Development and Application of Final Permanent Magnet Stirring during Continuous Casting of High Carbon Rectangular Billet

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Production of continuously cast high carbon steel that very low center macrosegregation is an important object in meeting high quality requirements. Apart from the widely known methods of reducing macrosegregation during continuous casting, final permanent magnet stirring (FPMS) provides an alternative for producing steel with low macrosegregation. The permanent magnet stirring featuring with low power dissipation and high intensity of magnetic field, which is suitable for final stirring conditions. In the present research, a three-dimensional unsteady coupled mathematical model based on the electromagnetic field analysis software Opera-3D and the flow field software Fluent has been developed to analysis the magnetic flux density, the electromagnetic force and the molten steel flow under different stirring frequencies of FPMS. The calculated results in the residual liquid pool show that the center magnetic flux density is nearly invariable equals to 1 335 Gs, the maximum electromagnetic force increases from 12 kN/m to 59 kN/m and the maximum tangential velocity in the width direction various form 0.09 m/s to 0.45 m/s as the stirring frequency increases from 1 Hz to 5 Hz. The industrial trials reveal that the FPMS with a stirring frequency of 5 Hz can effectively decrease the centre carbon segregation and improve the final product quality of high carbon steel.

KEY WORDS: continuous casting; final permanent magnet stirring; stirring frequency; flow velocity; center carbon macrosegregation.

1. Introduction

There have been various technologies to reduce the detrimental center carbon segregation in high carbon continuous casting, such as low temperature casting, mold electromagnetic stirring, thermal soft reduction, mechanical soft reduction, large reduction and final electromagnetic stirring.1–3) The continuous casting of high carbon 82A steel with a section size of 180 mm × 240 mm has been improved considerably by low temperature casting and proper using of final electromagnetic stirring (FEMS), but their center carbon segregation appears not to be enough to satisfy customer’s demand for best quality. Center segregation in high carbon steel results in a high concentrations of chemical components especially carbon element and has great influence on the quality of final product.4,5) Therefore, on account of the very important potential for industrial applications, the final permanent magnet stirring (FPMS) was invented in order to reduce the center carbon macrosegregation of the middle size rectangular billets.

However, very little fundamental work has been reported in permanent magnet stirring especially for continuous casting process. Vives6,7) developed an electromagnetic device, which is based on the use of rotating permanent magnets and which allows the production of intense three-dimensional multiphase flows in solidifying semisolid alloy slurries. Besides, Vives considers this process can be applied to the direct continuous casting of billets and slabs and is characterized by very low electric power consumption. In the present FPMS device, the permanent magnets are driven by hydraulic system with different rotation speeds and that produced a rotating magnetic field. The magnetic field depends on the permanent magnet materials and high-magnetic flux density can be achieved with a strong magnetic materials. The permanent magnet stirrer is characterized as low power dissipation, low operating frequency and high intensity of magnetic field.

Magnetohydrodynamic (MHD) simulation is one of the useful and practicable tools for studying the motion behavior of molten steel during electromagnetic stirring process. Fujisaki et al.8–10) developed a three dimensional numerical model to simulate the magnetic field characteristics in continuous casting with M-EMS. Spitzer et al.11) developed a two-dimensional model for calculating the electromagnetic force (EMF) distribution in a round billet with M-EMS and Song et al.12) developed a 3D model for the numerical simulation of magnetic field and molten steel flow in billet continuous casting with S-EMS. However, the simulation calculation of FPMS has not previously reported in literature.
especially in continuous casting process.

The main goal of this work is to develop a 3D model to simulate the magnetic field characteristics and flow field characteristics with FPMS. The electromagnetic field analysis software Opera-3D is specialized in calculating static or time varying magnetic fields with a finite element environment for the complete analysis and design of electromagnetic applications in 3 dimensions and the flow field software Fluent is used to calculate the fluid flow velocity in different magnetic forces. So, a three-dimensional unsteady coupled mathematical model based on the above two software has been developed to calculate the magnetic field, the electromagnetic force and the molten steel flow under different stirring frequencies of FPMS. Besides, an industrial plant trial is conducted to verify the calculated results and investigate the influence of FPMS on the inner quality of high carbon 82A steel.

