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Development of Roller Ends Forced-Contact Model and Cambering Technology for UCM Temper Mill (I)*

——Development of Roller Ends Forced-Contact Model and the Computational Model of Flatness for UCM Temper Mill

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Abstract

Roller ends forced-contact and overmuch roll consumption are the widespread problems in temper rolling process of thin strip for two-stand UCM temper mill. Fully thinking the equipment and technology characteristics of UCM temper mill, we took the newly-built 1220 UCM temper mill of Baosteel as the research object in this paper. A model of roller ends forced-contact and a calculation model of flatness for UCM temper mill are established after a great deal of site tracing and theoretical researches. On this basis, an optimal mathematical model of roll shape which is suited for UCM temper mill is developed. Working roll curve is the combination of cosine curve and high order curve. The cosine subentry is used to control edge wave, the high order curve subentry is used to control roller ends forced-contact. Furthermore, the chamfering curve of middle roller end is optimized. Those are the innovations. Through the above-mentioned technology, pressure distribution between rollers caused by the shift of middle roll becomes more homogeneous, pressure peak disappeared, working life of roll is improved effectively as well. Relevant technologies have been used to the practice of 1220 UCM temper mill of Baosteel and have achieved good use effects, which is of further extending application value [1].

Keywords: UCM, Temper Mill, Forced-Contact, Roll Shape, Roll Consumption

1. Introduction

Cold rolled thin strip production developed rapidly with the huge demand in household appliances, automobile, electronic, can-manufacturing in recent years. Temper rolling is the process nearest to finished product, it plays a vital role to the shape and mechanical property of rolled strip. In addition, it is found in practice that the contact of working rolls outside the plate width will appear when thin and narrow strip are temper rolled. The forced-contact of working roller ends will lead to that only partial presetting rolling force are used to make the metal deformed and the rest cause the roller ends squashed which will lead to the actual elongation is smaller than design value. And the product performance will not meet the users' demand. Moreover, after the forced-contact of working roller ends happened, the rolling force consumed in the flattening of roller ends also increased with the increase of presetting rolling force. The increased rolling force will waste in the forced-contact of working roller ends mostly when the rolling force increases to the certain extent. So that the increase of rolling force not only failed to increase elongation, but will shorten the rollers' lifespan. Particularly, if the original shape model is still used, strip shape will not reach the target and even bring new shape defects.

Formerly, the cambering of four high cold mill in production site only aimed to a single wave, for example,

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when there are many edge waves, the convex roll-shape of working roll and backup roll is often adopted; when there are many center waves, the disposition form of roll configuration curves is the concave roll-shape of working roll and plain roll-shape of backup roll. These above disposition forms of roll configuration curves often can't do anything about complex waves, even will lead to new wave defects. So, how to calculate the forced-contact value and relevant shape value accurately in the process of temper rolling and provide a relevant compensation technique is the emphasis of field tackling key problems. Therefore, a model of roller ends forced-contact and a computational model of flatness which is suited for UCM temper mill is established after lots of field tracing and theoretical research. Moreover, on the basis of this, starting with the roll crown optimization of working rolls and intermediate rolls, strip shape, roll consumption and the management of roll forced-contact are considered as well. A mathematical model of roll crown optimization which is suited for the working rolls and intermediate rolls of UCM temper mill is developed. Relevant technologies have been used to the practice of 1220 UCM temper mill of Baosteel and have achieved good use effects, which is of further extending application value.

2. The Model of Roller Ends Forced-Contact and Shape Calculation for the Process of UCM Temper Rolling

2.1. Introduction of Roller Ends Forced-Contact

What is called the forced-contact of roller ends is refer to the phenomenon that the contact of working rolls outside the plate width when paper-thin strip is temper rolled. As shown in **Figure 1**.

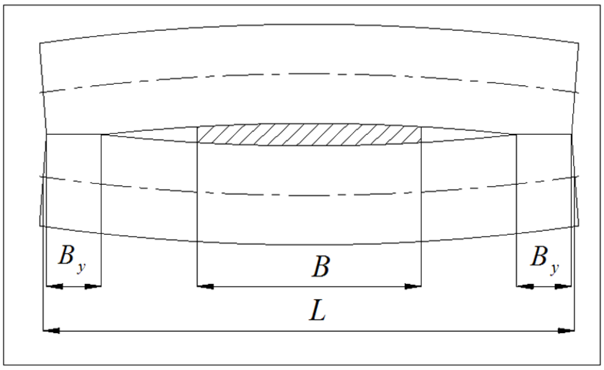

Figure 1. The Schematic diagram of the forced-contact of roller ends.

