On the Importance of Electric Currents Flowing directly into the Mould during an ESR Process

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In the present paper a numerical model is developed to predict the exact electric current paths in the slag region of an Electro-Slag-Remelting (ESR) process. The model solves the momentum and energy equations. The solidification of the slag at the mould is modelled with an enthalpy-porosity approach. The magnitude of the Joule heating and the Lorentz force are derived from the computed electric current lines. The localization where the Joule heating occurs controls the temperature distribution. The electric current distribution is in turn influenced by the temperature field through the temperature dependant electric conductivity. With this numerical tool the electric current paths are exactly computed by choosing the less resistive way to the liquid pool, or to the mould. For a given electric intensity the model predicts the power generated by the system and the solidified slag thickness at the mould. The model is validated by comparing its results with experiments on a small scale ESR process with high current density.

Keywords: electro slag remelting, magneto-hydrodynamic, simulation, Fluent, slag, solidification, heat flux, mould.

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Introduction

The Electro-Slag-Remelting (ESR) is an advanced technology for the production of high quality materials, e.g. hot work tool steels or nickel base alloys. An alternating current (AC) is passed from a conventionally cast solid electrode through a layer of molten slag to the baseplate (**Figure 1**). Due to the electrical resistivity of the slag, Joule heating is generated and the slag transfers this energy to the ingot and mould surfaces and, most important, to the melting electrode tip. The molten metal produced in the form of droplets passes through the slag and feeds a liquid pool which finally solidifies directionally. The slag and the ingot are contained in a water cooled copper mould. As also the baseplate is water cooled, a heat flow regime is imposed that leads to controlled solidification, and by that, to an improved microstructure of ESR ingots [1-6].

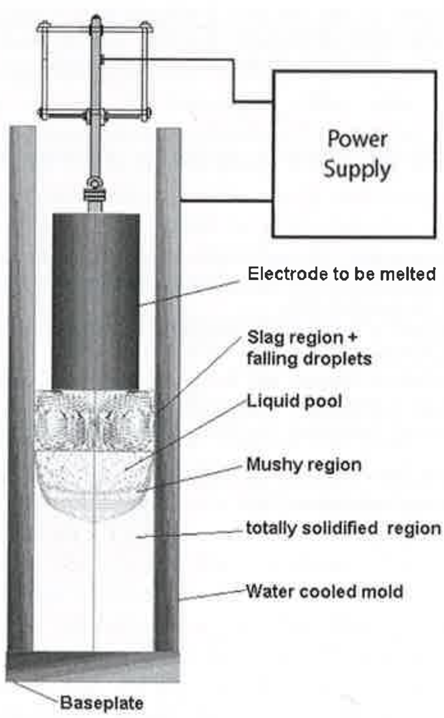


Figure 1. Schematic view of the ESR system.

Since the electric current controls the magnitude and the location of Joule heating, proper modelling of the involved melting process depends on the ability to predict the right electric current pattern in the system. One of the most important parameters is the electrical conductivity of the slag. This parameter increases strongly in magnitude with increasing temperature, so the slag is much more conducting in its liquid phase than in its solid phase. It is generally assumed [1-6] that due to its very low electric conductivity, the solidified slag layer perfectly insulates the slag from the copper mould. Depending on the chemical composition of the slag, the ratio between liquid and solid slag electric conductivity is of the order of 10-100. This ratio depends strongly on the actual temperature of the slag-skin layer.

Most of the simulations found in literature use the hypothesis of a perfectly insulated mould which has also the advantage to considerably simplify the formulation of the electromagnetic boundary conditions at the mould. The fact that in most of the industrial ESR devices the mould and the baseplate are in contact induces the possibility that the current, instead of crossing the slag thickness, might directly go to the mould. Based on the values given in **Table 1**, the thickness of the solidified slag is small (e_S ~0.1-5 mm), and the radial resistance of this layer ($\sim e_s \sigma_S$) is smaller or of the same order of magnitude as the vertical resistance of liquid slag ($\sim h/\sigma_l$). By imposing a vertical current, Kharicha et al. [7] have theoretically considered the influence of mould currents on the hydrodynamic interaction between a layer of slag and a layer of steel. The shape of the slag/steel interface was found to be considerably modified when the current was not allowed to enter into the mould. More recently, A.D. Patel [8] accounted for a mould current by artificially directing 20 % of the total current towards the mould. However, this model was not able to predict the exact ratio between current flowing into the mould and current flowing into the liquid pool.

