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Experimental study of the effect of the simultaneous treatment of the melt with different currents on the quality indicators of castings

The purpose of the work is to obtain results that would confirm the effectiveness and perspective of using the method of simultaneous treatment of a liquid alloy based on Al with different types of currents in foundry technologies.

As it is known the different types of current passing through the melt (alternating, constant, pulsed) are differ from each other by their different functional capabilities. The each types of currents generate electromagnetic fields with different amplitude-frequency characteristics and distribution, which determine the sphere of influence. The work proposed to use an innovative principle of simultaneous passing of at least two currents with different electrical characteristics through the melt and with different variants of electrode systems. This method made it possible to affect more effectively on the structure and properties of the melt and, in turn, improve the service characteristics of the casting.

In the work, two series of experiments were performed with the application of melt treatment with three types of currents and three types of electrode systems in different combinations. Ingot alloys of the Al-Si system was treated: AK7 (GOST 1583-93), chemical composition: Si (7.3 %); Fe (0.5 %); Cu (0.5 %); Mn (0.07 %); Mg (0.07 %); Zn (0.2 %); Pb (0.01 %), Al base; and non-standard pre-eutectic silumin additionally doped with certain components (Si (8 %); Fe (0.79 %); Cu (1.98 %); Mn (0.1 %); Mg (0.27 %); Zn (0.44 %), Al base). In contrast to the treatment of one type of current, an increase the mechanical properties of castings and an effective modification of the elements of the solid state structure were achieved. Thus, for the first grade of alloy, σ_B was increased by 13 %, and δ — by 1.5 times. Also after simultaneous treatment with different types of currents with defined modes, the value of Ψ was recorded at the level of 4.4 %. For the AK7 alloy, this indicator is not even specified by the standard. For the second grade of alloy, after simultaneous treatment with different types of currents, significant grinding of intermetallics to sizes from 8 μm to 11 μm was observed, while compared to the original sample, there is practically no segregation of the intermetallic component by size. The structure of the treated samples is distinguished by the grinding of silicon particles in the eutectic. The total energy consumption, under certain conditions, for both brands of alloys was reduced by 3 times. The main mechanism of a positive change in the crystallization ability of the melt is formation of electromagnetic fields superposition with more powerful thermoforce effect in the treatment object by passing different types of currents simultaneously than when using one type of current.

Key words: melt, physical experiment, electric currents, crystallization ability, mechanical properties, structural-phase composition, treatment success.

Introduction. In recent years, the scientific knowledge on the problem of conductive electric current treatment (CECT) of a metal alloy in a liquid state for foundry technologies has been actively replenished with new data, which are mostly obtained by methods of mathematical modeling of the generated processes. The physical experiment adds its contribution, convincingly showing the effects that affect the structure and properties of the final product — casting.

An invariable feature of research is that their authors use one type of current to influence the melt: direct current (DC or CC), alternating current (AC), pulsed current (PC). Based on experimental data, we note the following. Constant current amplitude (CC) is mainly characterized by thermal action. PC is distinguished mainly by force influence. DC and AC have a complex thermoforce effect on the melt [1; 2]. In addition, it was previously shown [3; 4] that different types of current

in the treatment object are formed different functional effects on the melt according to individual features. First of all, this concerns the distribution of the primary (basic) electric field and secondary electromagnetic, thermal, and acoustic fields, as well as metal flows [4–6] in the melt. In the complex, these fields are the sphere of influence on the melt through its integral loading.

In our opinion, this particular feature of CECT will be able to increase its efficiency under the conditions of using the method of simultaneous treatment of the melt with different types of currents ($M - C$). For this, it is necessary to find conditions under which higher quality indicators of cast metal are ensured than with one type of current. Of course, under the condition that energy costs for processing do not increase.

The basis for such an assumption can be known results, such as the effective simultaneous influence of crossed electric and magnetic fields on the structure formation processes of the crystallizing melt [7]. And the positive effect of the simultaneous treatment of silumin (CC+PC) in the temperature interval of solidus standing in order to obtain a globular structure was also experimentally proven [8].

