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MOVEMENT OF THE SOLID–LIQUID INTERFACE IN GALLIUM ALLOY UNDER THE ACTION OF ROTATING MAGNETIC FIELD

I. Kolesnichenko[1,2], *A. Pavlinov*[1], *R. Khalilov*[1]

[1] *Institute of Continuous Media Mechanics, Perm, Russia*
[2] *Perm National Research Polytechnic University, Perm, Russia*
e-Mail: kiv@icmm.ru

The process of gallium alloy crystallization under stirring conditions is studied experimentally. A stirring flow is induced by an external rotating magnetic field generated by an MHD stirrer containing a cylindrical vessel with a 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 "Mexican hat" wavelet. The evolution of the interface during crystallization has been investigated for stirring flows of various intensity.

Introduction. Many technological processes (continuous ingot casting, preparation of special alloys) are accompanied by crystallization of metal in the liquid phase. The efficiency of these processes can be essentially improved by stirring molten metals. Under real operation conditions, validity test of currently used stirring regimes is a very complicated problem. Experiments with metals in industrial environment require greater efforts and special equipment. Modelling of the metallurgical processes in the laboratory conditions using special metal alloys with the low melting point makes it possible to avoid this restriction [1]-[4]. With the development of modern, high precision devices, the analysis of these processes can be accomplished under the laboratory conditions.

The presented paper describes a method to study the process of crystallization in a gallium alloy. The volume of liquid metal is under the action of an alternating magnetic filed. In the liquid metal, the alternating magnetic field 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 the cylindrical volume of liquid metal [1]–[4]. The coils generate a rotating magnetic field (RMF). A cylindrical vessel filled with liquid metal (magnesium, aluminum, lead, tin, etc.) is placed inside the stirrer.

The described experimental investigation was focused on the process of crystallization in a gallium alloy filling a cylindrical vessel with rigid boundaries. The end faces of the cylinder had different temperatures. The evolution of the interphase boundary was investigated using the Ultrasonic Doppler Velocimeter (UDV). The advantage of this technique is the absence of interference with the melting and stirring processes, because the sensors are located at a considerable distance from the region of the interface displacement. This peculiarity of the experimental scheme sets it apart from the methods, which require deep penetration into liquid metal, for example, the sounding technique. It should be noted that similar investigations have been successfully carried out by other researchers [5]–[8]. However, in each particular situation, every research has its own features determined by the size of the explored region, the type of metal and by the form of MHD effect. Therefore, the obtained results are not general, which makes it necessary to carry out additional investigations. This work continues our previous research [1]–[4] concerned with the process of liquid metal stirring with the aid of an MHD stirrer designed and produced in the Laboratory of Physical Hydrodynamics at the Institute of Continuous Media Mechanics (the Ural Branch of RAS). The physical experiments allowing to estimate the influence of stirring on the structure of continuously cast ingots were carried out along with mathematical modelling and numerical calculations. It is necessary to note that the obtained results are used to check the accuracy of the calculations made basing on the developed mathematical model of the examined process.

1. Experimental setup. The main unit of the experimental setup is the MHD stirrer *1* (Fig. 1) connected to a power supply source *2*. In our experiment, we used a three-phase transformer for this purpose. The parameters of the stirrer are described and investigated in [2, 3]. A cylindrical cavity of 0.197 m in diameter and 0.320 m in length inside the stirrer is designed to place a vessel with a liquid metal. The stirrer generates either a traveling or a rotating magnetic field in the liquid metal.

The crystallization process was studied with a gallium alloy Ga-Zn-Sn (87.5% Ga, 10.5% Zn, 2% Sn). This eutectic alloy crystallizes at $T_\mathrm{C} = 17°\mathrm{C}$. With this alloy, the length of the transition zone from solid to liquid state is rather small, which makes it possible to determine the position of the solid–liquid (S/L) interface with a sufficient accuracy. The liquid metal is poured into a vertical cylindrical vessel *3* (Fig. 1). The walls of the vessel are made of stainless steel 0.006 m thick. The bottom of the vessel is made of copper and serves as a heat exchanger *4*. The heat exchanger is connected to a thermostat *5*, which uses an alcohol-containing fluid. In our experiment, the bottom of the heat exchanger was cooled to a preset temperature T_1, which was lower than the temperature of alloy crystallization ($T_1 < T_\mathrm{C}$). Another cylindrical heat exchanger *6* was located above the vessel. It was connected to a thermostat *7*, which operated with 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 ($T_2 > T_\mathrm{C}$). The liquids inside the heat exchangers flow through a complex system of channels, which provides a uniform temperature distribution over the surface. The external surface of the channel is covered with a thermal insulation material.

