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Rolling-schedule multi-objective optimization based on influence function for thin-gauge steel strip in tandem cold rolling

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Influence function.

Abstract. The setting of rolling schedule in tandem cold mill is one of the most crucial contents in rolling process, which will have a direct impact on product quality and production efficiency. According to the actual requirements in the rolling process, a multi-objective function based on influence function method was built. The objective function was aimed specially at thin gauge strip and solved by Tabu search algorithm. Meanwhile, in order to avoid strip slipping by the reduction of friction coefficient, the tension schedule was corrected according to the rolling length of work roll. The proposed optimization method was successfully applied to a 1450-mm 5-stand tandem cold mill. Application results show that the optimized rolling schedules are more close to the actual requirements and the flatness quality is improved greatly.

1. Introduction

In the tandem cold rolling process control system, development of rolling schedule is the most fundamental work and the core of the production process. Reasonable design of the rolling schedule has a deep impact on the yield and quality of finished steel. In recent years, many researchers have proposed different rolling schedule optimization algorithms for tandem cold rolling [1-5]. Zhao et al. took equipower margin and overcoming scratch as objective functions to establish rolling-schedule multi-objective optimized model and optimized it with adaptive chaoticmutation shuffled frog leaping algorithms.

Yang et al. adopted a genetic algorithm to optimize rolling schedule by the targets of load equalization and fine shape [6]. Wei et al. put forward a rolling-force revised model and designed an improved adaptive genetic algorithm for rolling-schedule optimization calculation. Che et al. adopted equal relative load as objective function, used SUMT algorithm to change constraints to non-binding conditions, and applied a PSO algorithm to optimize objective functions. Mehrdad Poursina et al. used a genetic algorithm to optimize the process from the power consumption and damage evolution points of view [7]. Yang et al. used BP neural network to predict rolling force and multi-objective fuzzy method to optimize objective functions [8].

In the past decade, with the rapid development of rolling technology and modern rolling-mill design theory, people applied optimization techniques to the rolling fields gradually and rolling schedule optimization design has made considerable progress. The products with higher dimensional accuracy and better mechanical property have been produced. Among them, cold rolled sheet has been applied to electronics, automobile, light industry, textile, and other sectors widely due to its characteristics like good flatness,

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bright surface, and uniform performance [9-14]. However, with the explosive development of modern industrial technology and automated production processes, sectors of the national economy feel the increasingly widespread need for rolled products with higher precision of dimensions. Thus, in this article, rolling schedule optimization algorithm is proposed for thin gauge strip to obtain products of better flatness and performance.

2. Online calculation models for control parameters

2.1. Deformation resistance model

Deformation resistance reflects the effects of accumulated work hardening in tandem cold rolling and is the most basic technological parameter in process control and calculation of the mechanical parameters in the model system, as shown in Figure 1. The model takes the influence of the initial material and accumulated strain rate on the deformation resistance of cold rolled strip into account. The deformation resistance model is shown as follows:

$$k = \frac{2}{\sqrt{3}}\mu_0 k_0 \left(\frac{2}{\sqrt{3}}\ln\frac{h_0}{h} + \varepsilon_0\right)^{\mu_1 \times \varepsilon_1}, \tag{1}$$

where, k is deformation resistance; k_0 is deformation resistance reference constant considering material characteristics; h_0 is entry thickness; h is target thickness; μ_0 and μ_1 are adaptive learning coefficients; and ε_0 and ε_1 are model parameters.

2.2. Rolling-force model

The rolling-force model can be expressed as:

$$F = Bl_c'\theta K K_T, \tag{2}$$

where, F is rolling force; B is strip width; l_c' is the horizontal projection length of roll and rolled-piece contact arc considering flattening; θ is influence coefficient considering stress state in deformation zone; K is metal deformation resistance; and K_T is influence coefficient of front and back tensile stresses to rolling force.

The stress state in deformation zone and its distribution depend on the geometry of the deformation zone, which can be expressed with the ratio of contact arc length l_c and average thickness h_m. In tandem cold rolling, the average thickness of the deformation zone is smaller, which makes $l_c/h_m > 1$. Complex stress state occurs in deformation zone because of the friction in the contact surface of roll and the rolled piece; by this time, the average deformation resistance that should be exerted to contact arc is k_m.

$$k_m = \theta K. \tag{3}$$

The calculation of θ is performed by using Hill formula:

$$\theta = 1.08 + 1.79\varphi\delta\sqrt{1-\delta}\sqrt{\frac{R'}{h}} - 1.02\delta, \tag{4}$$

where, φ is contact arc friction coefficient; δ is deformation degree, $\delta = \frac{h_0 - h}{h_0}$; and R' is roll radius considering flattening.

It can be seen in Eq. (1) that, in the cold deformation state, the work hardening of metal increases with the deformation degree and the deformation resistance improves observably. When thin-gauge steel strips are rolled, average deformation resistance increases according to either Eqs. (3) and (4), which makes the rolling process difficult and not easy to obtain good strip shape. Therefore, it is particularly important to design a rolling-schedule multi-objective optimization function for thin-gauge steel strip in tandem cold rolling.

