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Numerical investigation of the influence of forced convection induced by a travelling magnetic field during solidification of metallic alloys.

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Abstract

Numerical experiments of Bridgman solidification of *Al*-3.5*wt*%-*Ni* under forced convection induced by a travelling magnetic field (TMF) have been realized. The influence of the forced convection on segregation has been investigated and qualitatively compared with experimental results and a good agreement has been obtained. It is found that the TMF promotes segregation through the formation of large channels. A phenomenon of instability due to the competition between natural and forced convection in the mushy zone impacts on segregations has been shown.

Introduction

The study of metallic alloys solidification is of increasing importance since the properties of most alloys depend largely upon the degree of control, which can be applied during solidification. One of the major problems lies in the non-uniform distribution of solute concentration that is inherent to solidification. These concentration variations, also known as segregations, appear at the mesoscopic scale (freckles) and/or at the ingot scale (macrosegregation) [1] in a solidified sample. Naturally these concentration variations have important repercussions on materials properties; therefore, minimizing segregation is essential for the proper performance of alloys. It appears that the role of the gravity may be prominent for the evolution of segregation and can create unexpected concentration patterns. One of the possibilities to counter this effect is to impose a forced convection, which is easier to control.

The present paper deals with a numerical study of directional solidification under forced convection induced by a travelling magnetic field (TMF). The impact of TMF and gravity on segregations of an *Al* 3.5 *wt*% *Ni* alloy has been examined.

1. General consideration on travelling magnetic field (TMF)

1.1. General consideration on travelling magnetic field (TMF)

TMF is one of the ways to generate fluid motion in liquid metals. The method consists of applying a magnetic field in form of a wave travelling along the axis of the metallic load. In an axisymmetric geometry the corresponding electromagnetic forces are distributed in a meridian plane, and their mean values reduce to a single vertical component which is the effective driving force. To calculate the electromagnetic force, we make following assumptions.

In the case under consideration, we suppose that the magnetic field penetrates the sample. This hypothesis is justified since the inequality $R_{ind} << \delta_e$, where R_{ind} and δ_e are respectively the radius of the inductor and the skin depth (Eq.(1.1) [2]) is fulfilled.

$$\delta_e = \mathrm{Re}\left[\left(\left(\frac{\pi}{\tau}\right)^2 + i\mu\sigma\varpi\right)^{-1/2}\right] \quad (1.1)$$

τ is the pole pitch of the stirrer, $\omega=2\pi f$ the circular frequency of TMF, μ the vacuum permeability and σ the electrical conductivity (see Tab. 1.). We suppose also that the applied magnetic field is weakly distorted by the induced electric current on the load. Then, assuming that the applied coil currents are distributed along an infinitely long ideal current sheet surrounding the sample, then the magnetic field is a single wave travelling along the same axis. In cylindrical polar coordinates the resulting electromagnetic force may be approximated by the following expressions [3]:

$$\mathbf{F}=\left(F_r=0, F_\theta=0, F_z\,(r)=\pm F_0\left(\frac{r}{R}\right)^2\right) \quad (1.2)$$

$$F_0=\frac{1}{4}\sigma\omega\kappa B_0^2 R^2 \quad (1.3)$$

This force is directly responsible for the existence of a meridian liquid motion due to the radial variation of the axial component of the force. Note also that the direction of F_z may be reversed by only changing the polarities of the electric phases of the inductor.

Tab.1 : solidification and electromagnetic parameters

$\tau\,(mm)$	60	$G\,(K.m^{-1})$	3000
$f\,(Hz)$	50	$V_{pull}\,(\mu.s^{-1})$	10
$\sigma\,(\Omega^{-1}m^{-1})$	$3.8\,10^6$	$R\,(mm)$	4
$\delta_e\,(mm)$	22	$L_{num}/L_{exp}\,(mm)$	70/150

1.2. Description of the solidification case

The solidification experiments [4-5] are realized with a cylindrical sample of *Al-Ni 3.5%wt* alloy. Effects of the intensity of the magnetic field as well as its direction on segregation pattern are investigated. The experimental study reveals that forced convection creates an enriched layer, at the eutectic concentration, whose location (either peripheral or in the centre) depends on the direction of TMF. The size and the stability of this eutectic layer depend on the magnetic field intensity. Details of the experimental set-up and results are given elsewhere [4-5].

