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ORIGINAL ARTICLE

Analysis of transient heat source and coupling temperature field during cold strip rolling

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Abstract In the process of cold thin strip rolling, the effect of the roll gap heat source on the transient temperature of cold rolled strip is very significant, and especially for the lateral temperature difference fluctuation which easily leads to the additional shape deviation of the rolled strip. In this study, according to the new heat resource model, the coupled temperature field model with high precision can be established, and the influence of the heat resource on the transient temperature of the cold rolled strip can be obtained by comprehensively considering the emulsion heat transfer coefficient, the air cooling, and the heat conduction boundary conditions. Based on the above models and the actual working parameters, several cases were performed to show the detailed analyses of the transient temperature distributions under various rolling conditions. The results at different strip positions show that the lateral distributions of the roll gap heat source and the strip transient temperature at every stand or pass can be simulated well. This study can improve the calculation precision of the transient lateral temperature difference for the complex online shape deviations during cold thin strip rolling.

Keywords Cold rolled strip · Uneven roll gap heat resource · Transient lateral temperature difference · Friction heat · Deformation heat

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1 Introduction

With the rapid development of the cold rolling technology of ultra-thin strip, the requirements of each index and production stability in rolling process are becoming higher and higher. The strip shape, which is one of the most important indicators of the cold rolled thin strip, is difficult to be detected and controlled for the sake of many dynamic factors affecting the measurement accuracy and stability, such as the installation accuracy and deflection of the shape measuring roll, the crown and coil shape of the strip, and the transient temperature. Among them, the transient temperature's frequent fluctuations which have an irregular effect on the online strip shape is often ignored in most cases, especially for the reversible cold strip mill. The larger the roll gap heat source and the transient temperature difference of each pass are, the worse the shape measurement precision and the control stability are. Therefore, it is necessary to analyze the heat resource evolution mechanism and the transient temperature distribution under different working conditions. In addition, the new model will be able to provide key temperature adjustment parameters to further study the fine shape control process during cold rolling of the ultra-thin strip.

In most of previous studies on the cold strip rolling, the transient temperature fluctuation and the lateral uneven temperature difference, resulting in various calculation errors obviously, are often neglected, and most of theoretical research and engineering tests focused on process analyses and control models of the stable work roll thermal crown and the symmetrical strip temperature field [1–5]. With the rapid development of a large number of cold rolling technologies, a variety of cold strip rolling mathematical models become more and more accurate and widely applied in engineering practice. At present, many researchers have paid more attentions to the direct effect of the transient temperature field on complex deformation behaviors of the cold rolled strip, such as the thermal roll gap, the thermal expansion, the hot scratching defect, the thermal analysis of emulsion mixed-film lubrication, the transient hot friction, the thermal abrasion, the edge drop or the hot cross-section sizes, and the thermal effect on the online lateral thickness difference control and the real-time flatness state [6–19].

Over the years, the theoretical analyses of thermal behavior in rolling process have never been interrupted, and a lot of research results and test cases have been achieved. Lahoti et al. [2] made a preliminary analysis of the strip temperature distribution in the roll bite in 1978. In 1984, Tseng [3] used the finite difference method to simulate temperature distributions of the roll and the strip; however, this model did not consider the energy loss of the roll surface, and assumed the friction heat between the strip and the roll as a constant which obviously did not conform to the fact. In 1990, Tseng et al. [4] tried to make a coupling calculation of the roll and the strip for the transient temperature distribution by the variable separation method, which assumed that the friction model was not directly related to the thermal model, so its application range was limited. In 1990s, Sauer [5], Atack et al. [6], Abbaspour et al. [7], and Alaeil et al. [8], respectively, studied the thermal camber model in different rolling processes. In 1998, Chang [9] established a simple heat model related to the friction, but the model was too difficult to calculate the whole area of the roll and the strip. Up to early twenty-first century, Jiang et al. [10, 11] deeply analyzed the coupled deformation and temperature of strip rolling, and studied the roll edge contact in cold rolling of thin strip as well. In 2012, Wang et al. [12] studied the heat effect of stress on the strip shape. Moreover, some other researchers [13–19] respectively simulated the heat transfer effects on the transverse temperature distribution, the flatness, and the surface thermal scratch of strip.

Overall, the uniform heat source in the deformation zone is usually assumed in most of the traditional strip temperature field models, and has no any change throughout the cold rolling process because of the constant rolling conditions. For example, a parabolic distribution of transverse strip temperature can be generally obtained and has nothing to do with the rolling speed, the friction, the deformation resistance, the tension, the reduction, and so on, when the real-time temperature field and the transient heat source situations have changed. Especially, when the transient heat fluctuation and the strip transverse temperature of every stand or pass are ignored, the calculation precision and the control effect of strip deformation deviation will be affected inevitably.

Therefore, it is necessary to establish the new heat source model and the cold rolling strip temperature model with high precision by considering the comprehensive effect of real-time work condition parameters based on the actual rolling process, and then the regularities of the transient heat distribution and the accurate temperature fluctuation of the cold rolled strip may be obtained through the in-depth analysis about various factors, which contribute to the thermal effect of the transient temperature on the online shape measurement and the close-loop control of the cold strip rolling. In addition, it is so helpful in improving the production stability and technology indicator of the cold strip rolling in some ways.

2 Heat resource model of the cold rolling strip

2.1 Analysis of the heat resource

According to the previous theoretical analysis and engineering practice, obviously the roll gap heat source has a great impact on the roll thermal crown and the transient strip temperature distribution of the cold rolled strip, which directly determines the online temperature fluctuations and internal thermal stress distribution of the strip. So, it is generally known that the strip temperature difference is significant at every stand or pass in the cold strip rolling, and even there are some measurable transparent temperature fluctuations in the same rolling process of some passes. All of these are on account of the deformation heat and the friction heat which play important roles in the roll gap, so the transverse roll gap shape and the strip cross section must be changed with the irregular transient fluctuations of heat sources to a great extent. As shown in Fig. 1, the work roll radius is R, the roll radius taken into account of the elastic flattening is R', the strip entry thickness is h_0, the strip exit thickness is h_1, the central angle corresponding to the deformation zone contact arc is α, and the contact angle strip θ is related to the strip thickness h. In addition, the heat resource in the deformation zone includes the heat deformation heat and the friction heat. Suppose the friction heat between the roll surface and the strip surface (the contact area) is absorbed respectively by the strip and the roll according to some particular absorption ratio, and the deformation heat happened inside the strip itself (the deformation zone) is

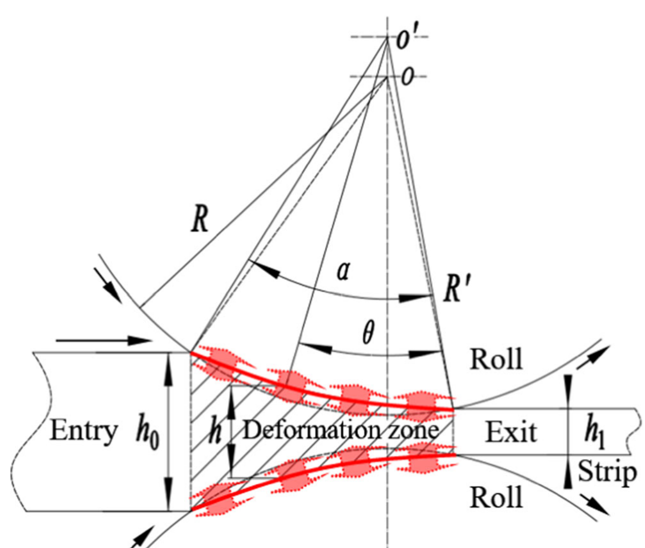


Fig. 1 Diagram of heat resources in the deformation zone

absorbed by itself as well. Figure 2 shows the relations of the heat resource, the strip temperature difference, and the thermal tensile stress.