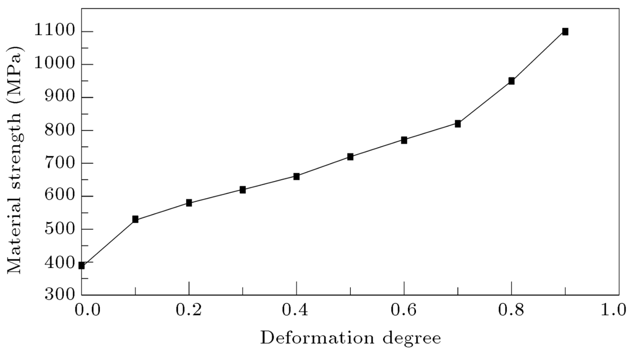

Figure 1. Work hardening curve of cold rolling.

3. Multi-objective function design

The optimization of rolling schedule in tandem cold rolling is to distribute reduction rate for each stand reasonably in the case the technological conditions are satisfied, in order to improve the product quality and rolling mill production efficiency. When designing the objective function, the machine type of mills, electrical conditions, and actual operating conditions to be satisfied should be taken into account to make all equipment maximize production capacity adequately without damaging it [15-20].

3.1. Power objective function

Take a five-stand tandem cold mill, for example, in order to maximize equipment capacity and increase productivity; rolling power is regarded as objective function for the first four stands. The purpose of this objective function is to make the set value of power, P_j, close to that of $P_{\text{nom},j}$ as far as possible. The objective function is designed as:

$$f_P = \frac{\sum_{j=1}^{4} k_{P,j}\cdot\left(\frac{P_j - P_{\mathrm{nom},j}}{P_{\mathrm{delta},j}}\right)^2}{\sum_{j=1}^{4} k_{P,j}}, \tag{5}$$

$$P_{\mathrm{nom},j} = P_{\max,j}.P_{\mathrm{ratio},j}, \tag{6}$$

$$P_{\mathrm{delta},j} = \frac{P_{\max,j} - P_{\min,j}}{2}, \tag{7}$$

where, j is stand number; f_P is power objective function; P_j is the set value of rolling power for stand j; $P_{\max,j}$ and $P_{\min,j}$ are the maximum and minimum of rolling power for stand j, respectively; $P_{\mathrm{ratio},j}$ is the ratio of rolling power to the maximum power for stand j; and $k_{P,j}$ is weighting coefficient associated with stands.

3.2. Tension objective function

Tension plays very important roles in tandem cold rolling, such as avoiding unevenness of strip, improving flatness, reducing the deformation resistance and deformation work, and adjusting the main motor load and strip thickness suitably; therefore, tension is one of the core problems in tandem cold rolling. The purpose of tension objective function is to make the set value of tension T_j close to that of $T_{\mathrm{nom},j}$ as far as possible. The objective function is designed as:

$$f_T = \frac{\sum_{j=1}^{4} k_{T,j}\cdot\left(\frac{T_j - T_{\mathrm{nom},j}}{T_{\mathrm{delta},j}}\right)^2}{\sum_{j=1}^{4} k_{T,j}}, \tag{8}$$

$$T_{\mathrm{nom},j} = \frac{T_{\max,j} + T_{\min,j}}{2}, \tag{9}$$

$$T_{\mathrm{delta},j} = \frac{T_{\max,j} - T_{\min,j}}{2}, \tag{10}$$

where, f_T is tension objective function; T_j is the set value of tension between stand j and stand $j+1$; $T_{\max,j}$ and $T_{\min,j}$ are the maximum and minimum of tension between stand j and stand $j+1$; and $k_{T,j}$ is weighting coefficient associated with stands.

3.3. Flatness objective function

It can be seen in the above analysis that in the rolling process of thin-gauge steel strip, larger deformation resistance will occur at the last stand. In order to improve the dimensional accuracy of strip and ensure the stability of the rolling process, good flatness is regarded as objective function for the last stand.

In the previous rolling-schedule optimization design, only crown or total pressure value determined by crown was taken into account and the rolling-schedule optimization problem was not really studied taking flatness as optimization function. By the strip-shape control theory, we know that the more uniform the transverse distribution of exit-strip front tensile stress, the better the flatness is. Therefore, exit strip forward tensile stress transverse distribution is used for representing flatness in this paper. The purpose of flatness objective function is to make the set value of forward tensile stress transverse distribution for the last stand close to the average value of forward tensile stress transverse distributions as far as possible. The objective function is designed as:

$$f_\sigma = \sqrt{\frac{1}{m}\sum_{g=1}^{m}[\sigma_5(g) - \bar{\sigma}]^2}, \tag{11}$$

where, f_σ is flatness objective function; m is measuring section number of contact length between strip and work roll; g is measuring section number; $\sigma_5(g)$ is forward tensile stress transverse distribution of rolled piece for the last stand; and $\bar{\sigma}$ is the average value of forward tensile stress transverse distributions for the last stand (in the context of this article, it is the fifth stand).

3.4. Establishment of multi-objective function

Based on the above objective conditions, a comprehensive multi-objective function on account of power, tension, and flatness is established. The multi-objective function is as follows:

$$f_{\mathrm{total}} = \frac{\lambda_P.f_P + \lambda_T.f_T + \lambda_\sigma.f_\sigma}{\lambda_P + \lambda_T + \lambda_\sigma}, \tag{12}$$

where, f_{total} is comprehensive multi-objective function; λ_P, λ_T, and λ_σ are objective-function weighting coefficients of power, tension, and flatness, respectively.

