The Control of Anisotropy in AluminiumAlloy Casting by the Magnetohydrodynamic Treatment Method

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Abstract **- Method of magnetohydrodynamic treatment (MHDT) of aluminium melts was developed under the project 16-43-242013 r_ofi_m "The influence of the induced electric field on the hydrogen ions in molten aluminium alloy" with the assistance of FBM "Russian fund of basic researches", Krasnoyarsk region government, Region state autonomous institution "Krasnoyarsk region scientific and scientific-technical activities support fund". Studies have shown that concentration of the alloying additives changed by the electric field which was induced in molten aluminium alloy 1417M in the direction of electric field vector. By the MHDT we can amend average value of concertation width of the ingot of the alloying elements such as cerium and lanthanum to 8 and 13 % respectively. Based on MHDT theory about movement of charged particles in induced electric field we can approve that experiment conditions (temperature 700°C, cooling time 3 min) contribute the growth of dendrites in the direction of induced electric field vector in molten aluminium alloy 1417M. Also MHDT can reduce differences in phase composition, chemical composition and mechanical characteristics throughout the high of the ingot 1417M alloy. Furthermore approbation of new electrictransfer element method in aluminium alloys which do not require the introduction of electrodes was held successfully.**

Keywords - aluminium alloys, MHD treatment, electric transfer elements, cerium, lanthanum

I. Introduction

It is very important to control the anisotropy of mechanical properties in aluminium alloys in field of aerospace applications [1, 2, 3, 4]. During the production anisotropic mechanical properties arise because of setting of precipitates and crystallographic texturing [5, 6, 7, 8]. The results of aluminium alloys 2024 series with plate inclusions research reducedin articles [9, 10, 11, 12]. Application of elastic stress state in the aging process significantly affects the distribution of inclusions namely on stress effect which leads to anisotropy of mechanical properties.

Mechanical properties of high-enthalpy alloys (HEAs) consider in article [13]. It was shown that hardness of HEAs fluctuates in range from 140 to 900 HV and depends on alloy composition and processing methods. Alloying, heat treatment and structure are influence on mechanical properties. Effect of different conditions such as temperature, aluminium content levels and directions of stresses, sample size, micro-stresses changed alloys structure. Influence of structure, grain size, alloying elements, processing options on tensile stress, plasticity, shape of tensile stress-strain curves, destruction after deformations discusses in articles [14, 15, 16, 17].

Casting alloys technology has one more variant of alloying elements and dopants concentration gradient. Heating and exposure of melt can lead to gravity settling. In aluminium alloy heavier elements (such as Cu, Zn, La, Ce and others) descend to the melt pot bottom, while lighter elements (Li) and gases (H_2, CO_2 and others) move to the melt pot top. This phenomenon causes the non-uniformity of mechanical properties by the high of ingot and the high of the finished cast product.Dendrites feature to grow up from cold side to the casting center also create the conditions for formation of mechanics characteristic gradient of detail.

During the research we have tested the possibility of a directional movement of ions in molten aluminium alloy using the magnetohydrodynamic processing of molten aluminiumalloy 1417M (chemical composition, % (mass): Al – base; 6 Ce; 3 La; 0,016 Pr; 0,24 Fe; 0,06Si). Researches in field of physical methods of influence on metal in the moment of structure formation indicate the ability to control metals and alloys crystallization process and receiving castings with a new set of operational characteristics [18-21]. Method of influence by electric current is one of them. The theoretical and practical results which were obtain in articles [22-25] shows us that there are ability of movement of alloying elements from casting body to the surface under the influence of electric current. However there is no general accepted theory of current influence on alloy yet.Questions about current influence on phase formation mechanisms in liquid-solid conditions with different type of solid inclusions conductivity are not studied to present. There are a lot of contradictions with respect to mechanism of elements mass transfer in internal casting layers under the constant current. The application of a method of current exposure on crystallizing casting in the mold is very limited due to the insufficient theoretical and technological development of this method[26].

