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Boundary determination of leveling capacity for plate roller leveler based on curvature integration method

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Abstract: Leveler is widely used to improve the quality of defective mild steel plates. Its typical ranges of the leveling capacity are constrained by three criteria, namely the maximum stroke of rollers, allowable total leveling force and motor power. In this work, an optimization model with equality and inequality constraints was built for the maximum yield stress search of each thickness of plates. The corresponding search procedure with three loops was given. The approximate range by the simplification model could be used as the initial value for the actual range search of the leveling capacity. Therefore, the search speed could be accelerated compared with a global search. The consistency of the analytical results and field data demonstrates the reliability of the proposed model and procedure. The typical ranges of the leveling capacity are expressed by several boundary curves which are helpful to judge whether the incoming plate can be leveled quickly or not. Also, these curves can be used to find the maximum yield stress for a specific thickness or the maximum thickness for a yield stress for plates.

Key words: plastic ratio; leveling capacity; curvature integration; plate

1 Introduction

Leveling is an important technology in the production line of plates. It is used to remove the typical plate defects (such as curl, gutter, middle waves and edge waves) generated in the rolling and cooling process [1−2]. There are many literatures about the research of the leveling process prediction. For example, PARK and HWANG [3] developed finite element method (FEM) programs for the analysis of the roller leveling process. HUH et al [4] found that undesirable strip shapes are corrected to a flat shape during the tension leveling process based on elasto-plastic finite element analysis. They calculated the quantitative level of curl and investigated the suitable intermesh for the elimination of the curl. BEHRENS et al [5] developed an analytical 3D simulation model to find a suitable adjustment of the leveler to reach a flat sheet metal. Also, the analytic model has been studied to predict the curvature distribution in the thickness [6−10]. The equipment which carries out the leveling technology is called the leveler. The structural feature and functions of the new generation leveler with advanced characteristics such as high stiffness frame, and adjustable leveling schedule are introduced, as well as simple introduction of the leveling capacity [11−14]. WANG et al [15] studied the evolvement of plate in 15-roller combination leveler. Their research approved that the combinatorial leveling technology could improve the leveling precision and leveling capacity.

Most of the present research focused on the leveling simulation and technology optimization about how to improve the residual stress and flatness of the plate. However, WANG et al [16] studied the leveling capacity, and analyzed the influence of the leveling speed, hardening coefficient and expected plastic ratio on the leveling capacity. They also compared the analytical results of leveling capacity with field data under three conditions. However, there are still some differences between them because of several simplifications. In this work, further precise study of the leveling capacity is made.

2 Model of determining accurate range of leveling capacity

The model proposed by WANG et al [16] can be summarized as follows. Equation (1) is deduced by the expected plastic ratio, and Eqs. (2) and (3) are the constraint expressions of total forces and motor power, respectively:

$$\sigma_{si} \le \frac{EH}{DS_o} \tag{1}$$

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$$\sigma_{si} \le \frac{3F_{sum}p}{4BH^2\sum_{i=2}^{N-1}\overline{M_i}} \tag{2}$$

$$\sigma_{si}^2\left\{\frac{DBH}{12E}\sum_{i=2}^{n-1}(1-\zeta_i)^2[\frac{3}{\zeta_i}+\frac{1}{4}(1-\zeta_i)(3+\zeta_i)]\right\}+$$
$$\sigma_{si}[(f+\frac{\mu d}{2})\frac{4BH^2}{3p}\sum_{i=2}^{N-1}\overline{M_i}] \le \frac{P_{sum}\eta D}{2V} \tag{3}$$

where E is the elastic modulus, σ_{si} is the yield stress of the plate after the ith strengthening, S_o is the overstrength (OVS) D is the diameter of the rollers, H and B are the thickness and width of the plate, respectively, N is the roll number, and p is the roll pitch. M_{ti} is the elastic limit inner moment of the plate under roller i, $M_{ti}=BH^2\sigma_{si}/6$, $\overline{M_i}$ is the moment ratio, $\overline{M_i}=M_i/M_{ti}$, and M_i is the inner moment of the plate under roller i. F_{sum} is the allowable total leveling force, V is the leveling speed, ζ_i is the elastic ratio of the plate under the ith roller, $\zeta_i=1-p_{li}$, and p_{li} is the plastic ratio of the plate under the ith roller. η is the total efficiency of the transmission system, d is the diameter of the rollers journal, f is the coefficient of the rolling friction between the roller and the plate, and μ is the friction coefficient between the roller journal and the bearing.

