1. Introduction

Electroslag remelting (ESR) is a remelting process with consumable electrodes for the production of special steels and super alloys with the characters of compact structure, homogeneous component and controlled solidification.1–3) Figure 1 shows the schematic sketch of the ESR process. Alternating or direct current flows from the consumable electrodes into the highly resistive calcium fluoride-based slag where the Joule heating is generated. The electrodes is heated by the Joule heating and melted in the form of droplets4–6) They travel through the less dense slag layer to the bottom of water-cooled mould where they solidify directionally. The ingot quality is dependent on the coupled interaction of electromagnetic field, flow field and temperature field. However, it is impractical to study the transfer phenomena in ESR process by trial and error due to the use of opaque materials and high temperatures. Consequently, the alternative method of numerical simulation has gained more and more attention.

In order to enhance the understanding of ESR process, researchers have developed a number of coupled multiphysical mathematical models in recent years. They have studied the transport phenomena by solving coupled Maxwell equations, momentum and energy conservation equations. However, the impact of metal droplets was simplified, which could be addressed with three different methods. The classical way is to apply a heat flux boundary at the slag/pool interface, which only considers the energy transport.7,8) The second way of describing the impact is to use a mass flux or Gaussian distribution of velocity profile at the slag/pool interface. The liquidus and solidus depth of the case ignoring the effects of metal droplets on electromagnetic field increases by 18% and 15% compared with that of the other case, respectively.

KEY WORDS: electroslag remelting; metal droplet; electromagnetic field; multiphase flow; mathematical simulation.

A transient 2D axisymmetry mathematical model is established to study the effect of the metal droplets on the electromagnetic field, fluid flow and temperature field. The electromagnetic field is solved with the electric potential method. The movement of droplet and phase boundary is tracked by the Volume of Fluid (VOF) model. The solidification is addressed by the enthalpy-porosity model. The governing equations are discretized based on the finite volume method and solved simultaneously using the commercial software FLUENT. The simulation results indicate that the falling process of droplet can be represented more exactly considering the effect of metal droplets on electromagnetic field. Otherwise the droplets can bridge between electrode and metal pool. The temperature and final velocity of the droplet passing through the slag/pool interface is 1992 K and 0.40 m/s when the effect of metal droplets on electromagnetic field is considered. On the other hand, that is 2019 K and 0.34 m/s correspondingly for the case ignoring the effect of metal droplets on electromagnetic field. Furthermore, the liquidus and solidus depth of the case ignoring the effects of metal droplets on electromagnetic field increases by 18% and 15% compared with that of the other case, respectively.

Fig. 1. Schematic sketch of ESR process. (Online version in color.)
pool interface considering the mass, momentum and energy transport. The third way modeling the droplets is to add mass, momentum and energy resources in the metal pool. From the point of hydrodynamics, electro slag remelting involving the interaction of molten slag and liquid metal is a typical multiphase flow process. Hence, increasing researchers utilize multiphase reveal to model the behavior of droplets directly, which is a simpler and more accurate method.

At present, the computation of electromagnetic field could be classified into two types in the simulation of ESR process using multiphase model. The first type is based on the assumption that the effect of metal droplets on the electromagnetic field is neglected, which is steady state and not changed with the phase distribution. The use of steady state electromagnetic field can save calculation time significantly. Rückert et al. ignored the effect of metal droplets on electromagnetic field, and solved the electromagnetic field using the User Defined Scalar (UDS) equations coupled with the VOF model to study the multiphase flow phenomenon. The model could predict the motion of droplets and solidification process. Wang et al. added the Joule heating and Lorentz force obtained by solving the electromagnetic field distribution with ANSYS EMAG to the energy and momentum conservation equations respectively, which are coupled with VOF model to investigate multiphase flow phenomena in an industrial scale ESR process. They neglected the impact of droplets on the electromagnetic field as well.

