Microstructure as an essential aspect of EN AW 7075 aluminum alloy quality influenced by electromagnetic field during continuous casting process

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Abstract

Microstructure assessment is crucial for the design and production of high-quality alloys such as cast aluminum alloy ingots. Along with the effect of a more homogeneous microstructure to result in much better mechanical properties, better as-cast alloy quality indicates a higher efficiency of the aluminum alloys production process. During the aluminum alloy solidification process many microstructural defects can occur, which deteriorate the mechanical properties and hence decrease the usability of such an ingot. Application of the electromagnetic field during the vertical continuous casting process significantly reduces occurrence of these defects. In the present study, EN AW 7075 alloy samples were cast with and without application of an electromagnetic field and examined regarding the microstructure, electrical conductivity, and changes in the phase composition. The obtained results clearly show that it is possible to decrease or avoid casting defects by the electromagnetic field application as verified by the microstructure characterization and quantification, electrical conductivity tests and differential thermal analysis (DTA).

Keywords: microstructure assessment; DTA analysis; electrical conductivity.

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1. INTRODUCTION

Electromagnetic casting, a technology that links magneto-hydrodynamics and casting provides possibilities that could have never been attained by the conventional casting process [1]. Initially, electromagnetic casting was used with the aim to produce better ingot surfaces, as confirmed in literature [2]. This is enabled by a convex surface meniscus formed at the liquid metal/mold interface as a result of a balance of acting forces. The potential force, which is a horizontal component of the Lorentz force density, is balanced by the molten metal static pressure force, resulting in reduction of the contact pressure at the interface [3]. It was indicated that the revolving component of this force density leads to the creation of a melt vortex in the crystallizer, which supports uniform distribution of alloying elements. In addition, temperature distribution is also more uniform within the melt, which was confirmed experimentally [4], as well as by mathematical modeling [5]. Proper combination of performance parameters of the electromagnetic field (EMF), namely the electromagnetic field intensity and frequency, can lead to efficient elimination of defects in as-cast ingots [6]. Hao *et al.* [7] have discussed the parameters, including the heat transfer influence on the mechanism of grain refinement. Mapelli *et al.* [8] found that significant effects can be also obtained by increasing the current intensity while keeping the frequency constant.

Effects of EMF application on the structure, constituents as well as mechanical characteristics of an Al-Zn-Mg-Cu alloy, *i.e.* EN AW 7075 Al alloy were comprehensively investigated in several papers [9-11]. This material may become porous,

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with uneven grain sizes leading to segregation and cracks, which usually appear during the conventional casting and solidification process. These effects may limit exploitation of such a superior construction alloy, by diminishing the quantity of usable casting. Hence, obtaining a homogeneous casting was a challenge for many research groups. At the very beginning, Prodhan *et al.* [12] analyzed the solidification process of aluminum in sand molds at applying varying currents (AC/DC). Also, combinations of EMF and slit mold construction [13], and electromagnetic and ultrasonic fields [14] were explored. With the same aim, a homogenization treatment was applied on the EN AW 7075 alloy produced by EMF casting [15]. The process development needed a theoretical elucidation, so Dong *et al.* [16], proposed a discussion on the EMF effects on the alloy microstructure. It was proposed that the required features of an ingot can be achieved by adjusting the performance parameters, having in mind the relation between the microstructure and mechanical characteristics [17]. Since the EN AW 7075 aluminum alloy is well known for its remarkably high strength, which is widely applied in aircraft and military industries, it continues to challenge researchers to achieve improvements by application of different casting techniques [18] or heat treatment procedures [19].

In the present work, we have studied the effects of casting with the EMF application on the microstructure of the EN AW 7075 aluminum alloy. There are clear indicators in the published research that some technological operations, including machining and long-term heat treatment can be avoided [20,21]. In this way, great savings in energy and production time can make this process superb.