2. Development of Final Permanent Magnet Stirring

2.1. Principle of Final Permanent Magnet Stirring

The FPMS is based on the use of rotating permanent magnets which allows the production of intensive stirring in the residual liquid pool during solidification process. Different form the inductive system of FEMS which is mainly comprises of induction coil fed with low-frequency current, the system of FPMS is inductively stirred using permanent magnets rotor driven by hydraulic system. The measured value of magnetic intensity in FPMS is about 1 350 Gs. Figure 1 shows the diagrammatic sketch of the final permanent magnet stirring and there are two permanent magnets in the device. The rotor is driven, with an angular velocity \( w \), by an adjustable speed motor through a hydraulic system permitting gradual variations of the speed ranging from 0 to 350 r/min. The relation between the inlet oil pressure and the rotation speed of permanent magnet is depicted in Fig. 2. As can be seen from Fig. 2 that the rotation speed increases by 20 r/min as the inlet oil pressure increases by 1.0 MPa.

When the permanent magnet rotates, each point of the molten metal is subject to a variable magnetic field which generates induced electric currents. The molten metal is set in rotation by electromagnetic body forces due to the interaction of electric current and magnetic field. The working principle of permanent magnet stirrer is explained for the case of rotational stirring frequency with different inlet oil pressures. The relation between the stirring frequency and the rotation speed of permanent magnet is expressed by Eq. (1).

\[
N = 60f / P \quad \text{.......................... (1)}
\]

where \( f \) is the stirring frequency, Hz; \( P \) is the number of poles; \( N \) is the rotation speed of permanent magnet, r/min.

Figure 3 demonstrates the relation between the inlet oil pressure and the stirring frequency of permanent magnet stirrer. In Fig. 3, the stirring frequency changes from 0 to 5 Hz as the inlet oil increases from 0 to 16 MPa and different stirring frequencies can be obtained by varying the inlet oil pressure.

2.2. Modeling of Final Permanent Magnet Stirring

2.2.1. Mathematical Model

In the mathematical model, Maxwell’s equations and Navier–Stokes equation are used to calculate the electromagnetic field in the conducting region and the flow field driven by the electromagnetic force, respectively. Electromagnetic field and fluid flow are coupled in order to calculate the interaction of the multiphysics fields during this process and the following assumptions are made to simplify the mathematical model.

(i) The molten steel flow in the center of rectangular billet is an incompressible and viscosity flow process.

(ii) The influences of the solidified shell and the mushy zone on the molten steel flow are not considered and the temperature distribution of liquid core is ignored.

The electromagnetic field distributions in rectangular billet including the magnetic flux density and the induced current density are obtained by solving Maxwell’s equations, which are shown as Eq. (2). The electromagnetic volume force density is defined as Eq. (3).
\[ \nabla \cdot \vec{B} = 0 \]
\[ \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \] ...........................(2)
\[ \nabla \times \vec{H} = \vec{j} + \frac{\partial \vec{D}}{\partial t} \]
\[ \vec{F} = \vec{j} \times \vec{B} \] ...........................(3)

where \( \vec{H} \) (A/m) is the magnetic field intensity; \( \vec{j} \) (A/m\(^2\)) is the induction current intensity; \( \vec{D} \) (C/m\(^2\)) is the electric displacement vector; \( \vec{E} \) (V/m) is the electric field intensity; \( \vec{B} \) (T) is the magnetic flux density; \( \vec{F} \) (N/m\(^3\)) is the electromagnetic force per unit volume.

Continuity equation and Navier-Stokes equation have been used to describe the flow field of remained molten steel in rectangular billet.

Continuity equation:
\[ \nabla \cdot \vec{V} = 0 \] ...............................(4)

Navier-Stokes equation:
\[ \rho \mu \frac{\partial \vec{V}}{\partial t} + \nabla \cdot \vec{P} = \rho \vec{g} + \vec{F}_M + \vec{F}_{other} \] ..........................(5)

where \( \rho \) (kg/m\(^3\)) is the density of steel; \( \vec{V} \) (m/s) is the velocity of steel; \( P \) (Pa) is the pressure; \( \mu \) is the effective viscosity, which is equal to the sum of turbulent viscosity (\( \mu_t \)) and kinetic viscosity (\( \mu_k \)); \( \vec{g} \) (m/s\(^2\)) is the acceleration of gravity; \( \vec{F}_M \) (N/m\(^3\)) is the time averaged electromagnetic force and \( \vec{F}_{other} \) (N/m\(^3\)) is the other interaction force.

2.2.2. Magnetic Flux Density of FPMS

The system structure of a 3D rectangular billet with FPMS is shown in Fig. 4(a). The FPMS is composed of 3 parts: two permanent magnets, a hydraulic system and a cooling system. In the model, the hydraulic system and the cooling system are ignored. In order to be close to the real plant condition and obtain an exact magnetic field distribution, the integrated geometrical model also includes an adequate thickness atmosphere layer that surrounds the FPMS system. The calculate static magnetic flux density of FPMS is shown in Fig. 4(b). The lines of magnetic force are from northpole to southpole of magnets and the calculated center magnetic flux density is 1 346 Gs.

