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A STUDY OF THE EFFECT OF ROTARY ELECTROMAGNETIC STIRRING ON THE SOLIDIFICATION MICROSTRUCTURE OF ALUMINUM ALLOYS

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Abstract

Electromagnetic stirring can be used in direct chill casting processes, in order to refine the cast microstructures, as well as to improve the surface quality of the Aluminum castings. The present paper reports on the effect of Rotary Electromagnetic Stirring (Rotary-EMS) on the cast microstructure of two different aluminum alloys, A356 and AA2024. Along with the casting experiments, a numerical model was developed in order to calculate the external Lorenz forces created within the ceramic crucible during electromagnetic stirring of the melt. The magnetic flux distribution was predicted by solving the Maxwell equations and then validated through previous experimental results. According to the casting experiments, the rotating magnetic field has a positive influence on the refinement of the dendritic structure of A356 samples. Similarly, electromagnetic stirring of AA2024 melt during solidification, helped in the homogenization of the alloying element distributions at both the micro and macro scales.

Introduction

Rotating electromagnetic fields have been widely employed in the metals casting industries, as well as for single crystal growth, in order to control the fluid flow and to improve the cast structures during solidification [1-3]. The technique has been mostly used in the continuous casting of steel and aluminum billets, aiming at improving the quality of these products by stirring the melt during solidification [4-6]. The Rotary-EMS in the mold region of the caster is applied for flow control, and for reducing the amount of inclusions and surface defects, while using electromagnetic stirring beneath the mold is used to, so as extend the equiaxed structure zone, and to decrease macro-segregation. Electromagnetic stirring has been successfully employed in both ferrous and non-ferrous alloy castings, to improve the product's quality, such as grain refinement, and homogeneity of the structure in terms of the distribution of alloying elements [3-6].

Various numerical and experimental studies can be found in the literature concerning the theory, and applications, of Rotary-EMS in materials manufacturing. Although the development and application of Rotary-EMS dates back to late 1900's for melt stirring in steel continuous casting [3, 4], research work has recently focused on the application of Rotary-EMS for other metal casting processes, in order to improve their microstructures and the quality of the casting products. Mappeli et.al, [7] studied the application of electromagnetic stirring for the homogenization of aluminum billet casting, by performing experimental work together with numerical modeling analysis, in a semi-continuous casting system. They proved that increasing current intensity resulted in the refinement of the grain size, and a better homogenization of the microstructural features. In another study, Lu et.al.[8], investigated the effect of a 3-phase rotary magnetic field on the refining of primary Silicon (Si), in the hypereutectic Al–Si alloy. The authors proved that an optimized electromagnetic intensity causes the precipitates to be refined and distributed homogeneously within the structure, while further increases of magnetic intensity makes the particles congregate and becomes coarser. A research study was carried out by Jung et.al. [9], in order to control the grain size of Al-7%Si, using a combination of EMS and Strontium “Sr” modification, as a grain refiner. They showed that melt stirring enhances the effect of “Sr” on the modification of the primary Al, and on the eutectic “Si” particles. Similarly, Metan et. al. [10] focused on the combined effects of a grain refiner, (AlTi5B1), and EMS, to control the grain size of hypoeutectic Al-Si alloy. They showed that the addition of a grain refiner is more effective in grain refinement, than EMS; nonetheless, it has been confirmed that the best grain refinement effect can be achieved through a combination of intensive electromagnetic stirring, when using a grain refiner. However, grain refining under intensive EMS leads to the formation of a segregation zone.

In the present study, the influence of rotational electromagnetic stirring on fluid flows, grain refinement, and a reduction in segregation, has been investigated for cast structure of Al-alloys. Two aluminum alloys, namely A356, and AA2024, were studied, in order to evaluate their microstructures and elemental segregations in the presence of a Rotary-EMS. The findings from this study are comparable with those already reported in the literature and could be of help in designing an appropriate Rotary-EMS unit for an alloy casting process.

Numerical and Experimental Description

Two types of Al alloys (A356 and AA2024) were melted in a ceramic crucible, to which a 3-phase electromagnetic field was applied. The melt was subsequently cooled and solidified under a rotary electromagnetic field. Besides the experiments, a numerical model was developed, in order to simulate the effect of Rotary-EMS on the fluid flows within the crucible region.

