Effects of electrode immersion depth and remelting rate on electroslag remelting process

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Abstract: In the electroslag remelting process, the electrode molten state is a critical factor determining the ingot quality, while the electrode immersion depth and melting rate are key factors for the stability of the electroslag re-melting process. Studies were carried out to investigate the microscopic and macroscopic effects of electrode immersion depth and melting rate on the potential distribution and heat density in the slag bath, and on the depth and shape of the molten bath. Based on the finite element method and the numerical solution method, the effect of the electrode immersion depth on the slag bath heat density was researched; the relationship between the electrode immersion depth and the slag resistance was obtained; and the unsteady-state model of the solidification process of the re-melting ingot was solved using the finite difference method. The mathematical model and physical model of the electrode melting process were established and solved; and the corresponding curves between the electrode molten-state and slag-bath physical parameters were obtained. The experimental results verified the simulated results studied in this paper.

Key words: electroslag remelting; electrode molten state; immersion depth; melting rate

ESR ingots are extensively used in aviation, aeronavigation, the military related industry and the energy industry. With the development of modern industry, the ESR ingots with larger tonnage and higher quality are urgently needed. Electroslag remelting is a complex physico-chemical reaction process. With the effect of electric field, magnetic field and temperature field, it is also a coupling reaction process of multi-physical fields [1]. The electrode melting rate and immersion depth into the slag bath are related to the multi-physical fields in the remelting process. They influence the potential distribution and heat density in the slag bath at the micro level, affect the depth and shape of the molten bath at the macro level, and then finally impact on the quality of the ingot produced. To keep the temperature field and melting pool in the electroslag remelting bath stable and uniform, it is necessary to conduct theoretical and experimental research on the effects of the electrode molten-state on the slag-bath physical parameters, mainly including the effects of the electrode immersion depth and electrode melting rate. In this paper, based on the mathematical modeling and finite element method, the effects of the electrode immersion depth and the electrode melting rate were studied.

1 Research method

The schematic diagram of electroslag remelting is shown in Fig. 1 [1].

To study the influence of electrode immersion depth on the slag-bath thermal field, and then get the relationship between the electrode immersion depth and the slag resistance, the finite element method and the self-adaptive meshing technique were used in this study based on the slag-bath electric potential field model. To obtain the relationship between electrode remelting speed and stable slag-bath depth, finite differential method was used to get numerical solution of the unstable ingot solidification process. The physical parameters in experiment were chosen using constant numerical method, which means a couple of parameters at low and high temperatures, respectively were used.

This study focuses on large ingot whose diameter is 800 mm and the remelting speed is about 4 kg·min⁻¹. Based on the similarity theory [2], experimental
parameters were designed as follows and experiments were conducted in laboratory. The geometric and remelting speed similarity scaling factor were set as 8, so the inner diameter of the mould in the experiment is 100 mm and the remelting speed is 0.5 kg·min⁻¹. The diameter of the electrode, \(d_e\) is \([3]\):
\[
d_e = K \cdot D_c
\]
where, \(D_c\) is diameter of the mould, \(K\) is loading ratio, assign \(K = 0.36\) in this study.

In the experiment, sensors were used to detect the parameters during the electrode remelting process, including the furnace transformer voltage, secondary voltage, inlet and outlet water temperature, and so on. The electrode length was calculated using soft detecting method. Substitute the detected parameters into the established mathematical models, thus the curves between the electrode immersion depth and remelting current, and the electrode melting rate and slag bath depth were obtained.

## 2 Effects of electrode immersion depth

### 2.1 Mathematical model

Because of the small magnetic Reynolds number in the electroslag remelting process, the current value of the slag bath is mainly dependent on electrical conduction \([4]\). In addition, compared with that in the main circuit, the induced current of the magnetic field is small and can be ignored. Suppose that every part of the slag bath shares the same conductance and the magnetic field is small and can be ignored. Suppose that compared with that in the main circuit, the induced current of the slag bath is mainly dependent on electrical conduction, the electric potential in the slag bath is as follows:
\[
\nabla^2 \phi = \frac{\partial^2 \phi}{\partial r^2} + \frac{1}{r} \frac{\partial \phi}{\partial r} + \frac{\partial^2 \phi}{\partial z^2} = 0
\]
(2)

where, \(\phi\) is the electric potential, \(r\) is the radius of slag bath.