In the present paper a numerical model is presented where no electric insulation hypothesis for the mould is made. The current is left free to choose the less resistive way. The model is applied to a slag region of a small scale ESR process where the pool/slag interface is assumed to be flat. Slag flow, temperature and turbulence fields are solved assuming axial symmetry of the system. Solidification is modelled with the enthalpy-porosity method of FLUENT. To illustrate the capability of the model two simulations are compared. The first uses the classical insulation hypothesis, whereas the second avoids this hypothesis. The results of the two simulations are then compared with experimental data.

Model Description

An electrode is put in contact with a cylindrical container filled with liquid slag (**Figure 2**). The material properties of the slag, e.g. the density (ρ) and the dynamical viscosity (μ_l) are considered to be temperature independent. Only, the electrical conductivity (σ) is taken as a function of temperature fitting data from experimental measurements [9]. The magnetic permeability (μ_0) is the same everywhere and equal to the vacuum magnetic permeability. **Table 1** lists typical physical properties of the slag, the geometry and the operating conditions used for the present simulations.

Flow dynamic and turbulence. The time-averaged fluid flow is modelled with the Navier-Stokes equation according to

$$\nabla \cdot \vec{u} = 0 \tag{1}$$

$$\rho \frac{D\vec{u}}{Dt} = -\nabla p + \nabla(\mu_{eff} \nabla \cdot \vec{u}) + \vec{S}_B + \vec{S}_D + \vec{S}_L \tag{2}$$

Here, p represents the pressure. The effect of turbulent mixing (μ_t) is taken into account within the effective viscosity $\mu_{eff} = \mu_l + \mu_t$. The Boussinesq approximation is used for determining the buoyancy force

$$\vec{S}_B = \rho \beta \vec{g}(T - T_{refB}) \tag{3}$$

where g is the gravitational acceleration, β the thermal buoyancy coefficient and T_{refB} its corresponding reference temperature. The momentum sink $\vec{S}_D$ due to the interaction between the slag flow and the developing slag mushy layer is detailed in the next section (see Eq. (8)). The last term on the right hand side of Eq. (2) represents the Lorentz force. It is detailed in the section devoted to the treatment of the electromagnetic force. A non-slip boundary condition is imposed at all boundaries except at the exposed slag surface and at the slag/pool interface, where free slip conditions are used. The turbulence level is estimated through the RNG k-ε turbulence model where the equations for the transport of turbulent kinetic energy, k, and its dissipation, ε, are solved.

Energy and solidification. The energy conservation equation of the enthalpy-formulation is

$$\rho\, c_p \frac{DT}{Dt} = \nabla(k_{eff} \nabla T) + Q_{Joule} + Q_L \tag{4}$$

where h is the sensitive enthalpy defined as

$$h = h_{ref} + \int_{T_{ref}}^{T} c_p\, dT \tag{5}$$

Here h_{ref} is the reference enthalpy at the reference temperature, T_{ref}, and c_p is the specific heat. k_{eff} is the

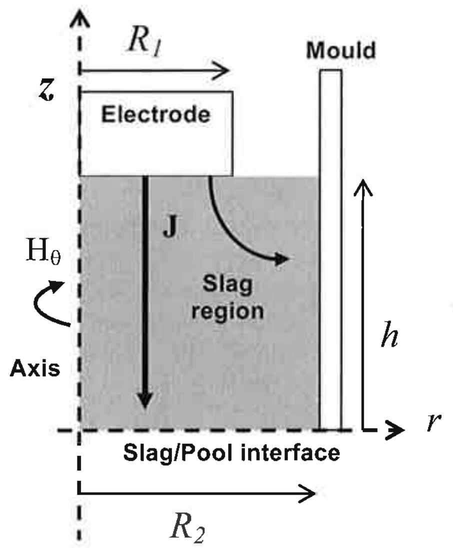


Figure 2. Calculation domain: the slag region.

