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Temperature field of steel plate cooling process after plate rolling

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Abstract

Based on numerical calculation with Matlab, the study on cooling process after plate rolling is carried out, and the temperature field distribution of the plate varying with the time is obtained. The effects of the plate thickness, final rolling temperature, cooling water temperature, average flow rate of the cooling water, carbon content of the plate and cooling method on the plate surface and central temperatures as well as final cooling temperature are discussed. For the same cooling time, the plate surface and central temperatures as well as their temperature difference increase; with the decrease in rolling temperature and the increase in average flow rate of the cooling water, the plate surface and central temperatures decrease. Compared with the single water cooling process, the temperature difference between the plate centre and surface based on intermittent cooling is lower. In this case, the temperature uniformity of the plate is better, and the corresponding thermal stress is lower. The fitting equation of the final cooling temperature with respect to plate thickness, final rolling temperature, cooling water temperature and average flow rate of the cooling water is obtained.

Keywords: Steel plate; Matlab; Air cooling; Laminar cooling; Generalized thermodynamic optimization.

1. Introduction

In the production process of the plate casting and rolling [1-7], the cooling process after plate rolling is an important process, which determines the quality, mechanics and structure property of the steel. Therefore, it is important to investigate the plate temperature characteristics of the cooling process after plate rolling, and many scholars show great interests in this field.

Guan et al [8] derived the analytic solution of one-dimensional temperature field for laminar cooling of hot rolling process, and obtained the optimal heat transfer coefficient model according to the actual data of laminar cooling process. Auzinger and Parzer [9] investigated the one-dimensional laminar cooling problem for hot strip by using feedforward control and closed-loop control, and obtained a precise coiling temperature within narrow tolerance. Wang et al [10] further introduced the feedforward and feedback control models as well as the self-learning model to control the coiling temperature of the hot strip, and the results showed that these models were simple, effective and precise. Xie et al [11] developed an intelligent control scheme for hot strip rolling by using the close-loop fuzzy control method, and demonstrated the control accuracy of the coiling temperature by using the proposed method. Zheng et al [12] proposed a distributed model predictive control for one-dimensional hot strip laminar cooling process, and used the Extended Kalman Filter to estimate the strip temperature. The proposed method was proved to be effective according to both simulation and experiment results, and this method was also excellently applied in controlling the coiling temperature of the hot strip [13]. Some scholars also built two-dimensional models to analyze this problem [14-18]. Yu [14], Lin [15] and Wang [16] built the two-dimensional temperature distribution models of laminar cooling processes after rolling based on finite difference method. Wang et al [17] analyzed the temperature variation inside the hot plate by using finite element method, and the variation rules of the plate temperature in terms of its thickness and flow rate were obtained. Dong et al [18] used the weighted multiple models adaptive controller to analyze the temperature characteristic of the laminar cooling process after plate rolling, and this controller exhibited its advantage over the conventional one. Moreover, Zhang et al [19] analyzed the cooling efficiency of the laminar cooling process for plate rolling, and Liu [20] investigated the microstructure of the pipeline steel during its cooling process.

The final cooling temperature of the plate is influenced by many parameters; therefore, to find the relationship between the final cooling temperature and these parameters is a meaningful work. In this study, the one-dimensional heat transfer problem of the cooling process after plate rolling at unsteady state will be investigated based on numerical calculation with Matlab. The effects of the plate thickness, final rolling temperature, cooling water temperature, average flow rate of the cooling water, carbon content of the plate and cooling method on the plate surface and central temperatures as well as final cooling temperature will be discussed. The major purpose of this paper is to obtain the fitting equation of the final cooling temperature with respect to the parameters during the cooling process, and to analyze the influence of these parameters on the final cooling temperature. The results obtained can provide some new guidelines for the designs and operations of the cooling system after plate rolling.