The aim of the work is to obtain results that would confirm the effectiveness and perspective of using the simultaneous treatment method of a liquid alloy based on

Al with different types of currents in foundry technologies.

Characteristics of problem situation. The sphere of influence on melt is the physical fields that are formed during CECT. It is their integral action that transforms the melt into another thermodynamic state.

For $M - C$, it is possible to use various options of electrode systems. Which, are known, form the topology of the basic electric field with corresponding consequences for the distribution of secondary fields [9; 10]. For example, the Fig. 1 shows four such options for two current sources. Although there may be three or four current sources. But, for the presented electrode systems in Fig. 1 should be added that with parallel electrode and crossed gaps (Fig. 1 *b, c*) it is possible to provide multidirectional polarities. Thus, we get a multi-variant principle of application of $M - C$, which expands the possibilities of finding conditions for increasing the efficiency of CECT.

In variant (*a*) in Fig. 1, one interelectrode gap is formed for two currents. While the other three variants form autonomous interelectrode gaps.

The question arises, how is the superposition of electric currents formed? The answer to this question will make it possible to determine an adequate procedure and simulation modeling algorithms in the future.

Fig. 2 shows a comparison of oscillograms of the

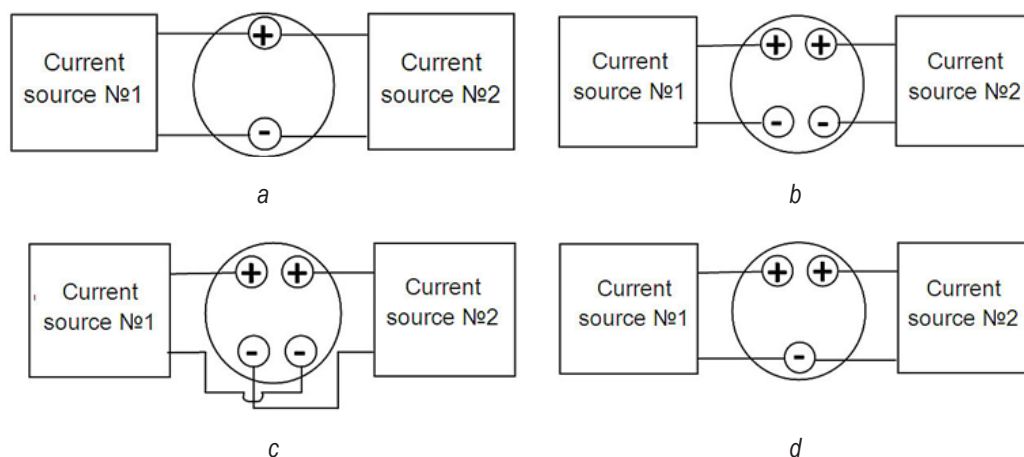


Fig. 1. Examples of variants of electrode systems: *a* — two-electrode system; *b* — four-electrode with parallel currents; *c* — four-electrode with crossed currents; *d* — three-electrode with V-shaped currents

currents flowing in the interelectrode spaces according to different versions of the electrode systems.

As we can see, for a two-electrode system, the superposition of currents has signs of their additivity. But autonomous pairs of electrodes have their own conduction channels and have no signs of current additivity. In this case, the superposition of electric fields generated by different types of currents should be determined using simulation modeling methods. In experimental studies, one should expect a different effect on the treated object of the specified variants of the superposition of electromagnetic fields.

When studying the effect of $M - C$, the previously obtained conditions of CECT with one type of current should be used [10–14]. To lead current into the melt, we use thin titanium electrodes with an insulated side surface. The end of the anode is located near the

bottom of the container (crucible), and the cathode — at the surface of the melt. The optimal dose of electrical energy density (W) which should lead into the melt, is determined by the previously obtained ratio $W/E \approx 1$ [12; 13], where E is the same order of magnitude as the crystallization energy density ($\sim 10^8$ J/m³). For alloys based on Al, this dose corresponds to the interval from $0.6 \cdot 10^8$ J/m³ to $6 \cdot 10^8$ J/m³ during the treatment time t . Thus, for a separate mass of the alloy, using the ratio $W/E \approx 1$, the processing time was preliminarily determined in the experiment with its selected parameters. The melt was processed at a temperature that did not exceed the standing temperature of the liquidus by 100 °C. The main role of the physical experiment is to establish the final effect of CECT, in particular, with $M - S$. That is, obtaining high indicators of the quality of castings.