Table 1. Process parameters and averaged material properties used.

Typical ESR slag	
Density	2800 kg/m^3
Viscosity	0.04 kg/m/s
Liquidus temperature	1450 K
Solidus temperature	1300 K
Latent heat of fusion	1.5*10^4 J/kg
Specific heat, liquid	1255 J/kg/K
Thermal expan. coefficient	2.5 x 10^{-4} K^{-1}
Electric conductivity, 1000 K	1.0x10^1 (Ωm)$^{-1}$
Electric conductivity, 1870 K	1.2x10^2 (Ωm)$^{-1}$
Thermal conductivity, 2000 K	6.0 W/m/K
Thermal conductivity, 750 K	0.5 W/m/K
Geometry	
Slag height(h)	125 mm
Electrode diameter (2xR_1)	130 mm
Ingot diameter (2xR_2)	200 mm
Operating conditions (experimental ESR)	
Electric current	5 Hz, 4.5 kA
Slag emissivity, far field temperature	0.8, 400 K

effective thermal conductivity which is defined as $k_{eff} = k + k_t$. Here, k defines the thermal conductivity of the material and k_t the "turbulent" thermal conductivity.

The latent heat released Q_L in a single phase solidification model can be written as

$$Q_L = -\rho L \frac{\partial f_l}{\partial t} - \rho L \vec{u}_{cast} \cdot \nabla f_l \tag{6}$$

The latent heat, L, is released in the mushy zone. A linear relation between temperature and liquid fraction f_l is assumed

$$f_l = \frac{T - T_{Solidus}}{T_{Liquidus} - T_{Solidus}} . \tag{7}$$

During the ESR process the slag level is shifted upward as the pool is filled by the falling metal droplets, which are created at the melting electrode. In the present work only the steady state is of interest. Therefore, e.g. the first term of Eq. (6) can be neglected. Due to the small magnitude of both the casting velocity, $\vec{u}_{cast}$ (~10^{-4} m/s), and the latent heat of fusion, L, and compared to the Joule heating source considered in Eq. (4), the second term of Eq. (6) can also be neglected. A second reason to neglect this term lies in the fact that the gradient of liquid fraction (radially oriented) is mostly perpendicular to the casting velocity (vertically oriented). In the present investigation the mould is considered at rest, i.e. $\vec{u}_{cast} = 0$.

The pressure drop caused by the presence of solid material is considered as a momentum sink S_D in the momentum conservation equation. The mushy zone is treated as a porous region with volume fraction of pores equal to the liquid fraction f_l. The momentum sink for slag, applying the Blake-Kozeny law, is

$$\vec{S}_D = -\frac{(1-f_l)^2}{f_l^3} A_{mush} \vec{u} . \tag{8}$$

Here A_{mush} is the mushy zone constant taken to be equal to 10^4. A corresponding sink term is also added to the turbulence equations in the mush areas.

In the present investigation the influence of the falling steel droplets on the heat transfer is not taken into account.

Electromagnetics. The imposed vertical current is distributed over the entire domain according to the distribution of the slag electric conductivity. For sinusoidal AC field, we can express an induced magnetic field (in complex notation) as

$$H_\theta = \tilde{H}_\theta e^{i\omega t} . \tag{9}$$

The complex amplitude $\tilde{H}_\theta$ is a function of the position, and ω is the angular frequency. The equation to be solved can be expressed as

$$\frac{\partial}{\partial r}\left(\frac{1}{\sigma \cdot r}\frac{\partial}{\partial r}(r\tilde{H}_\theta)\right) + \frac{\partial}{\partial z}\left(\frac{1}{\sigma \cdot}\frac{\partial}{\partial z}(\tilde{H}_\theta)\right) = i\omega \tilde{H}_\theta \tag{10}$$

The influence of the thermal turbulence is neglected. The electrical conductivity is taken to be equal to the electrical conductivity at the time-averaged temperature T. The solution is performed for both real and imaginary parts of Eq. (10). Once the magnetic flux is known, the electric current density is obtained through

$$\tilde{\vec{j}} = \vec{\nabla} \times (\tilde{H}_\theta \vec{e}_\theta) . \tag{11}$$

Due to the very high difference between the electrical conductivity of steel and slag, the radial current is assumed to be zero at the electrode and at the slag/pool interface. Therefore, from Eq. (11), it follows that

$$j_r = 0 \Rightarrow \partial \tilde{H}_\theta / \partial z = 0 . \tag{12}$$

Applying Ampere's law at the exposed slag surface gives the condition for the magnetic flux

$$\tilde{H}_\theta(r) = I_0 / 2\pi r \tag{13}$$

where I_o denotes the amplitude of the total current, and r the radial distance to the symmetry axis.

