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The Simulation and Optimization of an Electromagnetic Field in a Vertical Continuous Casting Mold for a Large Bloom

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Abstract: The electromagnetic model of a large-bloom continuous casting was established to simulate the magnetic field. The model 3600 digital, high-precision, three-dimensional Gaussian meter was used to measure the internal magnetic field of mold electromagnetic stirring (M-EMS). The distribution of simulated magnetic field was basically consistent with that of the measured magnetic field; the accuracy of electromagnetic stirring model was verified. With the increase of current frequency, the electromagnetic force first increases and then decreases; when the current frequency is 9 Hz, the electromagnetic force reaches its maximum value. A bipolar electromagnetic stirring model is proposed; the influence of current intensity and distance were investigated. With the increase of current intensity of lower mold electromagnetic stirring (M-EMSB), the internal magnetic intensity of upper mold electromagnetic stirring (M-EMSA) gradually increases, and the middle region is gradually filled by magnetic field. With the increase of the distance, the range of the low-intensity magnetic field expands. When the current intensity of the M-EMSB is 320 A, and the distance is 400 mm, an 8 mT uniform magnetic field in the range of 1.2 m is formed. Compared with the traditional continuous casting electromagnetic agitator, the center equiaxial crystal of bipolar electromagnetic agitator increases from 30.3% to 49.5%.

Keywords: numerical simulation; vertical continuous casting; bipolar electromagnetic stirring; electromagnetic field

1. Introduction

With the maturation of electromagnetic stirring technology, it has been widely used in the production of large-bloom continuous casting. According to the metallurgical effect and the installation position of electromagnetic agitator, it is usually divided into mold electromagnetic stirring (M-EMS), strand electromagnetic stirring (S-EMS), electromagnetic stirring (F-EMS) and combinations (M + S-EMS, M + F-EMS, M + S + F-EMS) [1,2]. Among them, M-EMS generally adopts the method of rotating stirring to promote the absorption of inclusions by protective slag, improve the purity of casting billets, reduce the central defects and improve the quality of casting billets. The mold is mainly composed of copper material, which has a certain conductivity and certain magnetic shielding properties. The magnetic shielding properties restrict the penetration of the electromagnetic stirring magnetic field into the mold, affect the magnetic field strength and affect the effective stirring time. With the reduction of the frequency of alternating current, the permeability strength of magnetic field increases. Generally, the frequency of M-EMS is between 1 and 10 Hz.

Most billets with sections over 600 mm are produced by ingot casting. Due to the low solidification density, low production efficiency and low yield of ingot casting, China built the world's first vertical round billet caster with the largest section of 800 mm in 2015 [3]. The use of bipolar electromagnetic stirring technology further improves the uniformity and coverage of magnetic flux, improves the penetration of magnetic field and improves the solidification density of the large bloom. In order to accurately obtain the change law of a three-dimensional periodic magnetic field, the model 3600 digital, high-precision, three-dimensional Gaussian meter was used to measure the magnetic field, and the low frequency alternating magnetic field acquisition module was developed. The numerical simulation of the electromagnetic stirring magnetic field was carried out by using the verified electromagnetic model.

2. Magnetic Field Measurement

The three-dimensional periodic magnetic field inside mold of a vertical, round bloom caster was measured. As shown in Figure 1, the measuring instrument was the model 3600 digital, high-precision, three-dimensional Gaussian meter (CH-HALL, Beijing, China) with the low frequency alternating magnetic field acquisition module. The parameters of measuring instrument are shown in Table 1.

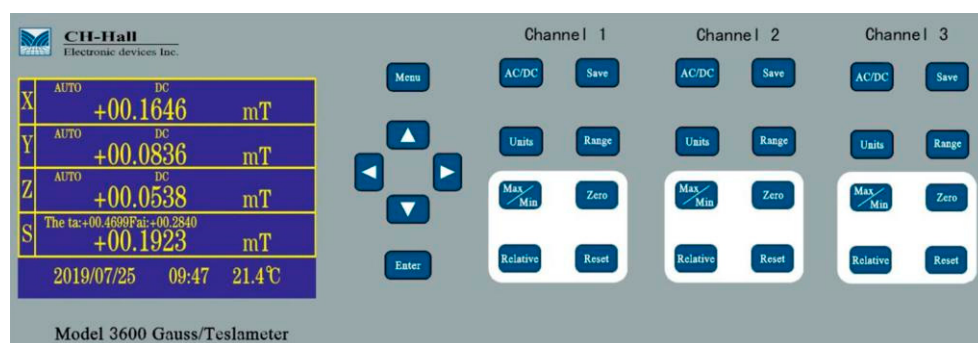


Figure 1. The model 3600 digital, high-precision, three-dimensional Gaussian meter.

