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Edited by
Matthew J. M. Krane, Alain Jardy, Rodney L. Williamson, and Joseph J. Beaman
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Edited by
Matthew J. M. Krane
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PREFACE

This proceedings volume represents the work presented at the tenth International Symposium on Liquid Metal Processing and Casting held in Austin, Texas, USA, from September 22-25, 2013. This symposium is held every other year to bring together an international group of researchers to discuss this important technical field and present their latest research results. The conference is the principal international forum for research and development in the fields of melting, refining and casting of special metals and alloys. Contributions cover a range of topics including vacuum arc and electroslag remelting, advances in process modeling, novel casting techniques, and characterization and modeling of inclusions, segregation, and structure in cast metals.

Papers from both the oral and poster sessions are included in this volume. The collection is divided into the following five areas: electroslag remelting (24 papers), defects (10 papers), vacuum arc remelting (4 papers), aluminum processing (3 papers), and a miscellaneous section with 11 papers on topics ranging from microsegregation to melt control. This volume contains a good mix of papers covering both experimental studies and mathematical modeling/simulation studies, with contributions from industry, academia, government laboratories, and teams from combinations of these institutions.

The organizers are pleased to welcome Mr. Rashmi Bhavsar, Global Materials Metier Manager for Schlumberger in Houston, Texas as the keynote speaker. His topic is

"Metal Alloy Challenges and Opportunities in the Oil and Gas Industry,"

which is in tune with the large demand for high quality metal products by this industry. Mr. Bhavsar has over three decades of experience working in the petroleum industry, with responsibility for material selection, alloy characterization, corrosion, welding, heat treating, surface treatment, and failure analysis for drilling and completion tools.

The Awards Committee would once again like to congratulate the authors of the LMPC 2011 Best Paper,

"Investigation of the Implications of the Current Conductive Mold Technology with Respect to the Internal and Surface Quality of ESR Ingots,"

authored by: H. Holzgruber, W. Holzgruber, A. Scheriau, M. Knabl, M. Kubin, J. Korp, R. Pierer.

The Conference Organizers are grateful to the members of the Scientific Committee who reviewed and sorted the abstracts and papers in a very short period of time. Ms. Rosalie Foster of the University of Texas was instrumental in setting up the logistics of the conference venue and Ms. Lisa Breese and the other TMS staff were very helpful in putting together the conference proceedings. The lead organizer would also like to thank Kyle Fezi and Alexander Plotkowski from Purdue University for help with paper reviews and copy editing.

The conference organizers are:

Matthew J. M. Krane  Purdue University, USA
Alain Jardy  Institut Jean Lamour, CNRS/Universite de Lorraine, France
Rodney L. Williamson  University of Texas at Austin, USA
Joseph J. Beaman  University of Texas at Austin, USA
ABOUT THE EDITORS

Matthew J. M. Krane

Dr. Matthew Krane is an Associate Professor of Materials Engineering at Purdue University and a member of the Purdue Center for Metal Casting Research. His research is on design, development, and modeling of materials processes, with a focus on transport phenomena and microstructural development in the solidification of metal alloys. He holds a Ph.D. (1996) from Purdue University in Mechanical Engineering, with a concentration on heat transfer and fluid flow in materials processing. His M.S. degree (1989) is from the University of Pennsylvania and his B.S. (1986) from Cornell University, both in mechanical engineering. In addition to consulting with the metals processing industry since the mid-1990s, he also worked on thermal packaging and manufacturing issues for Digital Equipment Corporation in Andover, Massachusetts. In 2006, he was a Visiting Research Fellow working in the Interdisciplinary Research Centre at the University of Birmingham (UK) and has a courtesy appointment in Purdue’s School of Mechanical Engineering. He has served as Chair of the TMS Process Modeling and Control and Solidification Committees and is on the international technical committees for the Modeling of Casting, Welding and Advanced Solidification Processes (MCWASP) and the Liquid Metal Processing and Casting (LMPC) conference series. Professor Krane’s teaching experience includes heat transfer, fluid mechanics, engineering design, materials processing, numerical modeling, and ethics in engineering practice.

Alain Jardy

After graduation at Nancy School of Mines and a Ph.D. (1984) from Institut National Polytechnique de Lorraine in Materials Science and Engineering, Dr. Alain Jardy joined the French CNRS (Centre National de la Recherche Scientifique). He is now a Senior Research Scientist at Institut Jean Lamour, a Laboratory of CNRS and the University of Lorraine, where he is the Head of the Research Group “Materials Processing.” He is involved in studies related to liquid metal processing, vacuum metallurgy and melting/remelting processes, which usually require the combination of several scientific skills, including thermodynamics, fluid flow, electromagnetics, and heat and mass transfer. Most of his work is performed in close collaboration with the metallurgical industry (e.g., steel, aluminum, titanium, zirconium, Ni-based superalloys) and associates mathematical modelling and laboratory-scale, pilot-scale or full-scale experiments. Dr. Jardy is the Head of the East Division of SF2M (French Society of Materials and Metallurgy), and is a Key Reader for Metallurgical and Materials Transactions B; he has authored or co-authored 70 publications in refereed journals and 80 conference papers, and supervised 18 Ph.D. theses. He has been a member of the Technical Committee of the Liquid Metal Processing and Casting (LMPC) conference for more than 12 years, and co-organized the 2003, 2007, and 2011 conferences in Nancy.
Rodney L. Williamson

Dr. Rodney Williamson currently holds a part-time research faculty position with the Advanced Manufacturing Center at the University of Texas, Austin, Texas, and is sole proprietor of Remelting Technologies Consulting. He is retired from Sandia National Laboratories where he worked for 23 years. While at Sandia he was instrumental in helping to form the Specialty Metals Processing Consortium (SMPC), a consortium of U.S. specialty alloy producers dedicated to pre-competitive research in the field of process metallurgy relating to nickel-base superalloys and titanium alloys. He holds a B.S. in chemistry from Brigham Young University (1976) and a Ph.D. in chemistry from the University of Washington (1983). He is currently working with colleagues at the University of Texas and the SMPC to apply advanced modeling and simulation techniques to control and monitor the vacuum arc remelting and electroslag remelting processes. He is a co-inventor on several patents in this field and is internationally recognized for his work in process metallurgy controls and diagnostic techniques. He has also conducted and published scientific and engineering research in the areas of optical and magnetic resonance spectroscopy, chemical laser diagnostics, metal vapor arc physics, thermal spray diagnostics and controls, and chemical sensor technology based on field-structured composite materials.

