J Mater Sci (2012) 47:793–796
DOI 10.1007/s10853-011-5855-3

Quantitative metallographic assessment of the electromagnetic casting influence on the microstructure of 7075 Al alloy

Aleksandra Patarić · Marija Mihailović · Zvonko Gulišija

Received: 20 April 2011 / Accepted: 4 August 2011 / Published online: 16 August 2011

Abstract This study presents an attempt to obtain the better quality of an aluminum super-high strength alloy by application of electromagnetic field during the casting process. The conventional continuous casting process of aluminum alloys causes many defects, such as surface imperfections, grain boundary segregation, non-uniform grain size, and porosity. The better ingot surface along with the homogeneous fine-grained microstructure, and hence the better mechanical properties of the ingot, can be achieved by applying the electromagnetic casting process. The microstructure characterization, accompanied by quantitative metallographic assessment, reveals that it is possible to avoid or decrease many defects of as cast ingots during electromagnetic casting process. In this article, the microstructure of the samples of as cast 7075 aluminum alloy, obtained with and without electromagnetic field influence, was analyzed by optical microscope and the variation of key alloying elements content, i.e., Zn and Mg, through the ingot cross section was examined by chemical analysis. Besides, the microstructural parameters such as dendrite arm spacing, interdendritic space width, as well as eutecticum and intermetallic phases volume fraction, were measured using linear method. The electromagnetic field influence on the microstructure of the as cast 7075 Al alloy was evaluated based on measured quantitative metallographic data.

A. Patarić (✉) · M. Mihailović · Z. Gulišija
Institute for Technology of Nuclear and Other Mineral Raw Materials, Franchet d'Esperey, 11000 Belgrade, Serbia
e-mail: a.pataric@itnms.ac.rs

M. Mihailović
e-mail: m.mihailovic@itnms.ac.rs

Z. Gulišija
e-mail: z.gulisija@itnms.ac.rs

Introduction

Electromagnetic casting (EMC) is the technology developed as by combining the magneto hydrodynamics and casting technique. For improving this technique of casting, many studies has been made the last few years. Electromagnetic casting provides the opportunity which has never been achieved by conventional casting process. At the beginning, the application of electromagnetic casting has been aimed to obtain the better ingot surface, due to the reduced contact pressure between the mold and the metal. The reduced contact pressure is the result of potential force acting, as a horizontal component of Lorentz force density, which is being balanced by static pressure of the molten metal, thus, resulting in the formation of the convex surface meniscus, i.e., the decrease of the metal/mold contact surface and their friction [1–5]. The other component of the Lorentz force density is a rotational component, resulting in a forced convection in the molten metal, enabling enhanced flow of the melt and homogeneous bulk distribution of alloying elements [6–9]. The recent researches show that combining the main operating parameters of electromagnetic field, such as frequency and strength of electromagnetic field, this process can efficiently eliminate the other defects of as cast ingots. In this way, the great savings in energy and time can be achieved, but it requires extensive research work to be done. The investigations on the effect of electromagnetic, magnetic, and hydrodynamic phenomena on Al ingots started over a decade ago [10–14], but very little attention was paid to the characterization of microstructure and evaluation of the quantitative microstructural parameters.

In this article, the special attention was paid to the effect of electromagnetic field on the quantitative microstructural parameters (morphology, size, volume fraction, and distribution of phases). Knowing the microstructure–mechanical properties correlation, it is possible to obtain preferred ingot properties by controlling the main operating parameters and at the same time to avoid needs for additional operations, such as machining and prolonged homogenization. The research here is aimed to establish the possibility to obtain better quality of ingots at the very start of the production process through the proper combination of the main operating parameters.

Experimental

The chemical composition of the used EN AW 7075 alloy is shown in Table 1.

This is heat treatable very high strength alloy with wide application in aero and military industry, but it is characterized by a number of defects that occur during the solidification process: porosity, hot cracks, non-uniform grain size, and crystal segregation.

The experimental equipment consists of medium frequency induction furnace IP-100 with 100 kg capacity. There is a drainpipe, at the bottom of the furnace, with graphite crystallizer that is intensively cooled with water, with the flow rate of 3.6 m^3/h. At the same level with the graphite ring, there is a low frequency magnetic field, placed around the crystallizer itself. The number of turns of the coil was $N = 40$. The strength of electromagnetic field was 8000 At. The testing samples were taken out of ingots with a diameter of 80 mm, obtained by vertical continual casting. The casting temperature was in the range of 710–720 °C and it was controlled by a digital pyrometer. The average casting speed was 1.5 mm/s. The frequency of electromagnetic field was 30 Hz, because both, our previous experience [15], and literature data [1, 3, 5–7] indicate that this is the optimal frequency. The current intensity was 200 A. The noteworthy data on EMC operating parameters were found in [16], with a little bit lower values of frequency and current intensity.

The microstructure and the frequency of the electromagnetic field are closely related. The samples series 1 were obtained from the ingot casted without the presence of electromagnetic field to enable the evaluation of the field effect on the microstructure at samples series 2, obtained from the ingot casted in the presence of electromagnetic field with the frequency of 30 Hz.

