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Direct chill casting of aluminium alloys under electromagnetic interaction by permanent magnet assembly

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Abstract. Direct chill casting is one of the methods used in industry to obtain good microstructure and properties of aluminium alloys. Nevertheless, for some alloys grain structure is not optimal. In this study, we offer the use of electromagnetic interaction to modify melt convection near the solidification interface. Solidification under various electromagnetic interactions has been widely studied, but usually at low solidification velocity and high thermal gradient. This type of interaction may succeed fragmentation of dendrite arms and transport of solidification nuclei thus leading to improved material structure and properties. Realization of experimental small-scale crystallizer and electromagnetic system has been described in this article.

1. Introduction

Aluminium alloys microstructure and physical properties may vary significantly depending on solidification velocity and temperature gradient at the solidification interface, and melt flow near solidification interface as well. In industry, aluminium alloys for extrusion and forging is prepared by using crystallizers, which ensure controlled solidification velocity and oriented solidification front direction [1]. There are several technical solutions how to achieve rapid solidification up to 10 mm/s and large diameter ingots. One of the most prevalent is direct chill casting, where heat is evacuated by spraying oil and water at the solid part of the ingot [2]. It has been demonstrated that pulsed or AC electromagnetic interaction during directional solidification can significantly modify solidification structure of aluminium alloys [3]. Electromagnetic force may influence the melt flow in several ways. Static magnetic field has two effects. Firstly, it damps the melt flow perpendicular to magnetic field lines, and, secondly, magnetic field interacts with electric current near the solidification interface and drives melt convection [4,5] and can deform the solidified dendrite arms [6]. Electric current may arise because of thermoelectric effect between solid and liquid phases in presence of temperature gradient along solidification interface [7] or current can be directly the melt, or induced by the alternating magnetic field. Diverse types of melt flow give different effects on solidification structure. For example, large scale flow may change solidification interface shape and influence the structure difference between core and outer crust of the ingot [8]. Whereas small dendrite-scale flow may succeed composition homogeneity and alter dendrite morphology. However, there is no direct link between melt convection during solidification and solidification microstructure, thus for each alloy and electromagnetic interaction series of experiments should be done.

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2. Experimental setup

Small scale direct chill casting experimental setup has been developed in MHD technology laboratory of Institute of Physics University of Latvia. Principal scheme of experimental setup is shown in Figure 1. Aim of the experimental setup is to test the possibility to influence solidification structure and impurity distribution in aluminium ingot by various electromagnetic interactions. Vertical DC magnetic field is applied by the permanent magnet system placed around the solidification zone. Solidification interface takes place in graphite tube at the middle of permanent magnet system where field induction reaches maximal value. Just below graphite tube the solid part of the aluminium rod is cooled by water spray. DC magnetic field interacts with injected electric current in the aluminium near the solidification interface.

