Effect of Electromagnetic Field on the Microstructure of Continual Casting Al 2024 Alloy Ingots

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Abstract: This paper presents the investigation into the possibility for application of production process for casting aluminum alloys under the influence of electromagnetic field. The presented results were obtained from microstructure examination of Al alloy 2024 ingots casted with or without electromagnetic field. The microstructure characterization shows that under the influence of low-frequency (30-50 Hz) electromagnetic field it is possible to obtain finer and more homogeneous microstructure with reduced porosity. At the same time, the present phases were identified by EDX analyses and it confirms that there was no modification in phase composition under the influence of electromagnetic field. In the end, it is obvious in which way the operation parameters should be varied in order to get a good quality of ingots.

Introduction

Electromagnetic casting (EMC) is the technology developed as by combining the magnetic hydrodynamics and casting technique [1,2]. Electromagnetic forces, arising from the interaction of Eddy currents induced in the metal by inductor magnetic field, cause an increased flow of the fluid, forced convection, more uniform temperature field and weak gravitation influence thus changing the conditions of solidification. The advantage of EMC reflects in obtaining a better quality of ingots compared to conventional continuous casting process. [3]. Namely, the structure obtained is finer and more uniform through the cross section, with reduced segregation of alloy element and porosity [4,5]. Apart from that, due to the reduced contact pressure (result of electromagnetic field effect) between the mould and the metal, the quality of ingot surface is improved, having no need for additional machine processing. The investigations conducted in the world [5] were aimed to investigate the effect of electromagnetic, magnetic and hydrodynamic phenomena on Al ingots, but very little attention was given to the characterization of microstructure and mechanical properties.

This paper, as a part of wider investigations, should contribute to better knowledge of the effect of electromagnetic field on the obtained microstructure (morphology, size, volume fraction and distribution of phases) and properties of Al alloys. The chosen alloy was EN AW 2024 heat treatable, intended for forge with wide industry use. It is characterized by a number of defects that occur during the solidification process: porosity, hot cracks, non-uniformal grain size and crystal segregation.

Since the quality of final product is directly affected by these defects it is necessary to prevent or reduce their appearance by the choice of the appropriate process and optimal parameters of casting. To compare the results of electromagnetic casting, the process of vertical continual casting without the presence of low frequency electromagnetic field was selected.

Experimental procedure

The chemical composition of the used alloy EN AW 2024 (AlCu4Mg1Mn) is shown in Table1.

Table 1. Chemical composition of alloy EN AW 2024

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ni	Ti
Content (%)	0.09	0.22	4.1	0.60	1.28	0.01	0.02	0.01	0.01

The medium frequency induction furnace of 100 kg capacity was used in the experiment. At the bottom of the furnace there is a drainpipe with graphite crystallizer that is intensively cooled with water. The low frequency magnetic field is placed around the crystallizer itself. The testing samples were obtained by vertical continual casting with pulse draw-out of ingots with diameter of 60 mm. The temperature of casting was 710–720°C and average casting speed was 1,5 mm/s. The operating parameters, during the casting of ingots, were strictly controlled and defined by various values of current (A), frequency (Hz) and strength of electromagnetic field (A_t), as shown in Table 2. The number of turns in the coil was N=40.

Table 2. Operating parameters upon casting of samples

Sample mark	Frequency (Hz)	Field strength (A_t)	Current (A)	Number of turns (N)
1	0	0	0	-
2	50	17600	440	40
3	30	8000	200	40

The sample 1 was casted without the presence of electromagnetic field to enable the observation of field effect on microstructure with samples 2 and 3. The microstructure characterization was carried out on as-cast samples and on homogenized samples (480 °C, 12^h).

