



Simulation and experimental studies of effect of current on oxygen transfer in electroslag remelting process



Qiang Wang^{a,b}, Fang Wang^c, Guangqiang Li^{a,b,*}, Yunming Gao^{a,b}, Baokuan Li^c

^aThe State Key Laboratory of Refractories and Metallurgy, Wuhan University of Science and Technology, Wuhan, Hubei 430081, China

^bKey Laboratory for Ferrous Metallurgy and Resources Utilization of Ministry of Education, Wuhan University of Science and Technology, Wuhan, Hubei 430081, China

^cSchool of Metallurgy, Northeastern University, Shenyang, Liaoning 110819, China

ARTICLE INFO

Article history:

Received 1 April 2017

Received in revised form 10 May 2017

Accepted 3 June 2017

Available online 13 June 2017

Keywords:

Electroslag remelting

Oxygen transfer

Thermochemical reaction

Electrochemical reaction

Numerical simulation

ABSTRACT

A transient three-dimensional (3D) coupled mathematical model has been established to clarify the effect of current on oxygen transfer behavior in electroslag remelting process. Finite volume approach was utilized to simultaneously solve the mass, momentum, energy, and species conservation equations. The oxygen transfer rates induced by the thermochemical and the electrochemical reactions at the slag-metal interfaces were defined by a metallurgical thermodynamic and kinetics module. A series of experiment was conducted, and the contents of oxygen in the metal and the ferrous oxide in the slag were detected. A reasonable agreement between the simulated and measured data is obtained. When the current changes from 80 A to 160 A, the highest temperature and the maximal Reynold number increases from 1931 K to 2334 K and from 247 to 498, respectively. The final oxygen mass percent in the metal increases from 0.0537% to 0.0577% when the current changes from 80 A to 100 A, but decreases to 0.0559% if the current increases to 120 A, and again rises to 0.0616% while the current constantly increases to 160 A.

© 2017 Elsevier Ltd. All rights reserved.

1. Introduction

Electroslag remelting (ESR) technology, widely used in metallurgical industry, could effectively remove nonmetallic inclusions and notably refine grain size in alloys [1]. A schematic of the ESR process was shown in Fig. 1. A direct current travels from a positive consumable electrode, which composition is the same as the designed alloy, to a negative baseplate, and creates lots of Joule heating in a highly resistive calcium fluoride-based molten slag. With enough heating, the electrode begins to melt. As a consequence, a dense metal droplet is formed at the electrode tip, and then sinks through the less dense slag [2]. In this process, the hot electrode is easily oxidized by air, which creates solid ferrous oxide at the side wall of the electrode. Then the solid ferrous oxide would be melted with the electrode, and continuously enter into the slag. Once the oxygen potential of the slag exceeds that of the metal, ferrous oxide in the slag would be decomposed at the slag-metal interfaces, and the oxygen is then transferred to the metal:



where [] and () indicate that the matter is in the metal and slag, respectively. As a result, the oxygen in the air would be brought into the metal, which goes against the alloy properties [3]. Shi et al. have experimentally studied the oxygen transfer in the ESR process [4]. The results indicated that using inert gas could effectively prevent the oxidation. The decrease amplitude of the oxygen content in the alloy however was smaller than expected. The electrochemical migration of the oxygen in the slag and metal, induced by the current, was assumed to be the main reason. Kato et al. found that the oxygen content in the ingot first reduced and then rose with an increasing current density [5]. The electrochemical transfer of the oxygen was enhanced by the greater current. Meanwhile, the electrode oxidation and the oxide thermal decomposition in the slag were also promoted. It was recognized that the final oxygen content in the remelted ingot was determined by the competition between the thermochemical and electrochemical reactions.

It is of interest then, to examine the nature of electrochemical and thermochemical reactions, with the aim of predicting how the current would influence the oxygen transfer behavior during the ESR process. Experimental results confirmed that the oxygen

* Corresponding author at: The State Key Laboratory of Refractories and Metallurgy, Wuhan University of Science and Technology, Wuhan, Hubei 430081, China.

E-mail address: liguangqiang@wust.edu.cn (G. Li).

