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Thermosolutal flow in steel ingots and the formation of mesosegregates

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ABSTRACT

The influence of the thermosolutal convection of the liquid steel in the solidifying core of a 3.3-ton ingot on the formation of banded mesosegregates is investigated by a multiscale solidification model. We first show how the thermosolutal flow structure in the solidifying core depends on the relation between the interacting thermal and solutal buoyancy forces and the coupling by the phase-change kinetics. We further show that banded mesosegregates are triggered by instabilities of the solidification front, that their location is determined by flow instabilities, and that their “A” or “V” orientation depends on the global direction of the flow circulation. Moreover, the results show that local remelting is not necessary to develop a channel mesosegregate. Destabilization of the mushy zone with local variations of the solidification velocity is sufficient.

1. Introduction

The typical pattern of macrosegregations encountered in steel ingots shows a negatively segregated zone at the bottom of the ingot and a positively segregated one at the top [1,2]. Frequently, mesosegregates (often called channel segregates) are also present, long narrow trails aligned in some preferred direction, with solute concentration greater than that of the surrounding regions. The two main types found in steel ingots are the banded V and A segregates. V segregates are typically found in the center of the ingot, while A segregates are found outside the V zone, in a zone parallel to the end of the branched columnar zone. Mesosegregates represent a severe casting defect, since the composition and crystalline structure of the solid within the narrow bands differ significantly from those of the nearby solid regions.

The main transport phenomena responsible for macro and mesosegregations were identified already a long time ago [1]: thermal and solutal natural convection of the liquid, flow due to solidification shrinkage, motion of free-floating equiaxed grains, and the deformations of the solid skeleton in the mushy zone. They act in association with the microsegregation which induces a difference in concentration between the solid and liquid phases at the dendrite scale. Any of these transport phenomena, which separate the solid and liquid phases at larger (macro- and meso-) scales, will then contribute to macro and mesosegregation formation.

Reviews on A and V segregate formation are found in [1,3] and more general reviews on macrosegregation in steel ingots in [1,2]. The detailed mechanism of formation of mesosegregates in steel ingots is still not well understood. Flemings [1], and Moore and Shah [3] rather loosely hypothesized on mechanisms due to

- Mesoscopic perturbations of the solidification of the porous solid skeleton in the coherent mushy zone and the flow of liquid following these perturbations.
- Instabilities in the form of mesoscopic remelted channels following the suction of liquid into the porous mushy zone due to solidification shrinkage.
- The mechanical collapse of the grains packed into a fragile porous layer towards the end of solidification of the ingot.

In this paper we discuss the first of these mechanisms and we show how banded mesosegregates can develop due to instabilities in the liquid-fraction field in the mushy zone. We show that their location depends on the location of flow instabilities, and their orientation (A or V orientation) on the flow direction in the ingot core. Further, we characterize the flow in the ingot core and its dependence on the relations between thermal and solutal buoyancy forces in the steel.

From a modelling point of view, important progress in the prediction of macro and mesosegregations was made with the application of the mixture theory and averaging procedures [2]. The application of models derived by these two theories showed their capability to predict macro and mesosegregations. Bennon

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Nomenclature

Latin symbols

C	concentration, mass %
$\overline{C}$	average mixture concentration, mass %
ΔC	characteristic concentration difference for the solutal buoyancy, mass %
c_p	specific heat, J/(kg K)
D	diffusion coefficient, m^2/s
d_g	equivalent grain diameter, m
$\vec{g}$	gravity acceleration, m/s^2
g_l	liquid volume fraction
g_s	solid volume fraction
h	specific enthalpy, J/kg
J^{Γ}	interfacial solute flux due to phase change, mass % kg/(m^3 s)
J^j	interfacial solute diffusion flux, mass % kg/(m^3 s)
k	thermal conductivity, W/(m K)
K	hydrodynamic permeability, m^2
k_K	Kozeny constant
k_p	equilibrium partition coefficient
L_f	latent heat, J/kg
l	characteristic pore size, m
m_L	liquidus line slope, °C/mass %
N	buoyancy ratio
N_0	nominal grain density, m^{-3}
P	pressure, Pa
Pr	Prandtl number
Ra_C	solutal Rayleigh number
Ra_T	thermal Rayleigh number
Re	Reynolds number
S_V	Specific area of the solid–liquid interface, m^2/m^3
Sc	Schmidt number
SDAS	secondary dendrite arm spacing, m
t	time, s
T	temperature, °C
ΔT	characteristic temperature difference for the thermal buoyancy, °C
ΔT_{uc}	local constitutional undercooling, °C
T_f	melting temperature of the pure substance (solvent), °C
$\vec{v}_l$	intrinsic average velocity of the liquid, m/s
d_0	initial grain diameter upon nucleation, m

