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Directional Solidification of Aluminum A360 under Moderate DC Magnetic Field and Electric Current

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Metal additive manufacturing is rapidly developing technology, but its application in wider scale is limited by several factors. One of these is expensive raw material, because it requires certain physical properties. Two most popular metal additive manufacturing methods are printing from powder and printing from wire. Wire is usually produced by drawing it from rod. Rod can be produced by directional solidification, which is well known method to study the microstructure formation depending on various parameters during solidification. In this study directional solidification of A360 aluminum alloy with electromagnetic interaction is investigated. Aluminum alloy is induction melted and then directionally solidified into the rod 12-20 mm in diameter. Aim of this work is to investigate the role of axial DC magnetic field and electric current interaction on the grain refinement and mechanical properties of A360 aluminum alloy. It is found that electromagnetic interaction can be the approach to refine the grains, regulate the growth of oriented columnar grains and to improve mechanical properties of the material.

Keywords: *Aluminum alloys, direct chill casting, directional solidification, electromagnetic processing of materials, mechanical properties.*

1. Introduction

Additive manufacturing of metals unlocks new possibilities to produce complicated custom shape parts in a short time and with less material consumption. Nowadays the metal 3D printing market is a rapidly rising industry of wide variety of applications[1]. With the market growth more resources are invested in development of new technologies and materials for additive manufacturing. For metal additive manufacturing it is important that the raw material has certain properties and fine-grained isotropic microstructure. Aluminum alloys are one on the perspective materials used for additive manufacturing because of their wide range of applications and low melting temperature[2]. Aluminum is perspective in various engineering applications because it is common material with lots of different alloys with fine-tuned properties for specific applications. There are several additive manufacturing methods how aluminum parts can be produced. Most common is additive manufacturing from powder[3]. Powder is sintered by laser or electric arc layer by layer. This process has several drawbacks, because it is slow, produces lot of waste, and raw material is expensive. For additive manufacturing aluminum powder should be spherical particles with narrow size distribution and isotropic microstructure. This powder is usually produced by atomization process[4]. Other alternative method is additive manufacturing using wire as starting material. Additive manufacturing from wire is cheaper and allows to achieve higher production speed, but accuracy is lower and shape possibilities are limited. This process is in fact metal inert gas welding process, where aluminum wire is welded to the part under inert gas stream[5]. Aluminum wire can be welded by electric arc or laser[6]. Wire for aluminum additive manufacturing is produced by drawing it from rod. Wire material for additive manufacturing needs to have fine grained isotropic structure, low porosity, and good homogeneity. These rods are being produced by directional solidification to avoid shrinkage porosity and large oriented grain growth. Direct chill casting is one of the methods for rod production, where rod is pulled from liquid melt and solid part is chilled by liquid or gas jets[7].

Control of metallic alloy solidification process is important because properties of the same alloy may vary in large amplitude depending on circumstances and processing during solidification. One of the methods is control of the melt flow during solidification, which greatly affects the local heat and mass transfer near the solidification interface. Electromagnetic contactless methods for improved solidification process are one of the ways how to decrease grain size and improve homogeneity of the metal alloys[8]. Electromagnetic interaction on directional solidification of metal alloys and composites have been investigated is various contexts showing that in many cases it is the means how to achieve different microstructure and improved mechanical properties[9]. There are numerous research works on various electromagnetic methods during directional solidification of various metallic alloys. Static magnetic field is used to damp the liquid phase convection. It is shown that even moderate magnetic field of 0.1 T is sufficient to significantly change the molten phase flow of Sn-Pb alloy as demonstrated by Hachani et al.[10]. If solidification velocity is low (up to 0.5 mm/s) directional solidification is significantly affected by static magnetic

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field, where the main mechanism for several metals can be thermoelectromagnetic effect at the solidification interface[11]. DC and pulsed electromagnetic interactions are known to have effect on dendrite breaking and grain refining[12]. Alternating magnetic field and DC magnetic field combination on the microstructure of directionally solidified alloys have been studied by several authors, showing the significance of these contactless methods on the microstructure and homogeneity of the solidified material[13,14].