2. Numerical simulations

2.1. Numerical model

All numerical results have been obtained from the model developed by Ciobanas [6] devoted to the prediction the solidification phenomena at the macroscale. The model is an Euler-Euler multi-phase model based on a statistical averaging method. Basically the model deals with the mass, momentum and solute/species balance, governed by two-phase transport equations (solid and liquid) and jump conditions. Since the thermal diffusivity of the alloys is quite high, it is considered that, locally the temperatures of the solid and the liquid phases are identical. Consequently, we don't consider two energy transport equations (for the liquid and the solid). We solve only the energy balance for the mixture.

As far as the microscale phenomena are concerned, we use the approach developed by Rappaz & Thévoz [7] and Wang & Beckermann [8]. This approach defines three phases, namely the solid phase, the interdendritic liquid phase and the extradendritic liquid phase. The distinction between the interdentritic and extradendritic liquid phase is based on the notion of granular envelope, which connects the tips of the dendritic arms. The addition of a third phase, interdendritic, allows calculating accurately a repartition of the solute inside the liquid. In order to close and to simplify the system, we make following hypotheses:

- The flow remains laminar in the liquid part;
- The solid growth is supposed to be columnar (no solid velocity);
- The momentum exchange between the liquid and solid phases in the mushy zone is achieved via a Darcy term involving a fluid permeability, which is based on the secondary arm spacing ($\lambda_2 = 100\ \mu m$ [9]);
- The interfacial phase change rate between the solid and the liquid is computed thanks to the interfacial species balance;
- The eutectic reaction is considered isothermal;
- Thermophysical properties are identical for the liquid phase and the solid phase (except for the mass diffusion coefficient).

The commercial finite volume software FLUENT is used as a basic solver. The whole solidification part is introduced via the User-Defined-Subroutines.
The full system is detailed in [6].

2.2. Numerical case

In simulations, we consider a cylindrical sample submitted to a directional solidification (Tab. 1.). The radius of the sample is the same as in the experiments, whereas the length (L_{num}) is taken smaller than the experimental (L_{exp}) one to reduce the computational time (Tab. 1.). However, the cylinder is long enough to keep a geometrical aspect ratio bigger than 1, that means that reduce of the length of the sample in calculations has little effect on the convection.

The varying parameters are the intensity of the magnetic fields (5mT, 10mT and 30mT) and the direction of electromagnetic force (hence of the flow) (1.2). Numerical parameters are given in Tab. 2.

Tab. 2 . Numerical parameters

Cell Number	28000
Cell size (mm)	0.1
Time step (s)	0.02
Model	2D axisymmetric
Time discretization scheme	1^{st} order implicit
Spatial dicretization scheme	2^{nd} order upwind

3. Results

The computed average concentrations for the two directions of the electromagnetic force are shown in Fig. 1. and Fig. 2. In Fig. 1., the flow is downward in the middle of the sample (case F+), while it is upward in Fig. 2. (case F-). Each figure exhibits segregation patterns for the three values of magnetic fields (5mT (left), 10mT (middle) and 30mT (right)) at solidification time t=2500s. At that time about 1cm of the sample is completely solidified.

The mushy zone is comprised between reference lines (at 1*cm* and 1.5*cm*) shown as black lines in Fig. 1. and Fig. 2.