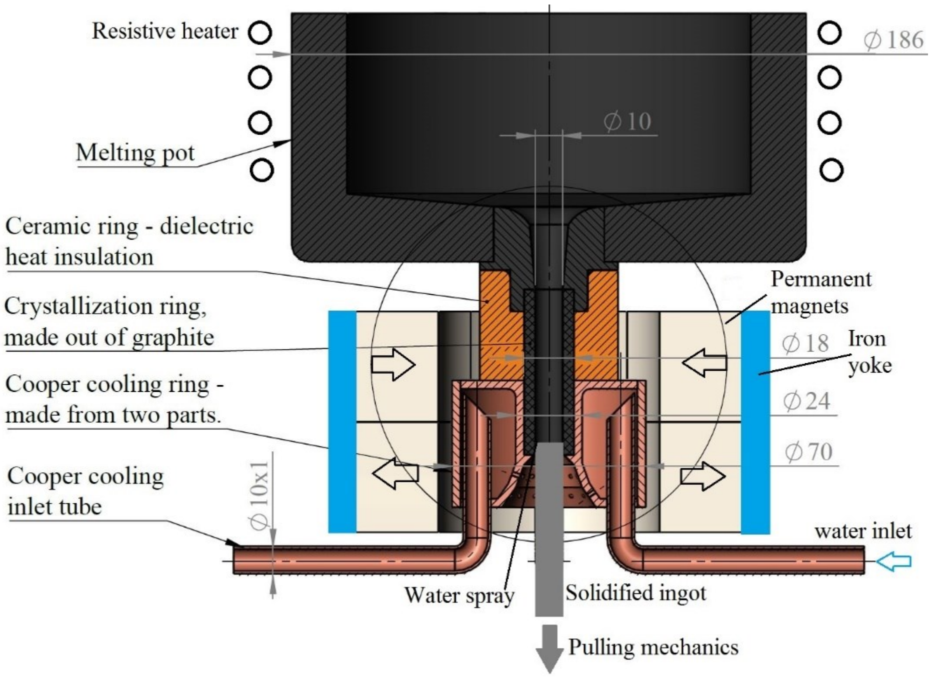

Figure 1. Principal scheme of the experimental setup.

3. Results and discussion

For the first experiments, it is planned to apply axial electric current through the solidification interface. In this case in the bulk of the solid and liquid parts magnetic field and current are parallel, thus there is no Lorentz force. However, at the dendritic solidification interface current redistribution takes place due to significant difference in electric conductivities between solid and liquid phases. It has been shown by previous work that such type of interaction may induce liquid phase flow at dendrite scale and modify solidification microstructure and segregation of the components. Parameters of experimental system has been chosen to induce electromagnetic forces in the melt comparable to similar studies described in literature [9].

In this work planned current density is starting from 1 A/mm^2. Electric current at the dendritic solidification interface is redistributed as shown in Figure 2. In this case current component perpendicular to magnetic field creates Lorentz force and local convection vortices around each dendrite arm is created. Typical primary dendrite scale of aluminium is 100 µm. Melt convection velocity can be estimated by balancing electromagnetic and viscous forces in simplified Navier-Stokes equation [9]. For aluminium 0.5 T axial magnetic field would give characteristic velocity of few centimetres per second, which could have significant effect at solidification velocities 1-3 mm/s.

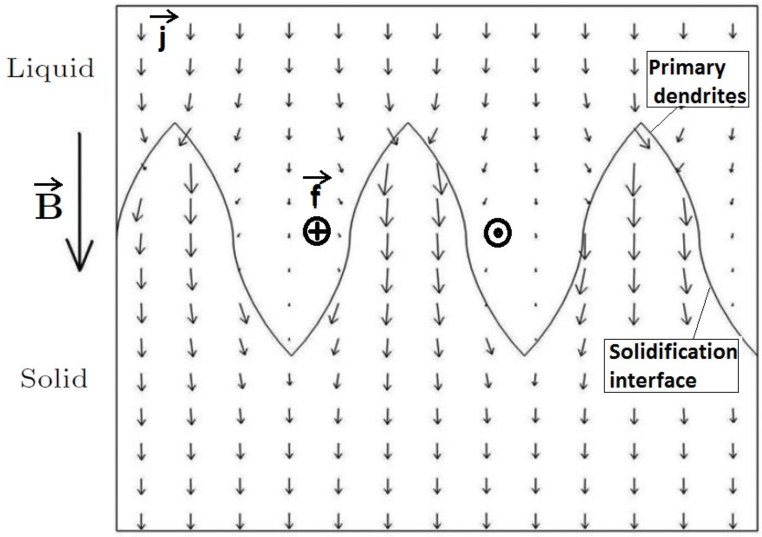

Figure 2. Electric current distribution at the dendritic solidification interface (B-magnetic field induction, j-current density, f-force density).

Permanent magnet system aimed to achieve 0.5 T is assembled from segment magnets. Iron yoke to optimize magnetic flux as shown in Figure 3(a). Inner cavity of magnet system is 80 mm in diameter and axial magnetic field induction at the middle is about 0.45 T as shown in Figure 3(b) by comparing measurements and numerical model. Low carbon soft iron yoke guides magnetic flux with minimal resistance thus magnetic field induction in the magnet is maximized. For these N42M type magnets maximum work temperature is 100 °C, thus magnets are protected from excess heat from hot zone by copper screen which is water cooled. Thus, magnets can be easily placed within several centimetres from molten aluminium. Permanent magnet systems can be designed for many applications, such as liquid metal pumps and stirrers, couplings and bearings, sensors, motors etc. [10,11] Halbach array principle is used in systems to increase and improve magnetic field distribution by creating permanent magnet arrays from many smaller magnets. Ways to optimize magnetic flux has been described by several authors [12, 13].