2. EXPERIMENTAL

2. 1. Sample casting

The experiment was conducted in a pilot scaled induction furnace with a drain and a graphite crystallizer, which is intensively water-cooled. The set-up consists of an induction coil surrounding the crystallizer, enabling to produce ingots of 80 mm in diameter during the vertical continuous casting process, with the possibility to change the field frequency during the same lot of material. The casting temperature was set to 720 °C. The experimental EMF frequency was set to 0, 20 and 30 Hz. This is chosen according to previous research [20], where it was shown that frequencies higher than 30 Hz do not improve properties of aluminum alloys. The current intensity was 200 A.

Three series of samples were produced, taken from ingots obtained at different operating parameters, and a representative sample from each of the series was selected. The set of samples numbered 1 are those cast without the EMF application and are considered as referring points for estimation of the EMF effects. The other samples, sets numbered 2 and 3, were produced by applying frequencies of 20 and 30 Hz, respectively. Each sample set was taken from five sites across the ingot cross-section. It must be noted that the sample position was considered, so that samples from different series were comparable.

2. 2. Sample characterization

The microstructure of samples was examined by optical and scanning electron microscopy (SEM). Optical microscopy was performed by a Leica Q500MC microscope (producer, country). Typical metallographic procedure implies using the Keller's and Barkerʹs reagent to expose morphology and to enable measuring of grain size [22].

The SEM micrographs were obtained by using a JEOL JSM-6610LV device (producer, country).

The electrical conductivity of samples was investigated by using a Sigmatest 2.069 (Foerster, country) by three measurements for each sample. Besides, a Shimadzu DTA-50 device (producer, country) was used for the differential thermal analysis (DTA). The analyses were conducted in nitrogen atmosphere, N_2, with flow rate of 20 ml min^{-1} and at a heating rate of 10 °C min^{-1}.

3. RESULTS AND DISCUSSION

3. 1. Microstructure characterization

For the study of the alloy microstructure, representative samples were chosen from each sample series 1.x, 2.x and 3.x, and marked as a sample 1, 2, and 3 respectively. Typical microstructures obtained by etching with the Keller's reagent of samples cast at various frequencies are presented in Figure 1. A more dendritic microstructure of the sample 1 obtained without the application of EMF is evident as compared to microstructures of the other two samples (obtained at EMF frequencies of 20 and 30 Hz), which are finer and exhibiting more distinctive cells. Obviously, the solidification process led to segregation of aluminum from the solid solution, which resulted in cellular and dendritic morphology. Microstructures of the samples obtained after etching in the Barker's reagent are presented in Figure 2.

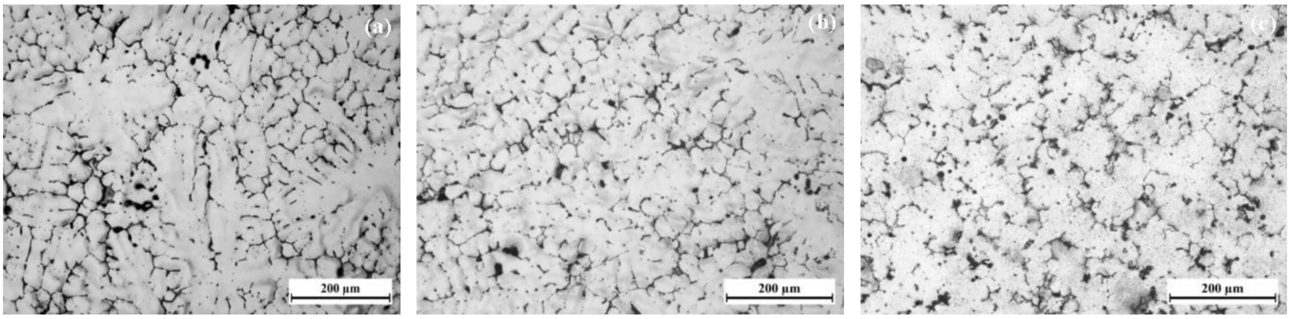

Figure 1. Optical micrographs of sample microstructures after etching with the Keller's reagent: a) sample 1 (control), b) sample 2 (20 Hz), c) sample 3 (30 Hz); (scale bar = 200 µm)