In the first case, presented in Fig. 1., the flow inside the mushy zone is oriented from the axis toward the side wall of the crucible. In this way, the solute rejected by the solidification front, is dragged from centre to the periphery of the sample. It leads to the solute enrichment of the side layers and to the impoverishment in the centre. In the second case (F-, Fig. 2), the flow direction is opposite to the previous case and the solute is dragged from sides to centre. For both flow directions, the values obtained for the enriched zones correspond to the eutectic one. For F- and F+, the segregation is even stronger with a higher convection (i.e. with increasing the magnetic field). Thus, according to simulations, segregation depends on the direction of the flow and on its intensity. These results are similar to experimental observations [4-5].

Numerical investigations have also revealed the influence of the intensity of the magnetic fields on the shape of the eutectic zones. For *B*=5*mT* and *B*=10*mT*, the segregation maps exhibit periodic pattern along the z-axis while the enriched zones are smooth for *B*=30*mT* for both the electromagnetic forces (1.2). To explain this instability we suppose a competition phenomenon between forced and natural convection. Indeed, in the case under consideration the rejected solute, Ni, is heavier than the mixture *AlNi3.5%wt*. Therefore, under the gravity, the enriched liquid tends to move downward. Interaction of flows caused by forced and natural convection and moving in opposite directions may explain observed segregations. To validate the influence of gravity on the oscillatory shape of the channel, a calculation for *B*=5*mT* without gravity has been conducted. Fig. 3. represents both the averaged concentration and the flow pattern at *t*=2500*s*, with (right) and without gravity (left). The present calculation has been carried out for a liquid flow upward in the middle of the sample (F-). Without gravity, the flow pattern is constituted of a unique vortex. Effect of gravity is exhibited through the formation of 3 vortices. The first vortex, $V_{1,}$ is created by the TMF in the liquid part it corresponds to the unique vortex in the case without gravity. Vortices V_2 and V_3 are due to interaction between forced and solutal convection. The flow moves up along the axis due to the electromagnetic force, however, the Ni-enriched zone is submitted to the gravity force and tends to move downward (creation of V_3). For *B*=5*mT* and *B*=10*mT*, the downward motion of the heavier liquid within V_3 cannot be countered by the forced convection. However, the solute captured by V_3 stays within the enriched axial channel, whereas an elongated vortex V_2 provides radial "spikes" of the solute. The vortex, V_2, corresponds to the flow inside the mushy zone induced by the force convection. For a higher magnetic field, B=30mT, the forced convection makes the influence of the gravity minor: the channel is stable.

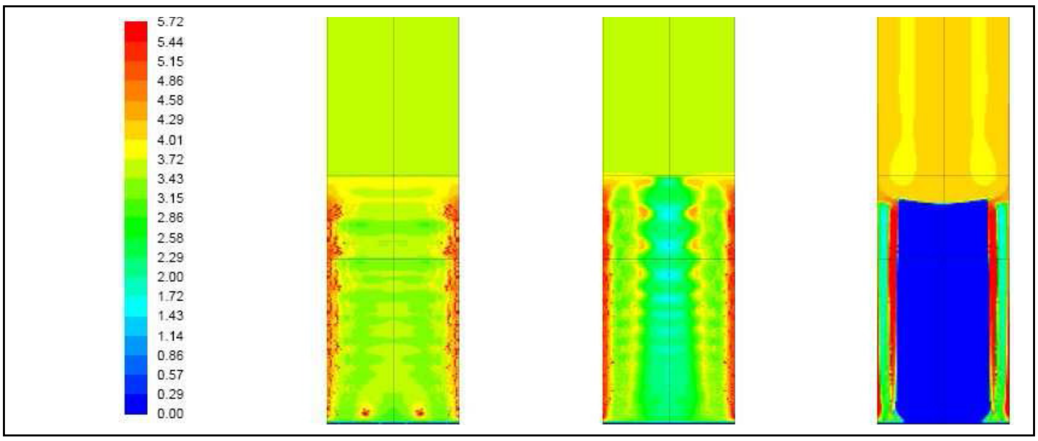

Fig. 1. Averaged concentration at t=2500s. Left B=5mT, middle B=10mT, right B=30mT. The flow is upward to the sides. The horizontal lines corresponds to the coordinates z=1cm and z=1.5cm

