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Simulation and control of high-order flatness in rolling wide titanium strip with 20-high mill

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Abstract: In wide titanium strip cold rolling process, the high-order flatness defect is one of the most difficult problem to be solved. Based on finite element method, considering the anisotropic mechanical characteristics of titanium, an implicit integration calculation model of rolls-strip for 20-high mill was developed, which can simulate the dynamic rolling process. The model was used to analyze the adjustment characteristics of high-order flatness on the 20-high mill. The simulation revealed as the increasing of the 1# & 7# AS-U or 2# & 6# AS-U press adjustment, the high-order flatness defect was more aggravated; And as the increasing of 3# & 5# AS-U or 4# AS-U press adjustment, the high-order flatness defect was alleviated to some extent. In addition, the high-order flatness cannot be effectively adjusted by roll shifting. Finally, the industrial test showed that increasing 4# AS-U press adjustment can effectively relieve the high-order flatness defect.

Keywords: 20-high mill; Wide titanium strip; High-order flatness defect; Adjustment characteristics; Finite element method

1. Introduction

Commercially pure titanium strip is a widely used titanium metal material, and its mechanical properties anisotropy and microstructure evolution law have attracted the attention of numerous scholars. Liu et al. [1] studied the anisotropy and forming characteristics of commercially pure titanium sheet under different rolling paths and found that cross rolling showed a smaller planar anisotropy. Liu et al. [2] studied the effects of cold rolling and annealing on the microstructure evolution of commercially pure titanium sheet and found that twinning was the dominant deformation mechanism when the cold rolling reduction is less than 40%, that 20% cold rolled sheet recrystallized almost completely when the annealing time reached 60min. Roth et al. [3] studied the anisotropy of mechanical behavior of commercially pure α -Ti samples cut along the rolling and transverse direction under tensile tests and suggested a mechanism based on the consideration of the dislocation glide anisotropy.

Compared to the research on the microstructure of commercially pure titanium, the research on the shape control of titanium strips in cold rolling process is not

sufficient. Zhu et al [4] analyzed the ridge buckle defect of the pure titanium cold rolling strip in the production process. Shi et al [5] studied the distribution of tensile stress of titanium strip in a continuous annealing furnace with FEM method.

The simulation model of a 20-high mill has been researched for a long time by a large number of scholars. Wang et al [6] used the influence function method to establish the elastic deformation model of the 20-high rolling mill. Yu et al [7] proposed a new 20-high mill method that can mesh element depended on the contact length between rolls or between the work roll and the strip. Zhang et al [8] introduced the method of the finite element stiffness matrix assembly when using the influence function method to calculate the roll deformation and coupled the plastic flatness model based on the three-dimensional difference method to establish a 20-high mill roll system and strip integrated rapid calculation model. Yuan et al [9] proposed that the roll was regarded as a semi-infinite body with finite length, and based on the boundary integral equation method, an accurate roll-to-roll

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flattening model was established. In addition, the 20-high mill simulation model based on the finite element method has high calculation accuracy because of few assumptions, but it is suitable for offline calculation due to the lengthy calculation time. Zhang et.al [10] established a three-dimensional 20-high mill finite element model with ANSYS and studied the contact pressure between rolls and the shape of the load roll gap. Li et.al [11] used the finite element method to establish a 20-high mill roll system and strip integrated elastic-plastic deformation statics model.

Besides the research on the simulation model of a 20-high mill, some scholars have also studied the quarter waves control of the 20-high mill. Hara et.al.[12] found that when rolling stainless steel on a 20-high mill, quarter waves could be effectively corrected by giving a concave profile partially to the 1st intermediate taper rolls. Faced with the disadvantages of difficulty in processing the concave roll contour of the 1st intermediate taper rolls, Kim et.al [13] studied the control ability of the intermediate multi-section taper roll contour on the quarter waves and found that quarter waves could be reduced remarkably by changing taper mode of the 1st intermediate roll. Aizawa et.al [14] found that the shape control range of quarter waves side and edge waves side was doubled by the introduced of FSBAs.

