Change in the structure of the aluminium alloy under the action of direct electric current

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Abstract. The capabilities of the method for producing cast aluminum alloys, including composite alloys, which include the transmission of direct electric current at the crystallization stage, are shown, and the results are studied for experiments on the crystallization of aluminum alloy (silumin: Si – 10.47 %; Cu – 1.75 %; Fe – <0.2 %; Cr – 0.02%; Mg - <0.02 %; Mn - <0.02 %; Ni – 0.08 %) under the action of direct electric current. Comparative study of the structure and porosity of the aluminum alloy, the crystallization of which occurred under the influence of electric current and without current, showed that the electric current leads to a change in the structure of the alloy, reducing porosity, creating a finely differentiated eutectic with a decrease in the dendritic parameter. The mechanism of influence of electric current on the movement of inclusions in the melt is based on the diffusion process. Within the framework of considering the diffusion flux created by the electric field of the current, the speed of the inclusion of crystalline silicon in the melt was calculated in a linear approximation, which shows the possibility of applying this effect in obtaining aluminum matrix composite materials.

Keywords: crystallization, electric current, electrotransfer, silumins, aluminum matrix composite materials, eutectic, dendritic parameter, porosity, hardness.

1. Introduction
At present, it is relevant to improve existing and create new technologies for the production of products with more reliable performance properties. These properties are usually laid at the stage of choosing the material of the product, the material that will provide its necessary properties and manufacturing technology of a particular product. In order to control the physical properties of the material and the operational properties of the product at various stages of the technological process of obtaining the product, additional external effects are used: mechanical, ultrasonic, electromagnetic [1-12]. Also the technologies for producing products from cast aluminum alloys, composite materials use the effect of electric current at the stage of modification, crystallization [2-5, 12].

Experimental problems of the effect of electric current on the physical properties of metals were solved already in the 19th century. Namely, the first experimental studies of non-thermal influence of electrical current on the physical properties of metals were carried out as early as 1844 by the German scientist G. Wertheim [13]. Wertheim conducted two series of experiments. In the first series, he measured the elongation of wire samples of various metals with a constant external mechanical load under the conditions of transmission of electric current (j ~ 107 - 108 A/m²), and also measured the temperature of wires. In the second series of experiments, he measured the elongation of the samples in the process of their deformation when using additionally only thermal effects, allowing to create a fixed sample temperature similar to the temperature created by the flowing...
current in the first series of experiments. According to the results of measurements of the elongation of the samples, the elastic modulus of the studied material was indirectly determined. It was revealed that the values of the elastic modulus of the same material are different when it is deformed under the action of current and without passing the current. The presence of the difference in the values of the modulus of elasticity of the material served as evidence of the non-thermal effect of electric current on the magnitude of the elastic modulus of the metal.

Then, more than 100 years later, scientists returned to the question of the application of electric current in technological processes for the treatment of hard-to-deform materials with the aim to improve their properties, such as strength, hardness, ductility, as noted in the works of O.A. Troitsky, N. Conrad et al. [14-19] observed a decrease in the deforming force in the form of a sharp decrease in the resistance of metal crystals to deformation under impact of the current of high density in a pulsed mode, which was named the electroplastic effect. The effect manifested itself in the form of characteristic discharges of a deforming force in the diagrams of stretching or compressing zinc single crystals or deformation jumps, which is associated with the accumulation of a sufficient number of dislocations, the movement of which can be detected by a jump in deforming force and indicates a nonthermal, anisotropic effect of electric current. The presence of impurities and an increase in their concentration led to an increase in the jump of the additional mechanical stress under the action of current. This is due to the loss of stability of a larger number of dislocations under the action of current, that is, upon doping of crystals, the uniformity of shear formation and the decrease in the effective size of regions of incomplete shear are increased. Electric current causes the structure to transform during plastic deformation. Its effect on one of the recrystallization process parameters — the recrystallization temperature, as well as on the result of the recrystallization process — grain size and hardness — was determined.

Starting from the 70s of the 20th century to the present, scientists study and put into practice the effect of electric current on the processes of modification and crystallization in order to control the properties of the alloy [2-12]. It was found that the use of electromagnetic effects at the stage of phase transition during crystallization of castings from non-ferrous alloys or at the stage of their modification allows changing the structure of the material and the properties of the product [2, 3, 5]. This is due to the fact that the treatment of the melt with an electric current during the crystallization stage makes it possible to influence the rate of heat and mass transfer processes, the formation of phases and the structure of the material of the product, and to regulate the distribution of alloying components. The electric field causes directional diffusion flows of ions in metals and alloys, leading to the movement of inclusions, activating the process of dissolution of pores. Being sinks or places of origin of vacancies, the interphase boundary regions affect the movement of vacancies and determine the formation of alloy properties. The use of electric current at the stage of crystallization, alloying, modification, allows by creating additional heat fluxes to intensify the processes occurring at the interphase boundaries both in the production of melts and in the production of cast composite materials. For example, when combining solid and liquid phases, as well as various components that are in a state of melt.

