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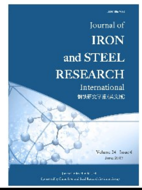

Modeling of flow and temperature distribution in electroslag remelting withdrawal process for fabricating large-scale slab ingots

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ABSTRACT

Currently, the market demands for large-scale and high-quality slab ingots are increasing significantly. A novel electroslag remelting withdrawal (ESRW) process with two series-connected electrodes and a T-shaped mould was developed to produce large-scale and high-quality slab ingots. It is very difficult to obtain large slab ingots with good surface quality and high width-to-thickness ratio. And it is not efficient for improving the quality of slab ingots by using trial-and-error-based approaches because the ESRW mechanisms are very complex. Thus, a three-dimensional mathematical model was developed to determine the relationship between process parameters and physical phenomena during the ESRW process. The relationship between the temperature field of the ESRW process and the surface quality of slab ingots was established. A good agreement between the simulated and measured temperature fields of slab ingots was obtained. The results indicate that the maximum values of current density, electromagnetic force and Joule heat all occur at the electrode-slag interface between the two electrodes. It can be found that the flow is turbulent and the temperature distribution is uniform in the slag pool with the influences of buoyancy and electromagnetic force. The wrinkles in the narrow faces of slab ingots are caused by the relatively lower input power. Increasing the electrode width and reducing the curvature can significantly improve the surface quality of slab ingots.

1. Introduction

Demands have increased in recent years for large-scale, high-quality slab ingots in the fields of die steel, pressure vessels and nuclear power. A 12Cr2Mo1R heavy plate has been widely applied in hydrogenation reactors because of its excellent antihydrogen and tempering stability characteristics[1]. Owing to the restriction of the compression ratio of continuous casting slabs, raw materials for producing high-quality 12Cr2Mo1R heavy plates still rely on large-scale slab ingots. The electroslag remelting withdrawal (ESRW) process with two series-connected electrodes and a T-shaped mould is a new technology to produce large-scale slab ingots based on conventional electroslag metallurgy technology. It has been proved that the technology will enhance the efficiency and metal yield of electroslag remelting (ESR) significantly, and produce high-quality and large-scale slabs for subsequent rolling[2,3]. The greatest technical difficulty in fabricating slab ingots lies in enforcing a uniform temperature between the center and the edge because the width-to-thickness ratio is often very large (>8∶1). Therefore, good surface quality is difficult to achieve for large-scale slab ingots. Two series-connected electrodes and a T-shaped mould are used to improve the surface quality, which is an important benefit of this technology. However, the mechanisms involved are very complex because ESRW technology has characteristics of both electroslag remelting and continuous casting. Moreover, production of slab ingots by ESRW results in a complex distribution of electric currents, magnetic fields, temperatures, and flow fields in the slag and molten metal pools. To improve slab quality, it is important to understand the relationship between the process parameters of ESRW and its physical phenomena.

Most research has focused on the influence of the process parameters on the internal quality of the ESR ingots[4-7]. However, their influence on the surface quality of ESR ingot is less frequently researched.

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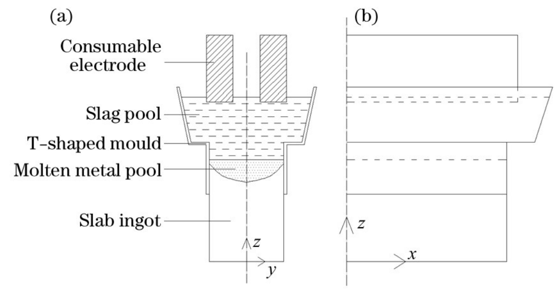
The quality of ESR ingot is dependent on the shape of the molten metal pool. In the traditional fixed-mould ESR process, methods to improve surface and internal qualities of the ESR ingot are often inconsistent. Reducing the melting speed of the consumable electrodes has often been used to improve the internal quality[8], such as segregation controlling and compact structure, of ESR ingots. However, surface defects occur easily when slow remelting speeds are used. The shape of the molten metal pool changes gradually in the traditional fixed-mould ESR process; thus, it is difficult to achieve the critical balance between surface quality and internal quality. For example, Li et al.[9] indicated that the shape of the molten metal pool changed from arc shape to V shape with increasing ingot height. ESRW technology can solve the above problems, because the ESRW process leads to a quasi-steady state while stripping. Most research has focused on small width-to-thickness-ratio ESR ingots, such as round[7,10,11] and square billets[12,13], but research on large width-to-thickness-ratio ESR billets has rarely been reported. However, the temperature field of a large width-to-thickness ESR billet is different from that of a small width-to-thickness ESR ingot.

Mathematical modeling is a valuable tool for enhancing fundamental understanding of the ingot production process and analyzing the effects of various factors on ingot quality[14,15]. In this study, a mathematical model was developed for describing the interaction of multiple physical fields during the ESRW slab ingot process, assuming a 3-dimensional geometry and a quasi-steady state. The electromagnetic field, magnetically driven fluid flow, and heat transfer were calculated, and the characteristics of velocity and temperature distribution during the process were determined. Based on the results of numerical simulation, the relationship between the process parameters and the surface quality of slab ingots was analyzed. After applying the optimized process parameters to an industrial test of ESRW at a plant in China, it was found that both the surface quality and the internal quality of the slab ingots were satisfactory.

2. Mathematical Model

2.1. Geometric model

The principal components of an ESRW system, as shown in Fig. 1(a), include two consumable electrodes, a molten slag pool, a liquid metal pool, a solidified ingot, a T-shaped water-cooled mould, and a drawing device. The alternating current is passed from one electrode through the molten slag to another electrode, and Joule heat occurs between the two electrodes. A solidified ingot is gradually stripped from the mould bottom. As shown in Fig. 1, a 3-dimensional, axisymmetric finite element model was established, pertaining to half geometry model. Front and side views of the simplified entity model are shown in Fig. 1(a,b), respectively. Detailed geometric dimensions and process parameters of ESRW are listed in Table 1. In the mesh of the calculation domain, the grid size of the liquid slag, the ingot, and the interface between slag and electrodes was 20, 25, and 5 mm, respectively.



(a) Side view; (b) Front view.
Fig. 1. Simplified entity model.

Table 1
Detailed geometric dimensions and process parameters of ESRW

Parameter	Value
Slag depth/mm	200
Height of bottom mold/mm	400
Slab thickness/mm	330
Slab width/mm	1430
Inserted depth of electrode/mm	15
Slab height/mm	1000
Electrode width/mm	1370
Electrode thickness/mm	150
Electrode interval/mm	60
Voltage of slag pool/V	60

2.2. Fundamental assumptions

The mathematical model to be described is based on the following assumptions:

(1) The process of ESRW is in quasi-steady state.

(2) The temperature of the slag contacting with the bottom of the electrodes is the liquidus temperature of steel.

(3) The interface of metal and slag is horizontal.

(4) The thermal physical property is related only to temperature.

(5) The heat sources are described as heated metal carried into the molten metal pool by droplets and latent heat released during the process of solidification embodied in the heat-transfer equation.

(6) Heat transfer of the molten metal pool is treated as conduction, and the heat transfer coefficient is replaced with an effective heat transfer coefficient.

(7) The flow in the slag pool is turbulent, and