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VARIATION OF THE RESISTANCE DURING THE ELECTRODE MOVEMENT IN THE ELECTROSLAG REMELTING PROCESS

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Abstract

In the present paper a transient 2D Magnetohydrodynamic model is used to explore the influence of the interface movements on the resistance swing in the static mould version of the Electro-Slag-Remelting (ESR) process. The model couple efficiently the electric current distribution with the movement of the electrode, the slag/gas, and the slag/metal pool interfaces. The solid slag skin is computed with a help of a 1D model that accounts for the mould current. Two electrode configurations are explored, a shallow and a 50 mm immersion depths.

Introduction

The Electro-Slag-Remelting (ESR) is an advanced technology for the production of components of e.g. high quality steels. To produce a high quality homogeneous ingot with good surface quality, the deviations in the process, such as melting rate or the immersion depth of the electrode need to be minimized. Optimisation of the process efficiency and surface quality are directly linked with the electrode immersion depth. The best results are believed to be obtained with constant immersion depth and as shallow as possible. Nevertheless, shallower is the immersion depth, the more difficult is to control the electric parameters (power, voltage). The extreme variations in voltage observed during such shallow immersion are attributed to the formation of air gap under the electrode, that can possibly lead to arcing and to deleterious oxidizing reactions. In opposite a too deep immersion depth is known to create poor surface and metallurgical quality in the final ingot.

No system currently exists to measure the depth directly, so it must be inferred from measured parameters of the process. The variation of the resistance, known as resistance swing, is the mostly used method for the control of the electrode position [1]. However, the increase in resistance swing can be reliably, but not quantitatively, related with the immersion depth. In addition, it is known that the control currently used in industry has experienced unexpected and unexplained difficulties, resulting in imperfections in the ingot being produced. This is why some efforts must be applied to the identification of process state, solely through analysis of electric process parameters.

The aim of the present work is to compute numerically the time evolution of the resistance. To achieve this goal it is important to identify the phenomena that can generate these electric fluctuations. Assuming that most of the resistance is generated within the slag cap, our analysis will focus on the electric properties of this region. The slag region experiences strong flow turbulence that can induce locally strong temperature fluctuations. The electric conductivity of a typical slag is not constant, instead it increases with temperature. If the temperature at a point located within the slag fluctuates, the Joule released at this point fluctuates as well. Recently, it was shown that these fluctuations have a considerable effect on the power generated in the slag [2]. A correction factor must be added to the Joule heating source, especially in area with strong thermal turbulence, i.e. under the electrode and at the vicinity of the mould [2]. Nevertheless, the estimated standard deviation of the total resistance was found to not exceed 3 %. By modifying the chemical composition of the slag, the electrochemical reactions may modify the average electric conductivity.

Large and sharp fluctuations of the resistance can only be generated by modifying the shape of the slag cap. The shape of the electrode tip being melted represents the first boundary. The time scale associated with a shape modification is in the order of minutes (5-20 min), assuming a constant immersion depth it cannot induce fast resistance fluctuations. The solid slag that develops at the mould (referred as slag skin) is a boundary that was considered for a long time as an electric insulator [3,4]. But recent experimental and numerical investigations on static mould ESR have shown that typically 20% (but up to 90 %) of the total current can cross it to enter directly into the mould [2,5]. The ratio mould current over the vertical current depends on the ratio between the electrode-mould radial distance and the slag cap height. A second factor is the ratio between the liquid slag and the slag skin electric conductivities. It is clear that a time fluctuation of the mould current intensity can induce a variation of the global resistance. The slag/ pool interface and the exposed slag surface are boundaries that are susceptible to move. Physically, the development of the heat and mass transfer at these interfaces is important for the final ingot quality, composition and cleanliness. Visual observations of the slag/air surface show a surface strongly affected by the slag eddies. Due to the presence of high temperatures, opacity of the materials, and the presence of the mould it is not possible to directly observe the behaviour the slag/pool interface. Although usually assumed flat, a previous work [6] using a Volume of fluid (VOF) model has shown that the interface between a layer of slag and steel layer in a cylindrical cavity is highly coupled with the distribution of the electric current. A full scale simulation of the ESR process using a VOF model has shown that the shape of the pool interface is likely to be non flat. Depending on whether a “flat” or “free” interface is assumed, an appreciable difference was found in the prediction of the pool shape and depth [7, 8]. This difference was due to a different magnitude and distribution of the Joule heat generated.

