INFLUENCE OF MHD STIRRING ON SOLIDIFICATION OF ALUMINUM ALLOY IN A CYLINDRICAL CRUCIBLE

DENISOV[1] S.A., DOLGIKH[1] V.M., KHRIPCHNKO[1,2] S.YU., KOLESNICHENKO[1] I.V., NIKULIN[1] L.V.
[1] Institute of Continuous Media Mechanics UB RAS (Russia)
[2] Perm National Research Polytechnic University (Russia)

Abstract: The processes taking place in a molten metal during its crystallization in the presence of MHD-stirring in a cylindrical crucible are investigated. We describe the results of physical and numerical experiments devoted to the study of directional crystallization of aluminum alloy in a cylindrical crucible in diverse MHD-stirring modes generated by travelling and rotating magnetic fields, and by their superposition. The experiments have shown that the types of magnetic (travelling or rotating) fields and their intensity determine the shape of crystallization front of ingots and the type of the grain structure of alloys (solid solutions and alloys with eutectic). They also affect the structural zone length, grain size, distribution of structural components, rigidity, and other mechanical characteristics of alloys in ingots cast using some form of MHD-stirring.

1. Introduction

MHD stirring ensures success when casting aluminum ingots (most commonly used for semi-continuous casting in metallurgy) because it provides homogeneous distribution of admixtures and alloy homogenization, produces a homogeneous fine-grain structure of solid solutions, reduces a specific fraction, and enhances the refinement and uniform distribution of second (intermetallic) phases, etc. MHD stirring can also be used for aluminum ingot casting in cylindrical moulds of finite volumes (equipment for this process is simple and cheap). It has been found that the properties of the molten metal in the presence of MHD-stirring are improved. However, MHD-stirring has some specific features, in particular, the stirring velocity during ingot solidification decreases when the volume of the liquid phase in the ingot reduces. That is why investigation of the process of crystallization of aluminum alloys in a finite volume in the presence of MHD-stirring has aroused a great deal of interest.

2. Presentation of the problem

In the numerical experiment, the process of crystallization of aluminum in a cylindrical crucible in the presence of MHD-stirring generated by travelling or rotating fields was considered. The wall and lid of the crucible were assumed to be thermally insulated, and the heat was taken away through the crucible bottom. Electromagnetic forces in a liquid metal were determined as in [1], and hydrodynamics and the process of crystallization were analyzed in terms of the k-ε model and using the enthalpy-porosity method [2]. The liquid phase was characterized by singular porosity, the solid phase – by zero porosity, and the intermediate phase – by the intermediate value of porosity. 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 metal.

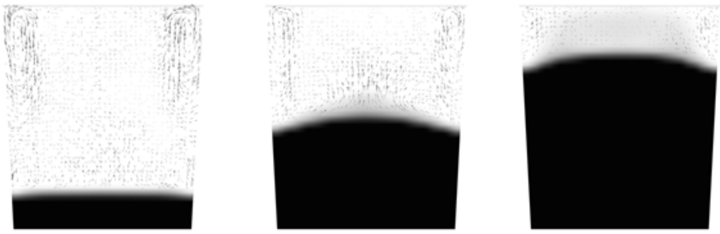

Figure 1: Evolution of the interface and velocity field during crystallization of the aluminum ingot in the rotating magnetic field, 6 A (6.09 mT; 50 Hz). Left – beginning of the process.

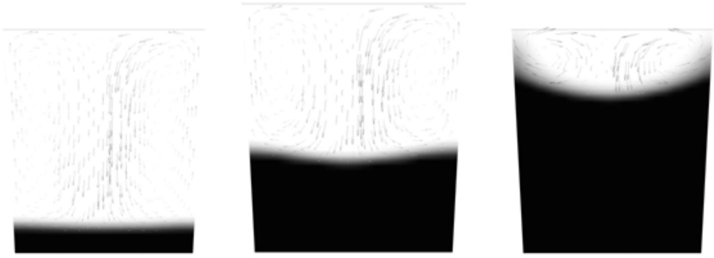

Figure 2: Evolution of the interface during crystallization of the aluminum ingot in the upward-traveling magnetic field, 3 A (3.98 mT; 50 Hz). Left – beginning of the process.