2.2. Establishment of the Model of Forced-Contact Value, Contact Width, Rolling Force and Shape of UCM Temper Mill

What can know after analysis is the model of mental deformation within the plate width still holds true even though the forced-contact of roller ends exists. Based on relevant model, the function of forward and backward tension (σ_{1i} and σ_{0i}) can be shown as follows:

$$\sigma_{1i} = f_1\left(\delta_{1i}, \delta_{0i}, L_i, B, T_0, T_1\right) \quad (1)$$

$$\sigma_{0i} = f_0\left(\delta_{1i}, \delta_{0i}, L_i, B, T_0, T_1\right) \quad (2)$$

where δ_{1i} is the transverse distribution value of strip thickness in exit, δ_{0i} is the transverse distribution value of strip thickness in entry, L_i is the transverse distribution value of length and used to express the incoming profile, B is the width of strip, T_0 is the average backward tension, T_1 is the average forward tension.

What is different is an additional pressure stress should be applied to the section of working roll which is outside the plate width in the load-carrying model of roller system if the forced-contact of roller ends is considered. As shown in **Figure 2**.

The model for elastic deformation of rolls still adopt the section dispersed way when the forced-contact of roller ends is considered, as shown in **Figure 2**. Assuming that the rolling force along the axis of roller is $q_z(x)$, the pressure between intermediate roll and working roll is $q_{mw}(x)$, the pressure between intermediate roll and back-up roll is $q_{mb}(x)$, the contacting pressure between working roll and working roll is $q_z(x)$. Assuming that the face length of working roll is l_w and be divided into N sections (N is odd), the number of sections correspond to working roll's left is NL, and the length of each section is $\Delta x = \frac{l_w}{N}$. In order to analyze conveniently, the pressure between rolls are expressed with $q_z(i)$, $q_{mw}(i)$, $q_{mb}(i)$, $q_y(i)$ respectively. The bending deflection equation for the left and right sides of working roll can be expressed as follows [2]:

$$f_{wl}(i) = \sum_{j=1}^{NL}\left[q_{mw}(j) - q_z(j)\right]G_w(i,j) - F_{WL}G_{Fw}(i) - \theta_w x(i) \quad (3)$$
$$1 \le i \le NL$$

$$f_{wr}(i) = \sum_{j=NL+2}^{N}\left[q_{mw}(j) - q_z(j)\right]G_w(i,j) - F_{WR}G_{Fw}(i) - \theta_w x(i) \quad (4)$$
$$NL + 2 \le i \le N$$

where F_{WL}, F_{WR} is the bending force acting on the left and right sides of working roll, $q_{mw}(i)$ is the pressure of i point between intermediate roll and working roll, $q_z(i)$ is the rolling force of i point, $q_y(i)$ is the contacting

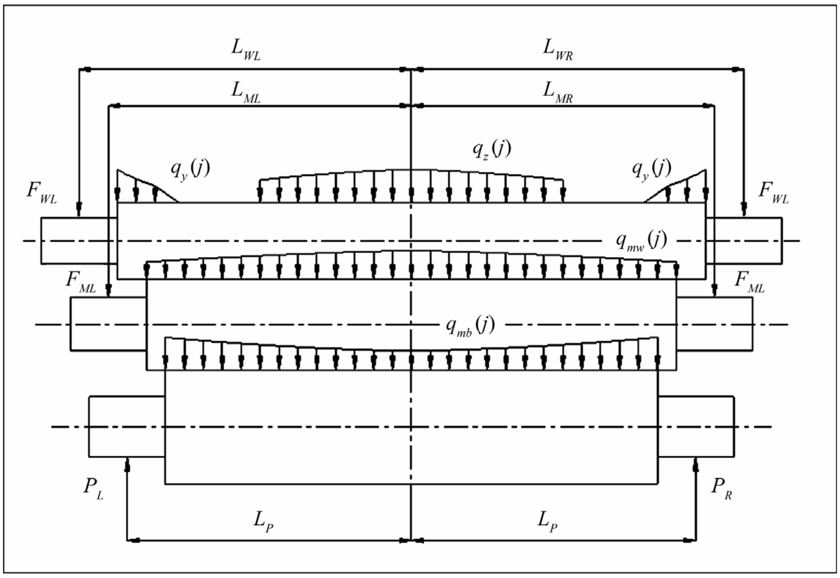

Figure 2. The Schematic diagram of force analysis of roller system when consider the forced-contact of roller ends.

