single one can precisely reflect the deviation conditions through rolling force difference and roll gap difference, but multiple origins could not. So the precondition of the control is to find an observation quantity that can precisely reflect the deviation condition stemming from different origins.

In this paper, firstly, the theoretical basis of deviation control is the theory of constant wedge ratio is proposed and then simulated by Marc.

Observation model of the wedge in the rolling process is set up. The difference between the target wedge calculated according to the theory of constant wedge ratio and the exit wedge calculated according to the observation model. Two deviation deterioration criteria, which are of great significance in determining the deviation condition, are set up according to the observation model. Then the open-loop control strategy of deviation control is set up and description of its application in tandem rolling is given.

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