FLOW STRUCTURES DURING SOLIDIFICATION OF METALLIC ALLOYS AFFECTED BY A ROTATING MAGNETIC FIELD

B. Willers[1], *P.A. Nikritjuk*[2], *K. Eckert*[2], *S. Eckert*[1]

[1] *Forschungszentrum Rossendorf, P.O.Box 510119, 01314 Dresden, Germany (b.willers@fz-rossendorf.de)*
[2] *Institute of Aerospace Engineering, Technische Universität Dresden, 01062Dresden, Germany*

Introduction. The application of electromagnetically driven flows during solidification improves the quality of casting ingots by promoting the formation of fine, equiaxed grains [1, 2, 3]. However, the understanding of the complex interaction between the flow and the solidification process has to be considered as incomplete. The lack of detailed knowledge on the transient flow dynamics obstructs the optimization of solidification processes by electromagnetic flow control and is consequently one of the reasons for the rather empirical application of melt agitation until now. The flow field resulting from a rotating magnetic field (RMF) for the isothermal case has already been investigated by numerous theoretical and experimental examinations. Usually, the role of the RMF driven convection during solidification has only been discussed in terms of the flow pattern well-known from the laminar, isothermal case being a superposition of a primary swirling flow in azimuthal direction and a secondary flow occurring as a double vortex in the r-z plane. Effects arising from the propagation of the solidification front, the extension of the mushy zone or the spin-up of the flow at higher cooling rates are almost not taken into account. The spin-up from rest of an isothermal liquid metal column driven by a rotating magnetic field ($10^3 < \mathrm{Ta} < 2{\cdot}10^6$) was examined by numerical simulations [4]. Three different flow regimes were identified, namely an initial adjustment phase, an inertial and an oscillatory phase. The latter is characterized by oscillations of toroidal vortices of the secondary flow and the appearance of Taylor-Görtler vortices along the lateral walls. This paper presents an experimental and numerical study regarding the influence of a bulk flow driven by a RMF on the solidification of Pb-Sn alloys in cylindrical molds.

1. Experimental set-up. The Pb-Sn alloys were solidified directionally using the experimental set-up shown in Fig. 1. The alloy resides in a cylindrical stainless steel mold having an internal diameter of $D_0 = 50\,\mathrm{mm}$ and a height of 100 mm. The side walls were covered by thermal insulation to prevent a radial heat transfer from the mold. The filling height for each charge was $H_0 = 60\,\mathrm{mm}$ leading to an aspect ratio $A = D_0/H_0$ of about 0.83. Experiments were performed with Sn-15wt%Pb prepared from 99.9% Pb and 99.9% Sn. The alloy was melted and heated until a superheat of 90 K using an electrical furnace. Approaching the superheat temperature, the mold was positioned on a water cooled copper chill. The agitation of the melt by RMF was simultaneously initiated with the cooling of the steel mold. The cooling chill was placed concentrically inside a magnetic inductor.

During solidification continuous temperature measurements were performed by means of a set of six thermocouples installed along the axis of the mold at different vertical positions. The ultrasound Doppler velocimetry (UDV) was used to measure the velocity inside the liquid phase as well as the position of the

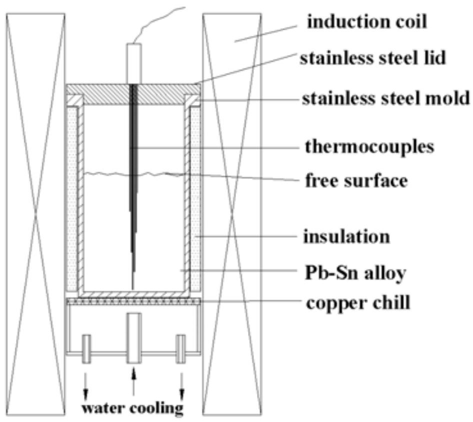


Fig. 1. Schematic view of the experimental set-up.

solidification front. For a more detailed description of the experimental set-up we refer to [3].

2. Numerical calculations. The principles of the classical mixture theory were applied to obtain a set of continuum conservation equations for binary, solidification system [5]. The material properties of the mixture were calculated from the properties of both phases in consideration of the apparent volume fractions. The molecular viscosity was modeled as a function of the solid fraction according to an approach proposed by Roplekar and Dantzig [6]. Assuming that both the low-frequency and low-induction conditions are fulfilled, the time-averaged, azimuthal Lorentz force in a finite cylinder was included in form of an analytical solution [7]. The model is based further on the following assumptions:

1. The Boussinesq approximation is used to take into account the variations of the density with the temperature. The dependency of all other material properties on the temperature is neglected.
2. The phases are in local thermodynamic equilibrium. The phase diagram is applied.
3. The flow of the liquid phase is supposed to be axisymmetric.
4. The solid and liquid phases are assumed to have the same velocity.