The current work presents the results given by a 2D Magnetohydrodynamic model coupled with the phases (steel, slag, gas) distribution. The model allows the movement of the electrode within the slag. The movements of the liquid interfaces are resolved in time and in space. The solidified slag skin thickness is considered with a 1D model which includes the influence of the electric current and the heat fluxes at the contact with the mould. Two different states are explored, one with shallow immersion depth, and a second with a deep penetration depth. In the present study, the influences of the melting, the solidification of the metallic pool and of the falling droplets on the electric current distribution are not taken into account.

Numerical Model

The axisymmetric calculation domain is presented in figure. 1. A rigid electrode is put in contact with a cylindrical container filled with a 10cm height layer of liquid slag and an equal quantity of liquid steel. Most of properties of steel, slag and gas (N_2) are assumed to be constant. The electrode supplies a total 5Hz AC current of I_0=5000 Amperes. The operating conditions as well as the material properties are presented in Table 1.

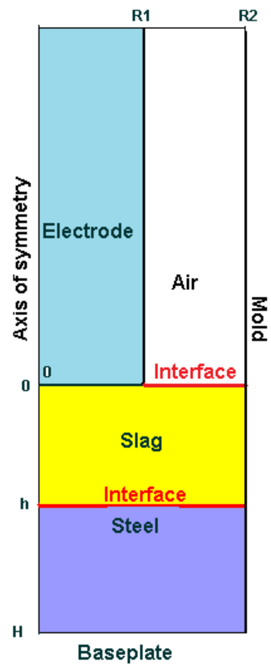

Figure 1. Calculation domain

Interface tracking

The Volume of fluid (VOF) method provides the possibility of tracking immiscible interfaces over a fixed Eulerian mesh. It is designed for two or more immiscible fluids where the position of the interface between the fluids is of interest. In the VOF method the motion of the interface between immiscible liquids of different properties is governed by a phase indicator, the so-called volume fraction *f*, and an interface tracking method. The volume fraction f_k is equal to 0 outside of liquid *k*, and equal to 1 inside. The evolution of the interface is calculated using the geometrical reconstruction scheme.

The local values of a physical property Θ (such as density, viscosity, electric conductivity) are interpolated by the following formula:

$$\Theta = \Theta_1 f_1 + \Theta_2 f_2 + \Theta_3 f_3 + \Theta_4 f_4 \,, \qquad (1)$$

where the subscripts 1-4 indicate the corresponding phase, 1 for slag, 2 for steel, 3 for solid steel (electrode), and 4 for air. An explicit version of the VOF technique was used for the present calculations. The value of the surface tension is fixed to 1 N/m at both air/slag and slag/melt interfaces. Depending on the dynamic of the interfaces, the typical calculation time step lies in the range of 10^{-2}-10^{-4} second.

Fluid flow

The motion of the slag, gas, and liquid steel is computed with the continuity and the Navier-Stokes equations. The no-slip condition is applied at all the walls. The electrode and the top air surface are modeled as velocity inlets with fixed velocities. To conserve the volume, whenever the electrode is pushed at a certain speed downwards or upward ($\vec{u} = \vec{u}_{ele}$), the equivalent speed is applied in the opposite direction at the top air surface $\vec{u} = -\frac{R_1^2}{R_2^2 - R_1^2}\vec{u}_{ele}$. The effect of the turbulence is estimated through an effective viscosity μ_t with the help of the Realizable *k*-ε. The no-slip condition is applied at all the walls (electrode, mould and baseplate boundary).