Experimental verification of $M - S$. An ingot charge



Fig. 2. Characteristic current oscillograms of the electrode systems presented in Fig. 1: *a* — sum of AC (50 Hz) and DC (100 Hz); *b* — the sum of DC (100 Hz) and PC (1 kHz); *c* — the sum of DC (100 Hz) and PC (1 kHz); *a*; *b* — two-electrode system; *c* — four-electrode system

of casting pre-eutectic alloys based on Al was smelted in a resistant furnace in metal lined crucibles at a melting temperature of 750 °C. The slag was removed, performed for 30 minutes with mixing of the melt. After 15 min. of isothermal aging, slag removed and melt was mixing again. Even then, they performed current treatment at a temperature of 750 °C and pouring into the mold. To obtain control samples, a melt that was not treated with current was poured. The mass of alloy $M = 570$ g, which was enough to obtain standard samples — witnesses for the study of mechanical properties. The sample mold was heated to 200 °C, the pouring temperature was from 700 °C to 710 °C. In the first series of experiments, the AK7 alloy was treated (GOST 1583-93), chemical composition: Si (7.3 %); Fe (0.5 %); Cu (0.5 %); Mn (0.07 %); Mg (0.07 %); Zn (0.2 %); Pb (0.01 %), Al base. For CECT, electrodes option (a) in Fig. 1 and AC (50 Hz) and DC (100 Hz) current sources were used. We compared the results of processing with one type of current with the results of processing according to the principles of M — C. The equality of the dose of the

energy density injected into the melt $W = 2 \cdot 10^8 \text{ J/m}^3$ was maintained, which was the same value both with CECT of one of the two types of current, and in total, with the production of M — C. At the same time, the processing time $t = 16$ min. In addition, M — C processing was performed for 10 min. and 5 min., that is, with lower energy consumption, respectively $W = 1.25 \cdot 10^8 \text{ J/m}^3$ and $W = 0.7 \cdot 10^8 \text{ J/m}^3$. Table 1 summarizes data on the mechanical properties of specimens. Fig. 3 shows their microstructures.

The application of M — C showed a better effect on the obtained mechanical properties than CECT with one type of current. Moreover, such a result was obtained by reducing the treatment time by almost 3 times, and, therefore, the energy consumption. Thus, σ_B was increased by 13 %, and δ — by 1.5 times. It is important to note that after M — C, the value Ψ was recorded at the level of 4.4 %. For the selected alloy, this indicator is not even indicated by the standard. Analysis of the microstructure of the specimens showed the presence of a homogeneous grain structure after M — C, grinding

Table 1

Mechanical properties of specimens

Treatment principle	Tensile strength, σ_B , MPa	Yield strength, $\sigma_{0.2}$, MPa	Elongation δ , %	Reduction, Ψ , %	Hardness, HB
Without treatment	161	103	2.0	—	76.5
AC (50 Гц), $t = 16$ min.; $W = 2 \cdot 10^8 \text{ J/m}^3$	145	102	2.4	—	76.5
DC (100 Гц), $t = 16$ min., $W = 2 \cdot 10^8 \text{ J/m}^3$	176	111	3.0	—	76.5
AC + DC, $t = 16$ min., $W = 2 \cdot 10^8 \text{ J/m}^3$	162	125	2.4	3.6	76.5
AC + DC, $t = 10$ min., $W = 1.25 \cdot 10^8 \text{ J/m}^3$	163	120	2.0	1.6	76.5
AC + DC, $t = 5$ min., $W = 0.7 \cdot 10^8 \text{ J/m}^3$	182	102	3.0	4.4	76.5
GOST 1583-93	157	—	2.0	—	> 50

of eutectic elements, and a more rounded form of α — Al. In the second series of experiments, according to the specified method, ingot pre-eutectic silumin, additionally alloying with certain components (Si (8 %); Fe (0.79 %); Cu (1.98 %); Mn (0.1 %); Mg (0.27 %); Zn (0.44 %), Al base) was melted. This alloy does not correspond

to the well-known brands defined by the standard. Therefore, we aimed to show the effectiveness of M — C, even on a non-standard alloy. Without treatment (Fig. 4), a significant amount of iron-containing β phase was found in the eutectic. Copper forms the compound CuAl_2 , and Mg and Si form the compound Mg_2Si . In