Currently, when cold rolling wide titanium strip with 1250 mm as the main width on a 20-high mill, it exhibits more complex flatness defect. During the cold rolling process from the entry thickness of 4.0 mm to the thickness of the finished product of 0.4 mm, the shape meter near the area 100 mm-300 mm from the edge shows compressive stress which indicating that this region and adjacent regions have uneven extension in the rolling direction, and the compression stress region extends relatively long, as shown in Fig.1. When rolling to thin gauges below 1.6mm, high-order waves begin to appear in the compressive stress area, as shown in Fig.2. Compared with quarter waves, it is closer to the edge. This research calls it high-order flatness defect.

Figure 1. Stress distribution on the shape meter.

Figure 2. High-order flatness defect. (a) during coiling; (b) during straightening.

The complex high-order flatness defect mentioned above proposes a new research subject, and it is necessary to study the high-order flatness defect control characteristics of 20-high mill. The roll system of the 20-high rolling mill has a complex structure, and the small roll diameter work roll is more prone to high-order deflection under the action of the rolling force. Coupled with the characteristics of anisotropic material in the elastoplastic stage of commercially pure titanium, the deformation behavior of the roll system and strip becomes quite complicated. Therefore, the study of high-order flatness defect requires a higher-precision calculation model.

However, the rolls-strip coupling model established by many scholars for 20-high mill with FEM belongs to the static model, which cannot realize the dynamic rolling between work rolls and strip. As a result, the contact arc length under the static model is twice than the actual situation, as shown in Figure 3. Thus, this research uses ABAQUS finite element software to establish an implicit integration calculation model of rolls-strip for 20-high mill that can realize dynamic rolling between work rolls and strip and analyzes the adjustment characteristics of shape control means.

Figure 3. Rolling deformation area. (a) under rotation model; (b) under static model.

2. Implicit FEM of rolls-strip integrated for 20-high mill

2.1 The structure of 20-high mill roll system

The roll system of 20-high mill is shown in Figure 4. The backing bearing is A, B, C, D, E, F, G, H, the 2nd intermediate roller is I, J, K, L, M, N, the 1st intermediate roller is O, P, Q, R, and the work roller is S, T. The 20-high mill is equipped with two kinds of shape control modes: crown adjustment of back-up rolls (AS-U) and the 1st intermediate taper roll online shifting. The overlapping length of the taper surface of the 1st intermediate roll and

the titanium strip is the amount of roll shifting. The rack of the AS-U adjustment mechanism is located between the B and C backup rolls. The AS-U adjustment mechanism had seven segments eccentric rings that could realize independent adjustment, as shown in Figure 5. Relative to the zero position of eccentric ring, the seven segments can realize eccentricity in the range of -0.28 mm to $+0.28\text{ mm}$, and the percentage can be adjusted from -100% to $+100\%$.

Figure 4. Roll system structure of 20-high mill.

Figure 5. The AS-U adjustment means of 20-high mill.

2.2 The model geometric parameters

The geometric dimensions of the rolls of 20-high mill are given in Table 1. The backup roll is comprised of mandrel, eccentric ring, backing bearing, and saddle. Ignoring the influence of the gap between these components, the backup roll is simplified into an integrated stepped structure, as shown in Figure 6. The 2nd intermediate roll and work roll adopt flat roll contour. The 1st intermediate roll adopts $230\text{ mm} \times 0.1\%$ single-sided taper roll contour (radius roll contour). The length of the

titanium strip is 40 mm and the width is 1250 mm, the thickness is 1.54 mm.

Table 1. Geometrical dimensions of rolls.

Roll	Length /mm	Diameter /mm
Backup roll	Fig.6	Fig.6
Second middle driving roll	1384	173
Second middle idler roll	1444	173
Intermediate roll	1580	102
Work roll	1414	63.5

Figure 6. The simplified structure of backup roll.

2.3 The model material parameters

In order to calculate the deflection and flattening state of the roll more accurately, the roll is defined as an elastic material in this model, as shown in Table 2.

Table 2. Roll material parameters.