pressure of *i* point between working roll and working roll, θ_w is the rigid corner of working roll which is relative to the rigid corner of back-up roll, *NL* is the number of sections which are correspond to the left part of working roll's medium line. $G_w(i, j)$ is the influence coefficient that the load of *j* section to the deflection of working roll's *i* section, it is the function of $x = (i - NL - 1)\Delta x$ and $x' = (j - NL - 1)\Delta x$:

$$G_w(i,j) = \begin{cases} k_1\left[\left(\frac{2x}{L_W}\right)^2\left(3\left(\frac{2x'}{L_W}\right)-\frac{2x}{L_W}\right)+(1+\nu)\frac{3k}{4}\left(\frac{2x}{L_W}\right)\left(\frac{2D_w}{L_W}\right)^2\right], & 0 \le x < x' \\ k_1\left[\left(\frac{2x'}{L_W}\right)^2\left(3\left(\frac{2x}{L_W}\right)-\frac{2x'}{L_W}\right)+(1+\nu)\frac{3k}{4}\left(\frac{2x}{L_W}\right)\left(\frac{2D_w}{L_W}\right)^2\right], & x' \le x \le \frac{L_W}{2} \end{cases} \quad (5)$$

where $k_1 = \frac{L_W{}^3}{48EI_w}$, $I_W = \frac{\pi D_w^4}{64}$, $k = 1.11$, L_W is the face length of working roll; $G_{Fw}(i)$ is the influence coefficient that the bending load F_w to the deflection of working roll's *i* section, the expression of $G_{Fw}(i)$ as follows:

$$G_{Fw}(i) = k_1\left[\left(\frac{2x}{L_W}\right)^2\left(3\left(\frac{l_x}{L_W}\right)-\frac{2x}{L_W}\right)+(1+\nu)\frac{3k}{4}\left(\frac{2x}{L_W}\right)\left(\frac{2D_w}{L_W}\right)^2\right] \quad 0 \le x < \frac{L_W}{2} \quad (6)$$

where l_x is the length of from working roll's one end to the center line (the length of actuating arm) To the F_{WL}, $l_x = L_{WL}$, but to the F_{WR}, $l_x = L_{WR}$.

In addition, the bending deflection equation along the vertical direction of intermediate roll is

Left side:

$$f_{ml}(i) = \sum_{j=1}^{NL}\left[q_{mb}(j) - q_{mw}(j)\right]G_m(i,j) - F_{ML}G_{Fm}(i) - \theta_m x(i) \quad 1 \le i \le NL \quad (7)$$

Right side:

$$f_{mr}(i) = \sum_{j=NL+2}^{N}\left[q_{mb}(j) - q_{mw}(j)\right]G_m(i,j) - F_{MR}G_{Fm}(i) - \theta_m x(i) \quad NL+2 \le i \le N \quad (8)$$

where F_{ML}, F_{MR} is the bending force acting on the left and right sides of intermediate roll; $q_{mb}(j)$ the pressure between intermediate roll and back-up roll; θ_m is the rigid corner of intermediate roll; $G_m(i, j)$ is the influence coefficient that the load of *j* section to the deflection of intermediate roll's *i* section, $G_{Fm}(i)$ is the influence coefficient that the bending load of intermediate roll to the deflection of intermediate roll's *i* section.

Here, the expressions of $G_m(i,j)$ and $G_{Fm}(i)$ approximate to the expressions of $G_w(i,j)$ and $G_{Fw}(i)$. So, the expressions of $G_m(i,j)$ and $G_{Fm}(i)$ can be obtained through the replacement of intermediate roller's parameters and working roller's parameters [3].

So, the bending deflection equation along the vertical direction of back-up roll is:

Left side:

$$f_{bl}(i) = -\sum_{j=1}^{NL} q_{mb}(j) G_b(i,j) + P_L G_P(i) \qquad 1 \le i \le NL \tag{9}$$

Right side:

$$f_{br}(i) = -\sum_{j=NL+2}^{N} q_{mb}(j) G_b(i,j) + P_R G_P(i) \qquad NL+2 \le i \le N \tag{10}$$

where P_L, P_R is the support force acting on the left and right sides of back-up roll; $G_b(i,j)$ is the influence coefficient that the load of *j* section to the deflection of back-up roll's *i* section; $G_P(i)$ is the influence coefficient that the support force to the deflection of back-up roll's *i* section

Here, $G_b(i,j)$ and $G_P(i)$ approximate to the expressions of $G_w(i,j)$ and $G_{Fw}(i)$, So, they can be obtained through the replacement of back-up roller's parameters and working roller's parameters.