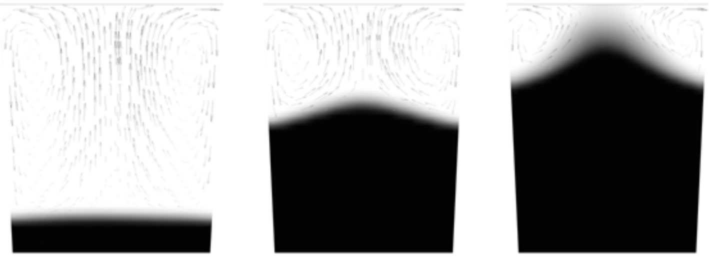

Figure3: Evolution of the interface during crystallization of the aluminum ingot in the downward-traveling magnetic field, 3 A (3.98 mT; 50 Hz). Left – beginning of the process.

The numerical experiment indicates (Fig.1) that as the solid phase volume fraction increases in the crucible in the presence of the rotating magnetic field, the interface remains flat for a long time. At the end of the process, i.e., when the liquid phase reduces sharply, the speed of rotation of metal decreases and the crystallization boundary rises in the middle of the crucible.

Under the action of the travelling magnetic field on the solidified metal, the crystallization pattern changes. When the magnetic field goes upward (Fig. 2), the interface has a small concave in the center of the crucible and rises slightly near its walls.

This depends upon the fact that the hot metal in the upper part of the crucible descends in the middle of the crucible, slowing down the process of aluminum crystallization. After cooling, the hot metal moves to the walls and solidifies there. At the end of the process, the velocity of a poloidal flow in the liquid phase of metal decreases much stronger than the velocity of a toroidal flow in the case of a travelling field. A descent of the interface in the middle of the crucible and its rise near the crucible walls become more pronounced.

When the magnetic field travels downward (Fig. 3), the hot metal descends near the walls, impeding the crystallization process. Then, it moves to the middle of the crucible and solidifies. In this case, even at the initial stages of the process, a convexity in the center of the interface occurs. The convexity becomes more marked as the crystallization proceeds. At such topology of the flow, the boundary of crystallization front in the metal is not flat, and its deformation increases in the course of the process.

We set up an experiment to determine the azimuthal velocity of liquid aluminum in the crucible (Fig.4), induced by the rotating magnetic field generated by an MHD-stirrer. The velocity was found with the aid of a turbine submerged into the liquid metal [1].

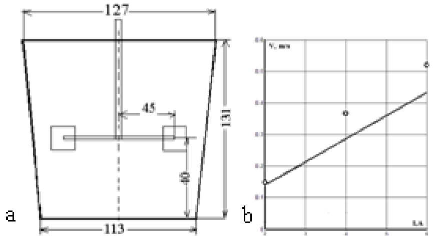

Figure 4: a - Crucible for liquid aluminum with a measuring turbine; b – maximum melt flow velocity V versus the inductor current (I, A) creating the rotating magnetic field. Solid line and points indicate, respectively, the results of numerical and physical experiments.

In the numerical experiment, the flow of aluminum in a closed cylinder was calculated. The physical experiment was conducted on silumine in the crucible with free surface, which provides an explanation for some divergence of the results of numerical and physical experiments with increasing electrical current in the inductor. Crystallization experiments were performed with Al-4.5%Zn and AK9ч alloys in the presence of MHD stirring. The alloys were poured at 680^0C into the crucible placed in the MHD-stirrer generating the travelling and rotating magnetic fields. The crucible walls were thermally insulated and could be heated, and the bottom was cooled by circulating water. After pouring the melt, the crucible was closed by an insulated lid (Fig. 5).

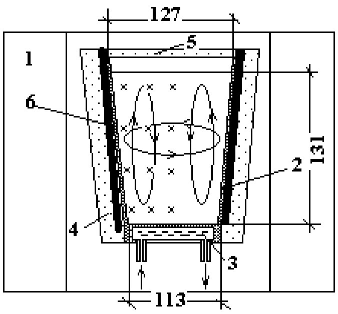

Figure 5: MHD stirrer with a crucible placed inside it:
1 – MHD-stirrer; 2 – crucible - crystallizer;
3 – water -cooled bottom; 4 – wall insulation;
5 – mullite-siliceous lid; 6 – heater.