The other type takes the effect of metal droplets on the electromagnetic field into account, which contributes to display the variation of physical fields more precisely. The computed electromagnetic field is dynamically adjusted from the transient phase distribution indicating that the Joule heating and Lorentz forces are recalculated at each time step. Kharicha et al. solved the electromagnetic field with electric potential method coupled with a VOF model to track the motion of metal droplets and phase boundaries, and concluded that the highest field intensity appears at the surface of droplets. Wang et al. developed a laboratory scale 3D multiphase-magnetohydrodynamic model considering the effect of metal droplets on electromagnetic field and studied the multiphase flow and solidification in ESR process. Glesselmann et al. studied the movement of droplets and solidification process using coupled multi zone models, which were solved with different time steps.

Based on the mentioned above, two cases are implemented with different types of electromagnetic field. Case 1 considers the effect of metal droplets on electromagnetic field. However, case 2 ignores the impact of metal droplets on electromagnetic field. This paper aims to explore the effect of different types of electromagnetic field on the motion of metal droplets, fluid flow and temperature distribution, which could be used to guide the choice of model assumption. In the present work, the electric potential method is used to solve the electromagnetic field. The VOF model is employed to track the motion of droplets and phase boundaries. Besides, the solidification is addressed by the enthalpy-porosity model. The droplet formation and departure process is analyzed in ESR process using different types of electromagnetic field. Furthermore, the effect of different types of electromagnetic field on the fundamental information of droplet through slag/pool interface and the metal pool are investigated.

2. Numerical Model

In the present study, the geometry is 2D axisymmetry shown in Fig. 2. A quasi steady state is used for the numerical simulation. The calculation domain includes a layer slag and the first 0.15 m below the slag/pool interface. A flat electrode tip and slag/pool interface is employed in this model where the immersion depth of electrode is neglected. According to the Boussinesq approximation, the density dependence on temperature only appears in the buoyance term, but others physical properties of slag and metal are assumed to be constant. The slag skin insulates copper mould from molten slag and ingot without current entering the mould.

2.1. Electromagnetic Field

In this paper, the well-known electric approach is used to calculate electromagnetic field. The electric potential is acquired from the current conservation equation:

\[ \nabla \cdot \bar{J} = 0 \]  \hspace{1cm} (1)

The current density \( \bar{J} \) includes two parts:

\[ \bar{J} = -\sigma \frac{\partial \bar{A}}{\partial t} - \sigma \nabla \varphi \] \hspace{1cm} (2)

The first term on the right hand side of Eq. (2) represents eddy current, which can be omitted when the electromagnetic field approaches steady state and a DC current is applied. The second term is the imposed current computed as a function of electric conductivity and electric scalar potential.

Here, \( \bar{J} \) is the current density, \( \sigma \) the electric conductivity, \( \bar{A} \) the magnetic vector potential, \( \varphi \) the electric scalar potential.

![Fig. 2. The geometry model. (Online version in color.)](image-url)
The magnetic induction intensity ($\vec{B}$) is obtained by solving the magnetic vector potential $\vec{A}$:

$$\nabla \times \vec{A} = \vec{B} \quad \text{............... (3)}$$

$$\nabla \times \left( \frac{1}{\mu_0} \nabla \times \vec{A} \right) = \vec{J} \quad \text{............... (4)}$$

In order to acquire a unique solution for Eq. (4), the divergence of magnetic vector potential is determined by the Coulomb gauge.

$$\nabla \cdot \vec{A} = 0 \quad \text{............... (5)}$$

$\vec{A}$ has only the radial $A_r$ and axial $A_z$ component in a 2D axisymmetry model.\(^{23}\) Equation (4) could be expressed as:

$$\nabla^2 A_r = \mu_0 J_z \quad \text{............... (6)}$$

$$\nabla^2 A_z = \mu_0 J_r - \frac{A_r}{r^2} \quad \text{............... (7)}$$

After the solution of electric potential and magnetic vector potential, the Lorentz force and Joule heating are calculated using Eqs. (8) and (9) and added as source terms to the momentum and energy conservation equations, respectively.

