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JOURNAL OF IRON AND STEEL RESEARCH, INTERNATIONAL. 2007, 14(5): 07-12, 30

Mathematical Model for Electroslag Remelting Process

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Abstract: A mathematical model, including electromagnetic field equation, fluid flow equation, and temperature field equation, was established for the simulation of the electroslag remelting process. The distribution of temperature field was obtained by solving this model. The relationship between the local solidification time and the interdendritic spacing during the ingot solidification process was established, which has been regarded as a criterion for the evaluation of the quality of crystallization. For a crucible of 950 mm in diameter, the local solidification time is more than 1 h at the center of the ingot with the longest interdendritic spacing, whereas it is the shortest at the edge of the ingot according to the calculated results. The model can be used to understand the ESR process and to predict the ingot quality.

Key words: electroslag; remelting; mathematical model; interdendritic spacing; local solidification time

Symbol List

C_1, C_2——Constants in κ-ε model;
C_d——Dissipation rate constant;
c_P——Specific heat;
d——Interdendritic spacing, m;
G——Generation term for turbulence kinetic energy;
g——Gravitational acceleration, $(m \cdot s^{-2})$;
H——Magnetic field intensity, $(A \cdot m^{-1})$;
$\tilde{H}$——Complex amplitude of H;
$\tilde{H}_r$, $\tilde{H}_\theta$, $\tilde{H}_z$——Magnetic field intensity in r, θ, and z direction, respectively;
h_{sw}——Overall heat transfer coefficient between slag and cooling water, $(W \cdot m^{-2} \cdot K^{-1})$;
$h_{w,i}$——Heat transfer coefficient of other position, $(W \cdot m^{-2} \cdot K^{-1})$;
I_0——Reference value of current, A;
J——Current intensity, $(A \cdot m^{-1})$;
$\tilde{J}$——Complex amplitude of J;
$\bar{\tilde{J}}_r$——Complex conjugation of $\tilde{J}$;
k_1, k_2——Coefficient, depending on steel grade;
k_{eff}——Effective thermal conductivity, $(W \cdot m^{-1} \cdot K^{-1})$;
Q_s——Rate of heat extraction from slag by metal droplets;
q_r——Radiant heat loss, J;
R——Radius, m;
r——Radial coordinate, m;
T——Temperature;
t——Time, s;
v_c——Solidification rate of ingot, $(m \cdot h^{-1})$;
v_r, v_z——Velocity of r and z direction, $(m \cdot h^{-1})$;
z——Axial coordinate, m;
z_S, z_L——Position of solidus and liquidus, m;
β——Coefficient of thermal expansion of slag;
ξ——Vorticity;
ψ——Stream function;
κ——Kinetic energy of turbulence;
ε——Dissipation rate of turbulence energy;
ρ——Density, $(kg \cdot m^{-3})$;
σ——Electrical conductivity, $(\Omega^{-1} \cdot m^{-1})$;
ω——Angular frequency of current, $(rad \cdot s^{-1})$;
μ——Viscosity of slag, $(Pa \cdot s^{-1})$;
μ_0——Magnetic permeability, $(H \cdot m^{-1})$;
μ_{eff}——Effective viscosity, $(Pa \cdot s^{-1})$;
μ_t——Turbulent viscosity;
Subscript
e——Electrode;
i——Ingot;
L——Metal pool;
m——Mushy zone;
s——Liquid slag.

