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Hot Rolled Strip Re-reddening Temperature Changing Law during Ultra-fast Cooling

Lian-yun JIANG[1], Chun-jiang ZHAO[2], Jian-hui SHI[1], Guo YUAN[1],
Xue-qiang WANG[3], Qing-xue HUANG[1]
(1. State Key Laboratory of Rolling and Automation, Northeastern University, Shenyang 110819, Liaoning, China, 2. School of Mechanical Engineering, Taiyuan University of Science and Technology, Taiyuan 030024, Shanxi, China; 3. Shougang Qian'an Iron and Steel Co., Ltd., Qian'an 064404, Hebei, China)

Abstract: Temperature deviation between surface and the center of hot rolled strip is formed during ultra-fast cooling (UFC). Surface temperature would rise when temperature deviation goes up to an extent, and strip re-reddening phenomenon will appear. Strip re-reddening affects the stability of strip microstructure, property and temperature control precision. Thus, it is necessary to conduct research on re-reddening temperature changing law to improve strip property and temperature control precision. Strip temperature trends for various strip thicknesses and ultra-fast cooling rates were obtained by numerical calculation method. Re-reddening temperature, temperature deviation between surface and center, and boundary layer position changing law were obtained. By comparison, some conclusions were obtained: UFC re-reddening temperature and laminar cooling (LC) re-reddening temperature were linear to ultra-fast cooling rate respectively. Ultra-fast cooling rate affected UFC re-reddening temperature greatly, but it had little effect on LC re-reddening temperature. Equations which were used to calculate UFC re-reddening temperature, LC re-reddening temperature and maximum temperature deviation were obtained. The position of boundary layer stayed in 1/4 strip thickness.

Key words: ultra-fast cooling; laminar cooling; cooling rate; re-reddening temperature

Currently, higher requirement about product property and cost has been proposed for hot strip mill. The controlled rolling and controlled cooling technology with ultra-fast cooling has achieved rapid development based on the superiority of low cost and high property[1].

The surface temperature of hot rolled strip will rise after ultra-fast cooling (UFC) or laminar cooling (LC), and the phenomenon is called as strip re-reddening. Strip re-reddening will affect stability of microstructure, properties[2-4] and temperature control precision of UFC system for hot strip mill[5]; thus, re-reddening temperature should be considered during setup of rolling and cooling processes. It is necessary to conduct deep research on the re-reddening temperature change in order to improve product property and temperature control precision.

In this paper, re-reddening temperature change of strip with various thicknesses during laminar cooling process was simulated[6,7], and the UFC process (air cooling process was conducted after UFC, but LC process was not conducted) was also simulated for steel plate[8]. The reliability of simulated data calculated by ANSYS was verified and re-reddening temperature changing rule was obtained for steel plate. The rolling and cooling process for hot rolled strip was different from steel plate; thus, deep research on the temperature change during cooling process of hot rolled strip was conducted, based on UFC in a 2 160 mm HSM (Hot Strip Mill) of Shougang Qian'an Iron and Steel Co., Ltd.

1 Numerical Modeling

Hot rolled strip undergoes air cooling, UFC, air cooling, LC and air cooling respectively during cooling on the run-out table in hot strip mill. The UFC equipment is installed between finishing mill and laminar cooling equipment. Heat exchange process will be conducted between strip surface and cooling water or ambient air, and two boundary conditions (the second and the third boundary conditions) can be imposed during calculation.

Under the second boundary condition, i.e., the Neumann condition, heat transfer coefficient should be specified for every node every time, while under the third boundary condition, that is, the Fourier condition, bulk temperature and heat exchange between cooling medium and hot rolled strip should be specified.

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Biography: Lian-yun JIANG, Doctor; **E-mail:** neu2015@163.com; **Received Date:** February 20, 2014

The second boundary condition can be used for simulation between strip surface and cooling medium in order to improve calculation precision and decrease calculation time. Heat transfer coefficient for various cooling processes can be obtained according to UFC rate and mathematical model in UFC control system. The surface temperature after cooling can be calculated by Eq. (1)[9,10] when heat transfer coefficient and physical parameters change as time goes on.

$$\frac{\mathrm{d}T}{\mathrm{d}\tau}=-\frac{2\alpha_{\mathrm{a}}}{c_P\rho h}(T-T_{\mathrm{m}})-\frac{2\alpha_{\mathrm{w}}}{c_p\rho h}(T-T_{\mathrm{w}}) \tag{1}$$

where, α_a and α_w are heat transfer coefficient for air cooling and water cooling respectively, W/(m^2·K); c_P is specific heat, J/(kg·°C); T is surface temperature, °C; T_m and T_w are ambient temperature and cooling water temperature respectively, °C; ρ is steel density, kg/m^3; h is strip thickness, mm; and τ is cooling time, s.