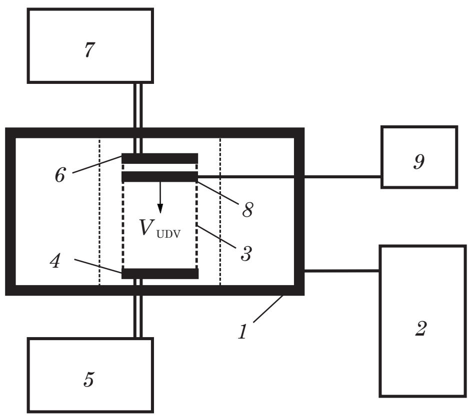

Fig. 1. Scheme of the experimental setup.

To trace the evolution of the S/L interface, we used a UDV 9 (DOP 2000, Model 2125, Signal Processing, Lausanne, Switzerland). The transducer generates a pulsing ultrasound (US) beam and receives the echo reflected from the S/L interface. By making measurements with different transducers, we have come to a conclusion that the 4 MHz transducer of 8 mm in diameter is the best device appropriate for the investigations of this kind. The sound velocity in the gallium alloy was $V_s = 2740$ m/s. Measurements were made with nine short-length UDV transducers, which were located in a horizontal plane *8* (Fig. 1) and connected to the UDV *9* in a multiplex mode. The transducers were located in a holder, which represented a copper plate as thick as 0.002 m. The holder had nine holes for installation of the transducers. The transducers were inserted into the holes, being installed flat about the plate surface. It is important that the upper boundary of the examined volume of liquid metal is flat. The holder with the transducers appeared to be fully immersed into the liquid metal. Thus, in this experiment, the height of the liquid metal in the cylindrical vessel was 0.240 m and its diameter was 0.096 m.

Prior to the experiment described above, we investigated the process of crystallization in a plane layer of liquid metal under the conditions of MHD stirring [9]. This investigation allowed us to observe the top free surface and to control the process using a video camera. Along with video camera observations, UDV measurements were made to detect the displacement of the interface. Based on the obtained results, the features of the method were studied. Therefore, the proposed measurement technique was checked for reliability. This study [9] was helpful because during the measurements in the cylindrical volume no visual control was possible.

During the experiments with the liquid metal in the cylindrical vessel, we determined an optimal regime for measurements. At the beginning of the experiment, the channel was kept at a temperature T_2, the thermostat was disconnected from the lower heat exchanger. The upper thermostat was kept at a constant temperature equaling T_2. The fluid in the cold thermostat was cooled to T_1. Then it was connected to the lower heat exchanger. This initiated the circulation of the cooling fluid through the lower heat exchanger and the sampling of UDV data.

2. Study of the S/L interface movement. During the experiment, the evolution of the velocity profile and echo level profile were recorded by nine UDV transducers. Fig. 2 shows the evolution of the echo profile obtained at crystallization. It should be noted that the sampling rate of the UDV transducers was selected in such a way that the time resolution would be sufficient for tracing a rather slow motion of the S/L interface. At the beginning of the experiment, on the echo profile, all transducers indicated a distinct interface between the liquid metal and the solid surface of the lower heat exchanger. The use of the eutectic alloy in the experiment suggests that the interface should be clearly defined. However, the experiments showed that the boundary was slightly diffused. The reasons to explain this effect are different. Firstly, the alloy might not be chemically pure. Secondly, during crystallization, the S/L interface has to be strictly parallel to the plane of transducer locations, otherwise it leads to diffuse reflection. Thirdly, the smoothness of the interface can be locally disrupted, which also results in the diffuse reflection. In view of these circumstances, we may obtain a profile with oscillations at the interface. Therefore, in this case, a search for a maximum is an inappropriate way to determine the interface position.

