CONTROL OF THE MACROSEGREGATIONS DURING SOLIDIFICATION OF A BINARY ALLOY BY MEANS OF A AC MAGNETIC FIELD

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Rezumat. *Un model numeric ce urmăreşte segregările în timpul solidificării în coloană a aliajelor binare este folosit pentru a analiza efectele unei convecţii forţate. Obiectivul nostru este de a studia modul în care segregările caracteristice în zona moale sunt influenţate de curgerile laminare cauzate atât de mişcare cât şi de câmpuri AC de intensitate moderată. Au fost testate numeroase tipuri de câmpuri magnetice şi anume în mişcare longitudinala, de rotaţie şi forţe electromagnetice uşor modulate. S-au efectuat calcule pentru două tipuri de aliaje şi anume cositor - plumb şi aluminiu – silicon. Rezultă că modul de segregare este influenţat de configuraţia curgerii. Această influenţă provine din cuplarea curgerii lichidului şi partea superioară a zonei moi în sensul distribuţie de presiune în lungul frontului de solidificare. Diferenţa de presiune în lungul frontului conduce la curgerea topiturii către regiunea moale. Un alt tip interesant de câmp magnetic în mişcare a fost testat. El constă într-un câmp magnetic în mişcare uşor modulat. Se arată că într-un anumit interval de valori ale perioadei de modulare canalele aproape că dispar. Macrosegregarea normală se păstrează, dar segregarea medie din zona moale este mai slabă decât în cazul convecţiei naturale. Perioada optimă depinde de intensitatea forţei electromagnetice cât şi de viteza de răcire. Ultimul fenomen menţionat nu poate s-a aibă loc în cazul unui câmp magnetic rotitor deoarece în acea configuraţie semnul gradientului de presiune în lungul frontului de solidificare rămâne neschimbat. Experimente de solidificare recente în câmpuri magnetice aflate în mişcare confirmă modul de segregare estimat.*

INTRODUCTION

In the processing of solute rich alloys, defects called macro segregations may result from the solidification step. They are characterized by composition differences on space domains at the scale of the product, degrade *deteriorat*ing 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 centimeters in length, a few millimeters 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 therelatively 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 may *produce* such channel segregates [3, 6-8].

Numerical models *have been* developed in the past ten years [9-15], 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 hydro dynamical 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 [10-15]. The effect of an electromagnetically forced convection on the solidification has been investigated numerically by means of a continuum model [16]. It was found that a strong turbulent flow was able to decrease the macrosegregations. Medina *et al.* [15] have investigated the effects of traveling magnetic field during the solidification of a binary alloy in the laminar flow regime. They found that the electromagnetic stirring affected the location of the channels according to the flow pattern.

In the present paper, we investigate the effects of an electromagnetically-forced convection on the segregations of a binary alloy by means of a columnar model of solidification. Precisely, the present work is aimed at evaluating:

(i) how the fluid flow in the mushy zone transports the solute and generates the segregations

(ii) whether it is possible to control the fluid flow by means of an electromagnetic stirring device and accordingly to master the segregation.

THE MATHEMATICAL MODEL AND THE APPLICATION CASE

All variables as well as the equations for conservation of energy, momentum, and solute are derived by means of an ensemble averaging procedure. The changes of the physical properties associated to 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 takes account of the liquid-solid interactions in the mush region. The Carman-Kozeny is used to determine the permeability. Regarding the liquid solute concentration in the mushy zone, two types of columnar models are used. In the first one (referred hereafter as model 1 [15]), the liquid solute concentration is linked to the temperature field thanks to the thermodynamical equilibrium law. In the second model (model 2) described by Ciobanas *et al.* [17], we introduce a departure of the solute liquid concentration form the local liquidus concentration. An envelope model is implemented in the mushy zone regarding the dendrite. We thus introduce both a solid fraction as well as an envelope volume fraction. That approach is similar with the method used to deal with the equiaxed solidification (Rappaz and Thevoz [18], Wang and Beckermann [12]). The thermodynamical equilibrium is assumed inside the dendrite skeleton, where the liquid concentration is governed by the phase diagram. However, in the envelope the liquid concentration is governed by a mass conservation equation involving a mass transfer coefficient. The general equations are described in detail in previous papers [15, 17]. The numerical model 1 has been already tested in the natural convection case by means of an experiment which consisted in the solidification of a liquid Sn-Bi10wt.% alloy contained in a parallelepiped-shaped box cooled from its side [19].

