Coupled model of temperature and phase transformation of hot rolling low carbon steel during cooling process

WANG Su-fen¹, LI Zhi-jie¹, Zhang defeng¹, Zhou donghai²

¹School of Mechanical Engineering, Quzhou University, Zhejing 324000 China
²YUANLI GROUP, Quzhou, Zhejing province 324000 China
E-Amail:wangsufen09@163.com

Abstract. For the cooling process of SPHC hot-rolled low carbon steel, a coupled prediction model of temperature and phase change was established by using finite element method. Considering the influence of latent heat of phase change on the two-dimensional temperature field of strip after rolling, the model of temperature and phase change is coupled solving by Avrami equation and the additive law of Scheil. The results show that the temperature distribution is not uniform along the width direction after the laminar cooling of hot-rolled low carbon steels, the calculated results of the model are well combined with the measured values, and can accurately predict the temperature distribution and room temperature structure of hot-rolled low carbon steel after cooling.

1. Introduction
In recent years, with the continuous development of steel rolling technology, the size accuracy of hot rolled low carbon steel has been increasingly improved, and the cooling after rolling has been paid more and more attention. The strip cooling after rolling is a very complicated process, which not only has a complex heat exchange process, but also includes the phase change and volume change of steel. In cooling process, the uneven cooling of strip results to uneven temperature distribution, so, the stress of thermal and phase transformation by phase expansion, when the stress reaches the yield limit of material, it can cause local plastic deformation of strip, and result the residual stress, which finally impact on the mechanical properties and strip shape quality of steel strip [1-4]. In the cooling process of strip steel, temperature control is the core factor that affects the final structure of the product, the temperature and the phase transition are interacted, and both must be coupled solution.

This paper, the two-dimensional temperature distribution is calculated by using the finite element method in the process of cooling, using phase transformation kinetics equation of Avrami and he additive law of Scheil, the phase transition process is calculate from A to F and A to P, considering the latent heat of phase change, it is developed temperature and phase change coupling model of hot rolled low carbon steel, and verified the accuracy of the models by comparison with the measured experiment.

2. Temperature field model during cooling

2.1. Temperature field calculation
The heat exchange process of strip cooling can ignore the heat flow in the length direction, and only consider the transverse and thickness direction. Consider the release of latent heat during phase
transformation, it is established the temperature field mathematical model \(^5\) by the two-dimensional heat conduction differential equation of strip steel with internal heat source as follows:

\[
\frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda \frac{\partial T}{\partial y}\right) + Q = \rho c \left(\frac{\partial T}{\partial t}\right)
\]  

(1)

Where, \(\lambda\) is the coefficient of thermal conductivity of steel, W/m \(^\circ\)C; \(T\) is the strip temperature, \(^\circ\)C; \(t\) is time, s; \(Q\) is the rate for inner heat source of strip steel, J/s, \(\rho\) \(c\) is the density of material, kg/m \(^3\); \(c\) is specific heat for material, J/(kg· K), \(x\) and \(y\) are the coordinate values of thickness direction and horizontal coordinates respectively, m.

2.2 Initial conditions and boundary conditions

It is the key to solving the mathematical model of strip temperature field for accurate determination of the initial conditions and boundary conditions, the initial condition is the outlet temperature of the finishing mill, and the boundary condition is the heat transfer coefficient of the cooling process.

The initial condition can be expressed as:

\[
t(x, y, t) = T_0 (t = 0, 0 \leq x \leq \frac{W}{2}, 0 \leq y \leq \frac{H}{2})
\]

(2)

Where, \(T_0\) is the temperature of the workpiece measured by the thermometer at the outlet of finishing mill, \(^\circ\)C; \(W\) is the width of the piece, m; \(H\) is the thickness of the piece, mm.

