1. Introduction

The initial solidification behavior of continuous casting strand is very complicated owing to simultaneous existence of liquid steel, slag, copper mold and mold oscillation. The initial solidification shell deforms periodically along with the periodical oscillation of mold, and finally the oscillation marks are formed at the surface of strand, it will become the cause of transverse crack and drawing breakout in some exceptional condition. Therefore, how to control the initial solidification behavior of strand, reduce and even eliminate the periodical deformation of meniscus and initial solidification shell, is the fundamental of improving surface quality of strand, increasing casting speed and production efficiency.

Enlightened by the aluminum casting without mold, controlling and improving the initial solidification behavior of strand by imposing electromagnetic field on the meniscus area is all through one of focuses was paid attention to by many metallurgical researchers. Due to the higher density, higher melting point, lower conductivity of steel, and the character limit of existing conductor, casting of steel without mold is really difficult to realize. In order to imposing high frequency electromagnetic field on the meniscus of strand permeating the copper mold, and keeping the existing favorable heat transfer and mechanical performances of copper mold at the same time, the slit mold was brought forward. The existing copper mold tube is split into some segments along the casting direction, and insulation materials are filled in the slits between segments. High frequency electromagnetic field can be imposed around the meniscus area of strand permeating the slit copper mold. Electromagnetic body force perpendicular to the surface and pointing to the inner of strand is formed in the strand, static pressure of liquid metal to shell and mold wall is counteracted partially accordingly. So the shape of meniscus can be controlled, and periodical deformation of initial shell can be reduced, this is so-called soft contact electromagnetic continuous casting technology. Consequently, the targets of decreasing the depth of oscillation marks, improving the quality of strand surface, lowering the breakout rates and increase of the casting speed can be realized.

Many researchers had carried out long-term research on soft contact solidification, they applied different frequency in this technology, and obtained corresponding results. In literature, the frequency was fixed on 11 and 6 kHz. Although the electromagnetic force was calculated, but the deep analysis about it was not carried out. Application of low frequency electromagnetic field was researched in literature, the frequency is aimed at 60 Hz. In literature, the authors researched the effect of intermittent high frequency magnetic field on initial solidification, the frequency is
fixed on 20 kHz. The authors of literature \(^6\) investigated the shape of meniscus under 5–100 kHz, considered the frequency should be set above 20 kHz. Frequency was aimed at 20 kHz in literature, \(^5\) and it was aimed at 25 kHz in literature, \(^3\) but the reason of selection of frequency was not given out.

In this paper, the distribution of electromagnetic field, action of electromagnetic body force permeating slit mold on strand, the decisive effect of frequency on soft contact solidification and optimal frequency range in billet slit mold are discussed here deeply.

### 2. Theoretical Foundation

The most radical governing equation for electromagnetic field is Maxwell equations. Electromagnetic harmonic wave of definite frequency is emitted by high frequency power source in soft contact technology. Within conductor,

\[
\rho = 0, \quad \vec{J} = \sigma \vec{E}
\]

where, \(\rho\), density of free charge (C/m\(^3\)); \(\vec{J}\), electric current density (A/m\(^2\)); \(\sigma\), electrical conductivity (S/m); \(\vec{E}\), electric field intensity (V/m).

The Maxwell equations of alternating electromagnetic field are obtained as:

\[
\nabla \times \vec{E} = i \omega \mu \vec{H} \quad \text{................................(1)}
\]

\[
\nabla \times \vec{H} = -i \omega \epsilon \vec{E} + \sigma \vec{E} \quad \text{................................(2)}
\]

\[
\nabla \cdot \vec{E} = 0 \quad \text{.............................(3)}
\]

\[
\nabla \cdot \vec{H} = 0 \quad \text{.............................(4)}
\]

Electromagnetic character equations of medium are stated as:

\[
\vec{D} = \epsilon \vec{E} \quad \text{.............................(5)}
\]

\[
\vec{B} = \mu \vec{H} \quad \text{.............................(6)}
\]

The Ohm law within conductor is given as:

\[
\vec{J} = \sigma \vec{E} \quad \text{.............................(7)}
\]

where, \(\vec{B}\), magnetic flux density (T); \(\vec{D}\), electric displacement vector (C/m\(^2\)); \(\vec{H}\), magnetic field intensity (A/m); \(\mu\), magnetic permeability (H/m); \(\epsilon\), dielectric constant (F/m).