The empirical value of heat transfer coefficient for air cooling was taken as 40 W/(m^2·K). Eq. (2) was obtained from Eq. (1) and it can be used to calculate heat transfer coefficient for water cooling.

$$\alpha_{\mathrm{w}}=-\frac{\alpha_{\mathrm{a}}(T-T_{\mathrm{m}})}{T-T_{\mathrm{w}}}-\frac{c_P\rho h}{2(T-T_{\mathrm{w}})}\frac{\mathrm{d}T}{\mathrm{d}\tau} \tag{2}$$

It can be seen from Eq. (2) that heat transfer coefficient may change during cooling process. Water temperature, ambient temperature, specific heat, steel density, strip thickness and heat transfer coefficient for air cooling keep almost the same during the cooling process, while surface temperature constantly changes. Thus, the main factor that affects heat transfer coefficient for water cooling is surface temperature. Strip temperature is 200−900 °C during strip cooling process, and heat transfer coefficient for water cooling can be obtained from Eq. (2) when strip temperatures are 200 °C, 250 °C, ..., 900 °C, respectively. The heat transfer coefficient of the left strip temperature can be obtained by linear interpolation method.

Strip temperature, cooling water temperature and ambient temperature are initial conditions for strip cooling process simulation. Strip initial temperature after rolling may be different for various steel grades. Initial water and air temperatures are all 27 °C. Cooling water density is 1 000 kg/m^3, and its specific heat is 998 J/(kg·°C). Steel density is 7 850 kg/m^3, and its specific heat is 448 J/(kg·°C). The steel conductivity is listed in Table 1[7].

Table 1 Steel conductivity at different strip temperatures

Temperature/°C	200	400	600	700	800	1 000
Conductivity/ (W·m^{-1}·K^{-1})	48.6	42.7	39.3	35.6	25.9	27.7

It can be seen from Table 1 that steel conductivity was linear with strip temperature when strip temperature is 200−800 °C and steel conductivity remains constant when strip temperature is 800−1 000 °C. Thus, steel conductivity can be obtained by linear interpolation method when strip temperature is 200−800 °C and average steel conductivity can be used when strip temperature is 800−1 000 °C.

2 Temperature Field Model

The thickness and width of hot rolled strip are 1.0−25.0 mm and 1.50−2.25 m, and the length is more than 100 m, so the strip thickness is far less than its width and length. The strip cooling process can be simplified as one-dimensional thermal conduction model. Eq. (3) is the strip temperature calculation model[11] based on the flowing suppositions:

(1) Heat transfer coefficient and physical parameters (density, conductivity and specific heat) are constant and these parameters will not change with time;

(2) Strip initial temperature is well-distributed and ambient temperature is constant.

$$T'(x,\tau)=(T_0-T_{\mathrm{m}})\frac{2\sin\mu_1}{\mu_1+\sin\mu_1\cos\mu_1}\cdot \cos(\mu_1\frac{x}{\delta})\exp(-\mu_1^2\frac{c\tau}{\delta^2})+T_{\mathrm{m}} \tag{3}$$

$$\cot\mu=\mu/Bi \tag{4}$$

$$Bi=\alpha\cdot\delta/\lambda \tag{5}$$

$$c=\lambda/\left(\rho\cdot c_P\right) \tag{6}$$

where, $T'(x,\tau)$ is strip temperature at location x along the thickness direction and time τ, °C; T_0 is strip initial temperature, °C; δ is half thickness of strip, m; λ is conductivity, W/(m·K); α is heat transfer coefficient (for air cooling, $\alpha=\alpha_a$; for water cooling, $\alpha=\alpha_w$), W/(m^2·K); Bi is Biot coefficient, a dimensionless number; $\mu=k\delta$, k is a constant, mm; μ_1 is first solution of Eq. (4) within 0−3.14; and x is node position along the thickness, m.

It can be known from Eqs. (3)−(6) that strip temperature will be well distributed when $Bi\to 0$, and great temperature gradient between the center and surface will form when $Bi\to\infty$. Bi will approach to 0 for air cooling because the heat transfer coefficient for air cooling is about 40 W/(m^2·K) in general. Bi is a fixed value between 0 and ∞ for water cooling.

Temperature gradient can form during water cooling process and surface temperature is lower than central temperature. Air cooling process will be conducted after water cooling and Bi will approach to 0 at this time. Strip temperature along the thickness will tend to be well distributed as time goes on. Central temperature will decrease and surface temperature may rise. So strip re-reddening phenomenon will appear.

Heat transfer coefficient and conductivity may change with cooling time going on and Eq. (3) is not suitable for calculation at this time. Finite element method can be used for calculation according to the