When the current intensity of M-EMS (VAI, Linz, Austria) was 400 A and the current frequency was 3 Hz; the three-dimensional periodic magnetic fields of A_axis and C_axis were measured in the mold. C_axis was the central axis of mold, and A_axis was 300 mm apart from C_axis. Figure 2 shows the measuring points inside the mold under the action of M-EMS. In the space range of 1000 mm inside the mold, the magnetic field in XYZ directions is measured at 50 mm intervals, and 21 measuring points on each axis.

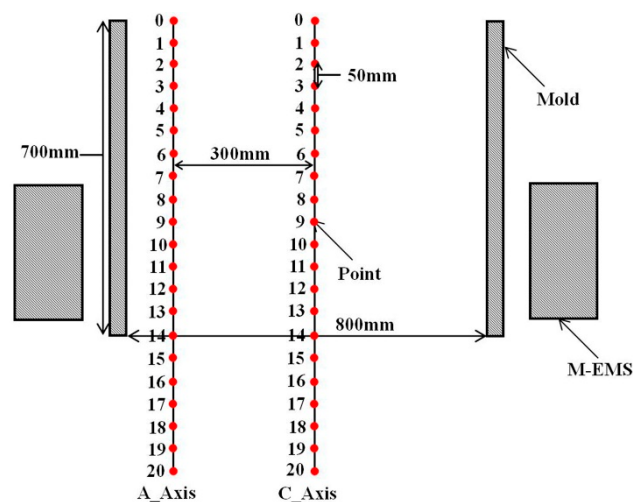


Figure 2. The measuring points inside the mold.

Figure 3 shows the measurements of the XYZ, three-dimensional, periodic magnetic fields of A_axis and C_axis, which can show the periodic variation law of the magnetic field in XYZ directions at each point. Comparing the XYZ, three-dimensional, periodic magnetic field CmplxMag at each point, the electromagnetic model of large-bloom continuous casting was verified.

