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A Multiscale Three-Dimensional Numerical Simulation of Electroslag Remelting Process

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Abstract
A three-dimensional, transient and multiscale mathematical model has been presented, which is able to reveal the coupled physical fields in the electroslag remelting (ESR) process. The mold is assumed to be conductive rather than insulated. The electric current, Lorentz force and Joule heating fields were demonstrated by Maxwell’s equations. The volume of fluid (VOF) approach was implemented for the metal droplet behavior. The solidification was modeled by an enthalpy-porosity formulation, in which the mushy zone was treated as a porous medium with porosity equal to the liquid fraction. Besides, the solute distribution was revealed by the continuum mixture model. The macro-model was linked to a meso-model through the flow and temperature fields. A regular network of square cells with a much finer scale was drawn for the grain structure with the cellular automaton (CA) technique. The continuous nucleation, which is based on the Gaussian distribution, was implemented to describe the heterogeneous nucleation. The growth kinetics of the dendritic tip was taken into account by the Kure-Giovanola-Trivedi (KGT) model. Moreover, a moving mesh was carried out to account the growing of ingot. The electric current flows to the mold lateral wall especially in the slag layer. A large amount of Joule heating around the metal droplet varies as it falls. The hottest region appears under the outer radius of the electrode tip, close to the slag/metal interface instead of the electrode tip. The metal pool becomes deeper with more power. The maximal temperature increases from 1951 K to 2015 K, and the maximum metal pool depth increases from 34.0 mm to 59.5 mm with the applied current ranging from 1000 A to 2000 A. The vertical columnar grains appear at the bottom of the ingot and an inverse V-shaped grain structure is observed at the upper part.

Key words: electroslag remelting; electromagnetism; two-phase flow; solidification; macrosegregation; microstructure

Introduction
ESR is an advanced technology of ingot production which is used in critical applications such as aeronautics, power generation, medicine, and tooling [1]. The passage of an alternating current (AC) from the electrode to the baseplate creates a Joule heating in the highly resistive calcium fluoride-based slag, which is sufficient to melt the electrode. The interaction between the self-induced magnetic field and the AC gives rise to the Lorentz force. Metal droplets sink through the less dense slag to form a liquid metal pool in the water-cooled mold. Heat loss to the mold solidifies the metal, forming an ingot and maintaining a liquid metal pool throughout the process. The redistribution of the compositions in the metal pool creates the macrosegregation in the final ingot [2].

Given the complicated phenomena involved, and the difficulty and expense of performing experiments on a real apparatus, numerical simulations constitute an attractive approach. Dilawari et al. [3] and Jardy et al. [4] developed a two-dimensional (2D) axisymmetric model, which accounts for the steady state Lorentz force, flow field and temperature distribution. In recent years, a transient comprehensive 2D axisymmetric model has been established by Weber et al. [5]. Moreover, the transports of the solutes as well as the inclusions during the process were illustrated by Kelkar et al. [6]. Yanke et al. [7] focused on the formation of the solidified slag skin. Kharicha et al. [8] and Hugo et al. [9] investigated the impact of the mould current on the Joule heating distribution. Fezi et al. [10] represented the effect of the current on the segregation level in the ESR ingot. Nastac et al. [11] adopted a stochastic numerical approach to model the formation of grain structure and secondary phases during the solidification of ESR ingot.

The present work aims to develop a transient 3D macro-model, which is able to show the varying of the physical fields in the ESR process. A one-way coupled meso-model is used to simulate grain structure development. A mesh model is built based on a real scale furnace, which was used to perform some experiments. The comparison of the experimental observations and simulated results is carried out.

Model Description

Electromagnetism
The magnetic Reynolds number, which expresses the ratio of the magnetic convection to magnetic diffusion, remains very low in the ESR process. The magnetic diffusion therefore dominates the electromagnetic phenomenon. The quasistatic magnetic equations are solved, because the changing of the magnetic diffusion is fast enough. Moreover, we use the phasor notation to account for the periodic time dependence.

The magnetic field intensity continuous at the inlet and bottom, and is related to the current on the top surface of slag
and the mold lateral wall. Finally, we can obtain the time-averaged Joule heating and Lorentz force fields.

**Fluid Flow**

The flow is modeled by the continuity equation and time-averaged Navier-Stokes equations. The source term \( F_l \) represents the thermal buoyancy determined by the Boussinesq approximation, and \( F_s \) is the solutal buoyancy induced by the solute redistribution. We treat the mushy zone as a porous medium where the porosity gradually decreases from 1 to 0 as the metal solidified, and thus \( F_s \) is the turbulent damping force solved by the Darcy’s law. The permeability of the mushy zone, which is determined by the Kozeny-Carman equation, is related to secondary dendrite arm spacing. The movement of the slag and the metal is weakly turbulent. The RNG k-ε turbulence model, which is able to capture the behavior of flows with lower Reynolds number, therefore is employed to calculate the turbulent viscosity. An enhanced wall function is employed to work with the RNG k-ε turbulence model, particularly since liquid metal has a low Prandtl number. The two-phase flow is tracked with the VOF approach. The continuum surface force model is implemented to consider the surface tension between the metal and slag.

An iterative procedure is used to include the varying melt rate related to the Joule heating, and the changing melt rate is imposed on the inlet. A no-slip condition is applied to the lateral wall and bottom. A zero shear stress is adopted on the top surface of the slag.

**Heat and Mass Transfer**

The energy conservation equation of the enthalpy-formulation is employed to demonstrate the temperature distribution. The enthalpy of the metal and the slag is computed as the sum of the sensible enthalpy and the latent heat released in the mushy zone.

