Journal of Materials Processing Tech. 262 (2018) 232–238

Contents lists available at ScienceDirect

Journal of Materials Processing Tech.

journal homepage: www.elsevier.com/locate/jmatprotec

Gradual-cooling solidification approach to alleviate macrosegregation in large steel ingots

Honghao Ge[a,b], Fengli Ren[a], Duanxin Cai[a], Jing Hao[c], Jun Li[a,d,*], Jianguo Li[a,d]

[a] School of Materials Science and Engineering, Shanghai Jiao Tong University, Shanghai, 200240, China
[b] Institute of Laser Advanced Manufacturing, Zhejiang University of Technology, Hangzhou, 310014, China
[c] Faculty of Science and Engineering, University of Nottingham Ningbo China, Ningbo, 315100, China
[d] Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration, Shanghai Jiao Tong University, Shanghai, 200240, China

ARTICLE INFO

Keywords:
Macrosegregation
Solidification
Steel ingot
Simulation

ABSTRACT

Based on the mechanisms of macrosegregation evolution in large steel ingots, an approach named as gradual-cooling solidification (GCS) was proposed to alleviate the macrosegregation of large steel ingots. A three-phase mixed columnar dendritic-equiaxed solidification model was employed to investigate the approach. The solidification model considered the dendritic structure of equiaxed grains, nucleation and growth of equiaxed crystals, growth of columnar trunks, thermal-solutal buoyancy, sedimentation of equiaxed crystals, and columnar-to-equiaxed transition (CET). After the verification of model accuracy by a reported experiment results of a 55-ton steel ingot, this model has been used to study the GCS approach. The simulation results showed that the GCS approach has significant potential to alleviate the macrosegregation of the large steel ingot; e.g., for a 55-ton steel ingot, the variation range of segregation value decreased from 0.854 in the conventional casting case to 0.077 in the GCS case.

1. Introduction

Macrosegregation is the macroscopic heterogeneity of a solute species that occurs in most large scale ingot castings, this heterogeneity becoming seriously with the increasing of ingot size, as reported recently by Ge et al (2018). The formation mechanism has been extensively studied for several decades. Hultgren (1973) suggested that macrosegregation may occur when relative motion (flow) appears between the solid phase and the surrounding liquid. Relative motion has been identified as having the following major phenomena: thermal buoyancy, solutal buoyancy, sedimentation or floatation of free moving grains (Li et al., 2014a) or inclusion (Li et al., 2014c), solidification contraction-induced fluid flow or deformation, stirring, and others. Because of indirect observation of macrosegregation during it forming, modeling is a general method for macrosegregation investigation. The model considered these relative motion incorporating with mass, momentum, species, and heat transfer.

Several models were developed to simulate the macrosegregation formation since the first attempt by Fujii et al. (1979) on mushy zone in 1970s. After that, Wang and Beckermann (1996) systematically studied the effects of the grain sedimentation and thermal-solutal buoyancy on the final macrosegregation in the 1990s. In the 2000s, Combeau et al. (2009) presented a study of the morphology and motion of equiaxed grains on the final macrosegregation but their model omitted the columnar phase. Later, Wu and Ludwig (2006, 2007) provided a mixed three-phase solidification model with consideration of the interaction among the bulk liquid, the equiaxed grains, and the columnar phases. Recently, Ge et al. (2017) presented a four-phase dendritic model to study the interaction between macrosegregation and shrinkage defects during solidification.

However, most above studies focused on the improvement of the simulation accuracy, and only a few studies have attempted to find an effective way to alleviate macrosegregation. Li et al. (2014b) made a research of the multiple pouring process on the control of macrosegregation. Sang et al. (2010) added solid steel balls into melt during the pouring process to reduce the degree of macrosegregation. Recently, Ren et al. (2017) proposed a so called layer casting method which proved to be a promising method to increase the homogeneity of ingots, however, a lot of efforts should be implemented to modify its shortages, such as inclusion problem.

In the current study, a gradual-cooling solidification (GCS) aiming at alleviating macrosegregation was proposed, which was verified using a dendritic equiaxed-columnar mixed solidification model based on our previous researches, i.e., two-phase dendritic model from Ge et al.

* Corresponding author at: School of Materials Science and Engineering, Shanghai Jiao Tong University, Shanghai, 200240, China.
E-mail address: li.jun@sjtu.edu.cn (J. Li).

https://doi.org/10.1016/j.jmatprotec.2018.06.041
Received 11 January 2018; Received in revised form 20 June 2018; Accepted 26 June 2018
Available online 28 June 2018
0924-0136/

Nomenclature

Symbol description (unit)