The location of the interface is determined by making use of wavelet analysis. This kind of analysis is well suited to study the irregular functions localized in

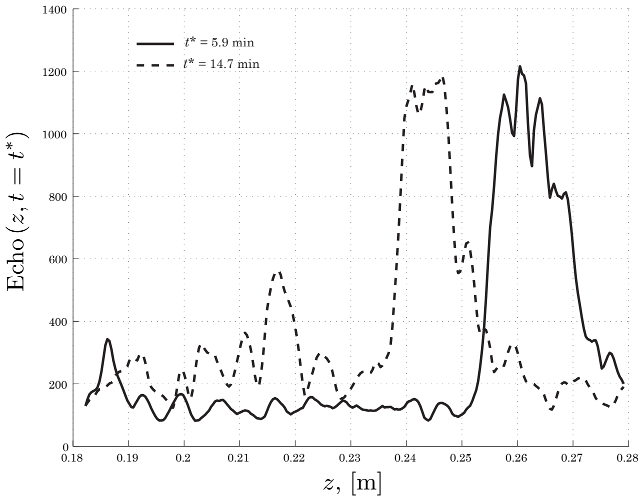

Fig. 2. Echo profile obtained basing of indications of one UDV transducer at different moments of the crystallization process.

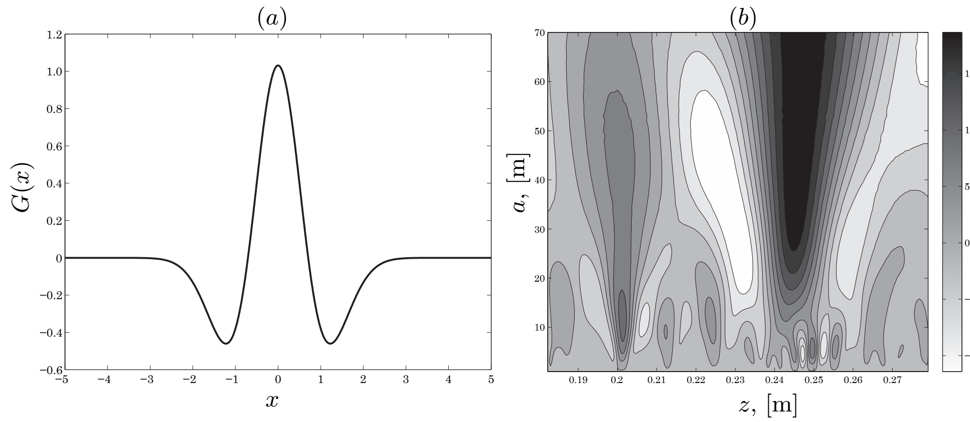

Fig. 3. (*a*) Wavelet "Mexican hat" applied for localization of the S/L interface; (*b*) examples of spectral wavelet planes obtained by wavelet analysis of the echo profile.

space. For our analysis we used the real-valued wavelet "Mexican hat" (Fig. 3*a*). The analysis allows to find the best location and the width of the selected wavelet on the echo profile. To this end, each echo profile was subject to a careful analysis, which eventually provided the spectral plane (Fig. 3*b*), involving a maximum. The horizontal coordinate of the maximum point identified the location of the wavelet on the echo profile, whereas the vertical coordinate defined the wavelet width.

The evolution of the echo profile obtained without the wavelet analysis is shown in Fig. 4*a*. The process time is plotted on the horizontal axis and the coordinates along the profile are plotted on the vertical axis. The variations in echo level are denoted by shades of grey. The application of the wavelet analysis yields the relation for the interface position, which is presented in Fig. 4*b*. It follows then that the wavelet analysis can be used to define the interface position and to estimate the error of a method based on the wavelet width. The proposed technique was applied to process the experimental data obtained at different values of the stirring flow intensity. Note that in all cases the temperature of the lower