Electromagnetics

To solve the electromagnetic field, two techniques can be used, one based on the induced magnetic field $\vec{H}_\theta$, and another based on the electric potential ϕ and magnetic potential $\vec{A}$. Due to its simplicity, the method based induced magnetic field is the most widely used technique [2-8]. With no mould current, a single (or double in AC) equation must be solved with very simple boundary conditions. When the possibility of having currents crossing the solid slag skin directly into the mould, the induction equation needs to be solved with the thin slag layer with enough grid point to correctly resolve the strong decrease in electric conductivity [2,5].

In the present work, the potential method A-ϕ has been used the solid slag layer is modeled and not directly solved [see next part]. The potential at the mould and at the base plate is fixed to 0. The method based on the electric potential allows us to write the mould current in the simple form:

$$j_m = \sigma_W \frac{\phi}{\delta}\,, \qquad (2)$$

Where σ_w is the average electric conductivity within the slag skin, assumed to be 100 times smaller than the conductivity of the slag at liquidus temperature. At the level of the metal pool no current is allowed to cross the slag skin $(j_m = 0)$.

Since the time resolution of the interface needs the use of very small time step, the choice is made here to resolve the oscillation of the imposed electric current. The boundary condition at the mould consists in equalizing the electric flux to the mould current when the adjacent cell is filled with slag, or to 0 in the other cases (air or metal). Usually the Lorentz force and the Joule heat source are introduced in the corresponding equations only after time averaging [2-8]. In the present approach these sources are oscillating in time around their main values, allowing a full coupling between the hydrodynamic, the electromagnetic and the thermal phenomena.

Heat Equation

The heat balance is of importance here in order to estimate the thickness of the solid slag skin. The melting and solidification of the metal is not considered. The energy equation is solved in the fluid domain.

$$\frac{D(\rho C_p T)}{Dt} = \nabla(k\nabla T) + \frac{j^2}{\sigma} \quad (3)$$

Where C_p , k, σ, are the mixture heat capacity, the heat conductivity, and the electric conductivity. The temperature at the electrode/slag contact surface is fixed at the alloy liquidus temperature. The P1 radiation model is used to compute the radiation in the gas media. This radiation model is necessary in order to correctly estimate the heat radiation fluxes for any shape of the exposed slag surface. At the gas level, the radiative emissivity of the electrode and of the mould is taken equal to 0.8. At the lateral, and at the bottom boundaries, the temperature is fixed at the slag liquidus temperature (1650 K).

Modeling of the solid slag thickness

The solid slag skin is not directly resolved but rather implicitly modelled. The present approach is inspired from concept of wall functions used in turbulence modelling when the mesh is not fine enough to resolve the turbulent and the viscous boundary layers. From the heat balance through the solid slag layer it is possible to extract a simple 1 D equation for the evolution of its thickness $\delta(z,t)$:

$$\underbrace{\rho(C_p\overline{T} - L)\left(\frac{\partial\delta}{\partial t} + u_{melt}\frac{\partial\delta}{\partial z}\right)}_{(a)} = \underbrace{-\rho C_p\delta\left(\frac{\partial\overline{T}}{\partial t} + u_{melt}\frac{\partial\overline{T}}{\partial z}\right)}_{(b)} \underbrace{- Q_{s->\delta}}_{(c)} \underbrace{+ Q_{\delta->m}}_{(d)} + \underbrace{\int\frac{j_m^2(r,z)}{\sigma(T)}dr}_{(e)} \quad (4)$$

The terms from left to the right are the contributions of the (a) latent heat released or absorbed, (b) the evolution of the average temperature of the solidified slag layer $\overline{T}$, (c) heat lost from the liquid slag to the solidified slag layer, (d) the heat lost from the solid slag to the cooper mould, and (e) the Joule heat dissipated within the solid slag layer.

A simple linear temperature profile is assumed through the solid slag layer, the volume average temperature within the layer is:

$$\overline{T} = \frac{T_{Liquidus} + T_{mould}}{2} \quad (5)$$

The effect of the elevation of the slag level during the melting is taken into account through the velocity u_{melt}, related to a fixed melt rate (2kg/min). This approach allows also the slag skin thickness to vary with the melt rate.