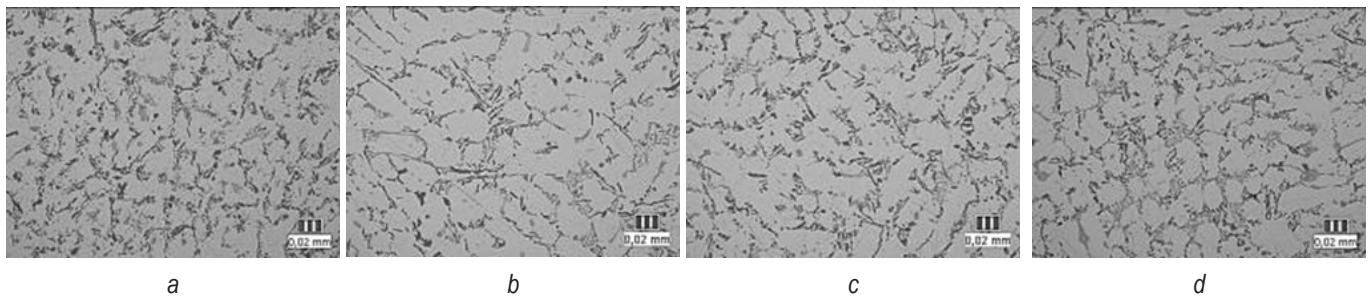


Fig. 3. Microstructures of specimens: *a* — without treatment, control; *b* — AC + DC, $t = 16$ min.; *c* — AC + DC, $t = 10$ min.; *d* — AC + DC, $t = 5$ min.

addition to these strengthening phases, Al_2CuMg (S-phase) and $\text{Al}_x\text{Mg}_5\text{Cu}_4\text{Si}_4$ (ω -phase) are present in small quantities, and also $\pi\text{-FeMg}_3\text{Si}_6\text{Al}_8$; $\text{Cu}_2\text{Mg}_2\text{Si}_6\text{Al}_{15}$; $\alpha\text{-(Fe, Mn)}_3\text{Si}_2\text{Al}_5$.

Table 2 shows the treatment modes of second series. Table 3 shows the quantitative characteristics of specimens microstructure. Microstructure control was

carried out using the Quick PHOTOINDUSTRIAL 3.2 program. Table 4 shows the indicators of mechanical properties.

To compare the given results and determine their rating, we will use such a non-standard indicator as treatment success [15; 16]. For each sample, the coefficient of treatment success k_s can be determined

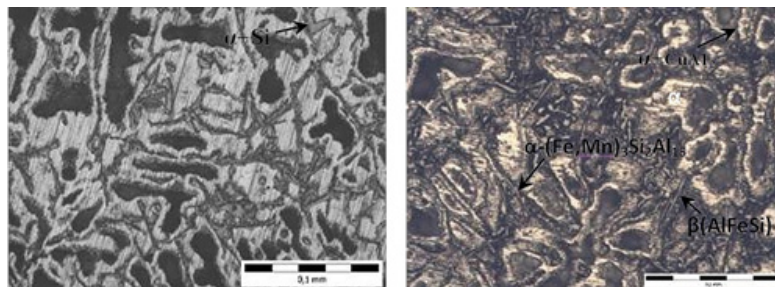


Fig. 4. Microstructure of the experimental alloy, without treatment

by the sum (or multiplying) of the relative indicators k_i , consisting of a comparison of such parameters as the minimum size of the primary dendrite; run of primary

dendrite size values; number of intermetallic phases; minimum size of intermetallics; range of intermetallic size values; temporary burst resistance. To calculate the value

