Meso-Segregations during Solidification in a Binary Alloy under the Influence of Convection

G. Quillet, A. Ciobanas, P. Lehmann and Y. Fautrelle

Abstract

We present a numerical model aimed at simulating the segregations during the columnar solidification of a binary alloy. A validation experiment has carried out with a Sn-Bi10wt% in order to test the numerical model. The slow-cooling conditions have been used in order to promote the formation of segregation. Our objective is to study how the segregation characteristics in the mushy zone are influenced by laminar flows driven both by buoyancy and by AC fields of moderate intensity. It is shown that the electromagnetic forces create a flow field both in the liquid zone and in the mushy zone. In the laminar regime, the electromagnetically-driven flow doesn’t suppress the composition inhomogeneities, but may modify the segregation pattern, especially the freckle distribution.

Introduction

In the processing of solute rich alloys, defects called macro segregations can result from the solidification step. They are characterized by composition differences on space domains at the scale of the product, deteriorating the properties of the material. In most cases, such defects are observed on macrographs of the product. One particularly striking form is the "channel segregate". Typical dimensions are several cm in length, a few mm in cross section, so that they appear as "freckles" on transverse sections. They were observed in different solidification processes (forge ingots, vacuum arc remelted ingots, directionally solidified turbine blades). A typical condition is a relatively slow solidification rate, in alloys having a relatively large solidification interval (nickel base alloys [1], high alloy steels [2,3], and also Pb-Sn alloys [4] or ammonium chloride solutions for laboratory studies [4,5]). It is admitted that some specific configurations in thermo-solutal convection in the solid-liquid mush can produce such channel segregates [3, 6-8].

Numerical models have been developed in the past ten years [9-14], in which equations for heat transfer, fluid flow, solidification and solute transfer are solved in a coupled way. The objective of such models is to simulate how operation parameters (alloy composition, thermal and hydrodynamic conditions) can influence some characteristics of the defects (composition difference, position in the product). Most of the models are based on space-averaged equations. The local equations are integrated in an elementary representative volume (REV) whose size is greater than the dendrite scale [10-13]. The effect of an electromagnetically forced convection on the solidification has been investigated numerically by means of a continuum model [14]. It was found that a strong turbulent flow was able to decreases the macro-segregations.

In the present paper, the model developed by Felicelli et al. [10,11] has been used. We have achieved a model of columnar solidification in the presence of forced convection. Precisely, the present work is aimed at evaluating:
(i) how the fluid flow in the mushy zone transports the solute and generates the segregations
whether it is possible to control the fluid flow by means of an electromagnetic stirring device and accordingly to master the segregation.

A validation experiment has been carried out. It consists in solidifying a Sn-Bi10wt% alloy. The geometrical configuration is somewhat similar to that investigated by Hebditsch and Hunt [15].

1. **The mathematical model and the application case**

The mush is represented by a continuum of variable liquid fraction. All variables are averaged on the elementary space volume. The equations for conservation of energy, momentum, and solute are adapted for the space-averaged variables. The changes of the physical properties associated with solidification are neglected. The buoyancy effect, thermal and solutal, is treated in the Boussinesq approximation. The equations to be solved are the momentum equations, the energy equation governing the single temperature field and the conservation of solute mass. The momentum equations involve a Darcy term which take account of the liquid-solid interactions in the mush region. The Carman-Kozeny is used to determine the permeability. Regarding the liquid solute concentration, thermodynamic equilibrium is assumed in the mushy zone. Diffusion effects are neglected in the solid. Remelting is allowed according to local values of the temperature. Since no solute diffusion is supposed to occur in the solid, the history of the solidification must be kept at each mush node in order to account correctly for the remelting when remelting occurs. Details of the model may be found in [16].

2. **The validation experiment and validation**

The numerical model has been tested in the natural convection case. The experiment consists in the solidification of a liquid Sn-Bi10wt% alloy contained in a parallelepiped-shaped box which is cooled from its side. The geometry is illustrated in Fig. 1. The measurements are performed thanks to thermocouples welded on a stainless steel crucible. On the first large side wall, there are twenty five thermocouples disposed in an array in order to record temperature maps. A qualitative pattern of the segregations have been obtained by means of X-ray radiographies (Fig. 2b). The X-rays are easily absorbed by the bismuth, and the grey-color contrast gives some indications on the solute distribution within the ingot. Solute concentration profiles are also obtained by a chemical analysis of the ingot (Fig. 2a).

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*Fig. 1. Geometry of the solidification experiment (Sn-Bi 10%wt) and thermal boundary conditions*
The experimental results illustrated by Figs. 2a,b confirm that there exists localized segregated channels as well as distributed segregations. The corresponding numerical results obtained in the two-dimensional case are shown in Figs. 2c,d. The segregations are mainly confined near the bottom wall of the ingot. This is a consequence of the natural convection which transports the heavier solute in the bottom part of the ingot as shown by Fig. 2c. Fig. 2d shows that freckles are also predicted by the numerical model, and their location is in agreement with the experiments (Fig. 2b).