2. Experiment

In this work we aim to experimentally study the simultaneously applied static magnetic field and DC electric current through the directionally solidified aluminum alloy rod. For these experiments we chose commercial A360 alloy, which is known material for dye casting. This alloy has dendritic solidification interface with profound mushy zone between solid and liquid phases[15].

Our experimental setup is designed to investigate electromagnetic interaction on the solidification interface during directional solidification of aluminum alloys using water jet direct chill casting. Magnetic field at the solidification interface has only axial component, but field gradient is rather high, thus precise position of solidification interface is important. Concept of permanent magnet assembly is similar as used in liquid silicon processing experiment[16]. Electric current can be applied through the solidification interface. One electrode is connected to the bottom seed rod, while the top electrode is immersed in the upper crucible with molten aluminum as shown in experimental scheme in Figure 1a. Aluminum is melted and heated up to 700 °C by induction in the top crucible. Crucible is sealed and argon pressure of 0.25 Bar is applied to increase the metal flow and to overcome the surface tension in case of small metal depth. Bottom seed rod is lowered by programmable stepper motor. Solidification takes place in the middle of the thermally resistant boron nitride tube. Thermal problem in the axisymmetric problem is numerically using Comsol Multiphysics software. Results are shown in Figure 1b.

Static magnetic field of 0.45 T is provided by permanent magnet assembly placed around the solidification zone. Magnet is assembled form 16 pieces of segment shape NdFeB N42 grade magnets and outer iron yoke. Magnet system is shown in Figure 2A, numerical model of magnetic flux density calculation is shown in Figure 2B. Calculated magnetic field values along central axis and radial coordinate at the middle of the magnet system are shown in Figure 2C and Figure 2D. In this way magnetic flux density in the 80 mm diameter bore of the magnet is increased. If electric current is applied parallel to the magnetic field, then Lorentz force appears at the solidification interface. In such configuration Lorentz force drives small scale melt rotation around each individual dendrite[17]. Microscale convection have influence on the heat and mass transfer.

3. Materials and Methods

A360 aluminum alloy is used for the experiments as it is alloy with well-known properties, which are summarized in Table 1. Primary dendrite sizes for this alloy solidified with velocity of 2 mm/s is around 50 μm[19], which agrees well with observations from our experiments. Electric current of 157 A is applied through the 20 mm diameter, thus current density of 0.5 A/mm^2 is reached. At the solidification interface magnetic field is applied parallel to electric current direction, thus Lorentz force appears only if current is diverging or converging.

Schematic picture of dendrite geometry during solidification is shown in Figure 3. Mushy zone thickness for binary alloy can be estimated from Equation 1[20].

$$h = \frac{m\left(C_E - C_0\right)}{\theta} \tag{1}$$

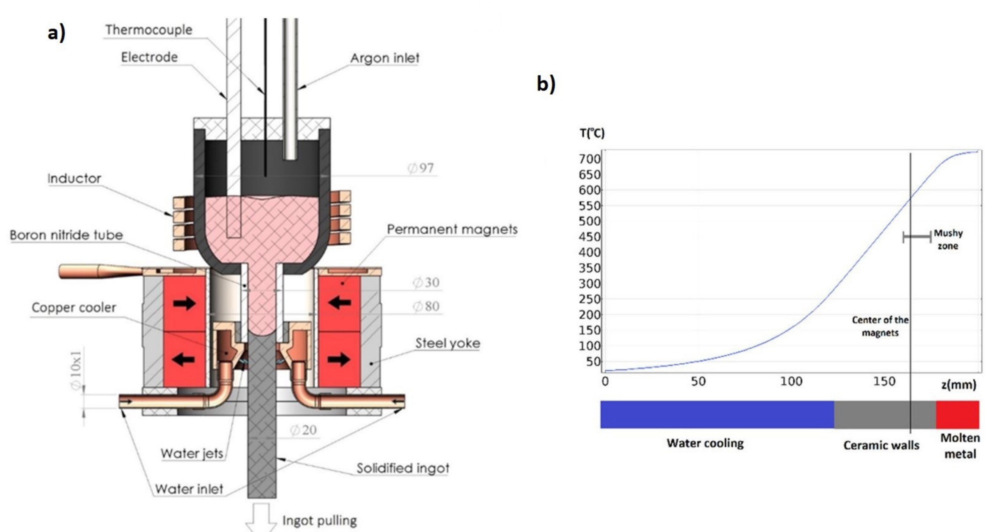

Figure 1. Directional solidification experiment: a) Cross section of the experimental setup; b) Temperature distribution along the symmetry axis.

