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Affecting the Crystallization of Al-based alloys by Electromagnetic Field

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Abstract

This article deal with non-conventional methods to affect the crystallization of Al-alloys by the application of electromagnetic field. The application of electromagnetic field is not technically complicated, it does not require mechanical contact with the melt, and the scale of the crystallization influence is not dependent on the thickness of the casting. Two experimental materials were used: AlSi10MgMn and AlSi8Cu2Mn and two values of electromagnetic induction: B = 0.1 T a B = 0.2 T. The best results for alloy AlSi10MgMn were achieved by application of electromagnetic field with induction B = 0.2 T; during this experiment the best mechanical properties were achieved - the biggest increase of mechanical properties was recorded. The best results for alloy AlSi8Cu2Mn were achieved by combination of electromagnetic field with induction B = 0.1 T and modification by 0.05 wt. % Sr. In this case we don´t recommend to use electromagnetic field with induction B = 0.2 T; because of deposition of coarse grains and decreasing of mechanical properties.

Keywords: Aluminum, Silicon, Inoculation, Strontium, Electromagnetic field

1. Introduction

The raising trend in the consumption of aluminum alloys due to their advantageous properties (low weight, excellent ratio strength/density, good corrosion resistance) is generally known. The quality and properties of foundry alloys depend on a number of factors, for example, chemical composition, shape and dimensions of the casting, metallurgical treatment of the melt, mold material, casting temperature, cooling rate, heat treatment, and the like. One of the most important processes in the casting preparation is the aluminum alloy melting process as well as the proper control of the melt treatment which favorably influences the mechanical and foundry properties of the casted materials. In addition to the classic methods of influencing primary crystallization, unconventional methods can be applied. One of the unconventional techniques of influencing crystallization in order to improve the properties of cast materials is the application of the energy fields, mainly electromagnetic methodologies are most prominent. In scientific and patent literature can be found a great number of methodologies based on the action of electromagnetic forces on the liquid metal, which differ mainly in the way they are induced, given by the concept and arrangement of devices [1-3].

First research works on the application of stirring of liquid metal at the time of its solidification in order to improve the castings quality were carried out by Russ Electroofen in 1939 and concerned the casting of non-ferrous metals and their alloys. In order to obtain the movement of the liquid metal in the crystallizer in the researches carried out at this period of time and also in the future, a physical factor in the form of a electromagnetic field defined as a system of two fields an electric and magnetic field was introduced [4]. The mutual relationship between these fields describes the Maxwell equation [4, 5]. Generated by the inductor powered by electric current intensity (I0) electromagnetic field affecting the solidifying metal (Figure 1) induces a local electromotive force (Em), whose size depends on the value of the local speed of the liquid metal (V) and magnetic induction (B) [5, 6].

$$E_m = \bar{V}\ x\ \bar{B} \qquad (1)$$

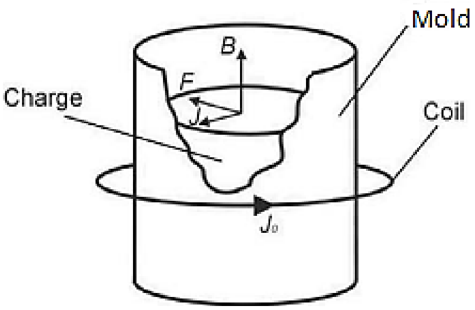

Fig. 1. Diagram of electromagnetic field influence on the liquid metal [7]

This is a consequence of the intersection of the magnetic field lines with the current guide in form of liquid metal. It also leads to inducing a eddy current of intensity I in liquid metal [5, 6]:

$$\bar{I} = \sigma\ (\bar{V}\ x\ \bar{B}) \qquad (2)$$

where:

V - electrical conductivity proper to the liquid metal.

The impact of the induced current on the magnetic field results in establishing of the Lorenz (magnetohydrodynamic) force (F) [5, 6]:

$$\bar{I} = \sigma\ [\bar{E} + (\bar{V}\ x\ \bar{B})] \qquad (3)$$

that puts liquid metal in motion e.g. rotary motion in the direction consistent with the direction of rotation of the magnetic field. Strength (F) has a maximum value when the vector (V) and (B) are perpendicular.