Numerical Model

A 3-D numerical model was developed to simulate the electromagnetic field induced within the crucible as a result of a 3-Phase Rotary-EMS. The liquid aluminum was considered as the working fluid for all simulations in this study. Figure 1 shows the calculation domain considered in this work.

In this study, the following assumptions were made and applied, in order to simplify the numerical modeling:

a) The molten metal was considered to be an incompressible, Newtonian fluid.
b) The working fluid was operating under isothermal conditions, and solidification of the molten metal was not considered.

c) The free surface of the liquid aluminum in crucible was assumed flat.
d) All the physical properties of the liquid aluminum were considered constant.
e) The electromagnetic field was considered to be harmonic and the excitation was assumed to be sinusoidal.

Based on the above assumptions, three-dimensional time-averaged Navier-Stokes equations, coupled with the continuity equation, the Standard k- ϵ turbulence equations, and the electromagnetic induction equation, were solved within the crucible cavity.

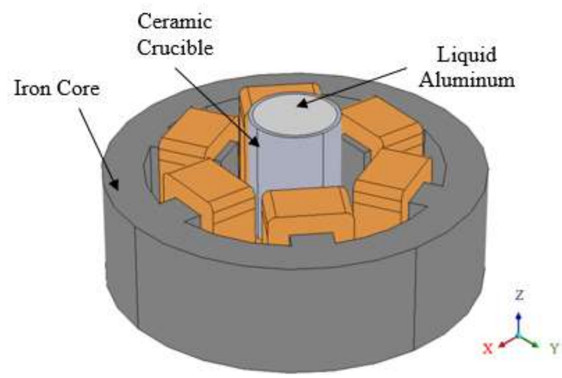


Fig.1. Calculation domain in a crucible using a three-phase Rotary-EMS

<u>Experimental Set-up and Procedure</u>

The experimental set-up consists of a vertical furnace surrounded by a 3-phase rotational electromagnetic device. A water cooling system was applied to circulate water inside its copper coils, in order to prevent any damage to them during electromagnetic stirring. A 220 V electrical power supply was used for this experiment. The power supply provides 10 Amp, and the current frequency on the input current can vary from 10Hz to 60 Hz.

The chemical composition of the A356 and AA2024 alloys were analyzed using Spark Emission Spectroscopy (SES), and are given in Table 1.

A ceramic crucible was used as the container for molten aluminum alloys. Small pieces of Al alloy were placed in the crucible, which was located in the furnace. The crucible was heated up to 730^{o} C, in order to melt the charge. To control the temperature of molten metal within the crucible, a K-type thermocouple was used. Once the aluminum alloys reached the correct temperature, the furnace was turned off and then the EMS system was switched on to stir the melt. The EMS system kept acting until solidification was completed. The solidified melt (ingot) was then removed from the crucible, and sectioned longitudinally, along its mid-plane. The mid-cross section samples were taken from the solidified ingot, for microstructural analysis. The metallographic samples, polished and etched using Keller’s etchant, were analyzed using an optical microscope (OM). The Scanning Electron equipped with Energy Dispersive X-Ray Spectroscopy (EDS) was used for the micro-analysis of the microstructure of cast samples.

Table 1. The chemical compositions of Aluminum alloys in (wt%)

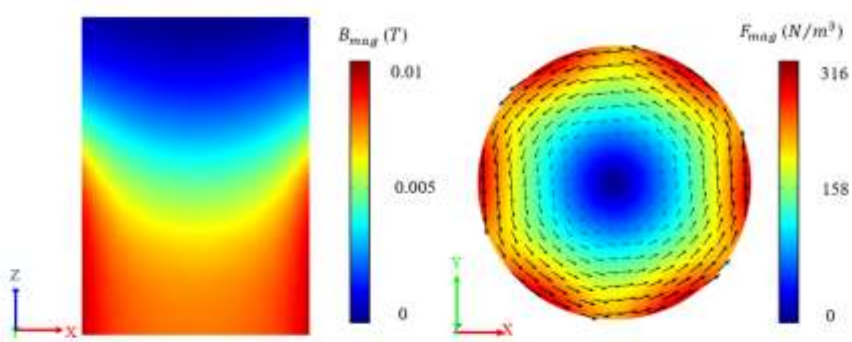
Elements / Alloy Type	Cu	Mg	Fe	Mn	Si	Zn	Cr	Ni	Ti	Al
A356	-	0.46	0.13	-	7.7	-	-	-	0.02	Balance
AA2024	4.53	1.51	0.464	0.534	0.33	0.089	0.014	0.1	0.011	Balance

Result and Discussion

In the first part of this section, the computed results of the EMS numerical model are presented, and discussed. Then, the experimental results regarding the effects of EMS on microstructure refinement of A356 casting, as well as the influence of EMS on the distribution of alloying elements in AA2024 alloy casting, are described.