3.5. Constraint conditions

1. Rolling force and rolling torque:

$$F_j \le F_{j\max}, \tag{13}$$

$$M_j \le M_{j\max}, \tag{14}$$

where, F_j is rolling force for stand j; $F_{j\max}$ is the maximum rolling force allowed for stand j; M_j is rolling torque for stand j; and $M_{j\max}$ is the maximum rolling torque allowed for stand j;

2. Power and tension:

$$P_j \le P_{j\max}, \tag{15}$$

$$T_{j\min} \le T_j \le T_{j\max}, \tag{16}$$

where, P_j is power for stand j; $P_{j\max}$ is motor rated power for stand j; T_j is tension between stand j and stand $j+1$; and $T_{j\min}$ and $T_{j\max}$ are the minimum and maximum tensions allowed between stand j and stand $j+1$, respectively;

3. Bite condition and sliding coefficient:

$$\Delta h_j \leq D_j(1-\cos\alpha_j), \tag{17}$$

$$S_j \leq S_{j\,\max}, \tag{18}$$

where, Δh_j is reduction rate for stand j; D_j is work roll diameter for stand j; α_j is bite angle for stand j; S_j is sliding coefficient for stand j; and $S_{j\,\max}$ is rated sliding coefficient for stand j;

4. Speed and temperature:

$$v_{\min} \leq v \leq v_{\max}, \tag{19}$$

$$r_{j\,\min} \leq r_j \leq r_{j\,\max}, \tag{20}$$

where, v is rolling speed; $v_{\min}$ is the minimum rolling speed for the last stand that satisfies productivity requirements; $v_{\max}$ is the allowed maximum speed for mechanical system; r_j is the temperature of strip at stand j; $r_{j\,\min}$ and $r_{j\,\max}$ are the minimum and maximum temperatures allowed by lubricant.

4. Influence-function-based flatness objective function

4.1. Influence function method

Influence function method is a kind of discretization method; its basic idea is discretizing the roll into a number of units, and discretizing the load and elastic deformation in the same way. Using the concept of influence function in mathematics and physics, we can get the deformation value of each unit, thus thickness distribution and tension distribution at the exit [21]. The following basic equations can be obtained in accordance with the concept of influence function:

1. Force-deformation relation equation:
   a) Work-roll elastic-bending equation:
   Resolve work roll into two cantilevers; determine deflections of both left and right sides, respectively:

$$\mathbf{Y}_{wL} = [\mathbf{G}]_w(\mathbf{Q}_{wiL} - \mathbf{P}_L) - \mathbf{G}_{wf}F_w, \tag{21}$$

$$\mathbf{Y}_{wR} = [\mathbf{G}]_w(\mathbf{Q}_{wiR} - \mathbf{P}_R) - \mathbf{G}_{wf}F_w, \tag{22}$$

   where, $\mathbf{Y}_{wL}$ and $\mathbf{Y}_{wR}$ are left and right part's deflection of work-roll barrel; $[\mathbf{G}]_w$ is work-roll bending influence function matrix; $\mathbf{Q}_{wiL}$ and $\mathbf{Q}_{wiR}$ are contact pressures of the left and right parts between work roll and intermediate roll; $\mathbf{P}_L$ and $\mathbf{P}_R$ are left and right part's rolling force of work-roll barrel; $\mathbf{G}_{wf}$ is work-roll bending-force influence function vector; and F_w is work-roll bending force;

   b) Intermediate-roll elastic-bending equation:
   Resolve intermediate roll into two cantilevers; determine deflections of both left and right sides, respectively:

$$\mathbf{Y}_{iL} = [\mathbf{G}]_i(\mathbf{Q}_{ibL} - \mathbf{Q}_{wiL}) - \mathbf{G}_{if}F_i, \tag{23}$$

$$\mathbf{Y}_{iR} = [\mathbf{G}]_i(\mathbf{Q}_{ibR} - \mathbf{Q}_{wiR}) - \mathbf{G}_{if}F_i, \tag{24}$$

   where, $\mathbf{Y}_{iL}$ and $\mathbf{Y}_{iR}$ are roll barrel left and right part's deflection of intermediate roll; $[\mathbf{G}]_i$ is intermediate-roll bending-influence function matrix; $\mathbf{Q}_{ibL}$ and $\mathbf{Q}_{ibR}$ are contact pressures of the left and right parts between intermediate roll and backup roll; $\mathbf{G}_{if}$ is intermediate-roll bending-force influence function vector; and F_i is intermediate-roll bending force;

   c) Backup-roll elastic-bending equation:
   Resolve backup roll into two cantilevers; determine deflections of both left and right sides, respectively:

$$\mathbf{Y}_{bL} = [\mathbf{G}]_b\mathbf{Q}_{ibL}, \tag{25}$$

$$\mathbf{Y}_{bR} = [\mathbf{G}]_b\mathbf{Q}_{ibR}, \tag{26}$$

   where, $\mathbf{Y}_{bL}$ and $\mathbf{Y}_{bR}$ are left and right part's deflection of backup-roll barrel; and $[\mathbf{G}]_b$ is backup-roll bending-influence function matrix;

   d) Work-roll elastic-flattening equation caused by rolling force:
   Determine work-roll elastic flattening caused by rolling force along the length of contact region of rolled piece and roll.

$$\mathbf{Y}_{ws} = [\mathbf{G}]_{ws}\mathbf{F}, \tag{27}$$

   where, $\mathbf{Y}_{ws}$ is work-roll elastic-flattening vector caused by rolling force; $[\mathbf{G}]_{ws}$ is work-roll elastic-flattening influence function matrix caused by rolling force; $\mathbf{F}$ is rolling force vector;

   e) Elastic flattening equation between work roll and intermediate roll:
   Determine elastic flattening along the length of contact region of work roll and intermediate roll.