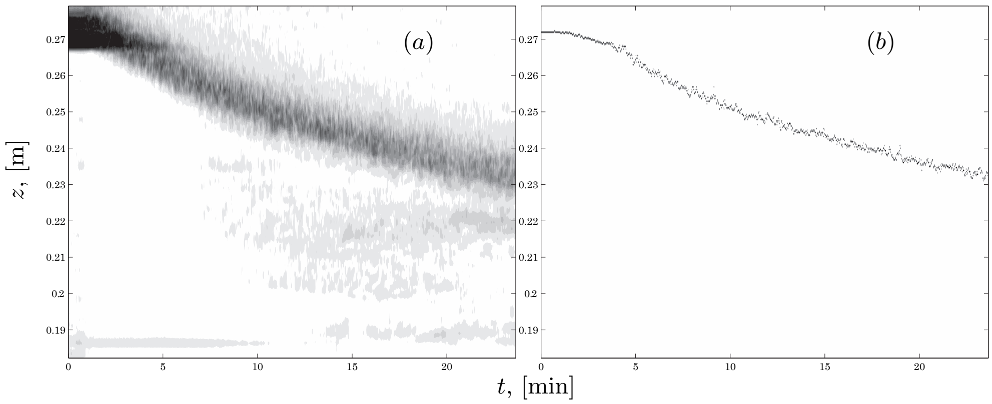

Fig. 4. (*a*) Spatial-temporal diagram of the echo profile obtained during crystallization. (*b*) Evolution of the interface obtained from (*a*) by wavelet analysis.

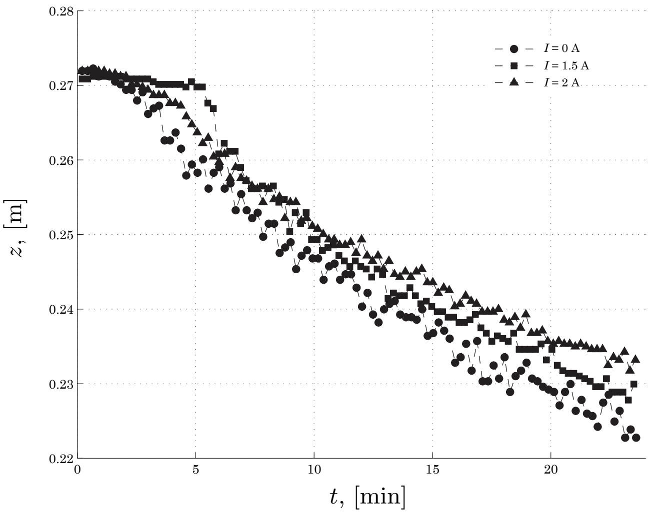

Fig. 5. Evolution of the S/L interface in the process of crystallization at different values of stirring flow intensity.

heat exchanger was $T_1 = -25°\text{C}$ and the temperature of the upper exchanger was $T_2 = +21°\text{C}$. The results of our experiment showed that with the increasing intensity of the stirring flow the rate of crystallization slightly decreased (Fig. 5).

3. Conclusions. Nowadays, the interest in MHD stirrers for liquid metals has quickened. These stirrers are generally used to stir the liquid–solid transition zone to improve the properties of cast ingots. A comprehensive experimental investigation of the crystallization process in different metals (aluminum, magnesium, steel) is the task of long time research. Therefore, our investigation has been performed with a model of the process. This paper studies the crystallization of the eutectic alloy Ga-Zn-Sn, with the melting point of +17 degrees centigrade and the effect of the stirring flow on the rate of crystallization. During the experiments, nine UDV transducers were used to make measurements. The preliminary tests showed that the echo profile was more suitable for studying the displacement of the interface. On the velocity profiles, the near-wall regions have the low resolution, which is the main disadvantage of the UDV technique and the main argument to use the echo profiles. The echo profile provides a clear cut image of the S/L interface. The UDV transducers were built-in into a specially designed brass holder, owing to which the upper boundary of the cylindrical volume remained flat. This proves to be rather an essential design of the holder in order to compare experiment with mathematical simulation (from the viewpoint of specified boundary conditions for velocity). Although in the presence of the brass plate with probes the boundary conditions for heat transfer are not perfect, we prefer this particular version of the experimental procedure.

The measurements made during crystallization faced some difficulties. On the echo profile, the S/L interphase becomes non perfect. We determined its position with reference to the wavelet analysis. A PC software 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 wavelet "Mexican hat". Upon finding the maximum on the spectral plane, we defined 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 magnetic field. It has been found that the stirring flows affect the process of crystallization, namely, they reduce its rate. This study was carried out for stirring flows of a relatively low intensity. Our experience suggests that high quality ingots are obtained in the case of moderate stirring intensity [4]. The obtained data will suffice for comparing the results of mathematical simulation with the experimental data.

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