Schwartz [11] introduced in theory the concept of electro-hydraulic force which is like buoyancy force in physical sense and expels admixture ions from cathode direction to anode direction. Epstein and Paskin in article [12] guess that component which has greater electric resistance should move to the anode.Skauni's, Epstein's, Paskin's and Angus's [13] quality criteria has many exceptions from general rule so they are unable to correctly predict even the effective charge sign.Trying of qualitative theoretical electric transmission analysisshows that it is very necessary to consider the force of electron-ionic interaction which conditioned by moving electrons from cathode to anode. They were able to show closed interconnection of electron transmission and electron resistance phenomena because both of them are determined by the same forces of electron-ionic interaction.

Using of magnetic thermodynamics for mixing metals in time of crystallization process began since 1930 [27, 28] and the grate volume of articles was carried out until the early 1980[29]. Electromagnetic casting and electromagnetic mixing are performed by the Lorenz force generated by inductor and moving of charged particles. In contradiction with electromagnetic casting where mixing occurs in surface layers of crystallization, electromagnetic mixing is aimed at creating convention streams in deeper layers near crystallization front. Thus we can use low-frequency magnetic fields to influence on melt inner layers at great depth by Lorenz force.

Electrolytes MHDT method [30, 31] is based on Lorenz force exposure on moving charged particles in magnetic field. The electric current induced in every unit cell of electrolyte if it moves with speed $u > 0$ in magnetic fieldand induction B.

So the Lorenz force is equal to

$$\overline{F_l} = q \cdot [\overline{u} \cdot \overline{B}] \quad (1)$$

Its value depends on charge (*q*), speed of charge movement relative to the magnetic field (*u*), induction of magnetic field(*B*). At the same time Lorentz force acts in opposite directionon negatively and positively charged particles.

If we consider infinitely small volume of liquid (melt), then the Lorenz force which acts on unit charge which provide in liquid is equal to

(2)

$$f = \sigma \cdot u \cdot B \quad (2)$$

Moreover the Lorenz force is perpendicular directed to the direction of technical liquid travel speed and magnetic field induction lines (σ - environs electrical conductivity). An oppositely directed movement of charges with different signs occurs under the action of the Lorenz force [32, 33].because of it there is the difference between electrical potentials between environs area therefore electrical current induced.

Choosing the necessary location of magnetic induction vector relative to the stream velocity vector we can purposefully act on the stiffness salt ions and redistribute them in the environs volume as it required in a particular case.

If temperature rises then electric conductivity falls down, at the same time there are no "crystal" bones between metal atoms in melt so they may exist in ionic form.

In liquid metal the electron conductivity decrease and ionic conductivity increase with temperature rising. The electromotor force inducing by the magnetic field due to its penetrating ability leads to the charged particles movement in entire melt volume.

Laboratory setup calculations and preparing for experiment are based on assumptions:

1) in time of current induction in magnetic field there is an impact on each single charged particle that request less energy than cathode and anode using;

2) the velocity of ions movement depends on its diameter, so that metal ions which has less diameter moves faster in electric field and form the concentration gradient along induced electric field lines;

3) electrons take part of charge transfer too, but the potential difference between top and bottom of melt may be removed by the conductive loop with a diameter of 10 times greater than the distance from magnetic field sources to the ingot.

The value of current density in the entire melt volume is calculated by the integrating (1) in X, Y и Z axis coordinates.

In this case if magnetic induction lines directed along X-axis and moving velocity vector of magnetic field source directed along the Y- axis, then it is necessary to calculate induced current density on Z-coordinate. Calculation formula of induced current density may be presented as:

$$j_z = e \cdot q \cdot c \cdot \mu_0 \cdot \mu \cdot u_{H+} \cdot U_x \cdot H_y \qquad (3)$$

e – electron charge, Kl; q – ion valence; c – ions concentration, mol/m^3;· u - ion mobility, m^2/V·c.

