Journal of Materials Processing Technology 187–188 (2007) 339–343

Journal of Materials Processing Technology

www.elsevier.com/locate/jmatprotec

Modelling of coupling flow and temperature fields in molten pool during twin-roll strip casting process

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Abstract

In twin-roll strip casting process, metal flow and temperature distribution in the molten pool directly affect the process stability and the quality of products. In this paper, a 3D coupling temperature-flow finite element method (FEM) simulation has been carried out and an inverse method was used to determine the boundary conditions between the roll and molten pool. For twin-roll casting of stainless steel, the influences of key processing parameters such as the pouring temperature and the height of liquid level on the temperature and flow fields are discussed. Calculated strip surface temperatures for different pouring temperatures are compared with the measured values, which shows they are in agreement.

Keywords: Twin-roll strip casting; Flow field; Temperature field; FEM simulation

1. Introduction

Twin-roll thin strip casting is a new technique which can produce a thin strip with a thickness of 1.0–6.0 mm directly from the liquidus steel. Twin-roll thin strip casting changes the traditional thin strip rolling significantly, making some production procedures, such as the continuous casting, heating and hot rolling become unnecessary and enabling the metal solidification and rolling deformation to occur simultaneously. The liquid metal experiences the plastic deformation during the solidification of twin-roll casting, and forms a solid strip in a short time [1]. Compared with the conventional thin strip casting, the twin-roll strip casting simplifies the production process significantly. It can save up to 70% equipment investment and 30–40% production cost. This technique can improve the microstructure of product, develop the products of new materials and produce the metallic products which have a hard formability and cannot be produced by a traditional method [2].

Twin-roll strip casting is a very complicated process, in which the heat transfer, solidification and plastic deformation [3,4] can be completed in less than 1 s, so it is very hard to find its formability just through several experiments. There are many reports about the influences of the processing parameters on the casting and rolling process [5–9]. However, most simulations were carried out through 2D model and only few focused on 3D model based on a lot of simplifications. This paper establishes a 3D coupling temperature-flow finite element method (FEM) simulation of twin-roll strip casting, studying the influence of the height of liquid level and pouring temperature on the temperature and flow fields in the molten pool. Simulation results can help us to control the twin-roll strip casting process and improve the quality of products in practice.

2. Mathematical model

The turbulent flow can be expressed by a general equation, and its variables are expressed by Φ.

$$\frac{\partial}{\partial t}(\rho C_{\Phi}\Phi)+\frac{\partial}{\partial x_k}(\rho u_k C_{\Phi}\Phi)=\frac{\partial}{\partial x_k}\left(\Gamma_{\Phi}\frac{\partial \Phi}{\partial x_k}\right)+S_{\Phi} \quad (1)$$

Table 1 presents the components of general equation. C_{Φ} is the coefficient of instant and convection item, Γ_{Φ} the coefficient of diffusion and S_{Φ} is the heat source.

$$\mu_{\text{eff}}=\mu+\mu_{\text{t}},\qquad \mu_{\text{t}}=\frac{\rho C_{\mu}k^2}{\varepsilon},\qquad K_{\text{eff}}=K_0+K_{\text{t}},$$
$$K_{\text{t}}=\frac{C_{\text{p}}\mu_{\text{t}}}{P_{\text{r}}} \quad (2)$$

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0924-0136/$ – see front matter
doi:10.1016/j.jmatprotec.2006.11.064

Table 1
Components of general equation

	Symbol			
	Φ	C_Φ	Γ_Φ	S_Φ
Continuous equation	1	1	0	0
Momentum equation in *x* direction	u_x	1	μ_{eff}	$\rho g_x - \frac{\partial P}{\partial x} + \frac{\partial}{\partial x}\left(\mu_{\mathrm{eff}}\frac{\partial u_x}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu_{\mathrm{eff}}\frac{\partial u_x}{\partial y}\right) + \frac{\partial}{\partial z}\left(\mu_{\mathrm{eff}}\frac{\partial u_x}{\partial z}\right)$
Momentum equation in *y* direction	u_y	1	μ_{eff}	$\rho g_y - \frac{\partial P}{\partial y} + \frac{\partial}{\partial x}\left(\mu_{\mathrm{eff}}\frac{\partial u_y}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu_{\mathrm{eff}}\frac{\partial u_y}{\partial y}\right) + \frac{\partial}{\partial z}\left(\mu_{\mathrm{eff}}\frac{\partial u_y}{\partial z}\right)$
Momentum equation in *z* direction	u_z	1	μ_{eff}	$\rho g_z - \frac{\partial P}{\partial z} + \frac{\partial}{\partial x}\left(\mu_{\mathrm{eff}}\frac{\partial u_z}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu_{\mathrm{eff}}\frac{\partial u_z}{\partial y}\right) + \frac{\partial}{\partial z}\left(\mu_{\mathrm{eff}}\frac{\partial u_z}{\partial z}\right)$
Energy equation	T	C_{p}	K_{eff}	Q_{v}
Turbulent energy equation	k		$\mu_{\mathrm{t}}/\sigma_k$	$\mu_{\mathrm{t}}\varphi - \rho\varepsilon$
Dissipation rate equation of turbulent energy diffusion	ε		$\mu_{\mathrm{t}}/\sigma_\varepsilon$	$C_1\frac{\varepsilon}{k}\mu_{\mathrm{t}}\varphi - C_2\frac{\rho\varepsilon^2}{k}$