For the roll gap heat source shown in Fig. 1, the varied heat source distribution is bound to bring about the transient strip temperature difference and the thermal stress deviation as shown in Fig. 2. For the common temperature distributions such as Fig. 2a or b, the transverse heat source distributions, which will lead to the various strip transverse temperature differences and the opposite thermal stress distributions, can be generally expressed by the positive parabola or the negative parabola in most cases. Then, the additional transient temperature shape error known as the thermal shape deviation must be formed with varying heat resource distributions. However, the cooling medium can obviously change the lateral temperature distribution and the thermal stress state of the strip even under the same deformation conditions as shown in Fig. 2c, d. In addition, there are two special heat sources, as shown in Fig. 2e, f, usually found in the transverse wedge material rolling or the special edge rolling technology, which can lead to the obvious asymmetrical rolling parameters or the significant shape deviations similar to the installation position deviations of the roll system or the detection roll. Moreover, these special distributions are more likely to cause the unstable rolling state or the obvious shape control error. Therefore, it is necessary to identify the transient temperature field based on the uneven roll gap source with the in-depth analysis, and it is helpful in reducing the temperature fluctuation and the transient lateral temperature difference in the process of cold thin strip rolling.

2.2 Mechanical model of the deformation zone

As shown in Fig. 3, the coordinate axis x represents the longitudinal (the rolling direction), and the coordinate axis y indicates the horizontal (perpendicular to the rolling direction), where the high direction (the strip thickness direction) is z, and the length of the elastic deformation zone is l. Firstly, the strip with width B_s in the deformation zone is divided into n longitudinal elements (usually n is an odd number), and then the central coordinate of each element $y_i(i=1,2,\cdots)$ can be set. So, the lateral displacement of each element in the deformation zone can be expressed as

$$U_i(x,y)=\left[1-\frac{h_i(x)-h_{1i}}{h_{0i}-h_{1i}}\right]u(y) \qquad (i=1,2,\cdots,n) \qquad (1)$$

where the entry thickness and the exit thickness of the ith strip element are respectively expressed as h_{0i} and h_{1i}, the thickness $h_i(x)$ of the strip element in the deformation zone is $h_i(x)=h_{1i}+(h_{0i}-h_{1i})(x/l)^2$, and $u(y)$ indicates the exit lateral displacement of the strip element.

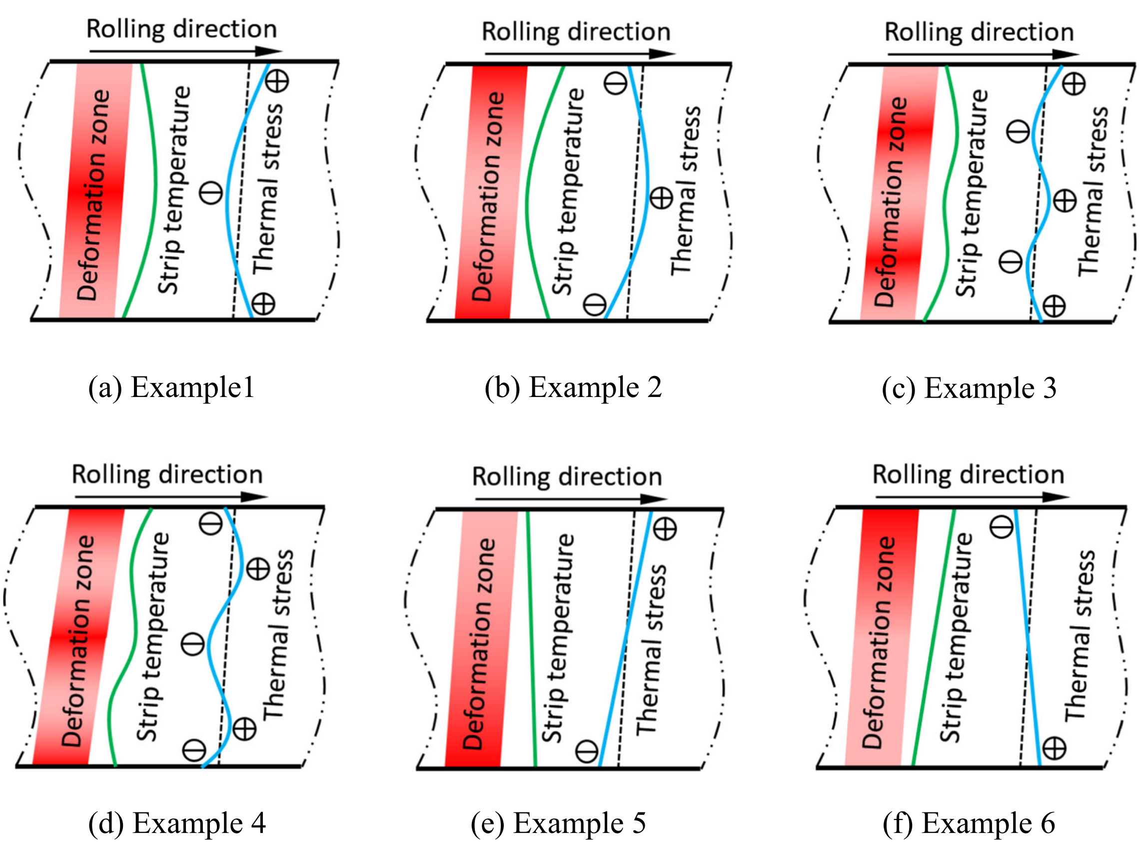


Fig. 2 Distribution laws of the different heat sources in the roll gap and its relationships with the strip temperature and the thermal stress in ideal state

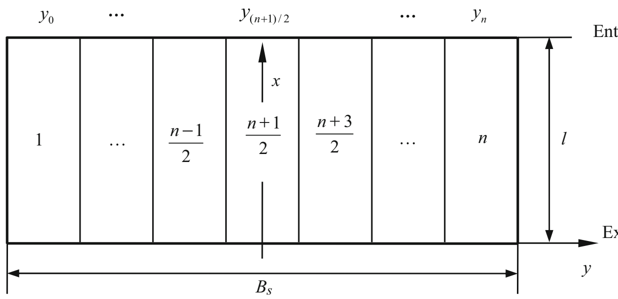


Fig. 3 Sketch diagram of the strip element division

Then the power of total deformation N_z can be expressed as

$$N_z = \overline{v}_1 \overline{h}_1 \sum_{i=1}^{n} \int_{y_{i-1}}^{y_i} F_i(y, u_{i-1}, u_i) \mathrm{d}y = N_z(u_0, u_1, \cdots, u_n) \quad (2)$$

where $\overline{v}_1$ and $\overline{h_1}$ are the average rolling speed and the average strip thickness respectively at the exit. According to the minimum energy principle, the lateral displacement of each element at the exit can be optimized by $\frac{\partial N_z}{\partial u_j} = \sum_{i=1}^{n} \int_{y_{i-1}}^{y_i} \frac{\partial F_z}{\partial u_j} \mathrm{d}y = 0$, and then the lateral distributions of both tensile stresses can be obtained.

$$\sigma_{0i} = \overline{\sigma}_0 + \frac{E}{1-\nu^2} \left\{ \frac{h_{1i}\overline{h}_0 \left(1+u_i'\right)}{h_{0i}\overline{h}_1 \left(1+\frac{u_n-u_0}{B}\right)} - \frac{l_{0i}}{\overline{l}_0} \right\} \quad (i = 1, 2, \cdots, n) \quad (3)$$

$$\sigma_{1i} = \overline{\sigma}_1 + \frac{E}{1-\nu^2} \left[1 + \frac{h_{1i}}{\overline{h}_1} - \frac{h_{0i}}{\overline{h}_0} - \frac{l_{0i}}{\overline{l}_0} + u_i' - \frac{u_n-u_0}{B_s} \right] \quad (i = 1, 2, \cdots, n) \quad (4)$$

$$p_{li} = \omega^o \omega_i^T l k_s \quad (5)$$

where E is the elastic modulus, ν is the Poisson's ratio, $\sigma_{0i}, \sigma_{1i}, p_{li}$ are the front tensile stress, the back tensile stress, and the unit width rolling force of each element respectively, k_s is the deformation resistance, ω^o is the influencing coefficient of some external factors on the rolling pressure besides the tensions, ω^T is the influence coefficient on the rolling force because of the tensions, and $\overline{\sigma}_1, \overline{\sigma}_0$ are the average front tensile stress and the average back tensile stress, respectively.

In order to accurately calculate the transient heat source status or the heat distribution at different locations of cold rolled strip in the deformation zone, a simultaneous strip metal deformation model and an elastic deformation model of the roll system should be coupled to solve this synchronization problem under various working conditions. In the process of modeling, for the roll system fixed laterally, all of the backup rolls and the work rolls must be meshed simultaneously with the strip for guaranteeing the coordinate correspondence of all elements. However, for the roll system which can be shifted (such as the work roll shifting or the intermediate roll shifting), the fixed rolls and the strip must be continually re-meshed with the shifting rolls (such as the shifting intermediate rolls or the shifting work rolls) according to the shifting displacement, and all nodes must be corresponding one by one using the node labels of all elements or the position fitting coordinates, as shown in Fig. 4.

The transverse distribution of the strip thickness can be solved by the influence coefficient method of the roll system elastic deformation, as shown in Eq. (6).

$$h_i = s_0 + 2f_{wi} + 2\delta_{wi} + \Delta D_{wi} \quad (i = 1, 2, \cdots, n) \quad (6)$$

where s_0 is the initial value of the roll gap, f_{wi} is the total displacement of the work roll axis, δ_{wi} is the elastic flattening amount of the work roll, and ΔD_{wi} is the work roll crown. Based on Eqs. (1)–(6), all mechanical parameters of every element can be guaranteed for the precise calculation of the deformation heat and the friction heat in the roll gap, and then the transient temperature distribution of online strip with high accuracy is able to be obtained.

2.3 Friction heat in the deformation zone

For the sake of convenient calculation and modeling efficiency, it is assumed that the friction coefficient μ between the strip and the roll in the deformation zone is a constant at some certain passes, and the friction heat Q_{mi} of each element in the deformation zone can be expressed as

$$Q_{mi} = 2WR'\mu b_i \int_0^{\alpha} p_i v_{si} \mathrm{d}\theta \quad (7)$$

where W is the energy coefficient, b_i is the element width, p_i is the rolling pressure of element width, and v_{si} is the sliding velocity.

According to Bullock's theory, when the relative motion between two surfaces occurs, some heat q will be into the surface 1 (such as the roll surface) by a constant dimensionless ratio κ, and the rest of heat will be into the surface 2 (such as the strip surface) by $(1-\kappa)$ at the same time. If the two kinds of materials with the speeds v_1 and v_2 respectively are the

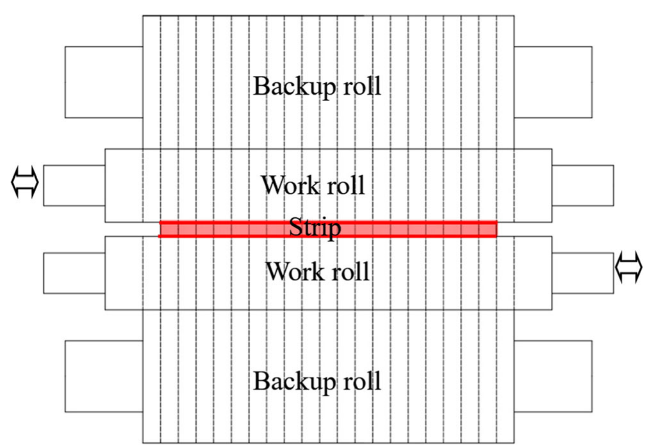


Fig. 4 Sketch diagram of the roll unit division

same, there is $\kappa = 1/\left(1+\sqrt{v_1/v_2}\right)$ at this time. For the cold rolling process, the two contact surfaces of *abcd* and *a'b'c'd'* in the deformation zone are shown in Fig. 5. If the roll's material is not only similar to the strip's material but also the instantaneous velocities of both are equal, then $\kappa \approx 0.5$. At this time, the friction heat in the gap can be divided into similar halves absorbed by the work roll and the strip, respectively.

2.4 Deformation heat in the deformation zone

In the process of continuous multi-stand or multi-pass cold rolling, there are different degrees of the work hardening and the metal deformation inside the strip, which not only result in an obvious change of its internal deformation power but also affect the friction power to a great extent. However, lots of traditional heat resource calculation methods usually assumed that the deformation of each point in the deformation zone was the same, which inevitably affected the calculation accuracy of the deformation heat and the transient temperature distribution in the gap, especially both edge zones of the strip. According to the above-mentioned element mechanical model, and then the deformation heat Q_{bi} of each element is obtained by an integral of each strip element's deformation power.

$$Q_{bi} = \frac{\eta}{\sqrt{R'\Delta h_i h_{1i}}}\int_0^{\alpha}\frac{2R'k_s\sin\theta}{h_{1i}+R'\theta^2}\mathrm{d}\theta \approx \frac{\eta}{\sqrt{R'\Delta h_i h_{1i}}}\int_0^{\alpha}\frac{2R'k_s\theta}{h_{1i}+R'\theta^2}\mathrm{d}\theta \quad (8)$$

where η is the heat energy conversion efficiency and Δh_i is the reduction.

2.5 Simulation of the heat source model

Based on the above heat source model, a simulation about some typical cold rolling parameters was performed. The strip width is 900 mm, the entry thickness is 1 mm, the exit thickness is 0.6 mm, and the front tension and the back tension are 100 kN, respectively. At the rolling process, the friction coefficient is 0.03, the rolling speed is 10 m/s, the deformation resistance is 500 MPa, and the bending force is 200 kN.

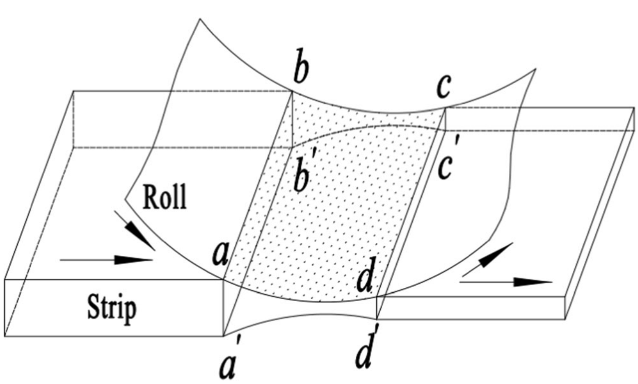


Fig. 5 Sketch diagram of the heat resource distribution in the deformation zone

Figure 6 shows the transverse distributions of the front tension, the back tension, the entry strip thickness, the exit strip thickness, the deformation heat, and the friction heat, respectively.

It can be seen from Fig. 6 that the lateral distribution of the roll gap's heat source is directly related to the strip crown, the lateral distributions of the tensions, and other mechanical parameters under the same conditions. In the cold strip rolling, the lateral roll gap must be adjusted constantly for improving the cross-sectional shape and the flatness status of the cold rolled strip, which will lead to the transverse distribution of internal heat source changed with the mechanical parameters. Compared with the hot rolling process, the reduction of the cold rolling strip is usually limited, as well as the thermal deformation is relatively stable. However, the friction heat is greatly changed especially for the reversible cold strip mill with frequent acceleration and deceleration processes in the rolling process, so the temperature change of each pass is often very big (from 60 to 180 °C). In addition, the heat distribution shown in Fig. 6, contrary to the lateral temperature distribution of the strip, will reduce or alleviate the lateral temperature difference of the strip to a certain extent. However, when the change of strip crown occurs along an opposite trend, it will show a consistent law similar to the strip lateral temperature distribution, and then the lateral temperature differences of the strip and the roll will be further increased. In short, the complex heat source must have a significant link with the roll thermal crown and the strip transient temperature, which not only affect the horizontal shape of roll gap but also alter the cross-sectional deformation and flatness of the strip, so the transient heat resource in the gap is a key factor in the thermos-mechanical coupled deformation model of cold rolled strip, and plays an important role in improving the shape control accuracy of the cold rolled strip.

In order to study the above problem, some simulation tests were carried out for the transient heat resource respectively changed with some special parameter such as the rolling velocity, the friction coefficient, the tension, and the deformation resistance. As shown in Fig. 7, compared with the hot rolling process, the friction heat of the cold strip rolling changes more obviously than the deformation heat because of the limitation of its reduction. In the meantime, the friction heat was far greater than the deformation heat which was relatively stable during cold strip rolling. It can be seen from Fig. 6, the friction heat significantly increases with the rolling speed, the friction coefficient, and the deformation resistance; however, the deformation heat and the friction heat simultaneously decrease with the front tension and the back tension. The simulation results show that the friction heat is most sensitive to the friction coefficient, and every 58 J in the friction heat will be added while increasing each 0.01 of the friction coefficient. However, for the continuous cold rolling process, usually the strip friction coefficient has a tiny variation in the steady rolling process and even gradually decreases while increasing the rolling speed. Especially, when the front tension and the back tension increase a lot, the rolling

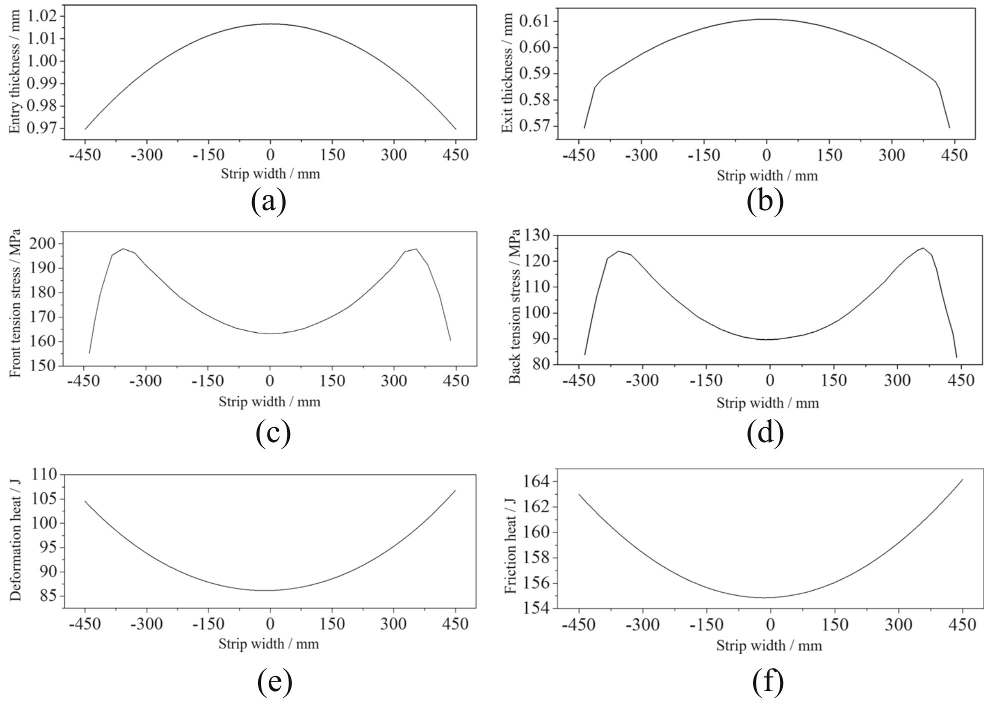


Fig. 6 Lateral distributions of the entry thickness (**a**), the exit thickness (**b**), the front tensile stress (**c**), the back tensile stress (**d**), the deformation heat (**e**), and the friction heat (**f**)

force and the friction force decrease apparently. In addition, when the strip rolling speed and the deformation resistance are higher and higher, the friction heat of cold rolling strip will take up a large portion in the heat resource of roll gap.

3 Transient temperature field model in the cold rolling process

3.1 Coupling temperature field model in the deformation zone

3.1.1 Element division of the strip

For the thin cold rolling strip, usually the temperature differences along the thickness direction or the highness direction can be ignored except the transverse transient temperature of the strip. Refer to the element divisions of Fig. 3, the temperature control point of every unit is at the center of each strip element as shown in Fig. 8, and thus the heat conduction finite difference equations with different boundary conditions can be constructed for the temperature units of the central elements and both edge elements of the strip.

For the central temperature units, the finite difference equation is expressed as

$$T_j^{'} = \frac{AB}{C} T_{j-1} + \frac{GB}{C} T_{j+1} + \frac{4B}{AC} T_{hj} - \left(\frac{AB}{C} + \frac{GB}{C} + \frac{4B}{AC} - 1 + H \right) T_j \tag{9}$$

where $A = \frac{h_j}{\mathrm{d}y_{j+1}/2 + \mathrm{d}y_j/2}$, $B = \lambda_0 \cdot \Delta t$, $C = \rho c h_j \cdot \mathrm{d}y$, $G = \frac{h_j}{\mathrm{d}y_{j-1}/2 + \mathrm{d}y_j/2}$, $H = \frac{\Delta t \left(Q_{bj} + \kappa Q_{mj} \right)}{\rho \cdot c}$, λ_0 is the strip heat conductivity coefficient, T_{hj} is the roll temperature, T_j is the strip temperature, ρ is the strip density, and c is the strip specific heat. And for the units of the strip left edge,

$$T_j^{'} = \frac{AB}{C} T_{j+1} + \frac{4B}{AC} T_{hj} + \frac{D}{C} T_a + H - \left(\frac{GB}{C} + \frac{4B}{AC} - 1 + \frac{D}{C} \right) T_j \tag{10}$$

where $D = \alpha_a \cdot \Delta t \cdot h_j$, α_a is the boundary heat transfer coefficient, and T_a is the ambient temperature. Similarly, for the units of the strip right edge,

$$T_j^{'} = \frac{AB}{C} T_{j-1} + \frac{4B}{AC} T_{hj} + \frac{D}{C} T_a + E - \left(\frac{AB}{C} + \frac{4B}{AC} - 1 + \frac{D}{C} \right) T_j \tag{11}$$

After rolling, the strip is no longer in contact with the work roll, for internal units

$$T_j^{'} = \frac{AB}{C} T_{j-1} + \frac{GB}{C} T_{j+1} + \frac{2F}{C} T_a - \left(\frac{AB + GB + 2F}{C} - 1 \right) T_j \alpha_w \tag{12}$$

where $F = \alpha_w \cdot \Delta t \cdot \mathrm{d}y$, α_w is the air heat transfer coefficient. Similarly, for the left side,

$$T_j^{'} = \frac{GB}{C} T_{j+1} + \frac{D + 2F}{C} T_a - \left(\frac{D + GB + 2F}{C} - 1 \right) T_j \tag{13}$$

For the right side,

$$T_j^{'} = \frac{AB}{C} T_{j-1} + \frac{D + 2F}{C} T_a - \left(\frac{D + AB + 2F}{C} - 1 \right) T_j \tag{14}$$

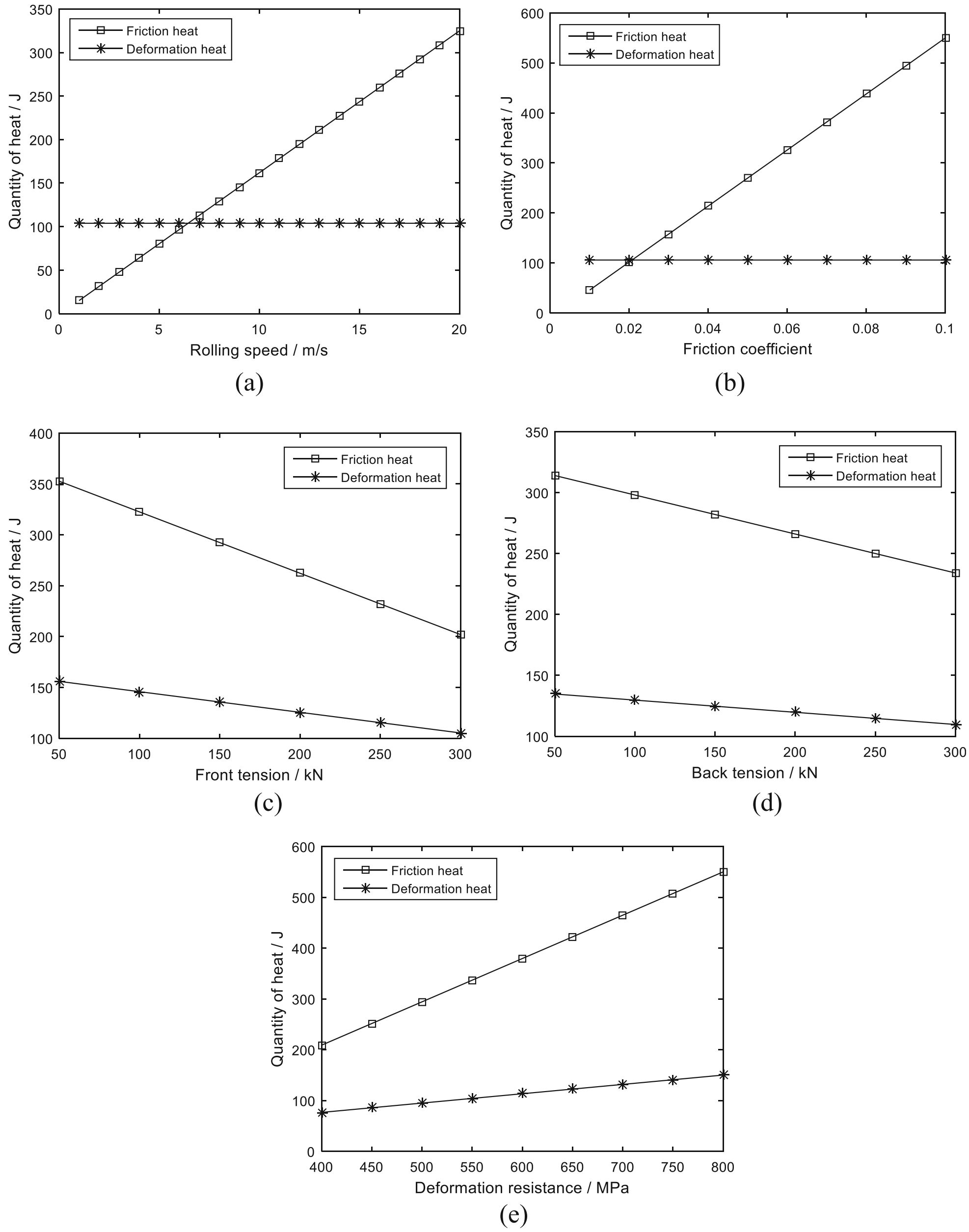


Fig. 7 Influences of some key factors, such as the rolling speed (**a**), the friction coefficient (**b**), the front tension (**c**), the back tension (**d**), and the deformation resistance (**e**), on the friction heat and the deformation heat

The emulsion is known to all that has a noticeable impact on the strip surface quality, the lubricating effect, and the roll gap shape. As far as the cold rolling process is concerned, it not only can reduce the friction coefficient and improve the cooling effect of the hot roll gap, but also affects the lateral distribution states of the heat source in the deformation zone and the temperature field to a great extent. A large number of studies show that the emulsion heat transfer coefficient is directly related to the concentration, the flow rate, and the injection mode [5–16]. On the other hand, because the working conditions are too complex to obtain the real theoretical analytic solution, then the average heat transfer coefficient $\overline{\alpha}_w$ of the emulsion can be usually obtained for most of mills by the experimental regression as

$$\overline{\alpha}_w = c_0 w^{c_1} T^{c_2} e^{c_3 + c_4 C_p} \tag{15}$$

where w is the flow density, T is the strip surface temperature, C_p is the emulsion concentration, and c_0~c_4 are the regression

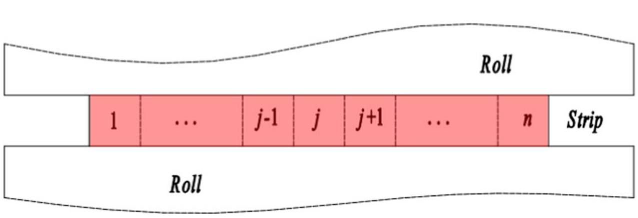


Fig. 8 Temperature units of the strip

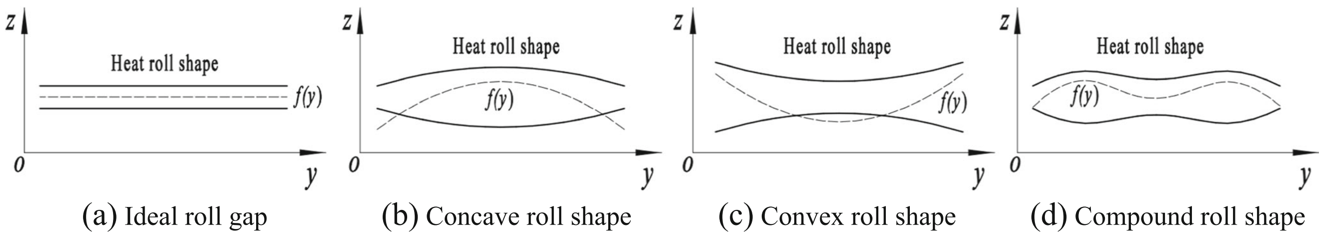


Fig. 9 Lateral distribution sketch diagrams of the emulsion heat transfer coefficient

coefficients. With the fast development of cold rolling technologies, the fine section cooling technology is becoming more and more popular and getting more attentions because of its effectiveness, the main method of which is to control the roll crown or the hot roll gap shape by adjusting the transverse distribution of the emulsion heat transfer coefficient. Suppose $\overline{\alpha}_w$ is the emulsion average heat transfer coefficient, and $f(y)$ is the distribution function of the emulsion heat transfer coefficient. As shown in Fig. 9, for different types of the hot roll shape corresponding to multiple varied emulsion heat transfer coefficients, Eq. (16) can be used to approximately represent its transverse distribution.

$$\alpha_w(y) = \overline{\alpha}_w f(y) \tag{16}$$

Corresponding to the unit partition of the temperature field model, Eqs. (15) and (16) can be expressed respectively as

$$\overline{\alpha}_{wj} = c_0 {w_j}^{c_1} {T_j}^{c_2} e^{c_3 + c_4 C_p}, \alpha_{wj} = \alpha_w\left(y_j\right) = \overline{\alpha}_{wj} f\left(y_j\right) \tag{17}$$

3.1.2 Unit division of the roll

According to the properties of all mediums around the roll, it can be divided into m zones such as the water cooling of the emulsion, the air cooling, and the contact heat conduction in the roll gap along the circumferential direction. Suppose the area of every unit along the circumferential direction is w_k, the roll surface temperature is T_{ck}, and the heat transfer coefficient is α_k [1]. In order to facilitate the calculation, the roll will be divided into some specific nodes corresponding to the strip elements along the transverse coordinates, and assumes the unit roll surface along the circumferential direction is heated evenly. Then, instead of above ones, the equivalent temperature $T_{eq,j}$ and the equivalent heat transfer coefficient $\alpha_{eq,j}$ of the appropriate medium along the jth transverse unit of roll can be expressed as shown in Eq. (18) and Fig. 10.

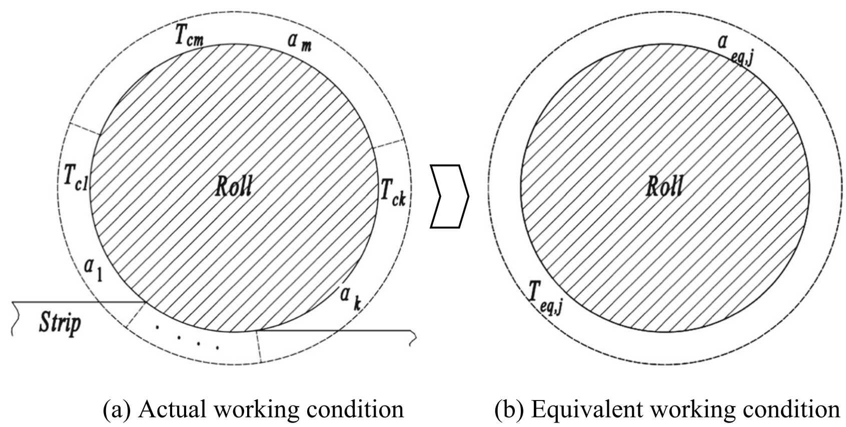
$$\alpha_{eq,j} = \frac{\sum_{k=1}^{m} \alpha_k w_k}{\sum_{k=1}^{m} w_k}, \quad T_{eq,j} = \frac{\sum_{k=1}^{m} T_{ck} \alpha_k w_k}{\alpha_{eq,j} \sum_{k=1}^{m} w_k} \tag{18}$$

A finite difference equation of the roll temperature field can be constructed based on the heat transfer theory in the cylindrical coordinate [1], and then the transient temperature distributions of the roll and the strip are iteratively solved by simultaneous coupling of both temperature difference models.

3.2 Heat transfer time and measured temperature points

The heat transfer times and the positions of temperature measurement during the process of cold strip tandem rolling are shown in Fig. 11. The contact time t_r in the deformation zone depends on the deformation zone length l and the roll circumferential speed v_r, so it can be approximately represented as $t_r = l/v_r \approx \sqrt{R' \Delta h}/v_r$. The heat transfer time t_a after rolling depends on the strip speed v_s and the distance l_s between two stands or from the end stand to the position of the shape measuring roll, so $t_a = l_s/v_s$.

Fig. 10 The equivalent heat coefficient and the equivalent temperature along the circumferential direction



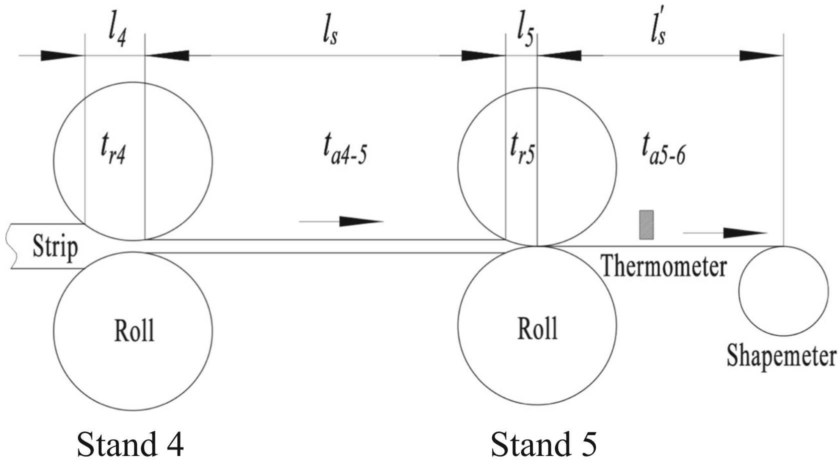


Fig. 11 The heat transfer time and the measured temperature points

Most of transient temperature measuring methods mainly include two types, such as the contact and the non-contact. Among them, the temperature sensitive element of the contact thermometer directly contacts with the measured object. Although there is some temperature delay phenomenon which results in the relative slow response, almost all of the contact temperature measurement devices have reliable measured data with the high measurement accuracy without any error compensations. Therefore, these can directly reflect the true temperature values of the actual measured object, and the detection accuracy of the contact thermometer can be up to ± 1 °C. On the contrary, the non-contact measurement instrument, such as the infrared thermometer, is not contacted with the measured medium, so it is difficult to measure the true temperature affected by external factors such as the object emissivity, the distance measurement, the dust and the water vapor, etc. in a dynamic environment. Especially, under the industrial fields or the bad environments, the measurement error of the non-contact ones is far larger than the contact type. For an example of the temperature measurement error from the non-contact thermometer, it is often higher than 20 °C in the cold strip rolling. So, for the comprehensive consideration, the contact thermometer is often selected to collect the transient temperature of online strip in this work.