In the cooling process after rolling, there are two cooling states with air cooling and water cooling. In the state of air cooling, there are two heat transfer modes: thermal radiation and thermal convection. Considering the effects of radiation and convection, and using Stefan-Boltzmann equation\(^6,7\), the heat exchange coefficient of air cooling is,

\[
h_0 = h_c + \frac{\sigma \varepsilon (T_\infty^4 - T_k^4)}{T_k - T_\infty}
\]

(3)

Among,

\[\varepsilon = 1.1 + \frac{T}{1000} (0.125 \frac{T}{1000} - 0.38)
\]

Where, \(h_c\) is natural convection heat transfer coefficient, \(\sigma\) is constant of Stefan-Boltzmann W/(m\(^2\)·K\(^4\)), \(\varepsilon\) is the radiation rate of strip surface, \(T_k\) is the surface temperature of the rolled piece, \(^\circ\)C, \(T_\infty\) is the ambient temperature, \(^\circ\)C.

The water-cooling process of strip steel is mainly affected by the strip surface temperature, cooling water amount and equipment conditions. The water-cooling heat exchange coefficient changes along the width direction. When the horizontal coordinate value of the rolled piece is less than or equal to 0.4 times of the width of the strip steel (\(x \leq 0.4\)), it can be expressed as:

\[
h_w^c = \frac{9.72 \times 10^4 k^{0.355}}{(T_k - T_\infty)^{0.645}} \left(\frac{2.5 - 1.5 \log T_\infty D}{p_l p_c}\right) \times 1.163
\]

(4)

When the horizontal coordinate value of the rolled piece is greater than 0.4 times of the strip width (\(x > 0.4\)), the heat exchange coefficient can be expressed as:

\[
h_w = h_w^c (1 + 0.25 \frac{10x - 4B}{B})
\]

(5)

Where, \(D\) is the diameter of the flow nozzle, m, \(p_l p_c\) are the nozzle spacing along the strip steel rolling direction and rolling vertical respectively, m, \(B\) is the width of the strip, m, \(k\) is water flow density, m\(^3\)/(min·m\(^2\)).
2.3 Physical parameters

In the model, the physical parameters such as thermal conductivity, specific heat and density were all taken as linear mean values of each phase, which can be expressed as: the thermal property parameters of materials mainly include thermal conductivity, density and specific heat capacity of materials. For hot rolled strip steel during 700 °C to 800 °C, the density of steel is almost same with the temperature changing, it is 7860 kg/m³, the coefficient of thermal conductivity and heat capacity of the materials is change with temperature changing, it has a great influence on the calculation results, so, it is very necessary for accuratting the physical parameters to precise the temperature and phase change. Heat capacity is refers to the unit mass of objects each raise or lower 1 °C, needs to absorb or release heat, the unit is J/(kg · K). The heat capacity of hot rolled strip can be calculated by the sum of product for the volume fraction of each phase and the heat product of each phase:

\[
c = \sum_{i=A,F,P} X_i c_i(T)
\]

Where, \( X_i \) is the volume fraction of each phase, \( c_i(T) \) is the specific heat of each phase.

Specific heat of each phase is a single value function of temperature, which can be expressed as:

\[
c_A = -2.0495 \times 10^4 T^3 + 0.552377 T^2 - 495.64 T + 12822.82
\]

\[
c_P = 1.777 \times 10^2 T^3 - 0.024 T^2 + 11.31 T - 1158.44
\]

\[
c_F = 1.148 T + 474.622
\]

Thermal conductivity refers to the heat transmitted with unit time and unit area under the unit temperature gradient, the unit is W/(m·K). In this paper, the changing of thermal conductivity with temperature is determined by thermal simulation, the formula for calculating thermal conductivity determined by polynomial fitting is as follows:

\[
\lambda = 44.35967 - 0.01096 T - 3.76725 \times 10^{-5} T^2 + 2.98038 \times 10^{-8} T^3
\]

3. Phase transition model of cooling process

3.1 Ferritic phase transition

In the continuous cooling process of hot-rolled low carbon steel, the phase transformation of γ to F and γ to P is considered to satisfy the additive law of Scheil after transition, so, be processed into the sum of a series of small isothermal phase transitions.