2. Cooling model after plate rolling

The cooling model after plate rolling is shown in Figure 1. In Figure 1(a), the plate enters the cooling system after the finishing rolling. Firstly, the plate experiences the air cooling stage, and the heat transfers between the plate and environment in this stage are mainly radiative and natural convection ones. Then, this plate experiences the water-cooling stage, and the cooling water forms a water layer in laminar state. The water cooling stage is a complex forced convection heat transfer one. Finally, the plate experiences another air cooling stage, and then enters the straightener to finish the cooling process. As shown in Figure 1(b), the thickness of the plate is H, the temperature of the plate is T (changing with the cooling time t), and its temperature at the initial time of the beginning air cooling stage is T_0.

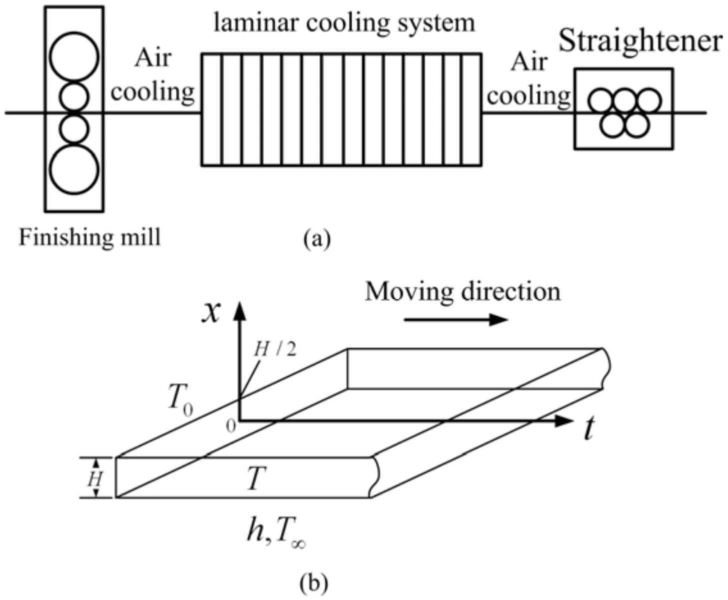

Figure 1. Cooling model after plate rolling

The length and width of the plate are greatly larger than its thickness. The latent heat of the phase change in the plate is ignored. In these cases, the cooling problem after plate rolling can be assumed to be one dimensional heat transfer problem in transient state

$$\frac{\rho c}{\lambda}\cdot\frac{\partial T}{\partial t}=\frac{\partial^2 T}{\partial x^2}\ (0<x<\frac{H}{2},t>0) \tag{1}$$

where ρ, c, λ, T and H are the density, specific heat capacity, thermal conductivity coefficient, temperature and thickness of the plate, respectively, and t is the cooling time. The corresponding boundary conditions are

$$T(x,0)=T_0\ (0\le x\le\frac{H}{2}) \tag{2}$$

$$\frac{\partial T}{\partial x}=0\ (x=0,t>0) \tag{3}$$

$$-\lambda\frac{\partial T}{\partial x}=h(T-T_\infty)\ (x=\frac{H}{2},t>0) \tag{4}$$

where h is the heat transfer coefficient, T_∞ is the environment (cooling water) temperature, and T_0 is the initial temperature of the plate.

From time 0 to t_1, the plate is in air cooling stage. Because the heat loss caused by heat convection in this stage is 7%-10% of the heat loss caused by radiative heat transfer, the heat loss caused by radiative heat transfer is only considered, and the calculation error caused by heat convection can be reduced by increasing the emissivity coefficient properly. The heat transfer coefficient at the air cooling stage can be given as [20]

$$h=h_a=\frac{\varepsilon\sigma(T_s^4-T_\infty^4)}{T_s-T_\infty} \tag{5}$$

where ε is emissive coefficient, σ is the Boltzmann constant, T_s is the surface temperature of the plate, and T_∞ is the temperature of the air. The value of ε ($\varepsilon\le 1$) depends on the kinds of the steels, plate surface temperature and oxidation degree of the plate surface, and ε is set as 0.85 when the heat convection between the plate and air as well as the heat conduction between the plate and roller are considered in this coefficient [20].