Numerical Modeling Results

The electromagnetic model was employed to predict the magnetic flux density pattern within the crucible. The selected frequency applied in this study was 10Hz. Figure 2 shows the magnetic flux distribution at the vertical center plane of the crucible, together with the averaged Lorentz forces generated at the horizontal cross- sectional plane, near the bottom of the crucible. Due to the location of the crucible vs the EMS system, the maximum magnetic field is induced at the bottom of the mold. Subsequently, the magnetic field starts to decay by moving from the bottom to the top of the crucible. Similarly, the magnitude of the magnetic flux density and the resultant Lorenz forces also decrease, from the surface to the centerline of the crucible.

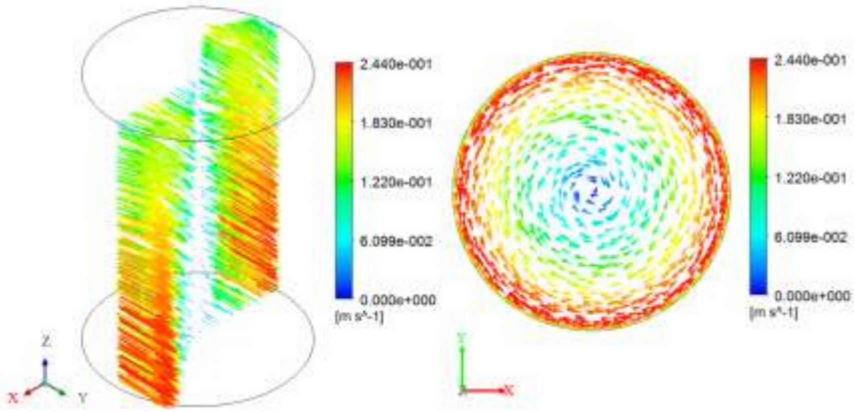


(a) (b)

Fig.2. (a) Magnetic flux density contours at the vertical central cross-sectional plane, and (b) Time-averaged Lorentz forces, at the horizontal cross sectional plane.

Figure 3 shows the velocity vectors at the horizontal cross- sectional plane near the bottom of the mold, and at the vertical center cross sectional plane. According to the magnitude and distribution of the Lorenz forces, the maximum magnitude of swirling flows appear at the edge of the crucible.

A comparison of Figure 2 with Figure 3, illustrates that there is a direct correlation between the magnetic flux density distributions, and the velocity field within the crucible. As shown in Figure 3, the intensity of swirling flows drops off, as moving from the bottom of the crucible to the top surface.



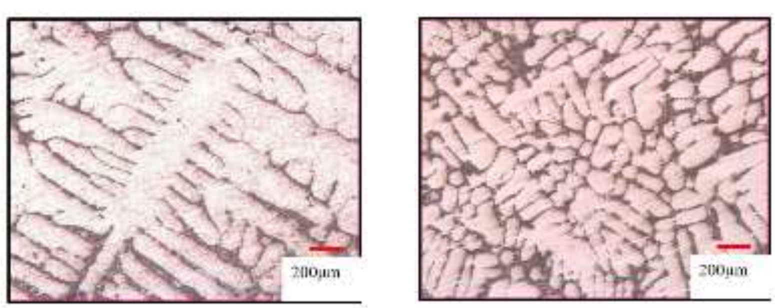
(a) (b)

Fig.3. Velocity vectors (a) at the vertical central cross-sectional plane, and (b) at the horizontal cross-sectional plane.

The Microstructural Effects of EMS on Casting A356 alloy

Figure 4 represents the microstructure of A356 casting samples, solidified in the crucible without, and in the presence of an electromagnetic field. As can be seen from this figure, the dendritic structure is significantly refined, by imposing an alternating magnetic field on the solidifying melt. Once an alternating magnetic field is applied to the solidifying melt, a Lorentz force distribution is developed within the liquid, in the vicinity of solid-liquid interface. This force field causes the melt, in the liquid, as well as in the mushy regions to move, leading to the fragmentation of dendrite's tips, and the refining of the cast structure.

