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CFD Modeling of the Electroslag Rapid Remelting (ESRR) Process

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Abstract

Electroslag rapid remelting (ESRR) process is used to produce high purity billet ingots in a cost-effective way. During the ESRR process, a T-shape mold is used, and it includes a graphite ring. The graphite ring would take most electric current (~ 90%) through the mold. A CFD model is proposed to improve our knowledge regarding to flow, thermal (solidification), and electromagnetic fields in the process. Calculations are performed both in 2D axisymmetric and 3D. The electric current path in the whole process and formation of solid slag layer in the T-shaped mold are analyzed. It is found that only a small amount of electric current can cross the inclined surface of the T-shape mold where a relatively thick skin layer forms.

Introduction

The standard ESR process can effectively control the solidification of ingot and produce homogenous structure with minimum defects. However, the melt rate of electrode is relatively low so that the whole process becomes uneconomical, especially for producing ingots of small size. On the other hand, the continuous casting technique seems more economical for producing such small ingots (billets), but deep liquid melt pool as formed during continuous casting leads to several centerline defects such as segregation and porosity. Continuous casting is not an adequate process to produce segregation prone alloys like tool steel or Nickle-based super alloys.

The electro slag rapid remelting (ESRR) process has advantages of both traditional ESR and continuous casting processes to produce billet ingots. As shown in Figure 1, a T-shape mold is used. It includes a graphite ring that takes most electric current through the mold. There are only a few monographs available discussing about this topic. A comprehensive description of the process was given by Holzgruber [1]. As reported by Alghisi et al [2], the first ESRR process with continuous casting concept using automatic manipulator was established in the beginning of 2002. Based on industrial praxis, the melt rate (in kg/h) of electrode in traditional ESR is strictly chosen as a portion of (0.6 to 1) ingot diameter (in mm). As such, production of ingots with diameter lower than 400 mm through ESR is very limited (very low melting rate) and uneconomical despite of their wide application area. In contrast, in the ESRR, the ratio of melt rate to ingot diameter can be as large as 3 to 10 to produce billets of 100 - 300 mm [3]. Currently, the research on the ESRR process is ongoing. The main purpose is to improve the design of the T-shape mold, to decrease overall heat loss in the process, and to obtain a higher temperature at metal meniscus [4].

In the present study, the electromagnetic, thermal, and flow fields in the whole process as well as solidification of the billet ingot (165x165 mm) are modeled. Firstly, for the sake of simplicity, a 2D axisymmetric model is applied. Afterwards, by performing a 3D simulation, we found that the 2D model can predict the behavior of the process with a relatively good accuracy. Here, details of the flow, electromagnetic, and thermal fields as well as solidification of the ingot are presented. Furthermore, the importance of the thickness of slag skin layer in the T-shape mold is highlighted. The main goal is to obtain some basic understanding of the formation of melt pool of the solidifying billet ingot in the ESRR process.

Modeling

Details of the numerical model including governing equations and boundary conditions for the transport phenomena (e.g. flow, thermal, electromagnetic) are presented in Ref. [5]. No slag skin was observed during the operation in the ingot region (skin thickness ~ 0) that is considered in the model. However, the formation of solidified slag layer in the T-shape mold is simulated implicitly by applying a thermal and electrical resistance at the slag-mold interface. A one-dimensional equation for the skin thickness (δ) along the T-shape mold can be extracted [6]:

$$\delta^2 \frac{j^2}{\sigma_{skin}} + \delta Q_{slag} - Q_{mold} = 0 \qquad (1)$$

In Eq. (1), (σ_{skin}) denotes the slag skin electrical conductivity, (j) is the current density flowing to the mold, (Q_{slag}) the heat flux coming from the liquid slag, and (Q_{mold}) the heat leaving to the mold. In the 2D axisymmetric model, cross sectional dimensions of the electrode (332x265 mm) and the billet ingot (165x165 mm) are substituted with their corresponding hydraulic diameter. All parameters used in our calculations are listed in Table 1.

