B. WANG, Z. G. YANG, X. F. ZHANG, Y. T. WANG, C. P. NIE, Q. LIU, H. B. DONG

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ANALYSIS OF THE EFFECTS OF ELECTROMAGNETIC STIRRING ON SOLIDIFICATION STRUCTURE OF BEARING STEEL

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In the current study, a 260 mm × 300 mm bloom mould was investigated, on which a method combining finite element and finite volume methods was applied to study the impacts of electromagnetic stirring on molten steel flow and heat transfer, and then the solidification structure of steel was tested. The obtained simulation results pertaining to magnetic fields were consistent with the onsite measured data. For the 260 mm × 300 mm bloom continuous casting of bearing steel, the appropriate value of current intensity of electromagnetic stirring was found to be 300 A.

Key words: bearing steel, bloom, continuous casting, electromagnetic stirring, solidification structure

INTRODUCTION

The ability of electromagnetic stirring to improve bloom quality has been recognized by the metallurgists. Electromagnetic stirring improves the equiaxed crystal *ratio* of blooms, as well as improves centre segregation by controlling the movement of molten steel, thereby affecting its heat and mass transfer [1]. Owing to the complexity of the continuous casting process, it is relatively difficult to measure the flow of molten steel in moulds through actual measurement and research. Therefore, numerical simulation is very necessary. In 1986, Spitze [2] and others used a numerical simulation method to study molten steel flow in a round billet mould under electromagnetic stirring; they discovered and focused on researching a second flow phenomenon. Their simulation results have been validated through experimental observations. Dubke [3,4] and others used the average depth approach to study a three-dimensional flow field in a rectangular slab under electromagnetic stirring. In the next few decades, domestic and international scholars conducted numerous simulation and experimental studies on continuous casting involving electromagnetic stirring [5-11]. However, these researchers mostly focussed only on the flow field distribution of molten steel under electromagnetic stirring, even though they investigated the temperature field distribution under electromagnetic stirring, they did not consider the impact of solidification on the flow field. Research for the three-dimensional flow of molten steel in the bloom mould with electromagnetic stirring has been actively pursued; however, research on solidification coupling calculations has rarely been reported.

In this study, electromagnetic stirring was carried out on a 260 mm × 300 mm bloom mould fabricated in a steel plant. A method combining numerical simulation and field measurement was employed to investigate the flow and solidification of molten steel in the mould. On the basis of the obtained results, the impacts of current intensity on the flow field and temperature field are discussed.

COMPUTATIONAL MODEL

Mathematical formulation

The three-dimensional (3D) incompressible fluid flow in continuous casting mold was modeled by calculating the continuity equation and momentum equation, using k - ε turbulent model. The energy control equation was used to calculate the heat transfer and solidification in the mold. The electromagnetic field formula for mold electromagnetic stirring includes Faraday law of electromagnetic induction, Ampere circuit law, Gauss law for magnetic fields, Ohm law, and constitutive equation. More details are available elsewhere [8-11].

Computational domain and boundary conditions

The geometry and the mesh system are shown in Figure 1. In order to reduce the impact of outlet reflux on calculations, the computational domain is extended to 2 000 mm. All the grids are divided into hexahedrons. The steel grade of this simulation is GCr15 bearing steel, and the main dimensions and parameters for the continuous casting process in the current study are listed in Table 1.

B. Wang, Z. G. Yang, X. F. Zhang, Y. T. Wang, C. P. Nie, Q. Liu, State Key Laboratory of Advanced Metallurgy, University of Science and Technology Beijing, Beijing, China
Z. G. Yang, Special Steel Plant, Laiwu Iron & Steel Co. Ltd., Laiwu, China
B. Wang, H. B. Dong, Department of Engineering, University of Leicester, Leicester, UK

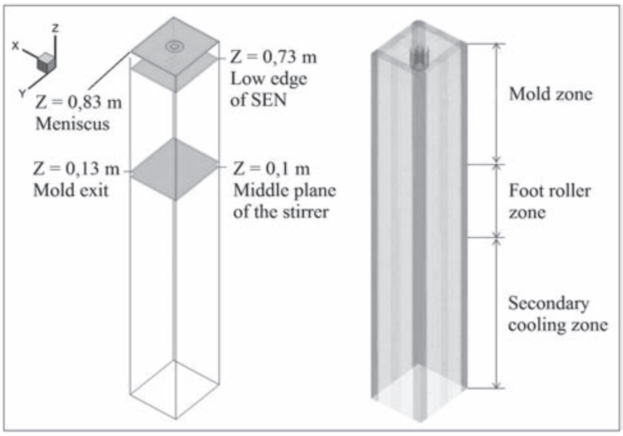

Figure 1 Geometric model of mold and mesh systems

For the calculation of electromagnetic fields, three-phase AC power is supplied to the coil windings. The boundary difference of each current phase is 120 degree. The boundary conditions for the magnetic field calculation is flux-parallel boundary condition.