Table 2

Treatment regimes at M — C in the second series of experiments

Specimen No.	Treatment regimes
26	Without treatment
27	Electrode system <i>b</i>) in Fig. 1, $t = 10$ min.; DC + AC
28	Electrode system <i>b</i>) in Fig. 1, $t = 16$ min.; DC + AC
29	Electrode system <i>b</i>) in Fig. 1, $t = 5$ min.; DC + AC
30	Electrode system <i>d</i>) in Fig. 1, $t = 5$ min.; DC + AC
31	Electrode system <i>a</i>) in Fig. 1, $t = 16$ min.; PC
32	Electrode system <i>a</i>) in Fig. 1, $t = 16$ min.; DC + PC
33	Electrode system <i>a</i>) in Fig. 1, $t = 10$ min.; DC + PC
34	Electrode system <i>a</i>) in Fig. 1, $t = 5$ min.; DC + PC
35	Electrode system <i>b</i>) in Fig. 1, $t = 16$ min.; DC + PC
36	Electrode system <i>b</i>) in Fig. 1, $t = 10$ min.; DC + PC
37	Electrode system <i>b</i>) in Fig. 1, $t = 5$ min.; DC + PC

Note. PC parameters; pulse frequency $f = 1$ kHz; period of current bipolar impulse $T = 43 \mu\text{s}$, energy of one pulse $W_0 \approx 0.022$ J. DC parameters: $I = 12$ A, $U = 0.8$ V, $f = 100$ Hz. AC parameters: $I = 16$ A, $U = 0.8$ V, $f = 50$ Hz. The treatment time t and the value W were determined in the same way as in the first series.

Table 3

Quantitative microstructure parameters of specimens

Specimen No.	Amount of eutectic, %	Minimum size of primary dendrite, μm	Maximum size of primary dendrite, μm	Range of primary dendrite size, μm	Amount of inter-metallic phases, %	Minimum size of inter-metalides, μm	Maximum size of inter-metalides, μm	Range of inter-metalides size, μm
26	24.32	16	155	139	10.92	20	89	69
27	32.8	11	60	49	10.45	20	60	40
28	28.5	9	63	54	7.58	11	28	17
29	26.34	12	94	82	11.89	8	30	22
30	25.43	9	50	41	8.63	8	23	15
31	21.98	8	38	30	2.8	7	25	18
32	31	15	87	72	6.5	7	76	69
33	27.99	12	87	75	6.37	11	30	19
34	29.63	11	57	46	3.94	11	20	9
35	20.53	10	76	66	4.78	10	15	5
36	22.98	12	70	58	5.19	13	144	131
37	35.96	10	60	50	5.73	8	16	8

Table 4

Quantitative indicators of mechanical properties

Specimen No.	Tensile strength σ_B , MPa	Elongation δ , %	Brinell hardness, HB
26	170	1.66	76.3
27	175	1.6	76.3
28	179	1.4	78.3
29	185	1.66	80.4
30	183	1.2	80.4
31	180	1.6	78.3
32	169	1.0	80.4
33	175	1.2	78.3
34	178	1.4	78.3
35	180	1.0	80.4
36	182	1.4	78.3
37	185	1.6	78.3

of k_i , it is necessary to divide the best indicator from the list by the indicator which characterized the specimen. For example, for specimen No. 37, indicator k_i , which characterized the minimum size of the primary dendrite, is equal to $8/10 = 0.8$. According to this procedure, the ratings of k_s coefficients for all specimens in the second series were determined. For the six specimens that had the best result, data are given in Table 5.

The data in Table 5 evidence that in the first four included specimens obtained by treatment with two electrodes with PC (No. 31), but at $t = 16$ min.; treatment with four electrodes with DC + PC (No. 37, No. 35) at $t = 5$ min. and $t = 16$ min.; by DC + PC treatment with

two electrodes at $t = 5$ min. (No. 34). As we can see, for the selected alloy of the second series, a positive result was obtained for both two- and four-electrode systems when using one and two currents together. But if pay attention to energy consumption, the advantage belongs to specimen No. 37 and specimen No. 34. As for the first series of experiments, we emphasize that treatment for 5 minutes, both according to scheme (a) and scheme (b) in Fig. 1, has the best perspective for further research. Note that treatment schemes (c) and (d) in Fig. 1 did not show rating results. Although it should be noted that only selected treatment regimes were used in this experiment. Thus, for the next analysis, the first four results in Table 5