Roll	Elasticity /MPa	Poisson ratio
Backup roll	2.19×10 ⁵	0.3
Second middle roll	2.05×10 ⁵	0.265
Intermediate roll	2.05×10 ⁵	0.265
Work roll	2.18×10 ⁵	0.28

The strip material is commercially pure titanium TA2, the main component (mass fraction %, Fe≤0.3, C≤0.1, N≤0.05, H≤0.015, O≤0.25, the rest is Ti). Because the symmetry of the hexagonal close-packed structure of pure titanium is not as good as that of body-centered cubic and face-centered cubic, the slip system and twinning modes are different when loading in different directions, so that under the same conditions, the anisotropy of the close-packed hexagonal structure is stronger. In order to make the characteristics of mechanical anisotropy of the strip be considered in the model, the strip is defined as an elastoplastic material with orthotropic anisotropy. Li et.al [15] studied the relationship between engineering constants and elastic matrix with the hexagonal crystal system structure. Wang et.al [16] proposed that the elastic matrix of the hexagonal crystal system has 5 independent components. The elastic matrix of commercially pure

titanium hexagonal crystal system expressed by engineering constants can be given:

$$\begin{bmatrix} \frac{1}{E_1} & -\frac{\mu_{12}}{E_1} & -\frac{\mu_{13}}{E_1} & 0 & 0 & 0 \\ -\frac{\mu_{12}}{E_1} & \frac{1}{E_2} & -\frac{\mu_{23}}{E_2} & 0 & 0 & 0 \\ -\frac{\mu_{13}}{E_1} & -\frac{\mu_{23}}{E_2} & \frac{1}{E_2} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{12}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{2(1+\mu_{23})}{E_2} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}} \end{bmatrix} \quad (1)$$

where 1 is the rolling direction, 2 is the lateral direction, and 3 is the thickness direction, 1, 2, 3 are the orthotropic principal axes, the rolling direction is the direction of the symmetrical principal axis of the hexagonal crystal system. E_i is the elastic modulus in the i direction, G_{ij} is the shear modulus between i and j direction, μ_{ij} is the Poisson's ratio of the shrinkage (extension) in the j direction caused by the tensile (compressive) stress in the i direction.

There are 5 independent elastic coefficients of commercially pure titanium TA2, which are $E_1, E_2, \mu_{12}, \mu_{23}, G_{12}$, the elastic stage parameters of commercially pure titanium TA2 can be obtained through the room temperature tensile test, as shown in Table 3.

Table 3. Material parameters of commercially pure titanium TA2 in elastic stage.

Variable description	Parameters	Value
Elastic modulus /MPa	E_1	102000
	E_2	112000
Poisson's ratio	μ_{12}	0.33
	μ_{23}	0.29
Shear modulus /MPa	G_{12}	38000

The deformation resistance of commercially pure titanium TA2 in the rolling direction is obtained through the compression test at room temperature, as shown in Table 4.

Table 4. Cold rolling deformation resistance of commercial pure titanium TA2.

Ture strain	Yield stress /MPa
0	439
0.1	596
0.2	695
0.3	766

In the research on plastic deformation of commercially pure titanium with significant anisotropy, Toussaint et.al [17] used the Hill'48 anisotropic yield criterion to simulate the stamping process of pure titanium scoliosis. Xue et.al [18] considered the material anisotropy when studying the deep drawing of commercially pure titanium and adopted the Hill'48 anisotropic yield criterion in the finite element simulation. In this study, the Hill'48 anisotropic yield criterion is used to describe the plastic deformation process of titanium strip. The Hill'48 anisotropic yield criterion is expressed by the following equation:

$$F(\sigma_{22} - \sigma_{33})^2 + G(\sigma_{33} - \sigma_{11})^2 + H(\sigma_{11} - \sigma_{22})^2 + 2L\sigma_{23}^2 + 2M\sigma_{31}^2 + 2N\sigma_{12}^2 = 1 \quad (2)$$

where F, G, H, L, M, N is the material parameters characterizing the anisotropy.