The electromagnetic body force imposed on conductor is described as:

\[
\vec{F} = \rho \vec{E} + \vec{J} \times \vec{B} \quad \text{.............................(8)}
\]

### 3. Analytical Model

#### 3.1. Attenuation of Harmonic Electromagnetic Wave Within Conductor

For electromagnetic wave of certain frequency transmitting perpendicularly into surface of conductor, Maxwell equations can be transformed as follows:

\[
\nabla^2 \vec{B} + i \omega \mu \sigma \vec{B} = 0 \quad \text{................................(9)}
\]

\[
\nabla \cdot \vec{B} = 0 \quad \text{.............................(10)}
\]

\[
\vec{E} = \frac{1}{\mu \sigma} \nabla \times \vec{B} \quad \text{.............................(11)}
\]

For planar electromagnetic wave, the solution for transmitting electromagnetic wave within conductor can be obtained by solving the above equations.

\[
\vec{B} = \vec{B}_0 e^{-\sqrt{\pi \mu \sigma}} \quad \text{................................(12)}
\]

where \(r\), coordinates along the transmitting direction of electromagnetic field (m); \(f\), frequency of electromagnetic wave (Hz); \(\vec{B}_0\), magnetic flux density of strand surface (Tesla).

\[
B_0 = \eta_0 \mu_0 l = \eta_0 \mu_0 l_0 e^{-\pi \sigma t} \quad \text{................................(13)}
\]

where \(\eta_t\), residual percentage of electromagnetic field passing through mold wall, related to frequency; \(t\), time (s).

The attenuation curves without dimension of electromagnetic wave of different frequencies within 6 mm copper wall, 40 mm radius steel strand and round copper mold filled by liquid steel are shown respectively in Figs. 1, 2 and 3. Physical characters of different relative mediums are listed in Table. 1. We can conclude from these figures that the electromagnetic wave decreases more rapidly with the increase of frequency. When frequency increases from 40 000 to 100 000 Hz, the attenuation curve does not change obviously.

#### 3.2. Electromagnetic Force

The electromagnetic body forces perpendicular to the surface of strand and pointing to the inner of conductor is described as:

\[
\vec{F}_r = \vec{J} \times \vec{B} \left( \frac{1}{\mu} \nabla \times \vec{B} \right) \times \vec{B} = \frac{1}{\mu} \vec{B} \times (\nabla \times \vec{B}) \quad \text{................................(14)}
\]
For electromagnetic solenoid, \( B_z = B_0 e^{-y \frac{\pi \mu_0 \sigma}{r}} \), \( B_z = 0 \), \( B_0 = 0 \) is taken into account, so following equations can be obtained,

\[
\vec{B} \times (\nabla \times \vec{B}) = \begin{pmatrix} \vec{e}_\theta & \vec{e}_r & \vec{e}_z \\ 0 & 0 & B_z \\ 0 & -\frac{\partial B_z}{\partial r} & 0 \end{pmatrix} = \left( \frac{\partial B_z}{\partial r} \right) \vec{e}_r \quad \text{(15)}
\]

\[
\vec{F}_r = -\frac{1}{\mu} \vec{B} \times (\nabla \times \vec{B}) = -\frac{1}{\mu} \left( \frac{\partial B_z}{\partial r} \right) \vec{e}_r \quad \text{.........(16)}
\]

Substituting the results of Eq. (12) into Eq. (16), Eq. (17) can be obtained as follows,

\[
\vec{F}_r = \frac{1}{\mu} \pi \frac{f \mu \sigma}{r} \left( B_0 \right)^2 e^{-2r \frac{\pi \mu \sigma}{r}} \quad \text{.........(17)}
\]

### 3.3. Electromagnetic Pressure

The centripetal pressure perpendicular to the surface of strand is obtained by taking \( F_r \), integral from surface \( r_0 \) to \( r \),

\[
p_r = \int_{r_0}^{r} \frac{\Delta \mu \Delta \theta}{\Delta \theta} \, dr = \int_{r_0}^{r} F_r \, dr \quad \text{.........(18)}
\]

\[
p_r = \frac{B_0^2}{2\mu} e^{-2r \frac{\pi \mu \sigma}{r}} \quad \text{.........(19)}
\]

