Effect of Electromagnetic stirring on the solidification of Al-7wt%Si alloy: experiment and simulation

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Abstract
To understand resulting effect of an electromagnetic stirring during solidification of alloy one should use either well-controlled experiments or numerical simulations. In the present work experiments on solidification of Al-7wt%Si alloy with RMF stirring performed in University of Miskolc are presented. Temperature data obtained during the experiments are used for simulations which are performed with a purely columnar solidification model. The numerical code developed in the SIMAP laboratory based on the ensemble averaged multiphase model with the envelope approximation is used for the simulations.

Keywords: electromagnetic stirring, solidification, alloy, simulation, envelope model, segregation

Introduction
Alternating electromagnetic fields are widely used in alloys solidification to control the structure of the material. Generally, convection leads to a smaller primary and secondary dendrite spacing due to more intense mass transport in the liquid phase. Eventual fragmentation of solidified dendrites also promotes finer solidified structure. On the other hand forced convection can have negative impact because of directed mass flow through the mushy zone which leads to the segregation. Furthermore, transport of dendrite fragments also can affect composition distribution [1]. To examine these phenomena, two laboratory setups for directional solidification equipped with electromagnetic stirrer were constructed and equipped with thermocouples allowing for the temperature measurement along the sample during the solidification [2]. Obtained data were used in simulations of solidification process.

The solidification facility and experimental results
The sketch of the solidification facility is shown in Fig. 1. The Ø8x100 mm sample is placed into a holder cartridge whose lateral wall allows for the placement of 13 thermocouples lengthwise for the temperature data collection. The cartridge is connected to a copper cooling core and is placed into a quartz tube – making the sample holder assembly. The copper core is constantly in the water to provide a heat flux for the solidification. The whole sample is kept in a rotating magnetic field during the solidification experiment.

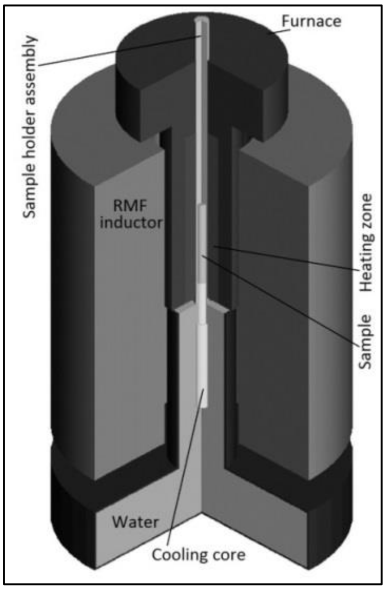

Fig. 1: The solidification facility equipped with RMF stirrer

The experiments are performed as follows:

1. The sample is heated up over a liquidus temperature,
2. An initial temperature gradient is set up in the sample using the cooling rod and the lowest zone of the furnace,
3. The lowering of the sample holder assembly is started – optionally with RMF stirring – to induce solidification.

The temperature field is recorded with National Instruments® data collector tool using a LabView® program. There are 3 zones in the furnace and the lowest zone is set to a higher temperature. In the beginning of the experiment the lower half of the sample is in the lowest hot zone, while the upper part of the sample is in a middle furnace zone which is colder. During the sample drawing its upper part first pass a warmer zone. Due to this, the thermocouples at higher positions first record an augmentation of the temperature, and then the cooling occurs as seen in Fig. 2.