The reasons of the difference between the analytical results and field data calculated by WANG et al [16] can be concluded as follows. First, the assumption of Eq. (1) is that the maximum bending curvature of plates can approach the curvature of rollers, as shown in Fig. 1, where D is the diameter of the roller, ρ is the bending radius of the plate, and p is the distance of adjacent rollers. However, the stroke of the rolling reduction, δ_2, (shown in Fig. 2) is limited because of the limited stroke of hydraulic cylinders (shown in Fig. 3), meaning that the range of the leveling capacity determined by Eq. (1) is enlarged.

The second reason is that the plastic ratio of the plate during leveling process is set by experiences in Eqs. (2) and (3). However, the plastic ratios should be analyzed according to the schedule of linearly decreasing roller gaps in proportion along the travel direction shown in Fig. 2. Therefore, the leveling force and torque must be calculated with some errors.

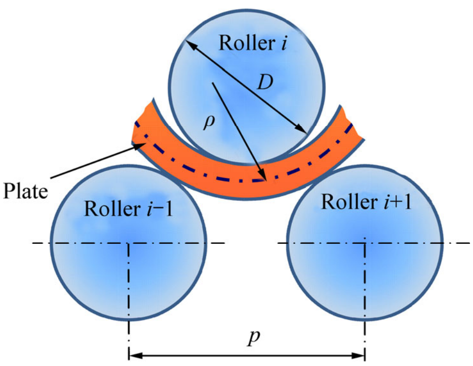

Fig. 1 Limited bending state

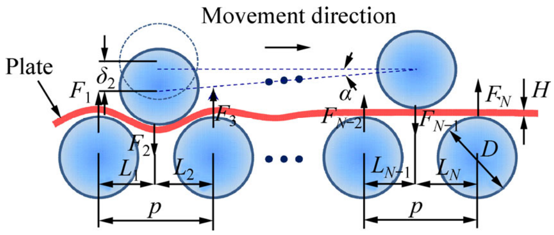

Fig. 2 Leveling process

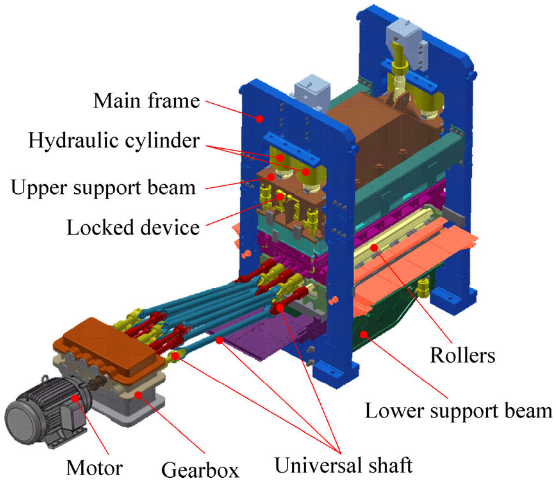

Fig. 3 3-D model of nine-roller leveler

In fact, the boundary curves of the leveling capacity derived from Eqs. (1) to (3) are not without merit because they are close to the field data with quick enough computational speed [16]. Therefore, the actual boundary curves could be searched near the former boundary curves which avoid the global search from the time-wasting.

The leveling capacity is wider if the boundary curves cover more area. Taking points A and B in Fig. 4 as an example, the higher the expected yield stress is (point B compared to point A), the larger the thickness (H_1) is. Consequently, the determination of boundary curves of the leveling capacity is an optimization process with equality and inequality constraints.

The objective function for each thickness, H_1, in Fig. 4 is to maximize the yield stress, namely

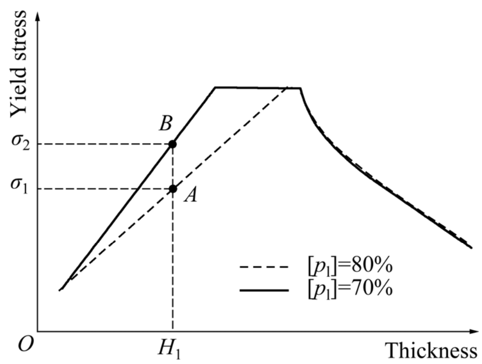

Fig. 4 Range compare of leveling capacity

$$\max\ \sigma_s = \text{function}(B, H, P_{sum}, F_{sum}) \tag{4}$$

The curvature integration model (Eqs. (5) and (6)) is proposed and further analyzed [8, 12, 17] as