Joseph J. Beaman

Dr. Joseph Beaman is the Earnest F. Gloyna Regents Chair in Engineering at the University of Texas. His career work has been in both manufacturing and control. His specific manufacturing research interest is in Solid Freeform Fabrication, a manufacturing technology that produces freeform solid objects directly from a computer model of the object without part-specific tooling or knowledge. Dr. Beaman coined this term in 1987. Professor Beaman initiated research in the area in 1985 and was the first academic researcher in the field. One of the most successful Solid Freeform Fabrication approaches, Selective Laser Sintering, was a process that was developed in his laboratory. Besides his work in Solid Freeform Fabrication, Professor Beaman has worked extensively with the special metals processing industry to develop next generation process control for remelting processes that are used to produce special metals alloys such as superalloys and titanium alloys. Dr. Beaman is a Fellow of the American Society of Mechanical Engineers and a recently elected member of the National Academy of Engineering.
Electroslag Remelting

LMPC 2013
Liquid Metal Processing & Casting 2013
COMPUTATIONAL MODELING OF ELECTROSLAG REMELTING (ESR) PROCESS USED FOR THE PRODUCTION OF HIGH-PERFORMANCE ALLOYS

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Electroslag Remelting, Computational Analysis, Unsteady Behavior, Macrosegregation

Abstract

This paper presents a comprehensive computational model for the prediction of the transient Electroslag Remelting (ESR) process for cylindrical ingots based on axisymmetric two-dimensional analysis. The model analyzes the behavior of the slag and growing ingot during the entire ESR process involving a hot-slag start with an initial transient, near-steady melting, hot-topping and subsequent solidification of the slag and ingot after melting ends. The results of model application for an illustrative ESR process for Alloy 718 and its validation using results from an industrial trial are presented. They demonstrate the comprehensive capabilities of the model in predicting the behavior of the ingot and slag during the entire process and properties of the final ingot produced. Such analysis can benefit the optimization of existing process schedules and design of new processes for different alloys and different ingot sizes.

Introduction

The Electroslag Remelting process (ESR) is a consumable electrode remelting process for producing high quality ingots used in aerospace and energy applications. Figure 1 shows a schematic diagram of the ESR process that uses a stationary water-cooled crucible containing the slag and ingot. Passage of an Alternating Current (AC) from the electrode to the crucible creates resistive heating in the slag that melts the electrode to build up the ingot in the crucible. A slag skin is formed at the slag-crucible interface that envelops the growing ingot. Further, as the ingot solidifies, it shrinks away from the crucible causing a loss of contact with the crucible. Thus, the ESR process involves complex interactions among the electromagnetic, flow and thermal processes which control the transfer of heat to the water-cooled crucible and, in turn, the ingot solidification process. The segregation of alloying elements into the molten pool during solidification also creates compositional nonuniformity in the ingot. Because of this complexity of the interacting physical phenomena, a trial and error approach can be inefficient for assessing the relationships between operational parameters and process performance. Mathematical modeling offers a scientific and cost-effective approach for developing a fundamental understanding of the governing physical processes and predicting the effect of various process variables on the quality of the ingot produced.
The objective of this research effort is to develop an efficient and comprehensive computational model for the analysis of transient ESR processes that can be used routinely by process engineers. Since a majority of ESR ingots produced for high-performance applications are cylindrical, the effort in this study has focused on the development of a model for 2-D axisymmetric conditions and it constitutes an extension of the steady-state model that was developed by Kelkar et al. [9]. The sections below describe the mathematical formulations of the physical phenomena underlying the ESR process, their computational solution and the application of the transient model for the analysis of actual casting of an ingot developed by Kelkar et al. [9]. The features of the transient model that are common with its steady-state formulation are not described in detail (e.g., the governing equations are not listed). This allows a concise and clear description of the complete computational model with an emphasis on the transient aspects of the ESR process analysis.

**Mathematical Formulation**

**Assumptions**

Appropriate assumptions are made in the development of a model that is computationally efficient and also addresses all the important physical phenomena that govern the transient behavior in the ESR process. The computational model is developed using an axisymmetric computational domain shown in Figure 2. It includes the slag and ingot regions in a unified manner. A frame of reference attached to the electrode-slag interface is utilized because the slag-metal interface is also stationary in this domain. This allows an accurate treatment of the electromagnetic, thermal and fluid dynamic interactions between the slag and metal phases for nominally planar slag-electrode and slag-metal interfaces. The growth of the ingot is addressed with a computational domain that expands at the instantaneous casting rate corresponding to the downward movement of the ingot-crucible interface in this frame of reference attached to the slag-metal interface. Heat transfer from the slag and ingot to the water-cooled crucible is a critical factor that governs the solidification process. A detailed analysis of mechanisms of heat transfer to the crucible for various remelting processes is presented by Yu [7]. A complete model of the VAR process that addresses the effect of the progressive loss of contact due to the shrinkage of the ingot on the heat transfer to the crucible is presented by Bertram et al. [8].

**Electromagnetics**

Practical ESR systems involve flow of Alternating Current in electrically conducting media so that magnetic field diffusion is the primary electromagnetic phenomenon. Further, the frequency of the AC power is sufficiently high so that the time scale for electromagnetic phenomena is orders of magnitude smaller than those for the flow and thermal phenomena. Hence, during transient analysis, electromagnetic fields are determined for the
Fluid Motion

The unsteady macro-level flow in the molten slag and metal pools is driven by the buoyancy and Lorentz forces. This unsteadiness arises from the finite length of the ingot and time-dependent melt schedule. The unsteady Navier-Stokes equations govern the turbulent flow in the molten slag and metal pools. The two-equation k-ε turbulence model is used for the determination of the spatially nonuniform mixing in the molten pools. As a result, the computational model is very general and applicable for a wide range of ingot sizes and processing conditions. It should be noted that the pool sizes in the ingot during the entire process and, after the end of melting, in the solidifying slag are not known a priori. They are determined by the corresponding temperature fields which are strongly influenced by the instantaneous ingot length and melt rate. Thus, the flow and temperature fields are coupled not only through the buoyancy force but also through phase change in the ingot and slag during and after melting.

The interaction of the flow fields across the slag-metal interface is automatically addressed through the use of the unified computational domain. The velocity in the mushy regions of the ingot (during and after melting) and slag (after melting) below an assumed Immobilization Liquid Fraction is set to the instantaneous velocity of the corresponding solid phase (Bertram et al., [8]). Thus, the solidified portion of the ingot moves at the instantaneous casting velocity while melting is ongoing. After the end of melting, solidified portions of the slag and ingot are stationary. The flow in the molten pools is subject to no-slip boundary conditions on all solid boundaries.