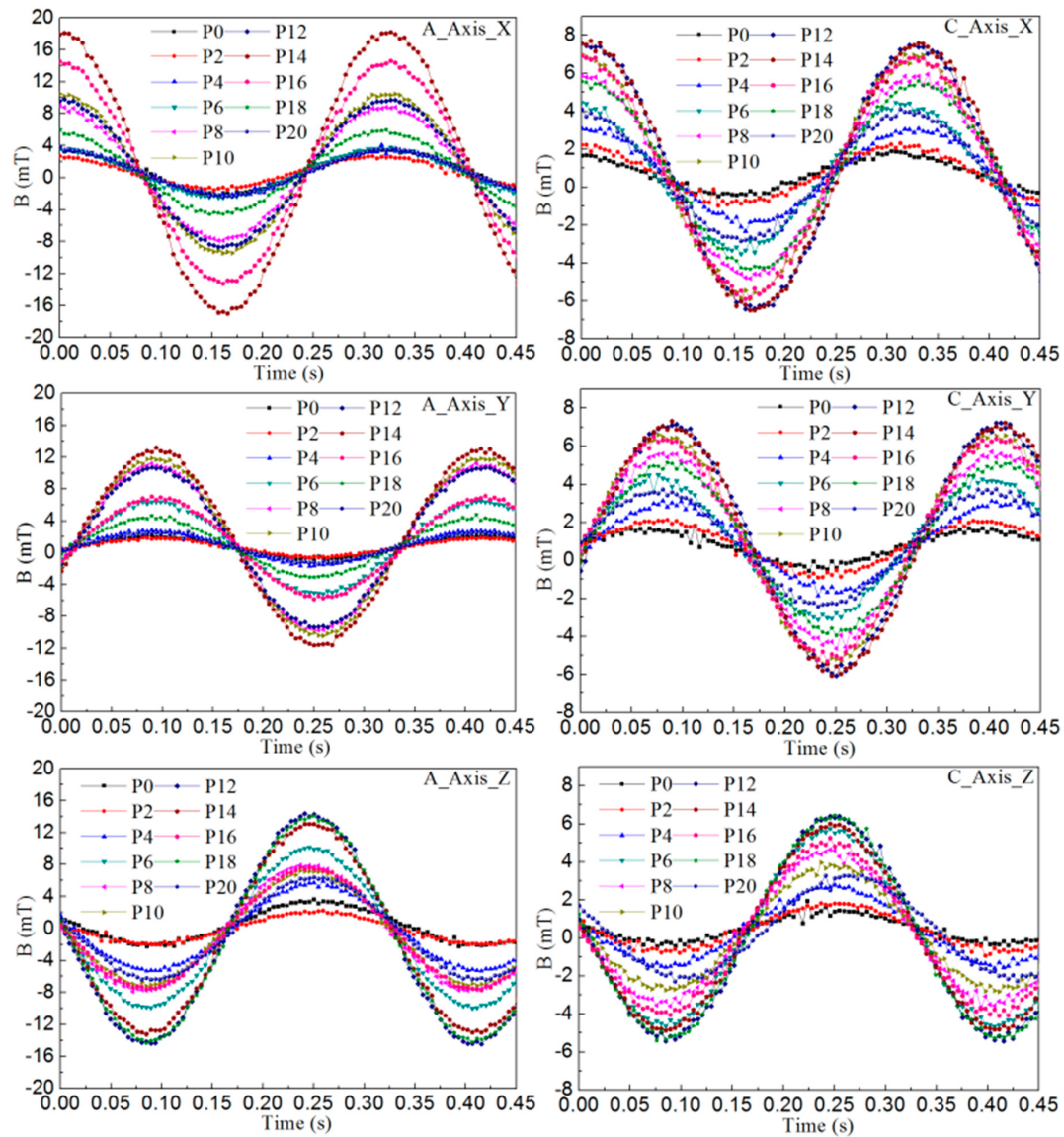


Figure 3. The measurements of the XYZ, three-dimensional, periodic magnetic fields of A_axis and C_axis.

Table 1. The parameters of model 3600 digital, high-precision, three-dimensional Gaussian meter.

Parameters	Value
Range	0–300000Gs/30T
Resolution ratio	0.0001 Gs/0.00001 mT
Measurement accuracy	0.05%
Response frequency	100 KHz

3. Modification of the Electromagnetic Model

3.1. Control Equations

Maxwell's equations are the foundation of macroscopic electromagnetic problems, and the basis and starting point of finite element analysis, as well as Ohm's law [4,5].

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \quad (1)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (2)$$

$$\nabla \times \mathbf{D} = \rho \quad (3)$$

$$\nabla \times \mathbf{B} = 0 \quad (4)$$

where H is the magnetic field intensity, A/m; J is the current density, A/m²; D is the electric flux density, C/m²; t is the time, s; E is the electric field intensity, V/m; B is the magnetic flux density, T; ρ is the charge density, C/m³. The medium factor equations are as follows:

$$\mathbf{B} = \mu \mathbf{H} \quad (5)$$

$$\mathbf{J} = \sigma \mathbf{E} \quad (6)$$

The relationship between the induced current and the excitation magnetic field given by Ohm's law is as follows [6]:

$$\mathbf{J} = \sigma(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \quad (7)$$

where μ is the magnetic conductivity; σ is the conductivity, S/m; v is the velocity, m/s.

The current frequency of M-EMS is very low, which belongs to the quasi-stable electromagnetic field, so the displacement current can be ignored. In the actual electromagnetic stirring, the magnetic Reynolds number is small, around 0.06, and the influence of flow on the magnetic flux density can be ignored. Combined with Lenz's law, the expression of induced electromagnetic force is obtained [7]:

$$\mathbf{F} = \mathbf{J} \times \mathbf{B} \quad (8)$$

J is represented by B :

$$\mathbf{F} = \frac{1}{\mu}(\mathbf{B} \cdot \nabla)\mathbf{B} - \frac{1}{2\mu}\nabla(\mathbf{B} \cdot \mathbf{B}) \quad (9)$$

The first item on the right is a rotational force, and the second term is a non-rotational force. It can be seen that the induced electromagnetic force under low frequency alternating magnetic field is mainly rotating force, which is also the force to promote the rotation of molten steel under the M-EMS.

3.2. Validation of the Electromagnetic Model

The structural diagram of M-EMS is shown in Figure 4a, which is mainly composed of three pairs of coils, an iron core and a magnet yoke. The electromagnetic model parameters of M-EMS are shown in Table 2. The horizontally-rotating magnetic field is formed in the mold, and the induced current in the molten steel is caused by the magnetic field to form the electromagnetic force, which causes the molten steel to rotate [8,9]. The magnetic field distribution of model was numerically simulated according to the electromagnetic model parameters, and the contour plot of the magnetic flux density in the longitudinal section is shown in Figure 4b, and the maximum value of the magnetic flux density can be observed at the lower edge of the mold. The copper plate of the mold has a certain conductivity and certain magnetic shielding properties, which makes it difficult for the magnetic field to penetrate the mold, and the magnetic field concentrates in the position without mold covering. The magnetic

shielding properties of the mold reduce the permeability magnetic flux density inside the round bloom, reduce the magnetic field area and reduce the effective stirring time of molten steel.