$$\int_0^{L_{i-1}} \kappa_x \mathrm{d}x \pm \theta_{i-1} \pm \theta_i = 0 \tag{5}$$

$$\mp\int_0^{L_{i-1}}\int_0^{L_{i-1}} \kappa_x \mathrm{d}x\mathrm{d}X - \theta_{i-1}L_{i-1} + R(1-\cos\theta_{i-1}) + R(1-\cos\theta_i) = \delta_i \tag{6}$$

where κ_x is the curvature of point B (shown in Fig. 5) at the neutral layer of the plate, θ_{i-1} and θ_i are defined as contact angles at the contact points respectively, p is the roller's pitch, R is the radius of rollers, and L_{i-1} is the distance between two contact points.

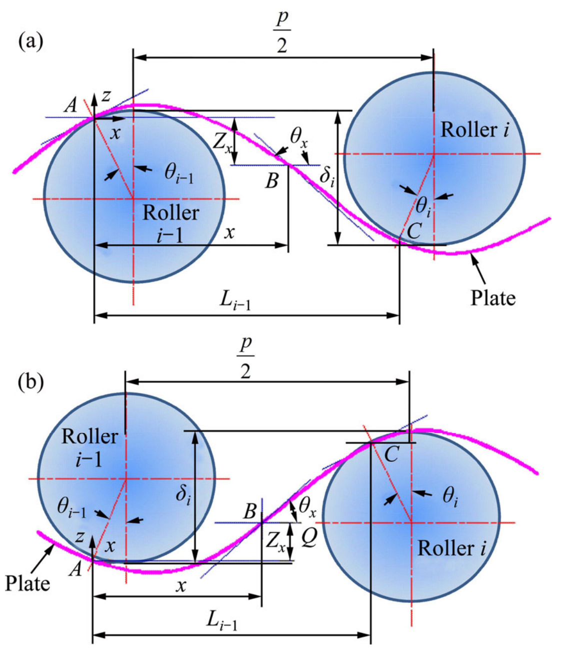

Fig. 5 Schematic layout of curvature integration model [17]: (a) Contact relationship among plate, odd roller and even roller; (b) Contact relationship among plate, even roller and odd roller

Equation (5) describes the contact relationship between the plate and rollers while Eq. (6) gives the relationship between the rolling gaps and bending degree of the plate during leveling process. They are the basic equations for the curvature analysis and must be satisfied during the search process. Therefore, the rolling reduction is a indirect design variable. The yield stress is the key parameter to judge the elastic-plastic state of the plate. As a consequence, the yield stress is not only the objective function, but also one of the design variables.

Equations (5) and (6) can be used to analyze the curvature distribution during the leveling process accurately so that the bending stress can be output in the next step. Then, the inner bending moment M_i under roller i can be integrated by Eq. (7).

$$M_i = \int_{-\frac{B}{2}}^{\frac{B}{2}}\int_{-\frac{H}{2}}^{\frac{H}{2}} \sigma(x) z \mathrm{d}y\mathrm{d}z \tag{7}$$

Further, considering the complicated bending stress distribution on the thickness direction, Eq. (7) can be discretized as

$$M_i = B\sum_{i=1}^{N_1} \sigma_i(x) z_i \Delta h \tag{8}$$

where Δh is the thickness of each layer, $\sigma_i(x)$ is the bending stress of the ith layer, and z_i is the distance from the ith layer to neutral layer, as shown in Fig. 6.

The leveling force of the ith roller based on the inner moment M_i (i=2, ⋯, N−1) can be deduced by the moment equilibrium principle:

$$F_i = \frac{\sum_{j=1}^{i-1}(-1)^j F_j \times \sum_{k=j}^{i} L_k + M_{i+1}}{L_i} \tag{9}$$

$$F_i = \frac{\sum_{j=1}^{i-1}(-1)^{j+1} F_j \times \sum_{k=j}^{i} L_k + M_{i+1}}{L_i} \tag{10}$$

where i is an odd number in Eq. (9) and i is an even number in Eq. (10).