$$\mathbf{Y}_{wi} = [\mathbf{G}]_{wi}\mathbf{Q}_{wi}, \tag{28}$$

   where, $\mathbf{Y}_{wi}$ is elastic flattening caused by pressure between work roll and intermediate roll; $[\mathbf{G}]_{wi}$ is elastic-flattening influence function matrix caused by pressure between work roll and intermediate roll; $\mathbf{Q}_{wi}$ is pressure vector between work roll and intermediate roll;

f) Elastic flattening equation between intermediate roll and backup roll:

Determine elastic flattening along the length of contact region of intermediate roll and backup roll.

$$\mathbf{Y}_{ib} = [\mathbf{G}]_{ib}\mathbf{Q}_{ib}, \tag{29}$$

where, $\mathbf{Y}_{ib}$ is elastic flattening caused by pressure between intermediate roll and backup roll; $[\mathbf{G}]_{ib}$ is elastic-flattening influence function matrix caused by pressure between intermediate roll and backup roll; and $\mathbf{Q}_{ib}$ is pressure vector between intermediate roll and backup roll.

2. Equilibrium equation:

a) Work-roll equilibrium equation:

Establish work-roll equilibrium equation by the force balance of work roll in the vertical direction.

$$\sum_{n=N_1}^{N_3} p(n) + 2F_w = \sum_{u=1}^{N_3} q_{wi}(u), \tag{30}$$

where, $p(n)$ is rolling force of measuring section n; $q_{wi}(u)$ is pressure of unit u between work roll and intermediate roll; N_1 is measuring section's total number of half the non-contact length between work roll and intermediate roll (equal to that of intermediate roll and backup roll); N_3 is measuring section's total number of contact length between work roll and intermediate roll (equal to that of intermediate roll and backup roll); and n and u are the numbers of measuring section;

b) Intermediate-roll equilibrium equation:

Establish intermediate-roll equilibrium equation by the force balance of intermediate roll in the vertical direction.

$$\sum_{u=1}^{N_3} q_{wi}(u) + 2F_i = \sum_{v=1}^{N_3} q_{ib}(v), \tag{31}$$

where, $q_{ib}(v)$ is pressure of unit v between intermediate roll and backup roll; v is the number of measuring sections.

3. Compatibility of deformation relation equation:

a) Compatibility equation of deformation between rolled piece and work roll is calculated by:

$$\mathbf{H} = \mathbf{H}_0 + (\mathbf{Y}_{ws} - \mathbf{Y}_{ws0}) - \mathbf{Y}_w + \mathbf{M}_w, \tag{32}$$

where, $\mathbf{H}$ is height of the rolled piece above the horizon passing through the central point after rolling; $\mathbf{H}_0$ is half of the height of the rolled piece at the central point after rolling; $\mathbf{Y}_{ws0}$ is work-roll elastic flattening caused by rolling force at the central point; $\mathbf{Y}_w$ is the deflection of the whole work-roll barrel; and $\mathbf{M}_w$ is work roll crown;

b) Compatibility equation of deformation between work roll and intermediate roll is:

$$\mathbf{Y}_{wi} = \mathbf{Y}_{wi0} + \mathbf{Y}_i - \mathbf{Y}_w - \mathbf{M}_w - \mathbf{M}_i, \tag{33}$$

where, $\mathbf{Y}_{wi0}$ is elastic flattening passing through the central point caused by press between work roll and intermediate roll; $\mathbf{Y}_i$ is the deflection of the whole intermediate-roll barrel; $\mathbf{M}_i$ is intermediate roll crown;

c) Compatibility equation of deformation between intermediate roll and backup roll:

$$\mathbf{Y}_{ib} = \mathbf{Y}_{ib0} + \mathbf{Y}_b - \mathbf{Y}_i - \mathbf{M}_i - \mathbf{M}_b, \tag{34}$$

where, $\mathbf{Y}_{ib0}$ is elastic flattening passing through the central point caused by press between intermediate roll and backup roll; and $\mathbf{M}_b$ is backup roll crown.

4.2. Calculation of tensile stress

On the basis of the above basic equations, and then using the corresponding rolling force formula, iterative algorithm can be used to calculate the elastic deformation of rolls, and forward tensile stress distribution can be found. The forward tensile stress calculation process is shown in Figure 2. When pressure iteration loop between work roll and intermediate roll meets the iteration accuracy, β_1, flattening iteration loop between work roll and intermediate roll meets the iteration accuracy, β_2, pressure iteration loop between intermediate roll and backup roll meets the iteration accuracy, β_3, flattening iteration loop between intermediate roll and backup roll meets the iteration accuracy, β_4, and strip thickness iteration loop meets the iteration accuracy, β_5, the actual distribution of forward tensile stress could be calculated.