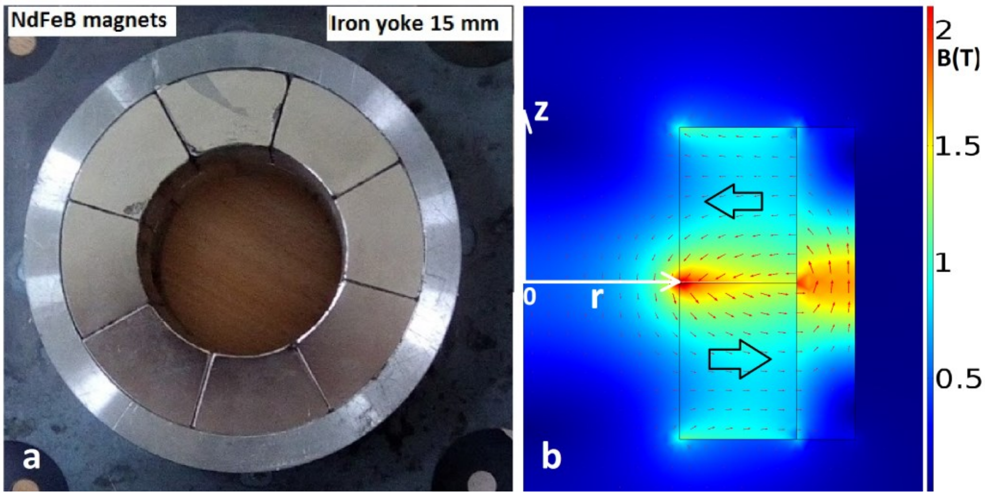

Figure 3. Magnet system: a) Assembled permanent magnet system; b) axysymmetric Comsol model (Magnetic field induction) Black arrows indicate magnetization direction.

Comparison between Comsol 5.0 numerical model and gaussmeter measurements shown in Figure 4. demonstrates that numerical calculations are accurate. Axysymmetric stationary model is solved to calculate the magnetic flux density. Yoke is assumed to be soft iron with saturation magnetization of 2.1 T, remanent flux density of the NdFeB magnets is 1.4 T. Triangular mesh consisting of 46000 elements is used for calculations. Difference may be explained by the facts that there are small gaps between magnet pieces and that magnetization is not entirely homogeneous. In our case ingot diameter is 10 mm thus inhomogeneity of magnetic field does not play a crucial role. If such magnetic field is provided by electromagnet, then number of ampere-turns necessary can be estimated from finite coil magnetic field induction formula:

$$B_z(z) = \frac{\mu_0 NI}{\sqrt{h^2 + R^2}}$$

Where h is height of the magnet, R is coil radius, μ_0 is vacuum permeability. For our case (h=10cm, R=4 cm, R_{outer}=9 cm) we get necessary ampere-turns IN=30 kA turns. Such electromagnet would be difficult to make and operate thus in this case permanent magnet assembly is definitively an advantage.

