Development of EMBr/EMS Multifunction Mold

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Abstract

EMBr (ElectroMagnetic Brake) and in-mold EMS (ElectroMagnetic Stirring) have been developed to control molten steel flow in a continuous casting mold. EMBr is able to stabilize the molten flow in the mold. EMBr is usually used to prevent breakout during high speed casting of medium carbon steel. In-mold EMS is effectively to improve surface quality of the cast such as interstitial free steel by forced flow of the molten steel in front of initially solidifying shell. Suitable molten flow pattern in the mold is depends on its casting condition and components. However, ordinary electromagnetic device has only one function of EMBr or EMS, so a multifunction device which can be selected EMBr or EMS in the mold is desirable. It is difficult to obtain sufficient performance both EMBr and EMS in only one electromagnetic device because the necessary structure of them is different. EMBr needs to generate large magnetic flux density by large teeth of iron core. A lot of small teeth are necessary for EMS to generate travelling magnetic field along the mold side uniformly. The structure and current applied method of the EMBr/EMS multifunction mold has been developed by numerical analysis of electromagnetic field and fluid flow dynamics. The EMBr/EMS multifunction mold has been applied to Kashima No.3 CC.

Key words : EMBr, EMS, continuous casting, multifunction mold

1. Introduction

EMBr and EMS are used widely to control molten steel flow in a continuous casting mold. EMBr is used to prevent breakout during high speed casting of medium carbon steel, and EMS is suitable for casting of interstitial free steel by forced flow of the molten steel in front of initially solidifying shell. Suitable molten flow pattern in the mold is depends on its casting condition and components. However, ordinary electromagnetic device has only one function of EMBr or EMS, so a multifunction device which can be selected EMBr or EMS in the mold is desirable. We have been developed the EMBr/EMS multifunction mold by numerical analysis of electromagnetic field and fluid flow dynamics.

2. Numerical analysis

2.1 Electromagnetic field analysis

The equation of electromagnetic analysis applied Galerkin's method is given by the following equations:

\[ G_i = \int (\nabla \times \mathbf{N}_i) \cdot (\nabla \times \mathbf{A}) dV - \int \mathbf{N}_i \cdot \mathbf{J}_e dV + \int \mathbf{N}_i \cdot \sigma \left( \frac{\partial \mathbf{A}}{\partial t} + \nabla \Phi \right) dV \]

(1)

\[ G_{\Phi} = -\int \nabla \mathbf{N}_i \cdot \left( \sigma \left( \frac{\partial \mathbf{A}}{\partial t} + \nabla \Phi \right) \right) dV \]

(2)

\( G_i \) and \( G_{\Phi} \) are the residual at the \( i \)th edge and \( i \)th node, \( \mathbf{N}_i \) is the vector shape function, \( \mathbf{N}_i \) is the scalar shape function and \( V \) is volume of an element. \( \nu \) is magnetic reluctivity, \( \mathbf{A} \) is magnetic vector potential, \( \mathbf{J}_e \) is external current density, \( \sigma \) is electric conductivity and \( \Phi \) is magnetic electric scalar potential. Magnetic flux density vector \( \mathbf{B} \) is given by \( \mathbf{B} = \nabla \times \mathbf{A} \).

For the analysis of the induction heating using alternating current, it is useful to represent \( \mathbf{A} \) and \( \Phi \) as a complex number. Therefore, the derivative of \( \mathbf{A} \) with respect time is replaced by the \( j \omega \mathbf{A} \), where \( j \) is the imaginary number and \( \omega \) is the angular frequency. Then, eddy current density \( \mathbf{J}_e \), Joule heat \( Q \) and Lorentz force \( \mathbf{F} \) are given as following equations:

\[ \mathbf{J}_e = -j \omega \sigma \mathbf{A} \]

\[ Q = \frac{1}{2} \sigma |\mathbf{B}|^2 \]

\[ \mathbf{F} = \nabla \times (\sigma \mathbf{A}) \]

For the analysis of the electromagnetic field and fluid flow dynamics, the following equations are used:

\[ \nabla \cdot \mathbf{B} = 0 \]

\[ \nabla \cdot \mathbf{v} = 0 \]

\[ \nabla \cdot (\rho \mathbf{v}) = 0 \]

\[ \mathbf{v} = -\nabla \Phi \]