We have investigated the case of a two-dimensional rectangular domain with a traveling magnetic field. Two types of alloys have been used, namely Pb-Sn10%wt. And Al-Si7%wt. The general scheme of the geometry as well as the boundary conditions are illustrated in Figure 1. In the present calculations the electromagnetic forces have been chosen in such a way that buoyancy is comparable to the electromagnetic forces. The corresponding non-dimensional parameter M is of order of unity, namely

$$M = \frac{F_0}{g\Delta\rho} = \mathrm{O}(1),$$

F_0, $\Delta\rho$ and g respectively being the typical amplitude of the electromagnetic forces, an estimate of the density variations and the gravity.

In the present two-dimensional case (Figure 1), the magnetic field is traveling in the vertical direction. The driving part of the electromagnetic forces then reduces to a single vertical component:

$$F_z(x) = m(t)\quad f_l F_0\left[\exp\left(-\frac{2x}{\delta}\right) + \exp\left(-\left(\frac{2(W-x)}{\delta}\right)\right)\right], \quad (1)$$

where f_l, δ, W and $m(t)$ respectively denote the liquid fraction, the electromagnetic skin depth, the pool width and a sinusoidal modulation function. In the present case, the values of δ and W are 5 mm, whilst the force amplitudes are $F_0 = 10^2$ and 10^3 N/m^3, respectively, in the cases of the Pb-Sn and Al-Si alloys.

Various types of stirring configurations have been considered: steady electromagnetic forces of various direction and slowly-modulated forces.

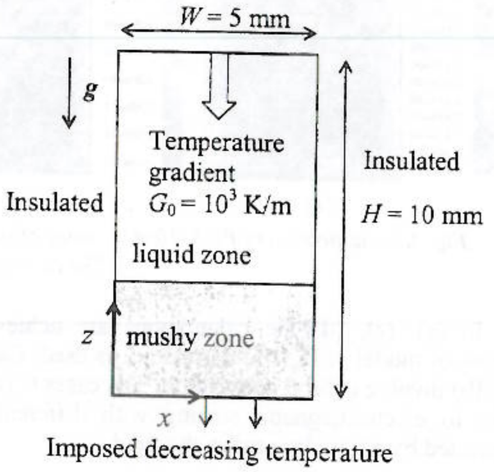
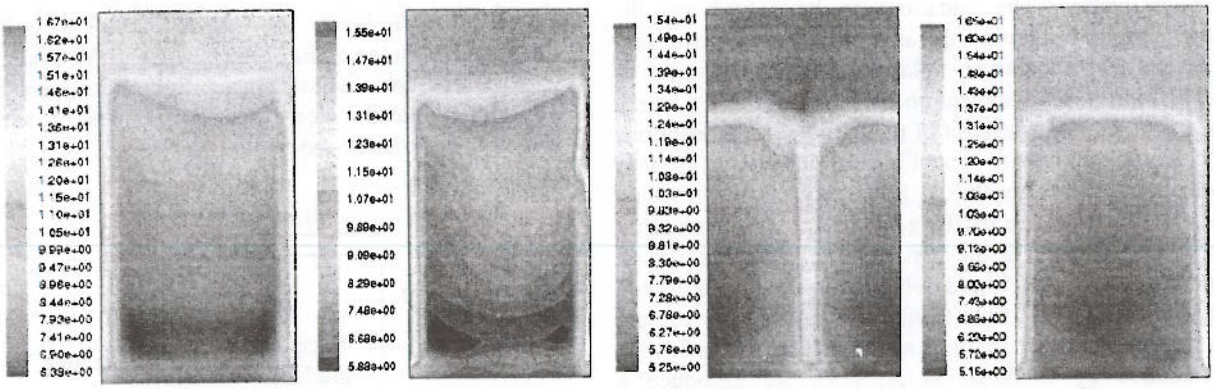


Fig. 1. Sketch of the geometry and thermal boundary conditions used in the numerical calculations with electromagnetic stirring. The applied temperature gradient is $G_0 = 10^3$ K/m.