The early stage of phase transition with γ to F, the phase transition is carried out by the "nucleation growth" mechanism, and the incremental change of phase change rate is increased by time increment [8], which can be expressed as:

\[
\Delta X_{F}^{(i)} = 4 \left( \frac{\pi}{3} \right)^{1/4} \left( I_{F}^{(i)} S_{\gamma} \right)^{1/4} \left( G_{F}^{(i)} \right)^{3/4} \left( \ln \left( \frac{1}{1 - X_{F}^{(i-1)}} \right) \right)^{3/4} \left( 1 - X_{F}^{(i-1)} \right) \Delta t^{(i)}
\]

The late stage of phase transition with γ to F, he phase transition is carried out by the "Position saturation" mechanism, the incremental phase change rate is expressed as:

\[
\Delta X_{F}^{(i)} = K_{1} S_{\gamma} G_{F}^{(i)} \left( 1 - X_{F}^{(i-1)} \right) \Delta t^{(i)}
\]

Where, \( S_{\gamma} \) is the effective grain boundary area per unit volume of austenite, mm², \( S_{\gamma} = 6 / d_{\gamma} \), \( d_{\gamma} \) is austenite diameter, mm. \( K_{i} \) is the constant, \( K_{i} = 8.99 \times 10^{-12} \exp(21100 / T) \), it can be obtained
by experimental determination. $F_i^{(t)}$, $G_i^{(t)}$ are the nucleation rate and growth rate of ferrite in this iteration step respectively.

3.2 Perlite phase transition

With the progress of ferrite phase transition, the molar fraction of carbon is increased on one side of austenite. When the carbon content reaches the extension line of Acm line in the austenite, the ferrite phase transition ends and begins to occur the pearlite transition. The volume fraction increment of the pearlite can be expressed as:

$$\Delta X_p^{(t)} = K_2 S_i G_p^{(t)} \left( 1 - X_p^{(t-1)} - X_{\text{total}}^f \right) \Delta t^{(t)}$$

(11)

Where, the value of $K_2$ is for $3 \times 10^3$, $G_p^{(t)}$ is the growth rate of perlite for this iterative step, which can be expressed as:

$$G_p^{(t)} = \Delta T^{(t)} D^{(t)} \left( C_{\gamma a}^{(t)} - C_{\gamma cm}^{(t)} \right)$$

(12)

Where, $\Delta T^{(t)}$ is the undercooling degree of phase transition during the $i$ time iteration, $C_{\gamma cm}^{(t)}$ is the molar fraction of the carbon on the side of $\gamma$ in the interface $\gamma/cm$, it can be solved by KRC model.

4. Verification and analysis of calculation results

In this paper, hot rolled strip of low carbon steel is researched by the steel mill with the size of length 1800 and width 900 and thickness 800. The chemical composition is shown in table 1. The cooling process is simulated by using the finite element model and the phase transformation model.

| Table 1. Chemical composition of the test steel (wt%) |
|---------|---------|---------|---------|---------|---------|---------|
| C       | Si      | Mn      | S       | P       | Al      |
| 0.08    | 0.03    | 0.35    | 0.02    | 0.025   | 0.03    |

The temperature distribution is researched in the curl the thermometer along the width direction, figure 1 is the temperature distribution with the calculated value and the measured in the center position along the width direction. It can be seen that the calculate values and measured values coincide well, the temperature difference is about 80 °C with strip center and edge, the temperature is falling significantly in the strip edge of 600 to 800mm, which reduced from 630 °C to 550 °C, this temperature difference can causes the stress of phase transformation and thermal for strip internal, and produces the residual stress, in the end, affects the quality with steel.