To solve the set of governing equations we applied an open source code of a 2D Navier–Stokes solver [8] with implemented SIMPLE algorithm. Convergence tests were performed to define proper grids and time steps leading to grid- and time-step independent solutions. In particular for $B = 3\,\mathrm{mT}$ we used a 100×260 $(CV_r \times CV_z)$ grid and a fixed time step 0.02 s. Several verification test were performed to validate the code. The comparison between numerical and experimental results with respect to the azimuthal velocity ath the surface of gallium column [9] and cooling curves measured during solidification experiments [3] showed a reasonable agreement [4, 10].

3. Results. Fig. 2 shows cooling curves obtained at the thermocouple position $z = 24\,\mathrm{mm}$ for different Taylor numbers. This comparison reveals the acceleration of the cooling process in the liquid phase. In this context we observe the development of a temperature plateau around the Liquidus temperature. The cooling curves also show distinct fluctuations of the temperature signals arising from the turbulent melt flow. UDV measurements of the vertical velocity component are displayed in Fig. 3. The double vortex structure can be observed during the initial phase of solidification. In the course of the process, the length of the measured profiles becomes shorter indicating the progress of the solidification front. The flow pattern undergoes permanent changes. Numerical results showing different stages

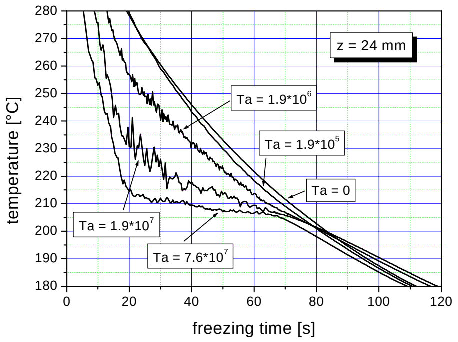


Fig. 2. Cooling curves measured at a thermocouple position $z = 24\,\mathrm{mm}$.

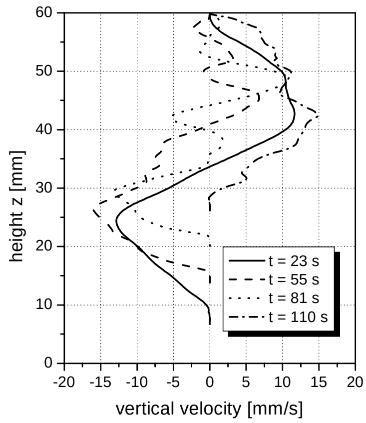


Fig. 3. UDV measurements of the vertical velocity profiles ($B = 5\,\mathrm{mT}$, $f = 50\,\mathrm{Hz}$, $r = 22\,\mathrm{mm}$).

of the secondary flow in the r-z-plane for a field strength of $3\,\mathrm{mT}$ are displayed in Fig. 4. Just after start-up the system undergoes a short, so-called initial adjustment phase. In this stage the pressure field is built up resulting in the well-known pattern of the primary, swirling and the secondary flow (see Fig. 4(left)). The subsequent inertial phase is characterized by an acceleration of the angular, primary flow until the forcing is balanced by the viscous dissipation in the Bödewadt layers developing on the horizontal boundaries (Fig. 4(middle)). During the braking phase (Figure 4(right)) the flow becomes more and more retarded due to the permanent increase of the aspect ratio A with advancing solidification strengthening the viscous friction excerted by the boundaries. Taylor–Görtler vortices appear

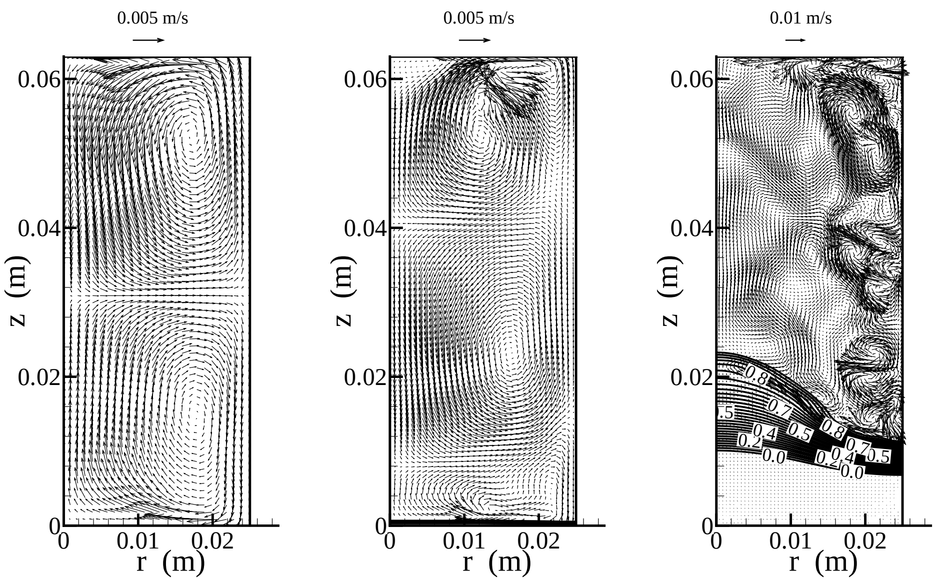
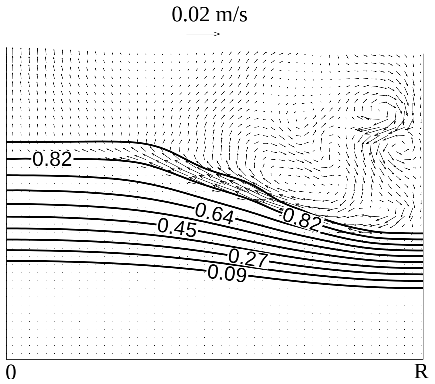