$$\vec{F} = \vec{J} \times \vec{B} \quad \text{............... (8)}$$

$$Q = \frac{\vec{J} \cdot \vec{j}}{\sigma} \quad \text{............... (9)}$$

The boundary conditions for electric potential and magnetic vector potential are derived from Eqs. (2) and (3). Zero electric potential is imposed at the outlet. Additionally, the exposed slag surface and mould wall are assumed to be insulated excepted the electrode tip where the flux of electric potential is described.\(^{17}\) The bottom boundaries and top boundaries share the identical magnetic field boundary condition, a magnetic induction flux of zero. The axial component of magnetic vector potential flux is prescribed to be insulated excepted the electrode tip where the flux of electric potential is described.\(^{17}\) The bottom boundaries and top boundaries share the identical magnetic field boundary condition, a magnetic induction flux of zero. The axial component of magnetic vector potential flux is prescribed to be insulated excepted the electrode tip where the flux of electric potential is described.\(^{17}\)

2.2. Fluid Flow

The flow of molten slag and liquid metal in ESR process is calculated with the mass and momentum conservation equations:\(^{24}\)

$$\nabla \cdot (\rho \vec{V}) = 0 \quad \text{............... (10)}$$

$$\frac{\partial (\rho \vec{V})}{\partial t} + \nabla \cdot (\rho \vec{V} \vec{V}) = \nabla \cdot (\mu (\nabla \vec{V} + (\nabla \vec{V})^T)) - \nabla P + \rho_0 \beta \tilde{g}(T - T_0) + \vec{F} + \vec{F}_p \quad \text{............... (11)}$$

Here, $\rho$ is the density, $\vec{V}$ the velocity, $\mu$ the dynamic viscosity, $\beta$ the thermal expansion coefficient, $\vec{F}$ the Lorentz force mentioned above, $\vec{F}_p$ the drag force blocking the flow in mushy zone.

The effect of turbulence is considered with the RNG $\kappa$-$\varepsilon$ model including an enhanced wall function employed at the near-wall region. The standard $\kappa$-$\varepsilon$ model is generally used for the flow of high Reynolds number. However, the RNG $\kappa$-$\varepsilon$ model blends the flow of high Reynolds number with the flow of low Reynolds number owning a wider class of flows than the standard $\kappa$-$\varepsilon$ model.\(^{18}\)

The electrode tip is modeled as a velocity inlet related to the melt rate, accompanied by an outflow condition at the outlet. No slip condition is applied at the exposed slag surface. Additionally, a zero shear stress is employed at the exposed slag surface.

The motion of metal droplets and phase boundaries is tracked with a geometric reconstruction VOF model, because it is a robust and reliable interface tracking technique. In this approach, the different phases are treated as a continuum sharing a single set of momentum equations.\(^{25,26}\)

The volume fraction of each of the phases in each cell is calculated with Eq. (12).

$$\frac{\partial (\rho_0 q \phi)}{\partial t} + \nabla \cdot (\rho_0 q \phi \vec{V}) = 0 \quad \text{............... (12)}$$

Here, $\phi$ is the volume fraction of the $q^{th}$ phase.

The material properties appearing in the transport equations are determined by the volume fraction of each of the phases in each cell. For example, in a two phase system, the property $\phi$ is interpolated by the following formula.

$$\phi = f_1 \phi_1 + f_2 \phi_2 \quad \text{With } f_1 + f_2 = 1 \quad \text{............... (13)}$$

2.3. Heat Transport and Solidification

The temperature field is obtained by solving the enthalpy conservation equation:\(^{19}\)

$$\frac{\partial (\rho H)}{\partial t} + \nabla \cdot (\rho \vec{V} H) = \nabla \cdot (k_{eff} \nabla T) + Q \quad \text{............... (14)}$$

Here, $k_{eff}$ is the effective thermal conductivity, $Q$ the Joule heating. $H$ is the enthalpy containing the sensible enthalpy and latent heat:

$$H = h + f_1 L \quad \text{and} \quad h = h_{solid} + \int_{T_{solid}}^{T} C_p dT \quad \text{............... (15)}$$

$f_1$ is the liquid fraction computed with the lever rule:

$$f_L = \frac{T - T_{solid}}{T_{liquidus} - T_{solidus}} \quad \text{............... (16)}$$