Forced liquid metal movement influences in diversified way on changes in structure of casting i.e. by changes of thermal and concentration conditions on crystallization front, which decrease or completely stops the velocity of columnar crystals growth [4-7] and by [4-8]:

- tear off of crystals from mould wall, which are transferred into metal bath, where they can convert in equiaxed crystals,
- parting of dendrite by coagulation and melting as result of influences of temperature fluctuation and breaking as result of energy of liquid metal movement,
- crystals transport from free surface to inside the liquid metal,
- crystals from over-cooled outside layer of bath are transported into liquid metal.

The submitted contribution is focused on electromagnetic methodology, which does not require mechanical contact and at the same time allows for a uniform influence on the casting process, regardless of casting shape. This is the application of the electromagnetic field itself (EEMF).

2. Methodology of work

Table 1.
Experimental materials and results of mechanical properties

Two alloys were selected for experimental work: AlSi10MgMn and AlSi8Cu2Mn. Experimental melts were carried out in the casting laboratory at the Department of Technological Engineering, Faculty of Mechanical Engineering, University of Žilina. Experimental samples were made by investment casting method into ceramic shell mold (Figure 2).

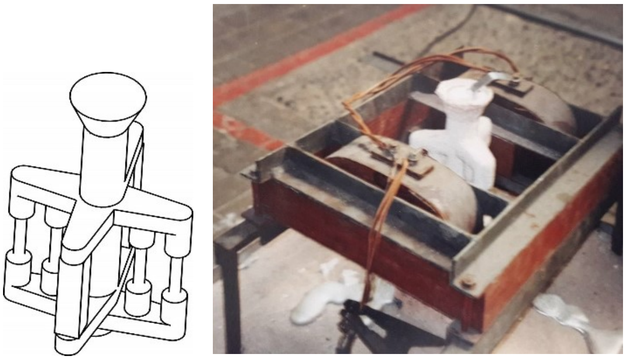

Fig. 2. Ceramic shell with experimental samples (left), shell position within electromagnet (right)

Molds were annealed at 900 ± 5 ° C in order to remove remaining moisture, then cooled to 400 ± 5 ° C and placed in the air gap of the solenoid so that the homogeneous electromagnetic field passed through the middle part of the casting [4]. An electromagnet has a core composed of transformer plates with attached coils facing inward. Solenoid design ensures maximum magnetic field homogeneity in the air gap, minimal field spread and high energy efficiency. The air gap dimensions for the used electromagnet were 175 x 175 mm and height 220 mm. In experimental work, two values of electromagnetic induction B = 0.1 T and B = 0.2 T were chosen on the basis of our previous knowledge. Pouring temperature was 720 ± 5 ° C. At each magnet induction value 3 samples were cast. The conditions of each melt are characterized in tab. 1.

3. Results of experiments

The study of electromagnetic field effect on the aluminum alloys crystallization was based on the comparison of:

- mechanical properties (tensile strength, tensile strength, hardness, shock toughness),
- microstructures of alloys,
- surface fractography.

Tab. 2 shows the composition of batch material for individual melts and the obtained results of the basic mechanical characteristics and also the impact properties of the evaluated materials. The results of the mechanical characteristics represent the average values obtained from the measurements.

Batch material	**Sample number**	**EM induction [T]**	**R_m [MPa]**	**A_5 [%]**	**HBW**	**KC [$J.cm^{-2}$]**
AlSi8Cu2Mn	1	0	153	2.2	102	2.6
	2	0.1	191	4.0	115	4.55
	3	0.2	144	1.8	106	2.475
	4	0.1+0.05 % Sr	191	3.9	114	5.25
AlSi10MgMn	5	0	141	3.7	80	16
	6	0.1	180	6.8	78	23.5
	7	0.2	180	6.9	79	23.75

It can be stated that the Rm and A_5 properties for AlSi8Cu2Mn alloy are (except sample number 3) higher than values given by the norm. The hardness reached more than twice the values prescribed by the norm. Electromagnetic field has also positive effect on HBW. For the AlSi10MgMn alloy, similar conclusions can be stated, because EMF has positive effect on mechanical properties in all cases. EMF has best effect on the A5, which has increased in both cases more than doubles.