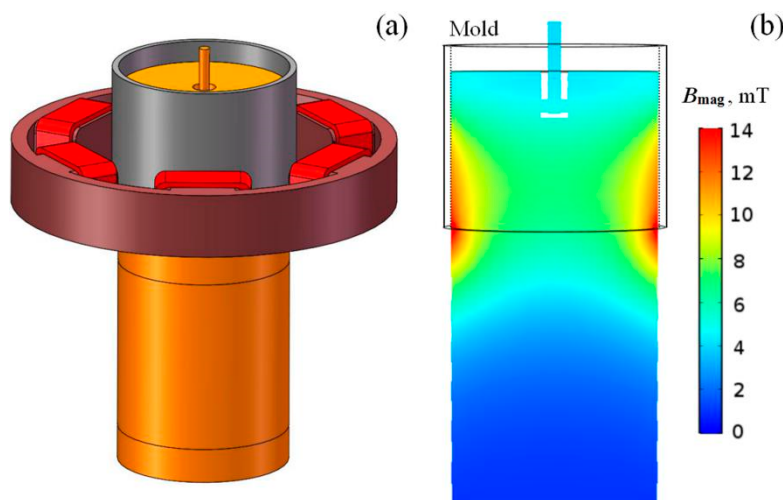


Figure 4. The structural diagram of mold electromagnetic stirring (M-EMS) (a) and the contour plot of the magnetic flux density in the longitudinal section (b).

Table 2. The electromagnetic model parameters of magnetic field of mold electromagnetic stirring (M-EMS).

Parameters	Value	Parameters	Value
Mold height	0.7 m	Relative permeability of molten steel	1
Current intensity	400 A	Relative permeability of mold	1
Current frequency	3 Hz	Bulk conductivity of coils	5.8×10^7 S/m
Relative permeability of iron core	1000	Bulk conductivity of molten steel	2.0×10^6 S/m
Relative permeability of coils	1	Bulk conductivity of mold	4.0×10^7 S/m

The large-bloom is generally produced by a four-hole submerged nozzle. When the permeability of magnetic flux density is not enough, the molten steel from the four-hole immersion nozzle will impact the shell of round bloom. The shell is partially melted by heat, resulting in uneven shell thickness and defects on the surface of round bloom [10,11].

Figure 5a shows the measurements of the XYZ, three-dimensional, periodic magnetic field at P16 of A_axis, and the XYZ, three-dimensional, periodic magnetic field CmplxMag is 6.0, 5.5 and 1.0 mT respectively. The XYZ, three-dimensional, periodic magnetic field CmplxMag of each point was integrated to obtain the comparison diagram of measured magnetic field CmplxMag and simulated magnetic field CmplxMag, as shown in Figure 5b. It can be seen that the maximum value of the magnetic field CmplxMag is P14, not P10, which is consistent with the maximum value of the magnetic flux density at the lower edge of the mold. The simulated magnetic field distribution is basically consistent with the measured magnetic field distribution, which verifies the accuracy of the electromagnetic model.

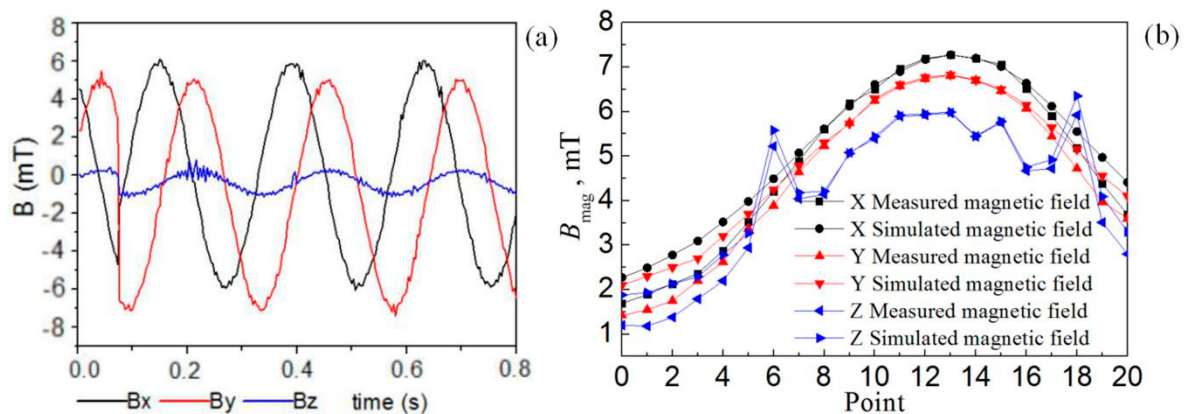


Figure 5. The measurements of the XYZ, three-dimensional, periodic magnetic field at P16 of A_axis, (a) and the comparison diagram of measured magnetic field CmplxMag and simulated magnetic field CmplxMag (b).

4. The Influences of Electromagnetic Parameters on a Magnetic Field

4.1. The Effect of Current Frequency on the Magnetic Field

The distributions of magnetic lines under different current frequencies in the round bloom are shown in Figure 6. When the current intensity of M-EMS is 400 A, the current frequency increases from 1 Hz to 35 Hz. The relationship between current frequency and electromagnetic force is shown in Figure 7. It can be seen that with the increase of current frequency, the electromagnetic force first increases and then decreases. When the current frequency is 9 Hz, the electromagnetic force reaches its maximum value.