The basic idea of the flowchart is: Assume tensile stress uniform distribution along horizontal direction, as well as its value, is equal to the average tensile stress. When the plate section calculated by uniform tensile stress meets the convergence precision, turn to tensile stress calculation; then, calculate the distribution of tensile stress according to the actual rolled-piece section till plate section distribution meets the convergence precision. The distribution of tensile stress obtained by influence function method can not only accord with the actual rolling situation, but also break through the limiting condition of equally distributed transversal thickness. The calculation steps of tensile stress distribution based on influence function method are as follows:

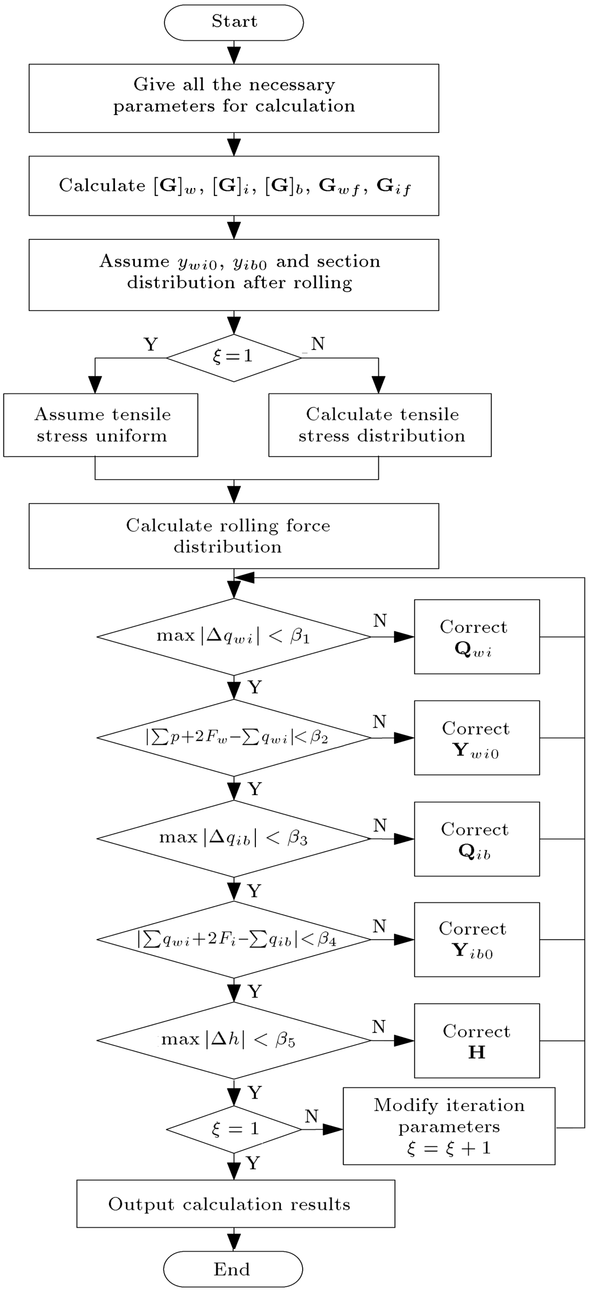

Figure 2. Flowchart of forward tensile stress calculation.

1. Calculate longitudinal strain deviation $\Delta\varpi(g)$ in accordance with known thickness and horizontal flow coefficients;
2. Calculate forward tensile stress according to:

$$\sigma'(g) = E_P\left[\overline{\Delta\varpi} + \eta\Delta\omega(g)\right] + \bar{\sigma}',$$

where, E_P is Young modulus of rolled piece; $\Delta\omega(g)$ is height-direction strain deviation of unit g; $\eta = -\Delta\varpi/\Delta\omega$; and $\bar{\sigma}'$ is average tensile stress;
3. Set $g = 1$;
4. Judge whether the calculated forward tensile stress $\sigma'(g)$ is less than the critical stress of warpage σ_0. If $\sigma'(g) < \sigma_0$, then $\sigma'(g) = 0$. If $\sigma'(g) \geq \sigma_0$, then save the value;
5. Judge whether $g = m$ is true. If not, set $g = g + 1$, turn to Eq. (4); If that is true, calculate tension T;
6. Judge whether $T = \sigma' \times hB$ is true. If not, correct the distribution of tensile stress; if that is true, output the result.

According to the distribution of forward tensile stress $\sigma'(g)$, the average value of the forward tensile stress of the last stand $\bar{\sigma}$ can be worked out as:

$$\bar{\sigma} = \frac{\sum\limits_{g=1}^{m} \sigma'(g)}{m}. \tag{35}$$

5. Optimization algorithm

5.1. Tabu search algorithm

Tabu search algorithm was first put forward by Glover in 1986. It is an expansion of the local neighborhood search and a simulation of human intelligent memory mechanism. The search process can escape local optima and then turn to other regions for search, because the inferior solutions could be accepted during the search process, making the algorithm own a strong climbing ability and avoid circuitous search. At the same time, some tabu good states are released by introducing aspiration criterion to improve the efficiency of optimization, which ensures diversity and effectiveness of the search process; also, the probability of getting a better solution or global optimal solution increases significantly. Tabu search algorithm is an intelligence shuffle algorithm different from GA and SA, which can overcome the defect of easy premature convergence and finally realize global optimization [22,23].

The basic idea of Tabu search algorithm is: Give a current solution and a neighborhood structure, and then determine a number of candidate solutions in the neighborhood of the current solution; if the objective function of the best candidate solution is superior to the reserved best solution, ignore the Tabu feature, replace the current solution and the best solution by the best candidate solution, add the corresponding feature to the Tabu list, and meanwhile modify the Tabu list. If the above-mentioned candidate solution is nonexistent, then, choose the best non-tabu solution in candidate solutions as the new current solution ignoring pros and cons of the current solution, meanwhile add the corresponding features of the solution to the Tabu list, modify the Tabu list repeatedly until stopping criterion is satisfied. Neighborhood structure, Tabu feature, Tabu list, and aspiration criterion are the keys for Tabu search algorithm; they influence optimization results directly.