The validation of the model is performed by a comparison of the measured and the calculated center magnetic flux density of FPMS under different stirring frequencies, as demonstrated in Fig. 5. It can be seen from the figure that the calculated center magnetic flux density remain unchanged and the measured data has a certain degree of random variability. However, the differentials between the results calculated by the model and measured data are within 11 Gs and the present model can be used to simulate the magnetic field.

The vector map of the magnetic flux density in rectangular billet under different stirring frequencies is illustrated in Fig. 6. The external field is strongest near the two permanent magnets and weakest in the direction perpendicular to the permanent magnet. A stronger induction current is generated due to the larger magnetic density near the magnet. Such a distribution is because of that there is only a pair of magnetic magnet in the FPMS. Besides, Fig. 6 indicates that the magnetic flux density in the rectangular billet is nearly invariable under different stirring frequencies and the maximum magnetic flux density is about 1 950 Gs and the minimum magnetic flux density remained about 240 Gs.

Magnetic flux density distribution in the width direction of rectangular billet at different stirring frequencies is given in Fig. 7. It can be seen from the figure that the distribution of magnetic flux density in the rectangular billet under different stirring frequencies changes very little and can be ignored. The magnetic flux density in the center of rectangular billet is about 1 335 Gs and the magnetic flux density decreases by about 600 Gs as the distance changes from billet edge to center liquid core. Besides, there are many theo-

Fig. 5. Comparison of measured and calculated magnetic flux density of FPMS under different stirring frequencies.

Fig. 4. Schematic of the FPMS simulation model (a) and the calculated magnetic flux density of FPMS (b).
ries on decaying law of electromagnetic field in metal, one of them is shown in Eq. (6). This is a simple equation where the magnetic flux density attenuates with negative exponent as the distance from magnet increases. The modeling results shown in Fig. 7 are in accordance with the calculated results of Eq. (6), demonstrate the same regularity.

\[
B = B_0 \exp\left(-x\sqrt{\pi f \mu \sigma}\right) \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (6)
\]

where \( x \) (m) is the distance from magnet; \( f \) (Hz) is the stirring frequency; \( B_0 \) (T) is the magnetic flux density in magnet; \( \mu \) is the permeability of tested metal and \( \sigma \) (S/m) is the conductivity of tested metal.

2.2.3. Electromagnetic Force of FPMS

A rotating magnetic field passing through the molten steel will induce eddy currents which travel in the direction perpendicular to the magnetic field. The interaction between the internal magnetic field and the eddy currents will produce an electromagnetic force. The electromagnetic force whose action is perpendicular to both the magnetic field and induced currents, will causes the stirring movement in the melt.

Figure 8 shows the vector map of electromagnetic force in the rectangular billet and liquid core under different stirring frequencies. The electromagnetic force acting on the rectangular billet is formed, which is in the direction of the rotating magnetic field. It also shows that the magnitude of the electromagnetic force at the edge of the rectangular billet is much higher than that at the central. Figure 9 shows the distribution of the electromagnetic force in the width direction of rectangular billet under different stirring frequencies. It is shown that the electromagnetic force increases with the increasing of stirring frequency in the width direction of rectangular billet and the electromagnetic force decreases as the distance from rectangular billet edge increases.

Figure 10 shows the maximum electromagnetic force in the shell and residual liquid pool under different stirring frequencies in FPMS. The electromagnetic force increases proportionally with the stirring frequency increasing. The maximum electromagnetic force in liquid core increases from 12 kN/m³ with a stirring frequency of 1 Hz to 59 kN/m³ with a stirring frequency of 5 Hz. The stirring frequency corresponding to this maximum electromagnetic force is maybe the optimum frequency, which is with a higher stirring frequency value for this FPMS system. To MEMS, the increasing exciting frequency is much more important to add electromagnetic force than that of increasing current density. It can be concluded that the electromagnetic force of FPMS could be effectively increased by adding stirring frequency.

2.2.4. Flow Field Characteristics of FPMS

Molten metal flow, in the source of solidification, affects basic quality aspects of the cast material such as grain structure and solute segregation. Thus, the velocity and distribution of electromagnetically driven flow in the molten metal can be a reference basis for the evaluation of FPMS effectiveness and its design feature. Stirring velocity magnitude and distribution in the melt are derived from the relevant magnetic body force distribution pattern.