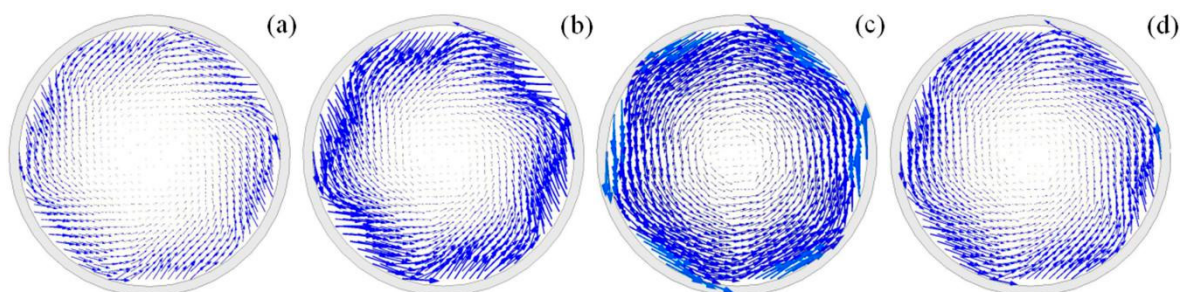


Figure 6. The distributions of magnetic lines under different current frequencies: (a) $f = 2$ Hz, $I = 400$ A; (b) $f = 4$ Hz, $I = 400$ A; (c) $f = 8$ Hz, $I = 400$ A; (d) $f = 12$ Hz, $I = 400$ A.

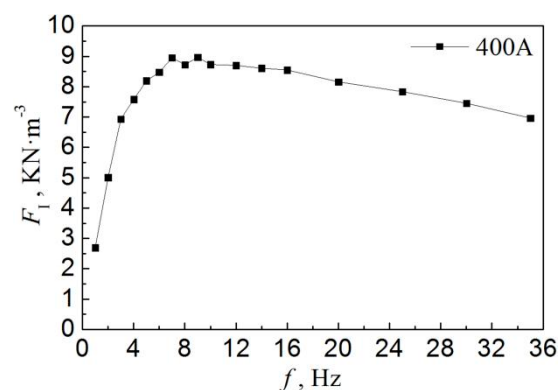


Figure 7. The relationship between current frequency and electromagnetic force.

When the current frequency is low, the induced current in the molten steel is weak, which is not conducive to improving the electromagnetic force inside the molten steel. The copper plate of the mold

has a certain conductivity and certain magnetic shielding properties. When the electromagnetic force reaches the maximum value, the permeability magnetic flux density inside the round bloom decreases with the increase of the current frequency, and the magnetic flux density and electromagnetic force in the molten steel decrease [12,13]. Therefore, the current frequency of M-EMS is mainly from 1 to 10 Hz.

4.2. The Effect of Current Intensity on the Magnetic Field

The distributions of magnetic lines under different current intensities in the round bloom are shown in Figure 8. When the current frequency of M-EMS is 3 Hz, the current intensity increases from 100 to 600 A; the relationship between current intensity and electromagnetic force is shown in Figure 9. It can be seen that the electromagnetic force increases with the increase of the current intensity [14,15].

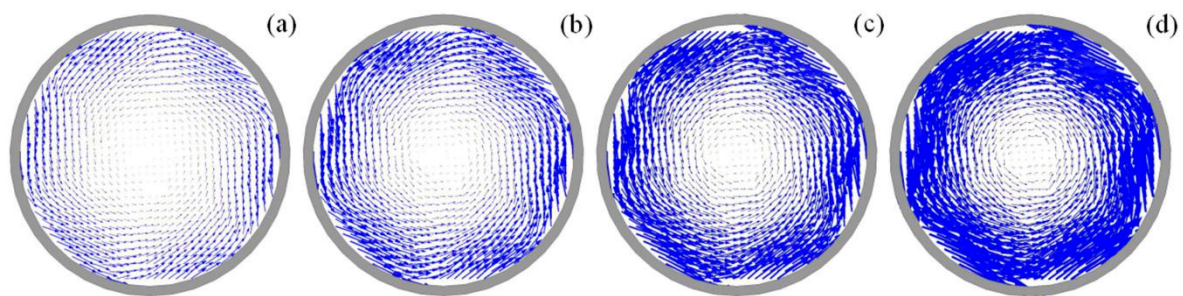


Figure 8. The distributions of magnetic lines under different current intensities: (a) $I = 200\text{ A}$, $f = 3\text{ Hz}$; (b) $I = 300\text{ A}$, $f = 3\text{ Hz}$; (c) $I = 400\text{ A}$, $f = 3\text{ Hz}$; (d) $I = 500\text{ A}$, $f = 3\text{ Hz}$.