The material parameters characterizing the anisotropy can be calculated:

$$\begin{cases} F = \frac{1}{2\sigma_0^2} \left(\frac{1}{R_{22}^2} + \frac{1}{R_{33}^2} - \frac{1}{R_{11}^2} \right), L = \frac{3}{2\sigma_0^2 R_{23}^2} \\ G = \frac{1}{2\sigma_0^2} \left(\frac{1}{R_{22}^2} + \frac{1}{R_{33}^2} - \frac{1}{R_{11}^2} \right), M = \frac{3}{2\sigma_0^2 R_{13}^2} \\ H = \frac{1}{2\sigma_0^2} \left(\frac{1}{R_{22}^2} + \frac{1}{R_{33}^2} - \frac{1}{R_{11}^2} \right), N = \frac{3}{2\sigma_0^2 R_{12}^2} \end{cases} \quad (3)$$

where σ_0 is the reference yield stress, the yield stress in the rolling direction is used as the reference yield stress. R_{11}, R_{22}, R_{33} is the anisotropic yield stress ratio of principal axis 1, 2, 3, R_{12}, R_{13}, R_{23} is the anisotropic shear yield stress ratio relative to the principal axis 3, 2, 1.

The anisotropic yield stress ratio can be calculated:

$$\begin{cases} R_{11} = \frac{\sigma_X}{\sigma_0}, R_{12} = \sqrt{3} \frac{\tau_T}{\sigma_0} \\ R_{22} = \frac{\sigma_Y}{\sigma_0}, R_{23} = \sqrt{3} \frac{\tau_R}{\sigma_0} \\ R_{33} = \frac{\sigma_Z}{\sigma_0}, R_{13} = \sqrt{3} \frac{\tau_S}{\sigma_0} \end{cases} \quad (4)$$

where $\sigma_X, \sigma_Y, \sigma_Z$ is the yield stress in anisotropic principal axis direction, τ_T, τ_R, τ_S is the shear yield stress relative to the anisotropic principal axis. Because the metal sheet is thin, τ_R and τ_S cannot be obtained, this study assumes $\tau_R = \tau_S = \tau_T$.

Wang et.al [19] studied the anisotropic yield stress of commercially pure titanium TA2. This study determined the anisotropic yield stress ratio based on its research results, as shown in Table 5.

Table 5. Commercial pure titanium TA2 anisotropic yield stress ratio.

Parameters	Value
R_{11}	1.00
R_{22}	1.27
R_{33}	1.32
R_{12}	0.99
R_{13}	0.99

2.4 Mesh

In order to ensure the calculation accuracy of the model, the mesh size is refined in the contact area between the rolls and the contact area between the rolls and strip. Considering that the grid torsion is too large in the process of rolling large deformation, and the linear reduction integral element solves the displacement more accurately when the grid is deformed by torsion. Therefore, the roll and the strip adopt the eight-node linear hexahedral non-coordinating element (C3D8R), as shown in Figure 7.

Figure. 7 The FEM model of 20-high mill with the mesh refinement near the contact area.

2.5 Boundary conditions and loading settings

The model realizes the contact between rolls, work rolls and the titanium strip by defining contact pairs. There are 26 contact pairs in the model. The model will not consider the friction between the rolls. According to field production experience and the friction coefficient curve of the Stone cold rolling [20], the friction coefficient between the work roll and the titanium strip is set 0.05.

The tie restraint method is adopted in the model to fix the rigid ring at the position of the eccentric ring corresponding to the backup roll, and the backup roll pressing and AS-U functions are realized by applying constraints and movement to the reference point of the rigid ring. At the same time, the reference point is set at the center of the end faces of the work roll. The rotation of the work roll is realized by applying constraints and movement to the reference point.

2.6 Model evaluation

To ensure the accuracy of numerical experiments, this study verifies the section profile and rolling force. The section profile of the titanium strip after rolling is measured online using an ultrasonic thickness gauge with a resolution of 1 μm . The industry verification conditions of the FEM model are as shown in Table 6. The average value of the thickness deviation between the measured profile and the simulated profile is 0.65%, as shown in Figure 8. When the thickness of the simulated exit center point is in agreement with the measured thickness of the exit center point, the deviation of the rolling force between the measured rolling force and the simulated rolling force is 8.18%. Both the profile and the rolling force deviation are within 10%, indicating that the model has high calculation accuracy.