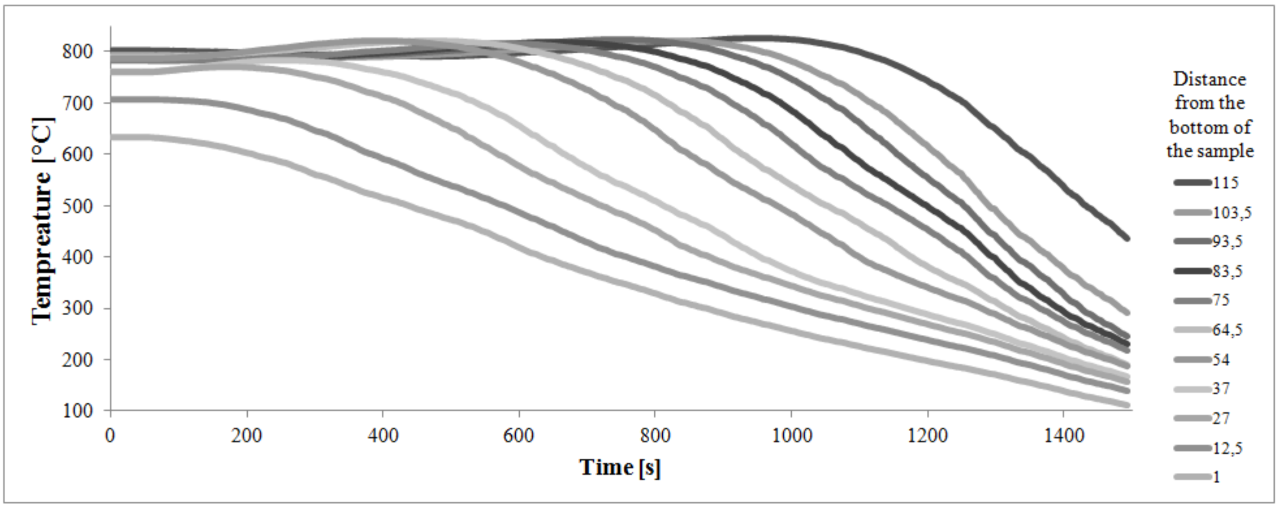

Fig. 2: Cooling curves obtained from the thermocouples during the solidification experiment with B=6 mT

The structures of two directionally solidified samples with and without electromagnetic stirring are shown in Fig. 3. As a result of the secondary flows, a strong central segregation appears.

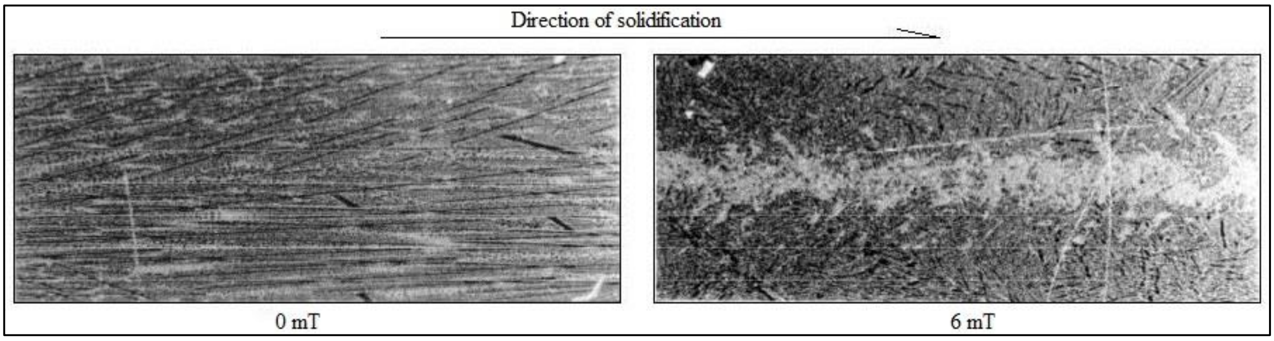

Fig 3: Microstructure of directionally solidified Al-7Si samples with (right) and without (left) RMF stirring. Light grey color corresponds to a higher concentration of the Si (eutectic structure).