5.2. Rolling schedule optimization design

For a five-stand tandem cold mill, the entrance thickness h_0, entrance tension T_0 for the first stand, the exit thickness h_5, and exit tension T_5 for the last stand are given according to empirical values. Therefore, choose a total of eight variables for thickness and tension between each pair of stands to be optimized. The optimization variables are as follows:

$$\mathbf{x} = (h_1, h_2, h_3, h_4, T_1, T_2, T_3, T_4)^T, \tag{36}$$

where, $\mathbf{x}$ is optimization vector; h_1, h_2, h_3, and h_4 are inter-stand thicknesses; and T_1, T_2, T_3, and T_4 are inter-stand tensions.

According to the inter-stand thicknesses and tensions, parameters like rolling force and power of each stand can be calculated based on the rolling models. The flowchart of rolling schedule calculation is shown in Figure 3.

The basic idea of the optimized design is: On the basis of the requirements of equipment and technology, determine the exit speed of the mill, inter-stand thicknesses, and inter-stand tensions according to the initial data of the incoming material. Calculate rolling parameters (rolling force, motor power, etc.) for the first time in accordance with known data and judge whether the power or speed goes over the limitation; if they exceed the limit, adjust the exit speed of the mill and recalculate the rolling parameters till they meet the limiting condition; then, calculate objective function. When the calculation is completed and it meets the condition of convergence, check the schedule and output it. If it does not meet the convergence condition, construct Tabu search algorithm and recalculate until the inter-stand thicknesses and inter-stand tensions that meet the limit of constraint conditions are worked out; meanwhile, make the value of the objective function minimum and check the schedule and output it; otherwise, alarm and finish calculation.

5.3. Tension schedule correction

In the tandem cold rolling, friction coefficient of rolls decreases and rolling force decreases with it; thus, strip slipping happens; therefore, it needs to compensate rolling force by means of correcting inter-stand tension. The specific operational process is: Calculate inter-stand tension by multi-objective optimization model; then, correct inter-stand tension through work-roll rolling length of each stand. The calculation formula is as follows:

$$T'_j = \rho_{j+1}.T_j \qquad (j = 1 \sim 4), \tag{37}$$

where, T'_j and T_j are correctional tension and model calculation tension between stand j and stand $j+1$, and ρ_{j+1} is tension correction coefficient determined by work-roll rolling length of stand $j+1$, as shown in Figure 4.

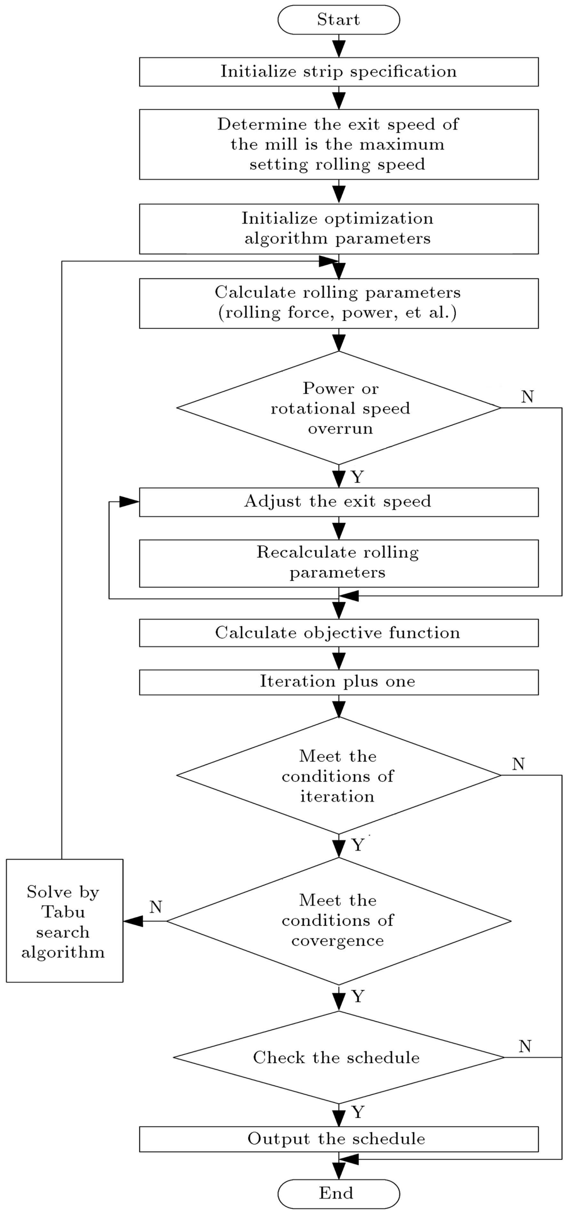

Figure 3. Flowchart of rolling schedule calculation.

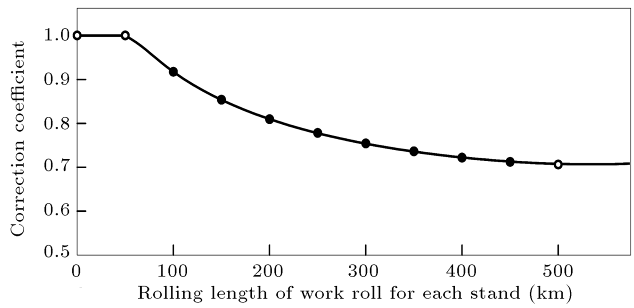

Figure 4. The diagram of tension correction coefficient.

The corresponding correction coefficient can be obtained according to the rolling length of work roll in Figure 4; then, by multiplying it by model calculation tension, revised tension schedule can be obtained.

