Research Article

Xingjuan Wang*, Hebin Jin, Liguang Zhu, Ran Liu*, and Tushun Song

Effect of high-frequency electromagnetic field on microstructure of mold flux

<https://doi.org/10.1515/htmp-2020-0037>

received June 15, 2019; accepted October 21, 2019

Abstract: Soft-contact of molten steel can be achieved by applying a high-frequency electromagnetic field above the mold of continuous casting, which can effectively eliminate surface defects and achieve billets with no cracks and no oscillation marks. It also has some influence on the mold flux. In this study, the effect of a high-frequency electromagnetic field (20 kHz) on a mold flux flow field was simulated using a finite element software, and the slag film was extracted using a slag film simulator. The effect of the high-frequency magnetic field on the microstructure of the mold flux was analyzed using X-ray diffraction, Raman spectroscopy, and mineral phase testing. The results show that the high-frequency electromagnetic field disrupts the orderly movement and increases the movement rate of the liquid flux. The precipitate phase of the slag film did not change, but the silicate dimer Q_1 decreased, the chain Q_2 increased, and the network degree was increased. The slag film structure changed from the original two-layer form of crystalline layer–glass layer into a three-layer form of crystal layer–glass layer–crystal, and the crystallization ratio increased by 35% on average. The grain-size melilite granularity was reduced from the original 0.12 to 0.005 mm.

Keywords: soft contact electromagnetic continuous casting, mold flux, flow field, crystallization

1 Introduction

Soft-contact electromagnetic continuous casting technology can significantly improve the billet surface quality, which has been an interest in the field of metallurgy [1]. The basic principle of this technology is that a group of induction coils with an alternating current (AC) is placed at the top of the mold. The electromagnetic stress produced by the AC magnetic field reduces the contact pressure between the molten steel and mold wall and decreases the effect of mold oscillation on the billet surface quality, such that the molten steel achieves a “soft contact” [2,3]. The principle diagram is shown in Figure 1.

Currently, soft-contact electromagnetic continuous casting technology research focuses mainly on the soft-contact mold, the electromagnetic field imposition method, the electromagnetic field distribution, meniscus shape control, and mechanisms for improving billet surface quality aspects [4–10]. However, there has been little research on the mold flux. Utech and Flemings [11] and Chedzey and Hurlle [12] proposed that the magnetic field can suppress the slag turbulence and improve the microscopic uniformity of the crystal growth. Okazawa et al. [13] studied the change of flux viscosity in mold flux, and the results showed that the flux viscosity decreased under direct current (DC) but increased under AC. The research by Na et al. [14] showed that the electromagnetic stress under a high-frequency electromagnetic field could increase the temperature of the billet and mold and reduce the slag film viscosity. Wang et al. [15] concluded that both DC and AC electric fields can effectively promote the crystallization of the slag. Studies on the effects of the electric field on flux mainly concentrated on the conductivity, viscosity, and crystallization characteristics under the action of DC or AC, while its influence on the microstructure of flux under a high-frequency alternating electromagnetic field has not yet been reported. It is well known that the metallurgical properties of mold flux are determined by its microstructure. It is necessary to study whether the

* **Corresponding author: Xingjuan Wang**, College of Metallurgy and Energy, North China University of Science and Technology, Tangshan 063210, China; Hebei Engineering Research Center of High Quality Steel Continuous Casting, Tangshan 063000, China, e-mail: wxingjuan@ncst.edu.cn

* **Corresponding author: Ran Liu**, College of Metallurgy and Energy, North China University of Science and Technology, Tangshan 063210, China, e-mail: liuran@ncst.edu.cn

Hebin Jin: College of Metallurgy and Energy, North China University of Science and Technology, Tangshan 063210, China; Hebei Engineering Research Center of High Quality Steel Continuous Casting, Tangshan 063000, China

Liguang Zhu: Hebei University of Science and Technology, Shijiazhuang 050018, China

Tushun Song: Hebei Engineering Research Center of High Quality Steel Continuous Casting, Tangshan 063000, China

Figure 1: Principle diagram of soft-contact electromagnetic continuous casting.

microstructure and metallurgical properties of mold flux change and how they change due to the electromagnetic force when a high-frequency electromagnetic field is applied outside the continuous casting mold [16–18].