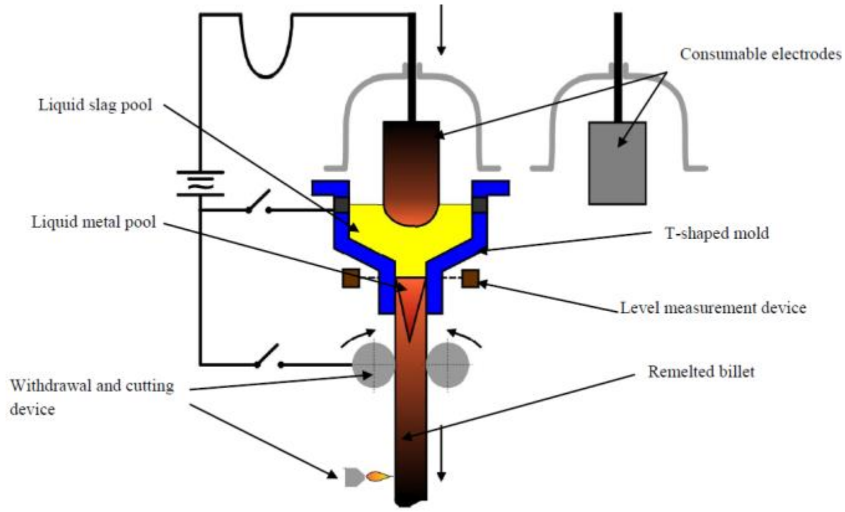

Figure 1. Schematic representation of the ESRR process. It is reprinted from Ref. [3].

Table 1. Parameters used in our calculations.

Mater. properties	**Slag**	**Steel**	**Operation parameters**	
Density (kg.m^{-3})	2440	7000	Ingot diam. (mm)	174
Viscosity (Pa.s)	0.01	0.0062	Elec. diam. (mm)	306
Specific heat (J.kg^{-1})	1255	500-800	T-mold diam. (mm)	580
Liq. therm. cond. (W.m^{-1}.k^{-1})	1.5-5	25-40	Slag height (m)	213
Sol. therm. cond. (W.m^{-1}.k^{-1})	0.5	16	Melt rate (kg.hr^{-1})	310
Therm. exp. Coeff. (K^{-1})	0.0001	0.00011	RMS current (kA)	6.7
Liquidus temp. (K)	1715	1773	Freq. (Hz)	50
Solidus temp. (K)	1598	1668	Power (MW)	0.36
Liq. e. cond. (ohm^{-1}.m^{-1})	130	8.8x10^5	Melt rate (kg.hr^{-1})	310
Sol. e. cond. (ohm^{-1}.m^{-1})	0.1	8.8x10^5		

Results and discussions

Figure 2a shows the modeling results for flow and thermal fields using the 2D model. The flow is driven by Lorentz and buoyancy forces in the slag. Furthermore, the flow is rotating clock-wisely (converging flow) under the edge of electrode which indicates that the Lorentz force is dominant. However, the flow is governed by thermal buoyancy and droplets impact in the bulk of liquid melt pool since only a slight amount of current (~ 10%) flows through the ingot region.

The temperature field is relatively uniform in both the slag and the melt pool due to intense mixing in the system. Except under the shadow of electrode where the slag is relatively hot as a consequence of high current density (released Joule heat). Two spots with high temperature are observed in the mold region including the graphite ring and the contact zone at ingot-mold interface (~ 3 cm). As illustrated in Figure 2b, the predicted temperature/solidification distribution using the 3D model is relatively similar to those calculated using the 2D model. It implies that the 2D model can give a good estimation of the overall behavior of ESRR system. Both models predict a shallow V-shape pool profile for the ingot. The electric current path in the T-shape mold is illustrated in Figure 2(c). Most of the electric current (~ 90%) is taken by the graphite ring. The remaining amount of the electric current (~10 %) cross the ingot-mold interface and then is taken at the bottom of ingot. Almost no current enters to the mold through the inclined surface of the T-shape mold where the skin layer is relatively thick as shown in Figure 2 (d). In contrast, a very thin layer of skin forms near the graphite ring as a consequence of elevated current density.

In the near future, further research can be carried out to investigate influences of droplets impact region entering to the pool, movement of slag-melt pool interface, and graphite to ingot electric current ratio.