Electric current density \((J)\) and local heat density \((\omega)\) are shown below:
\[
J = \sigma \left( \frac{\partial \phi}{\partial r} e_r + \frac{\partial \phi}{\partial z} e_z \right) \quad \omega = \sigma \left( \left( \frac{\partial \phi}{\partial r} \right)^2 + \left( \frac{\partial \phi}{\partial z} \right)^2 \right)
\]
where, \(\sigma\) is the conductance, \(e_r\) and \(e_z\) are the unit vector of \(r\) direction and \(z\) direction, respectively.

### 2.2 Boundary conditions

The boundary conditions of potential distribution in the slag bath are shown below in Fig. 2: when \(0 \leq r \leq r_m\) and \(z = z_e(r)\) or \(r = r_m\) and \(z_e \leq z \leq Z_s\), \(\phi = \phi_m\) then \(z_e(r)\) is calculated according to the equation (3):
\[
z_e(r) = Z_s + \frac{r}{r_m} (Z_s - Z_i)
\]
(3)

where, \(r_m\) is the electrode’s radius; \(r_m\) is the mould radius; \(y\) is the depth coordinate; \(z_e(r)\) is the distance between metallic bath and the electrode, when \(0 \leq r \leq r_m\) and \(z = Z_0, \phi = \phi_1\); when \(r_m \leq r \leq r_i\) and \(z = Z_s, \frac{\partial \phi}{\partial z} = 0\).

The resistance between slag bath and mould wall can be obtained according to Fig. 2 and is shown below.
\[
R_s = \frac{d_i}{(\sigma_s \pi D_m Z_i)}
\]
(4)

The resistance between the slag bath and the mould wall is:
\[
R_t = \frac{d_i}{(\sigma_s \pi D_m Z_m)}
\]
(5)

where, \(\delta_i\) and \(\delta_m\) are the slag-shell thickness of the slag bath area and the molten bath area, respectively, \(D_m\) is the diameter of the mould, \(Z_s\) and \(Z_m\) are the slag bath depth and the molten bath depth, respectively, \(\sigma_s, \sigma_m\) is the effective conductance considering the contact resistance of the slag shell and the mould. Therefore the total resistance can be got as:
\[
R_t = R_s + R_i = \frac{1}{\sigma_s \pi D_m Z_i} (\delta_i + \frac{Z_m - Z_i}{Z_m})
\]
(6)

The electric potential of the liquidus interface of the slag-bath is \(\phi(z)\), and the current density from slag to mould wall is shown below:
\[
\text{[\text{J}] = } \frac{\phi(z) - \phi_0}{R_t \pi D_m Z_i} \quad \text{when } r = r_m \text{ and } Z_0 \leq z \leq Z_s
\]
(7)

### 2.3 Finite element solution

The original technological parameters in the simulation of the remelting process with ANSYS finite element method are chosen based on experiments and shown in Table 1. The L-4 slag is developed by authors for large plate ingot ESR furnace, whose composition is shown in Table 2 and physical parameters are shown in Table 3.

During the electrode oscillating process, the relationship between \(d_i\) and \(d_t\) is:
where, $d_1$ is the swing distance of electrode, $d_2$ is the height of slag pool, $D_e$ is the diameter of electrode.

Based on the finite element method, the solid model of the slag pool was meshed by fourth-order discrete method. To enhance the precision accuracy, self-adaptive meshing technique was used and calculation error or residual error was limited to $1 \times 10^{-6}$.

To obtain the potential and electric current distribution of the slag bath based on the finite element method, numerical simulations were carried out when the immersion depth of electrode is 55 mm and the results are shown in Fig. 3 and Fig. 4. And it was found that, the inner current field and heat field were easy to be influenced by change of the electrode immersion depth, which would then influence the slag bath current resistance.

Assume that the furnace voltage remains stable, and make integral calculus to boundary current of the heat current field with the change of the electrode immersion depth, thus the relationship between melting current and electrode immersion depth is obtained, as shown in Fig. 5; and the relationship curve between slag resistance and electrode immersion depth is shown in Fig. 6.