For calculating the flow field and temperature field, the specific boundary conditions are as follows:

(1) Nozzle inlet: Inlet velocity is adopted. The temperature is the casting temperature of molten steel.

(2) Free surface: The free surface is defined as non-shear force adiabatic surface.

(3) Nozzle wall: The no-slip insulated adiabatic surface is adopted.

(4) Outlet of computational domain: The outflow boundary condition is adopted.

(5) Surface of mould and extension: The no-slip insulated surface is employed.

Table 1 **Main dimensions and parameters**

Parameter	Value
Mold cross section / mm × mm	260 × 300
SEN bore diameter / mm	36
SEN depth from the meniscus / mm	100
Copper mold height / mm	800
Casting speed / m·min^{-1}	0,55
EMS position from the top of mold to the stirrer midplane / mm	830
EMS coil current density / A	0 - 300
Density of molten steel / kg·m^{-3}	7 000
Viscosity of liquid steel / kg·m^{-1}·s^{-1}	0,0055
Specific heat of liquid steel / J·kg^{-1}·K^{-1}	811
Steel thermal conductivity / w·m^{-1}·K^{-1}	29,7
Liquidus temperature / K	1 729
Solidus temperature / K	1 607
Casting temperature / K	1 749

The coupling approaches

The simulation is divided into two stages: the calculation of the magnetic field and the calculation of the flow and temperature fields. First, ANSYS software and the Edge-based method are used to obtain the magnetic field distribution of the bloom under electromagnetic stirring. Then, the magnetic field data are compiled to a file format required by FLUENT software through self-programming, and is imported via a file to the MHD module of FLUENT. Three-dimensional coupling calculations for the magnetic, flow, and temperature fields are then carried out.

RESULTS AND DISCUSSIONS

Model validation

In order to verify the accuracy of the model, the magnetic field distribution of the mould is simulated under the no load condition at a current intensity of 200 A, and the magnetic induction intensity on the central axis lines of the mould electromagnetic stirring device is measured using a gauss meter (Model-5180, American Bell). The comparison of the measured and calculated values is showed in Figure 2. From Figure 2, it can be seen that the changing trend in calculated and measured values is consistent. The peak value of magnetic induction intensity does not appear at the centre of the stirrer.

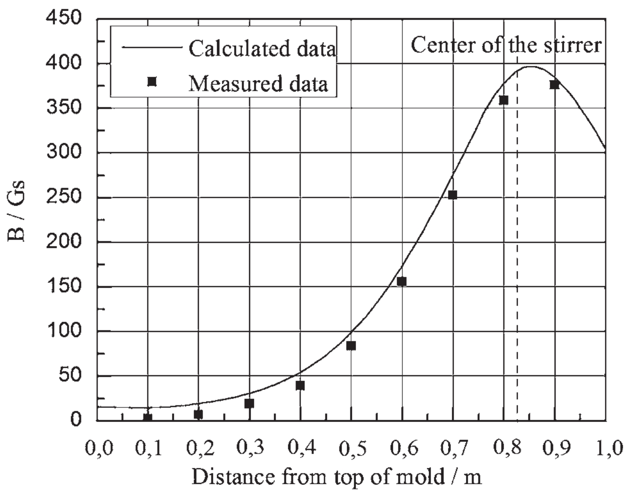

Figure 2 Comparison of the calculated and measured data along the axial direction in the center of stirrer

Effects of electromagnetic stirring on flow pattern

Figure 3 gives the distribution of velocity vector at the central cross section of the stirrer. From Figure 3, it can be seen that after applying electromagnetic stirring, the molten steel flow field has significant changes. Without electromagnetic stirring, the molten steel that is not solidified yet on the horizontal section of the mould showed only radial velocity from the centre toward the outside, as shown in Figure 3a. After applying electromagnetic stirring, the tangential electromagnetic force causes the molten steel to swirl in a rotating manner in the horizontal direction, as shown in Figure 3b.