The structure and properties of ingots solidified in magnetic fields were compared with those of ingots solidified in the absence of MHD-stirring. The influence of the rotating magnetic field on the microstructure of alloys Al-4.5%Zn and AK9ч is given in Fig .6. In the absence of MHD-action, the Al-4.5%Zn ingot consists of large dendrite crystals (Fig.6a). Application of the rotating magnetic field changes the large-dendrite structure of the ingot to the fine sub-dendrite structure (Fig. 6b). Such transformations were also observed in the eutectic alloy AK9ч. In Fig. 6c, the structure of the alloy solidified without the MHD-action is represented by dendrite crystals with the 1st order extended axis (dendrite trunk) and secondary branches, as well as by eutectic areas. Use of MHD stirring makes it possible to transform the morphology of dendrites: the dendrite axis becomes a compact grain in the center, where it is surrounded by the secondary branches of a spatial cluster (Fig. 6d).

Formation of the shape of grains in ingots depends on both the stirring flow and the intensity and directivity of heat sink cooling. At fast cooling of ingots in the zone adjacent to the water-cooled bottom of the crucible, one can observe the formation of columnar crystals oriented along the normal to the bottom surface (Fig. 7a) and slightly bent in the direction of rotation of the metal.

In the layer adjacent to the thermally insulated wall, the relatively equi-axial small crystals with arbitrary orientation are formed. Formation of such crystals takes place in the flow in a suspended state, and therefore the dynamic flow has only a minor effect on these crystals (Fig. 7b).

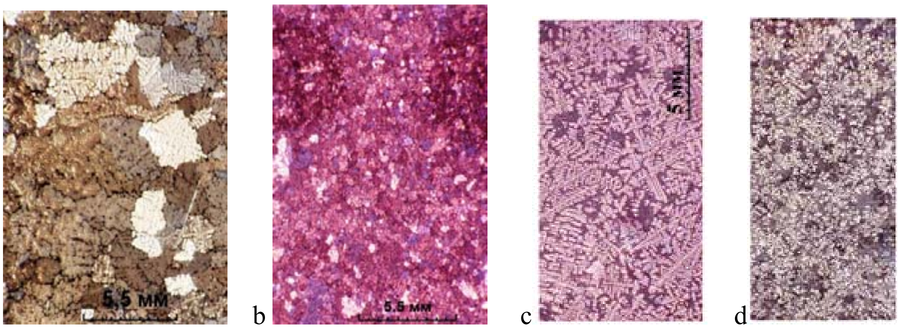
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Figure 6: Macrostructure of the solid solution of Al-4.5%Zn alloy without stirring (a) and under the action of the rotating magnetic field (b); the same for the eutectic АК9ч alloy: without stirring (c) and under the action of the rotating magnetic field (d); comments are given in the text (current of 4 A and induction of 4.6 mT).

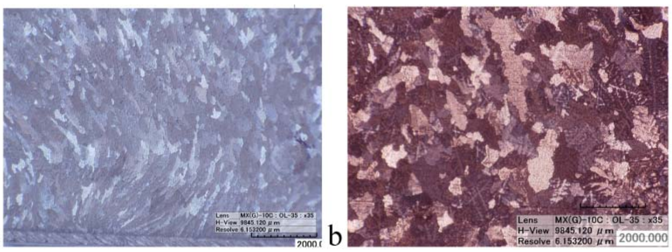
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Figure 7: Macrostructure of the Al-4.5%Zn alloy solidified in the rotating magnetic field: a – in the near-bottom zone of rapid cooling; b – in the layer adjacent to the thermally insulated wall of the crucible (inductor current of 4A, magnetic field induction of 4.6 mT).

Significant changes are observed in the microstructure of АК9ч alloy solidified under the action of the rotating field (Fig. 8). Application of the rotating magnetic field transforms the silicic phase: the plate-like shape practically disappears; relatively compact fragments randomly distributed in the matrix of aluminum solid solution prevail (Fig. 8d).