Heat Transfer and Phase Change

The temperature field within the slag and metal pools is determined by fluid motion and turbulent diffusion. It is important to note that, unlike the optically-opaque molten alloy, the slag is semi-transparent. Therefore, radiative heat exchange is the dominant mechanism in the molten slag. This is handled by using the Rosseland approximation (Siegel and Howell, [11]). It involves a diffusion treatment of radiation using a temperature-dependent radiative diffusivity that augments the molecular and turbulent diffusivity in the molten slag. In the solid ingot region, the temperature field is determined by the local solid velocity and conduction. In order to achieve efficiency of calculation, the solidification of the slag during and after melting is handled through separate physically motivated treatments as follows:

- During melting, the bulk slag is assumed to be molten and enclosed in a thin layer of the slag skin formed on the crucible surface.
- After melting ends, the bulk slag solidifies. The computational technique transitions smoothly from "thin slag-skin" to the "bulk-slag solidification".

The enthalpy-porosity technique (Brent et al., [12]) is used for addressing the solidification of the metal (during and after melting) and the slag (after end of melting). It uses the specified variation of the solid fraction with temperature for the slag and alloy to deduce the solid/liquid fraction at all points in the domain. It is useful to note that the slag and metal pools solidify independently after the end of melting but the exchange of heat across the slag-metal interface influences their solidification progress.

Heat loss at the slag-electrode interface is calculated from a global heat balance on the electrode for the instantaneous melt rate. The molten metal droplets formed at the slag-electrode interface are assumed to fall through the slag under thermal equilibrium conditions and appear in the metal pool below the slag-metal interface. The exposed surfaces of the slag and the ingot (in a short-collared crucible) lose heat by radiation and convection to the environment. The energy conservation equation accounts for material addition during ingot growth. Finally, heat loss to the crucible from the ingot bottom is calculated using an empirically prescribed heat transfer coefficient that is representative of the good metal-to-metal contact created by the weight of the ingot.

Heat Loss to Crucible During Melting

As described earlier, during the melting process, a thin slag skin is formed at the slag-crucible interface due to loss of heat to the cooling water. Further, the ingot grows into the envelope of the slag skin which influences the heat loss from the ingot to the cooling water. Note that, during melting, the thin slag skin located at the interface of the slag/ingot and crucible is assumed to lie on the outer radial boundary of the computational domain. The thermal resistance it creates for heat loss to the crucible is calculated through the boundary treatments discussed below.

Heat Loss from the Slag - At any instant in the process, the thickness of the slag skin varies over the slag-crucible interface depending on the local rate of heat transfer from the bulk slag to the crucible. An uneven contact of the slag skin with the inside surface of the crucible results in transfer of heat to the crucible by conduction across the slag skin and radiation from its exposed surface as described by Yu [7].

Heat Transfer from the Ingot to the Crucible - The ingot grows into the slag skin formed at the slag-skin interface thereby also creating an axial variation of the skin thickness on it. The slag skin has a finite thermal resistance and its presence on the ingot surface influences the rate of heat transfer from the ingot to the crucible. Further, this heat loss is even more strongly affected by the shrinkage of the ingot as it solidifies. The extent of this loss of contact and its effect on heat transfer between the ingot and the crucible is determined using the method of Bertram et al. [8]. This heat loss occurs by conduction through the skin thickness where the ingot has not separated from the crucible and radiation from the surface of the slag skin where ingot has shrunk away to cause a loss of contact with the crucible.

Heat Loss to Crucible After End of Melting

The bulk slag solidifies after the end of melting. Therefore, heat loss from the circumferential surface of the slag to the water flowing through the crucible is governed by exactly the same mechanisms as those for heat loss from the solidifying ingot to the cooling water. The only difference is that the temperature at which the solidified slag shrinks away from the ingot is expected to be much lower than that for the ingot.

Behavior of Inclusions

In ESR practice, inclusions may appear in the molten metal pool if they get embedded in the metal droplets that originate from the electrode. The slag and molten pools have very dissimilar transport properties (density and viscosity). Therefore, when an
inclusion crosses the slag-metal interface, it experiences very
different buoyancy (in magnitude) and drag (in magnitude and
direction as exerted by the relative velocity of the surrounding
fluid) forces. The relaxation time of an inclusion (time required to
attain its terminal velocity), in turn, depends on this net external
force and its inertia. The formulation of the equation governing
the motion of an inclusion addresses these unique aspects of the
ESR process. In addition, it also considers a temperature-
dependent dissolution rate of an inclusion. The motion of an
inclusion is tracked until it reaches the mushy zone or fully
dissolves in the molten pool. It is assumed that the time scale for
the change in the pool size is large relative to the residence time
of the inclusions. Hence, the instantaneous flow and temperature
fields in the ESR system at the time an inclusion enters the metal
pool are used in calculating its behavior.

**Thermal History and Defect Formation Probability**

The structure of the cast ingot is determined by its thermal history
during the solidification process. In an unsteady ESR process, the
thermal history at any point in the solidified ingot depends on
both its axial and radial locations. The evolving temperature field
in the growing ingot is determined by the energy conservation
equation. This calculation is coupled with a Lagrangian
framework for tracking the temperature of each elemental metal
volume to determine the thermal history of the growing ingot. The
thermal history calculation is very comprehensive and includes
donation not only of the local solidification time but also the
cooling rate, temperature gradient, isotherm angle and speed of
solidification at various solid fractions.

The goal of the remelting processes is to produce ingots that are
free of solidification defects (freckles for superalloys and steels).
Prediction of microsegregation by solving the species transport
equations in the interdendritic region from first principles is
computationally infeasible. Therefore, the method proposed by
Auburtin et al. [13] is utilized in this study. It captures the
underlying physics in an efficient manner by quantifying the
probability of freckle formation through the Rayleigh number for
thermosolutal convection in the interdendritic region. Thus, at
each point in the solidifying ingot, alloy-specific correlations are
used to relate the thermal history parameters to the corresponding
metallurgical structure parameters that are needed in the
calculation of the interdendritic Rayleigh number.

**Macrosegregation of Alloying Elements**

The properties of the cast ingot also depend on its macro-level
composition. The preferential rejection or absorption of the
alloying elements by the solid in the outer mushy region and
subsequent imperfect mixing in the pool redistributes these elements in the final solidified ingot. Solution of the unsteady
convection-diffusion equations for the concentrations of
individual alloying elements over the ingot during and after
melting is performed to determine their redistribution in the
solidifying ingot. In this calculation, it is assumed that individual
alloying elements are selectively rejected or absorbed by the solid
in the outer mushy region up to a limiting Segregation Solid
Fraction where they mix within the liquid metal pool due to
convection and turbulent diffusion. This segregation flux for each
alloying element at the boundary of the molten pool appears as a
source term in the corresponding convection-diffusion equation.