Summary

Electroslag rapid remelting (ESRR) process has been developed to produce billet ingots at high production rate in an economical manner. A T-shape mold is used, and it includes a graphite ring which takes most electric current through the mold. There are only a few reports available in the literature discussing about this topic. As such, a model is demanded to get insight into the process. For this purpose, a CFD model is proposed. Calculations are performed both in 2D axisymmetric and full 3D geometries. The 2D model can efficiently (low computational cost) predict the overall behavior of the ESRR with a relatively good accuracy. Detailed analyses of the current path in the whole system as well as formation of the slag skin layer in the T-shape mold are presented. It is found that a tiny amount of electric current can cross the skin layer near the inclined surface of the T-shape mold where a relatively thick skin layer forms. At last, further research activities are suggested.

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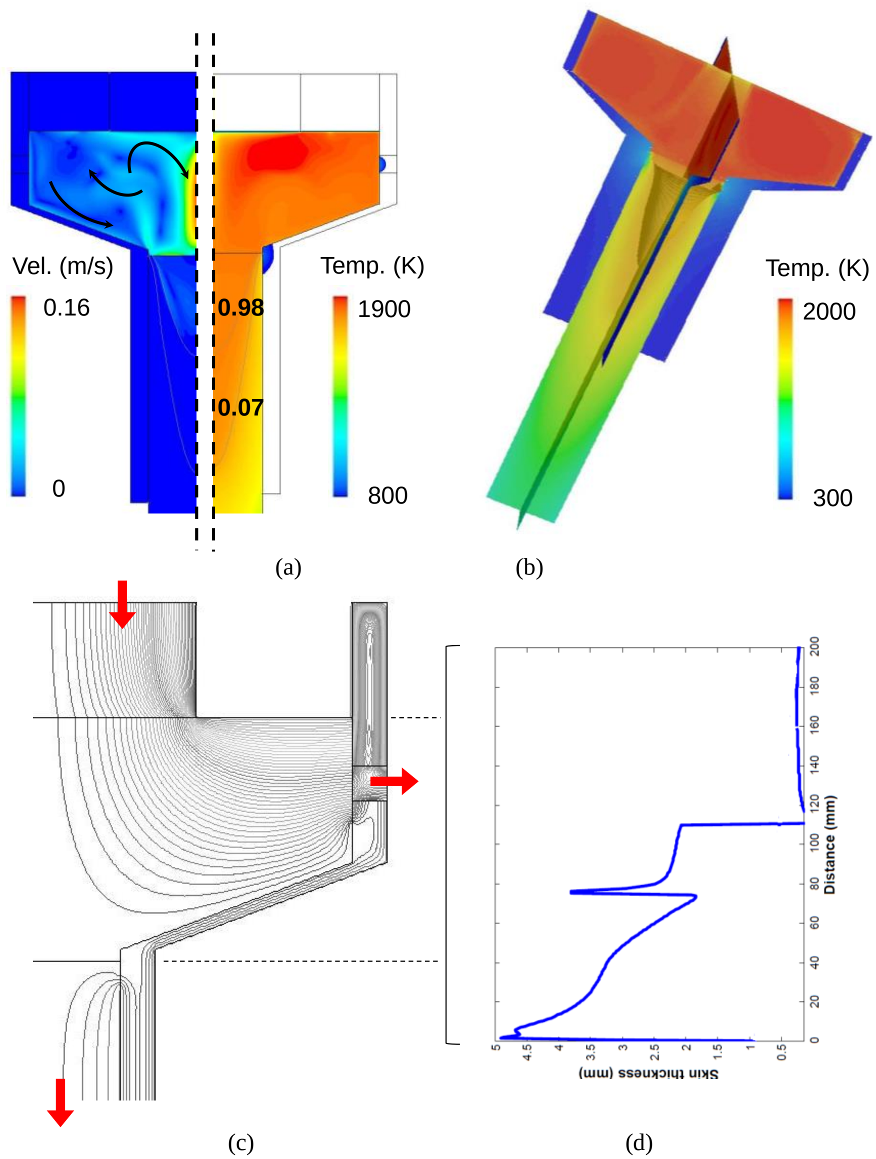

Figure 2. (a) Calculated velocity field (left half), and temperature field (right half) with the 2D model. Iso-lines of liquid fraction (0.98 and 0.07) are shown; (b) Calculated temperature field with the 3D model (two cross sections and the melt pool are shown); (c) The electric current path is shown, red arrows indicate the direction of the electric current; (d) Calculated thickness of slag skin layer in the T-shape part of the mold.