The deformation compatibility equation of working roll and intermediate roll:

$$f_{wi} = f_{mi} + K_{mw}\left[q_{mw}(NL+1) - q_{mw}(i)\right] - \frac{\Delta D_{wi} + \Delta D_{mi}}{2} \tag{11}$$

where $\Delta D_{wi} = D_{w1} - D_{wi}$, $\Delta D_{mi} = D_{m1} - D_{mi}$, K_{mw} is flattening coefficient between working roll and intermediate roll, and its expression is:

$$K_{mw} = 2\left[\frac{1-\nu^2}{\pi E}\left(\ln\frac{2R_w}{b_{mw}} + 0.407\right) + \frac{1-\nu^2}{\pi E}\left(\ln\frac{2R_m}{b_{mw}} + 0.036\right)\right] \tag{12}$$

where b_{mw} is half the contacting width of intermediate roll and working roll, and its expression can be obtained from Hertz formula:

$$b_{mw} = \sqrt{\frac{4}{\pi} q_{mw}^* \left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E}\right)\frac{R_w R_m}{R_w + R_m}} \tag{13}$$

where q_{mw}^* is contacting pressure per unit of face length between intermediate roll and working roll, ν_1, ν_2 are the poisson's ratio of working roll and intermediate roll, E_1, E_2 are young modulus of working roll and intermediate roll, R_w, R_m are radius of working roll and intermediate roll.

Considering that the material of working roll and intermediate roll is same, so the above formula can be written as follows:

$$b_{mw} = \sqrt{\frac{4\left(1-\nu^2\right)}{\pi}\frac{q_{mw}^*}{E}\frac{D_w D_m}{D_w + D_m}} \tag{14}$$

The deformation compatibility equation of intermediate roll and back-up roll:

$$f_{mi} = f_{bi} + K_{mb}\left[q_{mb}(NL+1) - q_{mb}(i)\right] - \frac{\Delta D_{bi} + \Delta D_{mi}}{2} \tag{15}$$

where K_{mb} is the flattening coefficient between intermediate roll and back-up roll, its expression approximate to the expression of K_{mw} and can be obtained through the replacement of R_w and R_m, R_m and R_b. Substituting each deflection and flattening coefficient into the two above deformation compatibility equation. For the deformation compatibility equation of working roll and intermediate roll:

Left side:

$$\begin{aligned}&\sum_{j=1}^{NL} q_{mw}(j)\left[G_w(i,j) + G_m(i,j)\right] + K_{mw} q_{mw}(i) - K_{mw} q_{mw}(NL+1) - \sum_{j=1}^{NL} q_{mb}(j) G_m(i,j) - (\theta_w - \theta_m) x(i) = C_i \\ &C_i = \sum_{j=1}^{nz} G_w(i,j) q_z(j) + F_{WL} G_{Fw}(i) - F_{ML} G_{Fm}(i) - \frac{\Delta D_{wi} + \Delta D_{mi}}{2} \qquad 1 \le i \le NL\end{aligned} \tag{16}$$

Right side:

$$\begin{aligned}&\sum_{j=NL+2}^{N} q_{mw}(j)\left[G_w(i,j) + G_m(i,j)\right] + K_{mw} q_{mw}(i) - K_{mw} q_{mw}(NL+1) - \sum_{j=NL+2}^{N} q_{mb}(j) G_m(i,j) - (\theta_w - \theta_m) x(i) = C_i \\ &C_i = \sum_{j=NL+2}^{N} G_w(i,j) q_z(j) + F_{WR} G_{Fw}(i) - F_{MR} G_{Fm}(i) - \frac{\Delta D_{wi} + \Delta D_{mi}}{2} \qquad NL+2 \le i \le N\end{aligned} \tag{17}$$

For the deformation compatibility equations of intermediate roll and back-up roll:

Left side:

$$\sum_{j=1}^{NL} q_{mb}(j)\left[G_m(i,j)+G_b(i,j)\right]+K_{mb}q_{mb}(i)-K_{mb}q_{mb}(NL+1)-\sum_{j=1}^{NL} q_{mw}(j)G_m(i,j)-\theta_m x(i)=D_i$$
$$D_i=F_{ML}G_{Fm}(i)+P_L G_{Fb}(i)-\frac{\Delta D_{mi}+\Delta D_{bi}}{2}\quad 1\le i\le NL \tag{18}$$

