APPLICATION OF THE ULTRASONIC DOPPLER VELOCIMETER TO STUDY THE FLOW AND SOLIDIFICATION PROCESSES IN AN ELECTRICALLY CONDUCTING FLUID

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The flow and crystallization processes in a thin layer of liquid metal are investigated. The flow in the layer is induced by an electromagnetic force. The inductor with a ferromagnetic C-core generates an alternating magnetic field in the layer. The flow makes it possible to stir the molten metal at the solidification stage. In this study, the Ultrasonic Doppler Velocimeter was used to measure the solidification front movement in a thin layer of liquid gallium. The obtained results have shown that the Ultrasonic Doppler Velocimeter can be effectively used to study the process of crystallization in liquid metals.

Introduction. The first research concerned with the application of liquid metal stirring at the time of solidification had been carried out by Russ Electroofen in 1939 and was intended to improve the quality of casting of non-ferrous metals and their alloys [1]. Nowadays, the needs of the steel industry have provoked further development of such studies; many technological processes are accompanied by the solidification of liquid metal under stirring conditions. About one billion tons of metal are solidified worldwide annually. However, there are no studies, which can unambiguously answer the question on the degree of influence of various factors on the quality of the ingot microstructure.

Industrial scale experiments with hot melts \(T \geq 700^\circ\text{C}\) are difficult to perform and, therefore, they are extremely expensive. To overcome this obstacle, a number of small scale model experiments devoted to the study of metal alloys with low melting points have been performed [2]. In the present study, we observed the solidification dynamics in a thin layer of the gallium eutectic alloy ZnGaSn (88% Ga, 10% Sn, 2% Zn) at room temperature. The efficiency of the solidification of alloys is determined by many factors. The changes of the solid–liquid interface during solidification can be discussed at three different length scales (macro, micro, and nano).

However, the solidification models often analyze crystallization events at the intermediate scale (meso-scale) [3]. In our studies, we rely solely on the macro-scale analysis. At this scale, only two phases are assumed to exist, solid and liquid, separated by a sharp solid/liquid interface. The time evolution of the solidification process can be characterized by the position of the boundary between the fully and partially crystallized metal (pieces of the solid phase floating in the liquid metal). This moving boundary is called the solid/liquid (S/L) interface. To determine the position of the S/L interface and the flow pattern, the Ultrasonic Doppler Velocimeter (UDV) was used.

1. Experimental setup. The experimental setup (Fig. 1) consists of a rectangular cell \((0.2 \text{ m} \times 0.1 \text{ m} \times 0.01 \text{ m})\), two thermostats, an AC power supply and a C-shaped inductor. Two opposite walls of the cell are copper heat exchangers. Two
other walls and the bottom of the cell are heat insulated. In the non-isothermal case, one of the walls is cooled to a temperature below the melting point of the alloy, and the solidification starts near this wall. The S/L interface moves in the layer plane in the direction of the hot heat exchanger. The cell filled with the metal is placed in the gap between the inductor poles. The magnetic field inductor is connected to the AC power supply. An alternating magnetic field is generated in the gap between these poles. This field penetrates the layer of liquid metal, and the magnetic field component orthogonal to the layer plane has the largest value in this case. Hence, we assume that the alternating magnetic field propagates through the local area of the layer under the core in the orthogonal direction (Fig. 2).

An alternating electric current is induced around this area in the layer. The interaction of this current with the initial magnetic field leads to the generation of an electromagnetic force directed toward the center of the core. This force, in turn, generates an in-plane vortex flow. If the area of the magnetic field influence is located at the center of the layer, a four-vortex flow will appear in the equilibrium case. After the inductor changes its position, the flow pattern changes as well. This flow pattern is stable if the value of the magnetic field does not exceed a certain threshold value. The flow instability causes the movement of vortices in the layer plane [4, 5]. As reported in [6], the velocity of the rotating liquid metal \( V \) is inversely proportional to the density of the metal \( \rho \), hence, with some approximation it can be suggested that

\[
V \approx \frac{B}{\rho}.
\]  

(1)
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In the discussed experiment, the core is located near the right wall of the cell (near the hot wall, Fig. 1) that results in the generation of a two-vortex flow. It has been found that in the absence of stirring the solidification is uneven and accompanied by the formation of dendrites. This enlarges the grain structure of the metal and impairs its properties. The stirring of the metal allows to smooth the S/L interface, to refine grains, to homogenize ingot properties and to destruct partially dendrites under the conditions of temperature fluctuations and energy transfer. Moreover, the stirring contributes to the uniform distribution of impurities and crystal grains transported by the flow, which also improves the properties of the ingot [7].