The tangential velocities in the liquid core under different stirring frequencies in the FPMS are shown in Figure 11. The molten steel in liquid core has a rotating velocity distribu-
by adding stirring frequency in the length direction of liquid core and the tangential velocity decreases as the distance from liquid core edge increases. The variation trends of the tangential velocity are consistent with the electromagnetic force.

Figure 13 shows the relationship between the maximum tangential velocity in the liquid core and the stirring frequency in FPMS. The tangential velocity increases with the stirring frequency increasing and its changing trend is consistent with the one shown in Fig. 10. The maximum tangential velocity in liquid core increases from 0.09 m/s with a stirring frequency of 1 Hz to 0.45 m/s with a stirring frequency of 5 Hz. To MEMS, a stirring velocity of 0.35 m/s to 0.5 m/s results in an 80% to 90% reduction in surface pinholes.\textsuperscript{15) To FEMS, a weak stirring velocity equals to 0.2 m/s can break the dendrite crystal and decrease the V-segregation.\textsuperscript{16) Besides, a larger stirring velocity in FEMS may generate negative segregation and lead to the deterioration of billet quality. However, to FPMS, there is no optimum velocity data reported and the determination of the optimum stirring frequency should combined the calculated results with the industrial trial results.

3. Application of Final Permanent Magnet Stirring

3.1. FPMS Tests

The objective of the FPMS trials carried out on rectangular billet was to assess the influence of FPMS process on the inner quality of the rectangular billet and final product. The 82A steel was produced by a straight curved caster with a section size of 180 mm $\times$ 240 mm. The permanent magnet stirrer was attached to the end of secondary cooling zone in rectangular billet caster. After installation of the FPMS units, FPMS tests are carried out in order to find out the optimum conditions of FPMS by varying the inlet oil pressures while other parameters remain unchanged. The casting speed was 0.9 m/min, the secondary cooling water intensity was 0.9 L/kg and the superheat of the molten steel was about 25°C. Test parameters for FPMS are presented in...
3.2. Results and Discussion

3.2.1. Effect of FPMS on Center Segregation of Rectangular Billet

In order to assess the effect of various inlet oil pressures on the inner quality of rectangular billet, the center segregation degree of carbon is obtained. The segregation index is evaluated by longitudinal cross section of 180 mm × 240 mm rectangular billet. The carbon segregation is determined by total ten drillings along the center line of the rectangular billet for every stirring parameter. Each sample is drilled out 4 mm in depth with a 5 mm diameter drill along the central longitudinal direction. The carbon segregation is defined as \( \frac{C}{C_0} \), where \( C \) is the center carbon content (drilling test), \( C_0 \) is the carbon content in liquid steel (tundish test).

It is important to select appropriate inlet oil pressure in a way that the optimum center carbon segregation is present. Figure 14 shows the relation between the mean center segregation degree of carbon and the inlet oil pressure. The results are shown in the Fig. 14 and combined with the Fig. 3 presenting that the mean carbon segregation degree reduces effectively at the inlet oil pressure above 7 MPa (2 Hz). Meanwhile, the center carbon segregation degree is 1.18 with No-FPMS. As the inlet oil pressure increases from 10 MPa (3 Hz) to 16 MPa (5 Hz), the carbon segregation degree decreases from 1.12 to 1.09. The optimum FPMS parameter to minimize the center carbon segregation has been obtained when the stirring frequency increasing from 2 Hz to 5 Hz. Therefore, for the decreases of center carbon segregation, increasing the stirring frequency is necessary to ensure that a sufficient stirring reaches the core to uniform segregation elements.

<table>
<thead>
<tr>
<th>Inlet Oil Pressure, MPa</th>
<th>Strands No.</th>
<th>Stirring Type</th>
<th>Test Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>No</td>
<td>A</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>FPMS</td>
<td>B</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>FPMS</td>
<td>C</td>
</tr>
<tr>
<td>13</td>
<td>1</td>
<td>FPMS</td>
<td>D</td>
</tr>
<tr>
<td>16</td>
<td>1</td>
<td>FPMS</td>
<td>E</td>
</tr>
</tbody>
</table>

Table 1. Test parameters for the final permanent magnet stirring.
3.2.2. Effect of FPMS on Internal Quality of Rectangular Billet

The optimum FPMS parameter of 5 Hz is obtained after the above industrial tests. The new technique has been adopted by industrial use. Although there are good results in segregation level at a stirring frequency of 5 Hz, further investigations have shown that the FPMS has a significant impact on the other internal qualities of rectangular billet.