Figure 5 illustrates the horizontal cross section of the A356 sample before, and after, etching the surface. According to Figure 5 (a), the macro cracks, and casting defects are decreased, by applying the rotating magnetic field, within the melt in the crucible. Additionally, the effect of EMS on grain refinement in the A356 alloy casting is observed.



(a) (b)

Fig.4. Microstructure of solidified A356 casting, (a) Without applying the EMS; (b) with the application of EMS.

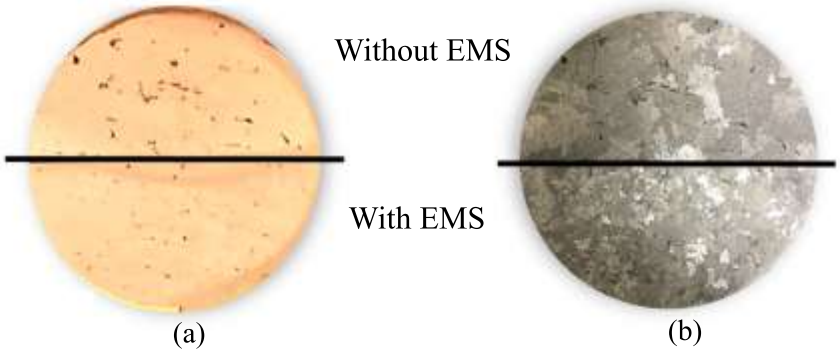


Fig.5. The effect of EMS on the microstructure, and the grain size of A356 alloy cast samples; (a)Before Etching and (b) after Etching.

<u>Electromagnetic Stirring Effect on the Segregation of Alloying Elements in AA2024 Casting</u>

For this set of experiment for AA2024, an EMS frequency of 10Hz was used for melt stirring. By applying EMS to the solidifying melt, the rotating flows cause the distribution of alloying elements to become more uniform. The elemental distribution map of copper and magnesium within the cast structure, with, and without, EMS, is illustrated in Figure 6, where lower Cu and Mg, segregations can be seen for the stirred sample.

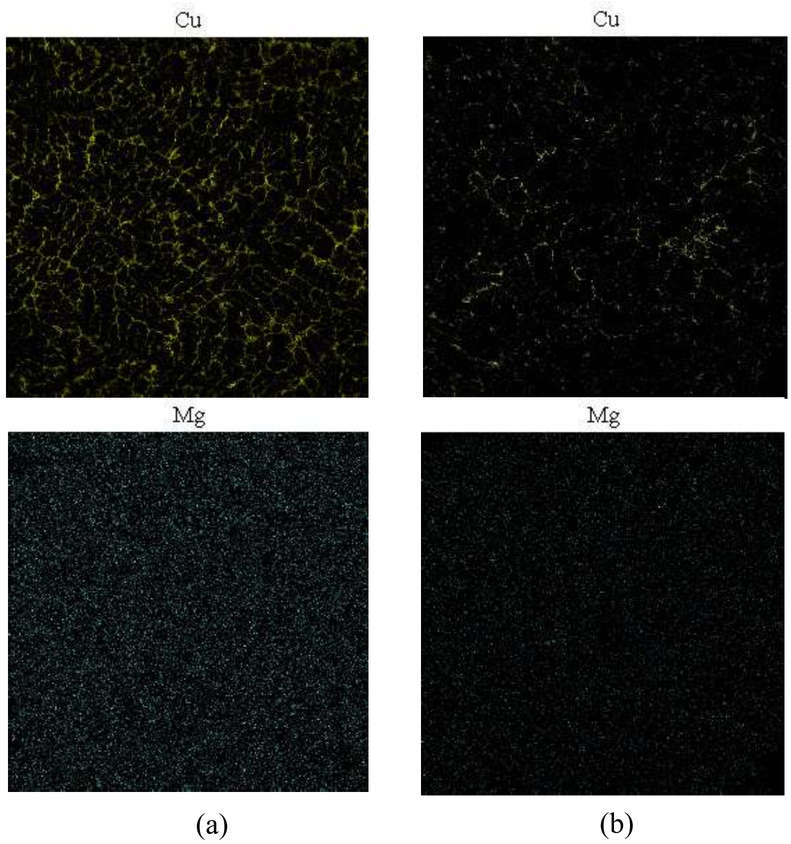


Fig.6. Dot elemental distribution map of Cu and Mg in AA2024 samples (a) without EMS; (b) with EMS

The rotational flow due to electromagnetic stirring also affects the segregation of alloying elements, at the macro-scale as well. This can be evaluated by measuring the concentration of alloying element in the center, and at the edge, of the casting, along the radial direction. The measurement of level of Cu element, at the center, and edge points, was carried out using Spark Emission Spectroscopy, and the results are presented in Table 2. The table presents the ratios of copper concentration at the center (C_{Center}), and at the edge point (C_{Edge}), as well as the average concentration ($C_{Average}$) of the element, plus the concentration difference ratio (so called as segregation index).

