DIRECTIONAL SOLIDIFICATION OF PB-SN ALLOYS AFFECTED BY A ROTATING MAGNETIC FIELD

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<u>_Summary_</u> An experimental and numerical study with respect to the influence of a rotating magnetic field (RMF) on the directional solidification of Pb85wt%Sn and Pb25wt%Sn alloys will be presented. The effect of the electromagnetically driven convection on solidification parameters such as the cooling rate, the temperature gradient G_L or the growth velocity of the liquidus isotherm V_T was investigated. Significant effects of the flow on the macro- and microstructure of the solidified ingots are evident.

Introduction

Many references from the cast metal literature are known discussing the effect of melt convection during the early stages of solidification on the grain structure. The application of mechanical or electromagnetic stirring, ultrasonic or sonic vibrations promotes the formation of fine, equiaxed grains [1,2]. However, there has been much speculation about the mechanism of this process. The prevalent interpretation favoured during the last decades is that the grain refinement results from a fragmentation of primary dendrites. The macrostructure of chill cast ingots generally consists of a columnar and an equiaxed zone. The occurrence and position of the transition between both zones was found to be influenced by casting parameters, including the temperature gradient, the cooling rate or the probe composition, respectively [3, 4]. Fluid flow occurring in the liquid phase was also found to affect the structure and position of CET [5]. Therefore, we studied the dependence of the CET on the Taylor number

$$Ta = \frac{\sigma \omega B^2 R^4}{2 \rho \nu^2} \qquad (1)$$

of the applied RMF with the field intensity B and the frequency $f = \omega/2\pi$ for a fluid container with radius R where σ, ρ and ν denote the electrical conductivity, the density and the kinematic viscosity of the fluid. The application of time varying magnetic fields can be considered as an effective tool to organize a well-defined flow structure in the liquid phase affecting the nucleation and solidification parameters. Main goal of our activities is to find a strategy for refining the microstructure of castings by an optimal combination of magnetic field intensity, field frequency and cooling rate.

Numerical calculations

| (a) | (b) | (c) | (d) |
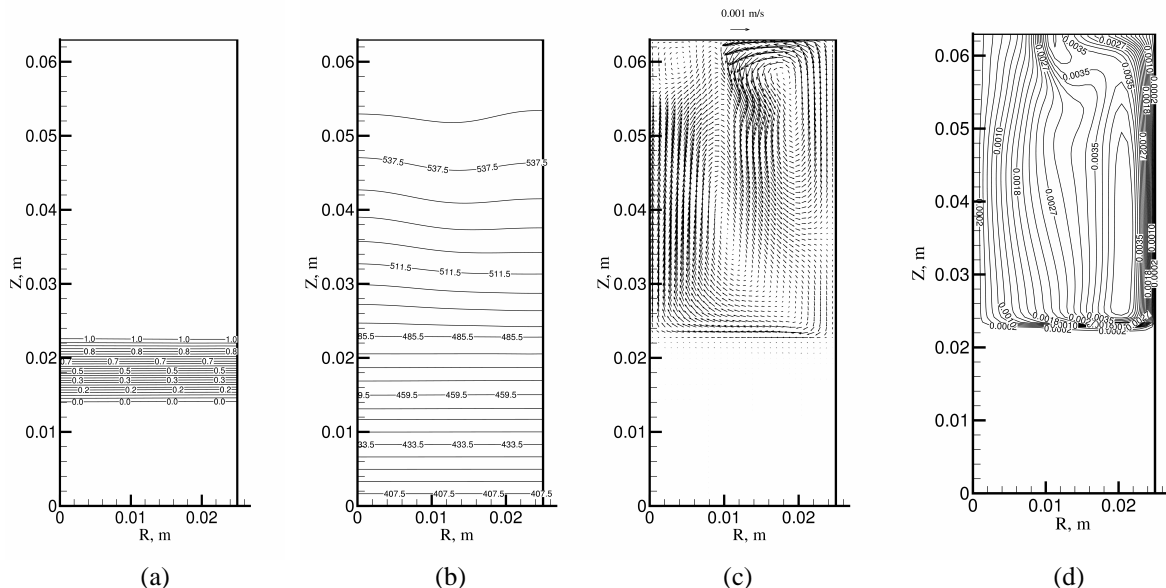
Figure 1. Predicted solidification behavior at t=60 sec for Taylor number $5.8 \cdot 10^4$. (a) volume fraction of liquid, (b) temperature field, (c) the meridional velocity field and (d) contour plot of the azimuthal velocity

A continuum formulation based model [6] has been adopted to study the solidification of binary alloys using the following assumptions: all transport properties of each phase, such as thermal and electrical conductivity or viscosity, are constant; the density of the solid phase equals the density of the liquid phase; the phases are in local thermodynamic equilibrium; buoyancy effects are negligible; the velocity of solid phase is zero. The Lorentz force term F_L has been included into the momentum conservation equation in order to take into account the effect of the applied magnetic field.