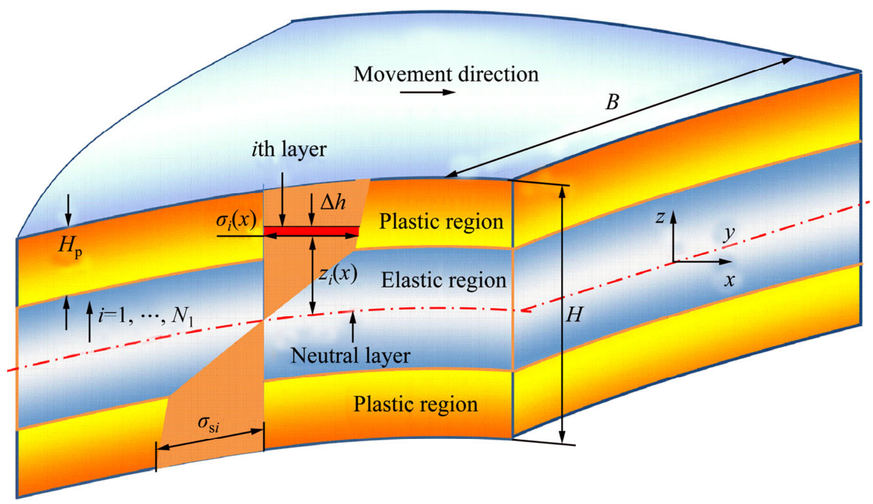

Fig. 6 Stress state on thickness direction

The total power of the transmission system can be calculated by

$$P=(T_{\rm f}+T_{\rm p})\frac{2V}{D} \tag{11}$$

where $T_{\rm f}$ is the friction torque and $T_{\rm f}=(f+\frac{ud}{2})\sum_{i=1}^{N}F_i$, $T_{\rm p}$ is the torque needed by the plastic deformation and $T_{\rm p}=\frac{D}{2}\sum_{i=1}^{N}\frac{BH\sigma_{\rm s}^2}{6E}(1-\zeta_i)^2\left[\frac{3}{\zeta_i}+\frac{1}{4}(1-\zeta_i)(3+\zeta_i)\right]$.

Also, the plastic ratio distribution can be extracted after the analysis of Eqs. (5) and (6). Therefore, the leveling parameters including the total leveling force, total power and plastic ratio are related directly with the yield stress $\sigma_{\rm s}$.

At least one of Eqs. (12)−(14) must be satisfied as equality constraints for the purpose of finding border points of the leveling capacity since the plastic ratio, leveling force and power can be analyzed accurately. Equation (12) means that the analytical plastic ratio must be close enough to the expected plastic ratio. Equations (13) or (14) means that the boundary point is found if the total force or the power approximates the allowable total force and motor power, respectively.

$$\left|\frac{[p_{\rm l}]-p_{\rm l}}{[p_{\rm l}]}\right|\le\varepsilon_1 \tag{12}$$

$$\frac{\left|\sum_{i=1}^{N}F_i-F_{\rm sum}\right|}{F_{\rm sum}}<\varepsilon_2 \tag{13}$$

$$\left|\left[\left(2V\sum_{i=1}^{N}T_i/\eta D\right)-P_{\rm moter}\right]/P_{\rm moter}\right|<\varepsilon_3 \tag{14}$$

where $[p_{\rm l}]$ is the expected plastic ratio, $p_{\rm l}$ is the analytical plastic ratio, and $p_{\rm l}=(H_{\rm p}/H)\times100\%$; $P_{\rm moter}$ is the power of the moter; $H_{\rm p}$ is the half thickness of the elastic deformation region shown in Fig. 6; ε_1 is an allowable tolerance. The overstretch (OVS, $S_{\rm o}$) is usually used to reflect the plastic ratio which is defined as

$$S_{\rm o}=\frac{1}{1-p_{\rm l}} \tag{15}$$

The search process of boundary curves of the leveling capacity is given in Fig. 7. The approximate range of the leveling capacity can be calculated and stored by Eqs. (1)−(3) in the first place. Then the ith thickness is read in the next step. To search the maximum yield stress for this thickness, the rolling reduction is initialized. The curvature distribution can be analyzed according to the method in Ref. [12] under this condition. Next, the plastic ratio is calculated and Eq. (12) is checked. The rolling reduction is modified until Eq. (12) is satisfied. The yield stress should be increased until at least Eq. (13) or Eq. (14) is true. This loop would stop if each thickness finds their corresponding maximum yield stress. All programs are carried out in Matlab®.

