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Experimental investigation of the effect of travelling magnetic field on the CET in Sn-10*wt.*%Pb alloy

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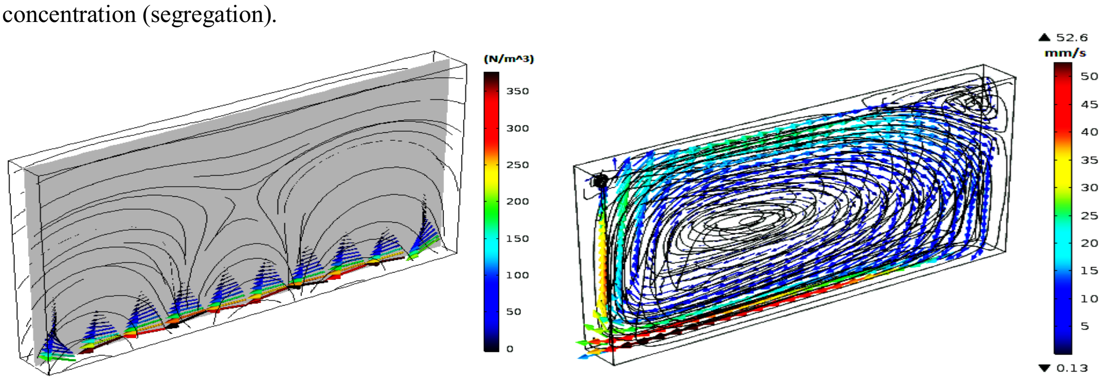
Abstract
In order to eliminate internal and surface defects, which appear in the ingots during solidification process of metallic alloys, homogeneous and fine structures are often required. Therefore, when the adjunction of inoculant substances is not possible, the electromagnetic stirring (EMS) process thanks to the use of travelling magnetic fields has technically shown its effectiveness. The present experiments consist to create convective movements in a Sn-10wt.%Pb liquid metal, by the action of an electromagnetic field during its solidification. A significant improvement in the columnar-equiaxed transition (CET) mechanism has been observed and consequently a fine equiaxed grain structure can then be detected. The main goal of this experimental study is to examine the effect of the EMS process on grain structures for that alloy as well as the corresponding segregations. In particular, it included the determination of the optimal experimental parameters to obtain a grain refinement, the characterization of their effect on the solidification and the understanding of the physical mechanisms driving grain refinement.

1. Introduction

The phase transition study related to the melting and solidification processes is the basis of many numerical and experimental researches, as well as of various engineering applications. In particular, the use of traveling magnetic fields (TMF) makes possible to stir liquid metal and control characteristics of its flow [1-3] and, hence, to affect heat and mass transfer in the melt (including the phase transition boundary) in the process of solidification [4-5]. The study of interaction between the parameters of electromagnetic effect and the structure of metal, its homogenization level, mechanical properties etc., as well as the study of the influence of these parameters on the metal melting rate at high frequency heating and solidification, remain extremely relevant until today. Solidification and melting, like many other thermal processes in industry, require strict thermal conditions during the process. For example, homogeneous temperature, solidification rate and temperature gradients during directional solidification exert a significant influence on a convective flow of liquid during solidification, and therefore have a great effect on the final product. For that purpose, a solidification benchmark experiment was designed and developed at SIMAP Laboratory in Grenoble in order to investigate the structure formation as well as solute macro-mesosegregation by means of a well-controlled meso-scale solidification experiment. Indeed, as the industrial continuous casting process is rigid and complex, the investigations were easier to carry out on the Benchmark installation at laboratory scale, enabling us to define the influence of each experimental parameter: thermal gradient, cooling rate, stirring direction, temperature of the liquid and composition of the alloy.