From time t_1 to t_2, the plate is in laminar cooling stage. The heat transfer coefficient between the plate and cooling water is relevant to the water flow rate w and the surface temperature T_s of the plate. Considering that the water densities at the upper and lower surfaces of the plate are not equal, the water flow rate is calculated by the average water flow rate w at the upper and lower surfaces. The heat transfer coefficient at laminar cooling stage can be given as [15]

$$h=h_w=124.674w^{0.663}\cdot 10^{-0.00147T_s} \tag{6}$$

From time t_2 to t_3, the plate is in air cooling stage again, and the equation of the heat transfer coefficient is the same as Eq. (5).

3. Solution of the plate temperature field based on Matlab and its analyses

The problem of Eqs. (1)-(6) is a one-dimensional heat transfer problem in transient and different time interval. Because this kind of one-dimensional partial differential equation with different time interval can be easily solved based on Matlab, the heat transfer problem in this paper will be solved by numerical calculations based on Matlab, and the effects of various parameters on the plate temperature field will be analyzed. In the calculations, it is set that $\rho=7850\text{kg/m}^3$, $H=20\text{mm}$, $T_\infty=25°\text{C}$, $\sigma=5.67\times10^{-8}W/(m^2\cdot k^4)$, $w=800L/(\min\cdot m^2)$, $T_0=930°\text{C}$, $t_1=20s$, $t_2=60s$ and $t_3=80s$; in the temperature characteristic analyses of the plate, these parameters mentioned above will keep constants if there is no special explanation. Although the density of the plate changes little with the increase in temperature, the thermal conductivity coefficient and specific heat capacity obviously change with the carbon content and temperature of the plate.

Figure 2 shows the effects of the carbon content on the thermal conductivity coefficient and specific heat capacity with different temperature [16]. The thermal conductivity coefficient and specific heat capacity between the known temperature points can be obtained by using interpolation method, and the low carbon steel (0.23%C) is taken as an example in this paper.

Figure 3 shows the three-dimensional diagram among the temperature T of the plate, time t and thickness x. From Figure 3, because of the air cooling and laminar cooling at the surface of the plate, its temperature decreases from its centre to the surface along the thickness direction, and the temperature change tendencies of the plate surface are different at different cooling stages.

Figure 4 further shows the characteristics of the temperatures at surface, $1/4$ thickness and centre of the plate as well as the temperature difference between the surface and centre. From Figure 4, the surface cooling rate of the plate at air cooling stage is $5.2\ \mathrm{K/s}$; this cooling rate at the laminar cooling stage reaches to $8.5\ \mathrm{K/s}$, and the change of the surface temperature at this stage is obvious; due to the heat transfer from the surface to the centre, the plate will experiences the self-tempering stage, the cooling rate at this stage is $1.5\ \mathrm{K/s}$, and the final cooling temperature of the plate is $517.2\ ^{\circ}\mathrm{C}$. The temperatures at $1/4$ thickness and centre of the plate decrease with the increase in cooling time; during the air cooling stage, the temperature difference between the plate centre and surface increases first, and then tends to be stable; during the laminar cooling stage, this temperature difference increases with the increase in cooling time; during the self-tempering stage, this temperature difference tends to be stable at a low value.

Figure 5 shows the effect of the plate thickness H on the characteristic of the plate temperature T versus the cooling time t. From Figure 5, with the increase in its thickness, the surface and central temperatures of the plate increase for the same cooling time, and the temperature difference between the surface and centre of the plate increases due to the same cooling ability. Figures 6 and 7 show the effects of the final rolling temperature T_0 and the average flow rate w on the final cooling temperature $T(t_3)$. From these figures, with the decrease in final rolling temperature and the increase in average flow rate of the cooling water, the plate surface and central temperatures decrease. In the cooling process after plate rolling, the optimal parameters are chased for in the specified range of the final cooling temperature. The fitting equation of the final cooling temperature with respect to the plate thickness H and average flow rate w of the cooling water can be given as

$$T(H/2,80) = -0.00177w^{0.878}H^{-1.567} + 1081.048 \quad (\mathrm{K}) \tag{7}$$

where $0.02 \le H \le 0.05\ (\mathrm{m})$ and $400 \le w \le 1000\ (\mathrm{L/min/m^2})$. For the fixed final cooling temperature, the corresponding optimal parameters can be obtained by using Eq. (7).