Right side:

$$\sum_{j=NL+2}^{N} q_{mb}(j)\left[G_m(i,j)+G_b(i,j)\right]+K_{mb}q_{mb}(i)-K_{mb}q_{mb}(NL+1)-\sum_{j=NL+2}^{N} q_{mw}(j)G_m(i,j)-\theta_m x(i)=D_i$$
$$D_i=F_{MR}G_{Fm}(i)+P_R G_{Fb}(i)-\frac{\Delta D_{mi}+\Delta D_{bi}}{2}\quad NL+2\le i\le N \tag{19}$$

And then, the number of unknown number is $2N+2$ in the above system of equations, but the number of equations is $2N-2$ in the above system of equations, there are lack of two equations of force equilibrium and two equations of momental equilibrium.

The equations of force equilibrium as follows:

$$\sum_{j=1}^{N} q_z(j)+F_{WL}+F_{WR}=\sum_{j=1}^{N} q_{mw}(j) \tag{20}$$

$$\sum_{j=1}^{N} q_{mw}(j)+F_{ML}+F_{MR}=\sum_{j=1}^{N} q_{mb}(j)=P_L+P_R \tag{21}$$

The equation of momental equilibrium for working rolls as follows:

$$\sum_{i=1}^{N} q_{mw}(i)x(i)=\sum_{i=1}^{N} q_z(i)x(i)+F_{WR}L_{WR}-F_{WL}L_{WL} \tag{22}$$

The equation of momental equilibrium for back-up rolls as follows:

$$\sum_{i=1}^{N} q_{mb}(i)x(i)=P_R L_{PR}-P_L L_{PL} \tag{23}$$

And then, both the number of unknown number and the number of equations are $2N+2$, so, the solutions can be obtained.

The deflection of working roll can be computed after getting the above solutions, and then h_i can be computed as well based on the following formulas:

$$h_i=\begin{cases} h_1-f_{wi}^u-f_{wi}^d-2K'\left[q_z(NL+1)-q_z(i)\right]+\dfrac{\Delta D_{wi}}{2}, & \text{(without contact)}\\ h_1-f_{wi}^u-f_{wi}^d-2K'q_z(NL+1)+2K_{ww}q_y(i)+\dfrac{\Delta D_{wi}}{2}, & \text{(having contact)}\end{cases} \tag{24}$$

where K' is the flattening coefficient between working roll and rolled piece , and its expression is [4]:

$$K'=\theta\left[\ln\frac{4R_w}{\Delta h+16\theta q'}+\frac{32\theta q'}{\Delta h+16\theta q'}\right] \tag{25}$$

Here, $\theta=\dfrac{1-\nu^2}{\pi E}$, Δh is absolute gauge reduction, q' is the force that acts on per unit of face length. K_{ww} is the flattening coefficient between working roll and working roll, its expression is similar to the expression of K'.

It should be noted that h_i is the concept of roll gap broadly. Within the width of strip, h_i represents the gauge distribution of strip in exit; but in the section of roll's contact, h_i is a negative and its absolute value represents the level of roll's forced-contact; outside the width of strip represents apparent roll gap.

Then, based on the above analysis, the following formula existed:

$$q_y(i)=\begin{cases}0 & h_i>0\\ h_i/(2\cdot K_{ww}), & h_i\le 0\end{cases}\quad 1\le i<N \tag{26}$$

Obviously, if $h_i<0$ existed from k point, which means the forced-contact between rolls appeared from k point. Assuming that the number of $h_i<0$ is k_1 on the left, and the number of $h_i<0$ is k_2 on the right, the width of roll's forced-contact is B_y, B_y satisfy the following formula:

$$B_y=(k_1+k_2)\cdot\Delta x \tag{27}$$

δ_i, the amount of roll's forced-contact can be expressed with the following formula:

$$\delta_i=\frac{|h_i|}{2}\quad 1\le i\le k_1 \ \text{ or } \ N-k_2\le i\le N \tag{28}$$

Now, P_Z', the actual rolling force is:

$$P_Z'=P_Z+\sum_{i=1}^{N} q_y(i) \tag{29}$$

Last, coupling (1) to (29), σ_{1i} the strip shape; B_y width of roll's forced-contact; δ_i the amount of roll ends' forced-contact and P_Z' the actual rolling force all can be obtained.