For the analysis of the fluid flow dynamics, the following equations are used:

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \]

\[ \frac{\partial \mathbf{v}}{\partial t} + \nabla \mathbf{v} \cdot (\rho \mathbf{v}) = -\nabla p + \nabla \cdot \mathbf{T} + \mathbf{F} \]

\[ \rho \mathbf{v} \cdot \mathbf{v} = \frac{1}{2} \nabla \cdot (\rho \mathbf{v}) + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) \]

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \]

\[ \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = -\nabla \mathbf{p} + \nabla \cdot \mathbf{T} + \mathbf{F} \]

\[ \nabla \cdot (\rho \mathbf{v}) = 0 \]

\[ \nabla \cdot (\rho \mathbf{v} \mathbf{v}) = 0 \]

\[ \mathbf{v} = 0 \]

\[ \mathbf{v} = 0 \]

\[ \mathbf{v} = 0 \]

\[ \mathbf{v} = 0 \]
\[ \mathbf{J}_* = -j\omega \mathbf{A} + \nabla \phi \]  \hspace{1cm} (3)\]

\[ Q = \frac{1}{2\sigma} \mathbf{J}_* \cdot \mathbf{J}_* \]  \hspace{1cm} (4)\]

\[ \mathbf{F} = \frac{1}{2} \text{Re}[\mathbf{J}_* \times \mathbf{B}] \]  \hspace{1cm} (5)\]

The symbol (*) denotes a complex number and (†) denotes a complex conjugate number.

After electromagnetic analysis, the structures of the multifunction mold had been designed as shown in Fig.1. The electromagnetic device of the multifunction mold has four iron teeth on wide side of the mold. Each iron tooth has an inner coil and an outer coil is wound over two iron teeth and two inner coils. Fig.2 shows applied current patterns for the multifunction mold. Direct current is applied for EMBr mode, and the two iron teeth wound by the outer coil are magnetized same direction as Fig.2(a). For EMS mode, 3-phase (U,V,W) alternating current are applied as shown in Fig.2(b) and travelling magnetic field and Lorentz force are generated in the molten steel. It is feature of the multifunction mold of EMS mode that Lorentz force at meniscus of the molten steel is max to obtain uniform stirring at the meniscus.

In the case of EMBr, magnetic flux density at the mold center of thickness needs over 0.3 T during high speed casting. Fig.4 shows dependence of magnetic flux density on the teeth width at the center of mold thickness. It is easy to generate large magnetic flux density by large teeth of iron core, but the large teeth are not suitable for EMS to generate travelling magnetic field. Teeth size were decided by minimum width to generate magnetic flux density over 0.3 T.

2.2 Heat transfer and Fluid flow analysis

The governing equations of incompressible fluid flow analysis are written by the continuity and Navier-Stokes equations with Boussinesq approximation and LES (Large Eddy Simulation) model [1]:

\[ f'_{g} + f_{1} + f_{s} = 1 \]  \hspace{1cm} (6)\]

