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Research Article

Analysis of Startup Process and Its Optimization for a Two-Stand Reversible Cold Rolling Mill

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Dynamic characteristic analysis of a two-stand reversible cold rolling mill in the startup process was carried out. The delay algorithm of the interstand thickness was proposed. A new method combined with the accelerated secant and the tangent methods was established to solve the simultaneous equations. The thickness and interstand tension transition processes with different static tension establishing processes were analyzed. Both mills were operated under constant rolling force control mode in the above process. The results show that the strip thickness in the rolling gap reduces in the static mill screwdown process. The entry stand runs inversely to establish the static interstand tension. This area becomes an abnormal thickness reduction area of the incoming strip. It results in several abnormal interstand tension increases in the subsequent startup process. The tension increase leads to an impact force on the strip that is the main reason of the strip breakage in the startup process. So the static tension establishing process was optimized, and the interstand tension fluctuation and the strip breakage accidents both reduced significantly. The results are beneficial to the startup process of the two-stand reversible cold rolling mill.

1. Introduction

Two-stand reversible cold rolling mills, a typical layout of which is shown in Figure 1, are also called compact cold mill (CCM). It was specially developed for moderate scale cold rolling plant. Strip breakage occurs frequently during the initial commission phase of some CCM, which has not been solved effectively. This phenomenon is the most severe when starting rolling or the strip running about an interstand distance which is called the startup process. In our mill about 30 strip breakage accidents occurred in this step in the most serious month. After taking some improving measures, the accidents caused by startup process still take up about one-fifth except the reasons of electric, technology, and incoming material. It is very difficult to investigate the causes in the actual rolling mill, while simulation is a feasible method to analyze the composite control system and is also an indispensable tool to establish new control systems or operation schemes.

The thickness control and tension establishing process of a five-stand tandem cold rolling mill (TCM) were analyzed using a linearization physical model based on dynamic tension differential equations and the thickness delay method by PHILLIPS [1]. It is the origin of computer simulation of continuous rolling processes. This method was usually used to analyze the automatic gauge control (AGC) systems of TCM [2]. The steady-state, dynamic behavior [3, 4] and disturbance rejection characteristics [5] of AGC systems were investigated. It was also used for transient property simulation of continuous rolling mills such as transient rolling characteristics [6] and control system performance [7]. And the interactions between interstand tension and thickness control [8], steady-state characteristic [9], and process sensitivity [10, 11] of the transient processes were obtained as well.

The above simulation processes were all carried out using the linearization algorithm. This linear approximation represents very well the system in simulation for small variations of process variables around the operation points. However, a

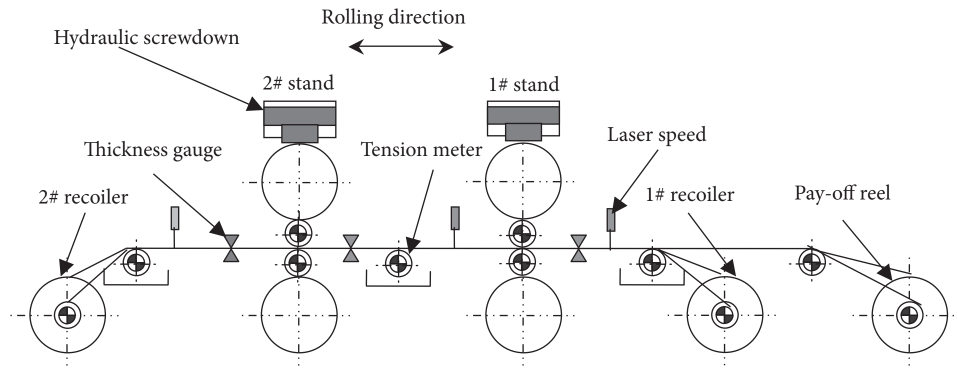


Figure 1: Typical two-stand reversible cold rolling mill.

big error would occur if the parameters variations are large; in other words, the linearization algorithm is not proper for simulating large disturbances. Then the nonlinear algorithm, which was proposed in around 1970s with the development of computer, should be a good choice. The transient characteristics of threading, acceleration, deceleration, and tail-out processes with and without AGC [12] were analyzed using the nonlinear method. And this method was also extended to strip crown control and rolling force analysis with a two-dimensional dynamic metal model [13].

For the thickness deviation is large at the stand position in the steady tension establishing process of some CCM. In the present study, at first, the dynamic characteristic analysis program was developed using nonlinear algorithms, in which the formulas of the rolling theory are numerically calculated directly without any approximation. Second, the transient process in the startup process was analyzed and the influence factors on the rolling stability were examined in detail. Finally, the optimization of the running status of the CCM startup process was presented and carried out in the production line. The running status of the new startup strategy was discussed.

2. Physical Equations and Calculation Methods

The mathematical model used for dynamic characteristic analysis includes the intrastand equations such as spring equation, rolling force equation, forward slip equation, and interstand equations such as tension continuity, thickness continuity, and tension differential equations connecting the adjacent stands [4]. The calculation methods used in the dynamic characteristic analysis include the thickness delay algorithm of each stand, the roll gap, and thickness calculation method under constant rolling force mode and the special solving method of dynamic continuous rolling status. The connections jointing the adjacent stands involve simulation of time delayed transport of thickness from one stand to the next and the calculation of interstand tension.