![Figure 2a](image1.png) ![Figure 2b](image2.png) ![Figure 2c](image3.png) ![Figure 2d](image4.png)

Fig. 2. Comparison between the experiments and the numerical model; (a) measured bismuth concentration map in wt\% after complete solidification; (b) X-ray radiograph of the solidified ingot showing the freckles; (c) calculated fluid flow during the solidification at t = 500s; (d) computed bismuth segregation map in wt\% at the end of the solidification.

### 3. Effect of the electromagnetic stirring

We have investigated two cases, namely

(i) a two-dimensional rectangular domain with a traveling magnetic field,

(ii) a cylindrical rod with a rotating magnetic field.

The two types of configurations are illustrated in Fig. 3. In the present calculations the electromagnetic forces have been chosen in such a way that buoyancy is comparable to the electromagnetic forces.
Fig. 3. Sketch of the geometry and thermal boundary conditions used in the numerical calculations with e.m.s.; (a) two-dimensional case with a linear electromagnetic stirrer, (b) three-dimensional case with a rotary electromagnetic stirrer, the flow pattern is sketched in the liquid zone.

In the two-dimensional case (Fig. 3a), the magnetic field is traveling in the vertical direction. The driving part of the electromagnetic forces then reduces to a single vertical component. Various types of stirring configuration have been considered. The numerical results are illustrated in Fig. 4. Without any electromagnetic forcing the segregation pattern consists of two lateral channels, or freckles, which induce two plumes in the liquid zone (Fig. 4a). The forced convection changes the location of the channel (Figs. 4b and 4c). It is shown that the location of the channel corresponds to the low pressure zones in the liquid region, e.g., the zone near the solidification front where the flow is oriented upward.

Fig. 4. Mixture concentration map in wt% (top) and velocity vectors in m/s (bottom) for various flow conditions in a Pb-wt10%Sn alloy at t = 900s in the two-dimensional case; (a) pure convection case; (b) single-stirrer case; (c) double stirrer case with an upward central flow.
In the three dimensional case, the cylindrical rod case has been considered. That geometry is illustrated in Fig. 3b. Here the electromagnetic stirring is generated by a rotating magnetic field. A first major simplification is made by considering the stirrer as infinitely long in the direction of the axis. The infinitely long stirrer case minimizes the meridian recirculating motion which is restricted to the Ekman pumping. Although the geometry as well as the force distribution are axisymmetric, the fully three-dimensional model has been used in that case. Figure 5 shows that without forced convection there appears several localized channels or freckles. That freckle configuration is in qualitative agreement with the experiments published by Sarazin and Hellawell [4]. The electromagnetic rotary stirring changes significantly the segregation pattern. It suppresses the various localized freckles and creates a single large channel in the center of the ingot as shown in Figure 6c.

![Fig. 5. Three dimensional solidification of a Pb-wt10%Sn cylindrical rod in the pure natural convection case at \( t = 1410 \) \( \text{s} \); a) liquid fraction viewed in a horizontal plane in the mushy zone; b) velocity vectors (m/s) in a meridian plane; c) mixture concentration (wt%) viewed in a horizontal plane and in a meridian plane.](image)

![Fig. 6. Three dimensional solidification of a Pb-wt10%Sn cylindrical rod with a superimposed rotary stirring at \( t = 2100 \) \( \text{s} \); a) velocity vectors (m/s) in the liquid zone viewed in a horizontal plane (1mm above the solidification front); b) velocity vectors (m/s) in the mushy zone viewed in a horizontal plane (1mm below the solidification front); c) mixture concentration (wt%) viewed in a meridian plane (interpolated values).](image)
Conclusions

From the above computations, we may draw various general conclusions regarding the effect of the electromagnetic stirring of moderate intensity. The electromagnetic stirring doesn’t suppress the macro-segregations and it only modifies them. Furthermore, the electromagnetic stirring may create and promotes the segregations. Segregations are essentially generated by the fluid motion within the mushy zone. That motion may be generated by three different mechanisms:
- mechanism 1: because of the thermodynamic equilibrium in the mushy region the liquid solute concentration exhibits gradients which are directly linked to the temperature gradients. Thus, those gradients (whether they are destabilizing) are responsible for solute natural convection.
- mechanism 2: the electromagnetic forces are rotational and acts directly on the liquid phase in the mushy zone to generate a fluid motion within the mush.
- mechanism 3: the liquid motion in the liquid zone may create pressure variations along the solidification front which force a liquid flow inside the mushy zone as in an usual porous medium; this is illustrated by the rotary stirring case where the liquid motion in the mushy zone is mainly radial due to the centrifugal pressure along the solidification front (see Figure 6b).

References

Authors
Prof. Fautrelle, Yves  Dr. Lehmann, Peter  Ciobanas, Alexandru  Dr. Quillet, Ghislain
EPM-MADYLAM, BP 95, 38402 Saint Martin d’Hères Cedex, France
E-mail: Yves.Fautrelle@inpg.fr