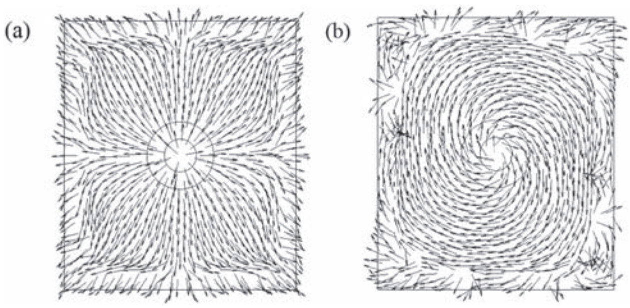

Figure 3 Distribution of velocity vector on *x-y* plane at $z = 0,1$ m: (a) without M-EMS; (b) with M-EMS ($I = 300$ A)

The rotational flow of molten steel could clean the solidification front, break columnar crystal tips, and promote the formation of equiaxed crystals.

Effects of electromagnetic stirring on the characteristics of solidification structure

Figure 4 gives the liquid phase distribution on the cross section at the mould outlet under different current intensity. The impact of electromagnetic stirring on the solid zone distribution at the mould outlet is not apparent. However, the liquid zone at the outlet cross section of the mould expands when current intensity increases. The main reasons for this are as follows. With increasing current intensity, the tangential and radial electromagnetic forced upon molten steel increases. The tendency of molten steel to move in all directions becomes stronger, and more amount of high-temperature molten steel moves outward. The liquid region at the mould outlet expands when the temperature of molten steel became uniform.

In order to get good metallurgical results, it is necessary for electromagnetic stirring to reach a certain level

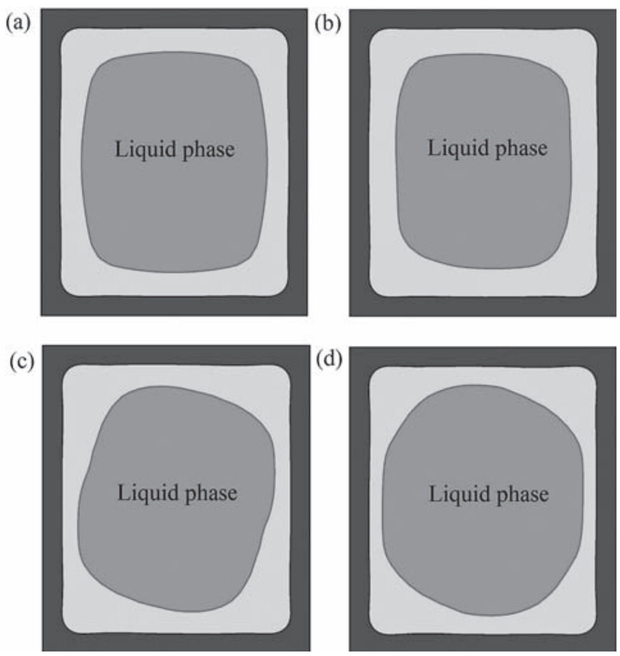

Figure 4 Distribution of liquid phase on *x-y* plane at $z = 0,13$ m for different current intensity: (a) 0 A; (b) 100 A; (c) 200 A; (d) 300 A

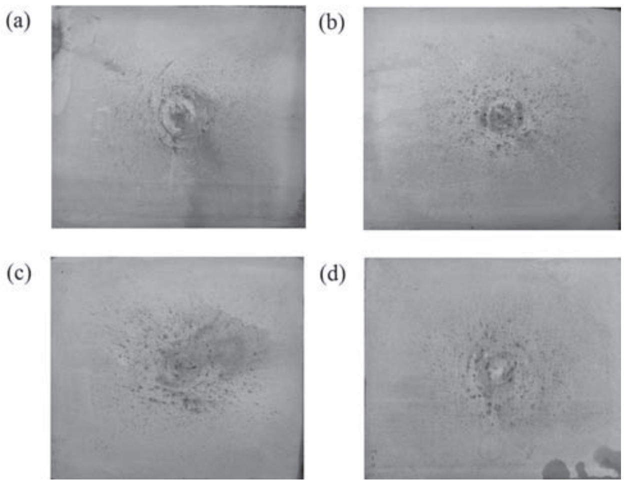

Figure 5 Effect of current intensity on the macrostructure of bearing steel: (a) 0 A; (b) 100 A; (c) 200 A; (d) 300 A

of stirring intensity to produce sufficient shearing force to break columnar crystal. Extensive practices and theoretical analysis indicate that the maximum speed of electromagnetic stirring should be maintained within the range 0,3 $m \cdot s^{-1}$ - 0,6 $m \cdot s^{-1}$ for blooms [12].