where μ_{eff} is the effective coefficient of viscosity, K_{eff} the effective coefficient of heat conductivity, K_0 the coefficient of molecular heat conductivity, K_{t} the coefficient of turbulent heat conductivity, C_{p} the specific heat, T the temperature, ρ the density, Q_{v} the internal heat source. u_x, u_y and u_z are the velocity components in the x, y and z directions, respectively, g_x, g_y and g_z are the components of gravity acceleration, P_{r} is the Prandtl value of turbulent flow. In the simulation, the value of P_{r} is 1. According to Launder and Spalding, the values of five constants in the equation are as follows: $C_1 = 1.44$; $C_2 = 1.92$; $C_\mu = 0.09$; $\sigma_k = 1.0$; $\sigma_\varepsilon = 1.3$.

In twin-roll strip casting process, the arborescent crystal usually exits before solidification. Because the growth of arborescent crystal is determined by the cooling rate, the wall function is not suitable to treat the solidification practically. In order to overcome the disadvantage of the wall function, a low Reynolds number is used to treat the turbulent flow, in which the equivalent viscosity of liquid metal is the sum of the turbulent viscosity and laminar viscosity [10,11].

3. Boundary conditions

Inlet of the submerged nozzle:

$$V_x = 0, \qquad V_y = -V_{\mathrm{in}}\sin\alpha, \qquad V_z = V_{\mathrm{in}}\cos\alpha,$$
$$k = aV_{\mathrm{in}}^2, \qquad \varepsilon = \frac{k^{1.5}}{R} \tag{3}$$

where V_x, V_y, V_z are the velocity components in the x, y and z directions, respectively; α is the outlet angle of the side-hole, V_{in} the entry pouring velocity, ε the dissipation rate of turbulent energy diffusion, k the turbulent energy, and R is the hydraulic dimension of submerged nozzle.

The values of the turbulent energy and dissipation rate of the turbulent energy diffusion can be obtained from the semi-empirical equation according to the calculation of the entry pouring velocity V_{in} [12]. In the paper, a is 0.01. Zero-sliding condition is applied on all the walls of submerged nozzle, and the nozzle is assumed to be insulative. In addition, the diffusion energy and dissipation energy on the walls are assumed zero.

The temperature boundary of the entry area is,

$$T = T_0 \tag{4}$$

where T_0 is the temperature of liquid steel in entry area.

Surface of molten pool:

$$V_y = 0, \qquad \frac{\partial V_x}{\partial y} = 0, \qquad \frac{\partial V_z}{\partial y} = 0, \qquad \frac{\partial k}{\partial y} = 0, \qquad \frac{\partial \varepsilon}{\partial y} = 0 \tag{5}$$

Central symmetric surface:

$$V_z = 0, \qquad \frac{\partial V_x}{\partial z} = 0, \qquad \frac{\partial V_y}{\partial z} = 0, \qquad \frac{\partial k}{\partial z} = 0, \qquad \frac{\partial \varepsilon}{\partial z} = 0 \tag{6}$$

Axially symmetric surface of casting roll:

$$V_x = 0, \qquad \frac{\partial V_y}{\partial x} = 0, \qquad \frac{\partial V_z}{\partial x} = 0, \qquad \frac{\partial k}{\partial x} = 0, \qquad \frac{\partial \varepsilon}{\partial x} = 0 \tag{7}$$

Contact surface of molten pool and side dam:

$$V_z = 0 \tag{8}$$

In the simulation, the coefficient of heat transfer in the molten pool was 400 W/m^2 K. Side dam should be heated above 1000 °C before casting, and the temperature of side dam was assumed as a constant due to its poor heat transfer. In this study, the temperature of the side dam was 1000 °C. Turbulent energy k, and dissipation rate ε of turbulent diffusion energy on all solid boundaries were assumed zero. So, the node velocities contacting with the casting roll are:

$$V_x = V\sin\theta, \qquad V_y = -V\cos\theta, \qquad V_z = 0 \tag{9}$$

where V is the surface velocity of the casting roll, and θ is the angle between the horizontal plane and the line from the node to the axis of the casting roll.

In this work, the difficulty of treating the heat transfer boundary condition was solved through an inverse method, which considers both the experimental and simulation results. The average value of the heat transfer coefficient between the molten pool