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Mathematical Modelling of the Flow Field, Temperature Distribution, Melting and Solidification in the Electrolslag Remelting Process

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Abstract

The Electroslag Remelting (ESR) process works with a consumable electrode, which is melted through a slag layer into a water-cooled mould applying alternating electric current. The ESR process produces large ingots of high quality, by controlled solidification and chemical refinement. It is important to predict, how certain process parameters affect the structure and chemical composition of the product. Due to the high costs and difficulties regarding physical modelling, numerical modelling is a competitive alternative. An understanding of the heat, momentum and mass transfer in the ESR process is the basis for further microscopic studies. Due to the transient application of the multiphase, non-isothermal fluid flow problem with magneto-hydrodynamic effects, melting and solidification, modelling is a complex task.

In this paper results of a numerical model to solve these transport phenomena are presented. In this model the electromagnetic field, the resulting Lorentz forces and the Joule Heating are modelled. The fluid flow field, the temperature distribution, the movement of the different phases and the melting and solidification resulting from the electromagnetic field are shown.

Introduction

The Electroslag Remelting Process is a remelting process with a consumable electrode. These kinds of processes produce large ingots of higher quality then that of the original material, by controlled solidification and chemical refinement. Alternating or direct current flows from the solid electrode through the slag layer and the metal pool to the bottom plate. The slag is heated due to Joule heating, because of the electrical resistance of the slag. The produced heat is transferred to the electrode, the ingot and the mould. The material on the electrode tip is melted. This material passes, in dependence of the melting rate as a droplet or as a stream, the slag layer and reaches the metal pool. The metal solidifies due to the mould cooling and builds an ingot with a high grade of directional solidification, which depends on the heat balance. On the surface of the ingot a small solidified

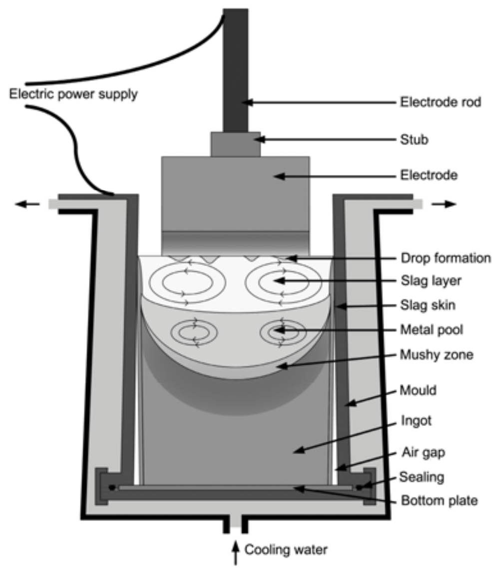

Fig. 1: Design of an ESR plant

slag film occurres during the solidification. This film is responsible for an electrical isolation between ingot and mould. Furthermore an air gap is built between ingot and mould due to the shrinkage during the solidification. All this attributes have to be taken into account during the mathematical modelling [4]. There is a primary interest to quantify the influence of certain process parameter to the structure and the chemical composition of the product. The fluid flow in the slag and in the metal pool has a big influence on the segregation. The fluid flow is driven by temperature differences and by the electromagnetic field. Fig. 1 shows the principle design of an ESR plant.

1. Simulated Process

A stainless steel (AISI 304) with a solidification interval of $\Delta T = 30$ K and a CaF2-CaO slag is used for the simulation, table 1. In table 2 the process parameters are shown. These parameters correspond with an experimental setup to validate the numerical results. The experiment has been carried out at an open ESR facility at the Institute for Process Metallurgy and Metal Recycling at RWTH Aachen University. The remelted ingot has been cutted lengthwise, sanded and etched to visualize the solidification structure. The depth of the solidification pool can be regognized in this way.

Tab. 1: Material data

Stainless steel AISI 304	Chromium	~ 18 %
	Nickel	~ 10 %
	Liquidus temperature T_{liq}	1740 K (1467 °C)
	Solidus temperature T_{sol}	1710 K (1437 °C)
Slag CaF2-CaO	Calcium oxide	~ 1.7 %

Tab. 2: Process parameters

Geometry	Diameter of the mould	$D_m = 0.160$ m
	Diameter of the electrode	$D_e = 0.110$ m
Electric power supply	Current	$I = 3000$ A
	Frequency	$f = 50$ Hz
	Mass flow rate	$\dot{m} = 0.64$ kg/s

2. Numerical Simulation

The commercial code FLUENT is used for the numerical simulation of the electroslag remelting process. A quasi steady state, where the fluxes are in equilibrium, is used for the numerical simulation. The slag and a part of the steel phase are simulated.

