Modeling and research of influence of the external magnetic field on processes in a metal melt, received in the heavy current arc furnace

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Abstract. