Research and Application of Model and Control Strategies for Hot Rolled Strip Cooling Process Based on Ultra-Fast Cooling System

Dong CHEN, Zhen-lei LI,* Yun-jie LI and Guo YUAN

State Key Laboratory of Rolling and Automation, Northeastern University, P. O. Box. 105, No. 11, Lane 3, Wenhua Road, HePing District Shenyang Liaoning, 110819 China.

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Ultra-fast cooling technology as an effective method for control microstructure and property, is widely used in hot rolled strips. For precise control of strip temperature in cooling process, a mathematical model based on UFC is established to calculate UFC-T and CT in high pressure mode, or only CT in low pressure mode. Temperature calculation compensation strategy is obtained to solve the situation that re-redenning after UFC process affects CT calculation. Furthermore, for existing self-learning strategy care less about evolution of strip temperature and has no ability to eliminate errors quickly, a multi-dimensional self-learning control strategy is proposed including dynamic self-learning gain, distributed temperature self-learning strategy and velocity coefficient for heat transfer self-learning. With help of proposed control strategies, strip temperature in cooling process is precise calculated and controlled. The model and strategies have been applied successfully in a 2050 HSM for development of low cost and feature strip products.

KEY WORDS: hot rolled strip; ultra-fast cooling; temperature compensation; multi-dimensional self-learning strategy.

1. Introduction

Process temperature is an important process parameter for hot-rolled strips, directly affecting microstructure and property. Recently, ultra-fast cooling (UFC) technology is widely used in development and production of hot rolled strips, because of its high cooling rate, which can reduce alloy element and improve microstructure and property. In order to get ideal microstructure of hot rolled strips, UFC and laminar cooling on run out table are jointly utilized to cool hot strips from FDT (Finishing Delivery Temperature) down to UFC-T (UFC delivery temperature) and CT (coil temperature) by setting process path. In addition, UFC can be used individually, by which cools strip to UFC-T, and then to CT in air condition. Therefore, precisely and highly flexible control of UFC-T and CT in cooling section is extremely important.

To achieve precise control of UFC-T and CT on run out table, many models and strategies are adopted. Physical model can achieve accuracy temperature control by describing heat transfer process. But for convenience industrial applications, the physical model is usually simplified. Statistical models have been developed to solve the situation that closely reflects reality as much accurately as possible. And there are also many artificial intelligence algorithm models, such as fuzzy control model, neural network model and instant base learning by k-NN algorithm are utilized to pursue better temperature precise and highly flexible control of path. However, limited by calculation accuracy, computational efficiency, stability, cost and other factors, the most widely applied in hot rolled strips are still physical models and statistical models. Simultaneously, in order to get precise control results, many control strategies, such as smith predictor control, element tracking control and self-adaptive strategy are adopted for the above two type models. And self-learning strategy is the core of model which determines strip temperature calculation accurate for the following segments or strips based on feedforward calculation. Thus, many researchers built self-adaptive process of temperature model according to their own understanding and practice. Some researchers proposed a concise method to realize self-learning just by the error between actual temperature drop and calculated temperature drop. Some studies proposed an adaptive fuzzy algorithm to conduct the dynamic stochastic adaptive control for process temperature. The above methods only seek temperature precision control but care less about the evolution of strip temperature. In these models, they only pay close attention to UFC-T and CT which can be measured. However, the evolution and cumulative error in cooling process are necessary to regulate for precise control of UFC-T and CT. In application, how to quickly correct deviation without manual intervention is still a hot issue. Especially, the deviation is far from the target, the fewer number of strips for adjusting in self-adaptive process is better.

In this paper, a physical and statistical model combined with control strategies are proposed and applied. By fully
consideration the re-reddening after UFC process, the evolution of strip temperature and strip velocity influence on heat transfer, the model can achieve higher precision with a dynamic self-learning gain.

2. Model for Hot Rolled Strip on Run-out Table Based on Ultra-fast Cooling

2.1. Description

The cooling after rolling process on run out table is illustrated in Fig. 1. The cooling zone is made up by UFC and laminar cooling. The UFC equipment lies between finishing exit roller and laminar cooling, with 30 top headers and 30 bottom headers, divided into 3 groups. The UFC pressure can be adjusted steplessly in range of 0.3–1.0 MPa for low and high pressure spray mode. Laminar cooling is consisted of U type top headers and straight bottom headers. The last two group are vernier cooling for fine cooling and feedback control, the rest groups are main cooling. The number of cooling headers and water flux of UFC are taken as control variables to adjust strip temperature to meet target UFC-T, while the main cooling and vernier cooling banks are used to make strip temperature to meet the target CT.

Once strip head goes into finishing zone, cooling system sends max flow and pressure of UFC to pump station based on PDI (Primary Data Input) & FSU (Finish mill set up), and then keeps the opening headers pressure and flux in a constant condition. The strip enters cooling zone with FDT and then keeps the opening headers pressure and flux in a constant condition. The strip enters cooling zone with FDT and then keeps the opening headers pressure and flux in a constant condition.

2.2. Mathematical Model of Strip Temperature on Run-out Table

Specially, heat transfer in the thickness direction is much higher than width direction and rolling direction for the high rolling velocity and uniform cooling capability of UFC headers, so heat dissipation along length and width directions could be ignored. The heat transfer equation is expressed as Eq. (1):

\[ \rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left[ k \frac{\partial T}{\partial x} \right] = 0 \] .......................... (1)

The boundary conditions of strip top surface and bottom surface can be described in form like Newton’s convection Eq. (2):

\[ \pm k \frac{\partial T}{\partial x} = h(T - T_o) \] .......................... (2)

Where, \( \rho \) is density of strip steels in kg/m\(^3\), \( c_p \) is specific heat in J/(kg·K), \( k \) is coefficient of thermal conductivity in W/(m·K), \( T \) is temperature of strip steels in K, \( \tau \) is heat transfer time in s, \( x \) is thickness direction, \( T_m \) is cooling water temperature in K, \( h \) is heat transfer coefficient in W/(m\(^2\)·K). Strip cooling on run out table is a complex process. To build a precise UFC-T and CT calculation model, heat transfer theory and mechanism of heat exchange should be taken into consideration. Due to nonlinear and time-variation characteristics of temperature control, some heat dissipation could not be accurately calculated. For conventional mathematical, complicated heat transfer process can be simplified, equivalent to water cooling and air cooling. So \( h(T - T_m) \) is heat transfer on the surface of strip with air and spray water.

For air cooling zone boundary conditions, the equivalent heat transfer coefficient is given by Eq. (3):

\[ h_a = \varepsilon K(T + T_o)(T^2 + T_o^2)^{1/2} \] .......................... (3)

Where, \( \varepsilon \) is radiation of strip, \( K \) is Stephen–Boltzmann constant in 5.67 \times 10^{-8} W/(m\(^2\)·K\(^4\)), \( T_o \) is ambient temperature in K.

For water cooling zone boundary conditions, the main factors which affect water convection heat transfer are water flow and temperature, strip velocity and thickness. In addition, water pressure in UFC process is also a key factor for water convection. So heat transfer coefficient of water cooling can be calculated as follows Eq. (4):

\[ h_w = \alpha A_i \cdot \frac{Q}{BL} (T) \exp(-A_3(T - T_o)) \left( \frac{T_n}{T_0} \right)^{A_4} \left( \frac{P}{P_o} \right)^{A_5} \left( \frac{V}{V_o} \right)^{A_6} \] .......................... (4)

Where, \( \alpha \) is correction coefficient of strip width, \( A_1 - A_6 \) are model coefficients, \( Q \) is summation water flow in m\(^3\)/h, \( T_w \) is measured water temperature in K, \( P \) is measured cooling water pressure in MPa, \( V \) is measured velocity of strip in m/s, \( T_o \) is reference cooling water temperature in K, \( P_o \) is reference water pressure in MPa, \( V_o \) is based velocity in m/s, \( B \) is width of cooling bank in m, \( L \) is length of cooling segment in m.

Fig. 1. Hot-rolled strip cooling process based UFC. (Online version in color.)
2.3. Temperature Calculation Compensation Strategy

In application of UFC system, the water pressure is 0.3 MPa–1.0 MPa, flux of each header is adjustable within 70–200 m³/h of high density nozzle and 100–320 m³/h of slit nozzle. Thus, the UFC system has three common mode, laminar mode with low pressure of 0.3 MPa and only four headers each bank are available, which makes the system having same cooling capacity with traditional laminar cooling, and only CT should be controlled. Compact cooling mode is same pressure with laminar, but cooling headers used in each bank is added to further develop cooling capacity. High pressure mode has highest cooling capacity with pressure of 0.8–1.0 MPa used for low cost and feature steels. The strip is fastly cooled below ferrite transformation start temperature at UFC-T, which is benefiting keep the hardened austenite and promoting nucleation of ferrite. Then cooled by laminar cooling to make strip temperature meet target CT, and finally obtaining ideal microstructure and property in the end. So, the cooling controller system should select the cooling mode based on product process, realize precision control of UFC-T and CT or only CT to meet the process requirements.

The UFC equipment is installed in upstream of laminar cooling, UFC-T controlled and measured accuracy directly affect control precision of CT, therefore, decoupling control is needed. The calculation process was be shown in Fig. 2. If high pressure cooling mode is selected by PDI, when the strip segment is under finishing delivery pyrometer, valve configuration and flux of UFC should be calculated with actual FDT, strip velocity, thickness, width and target UFC-T. Then the CT is calculated based calculated UFC-T and target UFC-T. After UFC cooling process, due to the complicated heat transfer process in the thickness direction of strip, the internal temperature of strip is significantly different with surface temperature, the strip has obvious re-reddening. Therefore, in temperature control process, re-reddening of strip thickness direction should be fully considered to eliminate the influence of re-reddening on strip temperature control.

Based on industrial production, temperature distribution of strip thickness t under ultra-fast cooling was studied to provide compensate data for eliminating the effect of strip re-reddening on temperature precision control. Taking the least squares method, ultra-fast cooling re-reddening temperature calculation formula of high pressure mode can be obtained by Eq. (5).

\[
\Delta T_{UFC} = 276.65 + 2.25 t + 0.025CR + 0.015 t^2 - 0.013 t \cdot CR
\]

In order to eliminate deviation by strip temperature re-reddening after UFC process, which directly affects control precision of CT. Equation (6) is used to calculate final temperature.

\[
T_{CT}^{final} = T_{CT}^{calc} + (1 - \gamma)T_{UFC-T}^{calc} + \Delta T_{UFC}
\]

Where, \(\Delta T_{UFC}\) is re-reddening temperature in K, \(CR\) is effective cooling rate in K/s, \(t\) is strip thickness in mm, \(T_{UFC-T}^{calc}\) is UFC-T calculated value in K, \(T_{UFC-T}^{act}\) is UFC-T measured value in K, \(T_{CT}^{calc}\) is used to calculate CT in K, \(\gamma\) is weighting coefficient.

3. Multi-dimensional Self-learning Control Strategy

3.1. Classical Model Self-learning Strategy

Due to the heat transfer formula is simplified and the measured deviations of detection equipment, the model must have a certain deviation in application process. In order to eliminate deviation between calculated and measured, model self-learning control strategy is developed. The self-learning process is calculated by comparing above mentioned two values, and updates coefficient to achieve accuracy calculation for current or next strip. Generally, the self-learning coefficient can be shown in Eqs. (7) and (8).

\[
Z = \frac{T_{FDT} - T_{CT}^{calc}}{T_{FDT} - T_{CT}^{act}}
\]
The cooling zone on run out table is divided into certain number cooling sections based on strip thickness. And strip element is same length with each cooling sections. When a strip segment passes through pyrometer of FDT, entrance and exit temperature of segment at each cooling section are obtained by cooling controller model based on measured FDT, velocity, thickness and TVD curve. TVD curve is time-velocity-distance curve of the whole strip, which can express strip velocity evolution of each segment on run out table. When strip segment under FDT pyrometer, the entrance and exit temperature as strip temperature evolution path is calculated and given.

As shown in Fig. 3, exit temperature of \( j \) cooling section, is denoted as \( T_{e,j} \), which is also the entrance temperature of \( j + 1 \) cooling section. At the exit of UFC system, the re-reddening temperature is considered for calculating strip temperature in laminar cooling process. During calculation, taking \( T_{i,j} \) as strip distribution in cooling process. Temperature and cooling section are discretized and forms a coordinate system to demonstrate temperature distribution where abscissa represents cooling section and ordinate represents temperature. So, the variable in \( x \) and \( y \) axis can be express in Eqs. (10) and (11).

\[
X = [1, 2, 3, \cdots, n]^T ..........(10)
\]

\[
Y = [T_{i,1}, T_{i,2}, T_{i,3}, \cdots, T_{i,n}] \quad i = 1, 2, 3, \cdots l ..........(11)
\]

Where, \( l \) is determined by coil length.

Each temperature interval \( (T_i, T_{i+1}, \cdots, T_{i+1}) \) has own self-learning coefficient \( Z_{i,j} \). So, strip temperature \( T_{i,j} \) located in \( T_i \) can be used to calculate \( T_{i,j+1} \) with self-learning coefficient \( Z_k \). Conversely, the deviation between calculated and measured \( T_{i,j+1} \) can also be used to revise self-learning coefficient \( Z_k \). Therefore, if we accurately get self-learning coefficient in the whole intervals, the \( T_{i,j} \) located in different interval can be calculated precisely. Because of actual temperature of \( T_{i,j} \) in cooling section cannot be measured except for the UFC-T and CT, therefore we make use of Eq. (12) to calculate temperature in cooling zones by inverse algorithm. In general, the Eq. (12) is used to calculate exit temperature of cooling section according to entrance temperature. Here, it was exploited to inverse operation for entrance temperature. Taking CT self-learning process for instance, CT is also exit temperature \( T_{i,n} \) of last cooling section, Bring the \( T_{i,n} \) into Eq. (12), the entrance temperature \( T_{i,n-1} \) of last cooling zone can be calculated. And \( T_{i,n-2} \) can be calculated by Eq. (12) with \( T_{i,n-1} \). In same way, all the temperature in cooling section can be calculated in turn. Then the actual temperature under cooling is used for distribution self-learning as shown in Fig. 4. Finally, new self-learning coefficient is updated to calculate temperature of body and tail part, calculated error can be reduced.

\[
T_{i,j}^c = (T_{i,j}^c - T_e) \exp\left(\frac{2ht}{\rho C_p}\right) + T_e ..........(12)
\]

Where, \( T_{i,j}^c \) is entrance temperature actual value of \( j \)th segment under the \( j + 1 \)th cooling section in K, \( T_{i,j+1}^c \) is exit temperature actual value of \( j \)th segment under the \( j + 1 \)th cooling section in K, \( h \) is heat transfer coefficient of \( j \)th cooling section in W/(m²·K), \( \tau \) is time of segment passing through \( j \)th cooling section in s, \( t \) is strip thickness in m.
The self-learning coefficient value can be calculated as follows Eq. (13):

\[ Z_m = \ln \left( \frac{T_{i,j}^{\text{act}} - T_w}{T_{i,j}^{\text{act}} - T_w} \right) \ln \left( \frac{T_{i,j+1}^{\text{rec}} - T_w}{T_{i,j+1}^{\text{rec}} - T_w} \right) \] \quad (13)

Where, \( Z_m \) is self-learning coefficient, \( T_{i,j}^{\text{rec}} \) is the exit temperature re-calculation value of \( i \)th segment under the \( j \)th cooling section in K, \( T_{i,j}^{\text{act}} \) is segment measured FDT in K.