EFFECT OF A PERMANENT TRAVELING ELECTROMAGNETIC STIRRING

Case of the lead-tin alloy. We consider first the solidification of a Pb-Sn10wt.% alloy. The boundary conditions are summarized in Figure 1. The cooling rate is 1K/min. The numerical results are illustrated in Figure 2. Without any electromagnetic forcing the segregation pattern consists of two lateral channels, or freckles, which induce two plumes in the liquid zone (Figure 2a). The forced convection changes the location of the channel (Figures. 2b and 2c). 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. In the present case, the electromagnetic stirring does not suppress the channel segregates but controls their location according to liquid flow pattern. The latter result has already been shown and explained by Medina *et al.* [15]. It is noticeable that the segregations are quite important both with and without stirring as shown in Figure 2 or Figure 5 for example. They may vary from 6 to 16%. Note that the two types of models yields quite similar results (cf. Figs. 2a and 2b).

Case of the aluminium-silicon alloy. We consider first the solidification of a Al-Si7wt.% alloy. The boundary conditions are identical to those of the lead-tin case. The cooling rate is higher and equal to 24 K/min. The numerical results are illustrated in Fig. 4a. The segregation pattern is similar to the previous case. Note however, that the central channel is significantly wider. Note that due to the envelope model the effective permeability of the mushy zone is higher than in the case of model 1.



(a) (b) (c) (d)

Fig. 2. Solidification of Pb-Sn10wt.%, maps of solute mean concentration for various the types of stirring at t = 1200s. The cooling rate is 1K/min. $F_0 = 10^3$ *N/m³.*

In (a), (c), (d) the calculations are achieved by means of model 1. In (b) the model 2 is used. Cases (a) and (b) involve natural convection. The cases (c) and (d) refer to electromagnetic stirring with different signs generated by a traveling magnetic field.

EFFECT OF A MODULATED TRAVELING ELECTROMAGNETIC STIRRING

The electromagnetic force (1) is now modulated by a sinusoidal function of time $\sin(2\pi t/p)$, p being the modulation period. Both models were used. The computed solute concentration maps are illustrated in Figures 3 and 5 in the case of Pb-Sn alloys and Figure 4 in the case of Al-Si alloys. It is shown that a modulated electromagnetic stirring may suppress the segregated channels if the modulation period t_m is chosen properly. If the value of p is too short, the flow is not sensitive to the Lorentz forces, and the segregation pattern is similar to that obtained in the natural convection case. Such a behavior is shown by the concentration maps illustrated in Figure 3a. For long modulation period, channels begin to form alternatively in the center and near the lateral walls as in the steady stirring case illustrated in Figures 2b, 2c. The corresponding segregation pattern keeps the memory of the channel formations and disappearances. This is clearly shown in Figures 3d and 4b,c,d. The disappearance of the channels is also visible on the vertical-average concentration profiles shown in Figure 5. For $p \approx 18$ s, the lateral segregations are almost suppressed. The latter result may be interpreted by considering both the required flow establishment time t_e and the transit time t_c of the flow inside the mushy zone. The transient time of the flow may be estimated by the turn-over time of the re-circulation in the liquid zone, namely