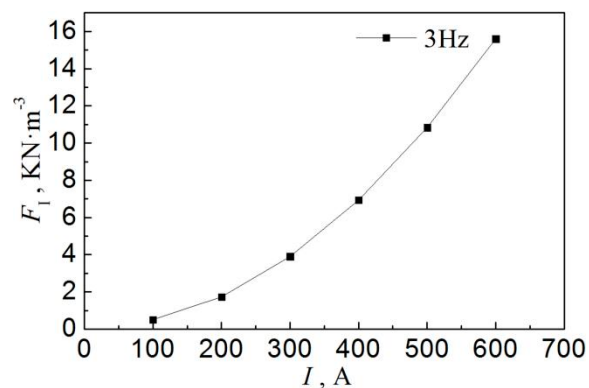


Figure 9. The relationship between current intensity and electromagnetic force.

5. Bipolar Electromagnetic Stirring

The bipolar electromagnetic stirring is composed of M-EMSA and M-EMSB (VAI, Linz, Austria); the structure diagram is shown in Figure 10a. Both M-EMSA and M-EMSB are 400 mm high, and the distance between the poles is 400 mm. For the production of a large bloom, the copper plate of mold has a certain conductivity and certain magnetic shielding properties. The strength of the alternating magnetic field of traditional M-EMS is weak and the effective stirring time of molten steel is short, and it is difficult to penetrate into the round bloom.

The bipolar electromagnetic stirring has a large range of uniform magnetic field. When the current frequency of M-EMSA is 2 Hz, the current intensity is 400 A; when the current frequency of M-EMSB is 2 Hz, the current intensity is 320 A. The contour plot of the magnetic flux density in the longitudinal section is shown in Figure 10b. For the production of 800mm section round bloom, the effective stirring longitudinal section area of the bipolar electromagnetic stirring is 0.72 m^2 , which is 375% larger than

the traditional M-EMS. The effective stirring time is 660 s, which is 260% larger than the traditional M-EMS. The current intensity formulas of bipolar electromagnetic stirring are Equation (10).

$$\begin{aligned} J_{M-1} &= J_0 \sin\left(4 \cdot \pi \cdot t \left[\frac{1}{s}\right]\right) & J_{M-2} &= J_0 \sin\left(4 \cdot \pi \cdot t \left[\frac{1}{s}\right] + \frac{2\pi}{3}\right) \\ J_{M-3} &= J_0 \sin\left(4 \cdot \pi \cdot t \left[\frac{1}{s}\right] + \frac{4\pi}{3}\right) \end{aligned} \quad (10)$$

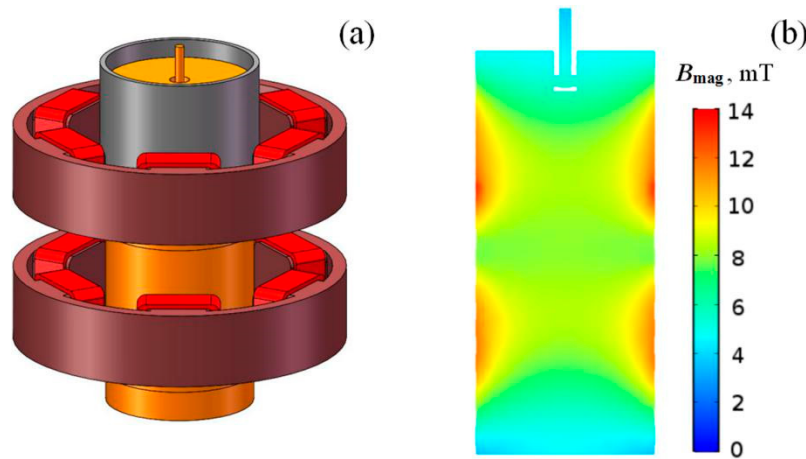


Figure 10. The structural diagram of bipolar electromagnetic stirring (a), and the contour plot of the magnetic flux density in the longitudinal section (b).

5.1. The Effect of the Current Intensity of M-EMSB on a Magnetic Field

When the current frequency of M-EMSA is 2 Hz, the current intensity is 400 A; when the current frequency of M-EMSB is 2 Hz, the current intensity is 200–400 A, and the distance between the poles is 400 mm. The distributions of magnetic fields under different current intensities of M-EMSB are shown in Figure 11a. With the increase of current intensity of M-EMSB, the internal magnetic field intensity of M-EMSA gradually increases, and the middle region is gradually filled by magnetic field. In the space range of 1900 mm inside the mold, the measurement interval is 50 mm, and Figure 11b shows the magnetic flux density values of C_axis under different current intensities. The unsuitable current intensity of M-EMSB is not conducive to the uniform distribution of the magnetic field. When the current intensity of the M-EMSB is 320 A, the magnetic field is evenly distributed in the round bloom, the intensity of uniform magnetic field is 8 mT and the range of action is 1.2 m high.