Figure 8 shows the effect of the carbon content on the surface temperature T of the plate. From Figure 8, with the increase in the carbon content, the surface temperatures of the rimmed steel (0.06%C), killed steel (0.08%C), low carbon steel (0.23%C) and medium carbon steel (0.4%C) decrease in turn, but the surface temperature of the Si-Mn steel locates between those of the low carbon steel (0.23%C) and medium carbon steel (0.4%C). Therefore, the final cooling temperature changes with the carbon content of the plate.

Figures 3-8 show the effects of parameters of the single water cooling stage on the temperature field of the plate, and the intermittent cooling is always applied in the actual cooling technology. Figure 9 shows a three-dimensional diagram among the temperature of the plate for three water cooling processes, time t and thickness x. In Figure 9, the plate experiences the air cooling stage in the beginning 20 seconds; from the 20th second to the 30th second, the 30th second to the 35th second, the 35th second to the 45th second, the 45th second to the 50th second, the 50th second to the 60th second and the 60th second to the 80th second, the plate experiences the water cooling stage, self-tempering stage, water cooling stage, self-tempering stage, water cooling stage, and final self-tempering stage, respectively. The cooling rates for the three water cooling stages are $6.4\ \mathrm{K/s}$, $9.2\ \mathrm{K/s}$ and $12.5\ \mathrm{K/s}$, respectively, and the cooling rates of the later two water cooling stages are larger than that of the single water cooling stage shown in Figure 3.

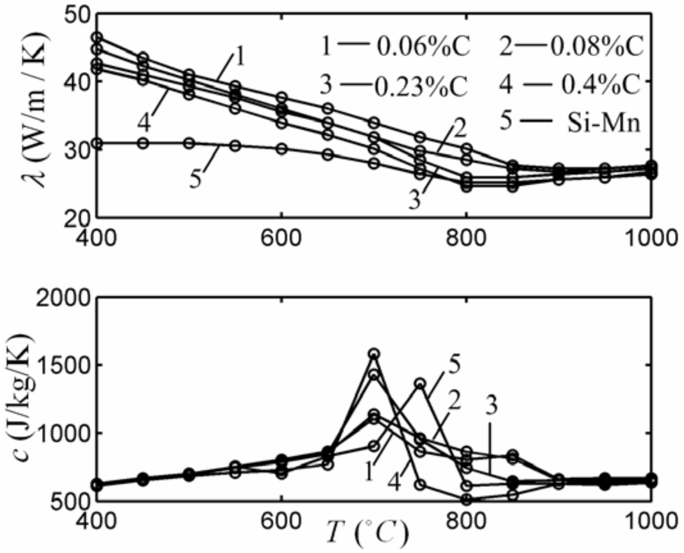

Figure 2. Characteristics of the thermal conductivity coefficients and specific heat capacities versus temperature with different kinds of steels [16]