Two-dimensional and three-dimensional modeling

We perform 2D and 3D modelling for the experiments in order to capture three-dimensional effects of the flow and their effect on the segregation. Two-dimensional modelling is made with an axisymmetric swirl for a rectangular calculation domain 4x100 mm meshed with 40000 uniform tetragonal cells. In three dimensions the calculations are made for a cylinder of 100 mm high and 8 mm diameter using 510600 hexahedrons with the biggest skewness 0.54. The modeling is performed with a commercial code Ansys Fluent® with UDF functions. . Both models have the same user defined functions written for the phase transition during the solidification and for the specie transport with segregation at the solid-liquid interface [3-4].Two hydrodynamic phases are considered, solid and liquid and Euler model is used. Three thermodynamic phases, namely, solid, interdendritic- and extradendritic liquid are considered according to the envelope

model [5-6]. The induced Lorenz force field is set as momentum source using analytical approximation since the length of the inductor is larger than that of the sample [7]. Darcy law is used to model the flow through the mushy zone.
Previous two-dimensional modeling was made for such experiments but with adiabatic conditions at the lateral wall, a given cooling rate at the bottom and a fixed thermal gradient at the top. In the present case the temperature dataset of experiments is used as a boundary condition along the lateral wall of the calculation domain. A linear interpolation in space for calculation points is made because there are 10 data points for 100 mm height, which are two orders of magnitude less than the number of cells along the height Fig. 5. Interpolation in time is also needed since the data collection interval is much higher than the used time steps in the model and also.

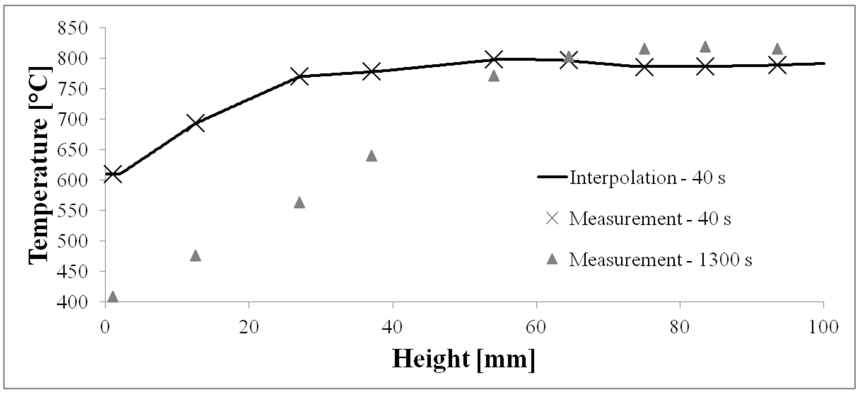

Fig 5: Temperature distribution along the sample from measurements and interpolation

Results of two-dimensional simulations
In Fig.6 results for the flow in the crucible and initial stage of the solidification are presented. In this case the flow consists of small vortices moving downward and upward near the lateral wall. An averaged axial flow may be identified in the center of the sample which is directed upward in the lower part of the sample and is descending for its upper half. The solidification started with a strong central segregation, but due to the temperature field, the whole cross section has been closed by the mushy zone. The blocked melt with higher concentration solidifies later than the melt near the wall (Fig 6.).