\[ \frac{\partial f_{s}}{\partial t} + \nabla (f_{s} \mathbf{U}_s) = 0 \]  \hspace{1cm} (7)\]
\[ \frac{\partial f_s}{\partial t} + \nabla (f_s \mathbf{U}_i) = -Rs \]  
\[ \frac{\partial f_s}{\partial t} + \nabla (f_s \mathbf{U}_i) = Rs \]  
\[ \rho_s \frac{D \mathbf{U}_s}{Dt} = \rho_f \frac{D \mathbf{U}_f}{Dt} + \frac{1}{2} \rho_f \left( \frac{D \mathbf{U}_f}{Dt} - \frac{D \mathbf{U}_s}{Dt} \right) - \frac{3 \mu_t}{4d} \operatorname{Re}_g C_{D_{sg}} (\mathbf{U}_s - \mathbf{U}_f) + (\rho_i - \rho_g) \mathbf{g} \]  
\[ \frac{\partial (f_i \rho_i \mathbf{U}_i)}{\partial t} + \nabla \cdot (f_i \rho_i \mathbf{U}_i \mathbf{U}_i) = \nabla \cdot \left( \frac{1}{2} f_i (\mu_i + \mu_t) (\nabla \mathbf{U}_i + \nabla \mathbf{U}_i^T) \right) - f_i \nabla P + f_i \left( \beta(T_i - T_0) \rho_g + \gamma (\mathbf{U}_i - \mathbf{U}_f) + \mathbf{F}_{\text{ele}} + \mathbf{F}_{\text{gas}} \right) \]  
\[ \frac{\partial T}{\partial t} + \nabla \cdot (f_i T \mathbf{U}_i + f_s T \mathbf{U}_s) = \frac{1}{\rho_C} \left( \nabla \cdot (\lambda_1 + \lambda_2) \nabla T \right) + \rho_s (\Delta H) \]  
\[ f_s = \frac{(T_i - T_0)/m_i}{(T_i - T_0)/m_i + (T_f - T_0)/m_f} \]  
\[ \operatorname{Re}_g = d_g \frac{\| \mathbf{U}_i - \mathbf{U}_g \|}{\rho_i / \mu_i} \]  
\[ C_{D_{sg}} = 0.4 + \frac{24}{\operatorname{Re}_g} + 6/(1 + \sqrt{\operatorname{Re}_g}) \]  
\[ \mu_t = \rho_f (C_{\text{cell}} \Delta T/4) / \mu_l \]  
\[ \gamma = \frac{150 \mu_t}{f_i \rho_i (\Delta_T/4)^2} \]  
\[ \mathbf{F}_{\text{gas}} = f_s \frac{3 \mu_t}{4d_g} \operatorname{Re}_g C_{D_{sg}} (\mathbf{U}_g - \mathbf{U}_f) \]  

Here \( f \) is volume fraction, \( \mathbf{U} \) is velocity vector, \( Rs \) is volumetric solidification rate, \( \rho \) is density, \( \mu \) is viscosity, \( d \) is diameter, \( g \) is gravity vector, \( \beta \) is coefficient of thermal expansion, \( P \) is pressure, \( T \) is temperature, \( T_0 \) is average temperature of the fluid, \( F_{\text{ele}} \) is Lorentz force density vector, \( \lambda \) is thermal conductivity, \( \Delta H \) is latent heat, \( m_i \) is liquidus slope, \( m_s \) is solidus slope, \( T_i \) is liquidus temperature, \( T_s \) is solidus temperature, \( \mu_t \) is turbulence viscosity of LES, \( S \) is velocity gradient tensor, \( D_2 \) is secondary dendrite arm interval. Subscripts \( l \), \( s \) and \( g \) indicate liquid phase, solid phase and gas phase.

Finite volume method[2] and SMAC method[3] is used to solve these equations and second-order central scheme is used for viscous and convective term with time marching method. The solidification temperature is calculated by lever rule and turbulent Prandtl number is equal to 1. Gas bubble is assumed incompressible and dispersed phase, shape is spherical and diameter is not changed. Momentum equation of gaseous phase is subject to Basset-Boussinesq-Oseen-Tchen equation[4]. How ever Basset term was neglected.

Fig. 5 shows velocity and temperature distribution of molten steel in the multifunction mold by fluid flow analysis using LES model. In the case of EMS, velocity in front of initially solidifying shell needs over 0.15 m/s to prevent capturing inclusions and bubbles into the solidification shell [5]. Flow pattern in the multifunction mold of EMBr mode is not much different from its in ordinary EMBr mold.

![Fig. 5. Velocity (m/s) and temperature (degree Celsius) distribution.](image-url)
3. Experimental result

Fig. 6 shows velocity distribution at solidification interface along wide side of the mold. Experimental velocity was evaluated from deflection angle of dendrite [6]. The stirring velocity in the multifunction mold of EMS mode is over 0.2-0.3 m/s measured from deflection angle of dendrite [5].

4. Conclusion

EMBr/EMS multifunction mold has been developed by numerical analysis. It has enough ability to generate magnetic flux density over 0.3 T for EMBr mode as same level as ordinary EMBr mold. And it obtains over 0.2 m/s stirring velocity for EMS mode enough to prevent capturing inclusions and bubbles into the solidifying shell. In this mold, EMBr/EMS mode is could be selected easily during casting for its condition and components. The EMBr/EMS multifunction mold has been applied to Kashima No.3 Caster now.

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