In this article, the influence of a high-frequency electromagnetic field on the flow field of a continuous casting protection mold flux was simulated using finite element software, and the mold flux film was extracted under a 20 kHz magnetic field. Viscosity, solidification, crystallization, and microstructure characteristics of the mold flux film were analyzed by X-ray diffraction (XRD), Raman spectroscopy, and mineral phase. The influence of high-frequency magnetic field on the liquid crystal characteristics of continuous casting mold flux was studied, which provided a theoretical basis for the selection of soft-contact electromagnetic mold flux.

2 Materials and methods

2.1 Sample preparation

The mold flux MW2, which is used in some steel plants, was selected as the experimental material, and its composition is presented in Table 1.

Molten mold flux has ionic properties, and the ions exhibit certain electromagnetic properties. In this study, the influence of a high-frequency electromagnetic field on the flow field of mold flux was first simulated using finite element analysis software. The mold flux is mainly composed of silicate, and the contents of the mold flux are slightly different. The influence of an AC electromagnetic field on the flow field of different molten mold flux is almost the same. Therefore, the effects are not only valid for MW2 but also valid for various types of silicate mold flux.

Conversely, to further study the microstructure, mold flux film was made using the slag film simulator, as shown in Figure 2. The size of the copper probe was $35 \times 20 \times 20 \text{ mm}^3$, and there were two thermocouples inside the copper probe. A cooling water flow rate through the probe of $0.2 \text{ m}^3 \text{ h}^{-1}$ was maintained to obtain the crystal morphology similar to that of the industry mold flux film. After the flux temperature increased to $1,400^\circ\text{C}$ and remained for 10 min, the copper probe was placed into the liquid mold flux. Timing began when the surface of the probe was in contact with the liquid slag surface. The probe was then removed after 45 s, and the solid mold flux film was attached to the probe, as shown in Figure 2. The cooled mold flux film was removed from the probe, as shown in Figure 3.

Table 1: Chemical composition of mold fluxes/%

Flux	SiO ₂	MgO	CaO	Fe ₂ O ₃	MnO ₂	Al ₂ O ₃	C	Na ₂ O	K ₂ O	F ⁻	R
MW2	32.54	0.80	38.02	0.33	0.11	3.42	7.29	7.50	0.11	8.61	1.17

Figure 2: Slag film simulator.

The mold flux film under the condition of no magnetic field was obtained using the mold flux film simulator in the traditional MoSi_2 tube furnace, and the mold flux film under the condition of high-frequency electromagnetic field was completed in a high-frequency heating furnace. Four water-cooled copper induction coils were arranged around the outside of the high-frequency heating furnace, and the power oscillation frequency was 20 kHz. The reliability of the equipment in the experimental process had an important effect on the measurement results. To ensure comparability of experimental results, the high-frequency heating furnace had the same furnace size as the traditional MoSi_2 tube furnace, and the thermocouple was placed in the same position at the bottom of the furnace to ensure that the test temperature was the same. Second, the same graphite crucible was used, and the test mold flux was 350 g in both conditions.

In the experiment, the mold flux temperature in the traditional MoSi_2 tube furnace increased to 1,400°C and remained at that temperature for 10 min, but in the high-frequency heating furnace, after the mold flux changed to liquid completely, the temperature could be stabilized to 1,400°C when the frequency of power oscillation was 20 kHz. Each group of tests was performed three times to ensure good reproducibility of the experimental results, and the average value was considered to be the test result.

2.2 Model establish

ANSYS finite element software was used to numerically calculate the electromagnetic field and the flux flow field in the mold. The electromagnetic force is loaded into the fluid model as a momentum source through the coupling of the electromagnetic field and the flow field [19]. The size and the direction of the velocity component of each node of the flux fluid were obtained.