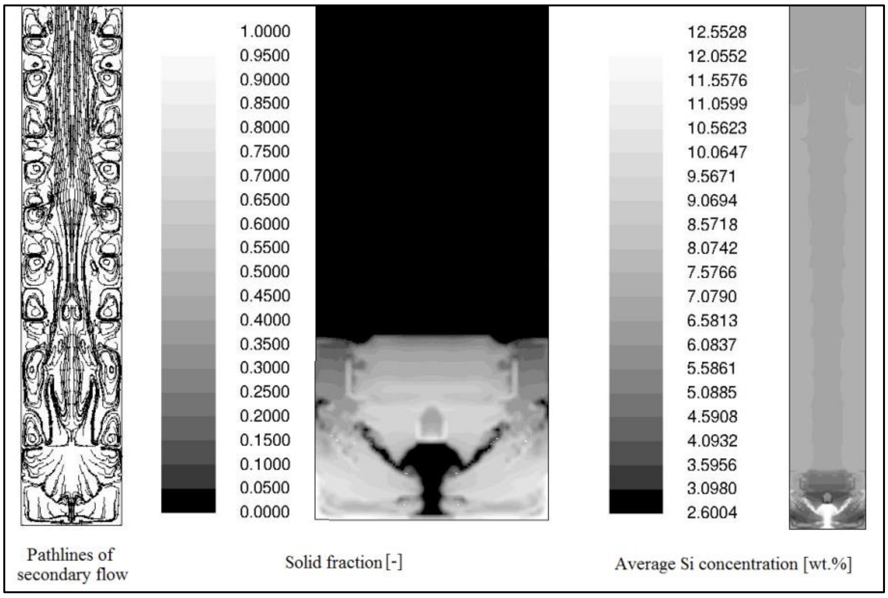

Fig. 6: Intermediate results of the 2D model at 95.26 seconds flow time

Results for three-dimensional simulation
The 3D model's computational time per time step is about 50-60 times higher than the 2D, so the following intermediate results can be presented. Similar to the 2D case, the induced secondary flow provides a central segregation and slows down the solidification process in the center as shown in Fig. 7.

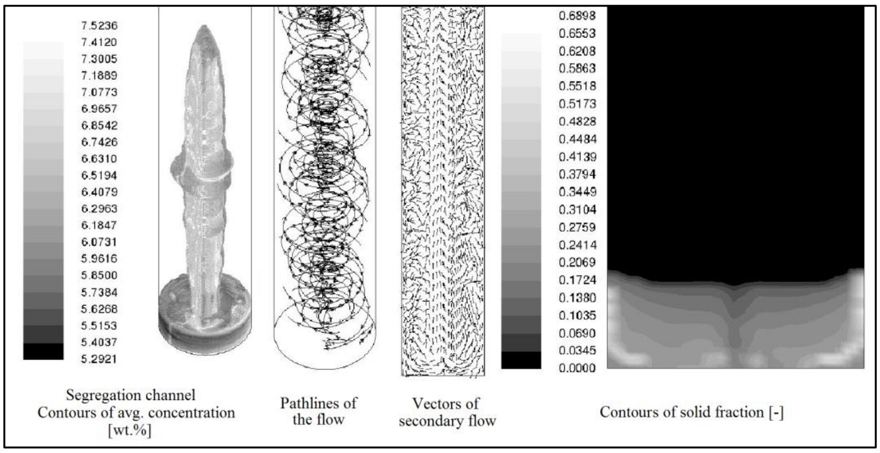

Fig. 7: Intermediate results of the 3D model at 24.7 seconds flow time

The need of the 3D domain is proven on Fig 8. The flow is shifting between axis-symmetric and asymmetric from one time step to another.

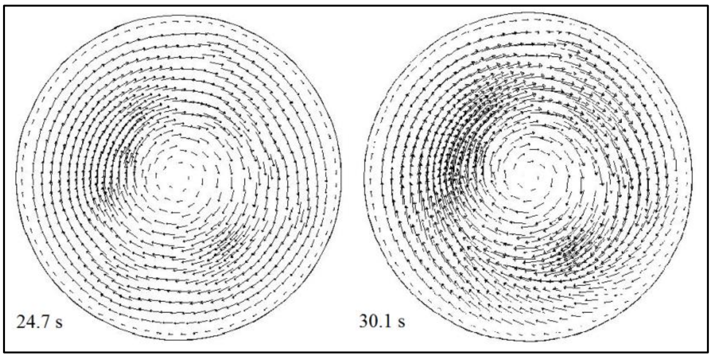

Fig. 8: Shifting between axis-symmetric and asymmetric flow pattern presented by vectors of velocity magnitude

Summary
A facility for examining the solidified structure of different alloys under natural or forced convection has been developed; and used for Al-7Si binary alloy. The solidified structures and a concentration map are presented. With the aid of the collected temperature data, 2D axisymmetric and 3D solidification models are provided using ensemble averaged envelope model.

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