2.1. Geometry

The first 0.147 m below the electrode are used for the simulation. The relevant transport of momentum, heat and mass transfer take place in this region. The solidification of the steel starts in this region, below the steel is a solidified ingot. The slag layer has a thickness of 0.067 m. The calculation is done 2-d axial symmetric. Therefore just one half of an ESR facility is meshed. The mesh contains 18400 cells with an step width of 0.8 mm. The inlet is situated directly below the electrode and has the same diameter as the electrode and is defined as velocity inlet, whereby the inlet velocity is in accordance with the remelting speed. The outlet extends across the whole cross section at the bottom of the grid. An electric isolating slag layer is assumed at the walls of the mould, therefore the alternating electric current is conducted only via inlet and outlet. The calculation is performed transient.

2.2 Multiphase flow

The multiphase flow is simulated with the Euler-Euler approach. In this approach the different phases are treated as a continuum. The phase boundaries in the model in this paper are calculated with the "Volume of Fluid" method [3,5].

The interfacial tension appeared on phase interfaces and minimised the free energy by reducing the interface. A special influence of the interfacial tension occurred during the drop formation. The interfacial tension is calculated by the "Continuum Surface Force" model of Brackbill [3,7].

2.3 Solidification model

An enthalpy-porosity [9,13,14] technique is used in FLUENT for modelling the solidification/melting process. In this technique, the melt interface is not tracked explicitly. Instead, a quantity called the liquid fraction, which indicates the fraction of the cell volume which is in liquid form, is associated with each cell in the domain. The liquid fraction is computed each iteration, based on an enthalpy balance.

The mushy zone is a region in which the liquid fraction lies between 0 and 1. It is modelled as a "pseudo" porous medium in which the porosity decreases from 1 to 0 as the material solidifies. When the material has fully solidified in a cell, the porosity becomes zero and hence the velocities also drop to zero.

The enthalpy due to melting and solidification is considered in the energy equation via an additional source term. The interaction between the flow and the solidified metal especially in the mushy zone is taken into account by a temperature dependent sink in the momentum equation [3,9,13,14].

2.4 Magnetohydrodynamic model (MHD model)

The transport equation of the magnetic field intensity for the investigated problem is:

$$\frac{\partial \vec{H}}{\partial t} = \Gamma_H \Delta \vec{H}\,. \tag{2.1}$$

Where $\Gamma_H = 1/(\sigma\mu_0)$ is the magnetic diffusion. The convective term can be neglected, due to a small magnetic Reynolds number. Therefore the magnetic equations are solvable independently from the flow field. Anyway it is necessary to solve the magnetic equation every time step, due to the influence of the droplet and phase boundary motion on the magnetic field. The magnetic field intensity is calculated via two User Defined Scalars, one for the real part and one for the imaginary part of the field intensity. The Lorentz force and the Joule heating are implemented in the momentum and energy equations, respectively, via source terms [1,2,6,8]. A detailed description of this model can be found in [10,11].

4 Results

The following figures show the results of the magnetic field and the resulting flow field. Furthermore the influence of different electric power supply is investigated. Due to the axial symmetric flow, just one half of the ESR is presented. More detailed results of the MHD model are described in [10,11,12].

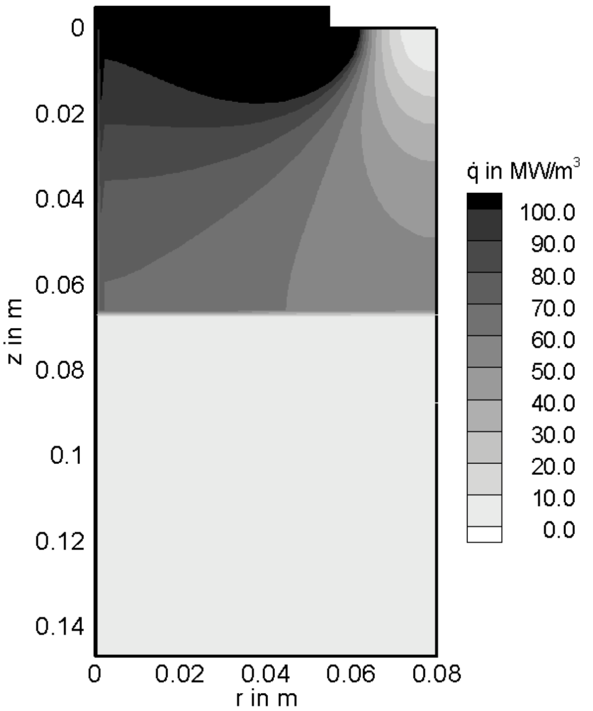

Fig. 2: Heat input due to Joule heating without motion of the steel-slag interface