2. Experiments and results
For this purpose, a study was carried out on the structure and porosity of the aluminum alloy, which crystallized under the influence of an electric current. For the experiment, a setup was used that allows for a method of producing shaped castings under conditions of direct current flow at the stage of filling the mold with the melt and subsequent solidification [6]. The electric current was passed directly through the melt in the process of filling the mold with it due to the sequential arrangement of the contacts in the mold. The crystallization of castings took place in sandy forms. As the material of the casting, an aluminum alloy was used the chemical composition of which was determined using spectral analysis on an LAES MATRIX atomic emission spectrometer with laser excitation. The chemical composition of the aluminum-based alloy was as follows: Si – 10.47 %; Cu – 1.75 %; Fe – <0.2 %; Cr – 0.02%; Mg - <0.02; Mn - <0.02 %; Ni – 0.08 % and, in accordance with the chemical composition, it can be attributed to silumin.

Siluminis is usually characterized by low solubility of silicon at high and low temperatures of the alloy, and therefore it is not possible to harden the alloy by heat treatment. In this case, modifying is a reliable method for improving mechanical properties. Modification of the structure, in terms of the transmission of electric current through the melt, the imposition of electromagnetic fields, ultrasonic effects, causes a change in the crystal structure of castings, increases the density of the material, provides a fine-crystalline structure and a high level of mechanical properties of aluminum alloys [1-3, 11, 12].
It should be borne in mind that casting aluminum alloys have a high tendency to oxidation and saturation with hydrogen, which leads to such types of scrap castings as gas porosity, the presence of slag and oxide inclusions. The tendency of aluminum alloys to interact with gases is due to increased activity of aluminum. Upon receipt of castings by sand casting, gases, nitrogen, oxygen, carbon and its oxides condensed on the surface penetrate the casting material at high temperatures. Particularly affected gas porosity in this case is the surface layer of the casting. The formation of gas pores is also possible due to the presence of undissolved gas bubbles in the aluminum melt.

In this regard, it was necessary to check the effect of electric current on the porosity of the sample material. Porosity was calculated not directly, but indirectly, as the relative difference in the density of the material due to current processing during crystallization:

$$\frac{\Delta \rho}{\rho} = \frac{\rho(I \neq 0) - \rho(I = 0)}{\rho(I \neq 0)} \cdot 100\%$$

During the crystallization of castings in the presence of current for a given alloy, the relative difference in the density of the material, in relation to the samples, crystallization of which occurred in the absence of the electric current \( I = 0\ A\ ), was: 

$$\frac{\Delta \rho}{\rho} \approx 3.80\%$$

at a current of \( I = 66\ A\ ).

It can be assumed that a decrease in the porosity of the alloy during crystallization in the presence of electric current may be due to the activation of filtration processes under the action of electric current, which compensate for the insufficient supply of castings. On the other hand, the electric current passed through the melt during the crystallization stage activates the process of mass transfer in the melt due to the influence on the electron-ion subsystem of the alloy [20, 21]. An electric current, representing an orderly movement of electrons, which will influence the formation of the dendritic structure of the alloy. As a result of the impact of electric current on the alloy during the crystallization process, the size of the dendritic cell should change and the hardness will increase.

The study of the structure of the material of the samples was carried out with an optical microscope (Leika DM ILM). The structure parameters were calculated using an image analysis computer program (Qwin). The dendritic parameter and the area of the solid solution were chosen as parameters for the comparative analysis.

The microstructure of the aluminum alloy crystallization which took place without the action of the electric current \( I = 0\) is shown in Figure 1 (a) and Figure 1 (b) shows the microstructure of the test silumin, crystallization is held by passing through the sample electric current of \( I = 66\ A\). The study showed that the transmission of electric current in the process of alloy crystallization leads to a decrease in the size of the dendritic parameter (DP) and to a change in the distribution of the eutectic in the alloy. The structure of the crystallized alloy without current (Figure 1 (a)) represents the characteristic dendritic cells of \(\alpha\)-solid solution and eutectic. The structure of the alloy which crystallization occurred during of the DC electric current the flow through the melt (Figure 1 (b)) has changes in the size of the dendritic cells. So in the absence of a current \( I = 0\) the value of the dendritic alloy parameter is on average 32.0 μm, and during crystallization with current passing by a force \( I = 66\ A\) the value of the dendritic parameter reaches 20 microns, the area of \(\alpha\)-solid solution changes by about 2 times. Eutectic has a more dispersed structure with a characteristic change in the length of the boundaries between eutectic colonies. In some areas, one can observe a more subtle differentiated structure of the eutectic (Figure 1 (b)).
Thus, there is a change in the configuration of the dendritic structure and its partial destruction. A fine-differentiated eutectic appears in the structure; no pronounced dendritic cells of α-solid solution are observed.