**Computational Solution**

The equations governing the electromagnetic, flow, thermal and
macrosegregation phenomena are solved using the framework of
the control volume method (Patankar, [14]). It involves
discretization of the axisymmetric domain into control volumes.
The discretization equations are constructed by integrating the
respective governing equations so that they represent exact
conservation of the underlying physical quantities. An implicit
time-stepping technique is used for discretizing the unsteady term.
Due to the nonlinear and coupled nature of the equations, multiple
iterations are needed to achieve convergence of the solution
within each time step. Several enhancements of the basic method
have been incorporated to address the special features of the
transient ESR process as discussed below.

**Ingot Growth** - In the frame of reference attached to the slag-
electrode interface, the growth of the ingot causes the interface
between the bottom surface of the ingot and crucible to gradually
uncover the computational grid. Special considerations are
required for constructing the discretization equations for the
"base-plate" control volume as it expands in size within each time
step due to the growing ingot. Further, computational efficiency is
achieved by limiting the computational solution to control
volumes that contain the slag and only the already formed ingot at
that time instant.

**AC Electromagnetics** - The solution of the magnetic diffusion
equation for AC power is achieved through the use of complex
variables. A staggered grid is utilized for calculating the current
density and Lorentz force fields.

**Inclusion Motion** - The equation of motion of an inclusion is
solved using a time-stepping technique that advances the inclusion
along its trajectory. It involves an adaptive determination of the
size of the time step to account for large differences in buoyancy
and drag forces within the slag and metal pools experienced by
the inclusion. This enables tracking the behavior of inclusions of a
wide range of densities and sizes in an efficient manner.

**Thermal History** - A Lagrangian technique is developed for an
accurate determination of the complete thermal history of each
elemental metal volume in the solidifying ingot. It involves
precise tracking of the location of each elemental metal volume in
the growing ingot from the instant it starts solidifying. This
enables determination of the time instants at which each elemental
volume within the ingot reaches various specific temperatures and
the corresponding cooling rates, isotherm angles and spatial
thermal gradients. These thermal history parameters are then
utilized for determining the probability of defect formation in
each elemental metal volume that has fully solidified.

**Macrosegregation** – The solution of the equation for concentration
of each alloying element accounts for convection and diffusion in
the pool, absence of diffusion in the solidified ingot and presence
of segregation flux in the control volumes over the pool boundary.

**Illustrative Application of the Computational Model**

The computational method described above has been incorporated
in the commercial software program MeltFlow-ESR [15]. This
program has been applied for the analysis of an ESR process of
Alloy 718 for which detailed pool markings were made by
SMPC [10]. Details of the process conditions, and the model predictions and their comparison with marked pool shapes are now discussed.

**Physical Situation**

The ESR process studied by SMPC involved casting of a long ingot of Alloy 718. The melt schedule involved two melting stages – first stage with casting at a lower melt rate and second at a higher melt rate, with a short transition between the two stages. A sufficiently long ingot was cast in each stage by maintaining the corresponding melt rate so as to reach steady conditions. The pool profiles were marked throughout the process and are very useful for validating the model. Table 1 lists the geometric details of the ESR system while Figure 3 shows the corresponding melt schedule. The temperature-dependence of material properties, including the variation of fraction solid with temperature, of the slag (70%CaF₂-15%CaO-15%Al₂O₃) and metal are incorporated in the analysis. Due to space constraints, only their representative values are listed in the Table 1. Properties of the slag correspond to the reported values from prior studies (e.g., Mills and Keene, [16]). Properties of the alloy are taken from the studies by Mills [17], Auburtin et al. [18] and Knorovsky et al. [19]. Also, the trajectories of inclusions of a wide range of diameters (0.1 mm to 30 mm) and relative densities (ratio of the density of inclusion to that of molten metal of 0.5 to 2.0) have been calculated.

A computational grid of 253(axial) x 35(radial) control volumes is used for the analysis. Calculations are made for the entire period which includes the durations for melting of the electrode and subsequent cooling of the slag and ingot after the end of melting when the electrode has been removed. This analysis required a total of fifteen hours on a PC with a 3 GHz Intel Processor.

**Results and Discussion**

The computational model provides detailed information about the distributions of the electromagnetic, flow, temperature, liquid fraction and alloy concentration fields in the slag and ingot during and after the end of melting, and also predicts the behavior of inclusions in the molten metal and slag pools during melting. In the sections below, results of analysis are discussed in terms of the overall process behavior and detailed field variations.

### Table 1. Physical properties and operating conditions used in the analysis of an ESR process for Alloy 718.

<table>
<thead>
<tr>
<th>Material</th>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Metal (Alloy 718)</strong></td>
<td>Density, liquid</td>
<td>7500 kg/m³</td>
</tr>
<tr>
<td></td>
<td>Viscosity, liquid</td>
<td>6×10⁻¹⁰ kg/m-s</td>
</tr>
<tr>
<td></td>
<td>Liquidus temperature</td>
<td>1623 K</td>
</tr>
<tr>
<td></td>
<td>Solidus temperature</td>
<td>1473 K</td>
</tr>
<tr>
<td></td>
<td>Latent heat of fusion</td>
<td>2.1×10⁵ J/kg</td>
</tr>
<tr>
<td></td>
<td>Specific heat, liquid</td>
<td>720 J/kg-K</td>
</tr>
<tr>
<td></td>
<td>Specific heat, solid (773 K)</td>
<td>512 J/kg-K</td>
</tr>
<tr>
<td></td>
<td>Vol. thermal expansion coeff., liquid</td>
<td>1.5×10⁻¹⁴ K⁻¹</td>
</tr>
<tr>
<td></td>
<td>Thermal conductivity, liquid</td>
<td>30.52 W/m-K</td>
</tr>
<tr>
<td></td>
<td>Thermal conductivity, solid (773 K)</td>
<td>16.72 W/m-K</td>
</tr>
<tr>
<td></td>
<td>Electric conductivity</td>
<td>7.6×10⁴ (Ω-m)⁻¹</td>
</tr>
<tr>
<td></td>
<td>% Concentrations (Segregation Coefficients) of Alloying Elements</td>
<td>0.56(1.20), 0.95(0.55), 0.025(0.28), 0.25(1.05), 18.18(1.12), 18.10(1.16), 5.25(0.35), 3.12(0.90)</td>
</tr>
<tr>
<td><strong>Slag</strong></td>
<td>Density, liquid</td>
<td>2800 kg/m³</td>
</tr>
<tr>
<td></td>
<td>Viscosity, liquid</td>
<td>3.5×10⁻¹⁰ kg/m-s</td>
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<td></td>
<td>Specific heat, liquid</td>
<td>1163 J/kg-K</td>
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<tr>
<td></td>
<td>Specific heat, solid (773)</td>
<td>1061 J/kg-K</td>
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<tr>
<td></td>
<td>Vol. thermal expansion coeff., liquid</td>
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<td>Thermal conductivity, liquid</td>
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<td></td>
<td>Thermal conductivity, solid (773 K)</td>
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<td>Liquidus temperature</td>
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<td></td>
<td>Solidus temperature</td>
<td>1618 K</td>
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<tr>
<td></td>
<td>Latent Heat</td>
<td>4.3×10³ J/kg</td>
</tr>
<tr>
<td><strong>Geometry</strong></td>
<td>Slag height</td>
<td>147 mm</td>
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<tr>
<td></td>
<td>Electrode diameter</td>
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</tr>
<tr>
<td></td>
<td>Ingot Diameter</td>
<td>384 mm</td>
</tr>
<tr>
<td></td>
<td>Final Ingot Length</td>
<td>2732 mm</td>
</tr>
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</table>