Table 6. The industry verification conditions of the FEM model.

Parameters	Value
Width strip/mm	1250
Entrance thickness/mm	1.555
Exit thickness/mm	1.208
Entrance tension/MPa	70
Exit tension/MPa	130
Amount of roll shift/mm	63
1# AS-U to 7# AS-U adjustment amount	-36%、19%、69%、12%、54%、-5%、-61%

Figure. 8 The comparison of measured and simulated thickness profiles.

3. Results and discussion

3.1 Lateral thickness difference after rolling without shape adjustment

In this part, the FEM model established above is used to calculate the rolled lateral thickness difference of the titanium strip without the shape adjustment. The simulation conditions are as shown in Table 7.

Table 7. The simulation conditions without shape adjustment.

Parameters	Value
Width strip/mm	1250
Entrance thickness/mm	1.540
Exit thickness/mm	1.211
Entrance tension/MPa	70
Exit tension/MPa	130
Amount of roll shift/mm	0
1# AS-U to 7# AS-U adjustment amount	0%

The lateral thickness difference after rolling is given in Figure 9. There is a local depression near the 100 mm-300 mm from the edge. This study defines the 100 mm-300 mm from the edge as the high-order flatness defect area, which is consistent with the compressive stress of the shape meter. It shows that the occurrence of high-order flatness defect is related to the local thickness reduction of the strip after rolling.

Figure. 9 Lateral thickness difference after rolling without shape adjustment.

In order to quantify the degree of depression in the high-order flatness defect area, according to the characteristics of depression in the thickness profile after rolling, the value of depression in the high-order flatness defect area can be calculated:

$$\gamma = \frac{(h_e + h_c)}{2} - h_d \quad (5)$$

where γ is the value of depression in the high-order flatness defect area. h_e is the thickness of the highest point near the edge of the titanium strip in the high-order flatness defect area, in order to reduce the influence of the volatility error of the simulation data, generally take the average value in the range of 10 mm near the highest point of the titanium strip edge. h_c is the thickness of the middle part of the titanium strip, in order to reduce the influence of the volatility error of the simulation data, generally take the average thickness in the range of 200 mm from the center of the titanium strip. h_d is the thickness of the lowest point in the high-order flatness defect area, in order to reduce the influence of the volatility error of the simulation data, generally take the average thickness in the range of 10 mm near the lowest thickness point.

The cold rolling process is a high tension rolling process, and the width of the strip is small. When the lateral thickness of the strip has uneven changes, it will cause uneven distribution of the longitudinal extension of the strip along the transverse direction, resulting flatness defect. Zhao et.al [21] studied the influence of lateral metal flow on the residual stress during hot rolling, and gave the relationship between the thickness and length of the strip before and after rolling without considering the lateral flow.

If the strip is divided into several equal width fiber strips along the transverse direction, the relationship between the length and thickness of a certain position fiber strip before and after rolling can be calculated:

$$l(y) = \frac{H(y)}{h(y)} \times L(y) \quad (6)$$

where $H(y)$ is the thickness before rolling at the y position. $L(y)$ is the length before rolling at the y position. $h(y)$ is the thickness after rolling at the y position. $l(y)$ is the length after rolling at the y position.

The lowest thickness after rolling in the high-order flatness defect area can be calculated:

$$h_\gamma = h_{aim} - \gamma \quad (7)$$

where h_γ is the lowest thickness after rolling in the high-order flatness defect area. h_{aim} is the target thickness after rolling in the high-order flatness defect area, this study is 1.211 mm. γ is calculated by formula (5).