II. Experiment

Calculations of the permanent magnetic field parameters and installation constructive elements were performed in ANSYS software package. Calculation of the magnetic field parameters, which is acting on melt, shows the sufficiently high uniformity of its distribution providing density of induced current providing in melt at level from 2,2×10^3 (near at edge of melt pot) to 3,7×10^{4}A/m^2(in the middle of melt pot).

Researches were carried out in aluminium alloy 1417M. Crystallization of melt was performed on MHDO unit with magnetic field velocity from 2 to 10 m/sec. Researches were carried out in comparison with control sample which were cast without MHDO influence (the magnetic field moving velocity equal 0) to eliminate the influence of unit structure features and ingot crystallization conditions.

Fig. 1. External viev of MHDO unit for molten aluminium alloys

MHDO unit (Fig. 1) has two disks rotating toward each other, which connected by a belt drive. Magnets are arranged in circle inside the magnet. Disks rotation occurs by means of electric motor with the maximal rotating speed 1380 rev/min. Melt pot with alloy puts between disks. Disks have smooth rotation speed regulating from 250 to 1400 rev/min. Disks speed rotation regulation realized by frequency converter. Protective ceramic cup installed between disks for melt pot installation. Ceramic form was further provided with a thermal isolated made of kaolin cardboard for magnetic disks heat prevention.

The induction of pulsating electric field by rotating sources of magnetic field was realized in developed laboratory MHDO unit. Calculation of current density which induced in alloy based on formulas (1)-(4) shows that currents vary from от 2,2×10^3(near the melt pot edge) до 3,7×10^{4}A/m^2(in the melt pot middle).

Shichtaluminium alloy billet (size 60x20x20 mm) was placed in ceramic melt pot (inside diameter 30 mm, high 40 mm). Schicht workpiece melting was made by high frequency currents on InterSELT unit. Heating was carried out by means of a two-bit inductor at 2-3 kVt unit power. The operating inductor frequency is equal 36 kHz. Heating was carried out to complete melting of schicht workpiece and bring temperature to 650 °C. Melt temperature was controlled by pyrometer. Average workpiece heating time is equal to 4-5 min. Melt was mixed by ceramics twigs after complete melting, oxide film removed from melt surface than melt pot was fitted into the MHDO unit. After that magnetic drive motor switched on and rotation speed was set at assigned level. MHDO was produced before the curing of the melt. Average times each ingot crystallization equal to 3 min.

III. DISCUSSION

A. *Investigation of MHDO influence on the chemical elements distribution in 1417M alloy casting*

Castings were sawn on a diametrical plane along the magnetic field movement direction. On each sample third: “bottom”, “middle” and “top” from edge to edge alloying elements measurements in aluminium melt were provided at 5 points. Concentration changes histograms were constructed after results average.

Ingots microstructure and local chemical composition have been investigated by scanning electron microscopy method (SEM) using the scanning electron microscope TescanVega 3 SBH with energy dispersive analyzer X-Act manufactured by OxfordInstruments. The INCA Crystal analysis system was used for basic chemical elements distribution map retrieval.

The slots foraluminium alloys phase and element composition determination were made with Struers (Denmark) equipment.The cross samples were cut with Labotom cutting machine. Than samples were pressed in polystyrene with CitoPress unit and micro-slots were produced on grinding and polishing machine Tegramin.

The casting produced with MHDO method La and Ce content determination results in contrast with control sample are given on the Fig. 2