2.1. Spring Equation. As the rolling mill is not perfectly rigid, the exit thickness can be expressed by the elastic equation of the rolling mill:

$$h = S + \frac{P}{K_m}. \tag{1}$$

2.2. Rolling Force Equation. The Hill's simplified form of Bland-Ford equation is selected as the rolling force equation in this study:

$$P = B\overline{k}\left[R'\left(H-h\right)\right]^{1/2} Q_p n_t \tag{2}$$

with $\overline{k} = a_1(\overline{\varepsilon} + a_2)^{a_3}$, $\overline{\varepsilon} = 0.4\varepsilon_H + 0.6\varepsilon_h$, $\varepsilon_H = 1 - H/H_0$, $\varepsilon_h = 1-h/H_0$, $R' = R[1+C_0P/(B(H-h))]$, $Q_p = 1.08+1.79\varepsilon f(R'/H)^{1/2} - 1.02\varepsilon$, and $\varepsilon = (H-h)/H$, $n_t = 1-[(1-\mu_t)t_f + \mu_t t_b]/\overline{k}$.

2.3. Forward Slip Equation. The width spread is small in the cold rolling process and can be ignored. The neutral angle is small as the deformation zone is narrow. The ratio of work roll diameter (D, $D = 2 * R$) to strip exit thickness (h) is far more than 1. So the D. Dresden [8] forward slip equation is used:

$$s_h = \frac{R'}{h} \cdot \gamma^2 \tag{3}$$

with $\gamma = (h/R')^{1/2} \tan((h/R')^{1/2} \cdot H_n/2)$, $H_n = H_b/2 - 1/(2f)\ln(H/h \cdot (1-t_f/k_h)/(1-t_b/k_H))$, $\alpha = (\Delta h/R')^{1/2}$, $H_b = 2 \cdot (R'/h)^{1/2} \arctan((R'/h)^{1/2} \cdot \alpha)$.

2.4. Interstand Tension Equation. The interstand strip thickness is uneven due to the interstand tension establishing process. So the interstand tension is solved by integrating the tension differential equation for a variable section [14]. The differential equation is related to the difference between the exit speed of the strip from one stand and entry speed to the subsequent stand. Thus, the forward tension is obtained by the stress strain relationship, and the back tension is obtained by the equalization principle of the interstand tension.

$$\mathrm{d}t_{fi} = \frac{E}{\left[h_i\left(\sum_{j=1}^{n} l_j/h_j\right)\right]\int\left(v_{H,i+1} - v_{h,i}\right)\mathrm{d}t},$$
$$t_{bi+1} = \frac{h_i}{H_{i+1}} \cdot t_{fi}. \tag{4}$$

2.5. Delay Algorithm of Interstand Thickness. For steady-state analysis, we have $h_i = H_{i+1}$, but in the dynamic characteristic analysis process the exit thickness of the ith stand h_i equals the entry thickness of the $i+1$th stand only when the position with thickness h_i reaches the $i+1$th stand. The point leaves the ith stand at time τ^n with strip thickness h_i^n and exit speed v_{hi}^n. The running distance will be $L_{ti}^n = v_{hi}^n \mathrm{d}\tau$ at the time $\tau^{n+1} = \tau^n + \mathrm{d}\tau$ when it moves with this speed for $\mathrm{d}\tau$. Then the exit thickness and exit speed will change to h_i^{n+1} and v_{hi}^{n+1}, respectively, due to the change of tension or other factors at time τ^{n+1}. Thus, the distance from the ith stand of this point is $L_{ti}^{n+1} = L_{ti}^n + v_{hi}^{n+1}\mathrm{d}\tau$ after $\mathrm{d}\tau$, and at time m the distance is $L_{ti}^m = \sum_{j=n}^{m} v_{hi}^j \mathrm{d}\tau$. If L_{ti}^m is equal to or larger than the interstand distance L_i, it is considered that the point reaches the $i+1$th stand. Therefore, the interstand delay thickness can be obtained in the converse way, while h_i and v_{hi} are put into the delay table [15]. In order to acquire the entry thickness of the $i+1$th stand H_{i+1} at time m, we only need to find out the time that the point leaves the ith stand and obtain h_i.

2.6. Solution of Simultaneous Equations. In the simulation process, the known variables are entry thickness and rolling force, and the unknown variables are exit thickness h_i and roll gap S_i respectively, since the mill is under constant force control mode.

The entry thickness is inquired from the delay table and the rolling force is the preset value. The exit thickness is obtained through solving the rolling force equation by the accelerated secant method or tangent method, and then the roll gap is obtained by the spring equation. However, the tangent method is stringent conditional convergence and highly sensitive to the initial solution. In opposite, the secant method requires two better initial solutions, and its convergence speed is slower than that of the tangent method. So a method combined by the accelerated secant and the tangent methods is proposed, as is shown in Figure 2.

First, a better initial solution for the tangent method is obtained by the accelerated secant method; then the tangent method is executed based on the above initial solution to achieve a better approximate solution. The rolling forces P_i^1 and P_i^2 are calculated corresponding to two given strip thicknesses h_i^1 and h_i^2, respectively, and a secant of the plastic curve is obtained by joining point (h_i^1, P_i^1) and point (h_i^2, P_i^2), respectively, which meets the constant rolling force curve at point (h_i^3, P_i). Then the rolling force P_i^3 with thickness h_i^3 can be obtained, and the point (h_i^3, P_i^3) is the solution of the first step.

Replacing point (h_i^1, P_i^1) with point (h_i^3, P_i^3), a new solution can be obtained. The calculation iterates until $|P_i^n - P_i| < \varepsilon_1$, where ε_1 is the convergence limit of the secant method. The point (h_i^n, P_i^n) is the required approximate solution.