3 Verification

In order to verify the proposed model and method, it is necessary to compare the results of the present analysis with some other credible data. A leveler consists of seven, 220 mm-in-diameter rollers, with a separation between contiguous rollers of 230 mm. Its allowable total leveling force and the motor power are 28000 kN and 320 kW, respectively. The maximum stroke of rollers is 20 mm. These initial data are listed in Table 1. Using our in-house program, the results are obtained in Fig. 8. It can be seen that the simulation results almost overlap with the field data. When OVS changes from 3 to 7 (plastic ratio changes from 66.7% to 85.7%, as shown in Fig. 9), the leveling capacity changes obviously. The ranges of the leveling capacity are a series of family curves. The leveling capacity decreases with the increment of the expected plastic ratio.

The boundary curves of the leveling capacity can be used quickly to judge whether an incoming plate can be leveled or not. For instance, the plate corresponding to point J_1 in Fig. 8 can be leveled safely because it is below all the curves. However, whether the plate corresponding to point J_4 in Fig. 8 can be leveled or not depends on the expected plastic ratio. It is easy to find that the maximum yield stresses of the plate with the thickness of 15 mm are 600 MPa (point J_2) and 720 MPa (point J_3) if the expected OVS values are 7 and 5, respectively. Also, the maximum thicknesses of the plate with the yield stress of 600 MPa are 15 mm and 21 mm if the expected OVS values are 7 and 5, respectively.

Further, it is necessary to find out why the points in Fig. 8 can consist of the final boundary curves of the leveling capacity. Taking the middle curve ($S_{\rm o}$=5, $[p_{\rm l}]$=80%) as an example, point A in Fig. 8 becomes the first boundary point because the required rolling reduction of the plate equals the maximum stoke of rollers, as shown in Fig. 10. Also, point B is another boundary point, and the other reason for point B is that the maximum yield stress in all the plates is 1000 MPa. For point C, one reason is the same with point B, and the other reason is that the total power of the plate at point C has approached the motor power, as shown in Fig. 11, although the sum of all the leveling forces of this plate is much smaller than allowable total leveling force, as shown in Fig. 12. This reason can be applied to the points from point C to point D. However, the basic reason changes to the factor of the leveling force from point E to point F, as shown in Fig. 12. In short, the principle of determining the boundary point is to check

