Numerical Investigation on the Effect of Slag Thickness on Metal Pool Profile in Electroslag Remelting Process

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A transient three-dimensional (3D) model was developed to understand the role slag thickness plays in the formation of the metal pool in the electroslag remelting (ESR) process. In this model, the solution of the mass, momentum and energy conservation equations were simultaneously implemented by the finite volume method with full coupling of the Joule heating and Lorentz force by solving the Maxwell’s equations. The movement of metal droplet was described by volume of fluid (VOF) approach. Additionally, the solidification was modeled using an enthalpy-based technique, where the mushy zone was treated as a porous medium. The experiment and simulation demonstrated a reasonable agreement. The results indicate that changing the slag thickness changes the slag temperature, but not monotonically. The slag temperature drops with the slag thickness up to 60 mm, beyond which the slag temperature rises. The melt rate decreases and then increases while the cooling intensity remains unchanged. As a consequence, the maximal metal pool depth reduces from 0.081 m to 0.067 m and slightly increases to 0.074 m.

KEY WORDS: electroslag remelting; solidification; slag thickness; metal pool; numerical simulation.

1. Introduction

ESR processes have been developed to produce high performance alloys for use in such fields as aeronautics, power generation, and tooling.\(^1\) Figure 1 shows a schematic of the ESR process. In this process, an alternating current (AC) is passed from the electrode to the baseplate, creating Joule heating in the highly resistive calcium fluoride-based molten slag. This heating is sufficient to melt the electrode. The interaction between the self-induced magnetic field and the AC gives rise to the Lorentz force. Dense metal droplets sink through the less dense molten slag to form a liquid metal pool in the water-cooled mold. Chemical refining occurs in the molten slag as the metal droplets fall. The metal is solidified as it loses heat to the mold, forming an ingot. A shallow liquid metal pool is maintained throughout the process. Finally, the AC is gradually reduced until all of the metal freezes.\(^2\)

As mentioned above, the Joule heating, which is the heat source of the ESR process, is generated by the slag. Varying the slag weight dramatically affects the solidification progress; it then logically influences the shape of the metal pool formed in the process. Moreover, it has been suggested that the metal pool profile profoundly alters the solute transport and macrosegregation map in the ESR ingot.\(^3\)\(^-\)\(^5\) Therefore, the effect of the slag weight on the metal pool profile should be clearly understood.

Given the complicated phenomena involved, and the difficulty and expense of performing experiments on a real apparatus, numerical simulations present an attractive approach to understanding the heat transfer and fluid flow in the process. In the past, efforts have been made to study the coupled electromagnetic, flow and temperature fields, and freezing in the ESR process.\(^6\)\(^-\)\(^9\) Weber et al. simulated the remelting of a nickel-based alloy by a two-dimensional axisymmetric model.\(^10\) The computed results matched well with experimental data. The model was then used to study the influence of the fill ratio on the ESR process. They hold that the amount of the Joule heating decreases with the increasing of the fill ratio, while its distribution becomes more homogeneous. Nevertheless, they did not consider the metal droplet. Li et al. employed a 3D finite element
model to understand the effects of the current frequency, electrode immersion depth and slag thickness on the current density and Joule heating distributions.\(^\text{11}\) They found that the maximum Joule heating density reduces by 53.2\% while the slag thickness increases from 0.15 m to 0.23 m. The velocity field and temperature distribution however were not demonstrated in their work. Wang et al. established a transient 3D model to investigate the effect of the current on the metal pool profile.\(^\text{12}\) The shapes of the metal pool profiles were similar to that of the isotherms. The shallow U-shaped metal pool changed to the deep V-shaped metal pool while the current ranged from 1 000 A to 2 000 A. Furthermore, the maximal metal pool depth increased from 34.0 mm to 59.5 mm.

As discussed above, there have been few attempts to numerically study the effect of the slag weight on heat transfer and magnetohydrodynamic flow in the ESR process. Because of this, the authors were motivated to establish a transient 3D comprehensive model that would study the role of the slag thickness on the solidification in this process. Here, we use the slag thickness to represent the slag weight due to a constant cross section of the mold. In addition, an experiment was carried out to validate the model.