Table 5

Success coefficient of specimens

Specimen	31	37	35	34	30	29
k_s	0.27	0.14	0.14	0.11	0.06	0.06

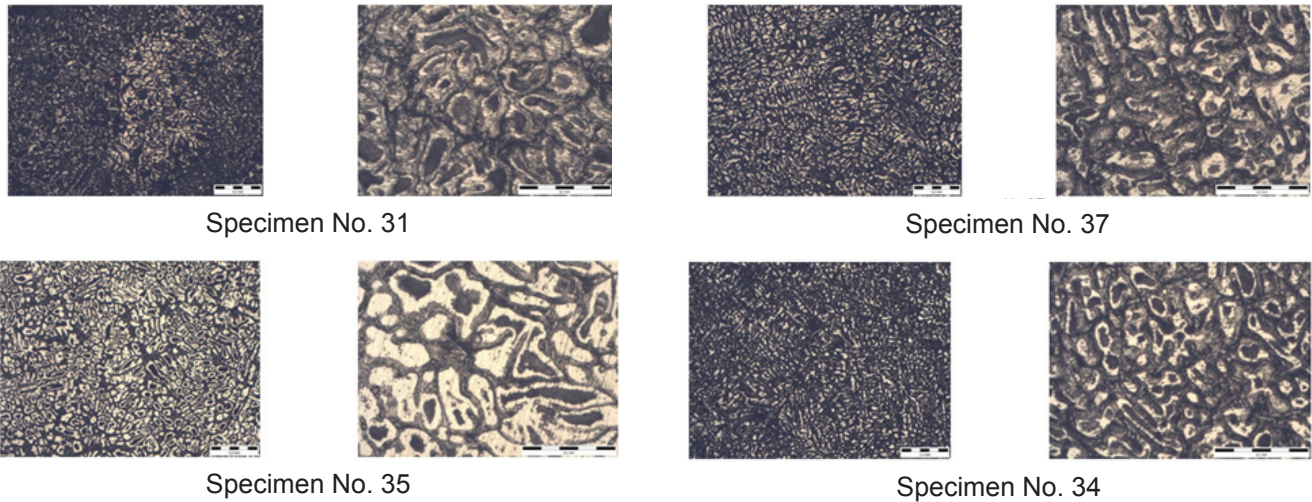


Fig. 5. Microstructures of best specimens from Table 5

should be selected. Fig. 5 shows the microstructures of the samples that had the best k_s values.

In both series of experiments, under the action of electric currents on the melt with the combined action of electromagnetic fields, the crystallization process and, accordingly, the microstructure of the specimens change.

Thus, for the non-standard alloy, there is grinding of structural components: significant grinding of intermetallics to sizes from $8\text{ }\mu\text{m}$ to $11\text{ }\mu\text{m}$, while compared to the original sample, there is practically no segregation of the intermetallic component by size. The primary dendrites of the solid solution were crushed almost twice. The growth forms of iron-containing intermetallics are changing. Partial dissolution of silicon inclusions and intermetallics in the solid solution is observed, as well as the formation of crystallization centers that increase the strength of aluminum grains and Al-Si eutectics. The growth of α -Al crystals occurs in the mode when first-order dendrites have rounded ends, and second- and third-order branches are practically absent. The structure of the treated samples is characterized by the grinding of silicon particles in the eutectic. Thus, the experimental studies conducted at this stage showed that the treatment of selected alloys with different types of currents makes it possible, depending on the types of currents and the electrode system, to effectively modify the structure of the treated alloy and reshape its structural and phase composition. The results of experimental studies confirmed the role of the combination of current types and the type of electrode system on the treatment result. The main mechanism of a positive change in the crystallization ability of the melt is formation of the electromagnetic fields superposition with more powerful thermoforce effect in the treatment object by passing different types of currents simultaneously than when using one type of current.