It is well known that porosities and shrinkage cavity occur in the center part of continuous casting blooms and billets.\(^{17,18}\) Twenty transverse sections of rectangular billet were cut continuously at stirring frequency of 0 and 5 Hz, respectively. The solidification structure defects of the samples were revealed by using hydrochloric acid erosion method. Figure 15 illustrates the central solidification structure of 82A steel without and with FPMS. The photo of the solidification structure without FPMS in Fig. 15(a) clearly shows that the central porosity and shrinkage cavity are apparent. In comparison to the rectangular billet without FPMS, the central porosity and shrinkage cavity are less pronounced and more uniform in distribution as shown in Fig. 15(b). What’s more, it also can be seen from Fig. 15(b) that there exist obvious circular stirring traces and the liquid in central is in rotation motion. It means that the residual molten metal in the central of rectangular billet is set in rotation by electromagnetic body force. Besides, negative segregation, called white band, derived from the excess stirring could not be observed in Fig. 15(b) and it shows that the maximum tangential velocity of 0.45 m/s in a stirring frequency of 5 Hz is appropriate.

The above forty transverse sections of rectangular billet have been investigated to count solidification defects such as central porosity and shrinkage cavity. The decrease of the grade of solidification defects means that there is a good internal quality in rectangular billet. A comparative assessment of the influence of FPMS process at a stirring frequency of 5 Hz on the grade of central porosity is given in Fig. 16. The results are shown in Fig. 16 presenting that the grade of central porosity with FPMS decreases compared with without FPMS. The frequency of grade of central porosity equals to 0.5 increases by about 40% and the frequency of grade of central porosity equals to 1.5 decreases by about 40% with the using of FPMS. The grades of central shrinkage cavity without and with FPMS are shown in Fig. 17. The grade of central shrinkage cavity is decreased by the use of FPMS. The frequency of grade of central shrinkage cavity equals to 0 increases from 0% to 20% and the frequency of grade of central shrinkage cavity equals to 1.5 decreases by about 20% with the use of FPMS.

3.2.3. Effect of FPMS on Segregation of Final Product

The final product of the rectangular billet is wire rod with a diameter of 5.5 mm. Wire rod with a center cementite network resulted from severe segregation not only shows low ductility in the center portion, but also exhibits cup fracture during drawing.\(^{19}\) To investigate how serious the segregation in wire rod was, forty samples (include twenty without FPMS specimens and twenty FPMS specimens with a stirring frequency of 5 Hz) were taken for 4% nitric acid alcohol erosion (as shown in Fig. 18). The diameter of the center black spot represents the grade of wire rod segregation and a larger diameter means that the segregation grade is higher and the segregation of wire rod is serious. From the investigation of the final product quality at a stirring frequency of 5 Hz in FPMS, improvement of internal qual-

![Fig. 14. The mean center carbon segregation in different inlet oil pressures of FPMS.](image1)

![Fig. 15. The central solidification structure of 82A steel (a) without and (b) with FPMS.](image2)

![Fig. 16. The grade of central porosity (a) without and (b) with FPMS.](image3)
ity in wire rod is confirmed and the results are shown in Fig. 19. By the application of FPMS technology, the frequency of wire rod segregation grade 2.0 decreases from 70% to 42.5%. This clearly indicates that continuous casting with FPMS is of importance to the improvement of final product quality.

4. Conclusions

A three-dimensional unsteady coupled mathematical model based on electromagnetic field analysis software Opera-3D and flow field software Fluent has been developed and an industrial plant trial was conducted to verify the calculated results and investigate the influence of FPMS on inner quality of 82A steel. The findings resulting from numerical simulation and trials can be summarized as follows:

(1) It can be summarized from the calculated results in residual liquid pool that the magnetic flux density is nearly invariable, the electromagnetic force increases proportionally and the maximum tangential velocity various form 0.09 m/s to 0.45 m/s as the stirring frequency of FPMS increases from 1 Hz to 5 Hz.

(2) Due to larger electromagnetic force and faster fluid flow velocity in the molten steel with greater stirring frequency, increasing the stirring frequency of FPMS is necessary to ensure that a sufficient stirring reaches the liquid core to uniform elements.

(3) The FPMS is an effective technology to improve center segregation in terms of decreasing carbon segregation level. Encouraging center segregation results are obtained for high carbon steel with the stirring frequency increasing from 2 Hz to 5 Hz.

(4) In comparison with No-FPMS, FPMS improved the solidification macrostructure and reduced the wire rod segregation, producing cast rectangular billet and final product of sound and uniform internal quality.

REFERENCES