2. Experimental process

The benchmark experiment developed in the SIMAP/EPM laboratory is a key tool for the validation of the numerical models by comparison with detailed measurements obtained with thoroughly controlled initial and thermal boundary conditions. In its principle, the experiment is similar to the well-known Hebditch and Hunt experiment [7], with a special emphasis on obtaining reproducible quantitative measurements. The Sn-Pb binary alloy pre-sample is enclosed in a rectangular cavity of 100 mm in length, 60 mm in height and 10 mm in width. All walls except for two narrow vertical ones are held at approximately insulating conditions during the whole process via a Kirchhoff box in vacuum conditions. The alloy is solidified by two temperature controllable heat exchangers. An array of fifty K-type thermocouples, is used to record the temperature field, and therefore the evolution of solidification. A linear stirrer is placed beneath the sample able to generate a TFM in order to homogenize the sample after the melting process until the end of the solidification stage. The reader is referred to the previous works [8-9] for further details concerning the description of the experimental setup. The experimentis equipped with a three-phase coil, which produces a pulsating electromagnetic force. Its amplitude and direction depend on the instantaneous value of the current flowing through the coil. Figure (1-a) illustrates the configuration of the resulting Lorentz forces distribution in space at chosen moment as well as the corresponding mean fluid flow. The behaviour of the stirred metal in the cavity can be described as follows. At the beginning the melt is under the effect of natural convection only. When the inductor is switched on, the resulting electromagnetic body force accelerates the fluid (see Fig.1-b). Analysis of velocity profiles seems to indicate that the flow configuration consists of a main vortex located in the central part with two small vortices at each upper corner. The present work is focused on the experimental investigation of the effect of the TMF, in particularly the stirring direction on the solidification process in terms of thermal behavior of the melt, grain structure and finally inhomogeneity of concentration (segregation).



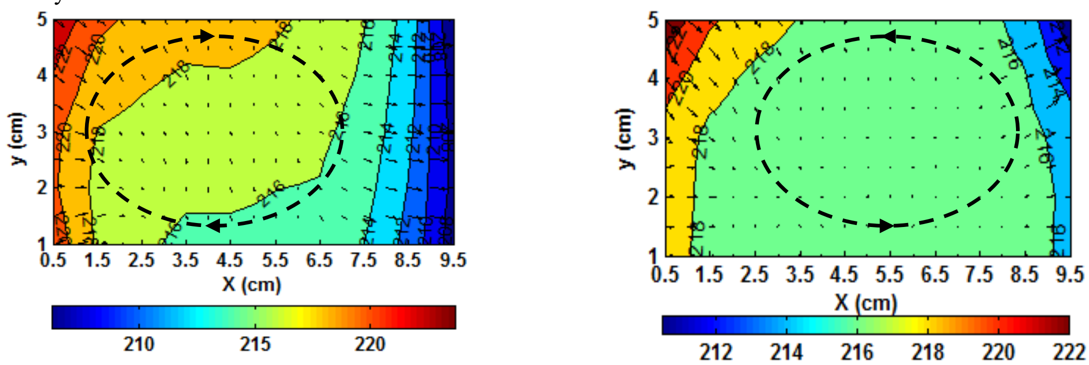
(a) **(b)**

Fig.1. 3D spatial evolution obtained from numerical simulation of: (a) electromagnetic forces witch the black lines correspond to the magnetic field streamlines and volume vectors are the Lorentz forces, (b) the flow configuration in the melt. The black lines correspond to the streamlines and volume vectors are the velocity field. Results obtained for *I = 8 A*, and *f = 50Hz*.

3. Results and discussions

3.1. Effect on the temperature field evolution

The experimental temperature maps provided in Fig. 2, are coupled with vectors indicating the local thermal gradients for two solidification cases (Case I: without any electromagnetic stirring and Case II: under EM stirring in the opposite direction of natural convection) at selected instant (t = 9 mn after the beginning of the solidification phase). In the stirred case, coil intensity is set to I = 8 A. The temperature gradients were calculated at each thermocouple location from the temperature difference between two adjacent points by means of a centred difference numerical scheme. The arrows correspond to the $-\vec{\nabla}T$ vector, which is proportional to local heat flux density.