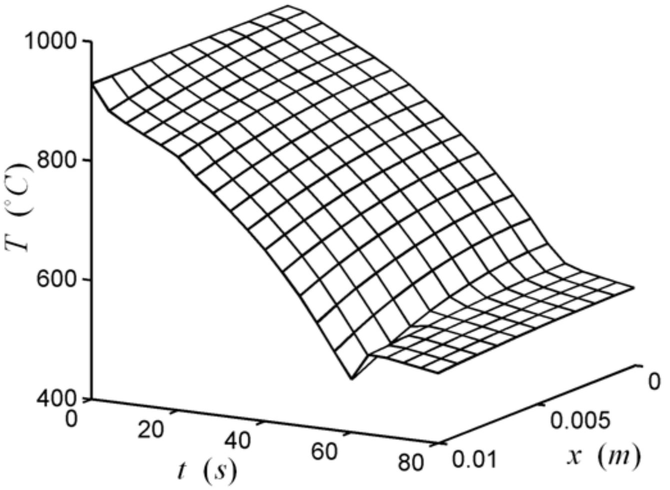

Figure 3. Three-dimensional diagram among T , t and x

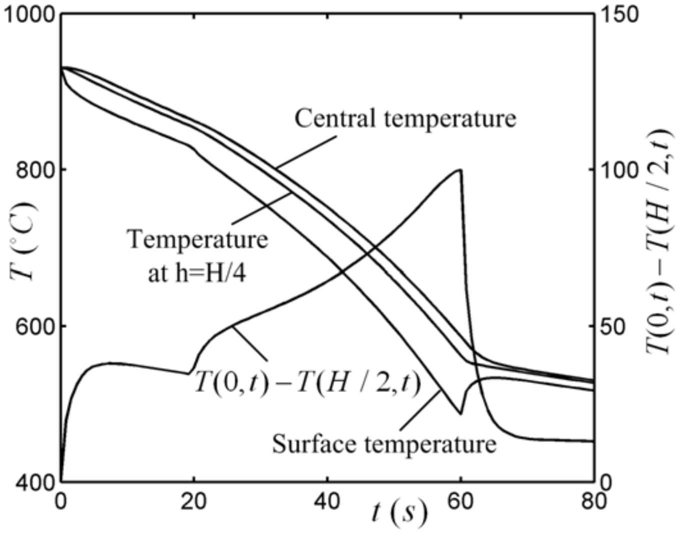

Figure 4. Temperature of the plate and temperature difference between the surface and centre

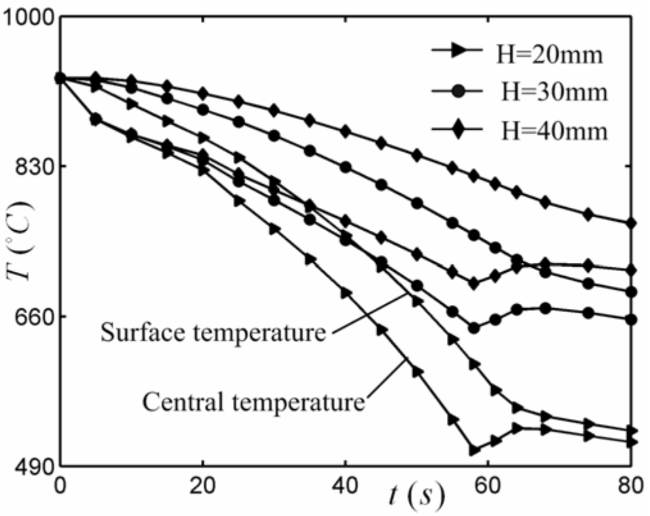

Figure 5. Effect of H on the characteristic of T versus t

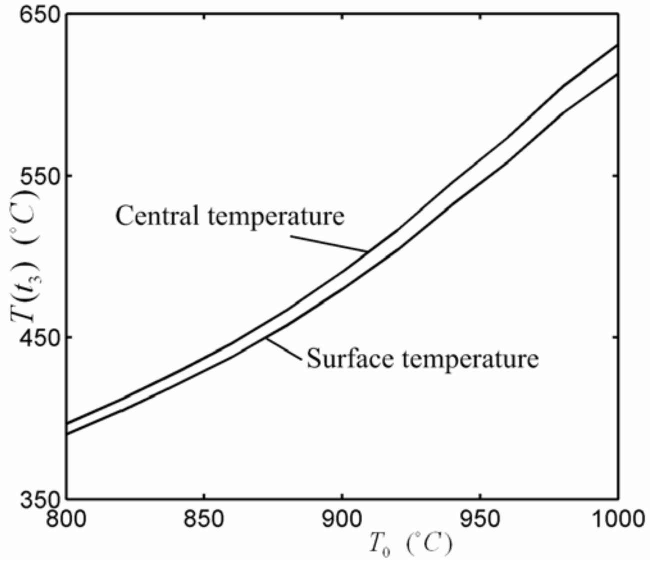

Figure 6. Characteristic of $T(t_3)$ versus T_0

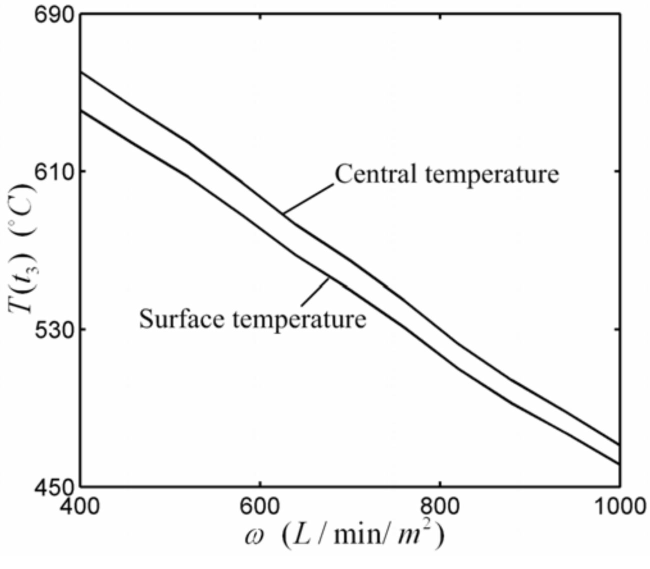

Figure 7. Characteristic of $T(t_3)$ versus w

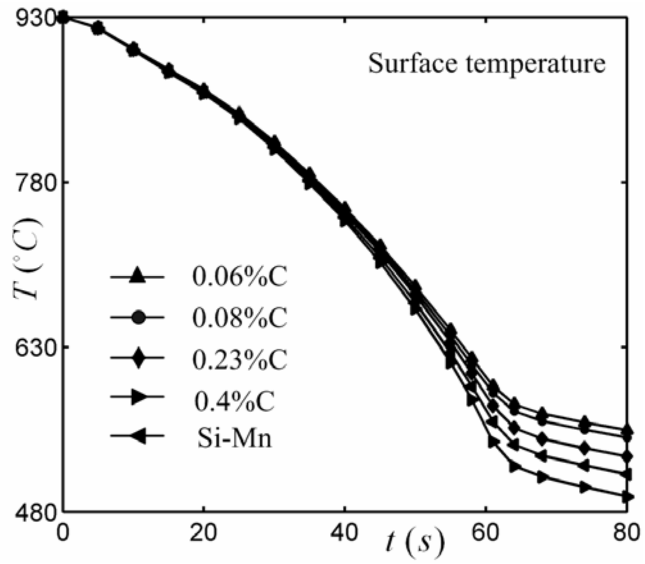

Figure 8. Effect of carbon content on the characteristic of T versus t

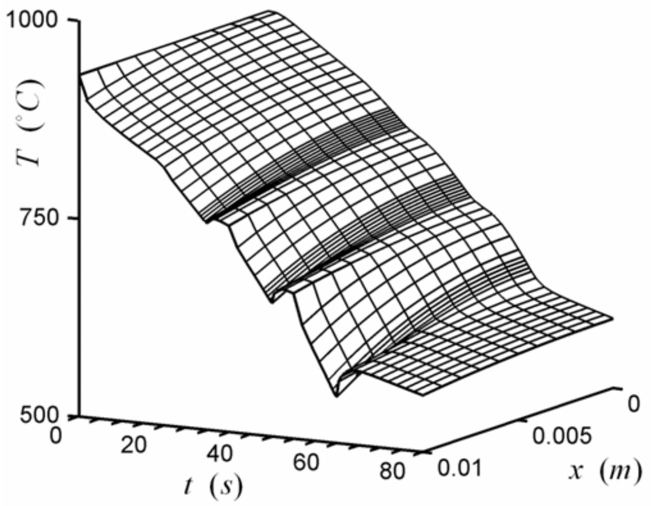

Figure 9. Three-dimensional diagram among T , t and x for intermittent cooling

Compared with the single water cooling stage, the intermittent cooling makes the temperature difference between the surface and centre of the plate be smaller; the temperature uniformity of the plate becomes better in this case, and the corresponding thermal stress be lower. Similar with Figs. 5-7, the effects of the plate thickness H , average water flow rate w, final rolling temperature T_0 and water cooling temperature T_∞ on the final temperature of the plate also can be given. The fitting equation of the final cooling temperature with respect to the plate thickness H , final rolling temperature T_0, cooling water temperature T_∞ and average flow rate w of the cooling water is given as following

