THE FLOW AND CRYSTALLIZATION OF LIQUID METAL IN THE PROCESS OF MHD-STIRRING

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Abstract : The process of crystallization of gallium alloy under stirring conditions is studied. A stirring flow is induced by the external rotating magnetic field generated by the MHD-stirrer containing a cylindrical vessel with gallium alloy. The evolution of the liquid-solid interface is studied by the UDV technique. The position of the interface on the echo profile is found by the wavelet analysis using the real-valued Gauss wavelet. The evolution of the interface during crystallization has been investigated for stirring flows of various intensity.

1. Introduction

Many technological processes (continuous ingot casting, preparation of special alloys) are accompanied by crystallization of metal in a liquid phase. The efficiency of these processes can be essentially improved by stirring molten metals. The paper describes a method of studying the process of crystallization in a gallium alloy. The volume of liquid metal is under the action of the alternating magnetic filed which induces a vortex electric current. The interaction of the electric current with the magnetic field generates an electromagnetic force, which initiates a vortex stirring flow. The stirrer consists of a ferromagnetic core and a set of copper coils, which generate an alternating magnetic field inside a cylindrical volume of liquid metal. The coils generate the rotating magnetic field (RMF) and travelling magnetic field (TMF). A cylindrical vessel filled with gallium eutectic is placed inside the stirrer. The described experimental and numerical investigation has focussed on the process of crystallization in a gallium alloy filling a cylindrical vessel with rigid boundaries. The end faces of the cylinder have different temperatures. The evolution of the interphase boundary was investigated using the Ultrasonic Doppler Velocimeter (UDV) [1, 2].

2. Experimental study

The main unit of the experimental setup is MHD-stirrer 1 (fig. 1), connected to power supply source 2. In our experiment, we used a three-phase transformer for this purpose. A cylindrical cavity of diameter 0.197m and length 0.320m inside the stirrer is designed to place a vessel with liquid metal. The stirrer generates either a travelling or a rotating magnetic field in the liquid metal. The investigation of the crystallization process was carried out for a gallium alloy Ga-Zn-Sn (87.5%Ga; 10.5%Zn; 2%Sn). This eutectic alloy crystallizes at $T_c=17^oC$. The length of the transition zone from a solid to liquid state is rather small for this alloy, which makes it possible to determine the position of the solid-liquid (S/L) interface with sufficient accuracy. Liquid metal is poured in a vertical cylindrical vessel 3 (fig. 1). The walls of the vessel are made of stainless steel 0.006m thick. The bottom of the vessel is made of copper and serves as heat exchanger 4. The exchanger is connected with thermostat 5, which uses alcohol-containing fluid. In our experiment the bottom heat exchanger was cooled to a preset temperature T_1, which was lower than the temperature of alloy crystallization ($T_1<T_c$). The second cylindrical heat exchanger 6 is located above the vessel. It is connected to thermostat 7, which operates on water. During the experiment the upper heat exchanger was heated to a preset temperature T_2, which was higher than the temperature of alloy crystallization ($T_2>T_c$).

The liquids inside the heat exchangers flow through a complex system of channels, which provides a uniform distribution of temperature over the surface. The external surface of the channel is covered by a thermal insulation material. Measurements were made with 9 short-length UDV transducers, which were located in a horizontal plane 8 and connected to UDV 9 in a multiplex mode.

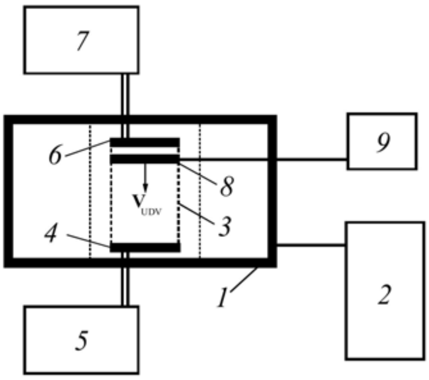

Figure 1: Scheme of experimental setup.

The evolution of the echo profile obtained without application of the wavelet analysis. The application of the wavelet analysis yields the relation for the interface position. It follows then that the wavelet-analysis can be used to define the interface position and to estimate the error of the method based on the wavelet width. The proposed technique was applied to processing of the experimental data obtained at different values of the stirring flow intensity. Note that in all cases the temperature of the lower heat exchanger was T_1=-25^{o}C, and the temperature of the upper exchanger was T_2=21^{o}C. The results of our experiment showed that with increasing intensity of the stirring flow the rate of crystallization decreases (fig. 2,3).