(a) Case I : non-stirred
T_{max} = 221.42°C; T_{min} = 202.72°C

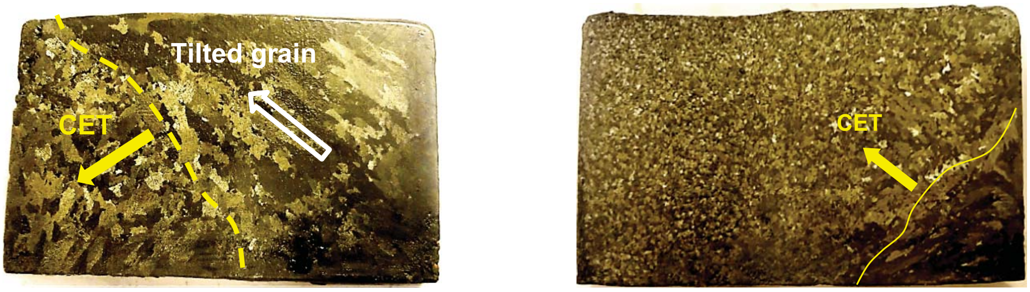
(b) Case II : e.m. stirred
T_{max} = 222.43 °C; T_{min} = 208.73 °C

Fig. 2. Instantaneous temperature maps with superimposed local temperature gradient vectors ($-\vec{\nabla}T$) for the four solidification experiments at t = 9 min. The experimental conditions are: Sn-10wt.%Pb alloy, ΔT = 40 K, CR = 0.03 K/s, inductor current I = 8 A.

Indeed the figure (2-b) show clearly the effect of electromagnetic stirring on temperature distribution, namely homogenization of temperature in the melt as well as modification of flow configuration. A comparative study shows that stirring in the opposite direction to convection modifies flow configuration significantly. This is shown by deformation of the isotherms, meaning that a vortex appears in the opposite direction with respect thermosolutal convection.

3.2. Effect on the grain structure

To evaluate the effect of the electromagnetic stirring in the opposite direction of natural convection on the final metallographic structure and grain size, macrostructures of ingots obtained from two solidification experiments were revealed by the procedure detailed in the works of Hachani et al. [6-8]. Fig. 3(a) shows the macrostructure of solidification of the Sn-10wt.%Pb under the effect of thermosolutal convection only. We observe that the dominant morphology of the macrostructure in this case is columnar with an equiaxed zone corresponding to the last liquid at the end of solidification. The process of columnar-to-equiaxed transition can be accounted for by the drop in temperature gradient in the liquid bath as shown by temperature maps illustrated in Fig. 2(a) (Case I). The upwind tilting of the columnar grains is consistent with the direction of natural convection. At the base of the ingot, we notice a growth of a second columnar structure of different orientation. A possible explanation is the effect of convection, which supplies ''cold'' liquid to the bottom part of the ingot, as indicated by Fig. 2(a). Note that the orientation of the columns in that region supports the aforementioned statement.



(a) Case I: without electromagnetic stirring **(b) Case II: stirring in the opposite direction to natural convection**

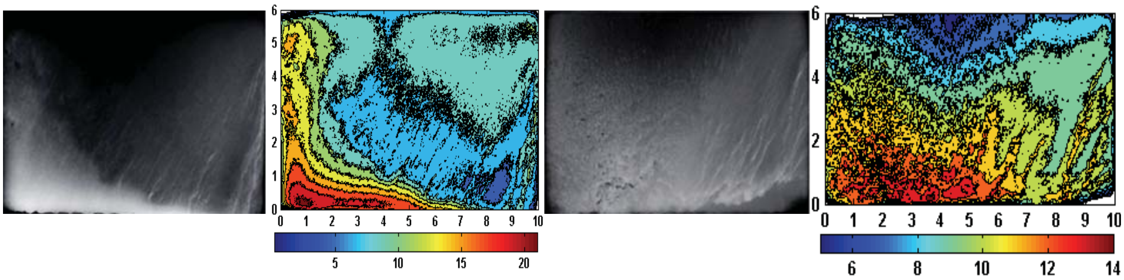
Fig. 3. Macrostructure on the lateral plane of different ingots of Sn-10.*wt*.%Pb. The experimental conditions are: temperature difference ΔT = 40 K, cooling rate CR = 0.03 K/s and the applied current intensity I = 8.2 A. Two cases are presented: (a) Case I solidification under the effect of natural convection only. (b) Case II solidification under the effect of electromagnetic stirring in the opposite direction to natural convection.