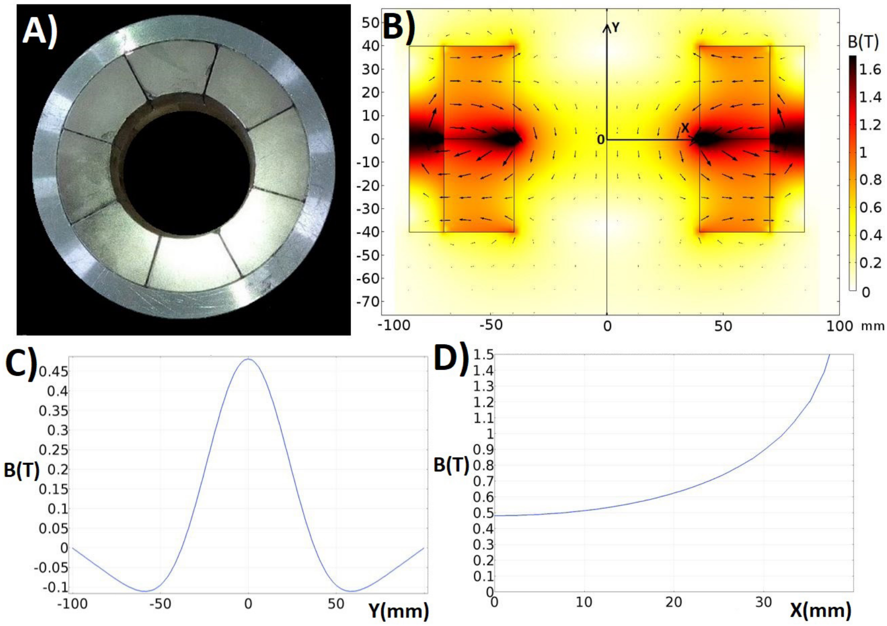

Figure 2. Permanent magnet system to create 0.45 T DC magnetic field in 80 mm diameter bore; a) Assembled magnet system; b) Axysymmetric numerical model; c) magnetic field induction along y axis; d) magnetic field induction along x axis.

Table 1. Physical properties of A360 alloy.

Property	Symbol	Value	Unit
Density (s)	ρ_s	2600	kg/m^3
Density (l)	ρ	2300	kg/m^3
Electric conductivity (s)	σ_s	8	Msim/m
Electric conductivity (l)	σ	4	Msim/m
Thermal conductivity	λ	100	W/m·K
Dynamic viscosity	μ	0.02	Pa·s
Liquidus slope	m	0.8	%/K
Eutectic concentration (Al-Si)	C_E	12.6	%
Melting temperature	T_m	557-596	^{o}C

A360 Composition[18]: Si 9-10%, Fe 1.3%, Cu 0.6%, Mg 0.5%, Ni 0.5%, Mn 0.35%, Sn 0.15%.

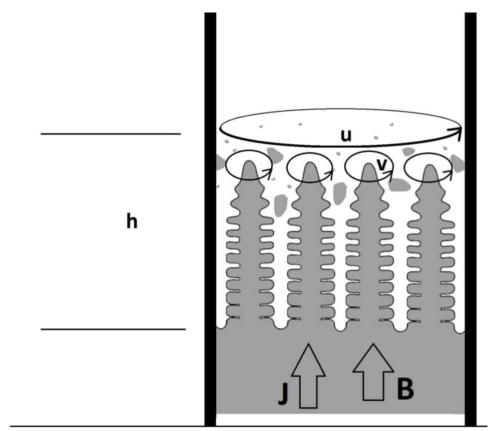

Figure 3. Schematic image of dendritic directional solidification and mushy zone. Electric current and magnetic field caused convection: u-crucible scale, v- dendrite scale.