The microstructure of the AlSi8Cu2Mn alloy without electromagnetic field effect, with electromagnetic field (B = 0.1 T and B = 0.2 T) and the combination of the Sr and electromagnetic field is documented in Fig. 3 to Fig. 6 (mag. 100x, etched 0.5 % HF). Initial structure of the unmodified alloy (Figure 3) consists of α-phase dendrites and the eutectic Si rods, which appear on the observed area as dark-gray needles or orbicular grains (depending on the rods orientation at the observed plane), with occasional occurrence of the vein-type orientation. Due to a higher values of Fe (0.5 wt. %), it is possible to see in the right part of the microstructure the occurrence of iron phases arranged in the so-called "Fish skeleton" morphology [8]. In Fig. 4 is an image of an AlSi8Cu2Mn material microstructure casted under the influence of electromagnetic field (B = 0.1 T). The image is characterized by the arrangement of the dendrites in one direction and partial rounding of the edges of the eutectic Si rods, which may be caused by a modifying effect of electromagnetic field on the microstructure. After increasing the magnitude of the electromagnetic induction to B = 0.2 T, the precipitation of the Si coarser grains can be observed in the metallographic image (Figure 5), which corresponds to the premodified structure of the alloy. Granular morphology of the silicon caused a rapid drop in tensile strength (from 191 to 144 MPa - see Table 2). Fig. 6 is a characteristic image of the modified AlSi8Cu2Mn alloy where precipitation of very fine rods (almost like fibers) of eutectic Si can be observed, which appear in the plane of the cut as a round grain. The fine structure of eutectic Si also confirms an increase in the toughness value compared to other methods of processing the liquid alloy.

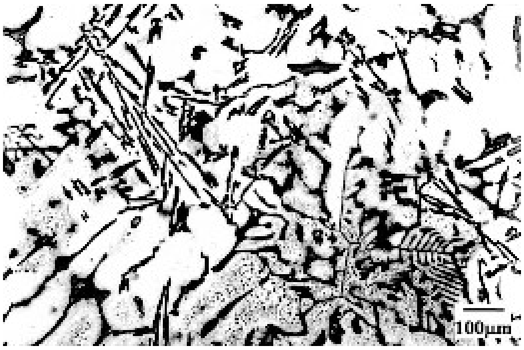

Fig. 3. Microstructure of AlSi8Cu2Mn alloy without EMF effect (mag. 100x)

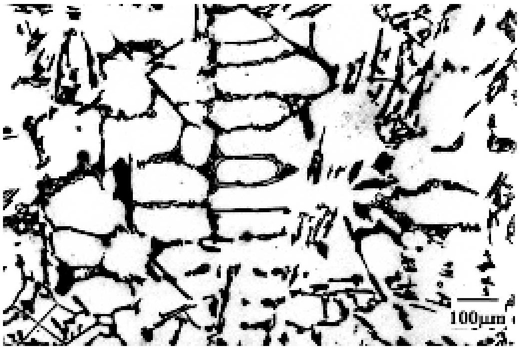

Fig. 4. Microstructure of AlSi8Cu2Mn alloy with EMF effect (B = 0.1 T, mag. 100x)

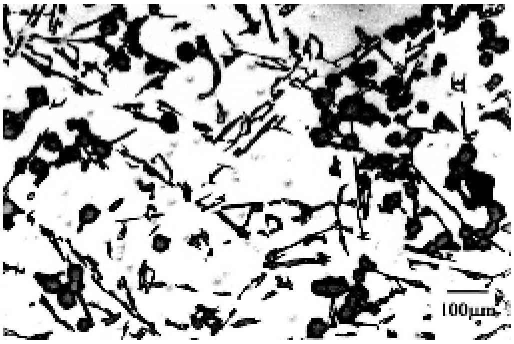

Fig. 5. Microstructure of AlSi8Cu2Mn alloy with EMF effect (B = 0.2 T, mag. 100x)