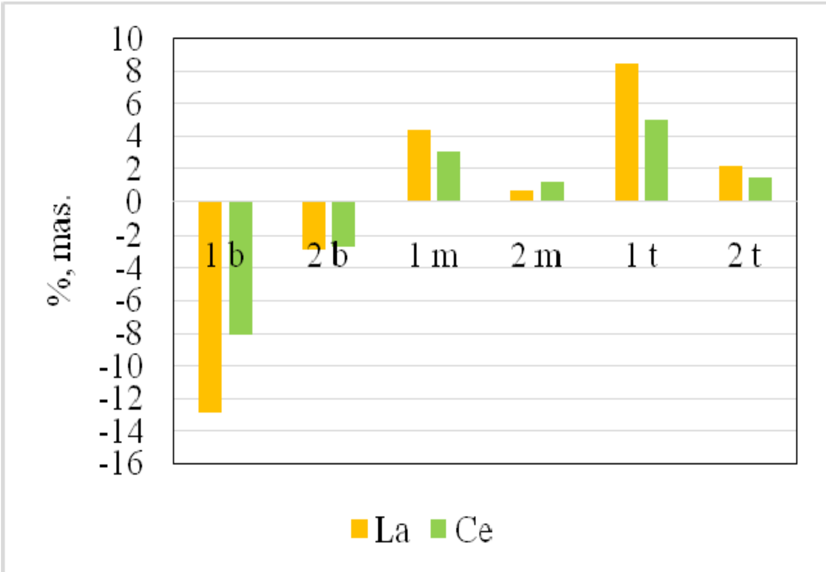


Fig. 2. Results of La and Ce content determination in ingots without MHDO (1) and after MHDO (2) (b – ingot bottom, m – ingot middle, t - ingot top)

Using MHDO method reduces the La and Ce ingots liquation in the vertical section from 20 and 13 % rel. mass, to 5 and 4 % rel. massrespectively. (Fig. 2)

B. *1417M alloy microstructure MHDO influence researching*

Study of MHDO influence on microstructure and element content was made for 1417M alloy. Sample for studies were made in longitudinal section throughout of the ingot. There are three areas were chosen for the analysis: top, middle and bottom of ingot. 1417M Alloy casting microstructures which was gained in areas near ingot edge, before and after MHDO reduced on Fig. 3. Pictures were obtained in the reflected electron mode where the contras determined by average phase atomic number.

1417M alloy microstructure is aluminium solid solution (gray areas Fig.3) and eutectic consist of aluminium crystals and aluminium, lanthanum and cerium compound (white colored structure consistence Fig.3). MHDO using leads to grinding and uniform distribution eutectic components over the ingot section.

Fine eutectic mainly formed which grains more evenly then initial sample (without MHDO). This is mainly noticeable on pictures from the middle of ingot.

Slot researches results which were received from experiment without and with MHDO using reduced at Fig.3 (zoom ×50).