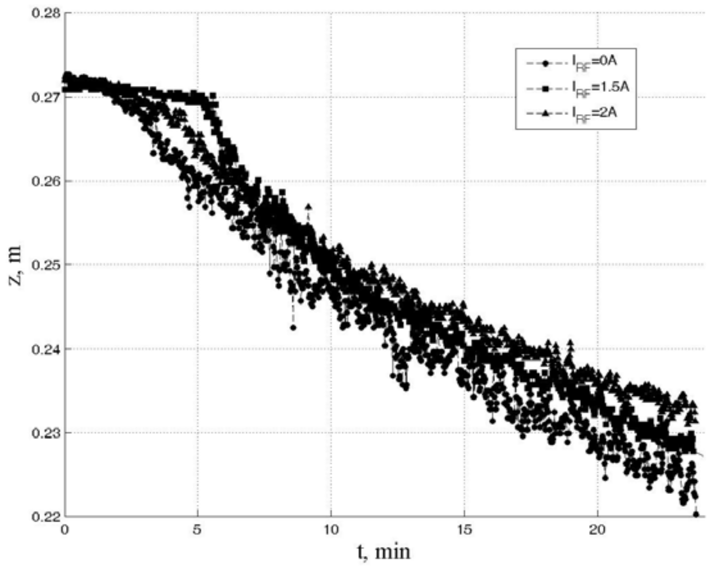

Figure 2: Evolution of the S/L interface in the process
of crystallization at different values of stirring flow intensity (RMF only).

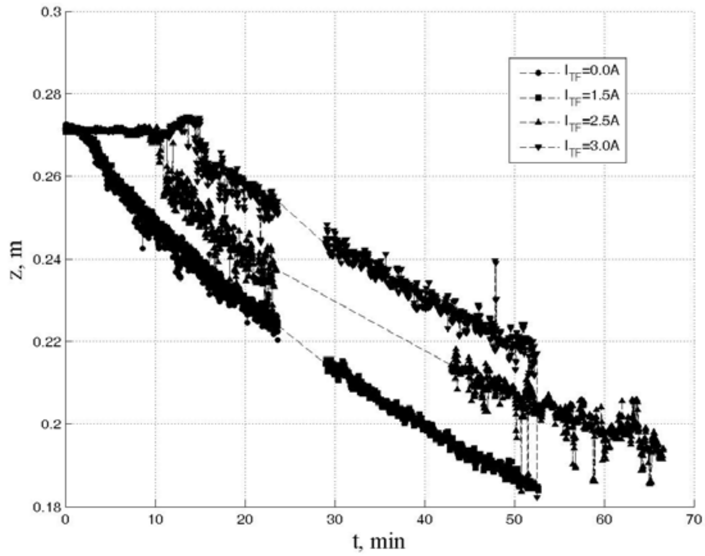

Figure 3: Evolution of the S/L interface in the process
of crystallization at different values of stirring flow intensity (TMF only).

3. Numerical study

In the numerical experiment we have studied the process of crystallization of gallium eutectic in a cylindrical crucible in the presence of MHD-stirring generated by traveling or rotating fields. The wall of the crucible were assumed to be thermally insulated, and the heat was taken away through the crucible lid. The heater is placed in the bottom. Electromagnetic forces in a liquid metal were determined as in [3], and hydrodynamics and the process of crystallization were analyzed in terms of the k-ε model and using the enthalpy - porosity method [4]. Boundary conditions used in the problem were prescribed similar to those of the physical experiment. The velocity component on solid boundaries was taken to be zero. The temperature on the upper and lower boundaries of the region was, respectively, higher and lower than the crystallization temperature of the metal. The heat flow through the side walls was absent. During calculations, the value of porosity varied, which made it possible to describe an increase in the solidified gallium eutectic (fig. 4,5).