The rolled length of the target thickness and the lowest thickness in the high-order flatness defect area can be calculated:

$$\begin{cases} l_{aim} = \frac{H}{h_{aim}} \times L \\ l_\gamma = \frac{H}{h_\gamma} \times L \end{cases} \quad (8)$$

where H is the thickness before rolling in the high-order flatness defect area, this study is 1.540 mm. L is the length before rolling in the high-order flatness defect area, this study is 1000 mm. h_{aim} and h_γ can be calculated by formula (7).

Flatness expressed by relative length difference can be calculated:

$$\lambda = \frac{\Delta l}{l} \times 10^5 \quad (9)$$

where λ is flatness value. Δl is the difference between the free fiber length after rolling and the standard fiber length after rolling. l is the standard fiber length after rolling.

By substituting formula (8) into equation (9):

$$\lambda_\gamma = \frac{h_{aim} - h_\gamma}{h_\gamma} \times 10^5 \quad (10)$$

where λ_γ is the flatness value caused by the local depression in the high-order flatness defect area, unit is IU.

The value of depression in the high-order flatness defect area (γ) is 1.7 μm , and the flatness value caused by the local

depression in the high-order flatness defect area (λ_y) is 140.6 IU. This shows that the local depression in the thickness profile after rolling will increase the length extension in the high-order flatness defect area, which leads to the high-order flatness defect.

3.2 Lateral thickness difference after rolling under AS-U press adjustment

The AS-U press adjustment is one of the essential shape control methods. It can adjust the lateral thickness of the titanium strip in real time through seven segments of eccentric rings. The diversity of transverse thickness control can be achieved through multiple combinations of 7 segments eccentric rings. In order to ensure the symmetry of the thickness profile in rolling process to prevent the occurrence of strip centerline deviation, in real time adjustment, the symmetrical position AS-U adjustment change should be as consistent as possible. Therefore, the AS-U press adjustment that is symmetrically distributed along the centerline of 20-high mill is basic form of AS-U adjustment. It is easy to know that the symmetrical position AS-U lifting adjustment characteristics should be opposite to the press adjustment characteristics. This study analyzes the adjustment characteristics of the symmetrical position AS-U press adjustment method to the high-order flatness defect. The simulation conditions are as shown in Table 8.

Table 8. The simulation conditions under AS-U press adjustment.

Parameters	Value
Width strip/mm	1250
Entrance thickness/mm	1.540
Exit thickness/mm	1.211
Entrance tension/MPa	70
Exit tension/MPa	130
Amount of roll shift/mm	0
1# AS-U to 7# AS-U	symmetrical position
adjustment amount	AS-U control +100%

The lateral thickness difference after rolling is shown in Figure 10. After the four groups of symmetrical position AS-U combinations control, there is local thickness depression near the 100 mm-300 mm area from the edge, which shows that the symmetrical position AS-U press adjustment cannot completely eliminate thickness depression in the high-order flatness defect area.

Figure. 10 Lateral thickness difference after rolling under AS-U press adjustment. (a) 1#&7# AS-U; (b) 2#&6# AS-U; (c) 3#&5# AS-U; (d) 4# AS-U.

After the symmetrical position AS-U combination control, the value of depression γ and the flatness value caused by the local depression λ_γ are in Table 9. After 1#&7# AS-U press adjustment, the value γ and λ_γ increased by 17.6% and after 2#&6# AS-U press adjustment, the value γ and λ_γ increased by 29.4%, 2#&6# AS-U press adjustment will aggravate the high-order flatness defect more easily. After 3#&5# AS-U and 4# AS-U press adjustment, the value γ and λ_γ decreased by 41.2%.

In order to better grasp the symmetrical position AS-U press adjustment characteristics on high-order flatness defect area, it is also necessary to master the symmetrical position AS-U press adjustment characteristics on the full width of titanium strip. This study uses the lateral thickness difference between AS-U press adjustment and without the AS-U press adjustment as the variation of thickness profile, as shown in Figure 11. It can be founded that increasing 1#&7# AS-U or 2#&6# AS-U press adjustment will decrease significantly the thickness of the 0 mm-75 mm area from the edge and aggravate the thickness depression in the high-order flatness defect area. The thickness of 0 mm-75 mm away from the edge decreasing ability of 2#&6# AS-U press adjustment is 2.6 times of that of 1#&7# AS-U press adjustment. In addition, increasing 3#&5# AS-U or 4# AS-U press adjustment will increase significantly the thickness of the 0 mm-75 mm area from the edge and relieve the thickness depression in the high-order flatness defect area. The thickness of 0-75 mm away from the edge increasing ability of 3#&5# AS-U press adjustment is 1.6 times of that of 4# AS-U press adjustment. In the case of large tension in cold rolling, the increase of tensile stress at the edge is easy to cause strip breakage, 4# AS-U press adjustment is more conducive to alleviate the high-order flatness defect.