![Figure 1. Temperature distribution along the width direction](image-url)
According to the phase transformation of hot rolled low carbon steel after rolling in different cooling, phase changing amount calculated by the numerical methods of Matlab, finishing outlet temperature of strip is 870 °C, and a single-phase austenitic organization, phase volume content is calculated through the simulation, and shown in figure 2. As can be seen from the figure, the microstructure is ferrite and pearlite with hot-rolled mild steel after cooling, and the ferrite content is 94.6%. The F content is first stable and then decreased along the width direction, while the P content is just right, the inflexion appears at about 600mm of strip width. This is because the cooling rate increased in the range of 600-800mm with the edge of the strip, the over-cooling degree increased, and inhibit the transformation of proeutectoid ferrite, so, it is reduced the actual transition temperature, this is cause the phase transition of ferrite ahead of time ending, and begin to pearlitic transformation.

In view of the actual rolling products, the sample are got in the center and edge of strip respectively, the microstructure was observed and analysis as shown in the figure 3, it can be seen from the diagram, structure of SPHC is a small amount of pearlite distributed on the ferrite matrix in room temperature. Comparating the sample microstructure of edge and central, ferrite content in edge sample is below the centers, this is consistent to the model calculating of figure 2. At the same time, the ferrite distribution at the edge of the sample is smaller and more diffuse, which is due to the increase of cooling rate at the edge, and inhibits the growth of F grain, so, it increases the surface area grain of boundary surface, and increases the nucleation position.
5. Conclusion
1. It is established the finite element model of the cooling process after rolling, and valid the calculation of temperature field along the width direction, the results show that calculated values and measured values coincide well, the difference temperature is about 80 °C in the center and edge strip, the temperature difference will make the phase transformation stress and thermal stress is generated in the strip producing residual stress, affect the quality with steel. This temperature difference can cause the stress of phase transformation and thermal for strip internal, and produce the residual stress, in the end, affect the quality with steel.
2. Considering the latent heat of phase change, the coupling model of temperature and phase change is determined, the phase transition amount of the strip as calculated in crimp progress, the predicting model was proved by sampling and analysis of rolling products.

Acknowledgement
Science and Technology Plan Projects of Quzhou (2014Y002) ;Science and Technology Plan Projects of Quzhou (2015Y006) ;The Talented Projects of Quzhou University (BSYJ201403)

References
[1] Wang Y F, Yu W, Xuan K L and et. Uneven cooling and control technique of high strength hot rolled steel strip[J]. Heat treatment metals, 2017, 42(08):192-7.
[2] Zhang D F, Lu J Sh, Lu J G and et. Thermo-Mechanical coupling computation and warping analysis during controlled-cooling of X65 heavy pipeline-plate [J]. Journal of central north university (natural science edition), 2013, 34(01):79-85.
[3] Yu W, Wang Y F. Relationship between cooling parameters and warping of hot rolled strips [J]. Chinese Journal of Engineering, 2016, 38(12):1734-1740
[4] Xu X Q, Han Q, FU S L and et. Temperature prediction model for hot rolled strip during laminar cooling process [J]. Journal of iron and steel research, 2012, 24(12):23-27.
[5] Serajzadeh S. Prediction of temperature distribution and phase transformation on the run-out table in the process of hot strip rolling[J]. Appl Math Modelling, 2003, 27(2):861-5.
[6] S.Sikdar, Mukhopadhyay. Numerical determination of heat transfer coefficient for boiling phenomenon at runout table of hot strip mill[J]. Iron making & Steel making, 2004, 31(6):495-502.
[7] Chen Y L, Yu W, Bai B. Numerical simulation of laminar cooling process for hot rolled strip with low residual stress. J Beijing Univ Technol, 2012, 38(10):1576-9.
[8] Liu J S, Yanagida K, Umio S, et al. The analysis of phase transformation for the prediction of microstructure change after hot forming [J]. ISIJ International, 2001, 41(12):1510-16.