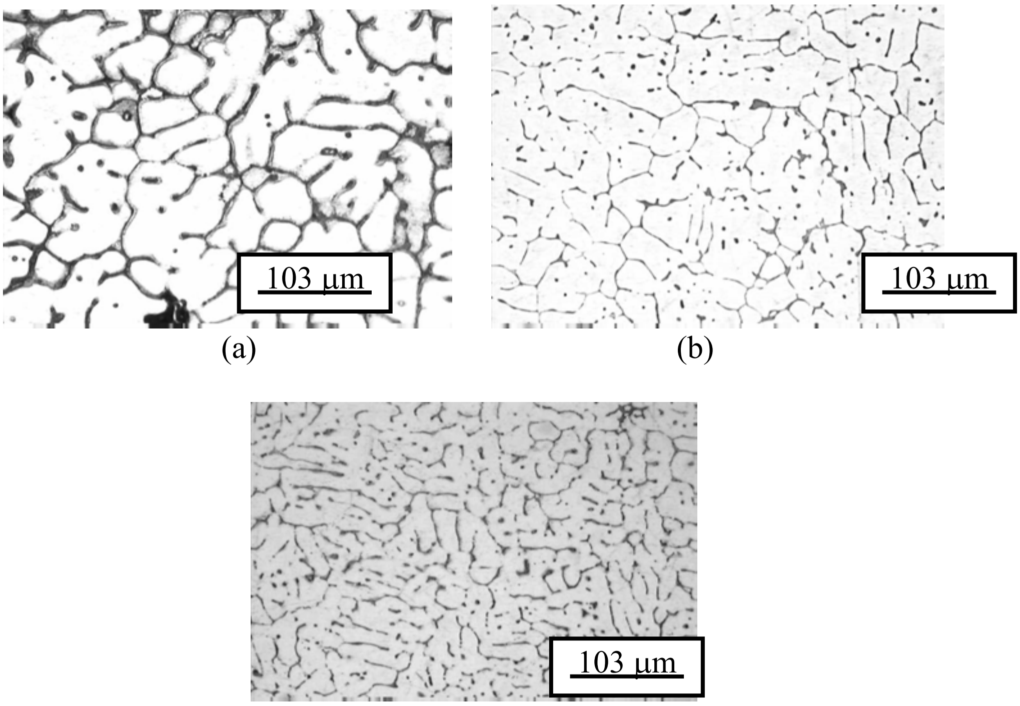
The microstructure was examined on a cross section of a sample after the usual metallographic preparation and etching in Keller's reagent (revealing morphology of Al segregation-solid solution and inter metallic phase) and anode oxidation with Barker's reagent (revealing size and shape of the grain in presence of dendrite segregation). For the quantitative microstructure analysis the image analysis device Leica Q500MC was used. Dendrite arm spacing (DAS), interdendritic space width (L_{IMF}), where intermetallic phases and eutecticum were separated, as well as their volume fraction, 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 dispersivity, directly affect the mechanical properties of the alloy, and they are the consequence of the solidification conditions.

Results and discussion

The characteristic appearance of microstructure of cross section of samples casted under different conditions is shown in Fig. 1. It is obvious that Al segregation from the solid solution resulted in cellular/dendritic morphology. Upon that, the structure of samples without the electromagnetic field effect, Fig. 1 (a) is more dendritic compared to the samples 2 and 3, where the cells are more distinctive. The finest and the most homogenous is the cross sectional structure of the sample 3 (f =30 Hz). This is also confirmed by the results of measurements of DAS and width of interdendritic space, L_{IMF}, Table 3. The volume fraction of inter metallic phase is increasing from sample 1 to 3.

Table 3. Statistical values of the measurement of structural parameters (as-cast samples)

Parameter / Sample	DAS (µm)			L_{IMF} (µm)			$V_{V\ IMF}$, %
	min	max	av	min	max	av	
1	8,2	283,6	46,1	0,8	12,63	3,6	6,55
2	0,81	212,6	39,5	0,41	14,29	3,28	8,08
3	0,81	166,9	30,7	0,40	25,3	3,15	9,4



(a) (b)

(c)

Fig. 1. Microstructure of sample cross section
(sample 1 (a), sample 2 (b), sample3 (c); Keller's reagent; 100x)

The decrease of microstructural parameters DAS and $L_{IMF,}$ observed in sample 1 to 3, was confirmedly the analysis of cumulative distribution curves, Fig. 2. However, the effect of electromagnetic field on parameter DAS is greater compared to L_{IMF}.