The secant's slope is

$$K_{gi}^{n-1} = \frac{\left(P_i^{n-1} - P_i^{n-2}\right)}{\left(h_i^{n-1} - h_i^{n-2}\right)}. \tag{5}$$

The new solution for the strip thickness is

$$h_i^n = \frac{\left(P_i - P_i^{n-1}\right)}{K_{gi}^{n-1}} + h_i^{n-1}. \tag{6}$$

Since the above approximate solution is obtained, taking point (h_i^n, P_i^n) as the initial solution of the tangent method and the equation solution with tangent method is carried out. The tangent's slope is obtained by the partial differential of (2), the rolling force model.

$$K_{qi}^n = \frac{\partial P_i}{\partial h_i} = \frac{-(P/H)\left\{-\left(0.6a_3/\left(\bar{\varepsilon}+a_2\right)\right)\left(H/H_0\right)\left(1/n_t\right) - (1/2\varepsilon)\left(R/R'\right) - \left(1.79f/2Q_p\right)\sqrt{R'/H}\left(1+R/R'\right) + 1.02/Q_p\right\}}{1 - \left(\left(R'-R\right)/2R\right)\left(1 + \left(1.79\varepsilon f/n_t\right)\sqrt{R'/H}\right)}. \tag{7}$$

The new solution for the strip thickness by the tangent method is

$$h_i^{n+1} = \frac{\left(P_i - P_i^n\right)}{K_{qi}^n} + h_i^n. \tag{8}$$

Replacing point (h_i^n, P_i^n) by point (h_i^{n+1}, P_i^{n+1}), a new solution can be obtained. The calculation iterates until $|P_i^m - P_i| < \varepsilon_2$, where ε_2 is the convergence limit of the tangent method, and the point (h_i^m, P_i^m) is approximate to the real solution.

Substituting (8) into (1), the rolling gap is

$$S_i{}^m = \frac{\left(P_i - P_i^{m-1}\right)}{K_{qi}^{m-1}} + h_i^{m-1} - \frac{P_i^m}{K_{mi}}. \tag{9}$$

2.7. Solving Step. Among the above mathematic equations and calculation methods, the solution of the simultaneous

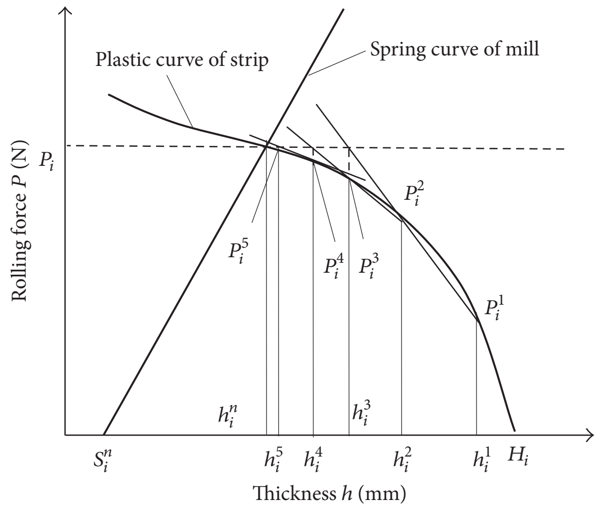


Figure 2: Schematic of simultaneous solution of the elastic-plasticity curve.

equations is essentially steady. In fact, the rolling force equation, forward and backward slip equations, friction coefficient, and spring equations are all steady. However, in the dynamic state, the steady equations and algorithms of each stand are correlative for the connection of the thickness delay equation and tension differential equation between the adjacent stands. So the rolling process simulation needs to solve huge combination equations including many algebraic equations of each stand, the interstand tension differential equation and the thickness delay equation. Then the parameters of each stand can be obtained by solving the combination equations at time τ_1. Taking the above parameters as constant, the parameters at new time $\tau_2 = \tau_1 + \mathrm{d}\tau$ are obtained by resolving the combination equations. Then the variation laws of each parameter, namely, the simulation results, are obtained with this method.

However, it is very difficult to solve the combination equations. So here a special calculation method which includes two steps is adopted [15]. First step, the parameters of each stand including $P_i^{(1)}$, $H_i^{(1)}$, $v_i^{(1)}$, $t_{fi}^{(1)}$, and $t_{bi}^{(1)}$ are constant at time τ_1; then the parameters including $S_i^{(1)}$, $h_i^{(1)}$, $s_{hi}^{(1)}$, $s_{Hi}^{(1)}$, $f_i^{(1)}$, $v_{hi}^{(1)}$, and $v_{Hi}^{(1)}$ are obtained by the calculation of steady equations. Second step, assume the above parameters to be constant in a small time interval; then the tension increment at time $\tau_2 = \tau_1 + \mathrm{d}\tau$ can be obtained from the tension differential equation; the interstand tension can be obtained by $t_{fi}^{(2)} = t_{fi}^{(1)} + \mathrm{d}t_{fi}^{(1)}$.

A new calculation process starts at time $\tau_2 = \tau_1 + \mathrm{d}\tau$. The entry thickness of each stand changes from $H_i^{(1)}$ to $H_i^{(2)}$ for the thickness delay effect and the interstand tension changes as well. Then the parameters of each stand such as $S_i^{(2)}$, $h_i^{(2)}$, $s_{hi}^{(2)}$, $s_{Hi}^{(2)}$, $f_i^{(2)}$, $v_{hi}^{(2)}$, and $v_{Hi}^{(2)}$ are recalculated. The parameters variation process of each stand can be obtained with this process being executed successively. This is the implementation method of dynamic characteristic analysis for the continuous rolling process.

3. Running Status Analyses

In order to find out the causes that result in strip breakage, the running status should be analyzed. Then the causes will be evaluated with the established simulation program, and the improving measure will be proposed. The forward tension of the exit stand and the back tension of the entry stand are tracking controlled by speed of the uncoiler and recoiler, respectively. So the influences of these two tension variations are not considered in this simulation process.