For A360 alloy with temperature gradient at the solidification interface of 7 K/mm we get that mushy zone thickness is 0.35 mm. This estimation is in good agreement with observed primary grain structure obtained in our experiments. To estimate the melt flow velocity during solidification, characteristic dimensionless numbers are calculated. MHD flow is characterized by interaction parameter N, which indicates ratio between electromagnetic and inertial forces.

$$N = \frac{\sigma B^2 R}{\rho u} \tag{2}$$

Hartman number characterizes ratio of electromagnetic force to the viscous forces:

$$Ha = BR\sqrt{\frac{\sigma}{\mu}} \tag{3}$$

Calculating dimensionless numbers for our experimental setup and using material properties from Table 1 we get. N=2000 and Ha=60, which means that inertial and viscous forces are small and melt flow is mainly governed by electromagnetic forces. Crucible scale flow is this case is small, because numerical model shows that solidification front is flat. Dendrite scale melt flow velocity can be estimated by solving simplified Navier-Stokes equation balancing viscous and electromagnetic forces and neglecting inertial term.

$$\mu \frac{u}{R^2} + \sigma u B^2 = jB\left(1 - \frac{\sigma_s}{\sigma}\right)c \quad (4)$$

Main component of the electric current and magnetic field is parallel. Perpendicular component depends on the ratio between electrical conductivities and the morphology of the mushy zone, which is represented by the constant c in Equation 4. Constant c shows what is the diameter/length ratio of primary dendrites. It can be estimated from mushy zone thickness and characteristic grain size in microstructure for a given alloy. In our case we can assume that c=1/5. From Equation 4 we can calculate that characteristic convection velocity is 0.8 mm/s. This means that local convection velocity around each dendrite arm is rather fast and makes two revolutions per second.

4. Results and Discussion

In interdendritic space melt flows from two neighboring dendrites partly cancels out while near the crucible wall flow is not compensated. From these analytical calculations we may conclude that small scale convection leads to improved heat and mass transfer near the dendrites. Convection is the mechanism, which helps to dissipate latent heat and homogenize the concentration. Numerical simulation, calculating current distribution, Lorentz force and liquid phase flow in mushy zone is developed in Comsol Multiphysics 6.0. Three-dimensional model in simplified dendrite mesh shows that current has component perpendicular to axis near the tip of the dendrites as shown in Figure 4a. Lorentz force distribution and velocity at the dendrite middle plane are shown in Figure 4b and Figure 4c. Velocity field confirms that in the middle between dendrites the flow is small, while it increases near the crucible wall. In vertical cross section velocity field does not extend far above the mush zone as shown in Figure 4d. Results of the numerical model are summarized in Figure 4. Velocity agreement between analytical estimation and numerical model are good. We conducted series of directional solidification experiments. Experimental setup is similar like classic Bridgman solidification experimental setup[21].

Directional solidification experiments with A360 aluminum alloy were done with solidification velocity of 2 mm/s. After directional solidification samples are cut and microscopy and microhardness and tensile strength tests are performed.

Microscopy pictures of the solidified samples are summarized in Figure 5, showing both transverse and longitudinal cross sections of the crystallized samples. Experimental results demonstrate that solidification without electromagnetic fields leads to columnar microstructure, which can be seen in Figure 5b. Applied static magnetic field causes this longitudinal structure to disappear as shown in Figure 5d. Such shift is columnar to equiaxed grain structure transition due to electromagnetic effect is known and reported in several scientific works. If electric current is injected parallel to magnetic field, significant small-scale melt convection takes place around the primary dendrites. This leads to radically increased heat transfer between solid and liquid phases, resulting in fine grained equiaxed structure formation and lots of eutectic phase regions, where components are well mixed.

Directionally solidified rod is machined into test samples 6 mm in diameter according to the ASTM E8 standard. Before mechanical testing samples were heat treated according to T6 heat treatment process. Ultimate tensile strength of the materials is tested using Zwick/Roell Z100 testing equipment. Our tested sample and 8 mm displacement sensor is shown on Figure 6a, while collection of samples are shown on Figure 6b. Standard A360 alloy ultimate tensile strength (UTS) is 317 MPa[22]. Stretching force versus displacement of all three