4 Verifications of industrial application

For example, the strip width of DD11 is 1005 mm, the density is 7800 kg/m^3, the specific heat is 470 J/ (kg·K), and the initial temperature is 40 °C. Meanwhile, the distance is 4 m between two adjacent stands, and the distance from the end stand to the shape measuring roll is 5 m. In addition, the emulsion's temperature is 55 °C and the heat transfer coefficient is 3500 J/(s·m^2·K). The heat transfer coefficient of air cooling is in 114–230 J/(s·m^2·K), there 200 J/ (s m^2·K). Moreover, the other rolling parameters are shown in Table 1, and Fig. 12 shows all of the heat source powers from every stand.

shown in Fig. 12, the deformation power of each stand is significantly reduced with the reduction in the cold rolling process. However, the friction power of each stand will increase with the rolling speed and the deformation resistance, and the friction powers are relatively larger except the first stand or pass. In addition, according to the simulation results of the strip temperature as shown in Fig. 13, there are different temperature distributions and the lateral temperature differences significantly affected by the rolling speed, the deformation resistance with an increasing trend. For example, the strip temperature at the first stand is 94.2 °C with the lateral temperature difference 5.4 °C, the strip temperature at the second

Table 1 The rolling parameters

StanStand no.	–	1	2	3	4	5
Thickness (mm)	2.73	2.05	1.31	0.89	0.63	0.47
Reduction rate (%)	–	24.82	36.17	31.70	29.89	25.07
Total reduction rate (%)	–	24.82	52.01	67.22	77.02	82.78
Unit front tension (MPa)	48.74	137.05	170.12	158.45	153.71	68.43
Total tension (kN)	133.68	282.58	223.88	142.42	96.8599	32.31
Deformation resistance (MPa)	–	543.57	673.83	788.85	824.81	911.77
Friction coefficient	–	0.153	0.070	0.046	0.029	0.027
Strip speed (m/s)	2.72	3.70	5.76	8.46	12.09	16.11

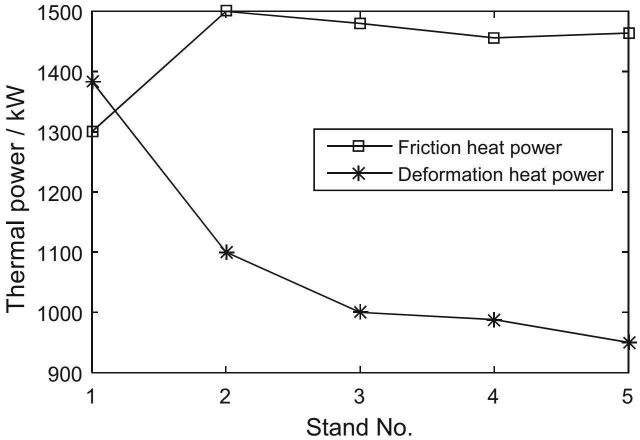


Fig. 12 Heat powers of all stands

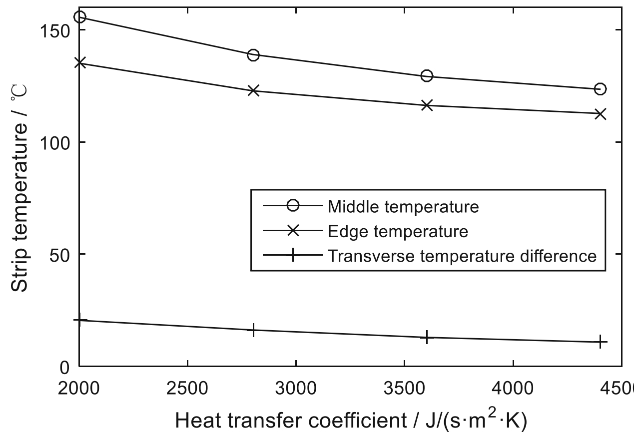


Fig. 14 Variations of the strip lateral temperature difference with different the heat transfer coefficients of the emulsion

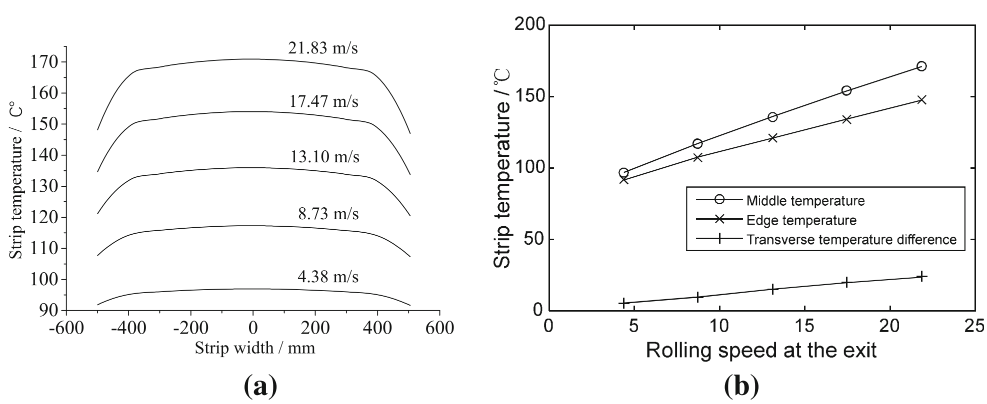
stand is 112.4 °C with the lateral temperature difference 9.6 °C, the third stand 128.45 °C with 15.1 °C, the fourth stand 144.15 °C with 19.7 °C, and the fifth stand 159.15 °C with 23.5 °C. Overall, obviously the strip transient temperature and its lateral difference are closely related with the heat resource in the roll gap which plays an important role in the whole cold rolling process. The greater the change of heat source is, the greater its influence on temperature field is, especially for the flatness control of the super-thin cold rolling strip. So, the first key aim of the transient temperature control is to adjust the heat resource of each stand for obtaining the reasonable cold rolling process, and in some ways, it will be helpful to improve the effectiveness of the shape detection and close-loop control.

An important method to control the heat source and strip temperature is to adjust the rolling rhythm and improve the heat transfer coefficient of the emulsion for reducing the average temperature and the lateral temperature difference of the strip. Under the current rolling conditions, improving the rolling rhythm of mill is usually limited. However, the research space of emulsion is still large by changing the emulsion heat transfer coefficient on the main factors, such as the emulsion concentration and the flow density. Under normal circumstances, the emulsion heat transfer coefficient is in 2000–4400 J/(s·m^2·K). Figure 14 shows the influence results of the different emulsion heat transfer coefficients on the strip temperature. The greater the heat transfer coefficient is, the higher the cooling efficiency of the strip and the smaller the transverse temperature difference.

Based on the above theoretical analysis and simulation results, at the same time, three different rolling reduction schedules as shown in Fig. 15 are set to analyze the influences of different rolling temperatures on the strip. The strip temperature fields are shown in Fig. 16.