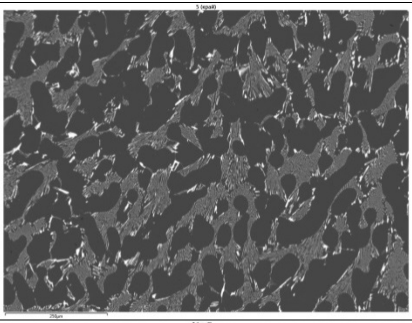
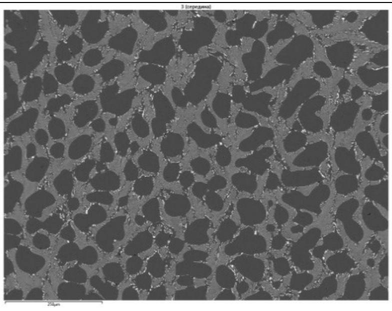
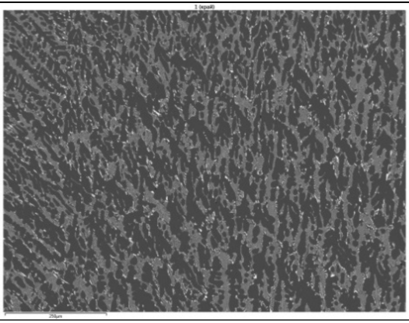
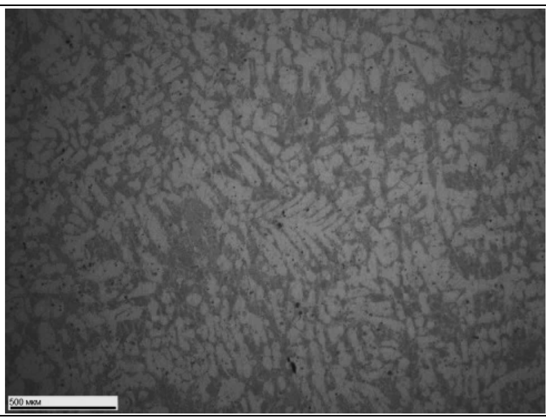
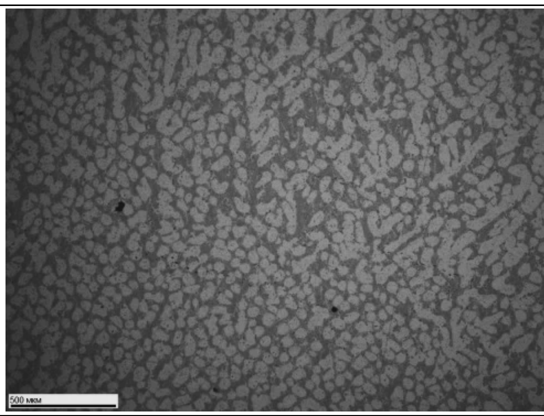
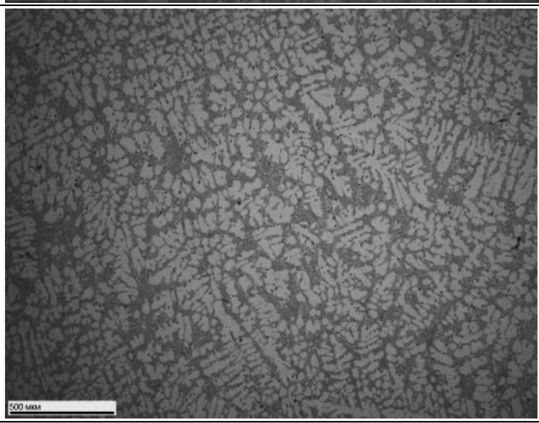
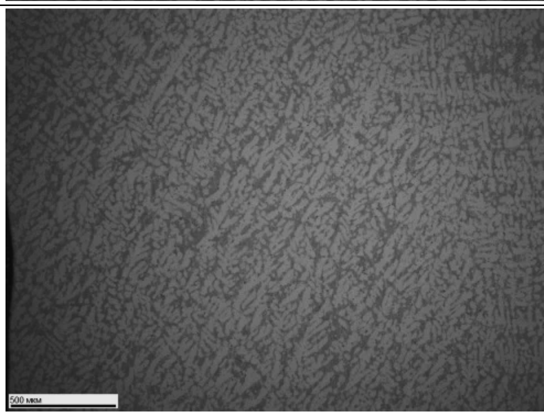
Casting top		
Casting bottom		
	Without MHDO	**After MHDO**

Fig. 3.1417M alloy casting microstructure

Casting crystallization occurs from bottom to top so that is the reason why there are some differences in bottom and top casting parts structure. As we can see (Fig.4) MHDO contributes alignment of microstructure at the casting. Crystal size in bottom and top casting areas vary without MHDO at 50-100 times and with MHDO at 2-5 times