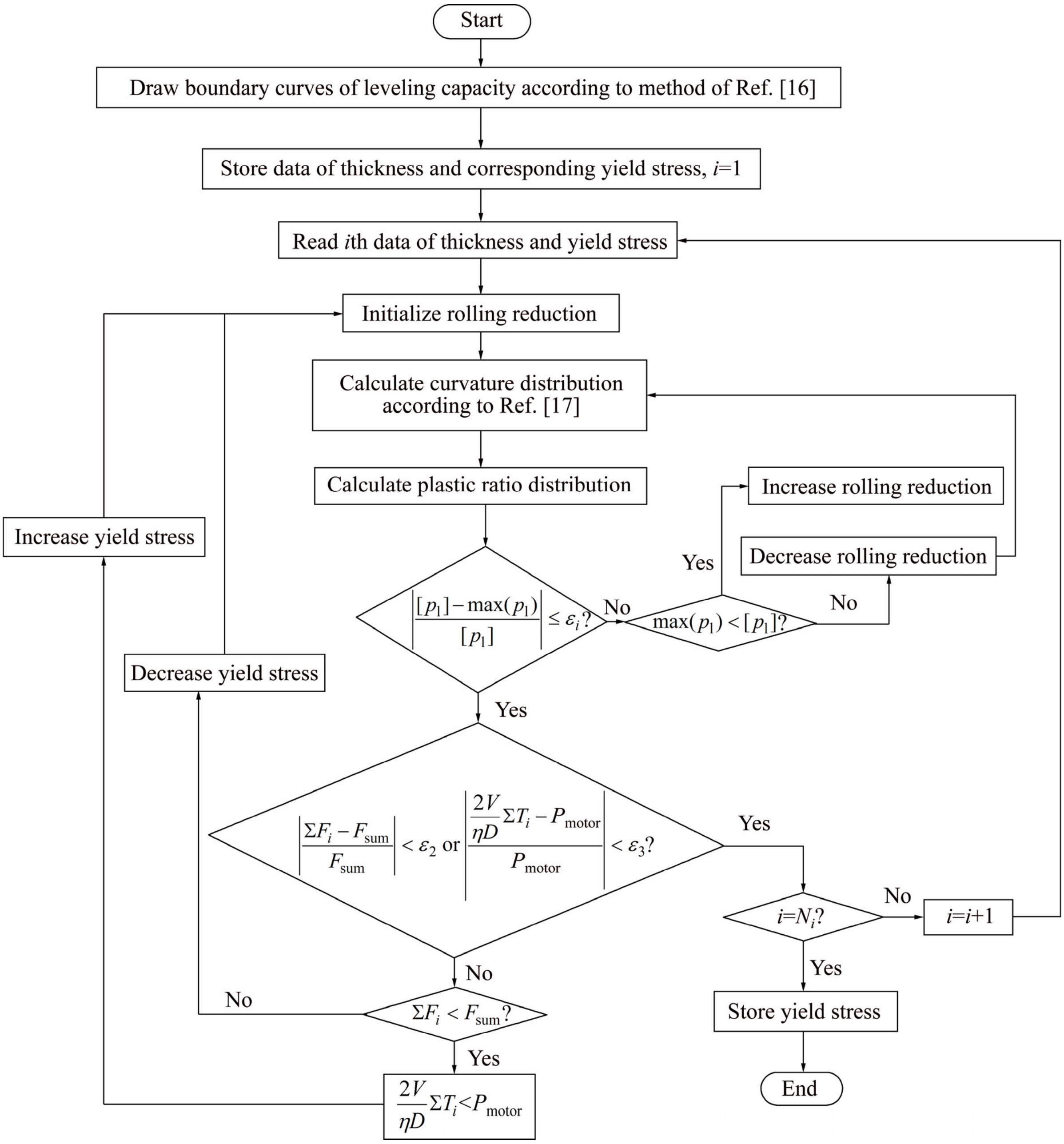

Fig. 7 Search process of boundary curves of leveling capacity

Table 1 Parameters and constants employed in verification model

Parameter	Value
Number of work rollers	7 (top: 3, bottom: 4)
Roller diameter/mm	220
Roller pitch/mm	230
Allowable total leveling force/kN	28000
Motor power/kW	320
Maximum stroke of rollers/mm	20
Diameter of roller journal/mm	120
Width of plate/mm	2150

whether the stroke of rollers, the total leveling force orpower rise to their own limits under the condition of guaranteeing the plastic ratio.

4 Discussion

The proposed model in this work is verified in Section 3. In this section, this model will be used to predict the leveling capacity for the third generation leveler, as shown in Fig. 3. The leveling conditions are listed in Table 2. It can be found that the coverage of the leveling capacity shrinks with the increase of the expected plastic ratio and width from Figs. 13−16. The comparative analysis shows that the linear part shown in