**Overall Process Behavior** - The behavior of the overall process can be quantified in terms of the evolution of the volumes of the molten slag and metal, slag skin thickness and heat losses at the various interfaces in the ESR system as shown in Figures 4 and 5 respectively. In the first part of the melting process, the molten metal pool increases with time as the ingot grows and then reaches a steady state corresponding to the lower melt rate. The pool size then rapidly adjusts as the melt rate transitions to its higher value in the second stage of melting. The thickness of the slag skin formed at the slag-metal interface also responds to the change in the ingot length and melting power. In the early stages, the slag is colder due to lower power and higher heat loss through the ingot bottom resulting in a thicker slag skin. After the ingot is sufficiently long, this thickness depends only on the melting conditions and reaches a constant value corresponding to the lower melt rate. As the melt rate transitions to the higher value, the skin thickness readjusts to a lower value as a result of a hotter slag. After the end of melting, the metal volume solidifies rapidly. The molten slag, however, takes longer to solidify due to its higher heat capacity and lower thermal conductivity. This behavior is consistent with observations of practical ESR processes.
A significant portion of the power used in the ESR process is lost to the cooling water through the slag-crucible interface. The heat loss flux to the crucible through the bottom face of the ingot is high in the initial stages and becomes insignificant once the ingot is sufficiently long. Finally, the radiative heat loss from the exposed surface of the slag shows a sudden increase after the end of melting because the electrode has been removed and the heat loss now occurs over the entire top surface of the slag.

Electromagnetic, Flow and Temperature Fields – Figures 6 and 7 show the electromagnetic, flow and temperature fields in the ingot. The electromagnetic fields show that the Joule heating is concentrated in the slag and the current is nearly uniformly distributed over its cross-section due to its low electrical conductivity. On the other hand, due to the high electrical conductivity of the ingot, the current distribution in the ingot shows the skin effect in which the current flow is concentrated in the region near the outer radius. The Lorentz force is in the direction perpendicular to the current density and is therefore mainly directed radially inward.
The volume of the molten metal is small and the pool profile is flat in the initial stages when the ingot length is short and the heat loss flux through the bottom of the ingot is significant. After process conditions have been steady for a sufficiently long time, the metal pool reaches a steady volume corresponding to the low-melt rate condition. The metal pool is thermally stably stratified except over the pool boundary. At the higher melting rate in the second part of melting, the pool is seen to be significantly deeper and the mushy zone longer. Unlike the metal pool, the slag is thermally unstably stratified and shows strong mixing with velocities at least an order of magnitude larger than those in the molten pool. (Note that the slag-metal interface is assumed to be flat and the velocity vector at each point in the domain is drawn to reflect the magnitude and direction of the corresponding local velocity.) After the end of melting, the metal volume shrinks rapidly. The slag temperature also falls below its liquidus temperature relatively quickly but the core slag volume remains in the semi-solid state even after the metal pool has solidified. Thus, the hot slag creates a natural hot topping and helps to reduce the size of the solidification cavity in the ingot.

Inclusion Motion - Figure 8 shows the flow and liquid fraction fields in the ESR system and, for clarity, trajectories of only selected inclusions of small and large diameters (0.1 and 30 mm) and densities slightly higher and significantly lower than that of the metal (relative densities of 1.15 and 0.5), at an instant in the process when conditions have reached a steady-state at the higher melt rate. It should be noted that the inclusions of relative density of 0.5 are lighter than the molten metal but still heavier than the slag. Inclusions of various sizes and densities follow very different paths through the molten metal and slag pools. Smaller inclusions tend to move with the fluid while large inclusions are
Thermal History and Freckle Formation Probability in the Final Ingot Composition of the Final Ingot

Intended Rayleigh Number

<table>
<thead>
<tr>
<th>Value</th>
<th>2.0E+01</th>
<th>5.9E+00</th>
<th>1.7E+00</th>
<th>5.1E-01</th>
<th>1.5E-01</th>
<th>4.5E-02</th>
<th>1.3E-02</th>
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<tr>
<td></td>
<td>5.9E+00</td>
<td>1.7E+00</td>
<td>5.1E-01</td>
<td>1.5E-01</td>
<td>4.5E-02</td>
<td>1.3E-02</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.7E+00</td>
<td>5.1E-01</td>
<td>1.5E-01</td>
<td>4.5E-02</td>
<td>1.3E-02</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
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<td>1.5E-01</td>
<td>4.5E-02</td>
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<td></td>
<td>1.3E-02</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

Local Solidification Time (s)

% Aluminum

-0.15 Π 0.15 0.3 0.45

% Niobium

Figure 9. Thermal history and probability of freckle formation (left), and compositions of Niobium and Aluminum (right) in the final ingot.