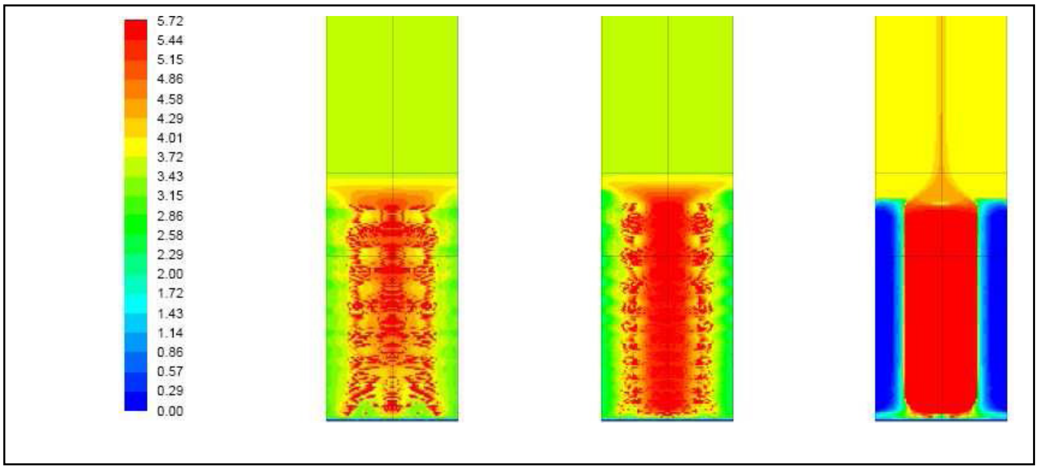

Fig. 2. Averaged concentration at t=2500s. Left B=5mT, middle B=10mT, right B=30mT. The flow is upward to the middle. The horizontal lines corresponds to the coordinates z=1cm and z=1.5cm

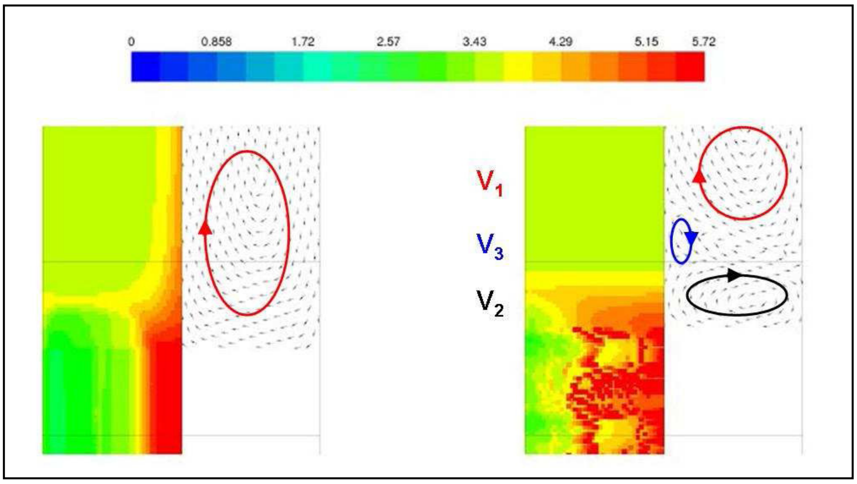

Fig. 3. Averaged concentration and flow pattern for B=5mT at t=2500s. Left: without buoyancy effect. Right: with buoyancy effect. The horizontal lines correspond to the coordinates z=1cm and z=1.5cm.

Conclusions

Numerical calculations and experimental results are in good agreement since the same trend concerning the influence of forced convection on segregation is obtained. The forced convection emphasizes segregations either on sides or in the middle (depending on the direction of the electromagnetic force). One of the most important results lies in the competition of natural and forced convection inside the mushy zone. It appears that even in forced convection the gravity impacts on segregations.

References

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