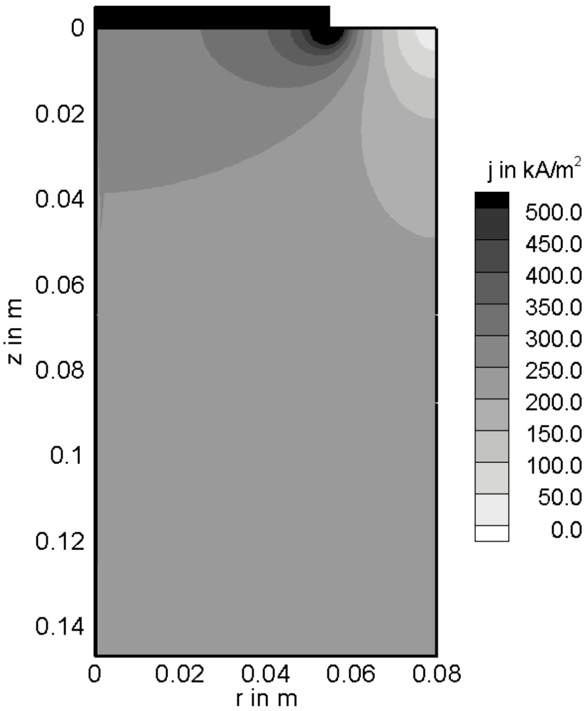

Fig. 3: Current density distribution without motion of the steel-slag interface

Fig. 2 shows the distribution of the heat input due to Joule heating for the magnetic field without motion of the interface between steel and slag. In the steel the Joule heating is negligible, due to the low electric resistance of the steel. In areas with a high current density in the slag (see fig. 3) the heat input is higher as in areas with a smaller current density. The current density is high at the electrode edge and below the electrode. At the upper edge of the mould the current density is very low, because of the isolating mould there is no need for the current flow to go there. Hence the heat input in this region is very low, too.

In fig. 4 and 5 the slag and steel fraction and the droplet movement at a certain time and the current density distribution at the same time can be seen. During the process different droplet types are generated. Usually the drop formation starts with a long droplet, which collapses to different small droplets. The drop formation takes place in the middle of the electrode due to the Lorentz force influenced flow field. The current density distribution shows now a high value not only close to the electrode edge, but also in the line where the droplet movement takes place. Due to the fact, that the current uses the way of smallest resistance and steel is a better conductor than slag, the current density is high there.

In fig. 6 the Lorentz force influenced flow field at the same time as in fig. 4 and 5 is shown. In the slag a vortex system is generated with a downward flow below the electrode and an upward flow near the mould wall. This distribution is caused by the Lorentz force, which directs the flow towards the symmetry axis. There the vortex fields hit each other and a downward flow is established. Near the mould wall a compensating upward flow is created. The influence of the Lorentz force at the steel flow is considerably lower. In the slag a Lorentz force dominated flow field is observed. Below the electrode the high velocities are caused by the droplet movement.