3.1. Startup Process Analyses. The original designed startup process of this CCM is as follows: threading completed → a lower rolling force reached → a static tension reached → the preset rolling force reached → the preset tension reached → rolling startup. The screwdown control mode, the interstand tension, rolling force, and mill speed variation processes of the startup process from Process Data Acquisition (PDA) system are shown in Figure 3(a). The rolling gap is set to 6 to 12 mm which is larger than the original strip thickness in the threading stage; that is to say, the rolling mills do not work and there is no thickness reduction in this stage. When the strip has passed the rolling mills and the recoiler has winded 3 to 4 circles, a small tension between the uncoiler and recoiler has been established, and the threading process completed. Then the stands under force control mode screw down to a lower rolling force which is about 4000 kN, and the strip was forced by the work roll to contact with the tension meter resulting in a small static tension. Next, the rolling stands both continue screwing down to the preset rolling force before mill's startup. Afterward, the entry stand moves inversely with a low speed in order to establish the interstand tension. In this process, the entry stand has made a short-time inverse rolling process which makes the strip become thinner on the entry side of the entry stand as is shown in Figure 3(b) [15].

After the above preparing process, the mills start rolling. The interstand tension is controlled by the speed of the entry stand in the subsequent startup process. On the entry side of both stands, the strip thickness is the same as the original thickness at this moment except the thickness reduction area of the entry stand as is shown in Figure 3(b). When mills start to run, the reduction area firstly enters the entry stand which is still under force control mode. It is to say that the entry stand will screw down to reach the preset rolling force, which makes the thickness reduction area even thinner as is shown in Figure 4(b). Meanwhile, the mass flow rate of the entry stand reduces which will cause the first interstand tension increase as is shown in Figure 4(b). The tension increase will cause an impact force on the strip. If the strip is thin or there are some defects strip breakage will occur. It is consistent with the strip breakage accident occurring at the moment of mills startup.

The time interval between the adjacent sample points is 0.03 s. The entry stand changed from force control mode to position control mode after running for about 1.5 s as is shown in Figure 4(a), while the exit stand is still under force control mode because the exit thickness has not reached the target thickness. So the exit stand will screw down to reach

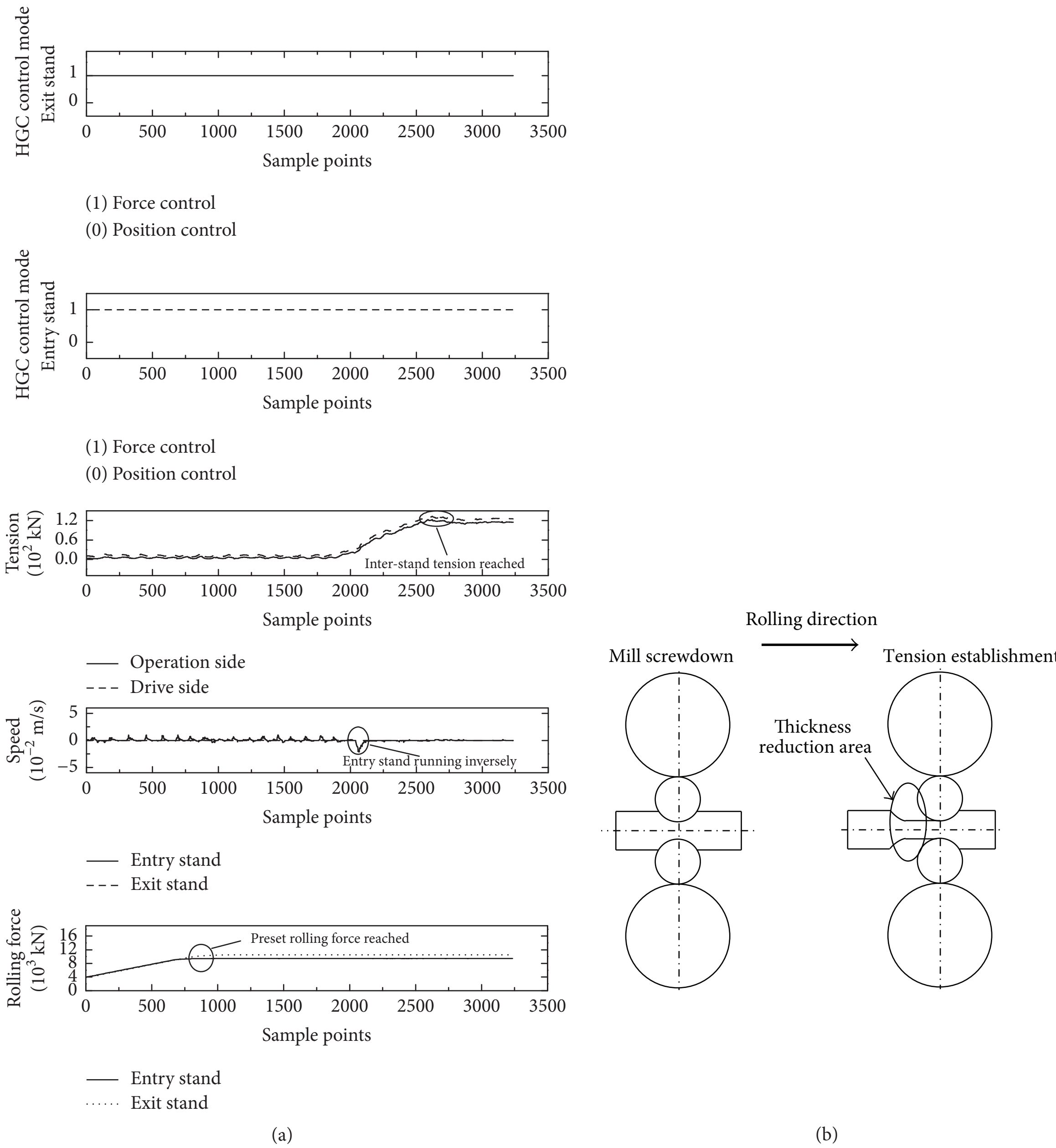
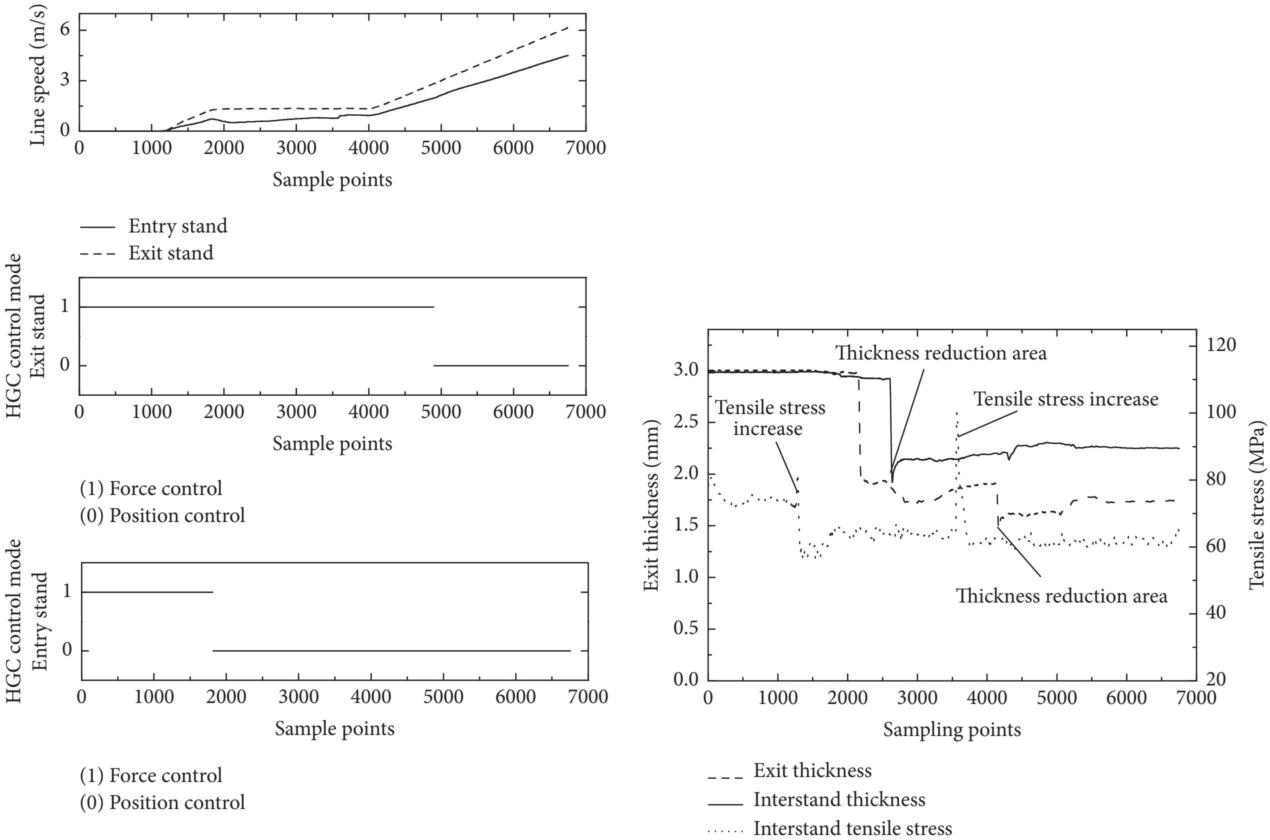