Table 9. The γ and the λ_γ after AS-U press adjustment.

Parameters	1#&7#	2#&6#	3#&5#	4#
$\gamma/\mu\text{m}$	2.0	2.2	1.0	1.0
λ_γ/IU	165.4	182.0	82.6	82.6

Figure. 11 Variation of section thickness under the press adjustment of symmetrical position AS-U. (a) 1#&7# AS-U or 2#&6# AS-U; (b) 3#&5# AS-U or 4# AS-U.

3.3 Lateral thickness difference after rolling under roll shift adjustment

The 1st intermediate taper roll can adjust the thickness of the edge area through online shifting. Therefore, the roll shifting adjustment is another important shape control method for a 20-high mill. This study analyzes the adjustment characteristics of the amount of roll shifting to the high-order flatness defect. The simulation conditions are as shown in Table 10.

Table 10. The simulation conditions under roll shift adjustment.

Parameters	Value
Width strip/mm	1250
Entrance thickness/mm	1.540
Exit thickness/mm	1.211
Entrance tension/MPa	70
Exit tension/MPa	130
Amount of roll shift/mm	30/50/70
1# AS-U to 7# AS-U	0%

adjustment amount

The lateral thickness difference after rolling is shown in Figure 12. After different amount of roll shift adjustment, there is local thickness depression near the 100 mm-300 mm area from the edge, which shows that roll shift adjustment also cannot completely eliminate thickness depression in the high-order flatness defect area.

Figure 12 Lateral thickness difference after rolling under roll shift adjustment. (a) roll shift 30 mm; (b) roll shift 50 mm; (c) roll shift 70 mm.

After the roll shift adjustment, the value of depression γ

and the flatness value caused by the local depression λ_γ are in Table 11. It can be found that there is no obvious change in the value of depression under different amount of roll shifting and the roll shift adjustment cannot effectively alleviate high-order flatness defect.

Table 11. The γ and the λ_γ after roll shift adjustment.

Parameters	Amount of roll shift/mm		
	30	50	70
$\gamma/\mu\text{m}$	1.7	1.8	1.7
λ_γ/IU	140.6	148.9	140.6

In order to compare the thickness change across the strip width after roll shift adjustment, this study uses the lateral thickness difference between the roll shift adjustment and without the roll shift adjustment as the variation of thickness profile, as shown in Figure 13. It can be founded that increasing amount of roll shift will increase significantly the thickness of the 0 mm-75 mm area from the edge. After the roll shift adjustment of 30 mm, 50 mm and 70 mm, the thickness of 0 mm -75 mm away from the edge will be increased 22.3%, 38.9%, 53.1% respectively. But there is no obvious change in the thickness of the other area.

Figure 13. Variation of section thickness under roll shift adjustment.

3.4 Industry test of 4# AS-U press adjustment characteristics

This study uses the 20-high mill FEM model to analysis the adjustment characteristics of the high-order flatness defect by two adjustment methods, and finds that the 3#&5# AS-U or 4# AS-U press adjustment can alleviate the local thickness depression in the high-order flatness defect area and thus reduce the compressive stress in the

high-order flatness defect area. In addition, when increasing 4# AS-U press adjustment, the thickness of the range of 0 mm-75 mm from the edge will increase and the thickness of the range of 200mm away from the center point will decrease. In other words, after 4v# control, the change value of the shape stress in the 0 mm -75mm area develops in the direction of tensile stress, and the shape stress in the area 200mm away from the center point develops in the direction of compressive stress. The industry test parameters are shown in table 12.