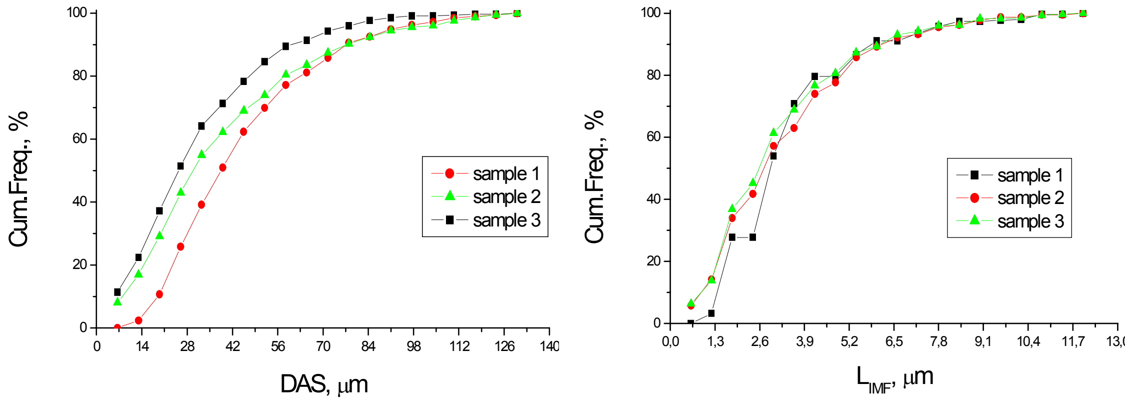
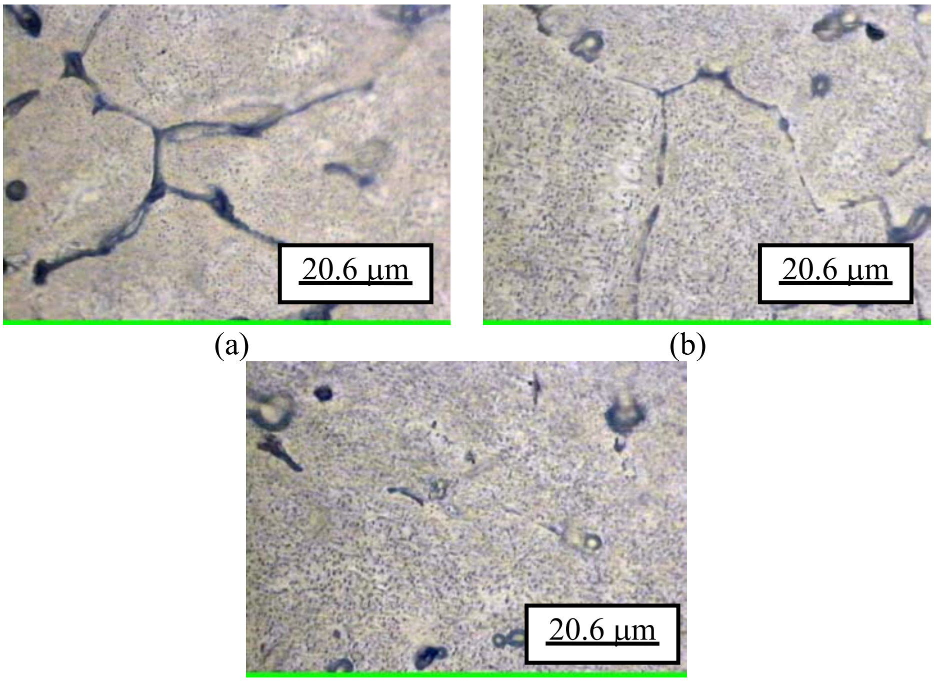