The solidification is addressed with the enthalpy-porosity model, where the mushy zone is treated as a porous medium in which the porosity decreases from 1 to 0 as the metal solidifies. The drag force added to momentum conservation equation as a source term is calculated with the darcy’s law:

$$\vec{F}_p = \frac{(1 - f_L)^2}{f_L^3} A_{mush} (\vec{V} - \vec{V}_{solidus}) \quad \text{and} \quad A_{mush} = \frac{180 \mu}{d_i^2} \quad \text{............... (17)}$$

$A_{mush}$ is the mushy zone constant, $d_i$ is the primary dendrite arm spacing taking the value of 300 $\mu m$.\(^{24}\)

In order to take the melting process into account in a simplified way, the temperature of the electrode tip is 30 K above the alloy liquidus temperature. An outflow condition is applied at the outlet where the temperature is extrapolated from within the domain. The heat loss to mould is expressed by an overall heat transfer coefficient. Both the convection
and radiation heat transfer are taken into account at the exposed slag surface.

2.4. Model Solution

In the present study, two cases are implemented to study the effects of different types of electromagnetic field on the motion of metal droplets, fluid flow and temperature distribution in ESR process. Case 1 takes the effect of metal droplets on electromagnetic field into account where the electromagnetic field is a function of phase distribution. However, Case 2 uses a steady electromagnetic field ignoring the impact of metal droplets on electromagnetic field. The governing equations of electromagnetic filed, fluid flow and heat transfer are discretized based on the finite volume method and solved using the commercial software FLUENT. The VOF interface is adjusted by the volume fraction of each of phases geometrically after the last iteration. In order to guarantee the convergence of solution, the typical calculation time step lies between $10^{-3} - 10^{-5}$ s, which is depending on the dynamic of the interfaces. The detailed properties of the slag and the metal, the operating conditions and the geometry parameters used in the present study are listed in Tables 1 and 2.

3. Results and Discussion

Figure 3 displays the fluctuation of electric resistance within slag of case 1. The resistance is calculated based on the Joule heating in slag using Eqs. (18) and (19). Starting from the time $t_1$, the resistance is continuously decreasing as the metal droplet elongates, and reaches the minimum value at the time $t_2$. Then the first droplet drips at the time $t_3$, which results in the resistance increasing suddenly. At the time $t_4$, the first droplet passes through the slag layer causing the intensive increase of resistance due to the reduction in volume of liquid metal in slag. The slag/pool interface oscillates for some time induced from the impact of droplets, which gives rise to the fluctuation of resistance slightly until the interface comes back to rest.

$$R(t) = \frac{1}{I^2} \int Q(\delta, t) d\delta \quad \ldots \ldots \ldots \ldots \ldots (18)$$

$$\delta R(t) = \left[R(t) - \frac{1}{2\pi} \int_{-\infty}^{t} R'(t) dt\right] R(t) \quad \ldots \ldots \ldots \ldots \ldots (19)$$

Figure 4 shows the field variations of electromagnetic quantities in ESR process for case 1. At the time $t_1$, a larger current density appears at the edge of electrode and droplet tip due to the accumulation of liquid metal at the bottom of electrode generating massive Joule heating at the nearby slag. The maximum magnetic field intensity is 0.0065 T at the edge of electrode, which interacts with current creating

### Table 1. Physical properties of slag and metal.

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<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Ref</th>
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</thead>
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<tr>
<td>Density, kgm$^{-3}$</td>
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<td>7 500</td>
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<tr>
<td>Dynamic viscosity, Pa·s</td>
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<td>0.006</td>
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<tr>
<td>Latent heat, kJkg$^{-1}$</td>
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</tr>
<tr>
<td>Specific heat, Jkg$^{-1}$K$^{-1}$</td>
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<tr>
<td>Thermal conductivity, Wm$^{-1}$K$^{-1}$</td>
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<tr>
<td>Electrical Conductivity, Ω$^{-1}$m$^{-1}$</td>
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<td>714 000</td>
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<tr>
<td>Magnetic permeability, Hm$^{-1}$</td>
<td>$1.26 \times 10^{-6}$</td>
<td>$1.26 \times 10^{-6}$</td>
</tr>
<tr>
<td>Thermal coefficient of cubical expansion, K$^{-1}$</td>
<td>$2.5 \times 10^{-4}$</td>
<td>$1 \times 10^{-4}$</td>
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<tr>
<td>Liquidus temperature, K</td>
<td>1 550</td>
<td>1 700</td>
</tr>
<tr>
<td>Solidus temperature, K</td>
<td>—</td>
<td>1 640</td>
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### Table 2. The operating conditions and geometry.