Changes in the structure of the alloy due to the influence of the electric field of the current on the structure of the alloy through the electron and ion subsystems and less related to external alloy cooling conditions.

3. Discussion of the experimental results

An important causal process affecting the features of the crystallization of metal melts in the presence of electric current during crystallization is electrotransference [21], as the phenomenon of directional migration of ions of the melt under the action of electric current. The unusual manifestation of electrical transfer at the interface between solid and liquid phases, that is, during a phase transition is associated with an increase in the mobility of impurities in the liquid-phase region. In a liquid melt, the influence of current on the formation of the microstructure of the alloy will be carried out through the ion and electronic subsystems.

The influence of the electric field on diffusion jumps of crystal ions is associated with the forces that act on the diffusing ion. Since the probabilities of jumps in the direction of the force and in the opposite direction are different, a directed diffusion electrotransfer of metal ions appears. At least two forces act on the ion: the first from the electric field of the current $F_i$, and the second from the side of the drifting electrons $-F_{ie}$. In this case, the resultant force acting on ion determined as

$$F = (z - z^*) e E$$

$\chi_e$ is the true ion charge, $z^*$ is the effective charge) [21].

To substantiate the physical mechanism of the influence of electric current on the redistribution of the eutectic in the alloy under study, a diffusion model was chosen. Analysis of inclusions movement was performed in the studied alloy at its crystallization under the influence of a constant electric current of $I = 66$ A. For this purpose, a diffusion flux created only by the electric field of the current was considered. In the linear approximation [21], the speed of movement of the inclusion $\nu$ will be proportional to the electric field strength $E$:

$$\nu = -2\chi_e \frac{De z}{\hbar kT} E,$$

(2)

where

$$\chi_e = \frac{\lambda_e - \lambda_{oe}}{2\lambda_e + \lambda_{oe}}$$

- coefficient determining the contribution of the electrical conductivity of the alloy, $\lambda_e$ and $\lambda_{oe}$.
- the electrical conductivity of the matrix and the inclusions, which in cubic crystals are scalars; \( D \) is the diffusion coefficient; \( k \) is the Boltzmann constant; \( e \) is the ion charge; \( f \) - correlation factor. The correlation factor takes into account that with a vacancy diffusion mechanism, the probability of an ion returning after a diffusion jump to its previous position exceeds the probability of its transition to a new position. In monatomic crystals, the \( f \) factor differs little from unity. For crystals with a face-centered cubic lattice, \( f = 0.781 \).

![Figure 2](image1.png)

**Figure 2.** The time dependences of the voltage drop \( U(t) \) (1) on the sample (alloy AK12) and current \( I(t) \) (2).

![Figure 3](image2.png)

**Figure 3.** The relative speed of movement of the inclusions \( v(t)/v(0) \) (curve 1), the ratio of the melt temperature to the eutectic temperature \( T/T_{ev} \) (curve 2).

The field strength in the sample was calculated from the experimental time dependences of the voltage drop and the current strength in it (Figure 2). Silicon was chosen as a transferring inclusions. When calculating it was taken into account that silicon with respect to aluminum is an non-conductive inclusion, since \( \lambda_{\infty} \ll \lambda_e \), and therefore the coefficient \( \chi_e \), characterizing the contribution of the electrical conductivity, was accepted as \( \chi_e = \frac{1}{2} \). In fig. 3 the curve 1 shows the relative speed of movement of inclusions \( v(t)/v(0) \) in the alloy AK12, and curve 2 - the ratio of the melt temperature to eutectic temperature \( T/T_{ev} \), \( T_{ev} = 850 \) K. Visible interval \( 1.0 \leq t \leq 4.5 \) s, wherein the speed of movement is virtually constant inclusions. By increasing the range of the lifetime of a given state, the electric field can influence the movement of inclusions in the melt.
As a result of the movement of vacancies during the transmission of electric current in the melt, pore dissolution will be observed, which is proved by the results of these studies - the porosity of the aluminum alloy, which crystallized under the influence of a direct electric current, decreases by about 4%.

4. Conclusions
Thus, the transmission of electric current during the crystallization of the alloy leads to a decrease in the size of the dendritic parameter and the formation of a finely differentiated eutectic in the alloy. The detected changes in the structure of the alloy are due to the influence of the electric field of the current on the structure of the alloy through the electron and ion subsystems and are not related to the external conditions of the cooling of the alloy. The change in the kinetics of dendritic growth and the destruction of the dendritic structure should affect the filling rate of the interdendritic space, which will reduce the likelihood of shrinkage porosity. Considering that electric current is a source of electric, magnetic, mechanical and thermal energy, the use of this type of influence at the stage of phase transition will allow to influence the dynamics of the process of forming a crystalline structure, to control the formation of alloys properties, as well as cast aluminum composite materials.

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