6. Results and analysis

The proposed multi-objective function optimization algorithm has been successfully applied to a process control system of 1450-mm five-stand tandem cold mill. The main plant parameters are as shown in Table 1.

Take a type of steel SPCC as an example; the entrance thickness is 2.30 mm, the exit thickness is 0.40 mm, and the width of the finished product is 1000 mm. The comparisons of power distributions and tension distributions between rolling schedule calculation adopting multi-objective optimization algorithm and traditional experience method are shown in Figures 5 and 6.

It can be seen in Figures 5 and 6 that under the conditions of meeting the technical requirements, the optimized schedule takes advantage of each stand's motor power reasonably and gives full play to the ability of motors. At the same time, rolling force distributions are less balanced in the schedule calculated by traditional method, while there are more balanced rolling force setting in the optimized one. During the rolling process of last stand, a smaller-constant rolling force is maintained, which can play a role in improving flatness.

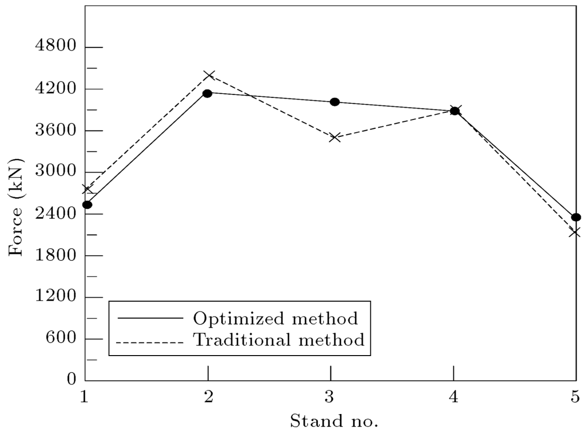

Figure 5. Power distributions for different methods.

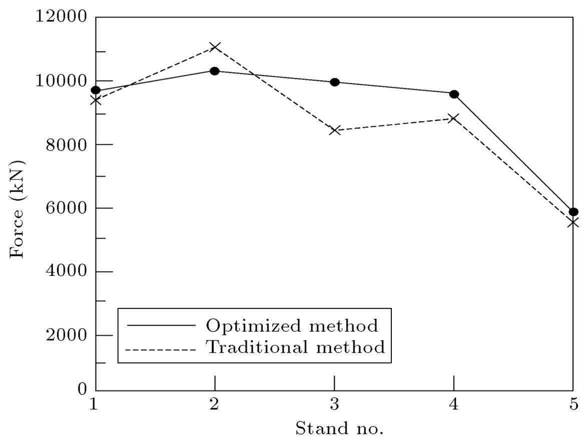

Figure 6. Force distributions for different methods.

Table 1. The main plant parameters of tandem cold mill.

Std.	Power (kW)	Rotate speed (rpm)	Gear ratio (i)	Work roll/ coiling block speed (rpm)
1	3000	300/900	1.91	157/471
2	4200	400/1200	1.91	209/628
3	4200	400/1200	1.357	295/884
4	4200	400/1200	1	400/1200
5	4200	400/1200	1	400/1200

The flatness measurements by adopting multi-objective optimization algorithm and traditional experience method are shown in Figures 7 and 8, respectively. As can be seen by comparing the two figures, flatness measurements by adopting multi-objective optimization algorithm are smooth and have small fluctuations, while flatness measurements by adopting traditional experience method have larger fluctuations, which affect the flatness seriously. The results of application validate the feasibility of the model.

7. Conclusions

1. Based on the influence function method, the flatness objective function is established and then

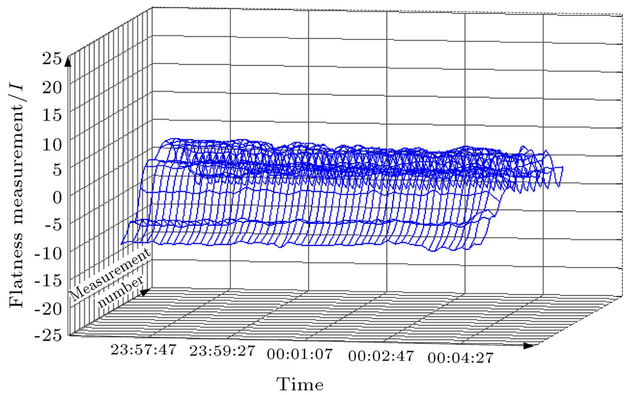

Figure 7. Optimized flatness measurement.

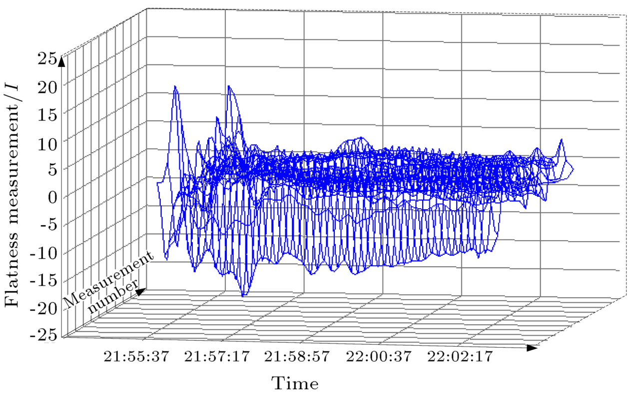

Figure 8. Non-optimized flatness measurement.

rolling-schedule multi-objective optimization model for thin-gauge strip is put forward. Tabu search algorithm is adopted to solve the objective function and a more reasonable rolling schedule is obtained;

2. Tension schedule is corrected according to the rolling length of work roll. The rolling force is compensated in order to avoid slipping of the strip caused by the decrease in friction coefficient;
3. The proposed method has been applied to a tandem cold rolling production line. Field application shows that the optimized rolling schedule can give full play to the capacity of equipment. Therefore, the productivity is enhanced. Meanwhile, quality and flatness of the product are also improved.