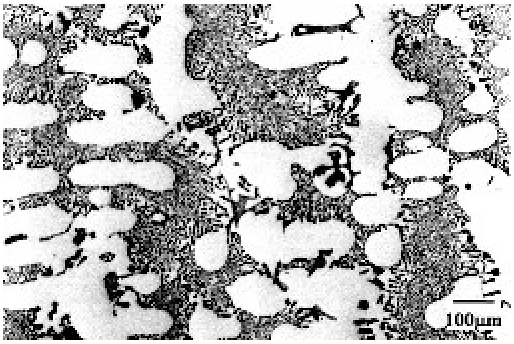

Fig. 6. Microstructure of AlSi8Cu2Mn alloy with EMF effect (B = 0.2 T) + modification 0.05 wt. % Sr (mag. 100x)

The microstructure of AlSi10MgMn alloy casted without EMF and with EMF is documented in fig. 7 and 8 (mag. 100x, etched 0.5 % HF).

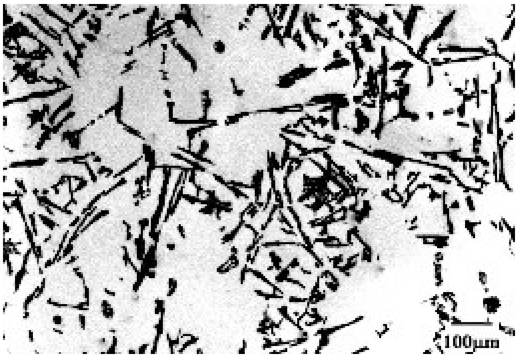

Fig. 7. Structure of AlSi8Cu2Mn without EMF effect (mag. 100x)

As with the previous alloy, structure of the non-modified AlSi10MgMn alloy is composed of α-phase dendrites and eutectic Si rods which are in the form of gray needles and rounded grains (Fig. 7).

Fig. 8. Structure with EMF effect (B = 0.2 T, AlSi10MgMn) (mag. 100x)

In Figure 8 is shown the microstructure of AlSi10MgMn alloy casted and crystallized under the influence of EMF with the electromagnetic induction B = 0.2 T. By closer look at the microstructure, we can observe finer dendrite of α-phase, slightly rounded ends of eutectic Si rods, and the rotation of the dendrite grains in two perpendicular directions [9, 10]. The morphology of eutectic Si corresponds with an unmodified state. It can be stated that the phases in the microstructure were more evenly distributed, indicating a positive influence of EMF on the casting mechanical properties (Table 1).

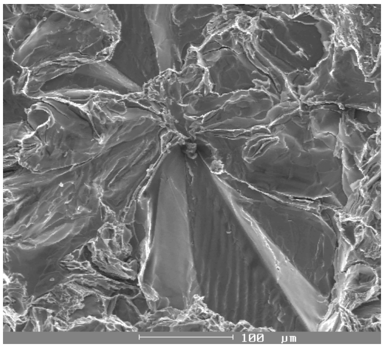

Fig. 9. Morphology of fracture area without EMF effect (AlSi8Cu2Mn)

The fracture area of the unmodified AlSi8Cu2Mn alloy was characterized by a mixed type of defects (majority of transcrystalline scission and small amount of plastic failure – plastically reshaped combs are turned to a socket morphology). Also few areas with the brittle failure can be observed at Fig. 9 [9, 10]. Fracture area of sample affected by EMF (B = 0.1 T) and modified by Sr (0.05 wt. %) was finer than the sample affected only by EMF. Area was characterized by fine fissile facets (related to the microstructure, Fig. 6) linked by plastically reshaped combs (Fig. 10).

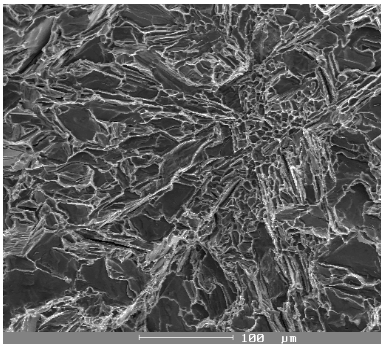

Fig. 10. Morphology with EMF effect (B = 0.1 T) + modification 0.05 wt. % Sr (AlSi8Cu2Mn)

The nature of the fracture areas of the non-affected and affected AlSi10MgMn alloy was not very different, and in both cases it was created by a mixed type of breaches (transcritical and intercrystalline). In the fractographic images, areas with predominant transcriptional cleavage with the occurrence of intercrystalline phases as well as areas of transcrystalline ductile fracture (plastically transformed ridges with hole morphology) and intercrystalline perturbation (Figure 11) were also observed. The shape of the alloy-affected alloy is shown in Figure 12, which documents transcriptional cleavage and intercrystalline disruption.