Figure 3: Schematic diagram and PDA of interstand tension establishing process: (a) schematic of interstand tension establishing process; (b) tension establishing process by entry stand.

the preset rolling force when the further reduced thickness reduction area reaches the exit stand. As a result, the thickness reduction area still exists on the exit thickness curve as is shown in Figure 4(b). The mass flow rate relationship between the exit stand and the recoiler is destroyed when the thickness reduction area passes the exit stand. There is a speed increase of the exit stand in order to retain this relationship and it causes the second tension increase as is shown in Figure 4(b) [15]. It is consistent with the strip breakage accident occurring with the strip running about an interstand distance. The mass flow rate relationship between the entry stand and the exit stand is also destroyed at the same time, and then the entry stand accelerates in order to meet the mass flow rate of the exit stand, while the speed of the exit stand is the reference speed of the whole system. Afterward, the exit stand changes from force control mode to position control mode about 2.0 s after the target thickness is detected by the exit gauge meter as is shown in Figure 4(a).

It can be seen from Figure 4(b) that there is one transition of the interstand thickness, while there are two transitions of the exit thickness. The first one is generated by the preset rolling force in the tension establishing process. And the second one is generated when the thickness transition position of the entry stand reaches the exit stand. Due to



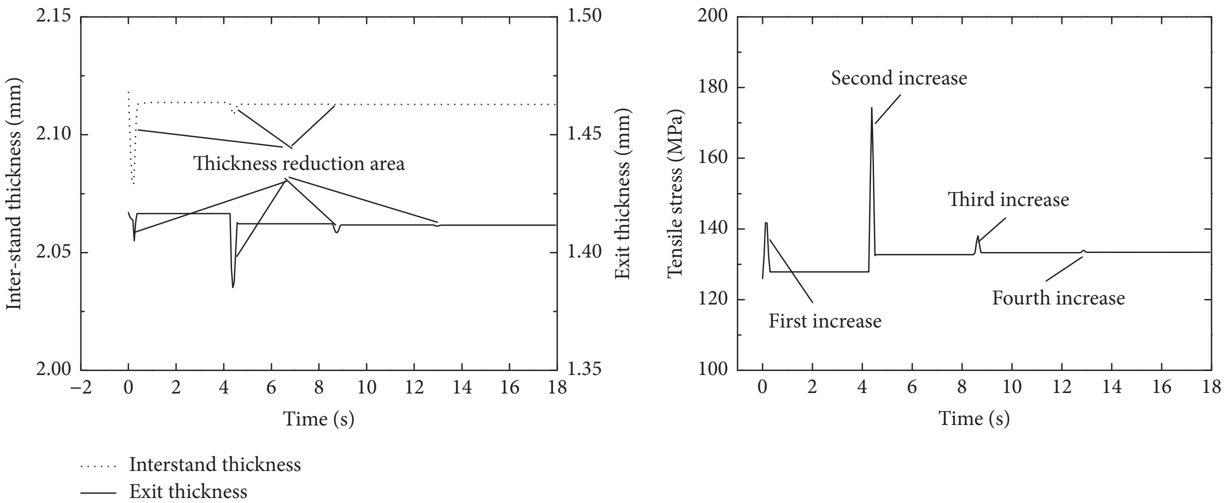
(a) (b)