Nomenclature

\vec{A}	specific surface area for reaction (m^{-1})	n	number of the electrons entering in the reaction
\vec{A}	magnetic potential vector ($\text{V}\cdot\text{s}/\text{m}$)	Q	activation energy of metal (J/mol)
$a_{(\text{FeO})}$	activity of ferrous oxide in the slag	Q_J	Joule heating (W/m^3)
$a_{[\text{Fe}]}$	activity of iron in the metal	p	pressure (Pa)
$a_{[\text{O}]}$	activity of oxygen in the metal	R	gas constant ($\text{J}/(\text{mol}\cdot\text{K})$)
\vec{B}	magnetic flux density (T)	S_T	mass transfer rate at the slag-metal interface caused by the thermochemical reaction
c	mass percent of species	S_E	mass transfer rate at the slag-metal interface caused by the electrochemical reaction
c_0	initial mass percent of species	T	temperature (K)
$c_{p,m}$	specific heat of metal at constant pressure ($\text{J}/(\text{kg}\cdot\text{K})$)	t	time (s)
$c_{p,s}$	specific heat of slag at constant pressure ($\text{J}/(\text{kg}\cdot\text{K})$)	\vec{v}	velocity (m/s)
D	diffusion coefficient of species (m^2/s)	$w_{[\text{Fe}]^*}$	mass percent of iron in the metal close to the slag-metal interface (%)
$D_{s,\text{FeO}}$	diffusion coefficient of ferrous oxide in slag (m^2/s)	$w_{[\text{O}]}$	mass percent of oxygen in the metal (%)
$D_{m,\text{FeO}}$	diffusion coefficient of ferrous oxide in metal (m^2/s)	$w_{(\text{FeO})}$	mass percent of iron in the slag (%)
$D_{s,\text{O}}$	diffusion coefficient of oxygen in slag (m^2/s)	$w_{(\text{FeO})}^*$	mass percent of iron in the slag close to the slag-metal interface (%)
$D_{m,\text{O}}$	diffusion coefficient of oxygen in metal (m^2/s)		
E	internal energy of mixture phase (J/m^3)		
e_O^j	interaction coefficient of the element j with respect to the oxygen		
F	Faraday law constant (C/mol)		
\vec{F}_e	Lorentz force (N/m^3)		
\vec{F}_s	solite buoyancy force (N/m^3)		
\vec{F}_{st}	surface tension (N/m^3)		
\vec{F}_t	thermal buoyancy force (N/m^3)		
$f_{[\text{O}]}$	activity coefficient of oxygen in the metal		
\vec{j}	current density (A/m^2)		
K	reaction equilibrium constant		
k	generation rate of the ferrous oxide (kg/s)		
k_0	constant for Eq. (27)		
k_T	effective thermal conductivity ($\text{W}/(\text{m}\cdot\text{K})$)		
L	latent heat of fusion (J/kg)		
L_{FeO}	ferrous oxide distribution ratio		
$M_{(Y_i)}$	molecular weight of species Y_i in slag		
\dot{m}	melt rate (kg/s)		

Greek symbols

α	volume fraction
$\bar{\mu}$	viscosity of mixture phase (Pa·s)
μ_0	permeability of vacuum (T·m/A)
$\bar{\sigma}$	electrical conductivity of mixture phase ($\Omega^{-1}\cdot\text{m}^{-1}$)
φ	electrical potential (V)
$\frac{\varphi_c}{\phi}$	concentration overpotential (V)
ϕ	mixture phase property
ϕ_m	metal property
ϕ_s	slag property
γ_{FeO}	activity factor of ferrous oxide
ρ_m	density of metal (kg/m^3)
ρ_s	density of slag (kg/m^3)
ξ	power coefficient

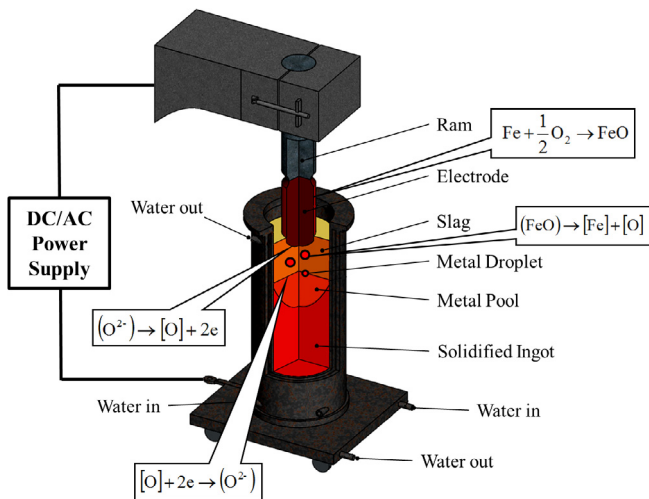


Fig. 1. Schematic of electroslag remelting process.

energy conservation equations. The Joule heating and Lorentz force, solved by Maxwell's equations, were coupled. The interface between the slag and metal was tracked using volume of fluid (VOF) method. Besides, the solidification was modeled by using an enthalpy-based technique. K. Fezi et al. have numerically investigated the mass transfer of five elements during the ESR process of Alloy 625. [9] The effect of the applied current on the macrosegregation of the five elements was demonstrated. The segregation increased with the increasing current to a maximum, beyond which the segregation slowly decreased. They indicated that it was due to the competition between the interdendritic flow and the cooling rate. In order to study the electrochemical reaction in a molten multi-ion slag, E. Karimi-Sibaki et al. have developed a coupled numerical model. [10] The ion transport is defined by the Poisson-Nernst-Planck equations, while the kinetics of the reaction at the slag-metal interface was described by the Butler-Volmer formula.

As discussed above, up to now, there have been few works concerning the oxygen transfer induced by the thermochemical and electrochemical reactions in the ESR process. This fact has motivated the present work, which purpose was to understand the effect of the current on MHD flow, heat transfer and oxygen migration. A transient 3D comprehensive model of the ESR process was built, in which a metallurgical thermodynamic and kinetics module was used to represent the mechanism of the oxygen thermochemical and electrochemical reactions. Besides, a series of experiments was carried out. The oxygen content in the remelted metal was measured by an oxygen and nitrogen analyzer, and

movement immensely depended on the distributions of the current density, velocity and temperature, which could be clearly clarified by numerical simulation.

Many numerical models have been proposed to describe the electromagnetic, flow, temperature fields, as well as the solidification during the ESR process. [6–8] The finite volume method was invoked to implement the solutions of the mass, momentum and

Download English Version:

<https://daneshyari.com/en/article/4994231>

Download Persian Version:

<https://daneshyari.com/article/4994231>

[Daneshyari.com](https://daneshyari.com)