Transition from Low to High Melt Rate

Low Melt Rate – Steady-State Reached
- Measured Pool Depth – 14 cm
- Calculated Pool Depth – 13 cm

High Melt Rate – Steady-State Reached
- Measured Pool Depth – 24 cm
- Calculated Pool Depth – 22 cm

Figure 10. Comparison of the predicted and measured pool profiles for the SMPC ESR trial (Experimental Results Courtesy of Special Metals Processing Consortium (SMPC)).
The ingot length is short. Therefore, the local solidification time is high at the ingot bottom due to the high rate of heat transfer to the crucible bottom face in the very initial stages of the process when the ingot length is short. Therefore, the local solidification time is very low in the bottom portion of the ingot. As the ingot length increases and melting conditions reach a steady state at the lower melt rate, transfer of heat occurs primarily in the radial direction. As a result, local solidification time is high in the center and decreases radially outward. As the process conditions transition to the higher melt rate, the cooling rate decreases somewhat resulting in a higher local solidification time at the ingot center. After the end of melting, pool shrinks rapidly from the side but not as fast at the top due to the insulating effect of the hot slag. As a result, cooling rate is lower at the ingot top.

The probability of freckle formation scales in proportion to the magnitude of interdendritic Rayleigh number and its variation in the ingot is noteworthy. In the regions of ingot where the cooling rate is high (bottom and outer radius), dendrites are closely spaced and freckle formation is less likely. In the center region, the spacing between the dendrites is larger due to lower cooling rates, but the gravity-driven flow is parallel to the primary dendrites for which the permeability is lower relative to that for secondary dendrites. Therefore, in the portions of the ingot that correspond to steady melting, the probability of freckle formation is highest in the mid-radius region due to a combination of reasonably large spacing between the dendrites and the direction of the flow (pool angle) that involves a component along the secondary dendrites. When the melt rate is higher, this effect is more pronounced. As a result, both the maximum value of the interdendritic Rayleigh number is higher and nonuniformity in its radial variation is stronger in the ingot formed at the higher melt rate.

**Ingot Composition - Variations in the concentrations of niobium and aluminum in the final ingot that result from macrosegregation are also shown in Figure 9. As the liquid metal solidifies, the solid formed preferentially rejects niobium and absorbs aluminum. The mass of the alloying element rejected into or depleted from the molten pool is redistributed into the pool due to the convective motion and diffusion. Since the motion of the molten metal is much weaker in the center of the pool, alloying elements from this region do not mix well with the bulk pool. As a result, the concentration of niobium varies in the radial direction with a higher concentration in the center of the ingot. Also, the pool is being enriched in niobium so that its radially-averaged concentration increases from the bottom of the ingot to the top of the ingot. The behavior for aluminum is exactly the reverse since it is preferentially absorbed by the solidifying alloy. The extent of segregation in the radial direction increases with the melt rate since the volume of the molten pool is higher and the mixing in the pool is weaker. Note that the redistributions of alloying elements during remelting depend on the assumptions made about the values of the limiting Segregation Solid Fraction, and element-specific effective segregation and molecular diffusion coefficients. Therefore, the results presented in Figure 9 are only for illustrating the capability of the model in predicting the compositional variation in the final ingot caused by macrosegregation.**

**Model Validation - A comparison of the predicted (green color) and the marked pool (dark color) profiles is shown in Figure 10. It is seen that the computational model reproduces the observed process behavior with good accuracy. Thus, in the initial stages of melting, the pool is flat and shallow. It transitions to a conventional pool shape and reaches a steady state after the ingot has grown to a sufficiently long length. It is important to note that this specific ESR melt showed an asymmetric ingot behavior when the melt rate transitioned from the low to high value. These three-dimensional effects cannot be resolved using the axisymmetric model discussed in this paper. But, the model correctly predicts the quick transition of the pool shape from its low-melt-rate profile with a smaller pool depth to its high-melt-rate profile that shows a deeper pool. Also, the predicted pool shapes and depths are consistent with their marked profiles. Measurements of ingot composition and investigations on the presence of freckles were not performed. However, the general aspects of their predicted behavior are deemed to be in agreement with corresponding observations in ESR practice.**

The results of analysis illustrate the comprehensive capabilities of the model in predicting the important aspects of practical ESR processes for the casting of cylindrical ingots.

**Summary and Conclusions**

The present paper describes a comprehensive computational model for the analysis of electromagnetics, flow, heat transfer, macrosegregation and inclusion motion in the transient ESR processes for axisymmetric conditions. The mathematical formulation and computational model incorporate several physically motivated enhancements for accurate and efficient analysis of the unique aspects of the transient ESR process. Analysis is performed for the period during melting when the ingot grows and also after the end of melting when the slag and the ingot pools solidify. Thermal history of the entire ingot is determined in a comprehensive manner. Further, it is utilized for a quantitative prediction of the probability of freckle formation in the ingot based on the Rayleigh number for interdendritic flow. Use of the model is illustrated for the analysis of a transient ESR process for Alloy 718. Field variations of current density, volumetric heating, molten pool flow, liquid fraction, temperature and inclusion motion at various time instants during the process, and the evolution of pool volumes and boundary heat losses illustrate the insights the model can provide into the behavior of the ESR process. The predicted pool profiles compare well with the profiles marked in the final ingot. Thus, the computational model offers a cost-effective method for reducing trial-and-error during process design and for producing ingots of high quality.

**Acknowledgments**

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References

A NUMERICAL STUDY ON THE INFLUENCE OF THE FREQUENCY OF THE APPLIED AC CURRENT ON THE ELECTROSLAG REMELTING PROCESS

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Keywords: Electroslag Remelting (ESR), Magnetohydrodynamics (MHD), Solidification, AC Current.

Abstract

Most conventional electroslag remelting (ESR) processes are operated with AC current, but the inductive loss of the power becomes a major problem when the process is operated at the high frequency for large scale ESR. Nowadays, the demand on large scale ingots has driven the people to think of operating the process with AC current at low frequency. Here the influence of the applied frequency of AC current on the large scale ESR process is numerically investigated. For this purpose, simulations with two operating AC frequencies (0.2 and 50 Hz) are performed. The main goal is to achieve some fundamental understanding of the two-phase flow and the formation of melt pool of the solidifying ingot under the influence of AC frequency. As we also know that the mold current (portion of electric current entering through solid slag skin into the mold) plays an important role in the process, calculations considering different current paths are also analyzed.

Introduction

The aim of the electroslag remelting (ESR) process is purifying and refining steel and other alloys such as Ni-based super alloys. Thermal energy is supplied to the process through the Joule heating that results in melting the electrode and formation of droplets. The droplets then pass through the slag and reach the liquid pool. The melt pool solidifies directionally and builds the high-grade ingot in a water-cooled mold [1].

In the ESR process the electromagnetic field drives the flow of the molten slag and liquid melt pool, thus the electrical parameters of the process have a significant effect on the quality of the final product. Currently, the ESR process is mostly operating with AC current (50 - 60 Hz) in order to minimize the negative impacts of the electrochemical reactions occurring in the slag.