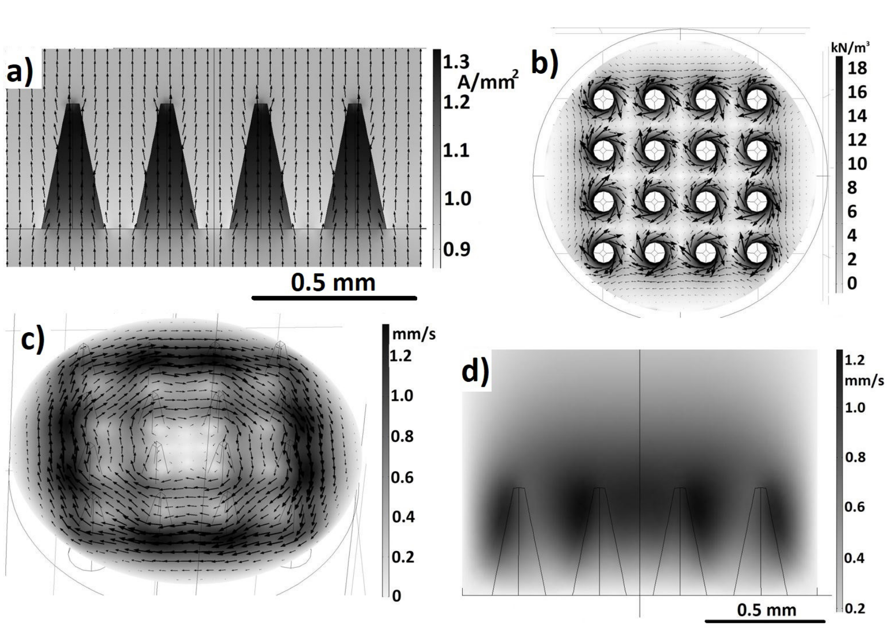

Figure 4. Numerical simulation results of melt flow in mushy zone: a) Electric current distribution; b) Lorentz force distribution at the middle height; c) Velocity distribution at the middle height; d) Velocity magnitude distribution at the vertical plain.

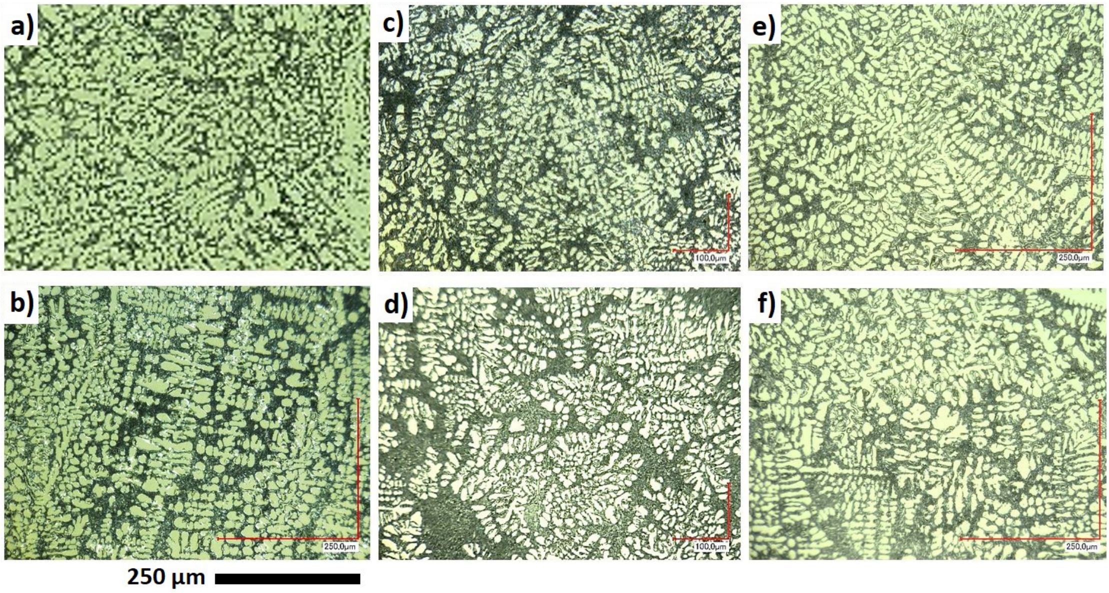

Figure 5. Directionally solidified A360 aluminium with solidification velocity of 2 mm/s. a,b) reference; c,d) B=0.4T, I=157 A; e,f) B=0.4T. Top row is perpendicular cross section, bottom is parallel to solidification direction.