Linear fitting method for slag resistances is used and the fitting curve is linear in two sections. According to Fig. 6, when the immersion depth varies from 13 mm to 55 mm, slag resistance changes slowly. However, when the depth increases from 1 mm to 13 mm, during which time the stable slag bath is forming, the resistance varies fast. So in the initial stages, the electrode immersion depth should be controlled accurately according to electric current changes. When the electrode immersion depth varies from 13 mm to 55 mm, the slag bath current resistance changes slowly, so electrode remelting speed can be controlled more precisely, which is beneficial to producing large ESR ingot.

### Table 1: Technological parameters in simulation of remelting processes

<table>
<thead>
<tr>
<th>Voltage of furnace mouth (V)</th>
<th>Slag system</th>
<th>Z₁ (mm)</th>
<th>Z₂ (mm)</th>
<th>Z₃ (mm)</th>
<th>δ₁ (mm)</th>
<th>δ₂ (mm)</th>
<th>Z₄ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>L-4</td>
<td>37</td>
<td>37</td>
<td>92</td>
<td>1.8</td>
<td>0.7</td>
<td>20</td>
</tr>
</tbody>
</table>

### Table 2: Composition of L-4 slag (wt.%)

<table>
<thead>
<tr>
<th>Slag system</th>
<th>CaF₂</th>
<th>Al₂O₃</th>
<th>CaO</th>
<th>SiO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-4</td>
<td>50–60</td>
<td>10–30</td>
<td>10–20</td>
<td>≤10</td>
</tr>
</tbody>
</table>

### Table 3: Physical parameters of L-4 slag

<table>
<thead>
<tr>
<th>Slag system</th>
<th>Slag conductance (Ω⁻¹·m⁻¹)</th>
<th>Effective conductance of slag shell (Ω⁻¹·m⁻¹)</th>
<th>Viscosity (Pa·s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-4</td>
<td>185</td>
<td>0.24 (1650 °C)</td>
<td>0.18</td>
</tr>
</tbody>
</table>

$$\pi D_e^2 \cdot d_i = \pi (D_e^2 - d_i^2) \cdot d_i \cdot \frac{d_1}{d_2} = \left( \frac{D_1}{D_2} \right)^2 - 1$$

![Fig. 3: Potential distribution of slag bath](image)

![Fig. 4: Distribution of electric current density in slag bath](image)

![Fig. 5: Curve between melting current and immersion depth of electrode](image)

![Fig. 6: Curve between slag resistance and immersion depth of electrode](image)
3 Effects of electrode melting rate

3.1 Mathematical model

Because the shape of the steel ingot is symmetrical, the 2-D model was established\(^6\). The mathematical model of electrode melting rate can be established in plane coordinates:

\[
\rho c_p \frac{\partial T}{\partial t} = \frac{1}{\partial r} \left( \frac{p}{\partial r} \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right) + S \tag{8}
\]

where, \(c_p\) is the equivalent specific heat capacity, \(\lambda\) is the effective thermal conductivity, \(p\) is the density of liquid metal, \(S\) is the inner heat source, and \(T\) is the temperature.

3.2 Boundary conditions

The structure diagram of the boundary layer is shown in Fig. 7. The boundary layer is made up of a slag shell, a mould wall and the air between them. The mould bottom is made of copper, and the top of the molten bath is the interface of slag and metal. Boundary conditions can be described as below\(^7\)–\(^8\).

When \(r = 0\) and \(Z_0 \leq z \leq Z_3\), the equation (9) can be obtained.

\[
\frac{\partial T}{\partial r} = 0 \tag{9}
\]

\[
-\lambda_{sl} \frac{\partial T}{\partial z} = h(T - T_w) \tag{10}
\]

\[
\lambda_{sl} = \frac{2\pi k_{Cu}}{\ln \left( \frac{1 + \delta_{Cu}}{r} \right)} \tag{11}
\]

where, \(R_s\) is the crystallizer radius, \(h\) is the heat transfer coefficient, \(k_{Cu}\) is the thermal conductivity of the mould wall, \(\delta_{Cu}\) and \(T_w\) are the thickness and temperature of the mould wall respectively.