In the model, the billet was $100 \times 100 \text{ mm}^2$, the mold height was 700 mm, the number of mold slit was 16, and the width of the slit was 0.5 mm. The exciting coil had four turns and was of 100 mm height and 40 mm width, and the top of the coil was at a distance of 50 mm from the top of the mold. The liquid steel surface was 100 mm from the top of the mold and located at the center of the coil. The power frequency was 20 kHz, the effective value of the current intensity was 630 A, the conductivity of steel was $8.5 \times 10^{-7} \Omega^{-1} \text{ cm}^{-1}$, and the relative permeability of copper and air was 1. The model of a high-frequency electromagnetic field in soft-contact electromagnetic continuous casting mold was established and calculated in a previous study [20].

2.2.1 Basic assumptions

To improve computational efficiency, basic assumptions are required for reasonable simplification and

Figure 3: Physical pictures of mold flux film.

are necessary in the process of numerical simulations [21,22]. The hypothetical conditions are as follows:

1. The flow of flux in the crucible is a steady-state incompressible viscous flow process.
2. The influence of other factors on the flow of flux is ignored.
3. The calculated boundary is a no-slip boundary; that is, the velocity is 0, $k = 0$, and $\varepsilon = 0$.

2.2.2 Fundamental equations

The fluid equation of flux under electromagnetic force is different from that of the ordinary fluid. Thus, it is necessary to add an electromagnetic force to the momentum equation as a momentum source [23,24]. The governing equations are as follows:

Continuity equation:

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} = 0. \quad (1)$$

Momentum equation (N-S equation):

X-direction:

$$\begin{aligned} & \rho \left(\frac{\partial u_x}{\partial \tau} + u_x \frac{\partial u_x}{\partial x} + u_y \frac{\partial u_x}{\partial y} + u_z \frac{\partial u_x}{\partial z} \right) \\ &= -\frac{\partial p}{\partial x} + \mu_{\text{eff}} \left[\frac{\partial^2 u_x}{\partial x^2} + \frac{\partial^2 u_x}{\partial y^2} + \frac{\partial^2 u_x}{\partial z^2} \right] + \rho G_x + F_{\text{emx}}. \end{aligned} \quad (2)$$

Y-direction:

$$\begin{aligned} & \rho \left(\frac{\partial u_y}{\partial \tau} + u_x \frac{\partial u_y}{\partial x} + u_y \frac{\partial u_y}{\partial y} + u_z \frac{\partial u_y}{\partial z} \right) \\ &= -\frac{\partial p}{\partial y} + \mu_{\text{eff}} \left[\frac{\partial^2 u_y}{\partial x^2} + \frac{\partial^2 u_y}{\partial y^2} + \frac{\partial^2 u_y}{\partial z^2} \right] + \rho G_y + F_{\text{emy}}. \end{aligned} \quad (3)$$

Z-direction:

$$\begin{aligned} & \rho \left(\frac{\partial u_z}{\partial \tau} + u_x \frac{\partial u_z}{\partial x} + u_y \frac{\partial u_z}{\partial y} + u_z \frac{\partial u_z}{\partial z} \right) \\ &= -\frac{\partial p}{\partial z} + \mu_{\text{eff}} \left[\frac{\partial^2 u_z}{\partial x^2} + \frac{\partial^2 u_z}{\partial y^2} + \frac{\partial^2 u_z}{\partial z^2} \right] + \rho G_z + F_{\text{emz}}. \end{aligned} \quad (4)$$

Turbulent kinetic energy equation k :

$$\begin{aligned} & \rho \left(u \frac{\partial k}{\partial x} + v \frac{\partial k}{\partial y} + w \frac{\partial k}{\partial z} \right) - \frac{\partial}{\partial x} \left(\frac{\mu_{\text{eff}}}{\sigma_k} \frac{\partial k}{\partial x} \right) - \frac{\partial}{\partial y} \left(\frac{\mu_{\text{eff}}}{\sigma_k} \frac{\partial k}{\partial y} \right) \\ & - \frac{\partial}{\partial z} \left(\frac{\mu_{\text{eff}}}{\sigma_k} \frac{\partial k}{\partial z} \right) = G - \rho \varepsilon. \end{aligned} \quad (5)$$