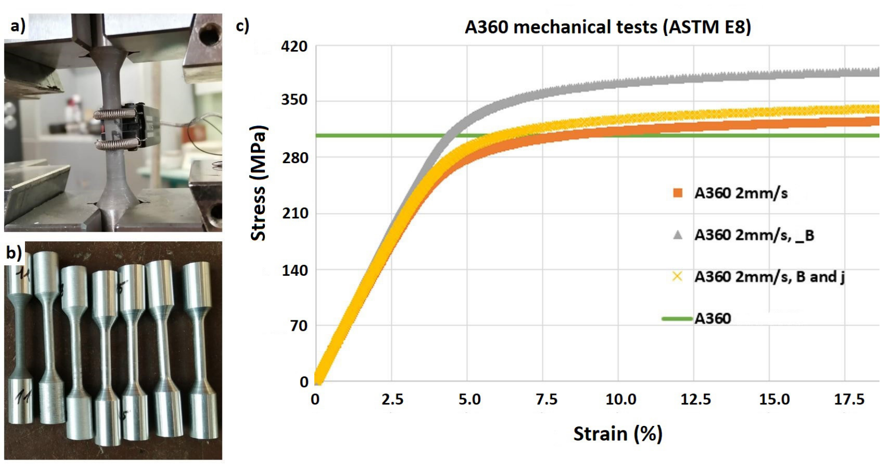

Figure 6. Mechanical test results: a) Elongation measurement sensor on the sample, b) Samples prepared according to ASTM E8 standard, c) Experimental results for different A360 samples.

Table 2. Comparison of mechanical properties between A360 alloy ingots solidified in various regimes.

	A360 Die casted[18]	Solidified at 2 mm/s	Solidified at 2mm/s (B_{DC}=0.4 T)	Solidified at 2mm/s (B_{DC}=0.4 T, j=1 A/mm^2)
Yield strength (MPa)	170	242	315	236
Youngs modulus (GPa)	70	70.6	71	70.8
Ultimate tensile strength (MPa)	317	322	395	346

samples are shown on Figure 6c. From these data mechanical properties are calculated and summarized in Table 2.

For all obtained samples the UTS was above the standard value. – for reference 332 MPa, for sample with magnetic field and current 346 MPa and surprisingly for only with magnetic field 395 MPa. For detailed analysis higher quantity of UTS tests should be done, however tests show that at least some electromagnetic treatment during crystallization can give an improvement in ultimate tensile strength. Similar tendency was obtained with sample fracture as well, it was observed that treated samples are more ductile. Youngs modulus of different sampled does not show significant variation and agreed well with the value from literature. Microhardness tests shows that for all samples Vickers hardness is 128 HV.

Experimental results demonstrate that microstructure of the solidified A360 aluminum alloy is affected by the applied electromagnetic interaction. It is found that applied axial magnetic field during directional solidification leads to finer grain structure and affects columnar to equiaxed transition (CET). It is known that CET can be affected by applied magnetic fields[23]. Magnetic field has several effects on liquid metal flow. Firstly, large scale convection perpendicular to magnetic field is suppressed and secondly electric current and magnetic field creates new convection in mushy zone. This type of microcirculation around oriented primary dendrite arms affects the heat transport and is responsible for improved microstructure. Numerical model of melt electromagnetic convection in Figure 4c and analytical estimation shows that melt flow of 1 mm/s exists in mushy zone as a result of current and applied magnetic field interaction. Directionally solidified material has better mechanical properties, than die casted sample. Directionally solidified sample with improved properties can be perspective raw material for drawing into high quality wire suitable for additive manufacturing.

5. Conclusions

This work demonstrates that directional solidification microstructure in aluminum A360 alloy can be modified by applied electromagnetic interaction with the axial static magnetic field and DC electric current. Lorentz force modifies columnar to equiaxed transition and refines grains, leading to more isotropic structure of directionally solidified ingot. Improved mechanical properties are observed in directionally solidified samples, with forced convection caused by electromagnetic forces. As a continuation of this work, it is planned to develop this method for electromagnetically improved Al alloy and Al based metal matrix composites for improved casting process.

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