Greek symbols

α	thermal diffusivity, m^2/s
β_C	solutal expansion coefficient, mass %$^{-1}$
β_T	thermal expansion coefficient, °C^{-1}
Γ	interfacial phase change rate, kg/(m^3 s)
δ	Dirac function (Eq. (17)), diffusion length, m
μ	dynamic viscosity, Pa s
ν	kinematic viscosity, m^2/s
ρ	density in the mass balances, kg/m^3
ρ_l^b	density in the buoyancy force, kg/m^3
τ	tortuosity
Φ_s	solid mass creation rate due to nucleation, kg/(m^3 s)
ω_z	vorticity perpendicular to the plane of the 2D flow, s^{-2}

Subscripts and superscripts

*	solid–liquid interface
crit	critical value for the laminar–turbulent transition
eut	eutectic
l	liquid phase
ref	reference state for the density
s	solid phase

and Incropera [4] were among the first to predict A mesosegregates in solidification from the side of an H_2O-30 wt%NH_4Cl solution in a rectangular cavity of 0.10 m height and 0.025 m width. Rady and coworkers [5] studied the same type of solution and the same cavity dimensions, and showed that, depending on the concentration of NH_4Cl, mesosegregates had an A orientation in the case of an H_2O-30 wt%NH_4Cl solution and a V orientation in the case of an H_2O-90 wt%NH_4Cl solution. The formation of these channels was associated with thermosolutal flow interactions that follow the onset of solidification. Medina et al. [6] and Willers et al. [7] simulated mesosegregates in the presence of magnetic melt stirring. They observed that the orientation of the mesosegregates depends on the direction of the forced flow induced by the stirring. Recently, Combeau and coworkers [8] for the first time predicted A mesosegregates in a model study of the solidification of an industrial 3.3-ton steel ingot. The higher computer performance allowed the use of denser computational grids; in the past the respective limitations did not allow for a sufficient grid resolution to model mesosegregates in industrial size ingots despite the successful prediction of the macroscale segregations [9,10]. Notably, in [8] we presented indications that mesosegregates in the steel ingot apparently stem from the localized instabilities of the advancement of the mushy zone front on the scale of several centimeters, and that these instabilities can be linked to the thermosolutal natural convection flow. In cases or in regions where the melt flow is quickly blocked by the low permeability, i.e. in zones where the solidification is fast or where strong packing of settling globular grains occurs, no mesosegregates were observed. When the settling grains have a dendritic morphology and form a more permeable sedimentation layer, on the other hand, they do not significantly modify the thermosolutal flow in the core and also do not affect the pattern of banded mesosegregates, in comparison to the case of a fixed solid phase.

The objective of this paper is to go further with the investigations on mesosegregate formation and to propose and endorse a hypothesis on the formation of mesosegregates by instabilities induced by the flow in the molten steel. We support this hypothesis by an analysis of a series of numerical simulations, studying the basic configurations of flow driven by thermosolutal natural convection in the solidifying mushy zone. We link the orientation of the mesosegregates to the direction of the flow circulation, which in turn depends on dominance of either thermal or solutal buoyancy forces driving the flow. We study these phenomena on a binary Fe-0.36%C 3.3-ton steel ingot of 2 m height and 0.6 m diameter [8], using the multiscale solidification model described in [8,11]. However, the present paper is not a predictive study of the segregation in the experimental ingot but a more fundamental study of the impact of the buoyancy ratio on the flow structure and in turn on the occurrence of instabilities of the mushy zone, resulting in banded mesosegregates. More detailed descriptions of the ingot, the model and its parameters are given in Appendix A. A very detailed account of the numerical solution procedure is given in [11].