Fig. 4. Meridional velocity vectors and liquid isolines during solidification after 3 s (left), 5 s (middle) and 35 s (right) at $B = 3\,\mathrm{mT}$, $f = 50\,\mathrm{Hz}$.



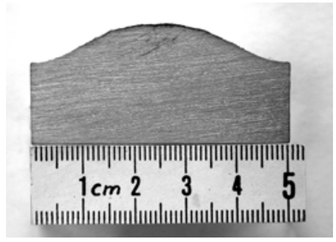


Fig. 5. Modification of the shape of the solidification front due to the heat transport by the T–G vortices: numerical prediction (left) and experimental result (right).

near the cylinder wall at the boundary, move towards the top and the bottom of the container and dissipate there.

One example for the direct influence of the forced convection on the solidification process becomes obvious in Fig. 5. The left picture shows the dissipation of the Taylor–Görtler vortices in the mushy zone as predicted by the numerical calculations. In the vicinity of the lateral walls these vortices transport hot liquid towards the solidification front. This results in a partial remelting of the front leading to a modification from a planar towards a curved shape as shown in Fig. 5. This phenomenon was also found in the experiments as it can be seen in the right picture of Fig. 5.

Acknowledgement. The research is supported by the Deutsche Forschungsgemeinschaft (DFG) in form of the SFB 609 Electromagnetic Flow Control in Metallurgy, Crystal Growth and Electrochemistry.

REFERENCES

1. C. Vives Hydrodynamic, thermal and crystallographical effects of an electromagnetically driven rotating flow in solidifying aluminium alloy melts. *Int. J. Heat Mass Transfer*, vol. 33 (1990), no. 12, pp. 2585–2598.
2. W.D. Griffiths, D.G. McCartney. The effect of electromagnetic stirring during solidification on the structure of Al-Si alloys. *Material Science and Engineering A*, vol. 216 (1996), pp. 47–60.
3. B. Willers, S. Eckert, U. Michel, I. Haase, G. Zouhar The columnar-to-equiaxed transition in Pb-Sn alloys affected by electromagnetically driven convection. *Material Science and Engineering A*, in press (2005)
4. P.A. Nikrityuk, K. Eckert, R. Grundmann. Numerical study of spin-up dynamics of a liquid metal stirred by rotating magnetic fields in a cylinder with the upper free surface. *Magnetohydrodynamics*, vol. 40 (2004), pp. 127–146.
5. W.D. Bennon, F.P. Incropera. A continuum model for momentum, heat and species transport in binary solid-liquid phase change systems: I. Model formulation. *Int. J. Heat Mass Transfer*, vol.30 (1987), no. 10, pp. 2161–2170.
6. J.K. Roplekar, J.A. Dantzig. A study of solidification with a rotating magnetic field. *Int. J. Cast Metals Research*, vol. 14 (2001), pp. 79–98.
7. Th. Kaiser, K.W. Benz. Taylor vortex instabilities induced by a rotating magnetic field: A numerical approach. *Phys. Fluids*, vol. 10 (1998), pp. 1104–1110.
8. J.H. Ferziger, M. Peric. *Computational methods for fluid dynamics* (Springer-Verlag. 3rd Edition, Berlin, Heidelberg, 2002, 423 p.)
9. P. Dold, K.W. Benz. Rotating magnetic fields: Fluid flow and crystal growth applications. *Progress in Crystal Growth and Characterization of Materials*, vol. 38 (1999), pp. 7-38.
10. P.A. Nikrityuk, K. Eckert, R. Grundmann. A numerical study of unidirectional solidification of a binary metal alloy influenced by a rotating magnetic field. *Int. J. Heat Mass Transfer*, submitted (2005).