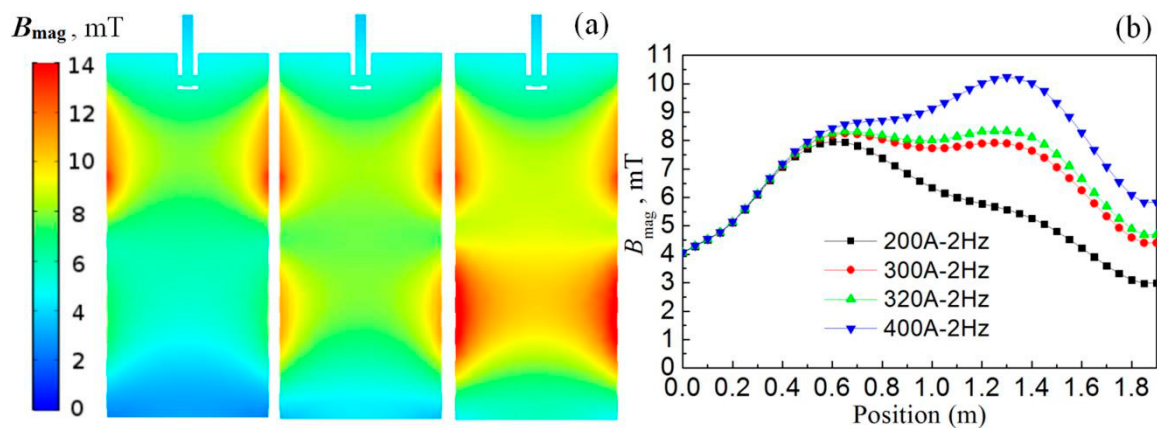


Figure 11. The distribution of magnetic field (a), and the magnetic flux density values of C_axis (b) under different current intensities of lower mold electromagnetic stirring (M-EMSB).

5.2. The Effect of the Distance Between the Poles on the Magnetic Field

When the current frequency of M-EMSA is 2 Hz, the current intensity is 400 A; when the current frequency of M-EMSB is 2 Hz, the current intensity is 320 A, and the distance between the poles is 400–600 mm. The distributions of the magnetic field under different distances are shown in Figure 12a. It can be seen that with the increase of the distance between the poles, the low-intensity magnetic field appears at the center of the magnetic field. The range of the low-intensity magnetic field increases with the increasing distance, which affects the uniformity of magnetic field. In the space range of 1900 mm inside the mold, the measurement interval is 50 mm, and Figure 12b shows the magnetic flux density values of C_{axis} at different distances. When the distance between the poles is 400 mm, there is a uniform magnetic field distribution in the round bloom.

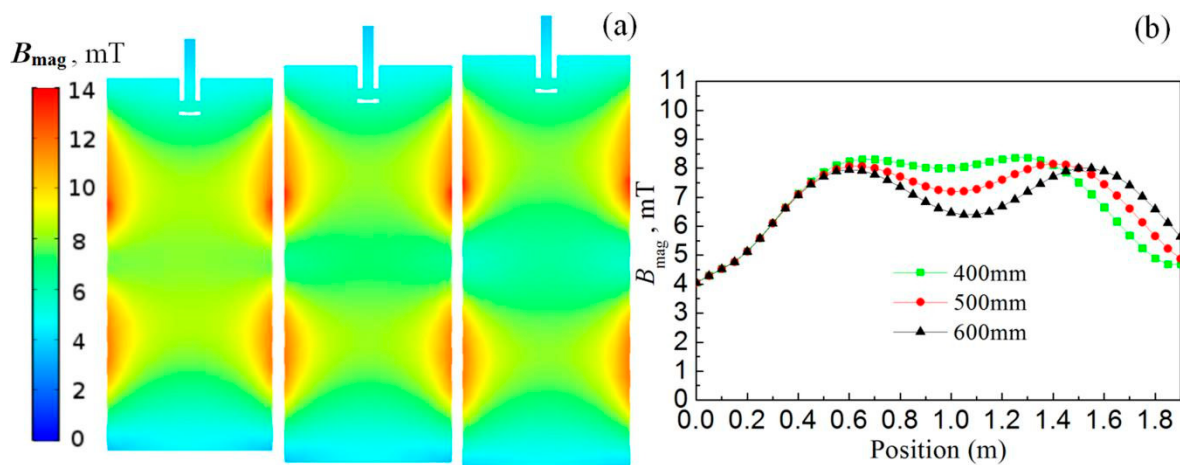


Figure 12. The distribution of the magnetic field (a), and the magnetic flux density values of C_{axis} (b) at different distances.