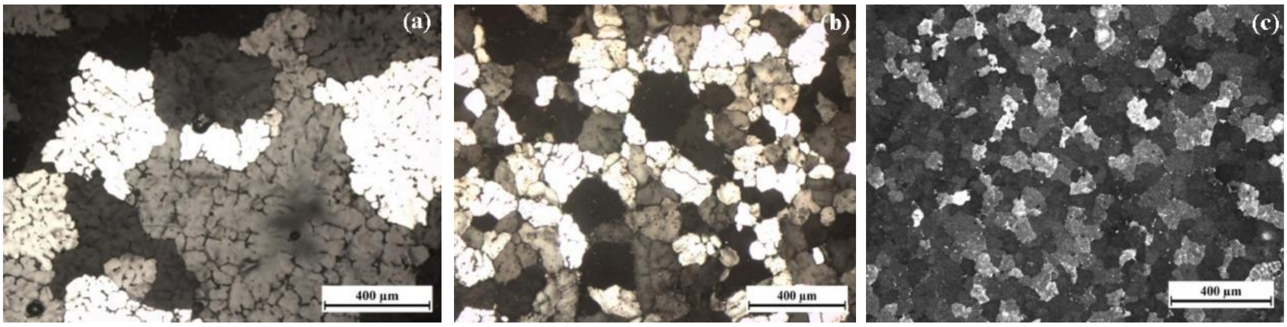

Figure 2. Optical micrographs of sample microstructures after etching with the Barker's reagent: a) sample 1 (control), b) sample 2 (20 Hz), c) sample 3 (30 Hz); (scale bar = 400 µm)

By analyzing the micrographs shown in Figure 2 it can be noticed that the sample 3 obtained at the EMF frequency of 30 Hz is the finest, with the smallest grain size. The sample 1 obtained without EMF application exhibited inhomogeneous structure with very uneven grain size. Table 1 summarizes the results of grain size measurements.

Table 1. Measured grain size values in as-cast EN AW Al 7075 alloys obtained with and without application of EMF at different frequencies

Sample	Grain size, µm			±σ / %
	Minum	Maximum	Average value	
Sample 1 (0 Hz)	124.96	464.96	344.41	3.2
Sample 2 (20 Hz)	98.36	266.75	197.56	3.9
Sample 3 (30 Hz)	87.28	189.35	101.98	3.1

The quantity of intermetallic phases and the secondary precipitates increased with the increase in the EMF frequency. Appearance of a secondary precipitate was observed in the sample 3 (30 Hz), as can be noticed in Fig. 3c. This secondary precipitate is uniform over the entire cross section.

The obtained results indicate that the EMF application during the continuous casting process provides a more homogeneous structure, not influencing the composition. Changes in the cast alloy composition could be obtained by annealing at desired temperatures.

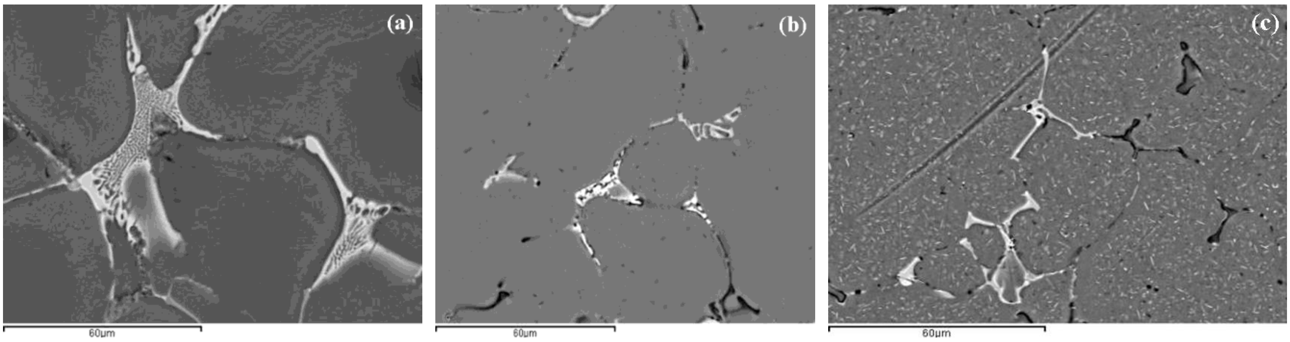

Figure 3. SEM micrographs of a) sample 1 (control), b) sample 2 (20 Hz), c) sample 3 (30 Hz); (scale bar = 60 μm)

3. 2. Electrical conductivity

Electrical conductivity of a solid solution can be an indication of its homogeneity due to the fact that different structural constituents exhibit different electrical conductivities, although this is not a distinctive measure.