When \(r = R_s\) and \(Z_0 \leq z \leq Z_3\), equation (12) can be obtained.

\[
\frac{2\pi}{\ln \left( \frac{1 + \delta_{sl}}{r} \right)} \frac{\partial T}{\partial r} = h(T - T_w) \tag{12}
\]

where, \(\delta_{sl}\) and \(\delta_{air}\) are the thicknesses of the slag layer and the air gap at sidewall respectively, \(k_{sl}\) and \(k_{air}\) are the thermal conductivities of the slag layer and the air gap at sidewall respectively.

When \(z = Z_3\) and \(0 \leq r \leq R_e\), the equations (13) and (14) can be obtained.

\[
-\lambda_{sl} \frac{\partial T}{\partial z} = h \left( T_e - T \right) + \frac{m}{\pi R_e} c_p \left( T_a - T \right) \chi \tag{13}
\]

\[
\chi = \begin{cases} 
0 & (r > R_e) \\
1 & (r \leq R_e) 
\end{cases} \tag{14}
\]

where, \(R_e\) is radius of the electrode, \(\lambda_{sl}\) is the heat conductivity when the depth is \(Z_3\), \(h_{sl}\) is the heat transfer coefficient of the interface between slags and metal, \(T_{sl}\) and \(T_{rd}\) are the temperature of slag bath and molten drops respectively, and \(m_e\) is the melting rate of electrode.

3.3 Numerical solution

By meshing and discretizing the governing equations and boundary conditions, the iterative computation was carried out. The experimental data were used for verifying the model parameters. Carbon structural steel of 45#, whose chemical compositions were listed in Table 4, was utilized in the experiment.

Table 4: Chemical compositions of 45# steel in experiment (wt.%)

<table>
<thead>
<tr>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Cr</th>
<th>Ni</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.43</td>
<td>0.57</td>
<td>0.23</td>
<td>0.11</td>
<td>0.09</td>
<td>0.14</td>
</tr>
</tbody>
</table>

The inner diameter of the mould is 100 mm and the diameter of the electrode is 36 mm according to equation (1). The L-4 slag system was used in the electroslag remelting process, and FeS was used to display the shape of the molten metal bath with sulphur print method. The furnace mouth voltage and slag bath depth are set as same as those in the ANSYS simulation, as shown in Table 1. The technological parameters in the experiment are shown in Table 5, where, \(H_1\) is the insert depth of the electrode, \(H_2\) is the cone height of the electrode.

The depth of the molten bath is the distance between the interface of slag and molten metal and the interface of molten metal and ingot, as shown in Fig. 8(a). The experimental results is shown in Fig. 8(b)\(^9\)–\(^10\). The results of the simulation and experiment are similar, which verifies that the model is reasonable.

Table 5: Technological parameters in experiment

<table>
<thead>
<tr>
<th>Electrical parameters</th>
<th>Depth of slag bath (mm)</th>
<th>Water flow (m(^3)/h(^-1))</th>
<th>Model parameters (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current (A)</td>
<td>Voltage (V)</td>
<td>92</td>
<td>1.4</td>
</tr>
</tbody>
</table>
The relationship curve between the melting rate and the maximum bath depth can be obtained by simulations and it is shown in Fig. 9. According to Fig. 9, the melting rate increases linearly with maximum bath depth. The similar experimental results were acquired when the slag bath depth varies from 50 mm to 100 mm.

4 Conclusions

(1) The relationship curve between slag resistance and electrode immersion depth is linear in the range from 7 mm to 55 mm. In addition, when the immersion depth is low, the slag resistance changes slowly. However, when the depth is high, the resistance varies more quickly.

(2) The relationship between the melting rate of electrode and the maximum molten bath depth is approximately linearly dependent when the slag bath depth varies from 50 mm to 100 mm.

(3) For a single-phase ESR furnace, with the increase of the slag bath depth, the slag resistance becomes more stable and the melting speed of the electrode becomes higher.

(4) It is found feasible to study the effect of electrode molten state on the electroslag remelting process with finite element method and adaptive meshing technique.

References


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