### 3.4. Velocity Coefficient for Heat Transfer Self-learning

In hot rolling strip process, strip velocity is a time-varying and large range parameter, which not only determines cooling time but also affects heat coefficient, finally significantly affects temperature control precision. TVD strategy can help to forecasting strip velocity,\(^1\) but strip velocity coefficient \( A_6 \) in Eq. (4). is not suitable all the time. According to water cooling heat transfer coefficient of ultra-fast cooling in Eq. (4), when the boundary conditions including water temperature, pressure and strip thickness are fixed, the relationship between water cooling heat transfer coefficient and actual velocity is simplified as follows Eq. (14):

\[ h_w \propto f = A \left( \frac{V}{V_0} \right)^{A_6} \] \quad (14)

Let \( f \) represent influence of strip velocity on heat transfer coefficient, when \( V_0 = 5 \) m/s, strip thickness is 10 mm, the relationship between \( f \) and velocity coefficient is shown in Fig. 5.

It can be seen from Fig. 5 that with increase of strip velocity, the water-cooling heat transfer coefficient decreases. At same strip velocity, with increase of strip velocity influence factor \( A_6 \), the influence of the strip velocity on water-cooling heat transfer coefficient is gradually...
increase by an exponential function. The velocity coefficient determines sensitivity of heat transfer on velocity change. Therefore, it is necessary to accurately obtain strip velocity coefficient $A_v$. A plus algorithm is adopted for strip velocity coefficient self-learning. And strip velocity coefficient is calculated by heat transfer formula with inverse algorithm.

$$f = A \left( \frac{V}{V_0} \right)^{A_v z} \quad \text{(15)}$$

4. **Online Application**

Once strip head enters cooling zone, self-learning calculate process is triggered on. First, distributed temperature self-learning will used to calculate different temperature interval self-learning coefficient by measured temperature of strip head part, and then adopting it to eliminate calculating deviation in following body and tail part of strip. **Figure 6(a)** shows temperature of Q345B with thickness of 6 mm on run out table, the deviation appears in strip head part, and deviations is eliminated in body and tail part of strip. When the designed segment in strip head part is pass through CT pyrometer, distributed temperature self-learning controller is triggered to calculate new self-learning coefficient by flow in Fig. 4. **Figure 6(b)** shows the designed segment temperature distribution in cooling process. For convenient calculation, the minimum interval in x and y axis are 25°C and a cooling section. After distribution self-learning process, the new self-learning coefficient is updated to calculate temperature of segment in body and tail part to ensure strip final temperature meets target CT.

As be shown in **Fig. 7**, the error between measured and target is about 70°C of 10.5 mm thickness. When adopting fixed gain 0.2, the error can be eliminated in following five strips without manual operation. However, after adopting dynamic gain, temperature deviation of second strip can be reduced to 20°C, and temperature of following third strip can meet target value.

The work proposed in this paper has been used in a 2050 mm HSM in China. The ultra-fast cooling system and cooling strategies have been applied in production of low-cost Q345B, X70, X80 and so on. By adopting temperature calculation compensation strategy and multi-dimensional self-learning control strategy, the model has a good performance with high temperature precision. The measured UFC-T was controlled within 25°C over 95% of the coil length, while measured CT was controlled within 18°C over 95% of the coil length.
5. Conclusions

(1) Cooling model for hot rolled strip based on UFC were described. The temperature calculation compensation strategy for strip was proposed, using the least squares method, ultra-fast cooling re-reddening temperature calculation formula of high pressure mode is obtained.


(3) The cooling model and strategy have already been applied in 2 050 mm industrial production line, and achieves high accuracy control of UFC-T and CT which lays solid foundation for stable production.

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