The predicted and measured temperature curves are in good agreement. *Figure 1* presents the spatial distributions of the volume fraction of liquid, the temperature and the velocity field 60 sec after the start of the solidification at the bottom of the container. It can be seen that fluid motion caused by the RMF at such small Taylor number has no influence on the shape of the mushy zone front due to the high cooling rate. The arising secondary flow in the radial-meridional plane was found to have a significant influence on the mass and heat transfer at the solidification front. Time-dependent calculations revealed that this secondary flow structure is strongly influenced by the advancement of the solidification front. The resulting permanent change of the aspect ratio of the fluid volume prevents the development of the double-vortex structure being well known for the isothermal case. These findings were confirmed by fluid velocity measurements during solidification.

Experimental results

The Pb-Sn alloys were solidified directionally from the bottom in a cylindrical stainless steel mold having an internal diameter of 50 mm, a height of 100 mm and a wall thickness of 3 mm. The side walls were covered by a 5 mm heat insulation to prevent a radial heat transfer from the mold. The filling height for each charge was 60 mm. During solidification continuous temperature measurements were performed by means of a set of six thermocouples installed in the center of the mold at vertical positions of 1.5, 11.5, 22, 32, 41.5 and 51.5 mm measured from the base of the ingot. The ultrasound Doppler velocimetry (UDV) was used to measure the velocity inside the liquid phase as well as the position of the solidification front. Selected transverse and longitudinal sections of the solidified specimens were polished and etched for microscopic examination.

The RMF drives a convection in the bulk liquid showing a distinct influence on the solidification parameters and the properties of the microstructure of the ingots. The fluid flow increases the heat transfer rate and decreases the temperature gradients in the melt. Such small temperature gradients reduce the probability of remelting of solid fragments ahead of the solidification front required for the promotion of the CET. Moreover, the temperature measurements also revealed the occurrence of strong temperature fluctuations arising from the turbulent flow in the vicinity of the solidification front. These fluctuations may promote a localized remelting of dendrites and thus the creation of solid fragments. Velocity measurements have been obtained in the melt during solidification with applied RMF by means of UDV. If the temperature falls below the liquidus isotherm, a strong decrease of the velocity amplitude was observed indicating a rapid increase of the fluid viscosity due to an increase of the solid fraction. The position where the velocity becomes zero can be approximately identified with the position of the solidification front as long as a columnar front grows.

If the ingot is solidified under the influence of forced bulk flow induced by RMF a CET can be observed. As shown in *Figure 2* the CET position is affected by the convection. An enhancement of the magnetic Taylor number *Ta* results in a reduction of the length of the columnar region. The distribution of the eutectic in the microstructure is not homogeneous. In the equiaxed domain an up to 10% higher eutectic content is observed as compared to the columnar region. The highest concentration of eutectic is found directly at the CET position (*Figure 3*).
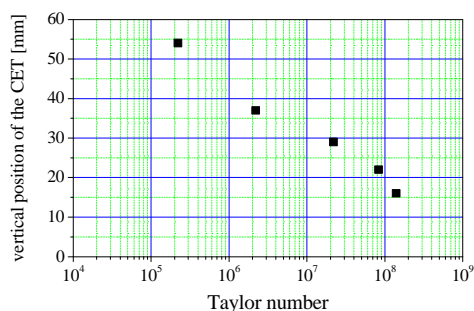
Figure 2. Position of the CET as function of the magnetic Taylor number *Ta*
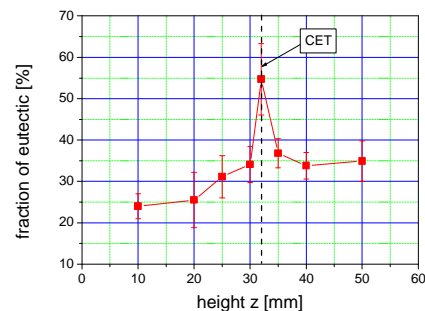
Figure 3. Volume fraction of the eutectic along the axis of the ingot for $Ta = 8 \cdot 10^6$

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