Fig. 2. Cumulative distribution curves of parameters DAS (a) and L_{IMF} (b) depending on operating parameters of electromagnetic field (as-cast samples)

The regions of extracted inter metallic phase, in the form of eutecticum or individually, become finer by the introduction of electromagnetic field and by decreasing of frequency (from 50 Hz in sample 2 to 30 Hz in sample 3). It is also found that porosity of interdendritic type and the grain size are significantly reduced from sample 1 to the sample 3.

The characteristic microstructure appearance at cross section of homogenized samples is shown in Fig.3. In general, it can be said for all three samples (1H, 2H and 3H) that there are no distinct zones without precipitate. The primary phases dissolution with uniform precipitation of secondary precipitate was occurred.



(c)

Fig. 3. Microstructure of sample cross section
sample 1H (a), sample 2H (b), sample 3H (c);(Keller's reagent; 200x)

The finest and the most homogenous is the cross sectional structure of the sample 3H. This is confirmed by the results of measurements of DAS and width of interdendritic space L_{IMF}, table 4., and in analysis of cumulative distribution curves Fig.4.

Table 4. Statistical values of the measurement of structural parameters (homogenized samples)

Parameter / Sample	DAS (µm)			L_{IMF} (µm)			$V_{V\ IMF}$, %
	min	max	av	min	max	av	
1H	8.61	226.49	65.37	0.17	14.19	3.07	4.85
2H	9.93	174.18	51.28	0.17	11.72	2.81	5.36
3H	12.58	168.87	40.81	0.17	12.21	2.57	7.05

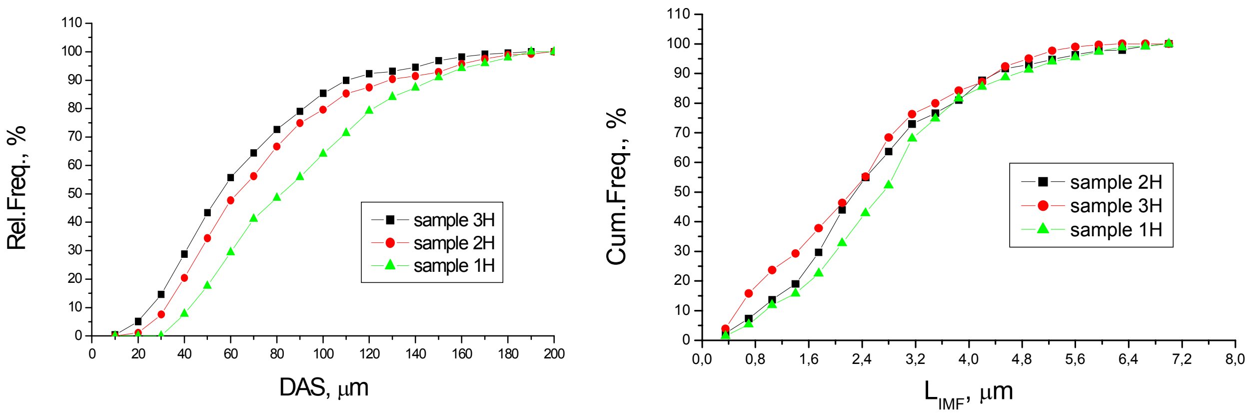


Fig. 4. Cumulative distribution curves of parameters DAS (a) and L_{IMF} (b) (homogenized samples)

With the homogenized samples, as well as as-cast samples, the greater effect of electromagnetic field on parameter DAS compared to L_{IMF} was observed. The increase of microstructural parameter DAS and the decrease of L_{IMF}, compared to the as-cast samples was occured after the homogenization annealing. However, the extent of these changes is not so great. This fact indicates that in the case of electromagnetic field application, the basically microstructural parameters, should be achieved during the casting process. In this way, it can be possible to create the conditions for homogenization annealing elimination.