The attenuation curves without dimension of electromagnetic body force and pressure imposed on the steel strand are shown respectively in Figs. 4 and 5. Electromagnetic body force and pressure changes a lot in strand according its frequency and distance from the surface. With the increase of frequency, the electromagnetic force suddenly decreases and pressure in the steel reaches rapidly to a fixed level. The electromagnetic force imposed to the inner of strand decrease fast to almost zero. When frequency increases from 40 000 to 100 000 Hz, the attenuation curve of electromagnetic body force and pressure does not change obviously.

### 4. Numerical Simulation

The total distribution of electromagnetic field in copper mold and steel strand is already comprehended by analytical model in part 3, the behavior of attenuation of electromagnetic field changes with its frequency. The slit structure of soft contact mold can not be easily simplified as 2-D structure, the electromagnetic field distribution and attenuation rule in the mold must be very complicated in space. So, the distribution and attenuation of electromagnetic parameters in some special regions such as slits and corners in soft contact mold must be grasped through 3-D electromagnetic field numerical simulation.

In this paper, a 2-D numerical model was established firstly to analyze the permeation conditions of high frequency electromagnetic wave across copper mold wall and insulated mold wall respectively simulating the segments and slits. And then a 3-D model was established to simulate the electromagnetic field distribution in soft contact mold.

### 4.1. Numerical Solution of Electromagnetic Field

Magnetic vector potential \( \vec{A} \) (Wb/m) and electric scalar

\[
\mathbf{E} = \nabla \times \vec{A} \quad \text{(20)}
\]

### Table 1. Physical characters of different medium.

| Medium | Electrical Resistivity \( \Omega \text{mm}^2/\text{m} \) | Temperature Coefficient of Resistivity \( 10^9/\text{°C} \) | Electrical Conductivity \( \text{A/V m} \) | Electrical Conductivity \( \text{A/V m} \) | Electrical Conductivity \( \text{A/V m} \) |
|--------|---------------------------------|-----------------------------|-----------------|----------------|----------------|
| Cu     | 0.0172                          | 3.90                        | 5.81×10^7       | 4.17×10^7      | —              |
| Steel  | 0.100                           | 5.00                        | 1×10^7          | —              | 0.11×10^7      |
potential $\phi$ (V) were inducted for solution of electromagnetic field.

$$\vec{B} = \nabla \times \vec{A} \quad \text{(20)}$$

$$\vec{E} = -\frac{\partial \vec{A}}{\partial t} - \nabla \phi \quad \text{(21)}$$

Inducting Lorentz limitative condition

$$\nabla \cdot \vec{A} = -\mu \epsilon \frac{\partial \phi}{\partial t} \quad \text{(22)}$$

into Maxwell equations, magnetic field and electric field were solved respectively to obtain the solution of electromagnetic parameters.

Physical characters of related mediums appeared in numerical simulation model are shown in Table 2. Related electromagnetic parameters set in numerical simulation model are shown in Table 3.

4.2. The 2-D Simulation Results

The distribution of high frequency (20,000 Hz) magnetic field in simplified 2-D mold segment model and slit model are respectively shown in Figs. 6 and 7.

In Fig. 6, the materials of mold wall were consisted of Cu and insulation materials. The materials in the middle of mold wall around strand meniscus is insulation materials, so the electromagnetic field can permeate entirely the mold wall and imposed on the metal strand completely. Due to the skin-concentrated effect of high frequency electromagnetic field, it almost imposes on the surface of metal strand. The thickness of skin-concentrated layer lies on the frequency of electromagnetic field.

In Fig. 7, the high frequency magnetic field is shielded completely by copper mold wall. So the high frequency electromagnetic wave can not permeate the metal mold without slit to impose on metal strand.

For further research on the details of high frequency electromagnetic field penetrating across slit copper mold and imposing on metal strand, it is really necessary to simulate the 3-D distribution of electromagnetic field, electromagnetic body force and eddy current in soft contact mold. So we established a 3-D model in the next step.