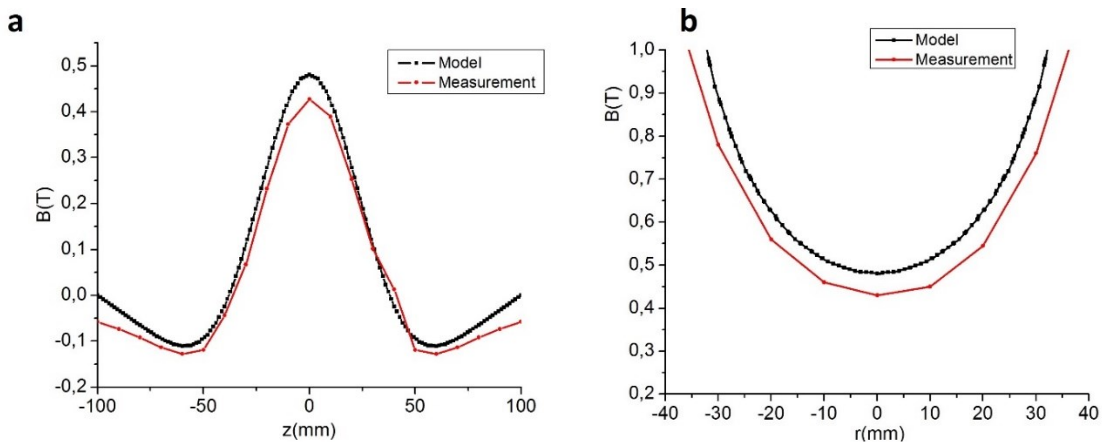

Figure 4. Comparison of numerical model and measurements. Magnetic field induction: a) Along axis of the magnet system; b) along radial position at the middle height.

NdFeB magnets with remanent flux density of 1.4 T are becoming more available nowadays, even in custom shapes. Limitation is size in magnetization direction which is around 5 cm. Larger magnet system with 20 cm diameter can be built in the same manner. Such system would require 8 liters of NdFeB magnets and 2 cm thick iron yoke to prevent oversaturation. Estimated price of the magnets would be around 3000 Eur. Total weight of the magnet system with yoke would be around 80 kg. Magnet system sizes are shown on Figure 5(a). Calculated flux density along z axis and along diameter are shown in Figure 5(b). More than 0.4 T can be achieved in 20 cm diameter magnet. With air filled electric coil this would require 71 kA turns. Thus, even for a larger application permanent magnet assembly is reasonable alternative for complicated electromagnet.

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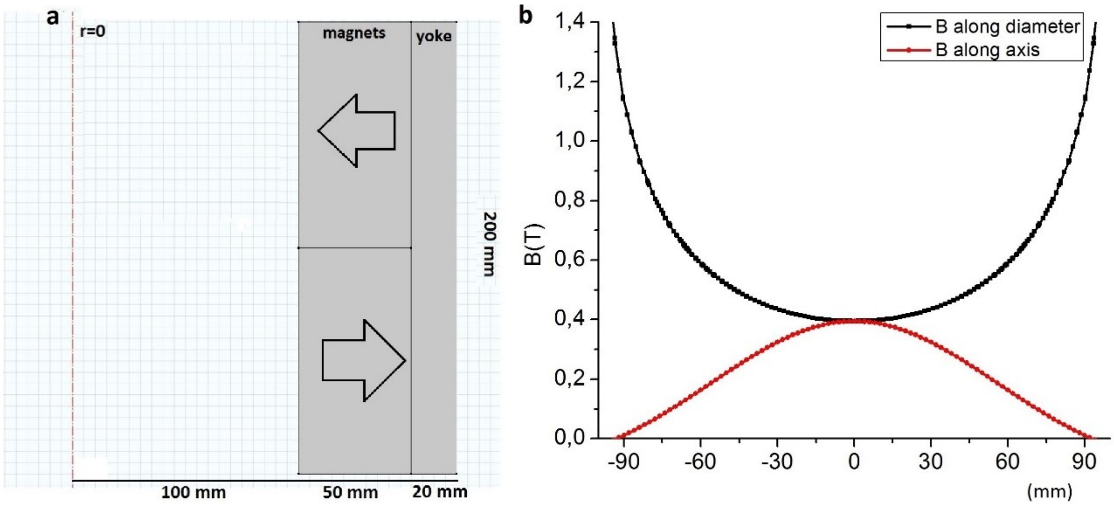

Figure 5. Magnet system for 200 mm diameter axial field assembled form segment magnets and iron yoke: a) cross section of the magnet system (with magnetization directions); b) magnetic field induction.

4. Conclusions

Direct chill casting is one of the promising technologies for high quality aluminium alloy production maintaining certain properties. Our current work is aimed to improve existing technology by investigating the potential applications of electromagnetic interaction to the process. Electromagnetic interaction on liquid aluminium is perspective because of relatively low melting temperature, high electrical conductivity and low density of the material. Thus, electromagnetic elements can be placed close to the liquid metal and smaller magnetic field amplitude is necessary to achieve sufficient force density in the melt. Designed permanent magnet assembly for DC field has shown its potential and in the future permanent magnets could replace superconducting magnets in several applications where moderate field is necessary.

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