2. Mathematical Modeling

2.1. Assumptions

In order to keep the computational time reasonable, the model relied on the following assumptions:

1. The domain included the slag, the metal pool and the ingot. The immersion depth of the electrode in the slag was ignored.\(^\text{10}\)
2. The density of slag and metal was assumed to be dependent on temperature. Besides, the effect of temperature on slag electric conductivity was also included. Other properties of slag and metal were assumed to be constant.\(^\text{13}\)
3. The slag and the ingot were electrically insulated from the mold by the solidified slag.\(^\text{6}\)
4. The solidification shrinkage was neglected.\(^\text{6}\)

2.2. Electromagnetism

The general transport equation for electromagnetic field was:\(^\text{14}\)

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \quad \ldots \ldots \quad (4)
\]

\[
\frac{\partial (\rho \vec{v})}{\partial t} + \nabla \cdot (\rho \vec{v} \vec{v}) + \vec{F}_e + \vec{F}_b + \vec{F}_d \ldots \ldots \quad (5)
\]

where \(\vec{F}_e\) was the Lorentz force and \(\vec{F}_b\) was the buoyancy force determined by the Boussinesq approximation. The damping force \(\vec{F}_d\), was employed to gradually block the velocity to zero in the mushy zone.

The RNG k-\(\epsilon\) turbulence model was used to calculate the turbulent viscosity. The standard k-\(\epsilon\) turbulence model was developed for flows with a high Reynolds number, but the RNG k-\(\epsilon\) turbulence model was able to also capture the behavior of flows with lower Reynolds number with an appropriate treatment of the near-wall region. An enhanced wall function was employed with the RNG k-\(\epsilon\) turbulence model, in particular since liquid metal had a low Prandtl number.\(^\text{15}\)

The interface between the metal and slag was tracked with the geometric reconstruction VOF approach, since it is a robust, powerful, and extensively applied technique. The continuum surface force model was implemented to consider the surface tension between the slag and metal.\(^\text{16}\)

2.4. Heat Transfer and Solidification

To obtain a precise prediction of the temperature distribution and solidification in the ESR process, the energy conservation equation of the enthalpy formulation was employed:\(^\text{17}\)

\[
\frac{\partial (\rho H)}{\partial t} + \nabla \cdot (\rho \vec{v} H) = \nabla \cdot (k_d \nabla T) + Q \quad \ldots \ldots \quad (6)
\]

The enthalpy of metal and slag was computed as the sum of the sensible enthalpy and the latent heat which is released in the mushy zone:\(^\text{18}\)

\[
H = h + f_i L \quad \text{and} \quad h = h_{\text{diff}} + \frac{r_c}{r_w} c_p dT \quad \ldots \ldots \quad (7)
\]

As mentioned above in Eq. (5), the velocity field must be blocked in the solid phase with the term \(\vec{F}_e\). An enthalpy-porosity formulation was used. It treats the mushy zone in the momentum equation as a “pseudo” porous medium in which the porosity gradually decreases from 1 to 0 as the metal solidifies. The permeability of the mushy zone is described by the Blake-Kozeny equation as:

\[
\vec{F}_d = \frac{(1 - f_p)^2}{f_p^2} A_{\text{mush}} \vec{v} \quad \text{and} \quad A_{\text{mush}} = \frac{180 \mu}{d_i^2} \quad \ldots \ldots \quad (8)
\]

where \(d_i\) indicated the primary dendrite arm spacing, and we take a value of 750 \(\mu m\) according to the reference.\(^\text{18}\)
2.5. Boundary Conditions

The magnetic field intensity was continuous at the inlet and bottom. It was also related to the current on the top surface of slag and the lateral walls:14)

\[ H_z = H_x = 0 \quad \text{................................. (9)} \]

\[ \frac{\partial H_z}{\partial z} = 0 \quad \text{................................. (10)} \]

Top surface of slag and lateral walls:

The melt rate, related to the Joule heating, was estimated:19)

\[ \dot{m} = \frac{\xi Q}{L} \quad \text{................................. (11)} \]

where \( \xi \) represented the power efficiency. It is difficult to estimate the exact value of the power efficiency, because it varies with different operating conditions. A reasonable power efficiency was obtained from literature, but was then adjusted according to the conditions of our experiment. We took a value of 0.16.19)

A no-slip condition was applied to the lateral walls and bottom. Zero shear stress was adopted on the top surface of the slag. To simplify the consideration of the melting process, the temperature of the metal at the inlet was given by a parabolic profile. This parabolic profile had an approximate 30 K superheat and a peripheral boundary temperature close to the metal liquidus temperature. Equivalent heat transfer coefficients were applied to the lateral wall and bottom.10,12,20) The detailed physical properties and the geometrical and operating conditions were listed in Table 1.