For the simulation, which assumes that the current does not enter the mould, the boundary condition is the same as that at the slag free surface (Eq. (13)).

For the second case the mould is considered to be a perfectly conducting wall. Due to the high electrical conductivity of the copper mould the current entering the mould has almost no vertical component. Therefore, from Eq. (11), it follows that

$$j_z = 0 \Rightarrow \partial \tilde{H}_\theta / \partial r = -\tilde{H}_\theta / R_2 \tag{14}$$

The Lorentz force is equal to

$$\vec{S}_L = \mu_0 Real\left(\frac{1}{2}\tilde{\vec{j}} \times \tilde{H}_{\theta\, Conjugate}\right) \tag{15}$$

and the Joule heating term in Eq. (4) becomes

$$Q_{Joule} = Real\left(\frac{1}{2\sigma(T)}\tilde{\vec{j}} \times \tilde{\vec{j}}_{0\, Conjugate}\right) \tag{16}$$

The total power generated (or dissipated) during the process is the volume integral

$$P_{Joule} = \int Q_{Joule} 2\pi r dr dz \tag{17}$$

Numerical treatment. Assuming axial symmetry of the system, the calculation domain (Figure 2) consists of a rectangle. The computation domain is discretized into structured squared volume elements. The whole grid consists of 300*375 cells with a fine graded mesh in the mushy zone. Grid refinement was necessary in the vicinity of the walls and at the solidification front. The grid size was found to be small enough to fully resolve the flow and the thermal boundary layers at the electrode and the mould (y^+~ 0.1). All boundaries, the electrode, the interfaces slag/pool and slag/mould and the exposed slag surface are considered to be walls. Steel liquidus temperature is imposed at the electrode (1752 K). At the exposed slag surface, the heat is mainly lost through radiation. The interaction between the slag layer and the bottom steel pool is modelled with a heat transfer coefficient of 1000 $W/m^2/K$ and a free pool stream temperature of 1600 K.

Assuming very good physical contact between the solid slag and the mould, a constant value of heat transfer coefficient is applied over the entire height of the slag. To avoid contact between the liquid slag and the mould, the value of the heat transfer coefficient is progressively increased until the liquid fraction becomes strictly equal to zero all over the mould surface. The heat transfer coefficient is a result of the model, and not an input.

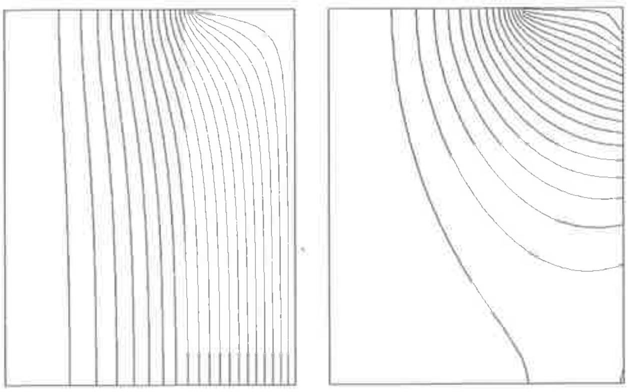
The calculation time for the steady-state turbulent flow and solidification result was 1 day with 3 nodes (Intel Pentium 4, 3.2 GHz, 1GB RAM) in parallel on a distributed memory cluster.

Results and Discussion

The two cases presented below were tested by comparing the results with experimental data published in [10]. The comparisons concern the total power generated in the slag region, as this quantity was experimentally measured during the process. Due to its characteristic microstructure, the thickness of the solidified slag layer at the mould has also been measured experimentally. Finally, the slag temperature has been measured with a thermo-couple from the free surface to the mid-height of the slag.