Turbulent kinetic energy dissipation rate equation ε :

$$\begin{aligned} & \rho \left(u \frac{\partial \varepsilon}{\partial x} + v \frac{\partial \varepsilon}{\partial y} + w \frac{\partial \varepsilon}{\partial z} \right) - \frac{\partial}{\partial x} \left(\frac{\mu_{\text{eff}}}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x} \right) - \frac{\partial}{\partial y} \left(\frac{\mu_{\text{eff}}}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial y} \right) \\ & - \frac{\partial}{\partial z} \left(\frac{\mu_{\text{eff}}}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial z} \right) = C_1 \frac{\varepsilon}{k} G - C_2 \rho \frac{\varepsilon^2}{k}. \end{aligned} \quad (6)$$

Equations (1)–(6) are combined in the formula:

$$G = \mu_t \frac{\partial u_i}{\partial x_i} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right), \quad (7)$$

where

$$\begin{aligned} \mu_{\text{eff}} &= \mu_t + \mu \\ \mu_t &= \rho C_\mu \frac{k^2}{\varepsilon}. \end{aligned} \quad (8)$$

The recommended values of Launder and Spalding are used for the five constants in the k - ε two-way model, as presented in Table 2.

In the aforementioned formulae:

v – velocity, m s^{-1}

v_x, v_y, v_z – velocity component in x, y , and z direction, m s^{-1}

ρ – density, kg m^{-3}

τ – time, s

u_i, u_j – time-averaged velocity of turbulent flow, m s^{-1}

p – pressure acting on a fluid microelement, Pa

μ_{eff} – effective viscosity coefficient, Pa s

G – body force component in x, y, z direction, N

G_x, G_y, G_z – body force, N

F_{em} – time-averaged electromagnetic force, N

μ – viscosity, Pa s

μ_t – turbulent momentum diffusion coefficient or turbulent viscosity coefficient, Pa s

k – turbulent energy, $\text{m}^2 \text{s}^{-2}$

ε – turbulent kinetic energy dissipation rate, $\text{m}^2 \text{s}^{-3}$

$\sigma_k, \sigma_\varepsilon$ – corresponding Prandtl number of turbulent energy k and dissipation rate ε .

2.2.3 Boundary conditions

Free surface: The shear stress on the surface is zero, the velocity component vertical to the liquid surface is zero,

Table 2: Five constants of the k - ε two-way model

C_1	C_2	C_μ	σ_k	σ_ε
1.44	1.92	0.09	1.0	1.3

and the derivative of other variables perpendicular to the free surface is also set to zero. That is,

$$\frac{\partial \phi}{\partial n} = 0, \quad \phi = v, k, \varepsilon. \quad (9)$$

The side wall is set as the fixed surface, that is, $v = 0$.

Exit: The gradient of any variable in the normal direction is zero, that is,

$$\frac{\partial \phi}{\partial n} = 0, \quad \phi = v, k, \varepsilon. \quad (10)$$

2.2.4 Model

In continuous casting, the molten mold flux exists on the free surface of the molten steel and the gap between shell and mold. To fully observe the effect of the electromagnetic field on the flow field of molten mold flux, it is assumed that the mold flux is filled with mold. The flux viscosity is $0.007 \text{ kg m}^{-1} \text{ s}^{-1}$, and the density is 700 kg m^{-3} . The computational accuracy and computational complexity were considered comprehensively in the mesh process, and the skin effect of the electromagnetic field was taken into account. The mesh grid density was gradually encrypted from the flux center to the surface, the ratio of the grid step size was 4, and the minimum step size was 2 mm. The mesh was consistent with the electromagnetic field model to transfer the data accurately. The simulated fluid model and the mesh division are shown in Figure 4.