Conclusions

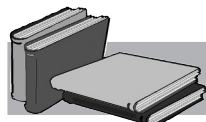
1. For the effective preparation of the alloy in the liquid state for crystallization, it is proposed to use the innovative principle of simultaneous passage through the melt of at least two currents with different electrical characteristics with different options of electrode systems.

2. The results of physical experiments with treatment of cast aluminum alloys with direct (rectified) current, alternating and pulsed current, as well as two-, three- and four-electrode systems showed the effectiveness and prospects of using a new method of melt treatment in foundry. Note that only selected treatment modes were implemented in this study. For a more thorough analysis of the method, it is necessary to expand the set of treatment parameters.

3. In contrast to the traditional principle of treatment the melt with one type of current, an increase in the mechanical properties of castings and an effective modification of the elements of the solid state structure have been achieved. At the same time, the total energy consumption per treatment can be reduced by almost 3 times.

4. In our opinion, a positive change in the crystallization ability of the melt is achieved mainly through by the formation of a superposition of electromagnetic fields with a more powerful thermal and force effect in the object of processing while passing different types of currents than when using one type of current.

5. The development of scientific and scientific-technological principles of the principle of simultaneous processing of the melt with different currents will allow to determine both more effective modes of processing of the melt, as well as the principles of purposeful control of processes, which achieve the best processing result.



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Експериментальне дослідження впливу на показники якості виливків одночасної обробки розплаву різними струмами

Ціль роботи — отримати результати, які б підтверджували ефективність та перспективність застосування методу одночасної обробки рідкого сплаву на основі Al різними струмами у технологіях ливарного виробництва.

Як відомо, різні типи струму, що пропускають через розплав (змінний, постійний, імпульсний), характеризуються різними функціональними можливостями. Типи струмів генерують у розплаві відмінні за амплітудно-частотною характеристикою та розподілом різні первинні електромагнітні поля, які і визначають сферу впливу. У роботі запропоновано використовувати інноваційний принцип одночасного пропускання через розплав як мінімум двох струмів з різними електричними характеристиками при різних варіантах електродних систем. Це дало змогу більш ефективно вплинути на структуру та властивості розплаву та, в свою чергу, покращити службові характеристики виливка.

В роботі виконано дві серії експериментів з застосуванням обробки розплаву трьома типами струмів та трьома типами електродних систем у різних варіантах сполучення. Обробляли чушкові зливки системи Al-Si: АК7 (ГОСТ 1583-93), хімічного складу: Si (7,3 %); Fe (0,5 %); Cu (0,5 %); Mn (0,07 %); Mg (0,07 %); Zn (0,2 %); Pb (0,01 %), основа Al; та нестандартний доевтектичний силумін, додатково легований певними компонентами (Si (8 %); Fe (0,79 %); Cu (1,98 %); Mn (0,1 %); Mg (0,27 %); Zn (0,44 %), Al основа). На відміну від обробки розплаву одним типом струму досягнуто збільшення показників механічних властивостей виливків та ефективне модифікування елементів структури твердого стану. Так, для першої марки сплаву σ_B збільшено на 13 %, а δ — у 1,5 рази. Також, після одночасної обробки різними струмами зафіксовано величину Ψ на рівні 4,4 %. Для сплаву АК7 цей показник навіть не зазначено стандартом. Для другої марки сплаву після одночасної обробки різними струмами спостерігається значне подрібнення інтерметалідів до розмірів від 8 мкм до 11 мкм, при цьому порівняно з вихідним зразком, практично відсутня сегрегація інтерметалідної складової за розміром. Структура оброблених зразків відрізняється подрібненням частинок кремнію в евтектиці. Загальні енерговитрати, за окремих умов, для обох марок сплавів зменшено у 3 рази. Основним механізмом позитивної зміни кристалізаційної здатності розплаву є формування в об'єкті обробки при одночасному пропусканні різних струмів суперпозиції електромагнітних полів з більш потужною термосиловою дією, аніж при застосуванні одного типу струму.

Ключові слова

Розплав, фізичний експеримент, електричні струми, кристалізаційна здатність, механічні властивості, структурно-фазовий склад, успішність обробки.