References

1. Fiebig, E. and Zander, H. "Automation of tandem cold-rolling mills", *Metallurgical Plant and Technology*, **5**(3), pp. 88-97 (1982).
2. Bemporad, A., Bernardini, D., Cuzzola, F.A., et al. "Optimization-based automatic flatness control in cold tandem rolling", *Journal of Process Control*, **20**(4), pp. 396-407 (2010).
3. Liu, X.X. "Fuzzy multi-object optimization design of rolling schedule on cold continuous rolling mill", *Iron and Steel*, **35**(8), pp. 34-36 (2008) (in Chinese).
4. Wang, D.D., Tieu, A.K., de Boer, F.G., et al. "Toward a heuristic optimum design of rolling schedules for tandem cold rolling mills", *Engineering Applications of Artificial Intelligence*, **13**(4), pp. 397-406 (2000).
5. Chen, N.N., Fei, Q. and Hu, H.P. "Research on optimization algorithm applied in plate rolling schedule", *Applied Mechanics and Materials*, **1439**(06), pp. 296-301 (2011).
6. Yang, J.M., Che, H.J., Dou, F.P., et al. "Genetic algorithm-based optimization used in rollingschedule", *Journal of Iron and Steel Research International*, **15**(2), pp. 18-22 (2008).
7. Poursina, M., Dehkordi, N.T., Fattahi, A., et al. "Application of genetic algorithms to optimization of rolling schedules based on damage mechanics", *Simulation Modelling Practice and Theory*, **22**, pp. 61-73 (2012).
8. Yang, J.M., Zhang, Q., Che, H.J., et al. "Multi-objective optimization for tandem cold rollingschedule", *Journal of Iron and Steel Research (International)*, **17**(11), pp. 34-39 (2010).
9. Oduguwa, V., Roy, R. and Farrugia, D. "Fuzzy multi-objective optimization approach for rod shape design in long product rolling", *Lecture Notes in Artificial Intelligence*, **2715**, pp. 636-643 (2003).
10. Duenas, A. and Petrovic, D. "Multi-objective genetic algorithm for single machine scheduling problem underfuzziness", *Fuzzy Optimization and Decision Making*, **7**(1), pp. 87-104 (2008).
11. Bath, S.K., Dhillon, J.S. and Kothari, D.P. "Fuzzy satisfying stochastic multi-objective generation scheduling by weightage pattern search methods", *Electric Power Systems Research*, **69**(2-3), pp. 311-320 (2004).
12. Dhillon, J.S. and Kothari, D.P. "The surrogate worth trade-off approach for multi-objective thermal power dispatch problem", *Electric Power System Research*, **56**(2), pp. 103-110 (2000).
13. Liu, S.J. and Wu, B.C. "Optimum design of rolling schedule for tandem cold mill using SLPSO", *Applied Mechanics and Materials*, **1468**(06), pp. 443-446 (2012).
14. Lin, S. and Nan, Y.R. "Optimization of rolling schedule in tandem cold mill based on QPSO algorithm", *Advanced Materials Research*, **1046**(06), pp. 165-170 (2011).
15. Qi, X.D., Wang, T. and Xiao, H. "Optimization of pass schedule in hot strip rolling", *Journal of Iron and Steel Research, International*, **19**(8), pp. 25-28 (2012).
16. Hu, X.L., Zhao, Z., Wang, J., et al. "Optimization of holding temperature and holding thickness for controlled rolling on plate mill", *Journal of Iron and Steel Research, International*, **13**(3), p. 21 (2006).
17. Purshouse. R.C. and Fleming, P.J. "On the evolutionary optimization of many conflicting objectives", *IEEE Transactions on Evolutionary Computation*, **11**(6), pp. 770-784 (2007).
18. Pires, C.T.A., Ferreira, H.C., Sales, R.M., et al. "Set-up optimization for tandem cold mills: a case study", *Journal of Materials Processing Technology*, **173**(3), pp. 368-375 (2006).
19. Murakami, A.A., Nakayama, M., Okamoto, M., et al. "Optimization of pass schedules for a tandem cold mill", *Tetsu to Hagane-Journal of the Iron and Steel*, Institute of Japan, **90**(11), pp. 953-957 (2004).
20. Pires, C.T.D., Ferreira, H.C. and Sales, R.M. "Adaptation for tandem cold mill models", *Journal of Materials Processing Technology*, **209**(7), pp. 3592-3596 (2009).
21. Wang, G.D., *Flatness Control and Flatness Theory*, Metallurgy Industry Press, Beijing (1986) (in Chinese).
22. Mashayekhi, M., Torabian, N. and Poursina, M. "Continuum damage mechanics analysis of strip tearing in a tandem cold rolling process", *Simulation Modelling Practice and Theory*, **19**(2), pp. 612-625 (2011).
23. Calvo, J., Collins, L. and Yue, S. "Design of microalloyed steel hot rolling schedules by torsion testing: average schedule vs. real schedule", *Metallurgy & Metallurgical Engineering*, **50**(8), pp. 1193-1199 (2010).

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