Figure 4: HGC control mode, thickness, and tensile stress variations in the startup process: (a) HGC control mode and line speed variation; (b) tensile stress and thickness variation.

the special interstand tension establishing mode, there are two abnormal thickness reduction areas at the thickness transition position of the interstand and the exit thickness, respectively. Therefore, two sharp tension increases appear when the thickness transition area enters the entry and exit stands, respectively, and the second tension increase is larger than the first one. These tension increases will result in impact force to the strip. The strip at stand position is relatively thinner and becomes a weak section where the strip breakage may easily happen.

3.2. Influence of Thickness Transition Area on Rolling Status. It is necessary to analyze the influence of the thickness transition area on the rolling status in the startup process. And the variation of strip thickness and interstand tension in the startup stage were simulated using the model established above. A typical rolling schedule of the CCM to be used for simulation is listed in Table 1. The work roll diameter is 450 mm, its Young's modulus is 210 GPa, and Poisson ratio is 0.3. The longitudinal stiffness of mill is 5280 kN/mm. The two stands are identical. The distance between the stands is 4500 mm. The strip width is 1000 mm. The abnormal entry thickness variation form was considered as a half cycle sinusoidal type, the peak value of which is about 0.2 mm.

3.2.1. Simulation of the Original Startup Process. The thickness and interstand tension variation process in the startup stage with the interstand tension established by the speed of the entry stand are shown in Figure 5. There are three obvious thickness reduction areas on the interstand thickness curve, while there are four on the exit thickness curve as is shown in Figure 5(a). The first one on the interstand thickness curve was formed in the static interstand tension establishing process. And it was rolled by the entry stand in the following startup process that caused the first tension increase as is shown in Figure 5(b). This interstand tension increase results in a rolling force decrease which makes the exit thickness of both stands reduce. This is the reason of the first thickness reduction on the exit thickness curve. When the first thickness reduction area on the interstand thickness curve reaches the exit stand which is still under force control mode, it will screw down to reach the preset rolling force. The second thickness reduction area on the exit thickness curve formed as is shown in Figure 5(a) and it leads to the second interstand tension increase as is shown in Figure 5(b). This interstand tension increase again results in rolling forces decrease which makes the exit thickness of both stands reduce. This is the reason of the second thickness reduction on the interstand thickness curve.



(a) (b)

Figure 5: Thickness and tension variation in the startup process with tension established by the entry stand: (a) thickness variation; (b) tensile stress variation.

Table 1: Typical rolling schedule for simulation calculation.

Stand	Entry thickness H/mm	Exit thickness h/mm	Forward tension t_f/MPa	Back tension t_b/MPa	Rolling speed v/m·min^{-1}
Entry stand	3.000	2.120	126	29	—
Exit stand	2.120	1.417	84	126	574

The other thickness reductions are caused by the sequential effect of the previous abnormal thickness deviations. As a result, four obvious sharp tension increases appear in the startup process due to the thickness transition area as shown in Figure 5(b) [15]. The first and second tension increases corresponding to the thickness transition area reached the entry and exit stands. The third tension increase is due to the thickness deviation caused by the second tension increase reaching the exit stand. The fourth tension increase is due to the thickness deviation caused by the third tension increase reaching the exit stand. Therefore, the first and the second tension increases are relatively larger. The sequential thickness and tension deviations are relatively smaller, the influences of which on the strip are not that severe.

The simulation result is similar to the phenomenon which occurred in the rolling process confirming the validity of the simulation method. These tension increases will result in an impact force to the strip. The strip at stand position is relatively thinner but cold worked and becomes a weak section at these moments. Strip breakage accident may easily occur due to these tension increases. This is just the reason that results in the strip breakage at the moment of startup and when strip runs an interstand distance. In order to reduce the strip breakage accident, the impact force should be decreased or eliminated.

3.2.2. Simulation of the Startup Process with Static Interstand Tension Established by Exit Stand. In order to avoid the abnormal thickness reduction area formed in the static interstand tension establishing process due to the inverse rolling of the entry stand, a new static interstand tension establishing method is introduced. The difference from the original method is that once the preset rolling force is reached, the exit stand runs forward to build the interstand tension. So the thickness reduction area on the entry side of the entry stand is eliminated. The thickness and interstand tension variation process in the startup stage are shown in Figure 6. The mills are still under force control mode in the subsequent startup process. Since the abnormal thickness reduction area on the entry side of the entry stand is eliminated, the first thickness and tension fluctuations disappear as shown in Figures 6(a) and 6(b). There are two obvious thickness reduction areas on both the interstand and exit thickness curve and two tension increases. Although the fluctuations of thickness and tension do not disappear, the numbers decrease. There is still a thickness transition area for the incoming thickness of the exit stand. The interstand thickness is equal to the original thickness before the rolling process starts. Once rolling begins the interstand thickness gradually becomes the exit thickness of the entry stand, so there is an incoming thickness transition area of the exit stand. When this transition area reaches the exit stand the first tension increase occurs and it makes the rolling forces of both stands reduce. The exit thicknesses of both stands reduce at the same time. The subsequent thickness and tension fluctuation mode and mechanisms are similar to the original startup process as shown in Figure 6.