<table>
<thead>
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<th>Parameter</th>
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<tr>
<td>Geometry</td>
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<td>Electrode radius, mm</td>
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<tr>
<td>Mould radius, mm</td>
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<tr>
<td>Slag thickness, mm</td>
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<tr>
<td>Operation parameter</td>
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<td>Current (DC), A</td>
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<td>Heat transfer at the slag-air wall, Wm$^{-1}$K$^{-1}$</td>
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<tr>
<td>Emissivity of free slag surface</td>
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<tr>
<td>Heat transfer at the slag/mould interface, Wm$^{-1}$K$^{-1}$</td>
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</tr>
<tr>
<td>Heat transfer at the metal/mould interface, Wm$^{-1}$K$^{-1}$</td>
<td>590</td>
</tr>
<tr>
<td>Slag/metal interfacial tension, Nm$^{-1}$</td>
<td>0.9</td>
</tr>
<tr>
<td>Melt rate, kgh$^{-1}$</td>
<td>36</td>
</tr>
</tbody>
</table>

Fig. 3. The fluctuation of electric resistance within slag of case 1.
the maximum Lorentz force nearly 7,500 N/m³. At the time $t_2$, the necking phenomenon takes place due to the elongation of droplet under the coupling interaction of gravity, Lorentz force and interface tension. The current always choose preferentially to flow through the metal droplet for minimizing the electric resistance. The magnetic field intensity at the surface of droplet reaches up to 0.022 T, the distribution of which is consistent with the results reported by Kharicha.\(^{17}\)

At the time $t_3$, the first metal droplet detaches from the electrode tip. The maximum Lorentz force is $3.8 \times 10^7$ N/m³ at the surface of droplet where the primary effect of Lorentz force is to break the metal droplet avoiding the occurrence of liquid metal bridge. The liquid metal below the electrode is smashed into small droplets by the huge Lorentz force. Additionally, the magnetic field intensity and Joule heating reaches up to the maximum value at the surface of droplet.

Fig. 4. Field variables of the electromagnetic quantities in ESR process for case 1. (Online version in color.)
At the time $t_4$, the first droplet enters the metal pool causing the fluctuation of slag/pool. Besides, the opposite magnetic field appears around the small droplets where the current flows into slag radially. The maximum Lorentz force and Joule heating reduce to $5\times10^5$ N/m$^3$ and $1.1\times10^{11}$ W/m$^3$, respectively.

**Figure 5** represents the field variables of electromagnetic quantities in ESR process for case 2, which are not changed with phase distribution. Figure 5(a) is the current density vectors. It enters from electrode into slag and diverges at the edge of electrode generating the radial component, which decreases with the increase of axial distance and nearly vanishes at the slag/pool interface. The maximum current density is approximately $4.5\times10^5$ A/m$^2$. The distribution of magnetic field intensity is shown in Fig. 5(b), with the maximum value of 0.0065T at the edge of electrode. Figure 5(c) displays the Lorentz force vectors. The force field in the ingot decays from the wall to the center, which demonstrates an agreement with Patel’s results. The Joule heating under the electrode is obviously larger than other zone in slag as indicated in Fig. 4(d), with a maximum value of $8.5\times10^8$ W/m$^3$.

The motion of metal droplet in ESR process for case 2 is clearly observable in **Fig. 6**. The liquid metal accumulates at the bottom of electrode and elongates resulting in the necking phenomena. Then, the droplet drips from electrode tip when it approaches the slag/pool interface. Because the effect of metal droplets on electromagnetic field is ignored, the Lorentz force at the axis is almost negligible as seen from Fig. 5(c). Hence, the droplet could not be cut off by the Lorentz force, which is easy to bridge between electrode tip and metal pool. Rückert also found the phenomenon in the simulation of ESR process.28)

**Figure 7** is the velocity field at different times for case 1 and case 2. At the time $t_2$, there are two distinct loops in slag for both types of electromagnetic field. A counter-clockwise flow is driven by the Lorentz force at the bottom of electrode. Nevertheless, the buoyance dominates the clockwise flow near the mould wall. The velocity distribution of case 1 is similar to that of case 2, with the same maximum velocity of 0.28 m/s. At the time $t_4$, the first dripped droplet moves to the slag/pool interface. The maximum velocity is approximately 0.40 m/s for case 1. On the other hand, a lower maximum velocity of 0.34 m/s is seen in case 2. Note
that the velocity corresponds to the maximum velocity of the falling droplet.