3. Solution Procedure

The commercial software ANSYS-FLUENT 12.1 was employed to complete the simulation. The governing equations for the electromagnetism, two-phase flow, heat transfer and phase change were integrated over each control volume and solved simultaneously, using an iterative procedure. The widely used SIMPLE algorithm was employed for calculating the Navier-Stokes equations. All the equations were discretized by the second order upwind scheme for a higher accuracy. Before advancing, the iterative procedure continues until all normalized unscaled residuals were less than \( 10^{-6} \). The physical domain was discretized with a structured mesh. In addition, the slag layer moves upward during the process with the falling metal droplets. A dynamic mesh therefore was used so that the growing may be considered. The top row of the control volumes spawned a new row once it was 1.25 times the height of the other rows. Figure 2 shows the mesh at the initial state. Due to the complexity of the coupling calculation, the time step is kept small to ensure that the above convergence criteria were fulfilled. Using 8 cores of 3.10 GHz, one typical case’s calculations took approximately 120 CPU hours.

4. Results and Discussions

Figure 3 illustrates the electric current streamlines and Joule heating distribution at 2 000 s when the current was 1 500 A and the slag thickness was 60 mm. The electric current flows downward and to the outer edge of the slag layer. The skin effect is not observed, because the depth of the skin effect is approximately 85 mm larger than the ingot radius. More Joule heating is created in the slag due to the smaller electrical conductivity. The maximum Joule heating

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical properties of metal</td>
<td></td>
</tr>
<tr>
<td>Reference density, kg/m³</td>
<td>7 500</td>
</tr>
<tr>
<td>Liquidus/solidus temperature, K</td>
<td>1 623/1 588</td>
</tr>
<tr>
<td>Viscosity, Pa·s</td>
<td>0.0061</td>
</tr>
<tr>
<td>Latent heat of fusion, kJ/kg</td>
<td>270</td>
</tr>
<tr>
<td>Thermal conductivity, W/m·K</td>
<td>30.52</td>
</tr>
<tr>
<td>Specific heat, J/kg·K</td>
<td>752</td>
</tr>
<tr>
<td>Electric conductivity, Ω⁻¹·m⁻¹</td>
<td>7.14×10⁴</td>
</tr>
<tr>
<td>Magnetic permeability, H/m</td>
<td>1.257×10⁻⁷</td>
</tr>
<tr>
<td>Thermal coefficient of cubical expansion, K⁻¹</td>
<td>1.1×10⁴</td>
</tr>
</tbody>
</table>

| Physical properties of slag            |             |
| Reference density, kg/m³              | 2 800       |
| Liquidus temperature, K               | 1 710       |
| Viscosity, Pa·s                        | 0.025       |
| Thermal conductivity, W/m·K           | 10.46       |
| Specific heat, J/kg·K                  | 1 255       |
| Electric conductivity, Ω⁻¹·m⁻¹         | lnσ=−6 769.0/T+8.818 |
| Magnetic permeability, H/m             | 1.257×10⁻⁷  |
| Thermal coefficient of cubical expansion, K⁻¹ | 5.4×10⁻⁴    |

| Geometry                               |             |
| Electrode diameter, m                  | 0.055       |
| Ingot diameter, m                      | 0.12        |
| Slag height, m                         | 0.04/0.05/0.06/0.07 |

| Operating conditions                   |             |
| Current, A                             | 1 500       |
| Frequency, Hz                          | 50          |

Fig. 2. Mesh at the initial state and boundaries.
is found near the periphery of the inlet. Due to the sparser current density, the minimum Joule effect is located at the outer side of the top slag. Figure 4 represents the temperature distribution, which differs from the Joule effect field. The hottest area is located underneath the midradius of the slag region because of the flow.