Casting top		
Casting middle		

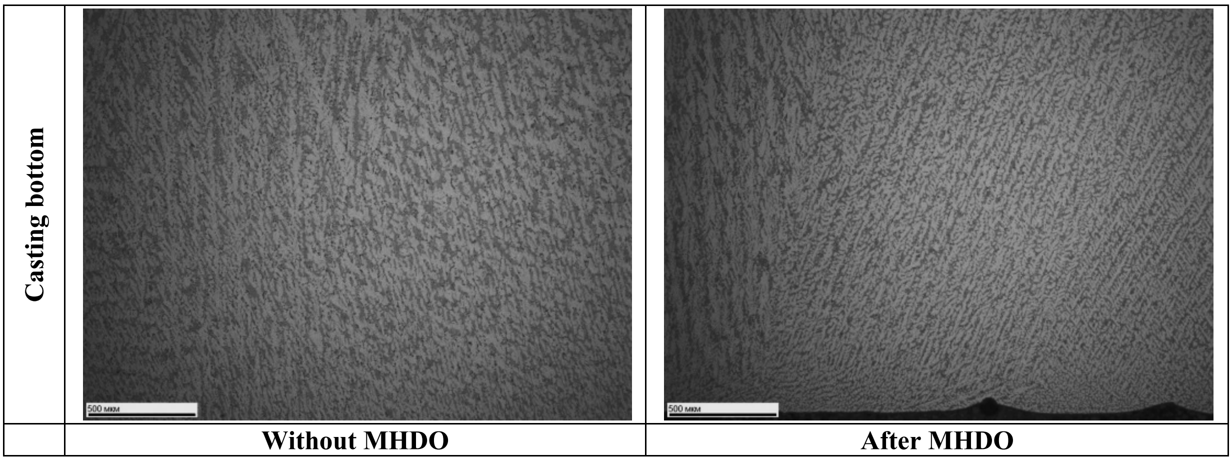


Fig. 4.1417M alloy casting microstructure

While ingot forming in moving magnetic field with MHDO intermetallic phase dendrites orientation occurs along induced electric field lines (lighter areas on shoots). At the same time occurs parallel dendrites smaller structure (Fig. 5).

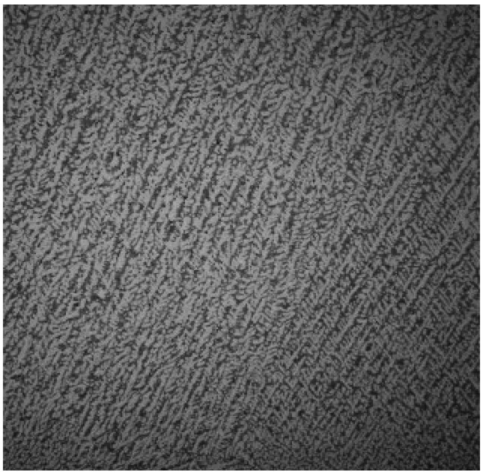


Fig. 5. 1417M alloy casting bottom part structure after MHDO

C. *Study of MHDO influence on 1417M alloy casting mechanic properties*

Sample to determine the impact toughness and short-term strength were cut from top and bottom parts of casting. The test results are shown in table 1.

TABLE 1. 1417M alloy samples test results

		KCU, kgs·sm^2	**σ_B, MPa**
Without MHDO	**Ingot top**	1,7	88
	Ingot bottom	2,1	106
WithMHDO	**Ingot top**	1,7	101
	Ingot bottom	1,7	106

Table 1 shows that alloy MHDO leads to mechanic characteristic alignment on the casting high: impact viscosity deviation from average value decreases from 10 to 0 % and short-term strength from 55 to 15%.

IV. CONCLUSIONS

MHDO melt unit which provides treatment aluminium melted alloy in time of crystallization stage by electric field induced by rotating magnetic field sources was designed and manufactured.

Studies of alloy MHDO influence on casting chemical, structure and mechanic properties was performed by contrast with control sample which was produced in the same conditions without MHDO. Studies results show that alloy MHDO provides:

– chemical composition alignment along casting cross section (reduction of La and Ce liquation along vertical cross section from 20 and 13 % rel. mass to 5 and 4 % rel. mass respectively);

– structure consistence size alignment (differences in crystal size in casting bottom and top parts decreases from 50-100 times to 2-5 times);

– mechanical characteristic of high casting value intervals of vary alignment (impact viscosity deviation from average value decreases from 10 to 0 % and short-term strength from 55 to 15%).

Studies have shown prospectors of metal alloy MHDO applications for aluminium alloy casting high chemical and structure homogeneity ensure for stable mechanics properties.

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