2.3. The Field Test of the Model of Roller Ends Forced-Contact and the Computational Model of Flatness for UCM Temper Mill

In order to verify the correctness of relevant models introduced in 2.2, the second stand of 1220 UCM temper mill of Baosteel was taken as research object particularly. The working roll, intermediate roll and back-up roll were all flat roll. 0.15 × 718 mm was chosen as specimen to do the forced-contact test (related equipments and process parameters as shown in the following **Table 1**). The value of contact width, actual rolling force and strip shape were given though test and also computed through the models at the same time.(It should be noted that the cutting method was adopted for the temper mill don't have shape meter.) And then, error analysis was proceeded through the comparison of test value and computed value, the results of error analysis are shown in the following **Table 2**. After the forced-contact test, the production of this specification proceeded with the elongation of 1.0% until roll changing. The length of rolling this moment was recorded in the following **Table 2** as well. It should be noted that the way to compute flatness errors is the following Equation (30). The following Equation (31) and Equation (32) are used to compute the maximum of computed shape value and actual shape value.

$$\Delta I = \sqrt{\sum_{i=1}^{20}\left(I_{1i} - I'_{1i}\right)^2} \tag{30}$$

$$I'_{\max} = \max\left\{I'_{1i}\right\} - \min\left\{I'_{1i}\right\} \tag{31}$$

$$I_{\max} = \max\left\{I_{1i}\right\} - \min\left\{I_{1i}\right\} \tag{32}$$

where ΔI is the flatness errors, I'_{1i} is the actual shape

Table 1. Equipments and process parameters of forced-contact test.

Parameter Name	Value
Specification of Strip (mm × mm)	0.15 × 718
Yield/Tensile Strength σ/MPa	230/280
Average Front Tension T_1/MPa	60
Average Back Tension T_0/MPa	150
Bending Force of Working Roll S_w/kN	75
Bending Force of Middle Roll S_m/kN	75
Shift Value of Middle Roll δ/mm	150
Elongationε/%*	0.25, 0.4, 0.6, 0.8, 1.0
Diameter of Working Roll D_W/mm	420
Work Roll Contour	Flat roll
Diameter of Intermediate Roll D_m/mm	400
Intermediate Roll Contour	Flat roll
Diameter of Back-up Roll D_b/mm	900
Back-up Roll Contour	Flat roll
Face Length of Working Roll L_W/mm	1220
Face Length of Middle Roll L_m/mm	1220
Face Length of Back-up Roll L_b/mm	1220
Center Distance between the Cylinders of Bending Working Roll l_w/mm	2100
Center Distance between the Cylinders of Bending Intermediate roll l_m/mm	2100
Center Distance between the Screwdown Screws of Back-up Roll l_b/mm	2100

Annotate: the setting elongation was ranked into five grades based on size for getting the contact conditions of the same specification in different elongations.

Table 2. Comparison between test results and computed results.

Elongationε/%		0.25	0.4	0.6	0.8	1.0	1.2
Contact Width B_y	Measured Value /mm	0	20.5	132	146	173	–
	Calculated Value/mm	0	18.2	121.1	137.9	181.2	–
	error/%	0	8.78	8.26	5.55	4.74	–
Rolling Force P'_z	Measured Value /kN	1020	1750	4420	6540	9300	–
	Calculated Value /kN	940	1920	4310	6750	9980	–
	Error /%	7.84	9.71	2.49	3.21	7.31	–
Shape Value	$I_{\max}$ /I-Unit	7.2	6.7	5.3	11.2	16.2	–
	$I'_{\max}$ /I-Unit	5.9	8.9	4.0	13.8	19.5	–
	ΔI /I-Unit	1.2	2.1	1.2	2.3	2.8	–
Rolling Length	L/km	–	–	–	–	26	–

value, I_{1i} is the computed shape value, $I_{1i} = \frac{-\left(1-v^2\right)\left(\sigma_{1i} - T_1\right)}{E} \times 10^5$ (where E and v are the young modulus and poisson's ratio respectively). I'_{max} is the maximum of actual shape value I_{max} is the maximum of computed shape value.

First of all, it can be seen through **Table 2** that there isn't roller ends' forced-contact when the elongation is 0.25% (the contact width is zero); and the roller ends' forced-contact begin to appear when the elongation is increased to 0.4%; later on, with the increase of elongation, the roller ends' forced-contact become worse and worse; when the elongation increased to 1.11%, the rolling force reach to the limit value 12000KN of temper mill and the elongation will not reach to 1.2%.

In addition, it also can be seen clearly through **Table 2** that the error is within 10% compared with test results when the model of Section 2.2 is adopted, and the error of shape value is within 3I. So, the model can fully satisfy the precision request in the engineering application.

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