Foundation Item: Item Sponsored by Weaponry Pre-Research Fund (51412020304QT0901)
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The ingot structure is a main objective to be controlled for electroslag remelting process, which determines the properties of the final steel products. A model for describing the ingot thermal field established in previous study[1] was not concerned with the thermal field of electrode, liquid slag, etc. However, all these thermal fields exist in the system, which should be considered in the model. As it is known, the electrode remelting process is a very complex system, involving electromagnetic fields, fluid flow phenomena, heat transfer, etc., which should be also considered in the simulation. The proper statement of the problem requires the definition of both the appropriate fluid flow equations and electromagnetic field equations. Ultimately these equations should be coupled with a heat-balance equation. In several earlier studies[2-5], the turbulent Navier-Stokes equations and thermal transfer equations were presented through the statement of Maxwell's equations, which described the velocity fields, electromagnetic fields, and temperature fields. In present study, a model involving electromagnetic fields, fluid flow, and thermal fields was established and temperature fields in the system was particularly emphasized as evaluation index of the model accuracy. Ballantyne[6] showed that the ingot structure is controlled by the local solidification time (*LST*) rather than by the pool profile. *LST* can never be obtained by measurement, but it can be achieved by calculation. However, till now, there is less model that can be used to calculate the *LST*. Moreover, *LST* in ingot can be used to calculate the interdendritic spacing, which is a criterion to assess an ingot quality. The purpose of the study is to establish predictive relationships among current input, pool profiles, *LST*, and interdendritic spacing for ESR process.

The study to be described is based on the following assumptions:

(1) Cylindrical symmetry about the centerline;

(2) Slag-electrode and slag-metal boundaries are presented by horizontal surfaces;

(3) Quasi-steady state;

(4) The effect of metal droplets on the motion of the slag is neglected;

(5) Voltage loss is only in the molten slag pool;

(6) Continuity of heat flux at all the external surfaces and at the slag-metal interface;

(7) The tip of the electrode is the liquidus temperature;

(8) The electrode and ingot are the infinite long conductor.

1 Mathematical Model

To calculate the temperature fields in the system, first, the Maxwell's equations to compute the electromagnetic force field and the turbulent Navier-Stokes equations to calculate the fluid flow should be solved. These equations influence each other. The physical concept used in the development of the mathematical model of the process is sketched in Fig. 1.

1.1 Transport equation for magnetic fields and boundary conditions

The magneto-hydrodynamic form of Maxwell's equations should be solved to calculate the electromagnetic force field. The transport equation for the magnetic field takes the following form at cylindrical symmetry[2,4,5,7,8]:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial \widehat{H}_\theta}{\partial r}\right)+\frac{\partial^2 H_\theta}{\partial z^2}=j\sigma\omega\mu_0\widehat{H}_\theta \tag{1}$$

where $j=\sqrt{-1}$, and the boundary conditions for Eqn. (1) are expressed using the following physical constraints:

$$\frac{\partial \widehat{H}_\theta}{\partial z}=0 \qquad (0\leqslant r\leqslant R_e,\ z=0);$$

$$\widehat{H}_\theta=\frac{I_0}{2\pi R_e} \qquad (r=R_e,\ 0\leqslant z\leqslant z_1);$$

$$\widehat{H}_\theta=\frac{I_0}{2\pi r} \qquad (R_e\leqslant r\leqslant R_m,\ z=z_1);$$

$$\widehat{H}_\theta=\frac{I_0}{2\pi R_i} \qquad (r=R_m,\ z_1\leqslant z\leqslant z_6);$$

$$\frac{1}{\sigma_e}\left(\frac{\partial \widehat{H}_\theta}{\partial r}+\frac{\widehat{H}_\theta}{r}\right)_e=\frac{1}{\sigma_s}\left(\frac{\partial \widehat{H}_\theta}{\partial r}+\frac{\widehat{H}_\theta}{r}\right)_s \qquad (r=R_e,\ z_1<z<z_2);$$

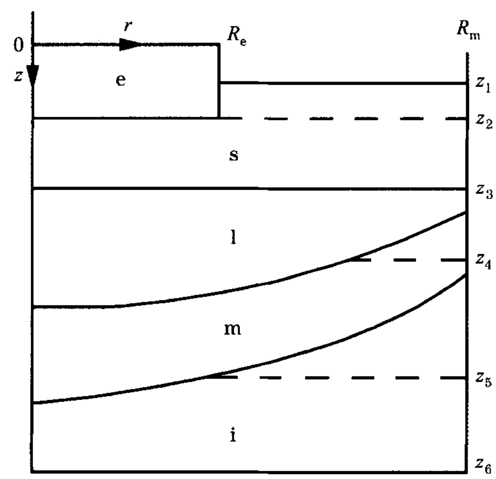

Fig. 1 Physical concept of process model