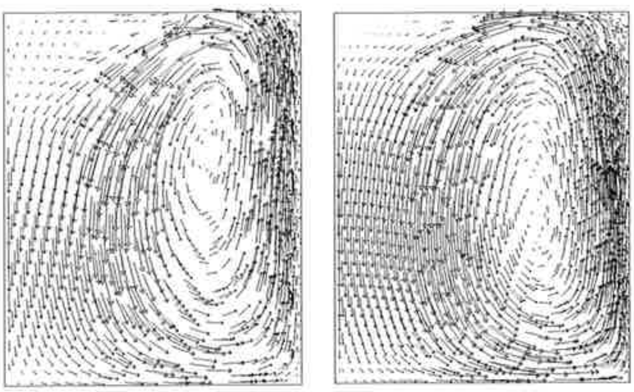
Insulating slag/mould interface. In the case of an electrically insulated mould, the computed current distribution is in accordance with the classical view of the ESR process (**Figure 3**). The current density is very high, and the main driving force for the slag flow is the Lorentz force. The latter creates an anti-clockwise motion of the mean flow (**Figure 4**). The location where the Joule heating is at its maximum is at the electrode extremity (**Figure 5**). The temperature of the slag is about 2700 K (**Figure 6**). The solidified slag layer shows a minimum thickness at the bottom slag/pool interface and a maximum thickness at the top slag surface (**Figure 7**). The maximum and minimum are separated by a large area with a nearly constant thickness. The bottom minimum is created by the hot flow impingement at the mould. In contact with the cold mould, the slag flow becomes cooler during ascending. The accumulation of cold slag at the top corner explains the thick slag layer. Compared to experimental data, the present configuration leads to sensible different slag thickness and different total Joule heat release (**Table 2**).

Conducting slag/mould interface. In this case the current is free to choose the less resistive way to reach



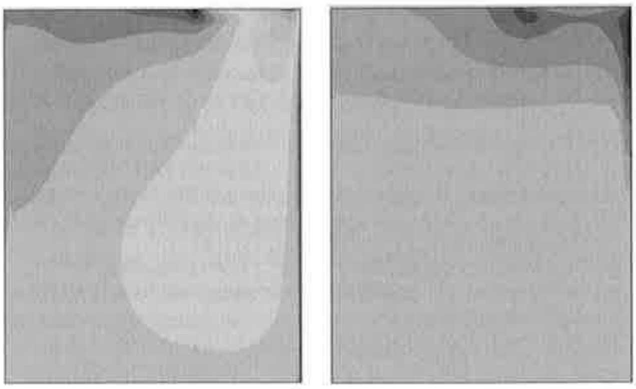
Insulating mould | Conducting mould

Figure 3. Electric current path



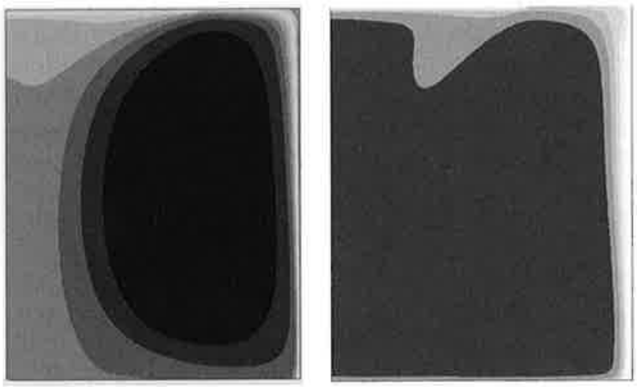
0 - 0.098 m/s Insulating mould | 0 – 0.11 m/s Conducting mould

Figure 4. Flow field



10^2 (light) - $3x10^8$ (dark) W/m^3 Insulating mould | 10^3 (light) - 10^7 (dark) W/m^3 Conducting mould

Figure 5. Joule heating distribution



450 (light) - 2750 K (dark) Insulating mould | 650 (light) - 2350 K (dark) Conducting mould