Table 2. Radial copper segregation ratios in AA2024 alloy casting, under different EMS conditions.

EMS condition	$C_{Center}/C_{Average}$	$C_{Edge}/C_{Average}$	$\Delta C/C_{Average}$
No stirring	1.84	0.58	1.26
With Stirring	1.17	0.78	0.4

As per the data presented in Table 2, by applying the EMS, the segregation index is decreased. This is a representative criterion for uniformity of distribution of alloying elements. The lower segregation index indicates a higher homogeneity of compositions within the castings.

Conclusions

Based on the current experimental and numerical results, the following conclusions can be drawn:

1. Flow patterns predicted by the numerical model reveal that a Rotary-EMS effectively stirs the melt, within the crucible, leading to enhancement of microstructure of the Al alloy castings.
2. Electromagnetic stirring of solidifying A356 melt leads to refinement of dendritic structure.
3. Electromagnetic stirring of AA2024 alloy during solidification resulted in a more uniform distribution of alloying elements.
4. Copper macro-segregation ratio at the center line of the ingot approaches 1, as a result of the EMS effect. This ratio changed from 1.84 for a non-stirred melt, to 1.17 for a stirred melt, for a frequency of 10Hz.

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References

1. P. Dold and K.W. Benz, "Rotating Magnetic Fields: Fluid Flow and Crystal Growth Applications", Progress in Crystal Growth and Characterization of Materials, 1999: pp. 7-38.
2. X.D. Wang,T.J. Li,Y. Fautrelle, M.D. Dupouy, J.Z. Jin, "Two Kinds of Magnetic Fields Induced by One Pair of Rotating Permanent Magnets and Their Application in Stirring and Controlling Molten Metal Flows", Journal of Crystal Growth, 2005, Vol. 275: pp.1473–1479.
3. K. Spitzer, M. Dubke, and K. Schwerdtfeger, "Rotational Electromagnetic Stirring in Continuous Casting of Round Strands", Metallurgical Transactions B, 1986, Vol. 17B: pp.119-131.
4. A.A. Tzavaras and H.D. Brody, "Electromagnetic Stirring and Continuous Casting – Achievements, Problems, and Goals", Journal of Metals, 1984, Vol. 36 (No. 3): pp. 31-37
5. L. Beitelman, "Effect of Mold EMS Design on Billet Casting Productivity and Product Quality", Canadian Metallurgical Quarterly, 1999, Vol. 38 (No. 5): pp. 301-309.
6. H. Q. Yu and M. Y. Zhu, "Influence of Electromagnetic Stirring on Transport Phenomena in Round Billet Continuous Casting Mold and Macrostructure of High Carbon Steel Billet", Ironmaking and Steelmaking, 2012, Vol. 39 (No. 8): pp. 574-584
7. C. Mapellia, A. Gruttadauriaa, and M. Peroni, "Application of Electromagnetic Stirring for the Homogenization of Aluminum Billet Cast in a Semi-Continuous Machine", Journal of Materials Processing Technology, 2010, Vol. 210 (No. 2): pp. 306–314.
8. D. Lu, Y. Jiang, G. Guan, R. Zhou, Z. Li, and R. Zhou, "Refinement of Primary Si in Hypereutectic Al–Si Alloy by Electromagnetic Stirring", Journal of Materials Processing Technology, 2007, Vol. 189: pp. 13–18.
9. B.I. Jung, C.H. Jung, T.K. Han, and Y.H. Kim, "Electromagnetic Stirring & Sr Modification in A356 Alloy", Journal of Materials Processing Technology, 2011, Vol. 111: pp. 69-73.
10. V. Metan, K. Eigenfeld, D. Rbiger, M. Leonhardt, and S. Eckert, "Grain Size Control in Al–Si Alloys by Grain Refinement and Electromagnetic Stirring", Journal of Alloys and Compounds, 2009, Vol. 487: pp. 163–172.