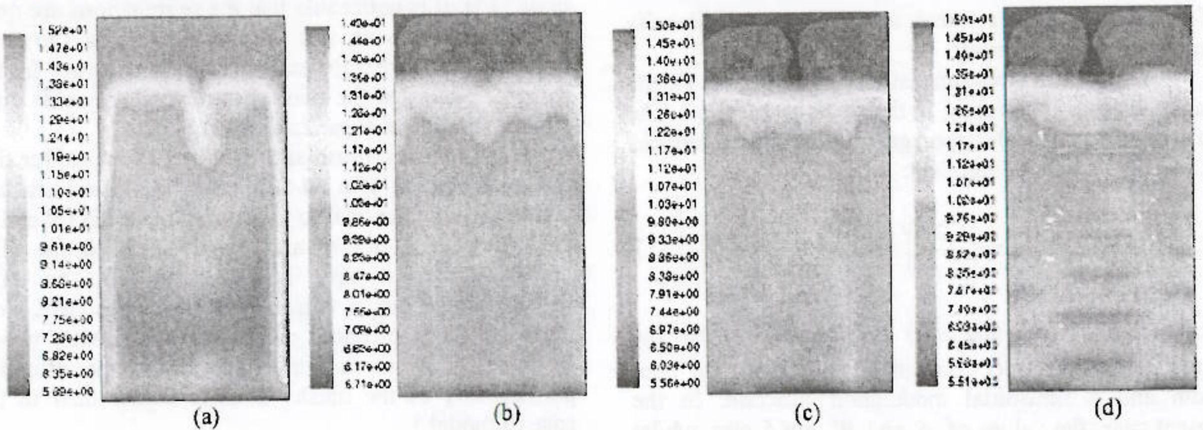
$$t_e \approx W / U_l \approx 1\text{s}, \qquad (2)$$

for a liquid velocity estimate U_l equal to 5 mm/s.

As for the transit time of the liquid in the mushy zone, its value involves the fluid velocity U_m. Following Medina *et al.* [15], U_m may estimated by a balance between the electromagnetic forces and the Darcy term which yields the following order of magnitude:

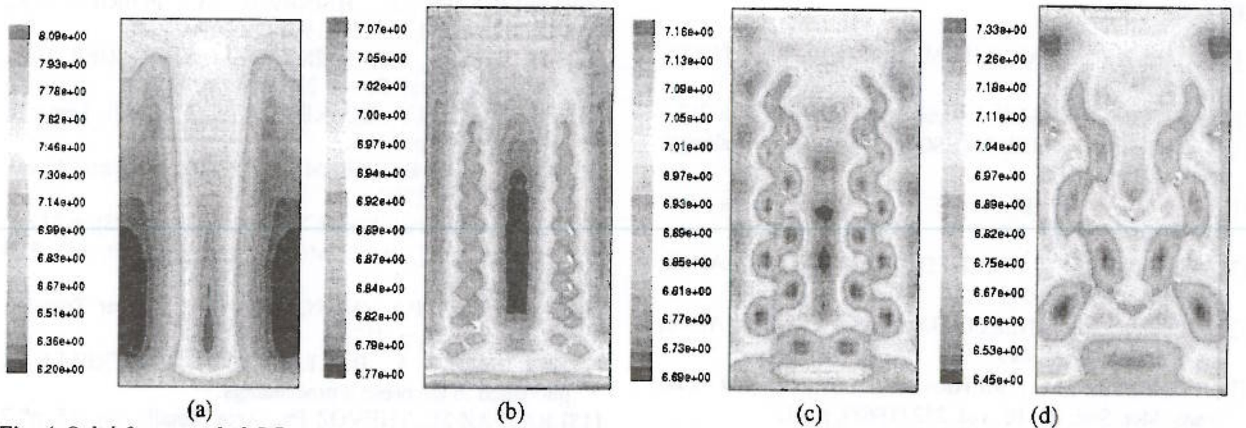
$$U_m \approx \frac{K_m F_0}{\mu}. \qquad (3)$$

Taking the value of the permeability $K_m = 1.4\times10^{-9}\text{m}^2$ which corresponds to the vicinity of the solidification front ($f_l = 0.8$) [15], the value of U_m is equal to 5.7×10^{-4}m/s. The corresponding value of t_c calculated by using a relation similar to (2) is 9s. The latter value is in agreement with the numerical calculations shown in Figure 3. Note that the normal segregation is also slightly reduced by the modulation when the optimal period is used.