The bipolar electromagnetic agitator is different from the traditional continuous casting electromagnetic agitator and has a unique structure. The magnetic field area of bipolar electromagnetic agitator is larger, covering the inside and the bottom of the mold. A reasonable bipolar electromagnetic agitator can increase the effective stirring time and the range of uniform magnetic field in the mold, which is beneficial to the uniform distribution of magnetic field. The uniform magnetic field formed a spiral flow field in the billet; the spiral flow field washed the leading edge of dendrite and increased the area of center equiaxial crystal region.

Regarding the production of a large bloom, it is still difficult for the electromagnetic stirring magnetic field to penetrate into the round bloom. The bipolar electromagnetic agitator can enhance the effect of electromagnetic stirring. As shown in Figure 13, compared with the traditional continuous casting electromagnetic agitator, the center equiaxial crystal of bipolar electromagnetic agitator increases from 30.3% to 49.5%, and the internal quality of round bloom is improved obviously. The billet conditions under different processes are shown in Table 3. The bipolar electromagnetic stirring technology combined with weak secondary cooling technology and multi-stage insulation technology can control the solidification quality of the billet.

Table 3. The billet conditions under different processes.

Production Method	M-EMS Pattern	Equiaxial Crystal	Yield
Vertical continuous casting	M-EMSA + M-EMSB	High	High
Curved continuous casting	M-EMS	Middle	High
Ingot casting	-	Low	Low

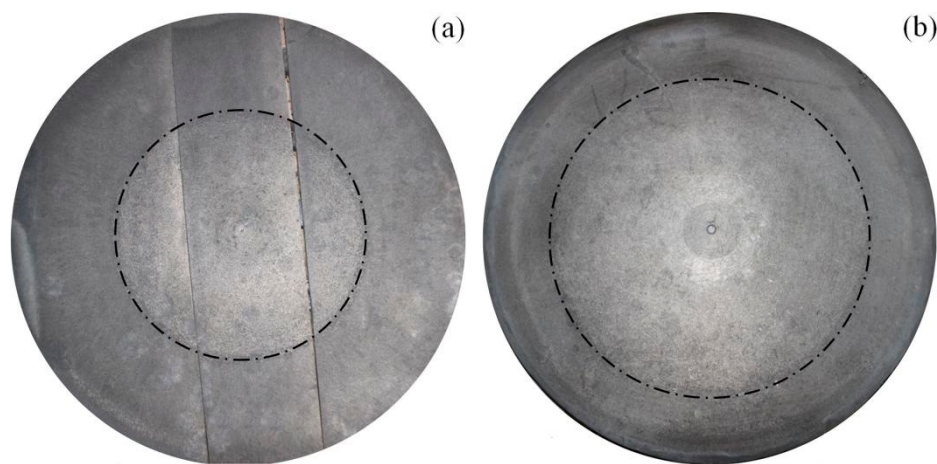


Figure 13. The macrostructure of 42CrMo Φ 800 round bloom. M-EMS is 2 Hz and 400 A (a). Upper mold electromagnetic stirring (M-EMSA) is 2 Hz and 400 A; M-EMSB is 2 Hz and 320 A (b).

6. Conclusions

The model 3600 digital, high-precision, three-dimensional Gaussian meter was used to measure the internal magnetic field of M-EMS, and compared with the simulated magnetic field, the accuracy of electromagnetic stirring model was verified. The influences of current intensity and current frequency on the magnetic field were discussed. A bipolar electromagnetic stirring model was proposed, and the influences of current intensity of M-EMSB and distance between the poles on the magnetic field were discussed. The following conclusions were obtained:

1. The copper plate of the mold has a certain conductivity and certain magnetic shielding properties; the magnetic field is concentrated at the lower edge of mold; the maximum magnetic flux density is located at P14.
2. When the current intensity of M-EMS is 400 A, the current frequency increases from 1 to 35 Hz; the electromagnetic force first increases and then decreases. When the current frequency is 9 Hz, the electromagnetic force reaches its maximum value. The electromagnetic force increases with the increase of the current intensity.
3. With the increase of current intensity of M-EMSB, the internal magnetic field intensity of M-EMSA gradually increases, and the middle region is gradually filled by a magnetic field. With the increase of the distance between the poles, the low-intensity magnetic field appears at the center of the magnetic field, and the range of the low-intensity magnetic field increases with the increase of the distance.
4. During the production of a large bloom, it is still difficult for the electromagnetic stirring magnetic field to penetrate into the round bloom. The bipolar electromagnetic agitator technology can enhance the effect of electromagnetic stirring. Compared with the traditional continuous casting electromagnetic agitator, the center equiaxial crystal of bipolar electromagnetic agitator increases from 30.3% to 49.5%, and the internal quality of round bloom is improved obviously.

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