The velocity field and the position of the L/S interface were determined using the Ultrasonic Doppler Velocimeter (UDV, DOP2000, Signal Processing). The main advantages of the UDV are non-invasive measurements, high spatial and temporal resolution and high sensitivity. It also provides accurate measurements of velocity (from 0.01 mm/s), which allows to use it in the study of fluid flows, whereas the existing optical methods, such as LDA or PIV, cannot be applied for these purposes. Moreover, the cell is heat insulated and placed inside the ferromagnetic inductor. Therefore, the UDV use is the only possible way to make measurements in this case. Just a few years ago, such experimental measurements were problematic due to the complexity of the available measurement techniques. Using the data obtained with the UDV, it is possible to calculate the probability density, the statistical moments, the temporal energy spectrum of velocity and to determine the position of the L/S interface.

Five UDV probes were installed in the hot wall of the cell. The probe emitted an ultrasonic wave of a certain frequency, which fell on the S/L interface and reflected from it. This is clearly seen in the graphs of the reflected echo profile. Taking into account this effect, we can determine the S/L interface in the opaque liquid metal.

2. Results and discussion. In order to study the effects of different temperature and stirring conditions on the solidification process, a series of experiments was performed at \{18.0; 20.0; 22.5\} °C at the hot heat exchanger and at 4.0 °C at the cold heat exchanger and under three stirring modes: no stirring, at \(I = 2\) A, and at \(I = 4\) A in the inductor coil. Experimental points reproducing the time evolution of the S/L interface position under different temperature and stirring conditions were obtained. These points can be approximated by the square root law. The solidification process is governed by the nonlinear law, which is a well-known fact described in [3, 8]. Our experiments have shown that the stirring does not change this law (Fig. 3).

![Fig. 3. Time evolution of the S/L interface position: (a) temperature conditions (\(I = 2\) A); (b) different mixing intensity.](image-url)
Fig. 4. (a) Time evolution of the S/L interface position for each UDV probe \((I = 2\, A, T = 20^\circ C)\). (b) The solidification rate for each UDV probe \((I = 2\, A, T = 20^\circ C)\).

Fig. 5. The melting process with stirring: \(T = 4 - 25^\circ C, I = 4\, A\). Top: the position of the S/L interface obtained with UDV; bottom: results of restoring the pattern of the structure of vortices. The patterns were obtained with the 6 min time interval.

In most cases, the S/L interface is determined with high accuracy in the central part of the layer (Fig. 4). The solidification rate for different probes is slightly different, it depends on the distance from the side walls of the cell (Fig. 4). It decreases with time and increases with the increasing stirring intensity. The S/L interface moves fast to a steady position (Fig. 4). It should be noted that at the present stage of research, we use the stirring of moderate intensity so that the induced current heats the liquid layer slightly.

The UDV probe measures only one velocity projection on the axis going through the center of the ultra sound beam (longitudinal velocity component). The multiplex mode with five probes makes it possible to obtain the matrix of the longitudinal component of velocity. Using the equation for compressible liquids \((\text{div}\, \mathbf{V} = 0)\) and the two-dimensional formulation of the problem, we can restore the two-dimensional stream function \((\Psi)\):

\[
V_x = -\frac{\partial \Psi}{\partial y}, \quad V_y = \frac{\partial \Psi}{\partial x}.
\]

(2)

Fig. 5 allows to trace the evolution of the S/L interface and eddies in time. Owing to the limited volume of the liquid (the inductor covers almost the whole area of the liquid phase), two vortices occur in the cell. As the liquid phase increases, the flow becomes a four-vortex one (Fig. 6).
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3. Conclusions. The results of investigation have shown that in a plane layer it is possible to create a stirring flow, which will affect the process of crystallization. The flow intensity can easily be controlled by adjusting the power source of the inductor coils. The flow topology can be controlled by changing the position of the inductor poles about the layer plane. The experiments have revealed one more factor contributing to the flow topology. In the process of crystallization (or, conversely, in the process of melting), the size of the liquid layer changes because part of the liquid is transferred into the solid phase (and vice versa), whereas the position of the inductor is left unchanged. However, the process can be represented as relative displacements of the inductor poles in the frame of reference coupled with the crystallization front. This leads to a change in the flow topology.

The results of test experiment showed that the error in determining the S/L interface position was ±5 mm for a cell length of 200 mm. This implies that UDV can be applied to define the location of S/L interface without any direct contact with the liquid. Under stirring conditions the shape of the interface between the solid and liquid phases varies according to the configuration of the flow. The solidification rate increases with the increasing intensity of stirring.

The examined configuration of the MHD layer can be assumed as a stirring mechanism for liquid metal or melt in a flat rectangular vessel. The existence of stirring flow prevents the inhomogeneous distribution of admixtures in the ingot and essentially improves its microstructure. By using several inductors it is possible to change significantly the flow topology, to prevent the appearance of stagnation zones and to improve the quality of stirring.

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