From Fig. 16, the different reduction schedules have a great influence on the online strip temperature of each stand. In case 1, setting the strip's reduction of each stand is the same, so the strip temperature increases gradually with every stand and will be up to the maximum at the end stand, which is mainly due to the strip rolling speed and the deformation resistance increases with different reductions in the rolling process. In the front stands, relatively, the reduction rate is so small with the limited heat from the roll gap. However, when the rolling speed and the deformation resistance increase rapidly with the reduction of each stand, especially at the end stand, the strip temperature increases significantly with massive friction heats which leads to the strip temperature more than 200 °C. Obviously, this

Fig. 13 Effects of the varied rolling speed on the lateral strip temperature (**a**) and the central strip temperature (**b**)



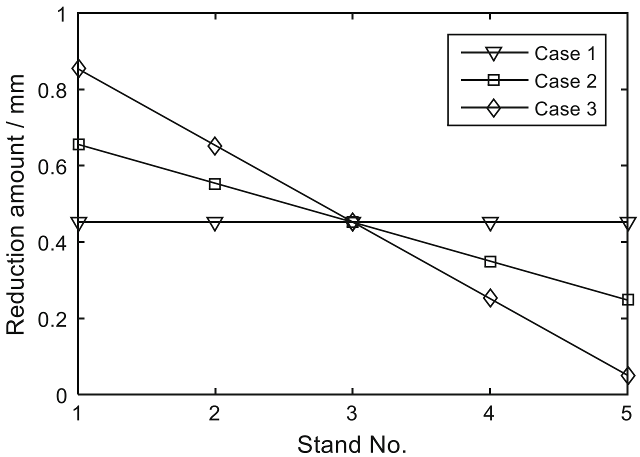


Fig. 15 Reduction assignments of three rolling systems

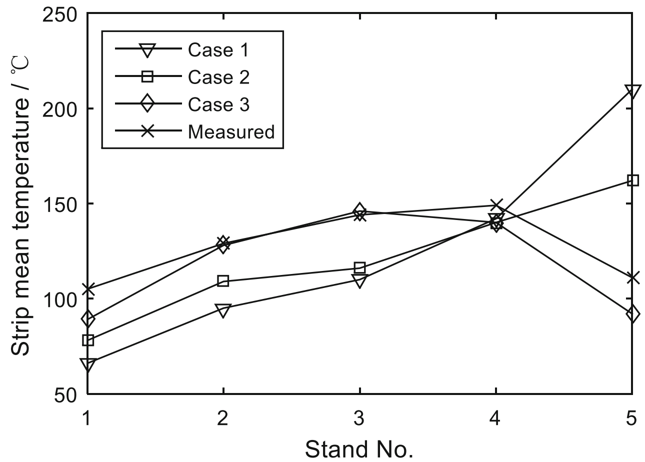
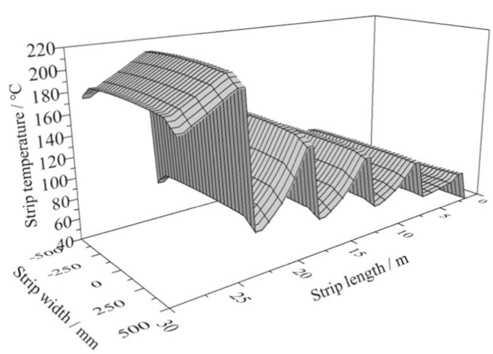


Fig. 17 Comparison of strip temperatures of three rolling systems

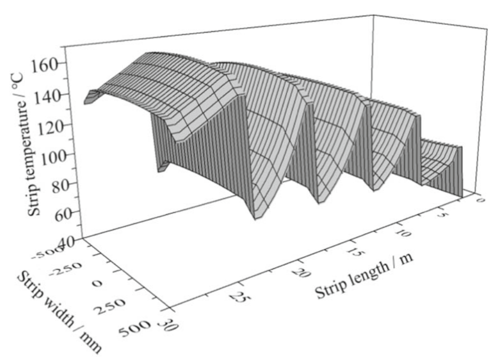
kind of reduction schedule is unreasonable and not recommended, because it will affect the stability of the roll gap and easily lead to some poor shapes. In case 2, after increasing the strip's reduction a little at the front stands and relatively reducing the reduction at the back stands, it can be seen that the strip temperature increases with the stands as in case 1. However, the change process is relatively flat, and the strip temperature at the end stand has reduced to 160 °C. In case 3 often used in industry, the reduction at the front stand is larger than that of the back stands, which can be helpful in improving the regulation effectiveness of the strip crown by greatly adjusting the roll gap. After that, decreasing the reduction at the back stands will be able to improve the roll gap stability and the strip shape quality, so the heat sources in the gaps of three front stands are obvious than those in cases 1 and 2, and the strip temperature will rapidly increase and reach 149 °C at the third stand. However, starting from the fourth stand, the strip temperature begins to decline because of the small reduction, the stable rolling speeds, and other parameters. At the end stand, the strip temperature has been controlled in 90 °C. Figure 17 shows the change curves of the strip average temperatures.

From the point of view of the whole rolling process, no matter what kinds of conditions are, there must have various

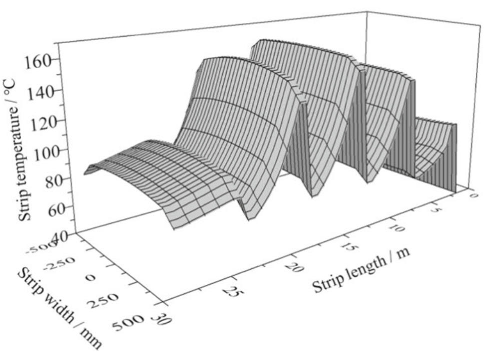
Fig. 16 Strip transient temperature fields of three rolling systems



(a) Case 1



(b) Case 2



(c) Case 3

degrees of the transverse temperature differences during the rolling process as shown in Fig. 13a. Obviously, different kinds of online temperatures will affect the roll gap shape and the strip flatness, so it is very important to adjust transient heat resources for stability and control accuracy of the rolling process, and it is one of the key contents in the future and should not be ignored in the modeling of the cold strip rolling of ultra-thin strip.

5 Conclusions

(1) In the process of cold strip rolling, the lateral temperature difference directly influences the transient shape of online strip with different degrees of extra shape errors, in which the roll gap heat source is one of important factors to lead to the transient fluctuation of the strip temperature. So, considering the transient effect of the heat source and its time delay characteristics on the temperature distribution, it is necessary to make a synchronous iterative calculation between the strip deformation and the roll elastic deformation for the irregular heat source distribution in the roll gap, and then the transient temperature and its lateral temperature difference for the subsequent process of shape measurement and control can be obtained by the coupling temperature field model.

(2) Simulation results show the transient heat resource in the roll gap has a great influence on the roll gap and the strip deformation, and thus it should not be ignored in the modeling of cold strip rolling. For the cold thin strip rolling, the heat resource will mainly change with the rolling speed, the friction coefficient, the deformation resistance, the tension, and the reduction schedules. At the same time, compared with the hot rolling process, the friction heat is more sensitive than the deformation heat in the cold rolling process, and the lateral distributions of the heat resource and the strip temperature are more complex and changeable to the online strip flatness. Therefore, the new heat resource model will be doomed to play more important roles in depth studies of the deformation mechanism and the shape close-loop control of the cold rolling strip.

(3) In almost all cases, the reduction system always has a great influence on the heat resource and the transient temperature in the deformation zone by the key factors, such as the rolling speed, the deformation resistance, the friction coefficient, the tensions, the emulsion distribution, and other parameters, and there are many opportunities to change the transient heat source and the temperature distribution of all stands or passes. Especially it is helpful in avoiding the frequent fluctuations of the strip transient temperature and its lateral difference which may directly affect the adjustment effectiveness of the roll gap and the strip flatness to a large extent.

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