Figure 4: Model mesh division of flux.

magnetic field (20 kHz). Because the velocity of molten mold flux is zero under the experimental conditions without the magnetic field, to be consistent with the experimental conditions, we assume that the flux flow velocity is zero in the absence of a magnetic field. By comparing the flow pattern of flux under the action of no magnetic field and a high-frequency magnetic field, after applying the high-frequency electromagnetic field, the electromagnetic force pushes the fluid on the external surface upward. When it reaches the top of the molten slag pool, it moves downward from the center, forming an inward vortex flow. Because of the coil position, the high-frequency electromagnetic field mainly affects the fluid flow in the upper part and has little effect on the flow of the lower part. The flow velocity of the molten mold flux is in the range of

3 Results and discussion

3.1 Numerical simulation of melt flux flow field

Figure 5 shows the distribution of the electromagnetic force vector of the mold flux on the upper surface. Figure 5 shows that the electromagnetic force mainly acts on the external surface of the mold flux under the action of the high-frequency electromagnetic field. Although there is no typical result like the skin effect of the molten steel, the direction of the electromagnetic force is mainly toward the center of the slag pool, and it also plays a certain role in stirring.

Figure 6 shows the distribution of the longitudinal profile flow field in the mold flux film center under the condition of no magnetic field and of the high-frequency

Figure 5: Electromagnetic force vector distribution of flux on the upper surface (N).

Figure 6: Flow field of flux under different conditions (m s^{-1}).

$0.0004\text{--}0.004 \text{ m s}^{-1}$ under the high-frequency electromagnetic field [25–28].

3.2 Microstructure analysis of mold flux

3.2.1 XRD testing

The aims of this article are to further detect the mineral phase composition in the mold flux film and to observe the influence of the electromagnetic field on the mineral phase. The slag film prepared under different conditions was ground to a particle size of 200 mesh (under $75 \mu\text{m}$), and an XRD experiment was performed using DX2500

X-ray diffractometer of Japan Science Co., Ltd, with radiation source Cu [29,30]. The experimental results are shown in Figure 7.

As shown in Figure 7, regardless of the application of a high-frequency electromagnetic field, the phase of the mold flux film was basically unchanged, and the main phase of the slag precipitation was melilite ($2\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{SiO}_2$). The diffraction intensity of various phases on the spectrum was reduced under the high-frequency electromagnetic field, showing that the phase precipitation or crystal development of the flux under the action of the high-frequency electromagnetic field was changed. There is no cuspidine precipitation in the whole experiment. The reason is that Na_2O content inhibits the formation of cuspidine and promotes the formation of melilite [31]. The content of Al_2O_3 is less than 6%, which can inhibit the formation of cuspidine in the mold flux [32].

3.2.2 Mineral phase analysis

To further study the microstructure of the mold flux film, a mineral phase analysis was carried out. First, a mold flux film with 5 mm thickness was cut using an ultra-thin slicer along the cross-section of the mold flux film samples (Figure 3(b)). It was cemented with turpentine glue, heated, and dried in an electric oven at $50\text{--}60^\circ\text{C}$ and ground to the flat light by grinder. Then with solid fir glue to fix the mold flux film sample on the carrier sheet, and was ground to $0.04\text{--}0.05 \text{ mm}$ thickness with a grinding machine again. Finally, the mold flux film was ground to 0.03 mm on glass

Figure 7: XRD pattern of mold flux film.

Figure 8: Layer structure and mineral phase morphology of the mold flux film under the polarized microscope.

plate with chromium trioxide as the polishing solution. A 0.03 mm thin sheet was made of the mold flux film cross-section without magnetic field and with magnetic field application, and the mineral phase structure and morphology of the thin sheet were observed under a polarized microscope [33–35]. Figure 8 shows the mineral phase structure and the morphology of the mold flux film without magnetic field and under the high-frequency magnetic field (20 kHz).

As shown in Figure 8, the mold flux film is a two-layer structure without magnetic field, with a thickness of approximately 2.15–2.58 mm. A glass layer near the side of the mold and a crystalline layer near the melt side were present, where the crystalline layer was composed of melilite. The crystallization ratio of the mold flux film was 55–65%, and the melilite was well developed, with a granularity of 0.12–0.79 mm. Conversely, the slag film structure was divided into three layers when the magnetic field was applied. A small amount of melilite crystallites appear in the glass phase close to the mold. The total thickness of the mold flux film was 2.32–3.84 mm. The crystallization ratio of the mold flux film was 75–85%, and the melilite in the crystallization phase had increased significantly, but its further development was limited. The particle size range of approximately 70% of the melilite was 0.005–0.05 mm.