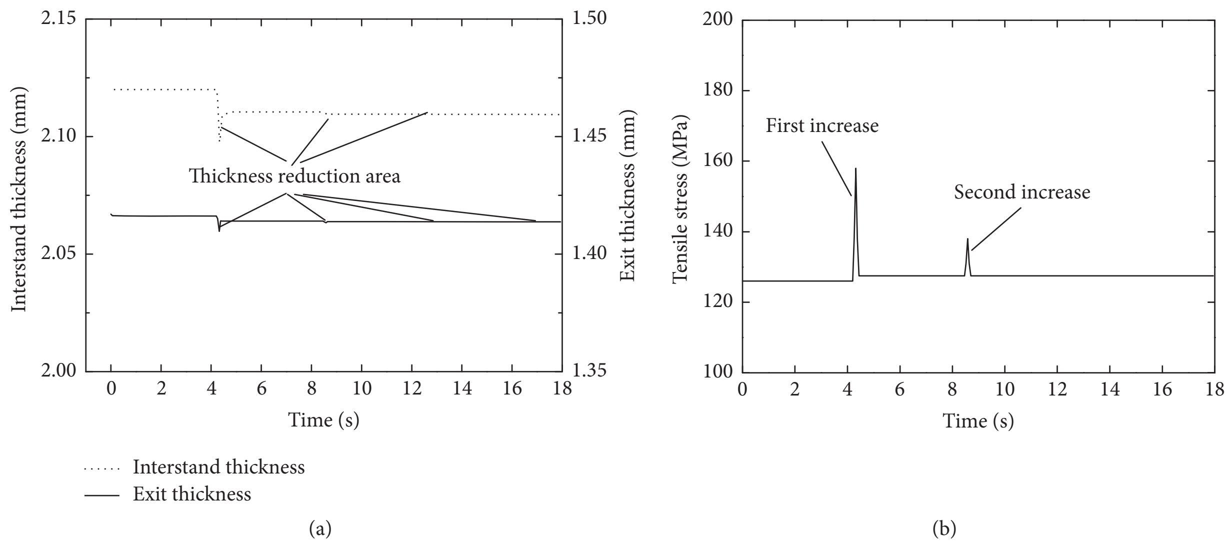


Figure 6: Thickness and tensile stress variations in the startup process with tension established by the exit stand: (a) thickness variation; (b) tensile stress variation.

4. Application and Discussions of New Startup Strategy

It can be obtained from the above analyses that the thickness transition area is the main reason that causes the sharp interstand tension increases, and the sharp interstand tension increases result in the strip breakage in the startup stage. The abnormal thickness reduction area at the thickness transition area is eliminated by changing the interstand tension establishing mode. So the thickness and tension fluctuation quantity decrease obviously. This illustrates that the abnormal thickness reduction area can make the thickness and interstand tension fluctuations much more severe. Furthermore, the abnormal thickness reduction area is thinner than any other position on the strip and it is the weak section.

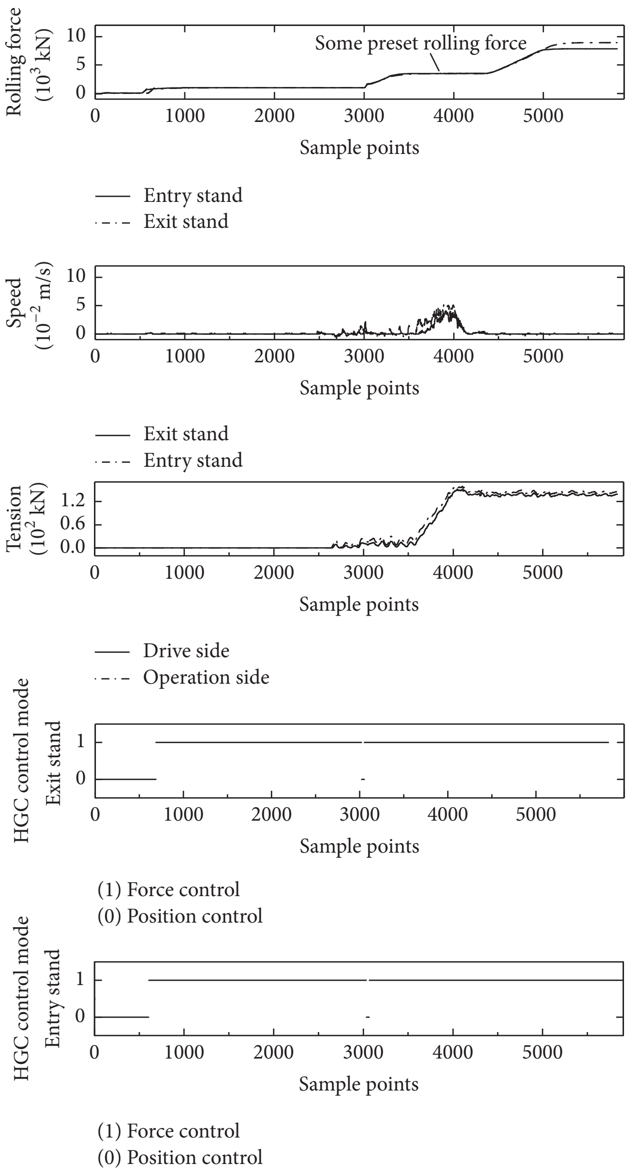
In the actual rolling process, the first two tension increases are severe and they are both caused by the thickness transition area of the entry stand due to the special interstand tension establishing mode. In order to avoid strip breakage in the startup process, the abnormal thickness reduction area should be decreased or eliminated. In other words, the startup mode should be modified or changed. It is difficult to change the startup process entirely as the practical rolling mill requires a complicated control program modification, which might affect the productivity. So taking some measure to decrease the thickness reduction amount could be a feasible way. The mill is still under force control mode. Then reducing the preset rolling force in the tension establishing stage becomes a proper choice without changing the control system.