In the present calculation the Joule heating source is simplified by using the average slag skin electric conductivity:

$$\int_{R_2}^{R_2+\delta}\frac{j_m^2}{\sigma(T)}2\pi r dr = 2\pi R_2\frac{j_m^2}{\sigma_w}\delta \quad (6)$$

The heat lost by the liquid slag is:

$$Q_{s->\delta} = -k\frac{\partial T}{\partial r}. \quad (7)$$

an excellent heat contact is assumed between the slag skin and the mould, the temperature at the interface slag skin/mould is assumed constant:

$$Q_{\delta->m} = k_{ss}\frac{T_{Liquidus} - T_{mould}}{\delta} \quad (8)$$

The variation of the slag skin is considered at the level of the slag. When the slag skin reaches the pool region it is simply shifted towards the bottom with a speed related to the melt rate.

In the next iteration the mould current is recomputed from the given slag thickness. Without the presence of mould current, the solid slag thickness is only controlled by the melting rate and the balance of heat fluxes at the mould. By adding a heat source within the slag skin, the presence of mould currents decreases this thickness, which in turn increases the quantity of mould current (Eq.2). This cycle of increases is stopped when the electric current has found the pattern that minimizes the global resistance. This simple approach can model the creation of the slag skin at the level of the exposed slag surface where time oscillations of the interface are expected. After having computed the electric currents pattern, the total electric resistance include the resistance of the liquid slag (volume integral) and of the slag skin (integrated over the slag height):

$$Res(t) = \frac{1}{I_0^2}\left(\int\frac{j^2(r,z,t)}{\sigma(T,t)}dv + \int\frac{j_m^2(z,t)}{\sigma_w}dz\right). \quad (9)$$

The time average resistance is :

$$\overline{Res(t)} = \frac{1}{2T_0}\int_{-T_0}^{T_0}Res(t)dt, \quad (10)$$

Table 1. Parameters used in the simulations.

Steel	
Density (kg·m^{-3})	6800
Viscosity (Kg·m^{-1}·s^{-1})	0.006
Specific heat, liquid (J·Kg^{-1}·K^{-1})	800
Thermal Conductivity, liquid(W·m^{-1}·K^{-1})	40
Electric Conductivity, liquid(ohm^{-1}·m^{-1})	880000
Slag	
Density, liquid (kg·m^{-3}) Solid	2700 3000
Viscosity (Kg·m^{-1}·s^{-1})	0.0025
Specific heat, liquid (J·Kg^{-1}·K^{-1}) solid	1200 1000
Thermal Conductivity, liquid(W·m^{-1}·K^{-1}) solid	10 0.5
Electric Conductivity, liquid(ohm^{-1}·m^{-1}) , solid	120 1.2
Thermal expansion coefficient (K^{-1})	2.5 x 10^{-4}
Liquidus temperature (K)	1650
Latent heat of fusion(W/kg)	4.5 x 10^{5}
Geometry Mould Thickness (mm)	30
Slag and metal height(mm)	100
Electrode diameter, R_1 (mm) Mould diameter, R_2 (mm)	135 200
Process parameter	
T_{mould}	480 K
I_0, f (A, 5Hz)	5000

Application of the model

Shallow immersion depth

In the case when the electrode is just put in contact with the slag surface, the simulation shows a strongly fluctuating slag/gas interface (Figure 2). During the calculations, the electric current intensity was progressively increased. Far before reaching the desired intensity, at about 1400 Amps, a large gas bubble was created between the electrode and the slag media (Figure 2). During the insertion of the gas, the electric current lines are shifted towards the electrode centre, this phenomena is at the origin of the strong increase of the resistance (Figure 3 point B). The strong decrease of resistance at the stage C is due to occurrence of a small surface contact between the slag and the electrode. Due to some flow turbulence, the electric contact is very unstable. Combined with hazardous electric contacts, the forward movement of the gas gap led to a new increase in resistance (Figure 3 stage D).