4.3. The 3-D Numerical Simulation

4.3.1. The Research Object

The research object is designing a soft contact continuous casting slit billet mold, the structure of soft contact mold is shown in Fig. 8, and its concrete size is shown in Fig. 9.

Here the structure and size of simulation model is same as the actual mold. Due to the symmetry of the billet mold, so the quarter of mold is researched. The inner size of the billet copper mold tube is $80 \times 80 \text{ mm}$, and its length is $200 \text{ mm}$, the thickness of copper wall is $6 \text{ mm}$. There are 4 slits were split along the casting direction on every side of copper mold, and insulation materials are filled into the slits...
between segments of mold, the size of every slit is $1 \times 6 \times 200$ mm. In view of simulation of gap between strand and mold wall and the divisional rationality of elements, the thickness of gap is set as 1 mm.

On the bases of the research results of reference literatures,$^4$–$^6$ the electromagnetic force imposed on meniscus region is considered maximal when strand meniscus is located at the middle position of induction coil height. So, in the research work, the liquid metal level was supposed as plane, and its position located at the middle of coil height.

4.3.2. Establishment of Finite Element Simulation Model

The finite element model was established according to the real structure of mold, the simulation area is shown in Fig. 10. Mold, strand, coil and sufficient free space were included.

Basic assumption:
1) The liquid metal level is supposed as plane, and the effect of meniscus shape on magnetic field was neglected.
2) The liquid metal level is located at middle of coil height.
3) Solidification process of strand is not considered.
4) Oscillation of mold is ignored.
5) Gap is not conductive.

There are 30 841 elements and 14 476 nodes totally in the finite element model.

On account of the symmetry of model, parallel flux conditions are set as boundary condition of symmetrical faces. The magnetic vector potential at the distance of 6 times mold height is set as zero.

The frequency parameters are set as 50, 1 000, 10 000, 20 000, 40 000, 100 000 Hz, and the ampere-turn of coil is 10 000.

4.3.3. Simulation Results

Magnetic flux density $\vec{B}$ is vector sum of $\vec{B}_x$, $\vec{B}_y$, and $\vec{B}_z$, its unit is Tesla. Electromagnetic force $\vec{F}$ is vector sum of $\vec{F}_x$, $\vec{F}_y$, $\vec{F}_z$, its unit is Newton, represents the integral value of volume density of electromagnetic force in element. In fact, there are so many elements of different size in a simulation model, the absolute value of electromagnetic force acted on different size element can not show the actual effect. So electromagnetic force must be transformed into electromagnetic body force, viz. volume density of electromagnetic force. Electromagnetic body force is the key parameter to explain the essence of function of high frequency electromagnetic field, it can explain and compare clearly the magnitude of electromagnetic force acted on any position in mold. So in the latter analysis, we transform electromagnetic force into electromagnetic body force, its unit is Newton/m$^3$. The unit of density of eddy current $JT$ is A/m$^2$.

The vector simulation results of 3-D electromagnetic field at 20 000 Hz frequency are shown in Figs. 11 to 14. The simulation results of magnetic flux density in whole region are shown in Fig. 11, its distribution is accorded very well with right hand spiral rule. At the same time, owing to
the shielding effect of metal on high frequency magnetic field, electromagnetic field mainly acts on the surface layer of metal strand. Magnetic flux density has its maximal value, 0.129 Tesla, in the gap near meniscus of strand in whole simulation area.

The simulation results of magnetic flux density in metal strand are shown in Fig. 12. Under the slit of mold, the magnetic flux density on surface of strand is higher than in other region of the strand, and it mainly acts on the surface layer. Magnetic flux density has its maximum value 0.12 Tesla at the surface of charge near meniscus, and decrease monotonously into the charge.

The simulation results of induction eddy current in metal strand, slit mold and coil are shown in Fig. 13. Under the action of high frequency magnetic field, eddy current mostly fixed on the surface of conductor, and form respectively a close loop in each separated conductor.

The distribution of electromagnetic force in metal strand is shown in Fig. 14. All of the electromagnetic forces are perpendicular to the surface and pointing to the inner of strand, and their values attenuate rapidly towards center of strand.