Figure 6. Temperature distribution

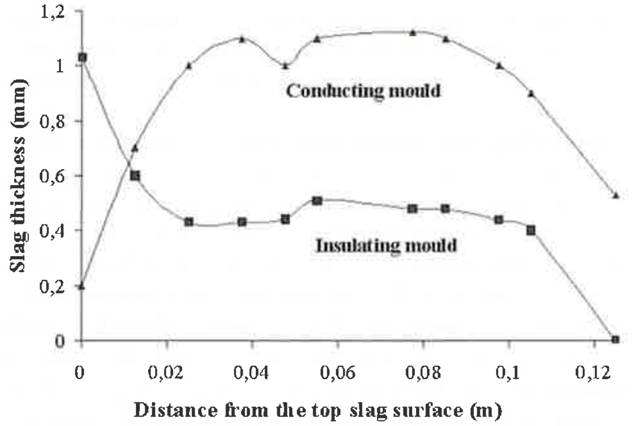


Figure 7. Estimated solidified slag thickness along the mould.

Table 2. Comparison between experimental and numerical results.

	Experimental	Numerical with insulating slag/mould interface	Numerical with conducting slag/mould interface
Total power P_{Joule}	185 kW	450 kW	165 kW
Averaged solid slag thickness	~1 mm	0.5 mm	1.2 mm
Maximum temperature	2300 K	2800 K	2400 K
Slag/water heat transfer coefficient	Unknown but > 10^3	25 000 W/m^2/K	4500 W/m^2/K

either the liquid pool or the mould. In Figure 4 it can be seen that 90 % of the current is able to cross the solid slag layer and to enter the mould. This proportion is far higher than expected. The consequence is that in the present configuration the solid slag layer has nearly no insulating effect. The region where the Joule heating occurs is extended from the electrode extremity to the vicinity of the mould (Figure 5). The key to understand the electric current configuration is the temperature distribution. Since hot slag is more conducting than cold slag, the current leaving the electrode is directed towards the hottest region. It can be observed that the main characteristics (direction and magnitude) of the flow are similar to that found with the insulating hypothesis (Figure 5).

The solidified slag layer now shows two minima, a first at the slag/pool interface, and a second at the level of the free slag surface (Figure 7). This top minimum is the direct consequence of the near-wall Joule heating, which is able to heat up the rising cold slag flow. The bottom minimum is also created by the hot flow impingement at the mould. The slag temperature is about 400K lower than in the insulating mould case, the reason lies in the fact that the power generated by the system is three times smaller (Table 2). A smaller slag temperature also explains the larger solidified slag thickness.

The resulting heat transfer coefficient from the two cases is quite high, almost equivalent to a perfect thermal contact between the solidified slag and the mould. Nevertheless, due to higher heat generation the insulating case needs a larger heat transfer coefficient than the conducting mold case to allow the existence of a solid slag layer.

The present case considering a conduction slag/mould interface shows definitively close results to experimental data (Table 2). The computed power generated in the slag and the solidified slag thickness, are of the same order as that found in the experiments.

Conclusions

The electric current path lines for an ESR process were computed according to the electric conductivity distribution in the slag domain including a thin solidified slag layer at the slag/mould interface. It has been shown that the resistance of the solid slag layer is not high enough to prevent the current to enter the mould. If an insulating assumption is used, the total heat generated in the slag region was found to be 140% higher than that really generated during the process. The computations with a conducting solid slag layer results in a by only 20% smaller value for the generated heat compared with the experiment. It should also be noticed that the results for the solid slag thickness obtained with the assumption of a conducting slag/mould interface, explain why heat flux measurements in the mould often show two peaks. The bottom peak is due to the hot slag flow impingement onto the mould, the peak at the top is due to the occurrence of the near-wall Joule heating created by the current entering the mould. The non-existence of the top peaks (in some ESR processes) could be a sign that only a little or no current enters directly the mould. In fact, the results of the model are extremely dependent on the actual variation of the electric conductivity with temperature. To stop the current from flowing into the mould, the solidified slag layer must be at least 1000 times more resistive than the liquid slag. It is clear that other slags and other geometries (fill ratio) can give totally different results. Nevertheless, through this work it is clear that the assumption that the electric current cannot cross the solidified slag layer must be used with extreme care.

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