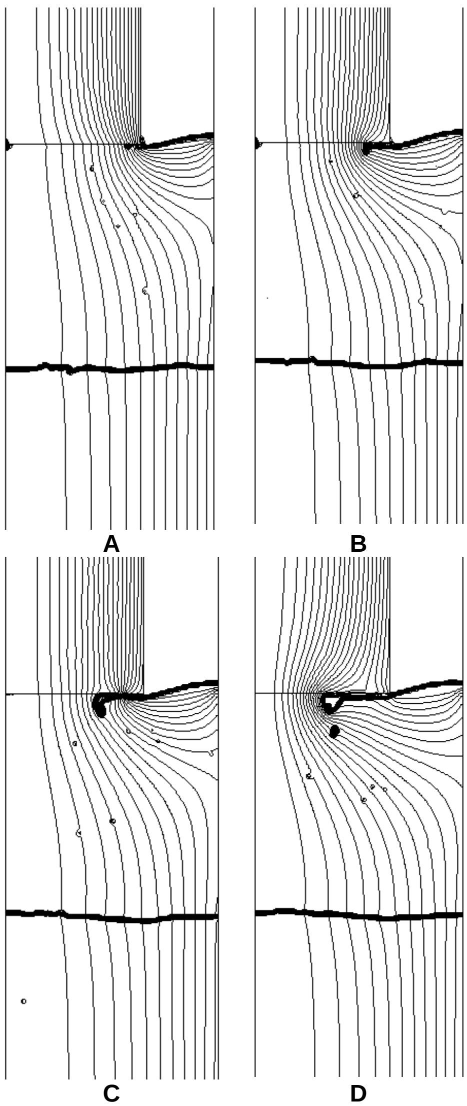

Figure 2: Electric current lines during the formation of an air gap between the slag and the electrode (see also figure 3)

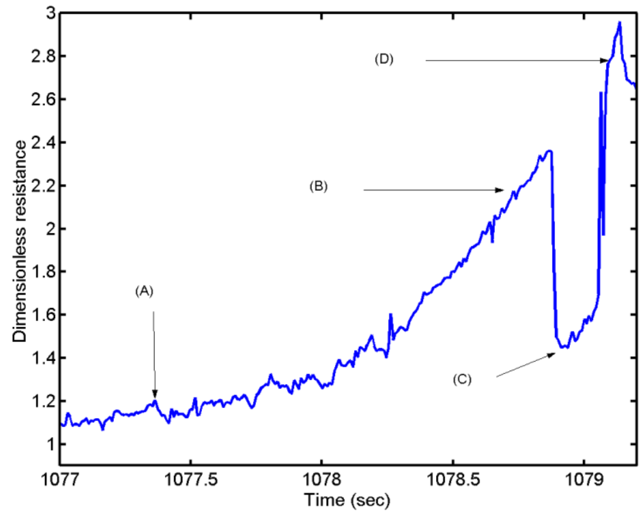

Figure 3: Evolution of the resistance during the formation of an air gap under the electrode