The fundamental information of droplets passing through the slag/pool interface in ESR process for case 1 and case 2 are obtained using the VOF model tracking the motion of droplets shown in Fig. 8. On the one hand, the radius, temperature and final velocity of droplet is approximately 7 mm, 1 992 K and 0.40 m/s respectively for case 1. On the other hand, that is 6 mm, 2 019 K and 0.34 m/s correspondingly for case 2. The calculated radius and final velocity is 6.3 mm and 0.44 m/s using Eqs. (19) and (20) respectively, which indicates that the simulation results agree well with the calculated values. The final velocity of droplet of case 2 is lower than that of case 1. The droplet of case 2 takes more time to pass through the slag layer, and absorb more heat from slag, with a higher superheat.

$$r_d = \frac{2.04\gamma}{g\Delta\rho} \quad \text{(20)}$$

$$V_f = \sqrt{\frac{A}{B}}$$

$$A = \frac{[\Delta\rho / (\rho_d + 0.5\rho)]g}{B = \frac{3}{5} \cdot \frac{C_0}{\rho_d^2 \rho_d + 0.5\rho}} \quad \text{(21)}$$

Figure 9 displays the temperature distribution in ESR process for case 1 and case 2. The hotter region is located below the edge of electrode for both cases, with a maximum temperature of 2 100 K and 2 095 K respectively. The slag below the electrode is colder than surrounding zone due to the heat loss to metal droplets. The bulk of slag has a relative uniform temperature distribution resulting from the turbulence mixing. However, a large temperature gradient exits near the mould wall under the action of cooling water. Besides, the maximum temperature of case 1 is approximately 1 967 K. In contrast, that of the other case is nearly 1 950 K.

Figure 10 shows the pool profile in ESR process for case 1 and case 2. The mushy zone and solidified ingot could be clearly recognized. In case 1, the liquidus and solidus depth is 33 mm and 39 mm individually. However, the solidified pool depth for case 2 is between 39 mm and 45 mm for the liquidus and solidus temperature, which increases by 18% and 15% compared with case 1, respectively. The metal pool profile is strongly depent on the heat transferred by metal droplets. The metal droplets enter metal pool with a higher temperature in case 2, which gives rise to a deeper pool profile.
4. Conclusions

In this paper, two cases are implemented by solving the Maxwell equations, momentum and energy conservation equations coupled with VOF model. Case 1 considers the impact of metal droplets on electromagnetic field. The droplet formation and departure process, fundamental information of droplet, fluid flow and temperature field for two cases are analyzed. The conclusions are summarized as follows:

(1) When the effect of metal droplets on electromagnetic field is considered, the current chooses in priority to flow through metal droplet. Moreover, the maximum value of electromagnetic quantities such as current density, magnetic field intensity, Lorentz force and Joule heating appears at the surface of droplet. The droplet is cut off by the huge Lorentz force in the process of passing through the slag layer, which can be represented more exactly considering the effect of metal droplets on electromagnetic field.

(2) When the effect of metal droplets on electromagnetic field is neglected, the electromagnetic quantities are not varied with phase distribution, with the maximum value at the edge of electrode. Besides, the droplet cannot be cut off in time due to the slight Lorentz force at the center, which is easy to bridge between electrode tip and metal pool causing short circuit.

(3) In case 1, the radius, temperature and final velocity of droplet passing through slag/pool interface is 7 mm, 1992 K and 0.40 m/s, respectively. However, that is 6 mm, 2019 K and 0.34 m/s for case 2, correspondingly. In addition, the liquidus and solids depth of case 2 increases by 18% and 15% compared with that of case 1, respectively.

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