Table 12. Industry test condition of 4# AS-U adjustment.

Parameters	Value
Width strip/mm	1250
Entrance thickness/mm	2.850
Exit thickness/mm	2.323
Entrance tension/MPa	70
Exit tension/MPa	120
Amount of roll shift/mm	46.8
AS-U adjustment amount	16%、-18%、19%、-
in other positions	16%、-1%、22%
4# AS-U adjustment amount before test	-3%
4# AS-U adjustment amount after test	+11%

The stress distribution on the shape meter before and after the industry test is shown in Figure 14. It can be found that the stress distribution has changed after increasing 4# AS-U press adjustment. The variation of stress distribution after 4# AS-U press adjustment is shown in Figure 15. The thickness decreases in the range of 200 mm from the center point, leading the stress distribution in this area to develop in the direction of compressive stress, simultaneously, the thickness of the high-order flatness defect area and the range of 0 mm-75 mm from the edge increases, leading the stress distribution in this area to develop in the direction of tensile stress. It shows that 4# AS-U press adjustment can alleviate high-order flatness defect to a certain extent. In addition, it also shows that the FEM model result can be highly consistent with the industry test result.

Figure. 14 4# AS-U adjustment test. (a) before industry test; (b) after industry test.

Figure. 15 The variation of stress distribution after industry test.

4. Conclusions

(1) Based on ABAQUS finite element software, an implicit integration calculation model of rolls-strip for 20-high mill is established, which considers the anisotropic mechanical characteristics of commercially pure titanium and can realize dynamic rolling process. By comparing with the industry data, the thickness deviation of the section was 0.65% and the rolling force deviation was 8.18%.

(2) The FEM model is used to calculate the adjustment characteristics of high-order flatness defect on two shape adjustment methods of 20-high mill, and it is found that the adjustment of roll shift cannot effectively control the high-order flatness defect, that 1#&7# AS-U or 2#&6# AS-U

press adjustment will increase the degree of high-order flatness defect, and that 3# AS-U or 4# AS-U can alleviate the degree of high-order flatness defect to a certain extent.

(3) According to the industry test, the compressive stress in the high-order flatness defect decreased after increasing the 4# AS-U press adjustment amount. The industry test result is consistent with the FEM model result, further verifying the high reliability of the 20-high mill model in this study.

Availability of data and materials

Not applicable

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Authors' contributions

GZ is responsible for writing the entire paper and conducting the simulation model. HL provided advice on the abstract. AH supervised the entire paper. CL and SC checked the validation results. WS provided advice on the conclusion. ZL and CH guided the industrial test. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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Figures

Figure 1

Stress distribution on the shape meter.

Figure 2

High-order flatness defect. (a) during coiling; (b) during straightening.

Figure 3

Rolling deformation area. (a) under rotation model; (b) under static model.

Figure 4

Roll system structure of 20-high mill.

Figure 5

The AS-U adjustment means of 20-high mill.

Figure 6

The simplified structure of backup roll.

Figure 7

The FEM model of 20-high mill with the mesh refinement near the contact area.

Figure 8

The comparison of measured and simulated thickness profiles.

Figure 9

Lateral thickness difference after rolling without shape adjustment.

Figure 10

Lateral thickness difference after rolling under AS-U press adjustment. (a) 1#&7# AS-U; (b) 2#&6# AS-U; (c) 3#&5# AS-U; (d) 4# AS-U.

Figure 11

Variation of section thickness under the press adjustment of symmetrical position AS-U. (a) 1#&7# AS-U or 2#&6# AS-U; (b) 3#&5# AS-U or 4# AS-U.

Figure 12

Lateral thickness difference after rolling under roll shift adjustment. (a) roll shift 30 mm; (b) roll shift 50 mm; (c) roll shift 70 mm.

Figure 13

Variation of section thickness under roll shift adjustment.

Figure 14

4# AS-U adjustment test. (a) before industry test; (b) after industry test.

Figure 15

The variation of stress distribution after industry test.