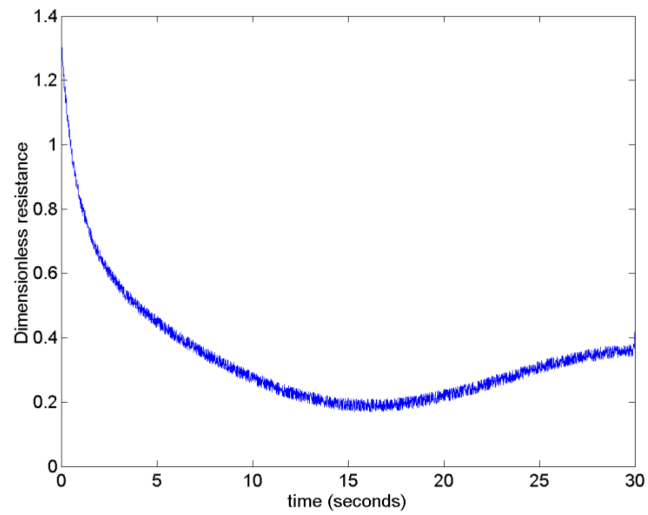

Figure 4: Average resistance during the electrode penetration into the slag

Immersion depth of 50 mm

The electrode is moved downward at a speed of 1.8 mm/s a shift of about 30 mm, corresponding to 50 mm electrode immersion depth. This speed, is relatively small compared to the maximum velocity calculated (~20 mm/s). During the electrode drive, the main resistance decreases dramatically (Figure 4). In opposite to the slag/pool interface, the slag/gas interface does not seem to be affected by the electrode movement (Figure 6-7). During the electrode movement, the elevation of the slag surface increases the surface through which the electric current enters the mould. Although the electrode is now closer to the liquid pool, the average proportion of mould current increased from 30 to 50 %. After 20 seconds, the calculations show an increase of the average resistance with time, it is due to the slow formation of the solid slag thickness and to the redirection of the electric current lines towards the liquid pool (Figure 6). The maximum amplitude of the interface slag/pool movement is about 2 cm, with main frequencies in the 1-30 Hz range. The computed solid slag thickness (Figure 7) is larger than in the previous case, except at the level of the electrode. This behaviour can be explained by a lower bulk temperature and lower amount of mould current usually associated with deep electrode penetration depth. The thinner layer observed at the level of the electrode is due to the presence of mould current and to flow convection.

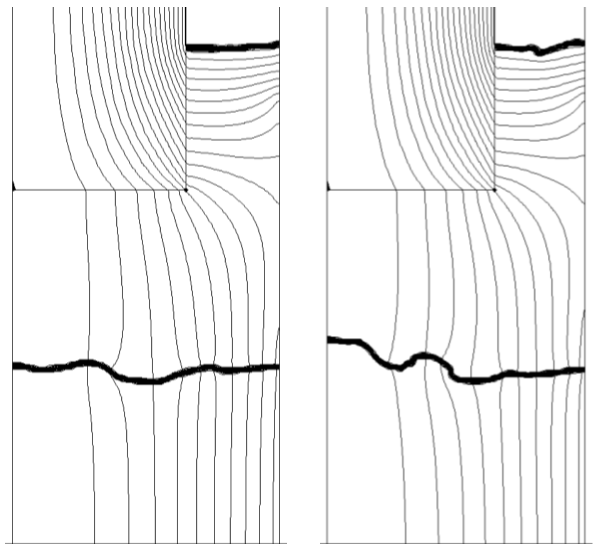

Figure 5: Electric current lines and interface positions at 15 seconds after end of electrode movement

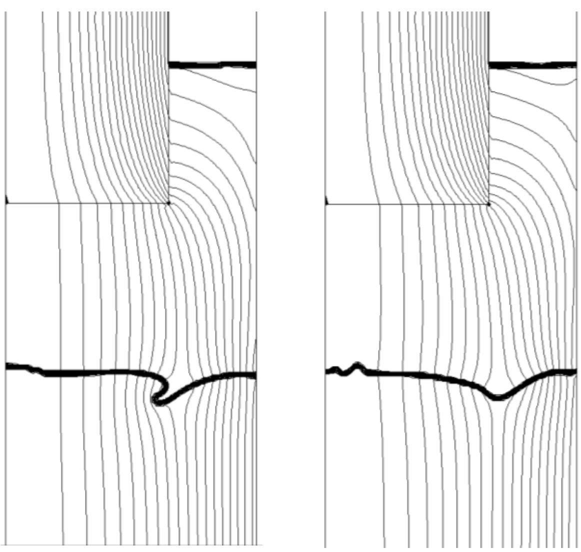

Figure 6: Three successive MHD configurations during steady state reached about 10 minutes after the electrode movement.