For the startup mode is not allowed to change entirely, the startup process is modified as shown in Figure 7(a): threading completed → a minimize rolling force reached → static tension reached → some preset rolling force reached → the preset tension reached → the preset rolling force reached → rolling startup. In the field application process, the preset rolling force for interstand tension establishing is half of the preset rolling force. As shown in Figure 7(b), the thickness reduction is very small and even disappears for using the developed new startup process. The second tension increase still exists, while the first tension increase disappears, but the tension increased amount decreases dramatically [15]. This tension increase is due to the strip rolled in the entry stand that enters the exit stand. It is an inevitable problem of the CCM with a static tension establishing process. The strip breakage accidents in the startup process are almost eliminated after the optimization of interstand tension establishing process.

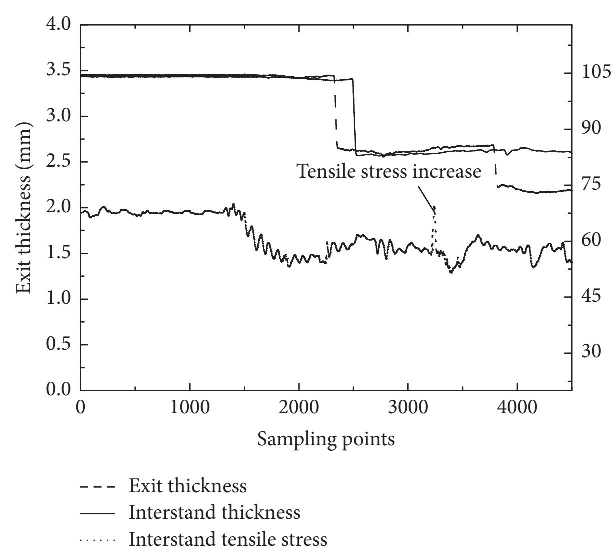
In addition, the preset rolling force of the strip head is larger, and the hydraulic gauge control (HGC) mode of the entry stand changes from force control to position control resulting in a thickness reduction. When this thickness reduction area reaches the exit stand, it also causes a sharp tension increase which may cause strip breakage. Therefore, in order to reduce the thickness reduction which can result in a sharp tension increase, the preset rolling force value of the strip head should also be decreased. Then the thickness fluctuation is reduced, the stability of interstand tension is improved, and the probability of strip breakage caused by unreasonable process parameters is reduced. Furthermore, the thickness and interstand tension fluctuation caused by deformation resistant fluctuation resulting from uneven cooling or friction variation can also result in strip breakage in this stage. So the homogeneity of strip temperature in the cooling process of hot strip and good lubrication condition are also very important to the rolling stability.

5. Conclusions

(1) The dynamic characteristic analysis of the CCM was developed using physical equations based on dynamic continuous rolling theory. In order to solve the rolling force



(a)



(b)

Figure 7: New tension establishing process, thickness, and tensile stress variations of modified startup process: (a) schematic of new interstand tension establishing process; (b) tensile stress and thickness variation.

equation, a new method combined with the accelerated secant and the tangent methods is proposed. The interstand tension was calculated by integrating the tension differential equation of variation section.

(2) Sharp tension increases are caused by the thickness transition area and abnormal thickness reduction area formed in the static tension establishing process. The tension increase results in an impact force on the strip, which is the main reason for strip breakage in the startup stage.

(3) The mill startup process is modified in order to reduce or eliminate the sharp tension increase and the abnormal thickness reduction area. The strip breakage accidents in the startup process are almost eliminated by using the new developed startup mode. The interstand tension and thickness fluctuations cannot be eliminated completely for the special static interstand tension establishing process.

Symbols

a_i: Deformation resistance parameters, $i = 1, 2, 3$
B: Strip width
C_0: Constant, $C_0 = 2.1208 \times 10^{-3}\ \mathrm{MPa}^{-1}$
E: Elastic modulus of strip
f: Friction coefficient
H_0: Thickness of incoming hot rolled strip

H: Strip entrance thickness
h: Strip exit thickness
Δh: Reduction of strip, $\Delta h = H - h$
K_{gi}: Plastic coefficient of strip by secant method, where $i = 1, 2$ denotes the stand number
K_m: Longitudinal stiffness of mill
K_{qi}: Plastic coefficient of strip by tangent method, where $i = 1, 2$ denotes the stand number
$\overline{k}$: Average deformation resistance
k_H: Deformation resistance of the strip entry section
k_h: Deformation resistance of the strip exit section
L: Interstand distance, where $\sum_{j=1}^{n} l_j = L$, $j = 1, \ldots, n$ is number of the interstand thickness segments
l_j: Length with the exit thickness h_j, where $j = 1, \ldots, n$ is number of the interstand thickness segments
n_t: Tension factor
P: Rolling force
Q_p: Stress state coefficient
R: Work roll radius
R': Flattening work roll radius
S: Roll gap
t_f: Forward tension stress
t_b: Back tension stress
v_H: Strip entrance speed
v_h: Strip exit speed
α: Bite angle
γ: Neutral angle
$\overline{\varepsilon}$: Average reduction ratio
ε: Reduction ratio
μ_t: Tension weighting coefficient, $\mu_t = 0.7$.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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