Comprehensive reviews of electrochemical reactions in the ESR process were presented by Peover and Mitchel [2-3]. In fact, the electric current is conducted by ions in the slag region [4]. Oxidation loss of elements such as Ti, Si, and Al is addressed as a big issue during DC remelting of the electrode in the ESR process [5-7]. The composition fluctuation of elements can significantly reduce the yield strength of the alloys. For instance, a major loss of Ti element (40-80 %) is reported by Etienne in a DC electrode remelting process [5]. Furthermore, the degree of sulphur removal by an ESR process operated with AC current is higher than by an ESR process operated with DC current [8]. Previously, Chang studied experimentally the effect of low frequency AC power supply on qualities of alloy steel [9]. It is generally recognized that the aforementioned alloying phenomena are due to electrochemical reactions taking place at the slag-metal interface when the process is operating with DC or quasi-DC current.

On the other hand, the inductive losses of the power for large scale ESR are the main disadvantage of operating the process at large frequencies. The demand on large scale ingots (diameter > 1 m) has increased since the last decade. Unfortunately, the inductive losses become more significant as the ingot size increases which are the major drawbacks of applying large frequency for large scale ESR process. Therefore, the industry intends to operate the process at low frequency (0.1 - 5 Hz).

Over the last decades, some efforts were done to model ESR process using CFD [10-12]. Additionally, attempts have been made to investigate the effect of frequency of the applied AC current on the ESR process using numerical simulation. Kharicha studied the effect of the AC electromagnetic field on the flow and slag-pool interfaces [13]. In addition, Liang studied the quality of the ingot for producing GH4169 under different current frequency for a small scale ESR process [14]. Furthermore, Li developed a 3D finite element model (FEM) considering current frequency to simulate the current density, magnetic field, electromagnetic force and Joule heating for the process [15].

In the current work, the influence of the applied frequency of AC power supply for a large scale ESR process using a static mold is investigated. The main goal is to achieve some fundamental understanding of the two-phase flow and the formation of melt pool of the solidifying ingot under the influence of AC frequency.

Numerical Model

In the present study, the Finite Volume Method (FVM) is used for simulation of the fluid flow, heat transfer, and electromagnetic field in the process. The buoyancy and Lorentz forces as well as Joule heating due to the electrical resistance in the whole system are taken into account. The temperature field is obtained by solving the enthalpy conservation equation where Joule heating is added as a source term [16]. The momentum equation is solved to determine the velocity field. The drag resistance of the solidifying dendrites to the flow in the two-phase mushy zone is modeled according to the Black-Kozeny model [17]. Additionally, Lorentz force is added as a source to the momentum equation.

The origin of the Lorentz force is the interaction between the electric current and the self-induced magnetic field in the system. For the sinusoidal AC field, the magnetic field can be expressed using the phasor notation \( \mathbf{B}_p = \mathbf{B}_p e^{j\omega t} \) where \( \mathbf{B}_p \) is a function of position. The magnetic field has only azimuthal direction since
there is no external magnetic field and the process conditions are axisymmetric. The equation for magnetic field that is derived from the Maxwell’s system of equations must be solved in cylindrical coordinate [18]. The equation is given as:

\[
\frac{\partial B_\phi}{\partial t} + \nabla \times \left( \frac{1}{\sigma \mu_0} \nabla \times B_\phi \right) + \nabla \left( \frac{1}{\sigma \mu_0} \frac{\partial (rB_\phi)}{\partial r} \right) = 0
\]  

(1)

where \( \mu_0 \) and \( \sigma \) denote the magnetic permeability and electric conductivity respectively.

After computing the real and imaginary components of the magnetic field, the electric current in the whole system can be obtained using the Ampere’s law that is expressed as:

\[
\mathbf{j} = \frac{1}{\mu_0} (\nabla \times \mathbf{B}_\phi) \tag{2}
\]

Finally, the time average Lorentz force and Joule heating can be computed:

\[
\mathbf{F}_L = \text{Re} \left( \frac{1}{2} \mathbf{j} \times \mathbf{B}_\phi \text{Conjugate} \right) \tag{3}
\]

\[
q_{\text{Joule}} = \text{Re} \left( \frac{1}{2\sigma} \mathbf{j} \times \mathbf{j} \text{Conjugate} \right) \tag{4}
\]

Configuration of the computational domain and boundaries are schematically shown in Figure 1. The computational domain includes the slag and ingot. A 2D axisymmetry calculation is performed. The slag-pool, electrode-slag, and slag-air interfaces are assumed to be flat. The electrode immersion depth is ignored.

The classical way to consider the impact of falling droplets is to use a mass flux of liquid metal at the slag-pool interface [19-20]. Another way of modeling the droplets is prescribing a Gaussian distribution of velocity profile at the contact interface between the slag and melt pool [18]. In fact, the impact of droplets is not limited only at the surface but deeply inside the melt pool. Therefore, we modify the model considering the impact of droplets by introducing the parameter called impact depth of droplets (\( \lambda \)). With this approach, the droplets are considered to be as the mass, energy, and momentum source carriers which deeply penetrate into the melt pool. The amounts of the sources are assumed to be linearly decreased from the slag-pool interface till the impact depth. The impact depth can be obtained by experiment or direct numerical simulation of droplet–liquid surface splash phenomenon. For our simulations, we assumed that the droplet size is 1 cm and the corresponding impact depth is 15 cm. Furthermore, it is assumed that the droplets enter the pool under the shadow of the electrode. Non-slip boundary condition is applied for the flow at the electrode-slag interface and at the mold wall, whereas at the slag-pool interface the condition is free-slip. The heat is transferred by convection and radiation between electrode and air, and at the slag-air interface. A value of 0.8 is applied for the emissivity for the mentioned boundaries. The heat is conducted to the mold passing through the slag skin layer from the slag and ingot. In addition, the air gap between the slag skin layer and mold due to shrinkage of solidified ingot is taken into account. The gap alters the thermal boundary condition from the conduction condition to a combined radiation-convection condition. The tip of the electrode (slag-electrode interface) where the droplets form takes the liquidus temperature of the alloy.

In addition, the boundary conditions for the magnetic flux, Eq.(1), are obtained using the Ampere’s law. The magnetic induction is prescribed at the slag-air and mould-water interfaces. The continuity of the magnetic induction is applied at the following interfaces: electrode-slag, slag-pool, slag-mold, and ingot-mold. Furthermore, an induction flux of zero is used for the ingot bottom. Details about the geometry and the average physical properties of the slag and steel are described in Table 1.