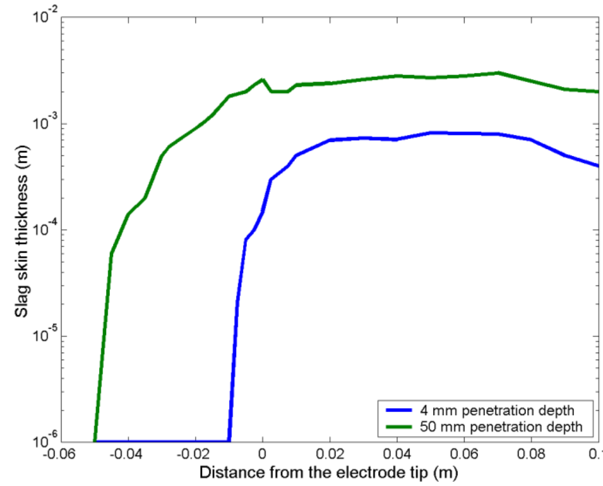

Figure 7: Evolution of the solid slag thickness along the mould wall during steady state.

Conclusion

ESR process is inherently a dynamic process. Analysis of time data of the resistance has the potential to expose a number of abnormal or undesired process attributes (arcing, too deep electrode penetration depth). In order to improve process diagnostics, the identification of these attributes remained an area of interest for a number of years. The increasing capability of computational power has opened the possibility to explore with CFD techniques complex coupled phenomena. A numerical model was built with good ability to handle free surfaces, and good flexibility to handle the dynamic electromagnetic fields. The model was applied to a small ESR process to explore the interaction between the interfaces and the quantity of mould current. The time evolution of the resistance was recorder for each simulation run. The strong coupling between the slag/pool, slag/air interfaces, and mould current gives a new insight into the nature of the MHD oscillation present in the ESR process. Considerable work needs to be performed to achieve a full understanding of the interface movement under the action of MHD forces. However in the real process, these fluctuations are likely to be three dimensional. Although numerical requirements for 3D MHD flows with free interfaces are considerable, the building of a 3D model of the ESR process is a necessity.

Acknowledgements

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References

1. D.K. Melgaard, R.L. Williamson, and J. J Beaman. "Controlling Remelting Processes for Superalloys and Aerospace Ti Alloys" *JOM,* 1998 March, p13-17
2. A. Kharicha , W. Schützenhöfer, A. Ludwig , G. Reiter, "Re formulation of the Joule heating in presence of turbulent fluctuation," *Int. J. Cast Metals Research*, 22 (2009), 155-9.

3. B. Hernandez-Morales and A. Mitchell, “Review of mathematical models of fluid flow, heat transfer, and mass transfer in electroslag remelting process”, *Ironmaking & Steelmaking,* Vol. 26 No. 6 (1999), p.423-438
4. V. Weber, A. Jardy, B. Dussoubs, D. Ablitzer, S. Ryberon, V. Schmitt, S. Hans, H. Poisson, “A comprehensive model of the electroslag remelting process: description and validation,” *Metall. Mater. Trans. B.* 14 january
5. A. *Kharicha* , W. *Schützenhöfer*, A. Ludwig , G. Reiter, M. Wu, “On the importance of electric currents flowing directly into the mould during an ESR process,” *Steel Research Int*., 79 (2008) 632-36.
6. Kharicha A., Ludwig A., Wu M. "Shape and Stability of the Slag/Melt Interface in a Small DC ESR Process" *Mater. Sci. Eng. A,* 413-4(2005)129-34.
7. Kharicha A., Schützenhöfer W., Ludwig A., Reiter G. "Influence of the slag/pool interface on the solidification in an electroslag remelting process" *Mater.Sci.Forum,* 649 (2010) 229-36.
8. A. Kharicha, A. Mackenbrock, A. Ludwig, W. Schützenhöfer, V. Maronnier, M. Wu, O. Köser, R. Tanzer: "Selected Numerical Investigations on ESR Process" *Int. Symp. Liquid Metal Processing and Casting (LMPC-07),* Sept. 2-5, 2007, Nancy, France. Eds. P.D. Lee, A. Mitchell, J.P. Bellot, A. Jardy, p 113-119