Local solute mass fraction is described by the species conservation equation. The convection diffusion is included, while the molecular diffusion is neglected. Besides, the elements motions are irrelevant. The liquidus and solidus temperatures are a function of the local solute concentration. The liquid fraction is updated by the liquid/solid interface temperature. The lever rule is used to describe the liquid/solid interface temperature, and the interfacial transfer of species at the liquid/solid interface as well as the species movement in the solid phase.

In order to consider the melting process in a more simplified way, the temperature of the metal at the inlet is given by a parabolic profile. This parabolic profile has an approximate 30 K superheat and a peripheral boundary temperature close to the metal liquidus temperature. Equivalent heat transfer coefficients are applied to the lateral wall and bottom. The concentration of each species at the inlet is equal to the nominal concentration in the AISI 201 stainless steel.

**CA Model**

A probabilistic approach based on the instantaneous nucleation and Gaussian distribution of nucleation sites is introduced in the present work. The grain growth is described by the KGT model depending on the local undercooling. The total undercooling is generally the sum of four contributions, which are associated with solute diffusion, thermal diffusion, attachment kinetics and solid-liquid interface curvature. Only the solute diffusion undercooling is considered, because the last three terms are negligibly small. The SDAS is a function of the temperature gradient, solidification rate and temperature difference.

**Results and Discussions**

**Electromagnetic Fields**

Fig. 1 illustrates the simulated current density and Joule heating density fields at 1400 s with the current of 2000 A. The electric current flows downward from the inlet to the two sides. The maximal current density is found just near the periphery of the inlet and the minimum is located at the outer side of the top slag. The skin effect is not observed, because the depth of skin effect is approximately 85 mm larger than the ingot radius. Most Joule heating is generated in the slag due to the smaller electrical conductivity. Moreover, the distribution of the Joule effect is similar to that of the current density. Fig. 2 displays the calculated Lorentz force and phase distribution. The inward Lorentz force generates a pinch effect. Thus, the metal moves toward the middle and forms a droplet. According to the Biot-Savart law, the force at the outer edge is larger than that at the middle.

**MHD Thermosolutal Convection**

Fig. 3 represents the simulated temperature distribution. The highest temperature region is just at the same place with the maximal Joule effect mentioned above. The slag becomes colder from the top and a lower temperature region is observed at the outer edge of the bottom slag. With more heat, the slag is hotter than the metal. The colder metal droplet therefore is heated by the slag during its falling. Due to the forced cooling in the ESR process, a large thermal gradient is achieved leading to a faster freezing speed.

Two pairs of vortices are found in the slag layer as shown in Fig. 4. The heat extracted by the cooling water results in a descent of the slag at the wall due to buoyancy. This causes a stable clockwise circulation, which can be seen on the right side of the figure. The downward flow at the lateral wall turns the corner to form a radial jet along the slag/metal interface. The strength of the jet diminishes as it moves inward and finally turns upward. At the center of the slag, a counterclockwise circulation is caused by the Lorentz force and the falling metal droplets. The heat extracted by the cooling water at the bottom and lateral wall, which drives the freezing of metal. A shallow metal pool therefore is formed. The flow in the metal pool is different from that in the slag. Due to the forced cooling, the thermal buoyancy
dominates the flow pattern. The clockwise cell in the pool results in the motion of heavy cold metal downward along the curved solidification front.

**Fig. 1** Current density and Joule heating fields.

**Fig. 2** Phase distribution and Lorentz force field.

**Fig. 3** Temperature distribution.

**Fig. 4** Streamlines and liquid fraction distribution.

### Solute Distribution
The Ni profiles for various times are demonstrated in Fig. 5. Due to the partition ratio, the Ni composition is expelled from the solid phase into the mushy zone resulting in a steep concentration gradient. Subsequently, the Ni-poor metal in the pool displaces the Ni-rich metal through the washing of the mushy zone by the thermal flow. The Ni composition therefore accumulates at the metal pool bottom, and the concentration increases with time. The thermal flow drains the Ni from the bottom to the upper part of the metal pool, giving rise to a wider zone with the ingot growing. In addition, a lower concentration region at the both sides of the bottom is observed, where the metal freezes faster at early times and the Ni is depleted.

### Grain Structure
**Fig. 6** shows the comparison of the grain morphology between the experiment and simulation. The calculated growth direction and size of the grain, as well as the metal pool profile agree closely with the experimental observation. The cooling at the bottom and lateral wall considerably influences the grain growth. The nucleation simultaneously occurs at the chill bottom and lateral wall yielding a thin layer of the equiaxed grain, and then the equiaxed grain transforms to the columnar grain. The growth direction of the columnar grain is approximately 45° with respect to the vertical axis referred to an inverse V-shaped grain structure. Moreover, the columnar grain can extend to the ingot center because of the large undercooling.
Conclusions
The present work represents a transient 3D macro-model of the ESR process. The solution of the mass, momentum, energy, and species conservation equations are simultaneously implemented by the finite volume method with full coupling of the Joule heating and Lorentz force through solving the Maxwell’s equations. Besides, a transient asymmetric meso-model is developed using the CA technique with a steady state Lorentz force and Joule heating fields. The electric field, Lorentz force field, Joule heating distribution, two-phase flow, temperature distribution, solidification sequence and the macrosegregation are clearly clarified. Moreover, two nondimensional criterions are first proposed to distinguish the effects of the Lorentz force, the thermal buoyancy and the solutal buoyancy. The evolution of the grain morphology with time is demonstrated. The present model is able to give a deeper understanding of the ESR process.

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