Three measurements of this parameter were carried out for each sample as shown in Table 2. Samples produced with the application of EMF exhibited higher conductivities in comparison to the sample produced by conventional continuous casting. Also, the sample 3 obtained at the highest EMF frequency of 30 Hz has shown the highest conductivity values, and hence it should be the most homogeneous solid solution. Accordingly, homogeneously distributed secondary precipitate in the primary solid solution is visible in Figure 3c. Occurrence of this secondary precipitate in this sample resulted in a decrease in the lattice deformation of the primary Al solid solution and therefore the highest conductivity values (Table 2).

Table 2. Measured values of electrical conductivity

Sample	Electrical conductivity, MS / m				
	Measuring I	Measuring II	Measuring III	Average value	σ
Sample 1 (0Hz)	13.56	13.54	13.22	13.44	0.25
Sample 2 (20Hz)	14.09	14.08	14.10	14.09	0,01
Sample 3 (30Hz)	18.42	18.38	18.39	18.40	0,03

3. 3. Differential thermal analysis

Figure 4 shows DTA curves of the sample produced by conventional continuous casting (sample 1) and the sample produced with the application of EMF at the frequency of 30 Hz (sample 3). These two samples have been chosen as the most different.

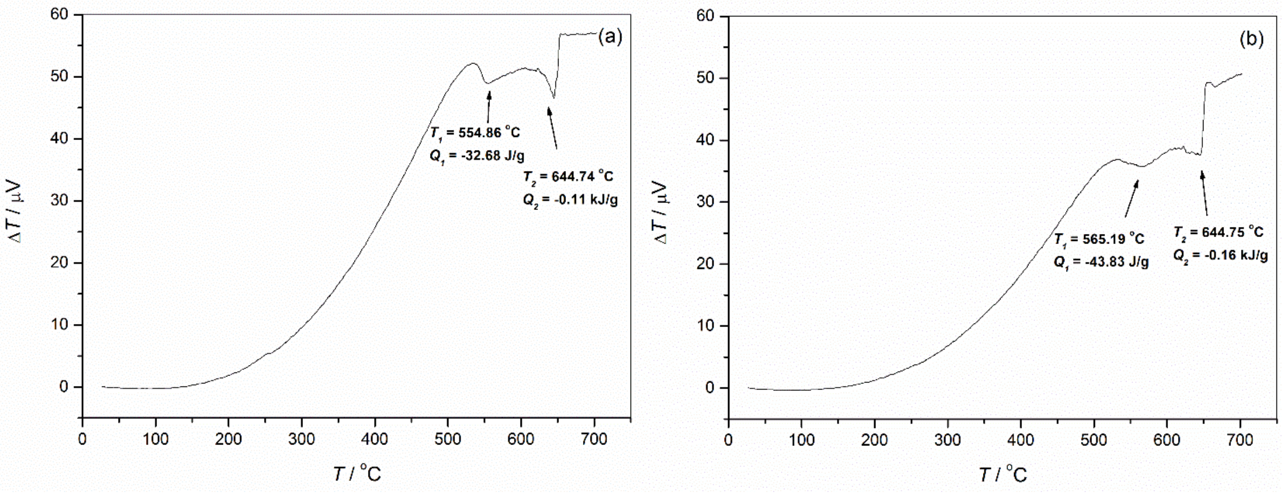

Figure 4. DTA curves of as-cast samples: a) sample 1, b) sample 3

Comparison of the thermograms shown in Figure 4 leads to a conclusion that the temperature range of both endothermic peaks is similar. This finding also indicates similar contents of non-equilibrium intermetallic phases, which precipitate either as eutectic or as individually precipitated phases, in both examined samples. There was a greater change in energy in the sample 3 as compared to the control sample 1. The absolute value of energy change at the temperature of 644.74 °C amounts to 45 % of that of the sample 1, while it is 34 % at the temperature of 565.19 °C (*i.e.* 554.86 °C for the sample 1). This finding means that the volume fraction of precipitated non-equilibrium intermetallic phases (IMP) in the sample 1 is lower than that in the sample 3.