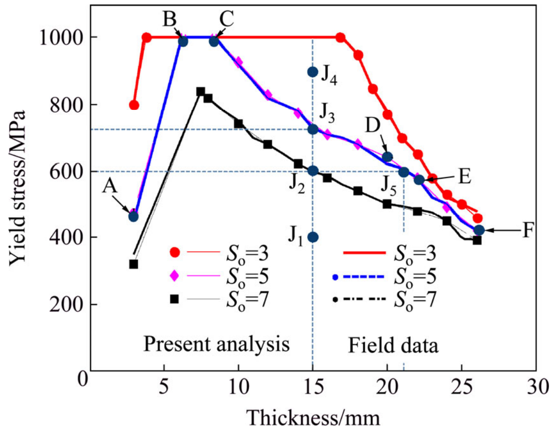

Fig. 8 Results comparison of proposed result and field production data

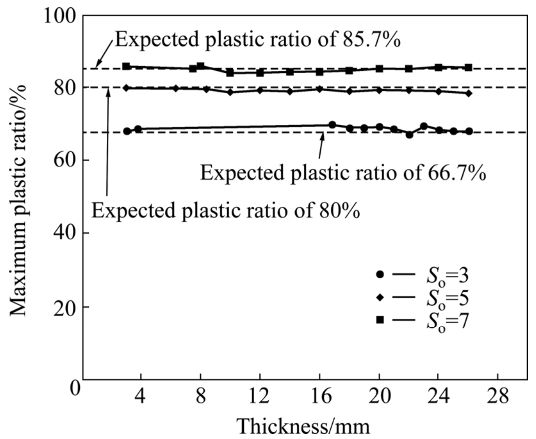

Fig. 9 Corresponding plastic ratio during leveling process of Fig. 8

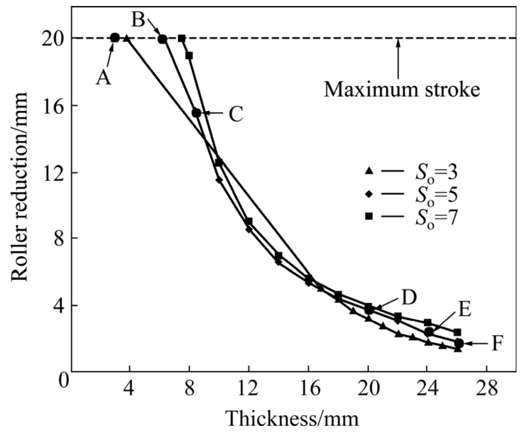

Fig. 10 Corresponding rolling reduction of Fig. 8

Fig. 13 is not affected by the width of plates. The reason is that the boundary points of the linear part are constrained by the maximum roller stroke. The total force and power of these points are far less than the allowable leveling force and motor power. The cross points of curves defined by Eqs. (13) and (14) move from top left corner gradually with the reduction of the expected plastic ratio for the same width. The reason is that the leveling capacity is wider for the lower expected

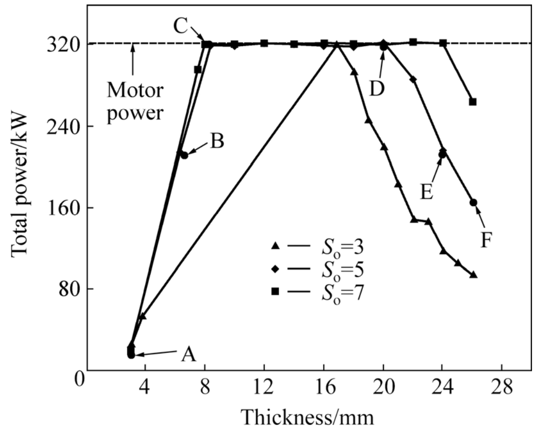

Fig. 11 Corresponding total leveling power

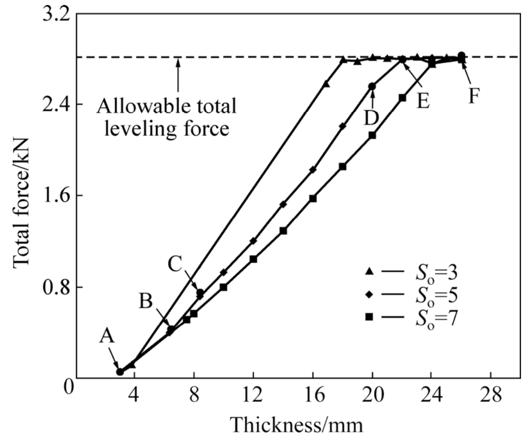

Fig. 12 Corresponding total leveling force

Table 2 Parameters and constants of third generation leveler

Parameter	Value
Number of work rollers	9 (top: 4, bottom: 5)
Roller diameter/mm	280
Roller pitch/mm	300
Diameter of roller journal/mm	160
Allowable total leveling force/kN	64000
Motor power/kW	1350
Maximum stroke of rollers/mm	20
Maximum yield stress of incoming	160