Through the above theoretical analysis, it can be found that when the current intensity is 300 A, M-EMS can meet the requirements of stirring intensity. Then the field test is carried out to verify the theoretical results. The central equiaxed crystal ratio and carbon segregation on the bloom cross section are measured, the method is as follows:

(1) Central equiaxed crystal ratio. According to the standard of GB 226-1991, the casting blooms taken from the same conditions were put into hydrochloric acid, heated to 60 - 80 ºC, and kept for 25 - 30 min. The macrostructure of the blooms would be emerged after washing and drying and then the equiaxed crystal ratio was calculated (Equiaxed crystal ratio = Area of the equiaxed crystal zone / Area of bloom section × 100 %).

(2) Carbon segregation. Drilling and sampling test technique was applied to measure the carbon segregation index on the cross section of bearing steel bloom.

Figure 5 shows the macroscopic structure of cross section under different current intensity at the frequency of 3 Hz. From Figure 5, it can be seen that as the current intensity increases, the central porosity and central shrinkage of the bloom gradually subsides. The internal quality of the bloom is also improved.

Figure 6 shows the impact of current intensity on the central equiaxed crystal ratio of continuous casting steel at different current intensity. From Figure 6, it can be discovered that when the current intensity is 300 A, the central equiaxed crystal ratio of the bloom is 26,2 %. It is an increase of 10 % compared to when the electromagnetic stirring is not used. The enhancement in the equiaxed crystal ratio is good for the refinement of solidified structure and improving the centre segregation.

The distribution of carbon segregation on the bloom cross section is given in Figure 7. When electromag-

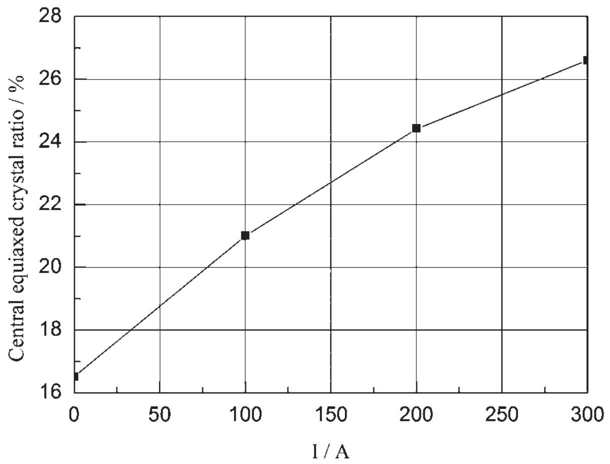

Figure 6 Effect of current intensity on central equiaxial crystal ratio of bearing steel

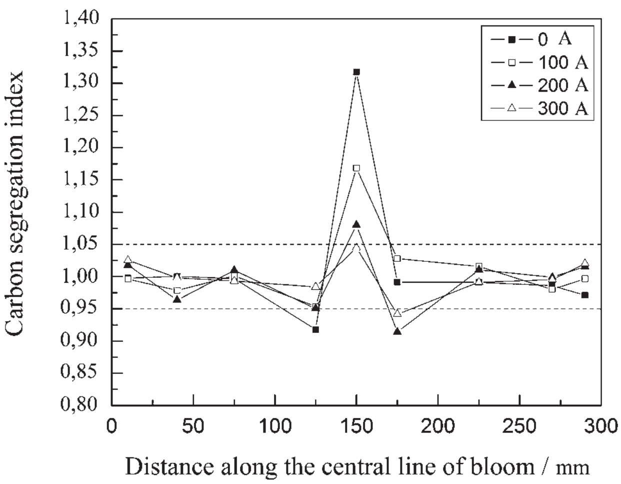

Figure 7 Effect of current intensity on distribution of carbon segregation

netic stirring is not used, the carbon segregation index at the bloom centre is 1,34. When the current intensity is 300 A, the central carbon segregation index of the bloom is 1,04 and the carbon segregation index of the bloom cross section is within the range 0,95 - 1,05. The macrosegregation of carbon has been definitely improved.

CONCLUSIONS

A method that is a combination of the finite element method and finite volume method is used to investigate the impact of electromagnetic stirring on flow and solidification of molten steel in a mould, and the simulation results was verified by field tests.

Under the effect of electromagnetic stirring, molten steel flows in rotation on a horizontal cross section; the liquid region at the outlet cross section of the mould expands with current intensity increasing.

For the 260 mm × 300 mm bloom continuous casting of GCr15 bearing steel, when the current intensity is 300 A of M-EMS, the central equiaxed crystal ratio increases by 10 % compared to when electromagnetic stirring is not applied. The carbon segregation index of the bloom cross section is within the range 0,95 - 1,05. Therefore, electromagnetic stirrer can achieve the aim of increasing equiaxed crystal ratio and improving carbon macrosegregation index very well.

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