It is necessary to validate our model. An experiment therefore was carried out using a mold with an open air atmosphere. The inner diameter, height, and mold wall thickness were 120 mm, 600 mm and 65 mm, respectively. The current used in the experiment was 1500 A, with a frequency of 50 Hz. The consumable electrode was AISI 201 stainless steel with a 55 mm diameter. The slag composition was calcium fluoride, 75 mass pct, and aluminum oxide, 25 mass pct. The slag cap thickness remained constant at 60 mm. The temperature was measured by a disposable W3Re/W25Re thermocouple. Figure 5 shows the comparison of the temperature. It is the most convenient point for us to place the thermocouple in the experiment. The simulated results are in reasonable agreement with the measurements, the model is found to be reliable. The discrepancies that exist can be explained by the uncertainty about the thermal boundary conditions as well as the material properties.

Figure 6 indicates the distribution of the two phases, velocity field and metal pool profile. Two pairs of vortices are found in the slag. The heat extracted by the cooling water results in a descent of the slag in the vicinity of the lateral wall. If the right side of the figure is observed, it is shown that this causes a stable clockwise circulation. Meanwhile, a counterclockwise cell is created by the Lorentz force and the falling metal droplet at the center of the slag. On the other hand, the temperature difference drives the liquid metal along the slag/metal interface toward the outer edge and, from there, down the mold wall. Lots of heat is therefore transferred to the cooling water that freezes the metal. A metal pool is formed as the ingot grows, because the cooling effect of the lateral wall outweighs that of the bottom. Subsequently, the metal moves toward the bottom along the oblique solidification front. Figure 7 displays the evolution of the highest temperature and time average melt rate as the slag thickness is varied. The highest temperature drops from 1994 K to 1979 K and then rises to 1988 K while the slag thickness ranges from 40 mm to 70 mm. Accordingly, the time average melt rate first decreases by approximately 16.9% and increases by around 9.5%. The minimum highest temperature and time average melt rate appear when the slag
thickness is 60 mm. It can be inferred that as the slag thickness is increased, more Joule heating is created in the slag. However, the contact area between the slag layer and mold lateral wall also becomes larger. More heat is taken away by the cooling water, and the amount exceeds that of the new produced Joule effect. As a result, the slag layer gets colder, and the melt rate decreases. The speed of the ingot growth reduces while the cooling intensity remains unchanged. A shallower metal sump is expected to be formed. With the slag thickness continuous to increase, the effect of the new generated Joule heating outweighs that of the lost heat. Subsequently, the slag temperature rebounds and the melt rate increases. The metal pool depth is supposed to increase since the ingot grows faster.

Figure 8 provides the metal pool profiles with the four slag thicknesses. Due to a colder slag and lower melt rate, the metal pool becomes shallower while the slag thickness increases from 40 mm to 60 mm. As mentioned above, the slag temperature and melt rate increase when the slag thickness is 70 mm, which definitely contributes to the metal sump volume. Besides, the measured metal pool shape closely agrees with the calculated pool shape, which validate our simulation.

5. Conclusions

A transient 3D model was established to investigate the effect of the slag thickness on the metal pool profile in the ESR process. The solution of the mass, momentum and energy conservation equations were simultaneously calculated by the finite volume method with full coupling of the Joule heating and Lorentz force through solving the Maxwell’s equations. The movement of the metal droplet was simulated by the VOF method. Besides, the freezing of the metal was solved using the enthalpy-based approach. The simulation closely agreed with the experiment.

Changing the slag thickness changes the slag temperature, but not monotonically. The slag temperature drops with the slag thickness up to 60 mm, beyond which the slag temperature rises. The melt rate decreases and then increases while the cooling intensity remains unchanged. As a result, the maximal metal pool depth reduces from 0.081 m to 0.067 m and slightly increases to 0.074 m. This phenomenon is due to the competition between the speed of the ingot growth to the cooling intensity.

Acknowledgements

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Nomenclature

\( A_{\text{mush}} \): mushy zone constant (Pa·s/m²)
\( \vec{B} \): magnetic flux density (T)
\( c_p \): specific heat at constant pressure (J/(kg·K))
\( d_1 \): primary dendrite arm spacing (μm)
\( f_l \): liquid fraction
\( \vec{F}_b \): buoyancy force (N/m³)
REFERENCES