The case of stirring in the opposite direction to thermosolutal convection is shown in Fig. 3(b). We notice that the area of the columnar region has regressed. Moreover, the columnar zone of the lower part has almost disappeared, while the equiaxed area has increased significantly. Indeed, the structure mainly consists of fine size equiaxed grains. A small columnar region is located in the bottom right angle of the ingot. It is important to note that the efficiency of electromagnetic stirring in refining the structure is improved significantly when we reversed the direction of stirring against natural convection. Details of the various cases are provided in [6]. This result can be attributed to electromagnetic stirring that exerts two main effects. First, the Lorentz force generates liquid metal convection that homogenizes the pool and lowers the temperature gradients, thereby creating favourable conditions for appearance of a CET. Second, a hot liquid impinging the solid-liquid interface can enhance fragmentation/remelting of the secondary arms. Transported by convection, under certain conditions these fragments can give birth to equiaxed grains. In parallel with the mechanical fragmentation effect, this stirring mode seems to have a significant consequence on the dendrite remelting process. Indeed, EM stirring generates an upward motion of lead-enriched liquid along the columnar front.

3.3. Effect on solute distribution

A post-mortem analysis of solute distribution in the sample was performed. A chemical method coupled with the ICP (Inductive Coupled Plasma) technique was used to determine quantitative analysis of solute distribution. X-ray analysis of the local lead composition (averaged in the sample thickness) were also performed. The results illustrated in Fig. 4-a shows the segregation distribution for the case of solidification under the effect of thermosolutal convection (Case I). Solute rejection starts from the right side of the sample (along with channeling

effects) so that, at the end of solidification, a lead-enriched area appears on the bottom left. This zone which corresponds
to the last solidified liquid has a concentration level exceeding 17%. However, a macrosegregation zone marked by the highest concentration (>18%) was observed in the bottom-right corner of the sample. This concentration peak corresponds to the formation of segregated channels at this location. We checked that the measured average concentration over the whole ingot was close to nominal concentration (10%).



(a) Case I :non-stirred ingot **(b) case II : e.m. stirred ingot**

Fig. 4. X-ray photos (left) and digital processing (right) of two solidified ingots showing the different types of meso and macrosegregation. The alloy is Sn-10 wt.%Pb. The light grey color corresponds to the lead-rich zones. The experimental conditions are: temperature difference DT = 40 K, cooling rate CR = 0.03 K/s, and intensity of the applied current I = 8 A. The composition scales in wt.% are indicated in the scale of the left-hand figures.

Fig. 4-b shows the case of solidification under the effect of electromagnetic stirring in the opposite direction to natural convection (Case II). We noticed a significant displacement of the macrosegregation area with a level of concentration ranging between 11% and 15%, which corresponds to the last liquid solidified. These results can be accounted for by development of the second solidification front (hot side), which distinguishes this case (see temperature maps shown in Fig. 2. The segregation pattern still consists of an upward plume resulting from the effect of two active contra-rotating vortices at the end of solidification. However, this case remains inactive on the elimination of the segregated channels in the right of the ingot for the same reasons cited in the previous case. Note that stirring slightly lowers the segregation level but does not suppress them.

4. Conclusion

In the light of the experimental comparative study presented in this work, we can deduce some findings and general conclusions about the effect of the electromagnetic stirring in the opposite direction to natural convection modes applied to the solidification process, particularly concerning the CET process. Indeed, this mode of stirring has shown its effectiveness in achieving the finest equiaxed structures. Also this stirring mode combines both the remelting and the mechanical fragmentation mechanisms. However, Electromagnetic stirring does not remove the segregated channels. Stirring can even create and promote segregation.

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