![Figure 1: Schematic representation of the computational domain for the ESR process.](image)

Table 1. Parameters used in the simulations.

<table>
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<th>Steel</th>
<th>Density (kg·m⁻³)</th>
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<td>Liquidus Temp. (K)</td>
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<td>Specific heat, liquid (J·Kg⁻¹·K⁻¹)</td>
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<tr>
<td></td>
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### Geometry (Static mold)

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<td>Slag height (m)</td>
<td>0.265</td>
</tr>
</tbody>
</table>

Several calculations under different operating conditions were performed using the commercial software FLUENT. Table 2 lists the operating conditions for the case studies.

Table 2. Operating conditions of the parameter studies

<table>
<thead>
<tr>
<th></th>
<th>RMS current (KA)</th>
<th>Frequency (Hz)</th>
<th>Mold current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case I</td>
<td>36.5</td>
<td>0.2</td>
<td>No</td>
</tr>
<tr>
<td>Case II</td>
<td>36.5</td>
<td>50</td>
<td>No</td>
</tr>
<tr>
<td>Case III</td>
<td>36.5</td>
<td>50</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Results

Case I
In Case I a low frequency (0.2 Hz) AC current is applied, and no current enters into mold. Figure 2 (a) shows the temperature field in the whole system and the isolines of solid fraction in the ingot region. The hottest area in the whole system is under the shadow of the slag-air interface.

In fact, an intense vortex forms under the edge of the electrode due to the Lorentz force and buoyancy force. The recirculation of the flow captures the released Joule heat in the slag region. The relative velocity between the melt and the ingot is illustrated in Figure 2 (b). The flow recirculation in the slag region corresponds to the maximum velocity in the whole system. The velocity is predicted to be much smaller in the melt pool than in the slag region. One point needs to be kept in mind is that the slag-pool interface is assumed to be stationary. This assumption would cause underestimation of the flow velocity in the melt pool especially in the vicinity of the slag.

The Lorentz force in the slag and melt pool is shown in Figure 2 (c). It is observed that the Lorentz force is quite homogeneously distributed. Exceptionally, the magnitude of the Lorentz force becomes large near the edge of the electrode. In fact, the variation in the Lorentz force and Joule heating in the slag region is consistent with the current density. Figure 2 (d) shows distributions of the current lines and Joule heating in the process. The maximum amount of Joule heating is released near the edge of the electrode where the current lines are denser. As a matter of fact, the amount of Joule heating is negligible in the electrode and ingot due to low electrical resistance of steel.

Figure 2. Contours of (a) the temperature field (b) magnitude of the relative velocity (c) Lorentz force and (d) Joule heating overlaid with the path of electric current for Case I. Isolines of fraction solid (0.02, 0.7 and 0.98) are plotted to indicate the mushy zone.

Figure 3. Contours of (a) the temperature field (b) magnitude of the relative velocity (c) Lorentz force and (d) Joule heating overlaid with the path of electric current for Case II. Isolines of fraction solid (0.02, 0.7 and 0.98) are plotted to indicate the mushy zone.
Case II

Figure 3 shows the contour of temperature, velocity, Lorentz force, and electric current together with Joule heating when the process is run under the frequency of 50 Hz. Again no current enters into mold since the skin layer is assumed to be an insulator. The region where the flow recirculates matches the hottest area in the slag zone as shown in Figure 3 (a). In the slag region, the Lorentz force is quite homogeneously distributed excluding the edge of the electrode where the force is the strongest. For this case, the force gradually increases from the bulk to the region near the mold wall in the melt pool as shown in Figure 3(c). This is due to change of electric current distribution once they enter the melt pool, as shown in Figure 3(d). The electric current flows radially towards the ingot surface as it passes the slag-pool interface. In fact, the electric current tends to flow along the ingot surface because of skin effect.

Case III

Figure 4 shows the modeling results of Case III. This case is same as Case II (50 Hz), but the electric current is allowed to cross the slag skin and enter into the mold.

The thickness of the slag skin layer is assumed to be 1 cm, and the contact length where the current can enter into the mold is 5 cm. Electric conductivities of the liquid slag and the solid slag skin are 100 and 48 respectively. In this case, around 90 % of total current is predicted to pass across the skin layer, as shown in Figure 4 (d). However, only 10 % of the total power is consumed in the skin layer. Due to the special current distribution in this case, strong Lorenz force is predicted in the region near the outer radius region of the slag layer and ingot, and only a very week Lorenz force acting in the bulk of the melt pool, as illustrated in Figure 4 (c).

Discussion

The shape of melt pool is an important indicator for the ESR process, and it determines the quality of the as-cast ingot. Parameters of the melt pool (depth, mush zone, standing height) are mainly governed by the global transport phenomena, which are in turn related to the flow intensity of different fluid regions. Intensity of the flow is evaluated by the time-averaged kinetic energy. Influence of the process operating parameters (Case I, II, III) on the average kinetic energy is analyzed (Table 3).

Table 3. Summary of the computed average kinetic energy in different fluid regions.

<table>
<thead>
<tr>
<th></th>
<th>Average kinetic energy in slag (J)</th>
<th>Average kinetic energy in melt pool (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case I</td>
<td>6.83</td>
<td>0.03</td>
</tr>
<tr>
<td>Case II</td>
<td>23.69</td>
<td>0.096</td>
</tr>
<tr>
<td>Case III</td>
<td>56.06</td>
<td>0.186</td>
</tr>
</tbody>
</table>

Effect of frequency

A comparison is made between Case I and Case II to analyze the effect of frequency of AC current as shown in Figure 5. The average kinetic energy in the slag for Case II is larger than that for Case I, see Table 3. It means that the present ESR process run with high frequency has a more severe mixing in the slag region than the process run with low frequency. The more severe the mixing in slag region, the larger the amount of energy being transport into the melt pool. Therefore, with the increase of the current frequency, the pool depth (distance between the slag-pool interface and the isoline of 0.02 solid fraction) is slightly increased. However, the isoline of 0.98 solid fraction moves down that results in thicker mushy zone for Case I than for Case II.

Additionally, the frequency of the AC current can affect the distribution of the Lorentz force at the region near to the slag-melt interface. As shown in Figure 5 (b), the electric current lines have similar distribution at the slag region independent of the applied frequency. Thus, the Lorentz force direction is identical for both cases, that is towards the axis of symmetry. However, at the slag-pool interface the direction is altered for Case II with 50 Hz frequency. It is horizontal and downward, as shown in Figure 6.