The high-frequency electromagnetic field had a significant effect on the overall morphology of the mold flux film, and the mold flux film changed from

the original two-layer structure form of crystalline layer–glass layer to a three-layer structure form of crystalline layer–glass layer–crystalline layer. The average thickness of the slag film increased by 50%. After applying the high-frequency electromagnetic field, the crystalline type of the mold flux film did not change. The types were still melilite. The development of melilite was obviously inhibited, and the granularity of the small-grain grade melilite decreased from 0.12 to 0.005 mm. Thus, the high-frequency electromagnetic field greatly reduced the granularity size of the grain in the slag film.

3.2.3 Effect of high-frequency electromagnetic field on silicate structure of mold flux

The mold flux belongs to silicate. There are five kinds of Si–O tetrahedron (Q_i) in silicate, each Q_i contains 1 Si^{4+} and 4 O^{2-} . The subscript i indicates that the Q_i contains i number of bridged oxygen, and $i = 0, 1, 2, 3$, or 4. These five Q_i are the primary microstructures [36], as shown in Figure 9.

In Raman spectroscopy, each of these five types of microstructure has its own specific peak position. The Raman shift near 578 cm^{-1} corresponds to the layered structure (Q_4), a 850 cm^{-1} region shift corresponds to the monomeric structure (Q_0), and a shift near 920 cm^{-1} corresponds to the dimer structure (Q_1). The chain silicate structure (Q_2) has a shift near $1,020\text{ cm}^{-1}$, and the ring silicate structure (Q_3) has a shift near $1,100\text{ cm}^{-1}$ [37].

The mold flux film sample was ground below 200 mesh and tested at room temperature with a Raman spectrometer. The test results are shown in Figure 10.

As shown in Figure 10, the Raman peak had no displacement after applying the high-frequency electromagnetic field, but the Raman strength decreased for dimer Q_1 , while the chain Q_2 increased. The types and relative quantities of silicate microstructure units changed after the magnetic field was applied. The dimer gradually changed to chain, the degree of silicate networking increased, the viscosity of the melt increased, the flow was suppressed, the heat transmission was inhibited, and the local supercooling degree was increased. The crystal development was inhibited.

Figure 9: Structure units of Q_i model.

Figure 10: Normal temperature Raman diagram of mold flux.

4 Conclusions

In this article, the effect of a high-frequency electromagnetic field (20 kHz) on mold flux flow field was simulated using finite element software ANSYS, the slag film was extracted using the slag film simulator, and the effect of the high-frequency magnetic field on the microstructure of the mold flux was analyzed with XRD, mineral phase, and Raman spectroscopy. The conclusions are as follows:

- (1) After applying the high-frequency electromagnetic field, the electromagnetic force pushed the fluid to form an inward vortex flow in the molten pool. Assuming that the flow velocity of molten mold flux was zero in the absence of magnetic field, the flow velocity of molten mold flux under 20 kHz high-frequency magnetic field reached $0.0004\text{--}0.004\text{ m s}^{-1}$.
- (2) Regardless of the application of a high-frequency electromagnetic field, the phase of the mold flux film was basically unchanged.
- (3) The high-frequency electromagnetic field had a significant effect on the overall morphology of the mold flux film. The mold flux film has changed from the original two-layer structure form of crystalline layer–glass layer to a three-layer structure form of crystalline layer–glass layer–crystalline layer.
- (4) The crystallization ratio increased by 35% on average, and the grain size of the melilite granularity was reduced from the original 0.12 to 0.005 mm.
- (5) The types and relative quantities of flux silicate microstructure units changed after the magnetic field was applied. The dimer gradually changed to chain, the degree of silicate networking increased, and the viscosity of the melt increased.

- (6) Motion disorder increased the number of mold flux film crystallites, and at the same time, the complex microstructure of flux inhibited the development of crystals. These are the main reasons for the increase of the crystallization ratio and the decrease of the grain size of the mold flux film under the action of a high-frequency electromagnetic field.

Acknowledgments: This work was supported by the National Natural Science Foundation of China (51404088 and 51774141) and the Natural Science Foundation of Hebei Province of China (E2015209217 and E2017209217).

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