Table 1 Chemical composition of alloy EN AW 7075

Element	Zn	Mg	Cu	Mn	Cr	Fe
Content %	5.51	2.29	1.45	0.13	0.19	0.14

The microstructure of samples was examined by optical microscopy using the image analysis device Leica Q500MC, after the usual metallographic preparation and etching in Keller's reagent (revealing morphology of Al segregation-solid solution and inter-metallic phase). The content variation of key alloying elements, Zn and Mg, was determined by chemical analysis of the samples taken from the cross section of both ingots, obtained with and without the electromagnetic field influence.

Results and discussion

Comparing the microstructure of samples series 1, obtained without the field effect (marked as sample 1) and of samples series 2 (marked as sample 2), obtained with the effect of electromagnetic field, it is obvious that the structure of sample 1 is more dendritic than the structure of sample 2, which is finer and with more emphasized cells. The characteristic microstructure appearance at the cross section of samples casted under different conditions is shown in Fig. 1. As it can be seen, the cellular/dendritic morphology is the result of Al segregation from the solid solution during the solidification process. Nevertheless, the morphology of the samples casted without the electromagnetic field effect, Fig. 1a, is more dendritic, in comparison with distinctive cells at Fig. 1b, obtained with the electromagnetic field influence.

Our studies have also included measurement of microstructural parameters: dendrite arm spacing (DAS), interdendritic space width (L_{IMP}) where intermetallic phases and eutecticum were separated, as well as their volume fraction, V_{VIMP}. They were acquired using linear method, through the measuring of total length of the line segments belonging to each phase and calculating the amount of intersects with phase boundaries. These parameters describe the structure dispersity and they are the consequence of the solidification conditions. For these quantitative microstructure analyses, the image analysis device Leica Q500MC was used (Table 2).

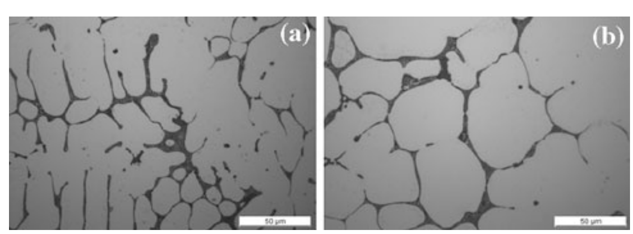

Fig. 1 Microstructure of sample cross section: sample 1 (**a**) and sample 2 (**b**), Keller's reagent, 500×

Table 2 Statistical values of the measurement of structural parameters

Parameter	DAS (μm)				L_{IMP} (μm)				V_{VIMP}	
Sample	Min	Max	av	$\pm\sigma$ (%)	Min	Max	av	$\pm\sigma$ (%)	$V_{VIMP\ (\%)}$	$\pm\sigma$ (%)
1	7.95	268.4	45.8	3.54	0.76	12.10	3.40	4.10	5.80	0.7
2	0.85	172.5	31.8	4.12	0.38	26.40	2.90	3.98	9.10	0.8

av an average value calculated over the entire measurement range

It can be seen that both parameters, DAS and L_{IMP}, decrease from sample 1, obtained without the electromagnetic field effect, toward the sample 2, casted with the electromagnetic filed presence, and that the decrease is a consequence of the electromagnetic field effect. These decreased parameters as a quantitative measure of microstructure are the result of applied low frequency (30 Hz) combined with higher current intensity (200 A). It also can be concluded, according to [15, 16], that applied low frequency and increased stirring current ensured finer grain size.

Since the conventional casting process does not provide a uniform motion of a melt and it causes slow loss of superheat at the mold/ingot interface, the appearance of many casting defects could not be avoided. On the other hand, during casting under the influence of electromagnetic field, due to the rotational component of the Lorentz force density, the strong electromagnetic stirring in the melt is achieved, so the dendrite arms are broken and detached, the heterogeneous nucleation is encouraged and the microstructure is more uniform through the entire cross section. The interdendritic space width is decreased under the influence of EMC, but the decrease of dendrite arm spacing is more considerable. This is a quantitative measure of the EMC influence on the microstructure of an ingot. This decrease of microstructural parameters, DAS and L_{IMP} can be obviously confirmed by the analysis of the cumulative distribution curves of both parameters, presented in Fig. 2a, b, respectively. The cumulative distribution curves, obtained as a sum of size classes frequency of occurrence for both, DAS and L_{IMP}.

The influence of the potential component of the Lorentz force density, besides the microstructure, can be observed at the macro level of the surface quality, as well. The quantitative measure of this influence can be followed through the analysis of the alloying elements content from the ingot surface, in sequential steps measurements, toward the ingot center.

The variation of elements content through the entire cross section was examined using chemical analysis. The Fig. 3 shows the distribution of alloying elements Zn and Mg along the radius of ingots. During the casting without electromagnetic field influence due to unequal conditions of solidification, the large inhomogeneity of alloying elements distribution can be seen.