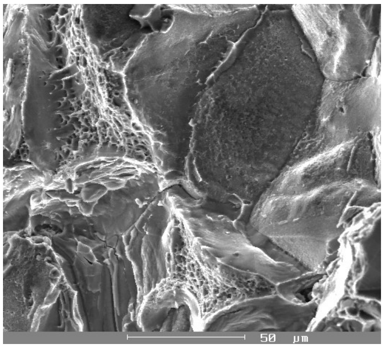

Fig. 11. Morphology without EMF effect (AlSi10MgMn)

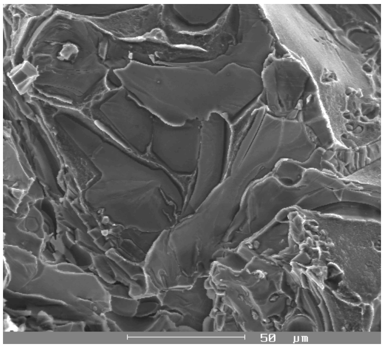

Fig. 12. Morphology with EMF effect (B = 0.2 T, AlSi10MgMn)

4. Discussion of results

AlSi8Cu2Mn alloy

Metallographic evaluation of the test samples showed that the EMF effect on alloy crystallization was accompanied by positive changes, for example by the α-phase refinement and more uniform phase distribution. Higher values of mechanical properties were obtained at the magnitude of the electromagnetic induction B = 0.1 T. The increase of the electromagnetic induction value to B = 0.2 T caused negative changes in mechanical properties and also in the microstructure (exclusion of the thickened eutectic silicon grains). The layout of the structural phases corresponds to the evaluated mechanical properties. At a value of B = 0.1 T, the tensile strength value increased by 25% compared to the sample casted without EMF effect. Elongation and impact strength values of the sample cast at B = 0.1 T increased by up to about 50 % compared to samples casted without EMF effect. Action of EMF accompanied by the modification with 0.05 wt. % Sr caused positive changes in the microstructure where eutectic silicon was excluded in the form of fine rods and fibers. During evaluation of the fracture area, intercrytalline cleavage with a small proportion of the ductile deformation can be observed for all samples, however after the modification, the fracture area is finer with the appearance of fine cleavage phases combined with plastically-formed ridges.

From the examined samples with regard to the obtained mechanical properties, casting in EMF with B = 0.1 T as well as a combination of EMF with simultaneous modification with 0.05 wt. % Sr seems optimal.

AlSi10MgMn alloy

By affecting the primary crystallization of the AlSi10MgMn alloy by electromagnetic field, positive changes in microstructure and mechanical properties were observed at both electromagnetic induction values B = 0.1 T and B = 0.2 T. At both electromagnetic induction magnitudes, almost the same increase in mechanical properties occurred, tensile strength increased by 28 %, the elongation by up to 87 %, and the notch toughness value by 48 % compared to samples casted without the EMF effect. The results obtained from the microstructural analysis are comparable to those obtained with the AlSi8Cu2Mn alloy (finer and more uniform α-phase distribution). The fracture areas of the EMF influenced samples and untreated samples did not differ significantly, in both cases mixed type of breaches occurred.

From the examined samples with regard to the obtained mechanical properties, casting in EMF with B = 0.2 T seems optimal.

5. Conclusions

The effect of the electromagnetic field on the crystallization of the studied alloys is positive. Based on conducted studies following conclusions have been formulated:

1. Forced liquid metal movement during solidification process by use of electromagnetic field influences effectively on refinement of selected components in multiphase structure (in our case α-phase).
2. Metallographic evaluation showed that the effect of EMF on alloy crystallization was manifested not only by α-phase refinement, but also by more uniform phase distribution and rounding of eutectic silicon rods.
3. Rotation of the dendrite axis into two perpendicular directions was observed after EMF effect.

For the application of mentioned method in the foundry practice, there is no need for a large input costs and for the investment casting technology seems like a method to produce castings with special properties.

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