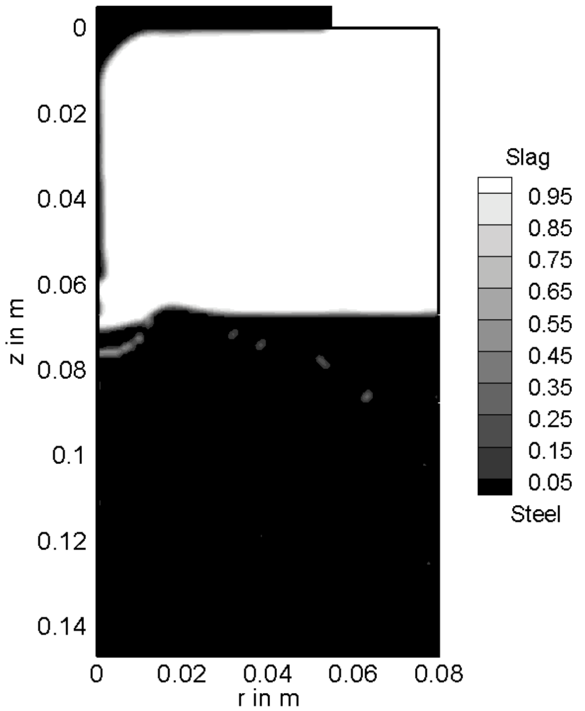

Fig. 4: Slag and steel fraction with droplet movement

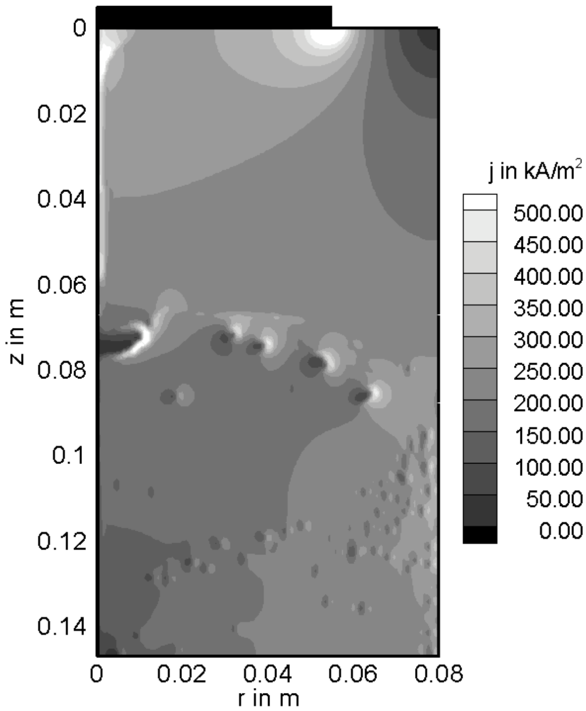

Fig. 5: Current density distribution with droplet movement

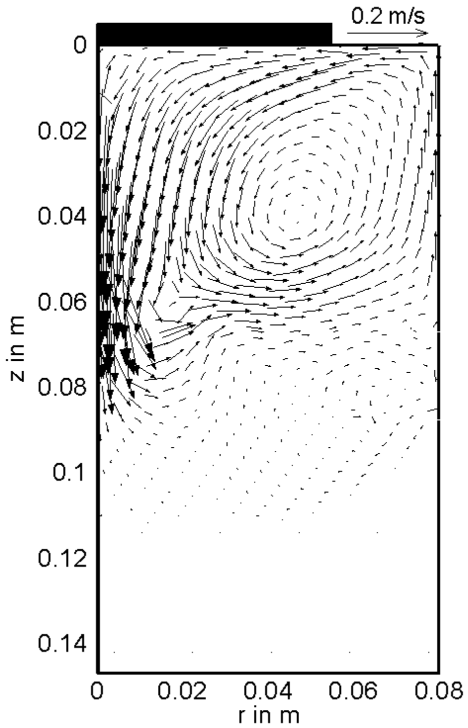

Fig. 6: Velocity vectors with droplet movement

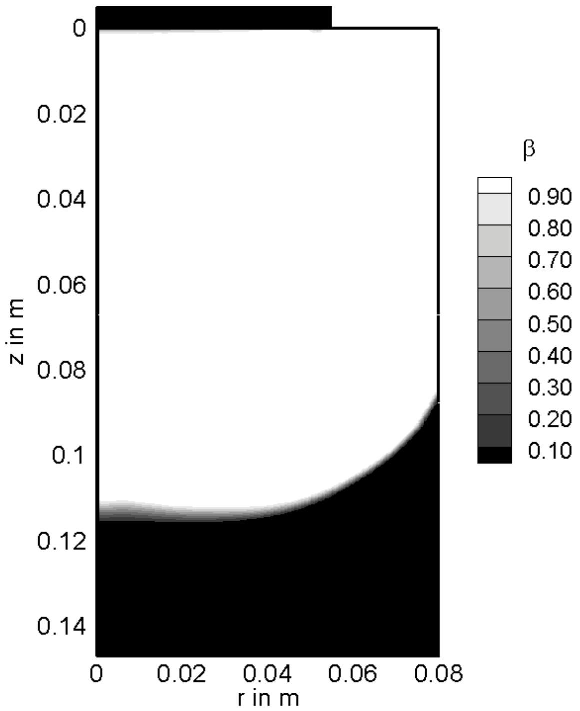

Fig. 7: Liquid fraction, solidification and mushy zone

In fig. 7 the liquid fraction of the steel is shown. The distribution of the solidification and the mushy zone can be recognized. A comparison between the depth of the meelting pool in the numerical calculation and in the experiment shows a good agreement between both. In the experiment a solidification pool depth of about 29.9 mm has been found. The numerical calculation shows a solidification pool depth between 25.5 and 29.5 mm for the liquidus and solidus temperature, respectively.

Conclusions

This paper presents numerical models to solve the complex transport phenomena in the ESR process. The “Volume of Fluid” method, with the “Continuum Surface Force” model to include the surface tension, is implemented to capture the multiphase flow. For the melting and solidification the enthalpy-porosity method is applied. The electromagnetic field, the resulting Lorentz forces and the Joule Heating are modelled assuming this field being independent of the flow. These models are combined with the turbulent flow and energy equations via additional source terms in these equations.

The model is capable to quantify the Lorentz force and the Joule heating. The calculated flow field shows vortices mainly influenced by the Lorentz force. The distribution of the slag and steel fraction and the movement of the droplets can be seen. Furthermore the model is able to predict the solidification and the mushy zone in the process. The comparison of pool depth between experiment and calculation shows a good agreement.

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