4.3.4. Analysis of Numerical Simulation Results

For further understanding the simulation results, 3 typical paths on the surface of metal strand are selected to analyze the change rule of electromagnetic parameters, and shown in Fig. 15. The results of numerical simulation were compared with the results of analytical model.

Path 3 is on the surface of strand, locates at the middle of segments between 2 slits and parallels to the axis of mold. Distribution of magnetic flux density and electromagnetic body force and their concrete values on path 3 are shown respectively in Figs 16 and 17. We can see from these two figures the changes of different frequency electromagnetic field along the casting direction. Along with the increase of frequency, the electromagnetic body force on path 3 increases greatly, especially at the location of liquid metal level. At the exit of mold, the value of electromagnetic body force decreases close to zero due to the sparseness of magnetic flux.

Attenuation of magnetic flux density and electromagnetic body force and their concrete values on path 1 are shown respectively in Figs. 18 and 19. Path 1 locates at the intersectant position of symmetry face and liquid level. The attenuation rate of magnetic flux density and body force increase rapidly, and the actual value of electromagnetic body force on the surface of metal strand is improved greatly with the increase of frequency.

The simulation results of magnetic flux density and electromagnetic body force on path 2 are shown in Figs. 20 and
Path 2 locates at the intersectant position of surface and liquid level of strand, crosses the regions under slits and segments of mold. We can see from these two figures, the uneven distribution of magnetic field is enhanced slightly with the increase of frequency. When the frequency is set as 40,000 Hz, the value of magnetic flux density at the slit region is 10% higher than the segments region on path 2, and that the distribution of electromagnetic body force on path 2 under different frequency are basically uniform. In Fig. 20, magnetic flux density $\vec{B}$ is vector sum of $\vec{B}_x$, $\vec{B}_y$, and $\vec{B}_z$. We can see from Fig. 22, vector $\vec{B}$ under slits of mold has angle with the surface of strand (direction Z), but vector $\vec{B}$ under segments runs parallel with the surface of strand. In fact, centripetal forces shown in Fig. 21 are formed mainly by $\vec{B}_z$, we can consider that vector $\vec{B}_z$ on path 2 is uniform, this is the reason of uniformity of electromagnetic body force shown in Fig. 21.

So we can conclude that electromagnetic field can be imposed homogeneously comparatively on the metal strand permeating slit copper mold. In the region near the corner of mold, the value of electromagnetic body force imposed.
on the corner of metal strand decreases, the reason is that the corner of copper mold has no slit.

5. Comparison of Results Obtained from Analytical Model and Numerical Simulation

Comparing Fig. 2 and Fig. 18, Fig. 2 shows attenuation of magnetic flux density without dimension from the surface to center of strand, and Fig. 18 shows the concrete attenuation value of magnetic flux density from the surface to the center of strand. The change trend of curves in these two figures agrees with each other.

The attenuation curves of electromagnetic body force without dimension are shown in Fig. 4, and the corresponding simulation value is shown in Fig. 19. From these two figures, we can conclude that the explanatory issues deduced from the two methods coincide well.

6. Conclusion

(1) The attenuation of magnetic flux density, electromagnetic body forces and magnetic pressure along the radius direction in copper mold filled with liquid steel can be grasped wholly by analytical model. From these analytic results, we can conclude that the optimal frequency adopted in soft contact technology should be set in the range of 20–40 kHz.

(2) The frequency of power supply is the key parameter for soft contact technology.

(3) In the range of 50–100 kHz, the value of electromagnetic body force imposed in metal strand, especially in the region around meniscus, increase greatly with the increase of frequency. But their uneven distribution on the transverse direction will be enhanced with the increase of frequency, especially when frequency changed from 40 to 100 kHz.

(4) From the simulation results on path 2, magnetic frequency ranges from 20–40 kHz is optimum in order to maintain meniscus homogeneously.

(5) When the frequency increases, the attenuation speeds of magnetic flux density and electromagnetic body force from the surface to the inner of metal strand increase, and the value of electromagnetic body forces at the surface of strand, especially at the liquid level, are enhanced greatly.

(6) Along with the casting direction, magnetic flux density and electromagnetic body force in strand decrease gradually to almost zero at the exit of slit mold.

(7) Electromagnetic field can permeate slit copper mold and act uniformly comparatively on the surface of strand.

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