The present phases in as-cast samples (1, 2 and3) were identified by EDX analyses and it confirms that there was no modification in phase composition under the influence of electromagnetic field. The results of EDX analyses are shown in Fig. 5. The present phases are: Mg_2Si, Al_2Cu, Al_3Fe, Al_3Mg_2, Al_6Mn i Al_4Mn.

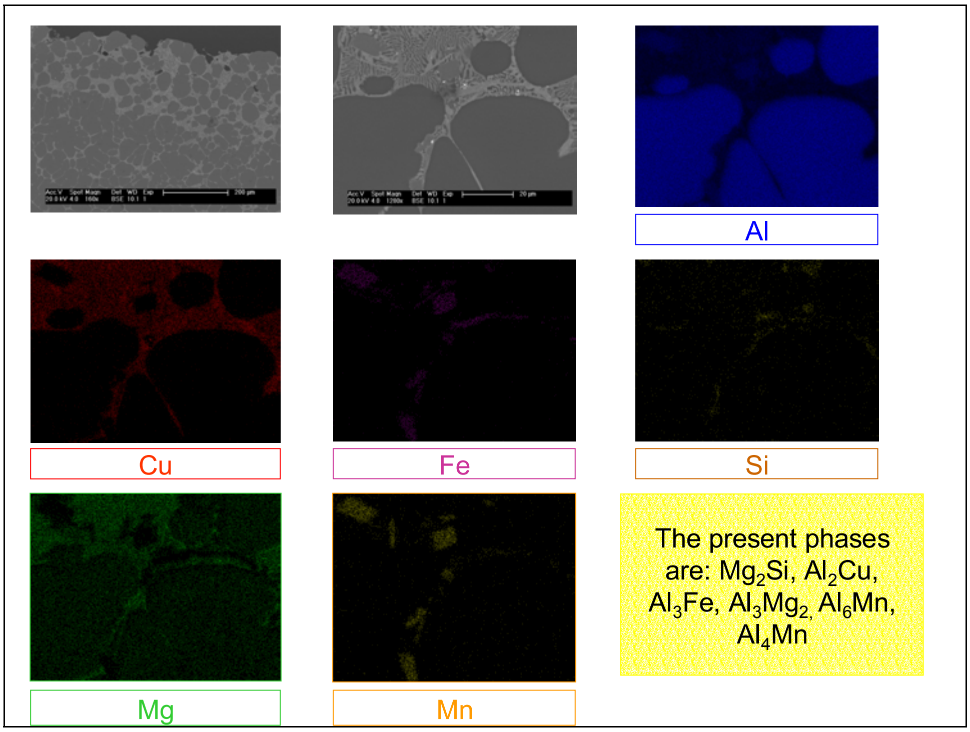


Fig. 5. The results of EDX analyses

Conclusion

Microstructure investigation results of alloy EN AW 2024 ingots obtained with and without the presence of electromagnetic field explicitly show its effect on the characteristics of the obtained microstructure. Besides the field presence, the electromagnetic field frequency effect was also investigated. With both, as-cast and homogenized samples, the field effect on DAS and grain size is stronger compared to its effect on interdendritic space width. However, intermetallic phases present between these dendrite branches, become finer with the increase of field intensity and the decrease of frequency. Besides, the EDX analyses confirmed that there is no field effect of alloy phase composition. Obtained results indicate that some steps in current technological process can be avoided. Further experiments should be carried out in order to find the optimal conditions for the production of ingots with the required quality, having in mind here exposed conclusions that the lower frequency and higher field intensity ensure the finer microstructure. Knowing the microstructure-mechanical properties correlation, further investigations will also include mechanical testing to achieve optimal properties of this alloy

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