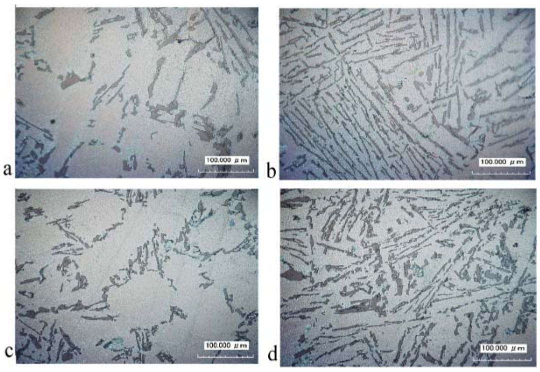
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Figure 8: Macrostructure of АК9ч alloy ingots solidified in the absence of MHD fields: secondary branches of dendrite (a) and eutectic area (b); macrostructure of АК9ч alloy solidified under the action of the rotating magnetic field: grain cross-section (c) and eutectic area (d) (inductor current 4 A, magnetic field induction 4.6 mT).

Quantitative estimation of the structural parameters of the alloy solidified in the presence of the rotating magnetic field of 4.6 mT (inductor current of 4A) and without it is given in Table 2.

Table 2. Sizes of dendrites of solid solution and silicic fragments in АК9ч alloy solidified with no MHD forces and under MHD stirring.

Parameters	Sizes
Length of the dendrite trunk in ingots with no MHD forces applied	4.0 – 4.5 mm
Overall size of the dendrite with modified morphology (through the external circuit) in ingots subjected to MHD forces	1.4 – 1.6 mm
Thickness of the secondary branches of dendrites in ingots with no MHD forces applied	0.06 – 0.09 mm
Thickness of the secondary branches of dendrites in ingots with applied MHD forces	0.08 – 0.10 mm

Sizes of silicic plates in eutectic in ingots with no MHD forces; (thickness/length)	(3–9)/(45–60) mm
Sizes of silicic plates in eutectic in ingots with application of MHD-forces; (thickness/length)	(10-13)/(29-40) mm

The Al-4.5%Zn alloys were used to evaluate the length of structural zones (the near-bottom zone of large oriented columnar crystals and the upper zone of randomly oriented large dendrites), grain size and rigidity (Figs. 9 and 10).

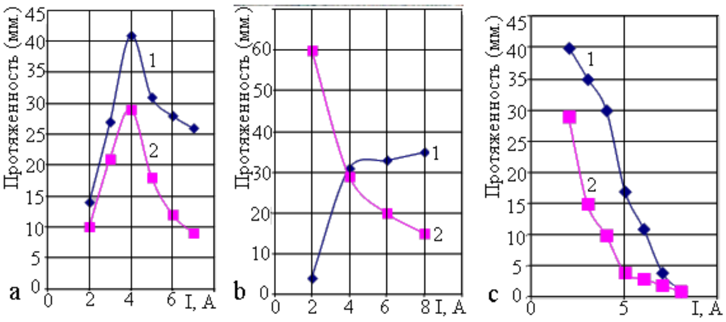
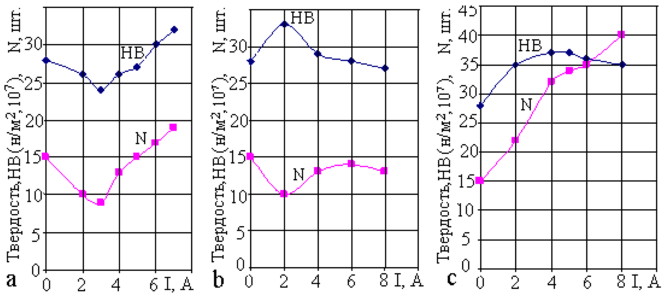


Figure 9: Structural zone length (mm) versus MHD-stirring modes: a – rotating field, b – travelling field; c- combined regime; 1 – near-bottom zone, 2 – upper zone; (Al- 4.5% Zn alloy, I, A – inductor current).

Figure 10: Influence of rotating (a) and travelling (b) fields and their joint action (c) on the HB hardness, n/m^2 and the number of grains, N, items in the Al- 4.5% Zn alloy.



3. Conclusion

Investigations showed that the crystalline structure of ingots depends on the type of MHD-stirring. Application of MHD-stirring changes significantly the structure of ingots, that is, the dendritic structure is transformed into the sub-dendritic one. The effect of transformation in many cases is defined by the rate of MHD-stirring. The rate of cooling during the solidification process influences the crystalline structure of ingots as well.

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References

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