Besides the IMP volume fraction, the size and distribution of these phases also affects both mechanical characteristics and electrical conductivity. It was proven that electrical resistivity increases with the increase in the thickness of intermetallic compounds [23]. The specimen with finer intermetallic phases, although exhibiting higher volume fractions, which is the case of the specimen 3, exhibits the highest values of electrical conductivity.

These results are in accordance with measured values of volume fractions of IMP for the same set of samples in our previous research [21]. The IMP volume fraction occurring in the sample 1 (control) is lower as compared to the sample 3 (30 Hz EMF). This analysis confirmed that the application of EMF influences the volume fraction of precipitated intermetallic phases, but it does not influence the alloy phase compositions.

4. CONCLUSION

Electromagnetic field has proven to be an effective tool to eliminate consequences of non-equilibrium solidification conditions during the conventional casting process. Microstructure of as-cast aluminum alloys is very significant because it defines further alloy exploitation possibilities. In the present study, the best results were achieved by the casting process with the application of EMF at 30 Hz frequency. It was shown that the microstructure becomes finer and more homogenous with increasing the frequency. The sample obtained at the highest frequency investigated (*i.e.* 30 Hz) had a less dendritic and more cellular microstructure. It is also observed that grains change in their size and shape from large and uneven grains to smaller and more uniform grains as the EMF was applied and frequency increased. At the same time, the highest applied EMF frequency (30 Hz) induced the appearance of a secondary precipitate, which is homogeneously distributed resulting in the highest values of electrical conductivity.

Differential thermal analysis confirmed that the EMF application did not change the phase composition of the alloy, but it affected the volume fraction of intermetallic phases. Hence, the usable properties of the alloy are improved. The application of EMF resulted in the finer structure and hence better properties of the alloy as-cast, so that usually applied additional thermal treatment can be avoided. Besides, better ingot surface quality, as a consequence of the uniform microstructure, enables avoidance of additional machinning. All this indicate that, together with better quality, EMF contributes to savings in material, energy, and time.

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SAŽETAK

Mikrostruktura kao bitan aspekt kvaliteta legure aluminijuma EN AW 7075 dobijene kontinuiranim procesom livenja pod uticajem elektromagnetnog polja

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(Naučni rad)

Određivanje i analiza mikrostrukture su presudni tokom dizajniranja i prilikom dobijanja legura aluminijuma visokog kvaliteta u livenom stanju. Pored neizbežne povezanosti homogenije mikrostrukture i boljih mehaničkih svojstava, bolji kvalitet u livenom stanju ukazuje i na veću efikasnost procesa proizvodnje legura aluminijuma. Tokom procesa očvršćavanja legure aluminijuma mogu se pojaviti mnogi mikrostrukturni nedostaci koji pogoršavaju mehanička svojstva, a samim tim i upotrebljivost takvog odlivka. Delovanje elektromagnetnog polja tokom procesa vertikalnog kontinualnog livenja značajno smanjuje pojavu ovih grešaka. Ovde prikazani rezultati dobijeni ispitivanjem mikrostrukture, električne provodljivosti i promene faznog sastava uzoraka legure EN AV 7075, odlivene u prisustvu elektromagnetnog polja, kao i bez njega, jasno pokazuju da je moguće smanjiti ili izbeći nedostatke livenja primenom elektromagnetnog polja. To je pokazano pomoću određivanja i analize mikrostrukture, ispitivanja električne provodljivosti i diferencijalne termičke analize (DTA).

Ključne reči: određivanje mikrostrukture; DTA analiza; električna provodljivost