$$T(H/2,80) = 70.779H^{0.0241}w^{-0.015}T_0^{0.509}T_\infty^{-0.00562}-1315.791 \quad (\mathrm{K}) \tag{8}$$

where $0.02 \le H \le 0.05\,(\mathrm{m})$, $400 \le w \le 1000\,(\mathrm{L/min/m^2})$, $1073 \le T_0 \le 1273\,(\mathrm{K})$ and $278 \le T_\infty \le 318\,(\mathrm{K})$. From Eq. (8), with the increases in the plate thickness H and final rolling temperature T_0 and the decrease in the average flow rate w, the final rolling temperature of the plate surface increase; the final rolling temperature T_0 has an obvious influence on the final rolling temperature of the plate surface, the plate thickness H and average flow rate w has the secondary influence, and the temperature T_∞ of the cooling water has little influence on this temperature. In the specified range of the final rolling temperature, Eq. (8) can provide some important guidelines for determinations of the optimal parameters (the plate thickness, final rolling temperature, cooling water temperature and average water flow rate) of the cooling system after plate rolling.

4. Conclusion

Based on numerical calculation with Matlab, the study on cooling process after plate rolling is carried out, and the temperature field distribution of the plate varying with the time is obtained. The effects of the plate thickness, final rolling temperature, cooling water temperature, average flow rate of the cooling water, carbon content of the plate and cooling method on the plate surface and central temperatures as well as final cooling temperature are discussed. The results show that the surface cooling rate of the plate at air cooling stage is $5.2\ \mathrm{K/s}$; this cooling rate at the laminar cooling process reaches to $8.5\ \mathrm{K/s}$, and the change of the surface temperature at this process is obvious; due to the heat transfer from the surface to the centre, the plate will experiences the self-tempering stage, the cooling rate at this stage is $1.5\ \mathrm{K/s}$, and the final cooling temperature of the plate is $517.2\ ^\circ\mathrm{C}$; during the laminar cooling stage, this temperature difference increases with the increase in cooling time; during the self-tempering stage, this temperature difference tends to be stable at a low value. For the same cooling time, with the increase in the plate thickness, the surface and central temperatures of the plate as well as the temperature difference between the surface and centre of the plate increase. With the decrease in final rolling temperature and the increase in average flow rate of the cooling water, the plate surface and central temperatures decrease. For the specified final cooling temperature, the optimal plate thickness H, final rolling temperature T_0, cooling water temperature T_∞ and average water flow rate w can be solved according to Eqs. (7) and (8). With the increase in the carbon content, the surface temperatures of the plate dot not always decrease. Compared with the single water cooling stage, the intermittent cooling makes the temperature difference between the surface and centre of the plate be smaller; the temperature uniformity of the plate becomes better in this case, and the corresponding thermal stress is lower. The results obtained in this paper can provide some important guidelines for the designs and operations of the cooling system after plate rolling.

The model in this paper is a one-dimensional transient problem, and the actual model of the cooling process is the three-dimensional one. The heat transfer coefficient at the air cooling and water cooling stages are empirical equations, which should be modified by feedback control. Therefore, one can consider a more complex cooling model after plate rolling. The cooling process after plate rolling is an important procedure in the production process of the plate casting and rolling. In this process, the temperature field of the plate and final cooling temperature are emphasized, the thermodynamic characteristic in the whole production process are rarely considered. The minimizations of the attenuation of the mass flux, of the temperature fluctuation of the materials flow as well as of the time-spatial domain of the materials flow are the core ideas of the minimum dissipation in the iron and steel production process [7]. Therefore, the next important work is to optimize the cooling process after plate rolling by combining the generalized thermodynamic optimization theory [21-41] and the idea of the minimum dissipation in the iron and steel production process.

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