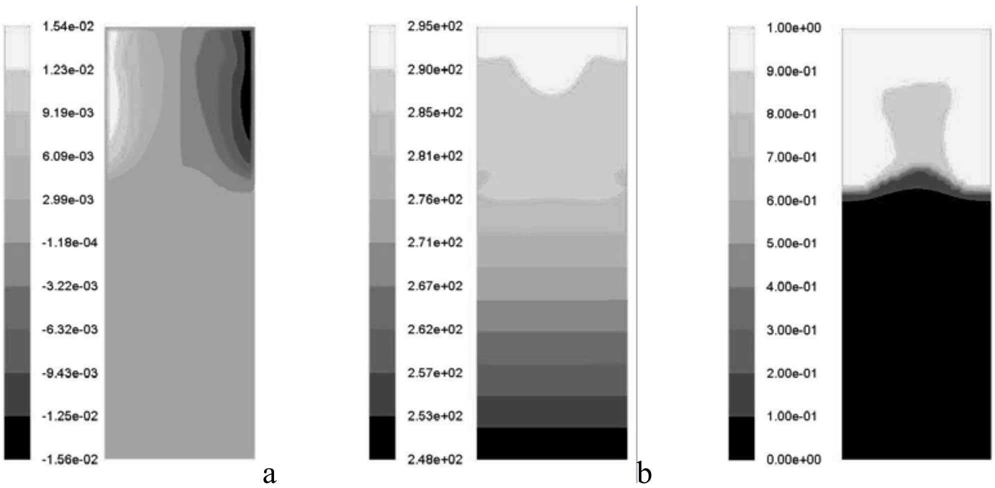

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Figure 4: Example of fields: (a) – azimuthal velocity, (b) – temperature,
(c) – S/L interface (RMF only, I_{RMF} = 0.5 A).

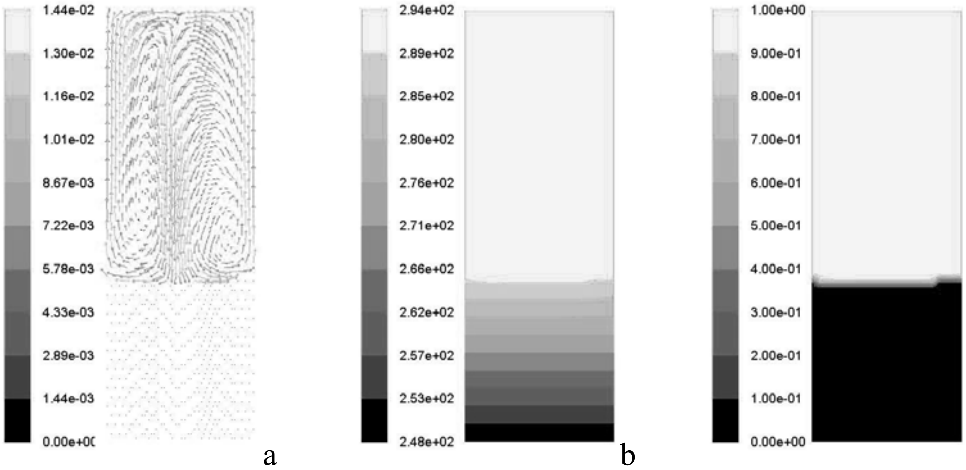

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Figure 5: Example of fields: (a) – poloidal velocity, (b) – temperature, (c) – S/L interface (TMF only, I_{TMF} = 2 A).

3. Conclusion

Measurements taken in the process of crystallization met some difficulties. The S/L interphase becomes non perfect on the echo profile. We determined its position using the wavelet analysis. The PC application has been developed to allow implementation of this analysis in the automatic mode. We analyzed the wavelet-spectrum constructed for each echo profile with the help of the real-valued Gauss wavelet. After finding the maximum on the spectral plane we determined the position of the interface and the width of the diffused zone and thus estimated the accuracy of the proposed technique. We also explored the flows generated by the rotating and travelling magnetic fields. It has been found that the stirring flows affect the process of crystallization, namely, they reduce its rate.

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4. References

[1] Oborin, P.; Kolesnichenko, I.: Application of the ultrasonic doppler velocimeter for study the flow and solidification processes in an electrically conducting fluid. Magnetohydrodynamics, 52 (2013), 231-236.
[2] Kolesnichenko, I.; Pavlinov, A.; Khalilov, R.: Movement of solid-liquid interface in gallium alloy under the action of rotating magnetic field. Magnetohydrodynamics, 49 (2013), 191-197.
[3] Kolesnichenko, I.; Khalilov, R.; Khripchenko, S.; Pavlinov, A.: MHD-stirrer for cylindrical moulds of continuous casting machines fabricated aluminum alloy ingots. Magnetohydrodynamics, 48 (2012), 221-233.
[4] Voller, V.R.; Prakash, C.: A Fixed-Grid Numerical Modeling Methodology for Convection-Diffusion Mushy Region Phase-Change Problems. Int. J. Heat Mass Transfer, 30 (1987), 1709–1720.