Symbol	Description (unit)
c_0	Initial concentration (wt.%)
c_{ref}	Reference concentration (wt.%)
C_{ls}, C_{lc}	Species exchange (kg m^{-3} s^{-1})
D_l	Diffusion coefficient (m^2 s^{-1})
f_l, f_s, f_{env}, f_c	Volume fraction (1)
$\vec{g_l}, \vec{g_s}$	Reduced gravity (m s^{-2})
H^*	Volume heat transfer coeff. (W m^{-3} K^{-1})
Δh_f	Latent heat (J kg^{-1})
k_l, k_s, k_c	Thermal conductivity (W m^{-1} K^{-1})
m	Slope of the liquidius in phase diagram (K)
n	Grain number density (m^{-3})
Q_{ls}, Q_{lc}, Q_{cs}	Energy transfer (J m^{-3} s^{-1})
S_{env}	Surface area concentration of envelope (m^{-1})
$\dot{T}$	Cooling rate (K s^{-1})
$\vec{u_l}, \vec{u_s}$	Velocity (m s^{-1})
v_{Rc}	Columnar growth speed in radius direction (m s^{-1})
v_{tip}	Dendrite tip velocity (m s^{-1})
Γ_{env}	Envelope transfer rate (kg m^{-3} s^{-1})
ρ_l, ρ_s, ρ_c	Density (kg m^{-3})
c_l, c_s, c_c	Species concentration (wt.%)
c_{mix}	Mix concentration (wt.%)
c_p	Specific heat (J kg^{-1} K^{-1})
d_s, d_{env}	Diameter of solid and envelop (m)
G	Temperature gradient (K m^{-1})
H	Heat transfer coefficient (W m^{-2} K^{-1})
h_l, h_s, h_c	Enthalpy (J kg^{-1})
k	Solute partitioning coeff. (1)
M_{ls}, M_{lc}	Net mass transfer rate (kg m^{-3} s^{-1})
N_e	Grain production rate by nucleation (m^{-3} s^{-1})
P	Pressure (N m^{-2})
S_s	Surface area concentration of solid phase (m^{-1})
T	Temperature (K)
T	Time (s)
U_{ls}, U_{lc}, U_{cs}	Momentum exchange rate (kg m^{-2} s^{-2})
v_{Rs}	Solid phase growth speed (m s^{-1})
β	Solidification shrinkage (1)
λ_1	Columnar grain space (m)
μ_l	Viscosity (kg m^{-1} s^{-1})

(2016) and mixed three-phase model from Li et al. (2014a). A schematic description of current process is presented in Fig. 1 including a conventional solidification process (CSP) and a gradual-cooling solidification (GCS) process. As shown in Fig. 1, the thermal insulation material (insulation bricks) averagely covered the iron mold after filling with the melt, and all the thermal insulation was averaged and divided into 16 parts along the height of the mold. The solidification started from the bottom part of the ingot when the first part of the thermal insulation material was removed. After a while, the second part of thermal insulation was removed, and the ingot continued solidifying due to the heat that was transferred out of the ingot. The thermal insulation material was removed piece by piece, and the melt gradually solidified from the bottom to the top. Therefore, the process was referred as the gradual-cooling solidification (GCS) process. The main difference between CSP and GCS was the location of the heat transfer. In the GCS case, heat transfer only occurred around the mold where the insulating material had been removed (Fig. 1(c)), while heat transfer occurred around the entire mold in the CSP case (Fig. 1(b)). In this paper, we just presented this process to exhibit its potential of macrosegregation alleviation based on simulation results.

2. Mathematical model

A dendritic equiaxed-columnar mixed solidification model was adopted in the current simulation to study the feasibility of GCS. Three individual phases were taken into account: liquid, dendritic equiaxed grains, and columnar grains. The model integrated the macroscopic phenomena of the mass, momentum, heat, and species transfer with the

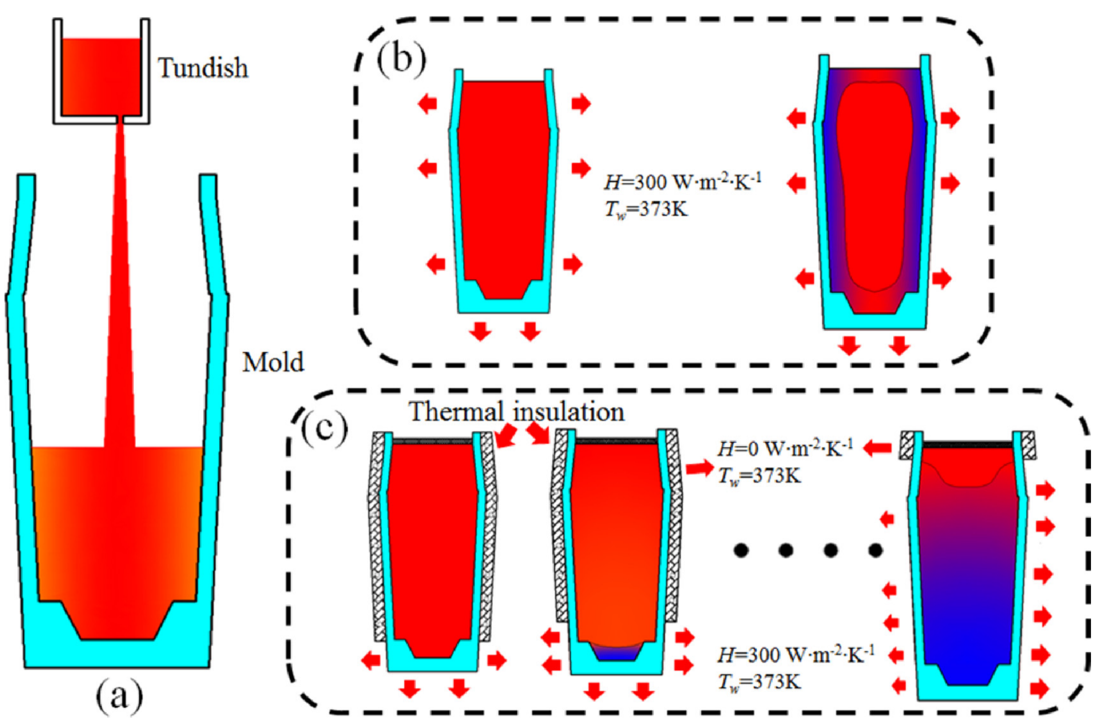

Fig. 1. Schematic description of (a) filling the ingot, (b) the conventional solidification process, (c) the gradual-cooling solidification process.