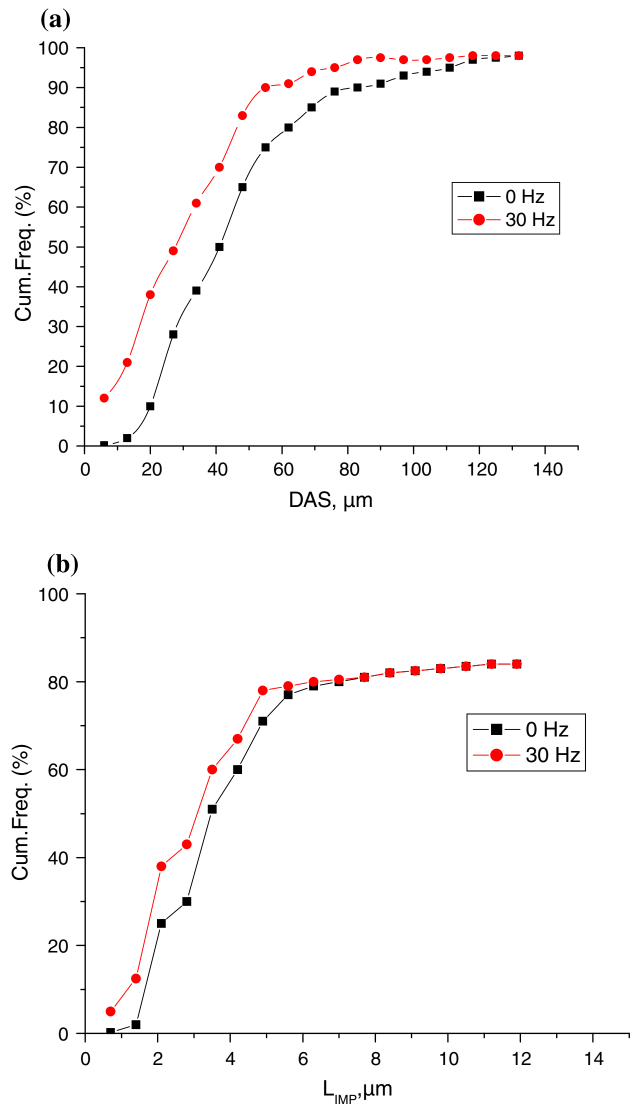

Fig. 2 Cumulative distribution curve of parameters DAS (**a**) and L_{IMP} (**b**) depending on operating parameters of electromagnetic field

On the surface of ingots, the content of alloying elements is significantly higher than in the center. The application of the electromagnetic field reduces the undercooling because the contact line between mold and metal is smaller, as the result of potential force, a horizontal component of Lorentz force density acting. In this way, the inhomogeneity of alloying elements distribution is reduced.

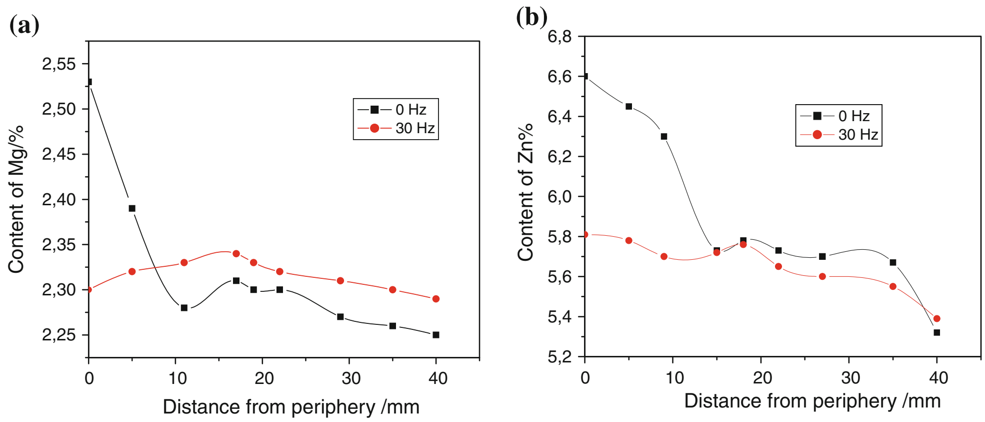

Fig. 3 Content of Mg element (**a**) and content of Zn element (**b**) along radius of samples with different casting conditions

Conclusions

The results presented in this article show the evident influence of the electromagnetic field during casting aluminum alloy 7075, as follows:

- low frequency of 30 Hz, and current intensity of 200 A, induced a finer and more homogenous microstructure;
- quantitative microstructural parameters, DAS and L_{IMP}, are decreased;
- inhomogeneity of alloying elements distribution is reduced.

Here, presented results are just a part of the wider research on the electromagnetic casting influence on the properties of Al alloys. The 7075 Al alloy is wrought alloy and further research will encompass investigation of EMC on mechanical properties of an ingot in terms of forging requirements, as well as the possibility to shorten or even avoid some steps of the long lasting and energy consumable process.

Acknowledgements The authors wish to thank the financial support from the Ministry of Science and Technological Development of the Republic of Serbia through the project 34002.

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