(a) (b) (c) (d)

Fig. 3. Solidification of Pb-Sn10wt.%, maps of solute mean concentration for various modulation periods at t = 1200s. The cooling rate is 1K/min. $F_0 = 10^3$ *N/m³. Calculations are achieved by means of model 1. (a) p = 4 s, (b) p = 12 s (c) p = 32 s, (d) p = 128 s.*



(a) (b) (c) (d)

Fig. 4. Solidification of Al-Si7wt.%, maps of solute mean concentration for various modulation periods at t = 40s. The cooling rate is 24 K/min. $F_0 = 10^2$ N/m^3 .Calculations are achieved by means of model 2. (a) constant electromagnetic force, (b) p = 2.5 s (c) p = 5 s, (d) p = 10 s.

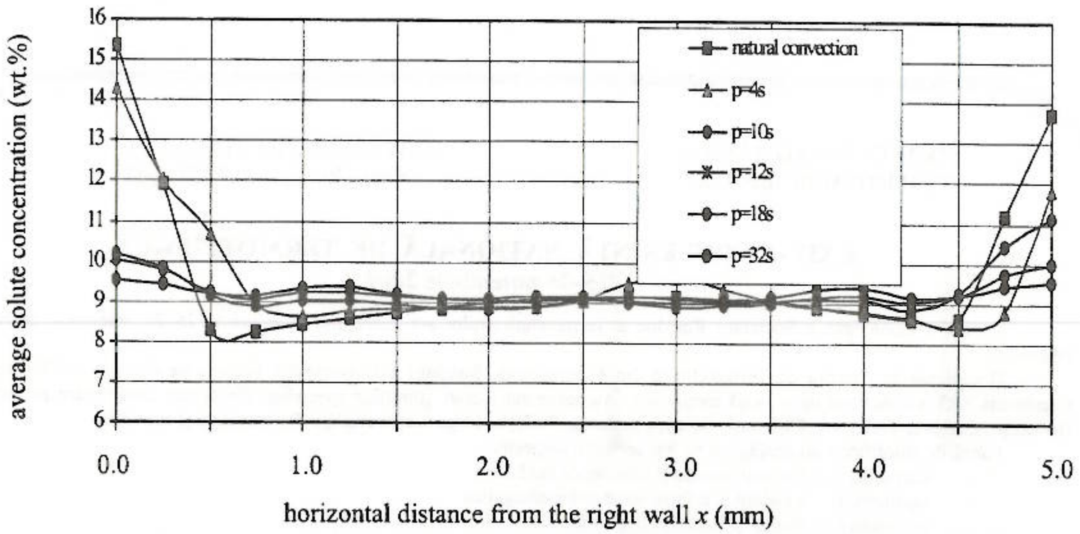


Fig. 5. Horizontal profiles of the mean solute concentration averaged along a vertical line for various modulation periods of the electromagnetic forces. Case of Pb-Sn10%wt. $F_0 = 10^3$ N/m^3.

CONCLUSIONS

From the above computations, we may draw various general conclusions regarding the effect of the electromagnetic stirring of moderate intensity. A steady electromagnetic stirring does not suppress the macrosegregations and it only modifies them. Such a stirring may even create and promote the segregations. However, the locations of the segregated channels are directly linked to the electromagnetic flow pattern and hence their location is predictable. For example, in the case of a rotary stirring, the random freckle pattern is replaced by a central channel [19].

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 act 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 a usual porous medium. We have shown in the present paper that any slow modulation of the electromagnetic forces may prevent partly or totally the formation of segregated channels. This is caused by the fact that the electromagnetic forces affect the flow in the mushy zone. The pressure gradient along the solidification front is almost zero in the average (with time), the draining effect is less pronounced, and the channel formation is prevented. A secondary consequence is the decrease of the normal macrosegregation in the liquid region. Note that such phenomena cannot occur in case of modulated rotating magnetic field. Validation experiments are under achievement in order to assess the present predictions.

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- secţiunea A - 88 de autori cu 104 lucrări;
- secţiunea B - 75 de autori cu 110 lucrări;
- secţiunea C - 53 de autori cu 72 lucrări.

Discuţiile ştiinţifice purtate în plen sau pe secţiuni au pus în evidenţă larga paletă de probleme termice aflată în atenţia specialiştilor din învăţământ, cercetare şi execuţie.

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