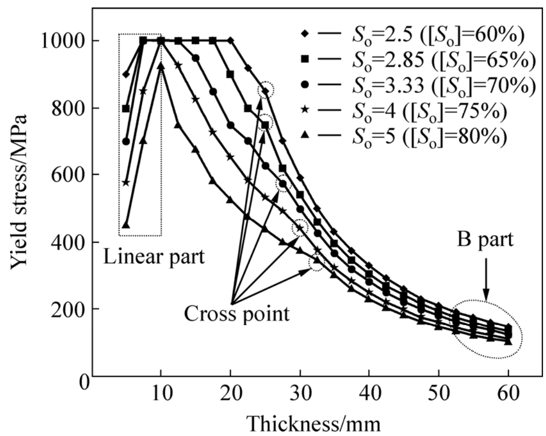

Fig. 13 Leveling capacity for plates with width of 3500 mm

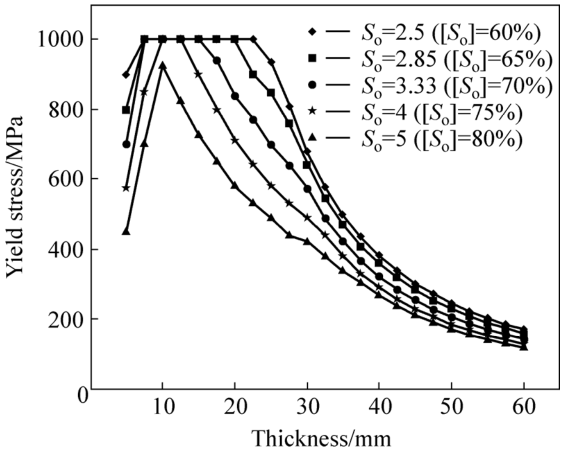

Fig. 14 Leveling capacity for plates with width of 3000 mm

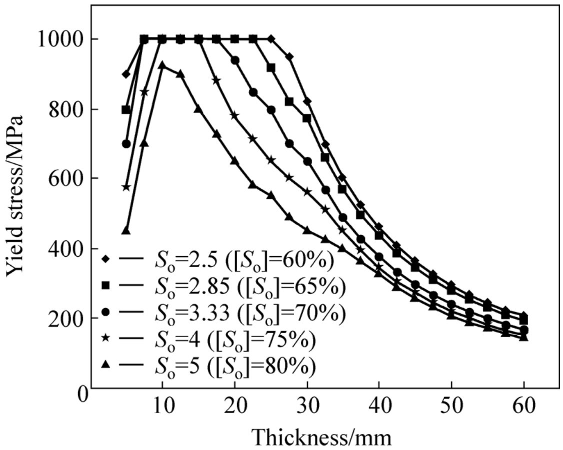

Fig. 15 Leveling capacity for plates with width of 2500 mm

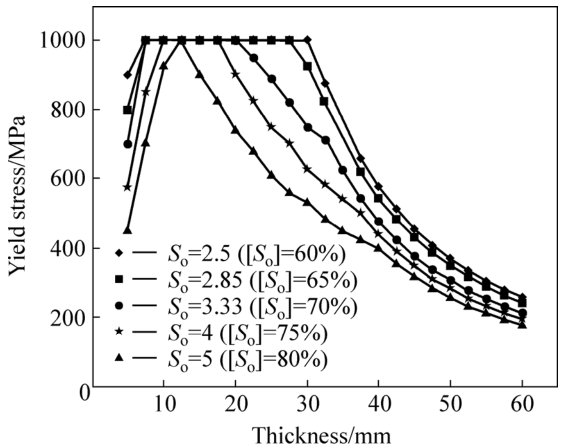

Fig. 16 Leveling capacity for plates with width of 2000 mm

plastic ratio. The curves of the leveling capacity determinated by the allowable leveling force are close enough for different expected plastic ratios when the thickness increases to 40 mm.

5 Conclusions

1) The final actual boundary curves of the leveling capacity are determined by the maximum stroke of rollers, allowable total leveling force and motor power based on the curvature integration method.

2) The overlap degree of the boundary curves of the leveling capacity between analytical results and field data approves that the proposed optimization model and procedure can predict the actual range of the leveling capacity.

3) One role of boundary curves of the leveling capacity is that the judgment whether the incoming plate can be leveled safely can be made easily and quickly according to its dimension, material characteristic and expected plastic ratio. The other role is to find the maximum yield stress for a specific thickness or the maximum thickness for a yield stress for the plate.

Nomenclature

H	Thickness of plate
B	Width of plate
H_p	Plastic deformation thickness of plate
E	Elastic modulus
σ_{si}	Yield stress of plate
p_l	Plastic ratio
ζ_i	Elastic deformation percentage
R	Radius of roller
D	Diameter of roller
d	Diameter of roller journal
p	Roller pitch
P_{sum}	Motor power
F_Σ	Sum leveling force
F_i	Leveling force of roller i
F_{sum}	Allowable total leveling force
M_{ti}	Inner moment of plate under roller i
M_i	Elastic limit moment
f	Rolling friction coefficient between roller and plate
μ	Friction coefficient between roller journal and bearing
η	Total efficiency of transmission system
κ_x	Curvature of plate
θ_{i-1}	Contact angle between roller i−1 and plate
θ_i	Contact angle between roller i and plate
L_{i-1}	Distance between two contact points

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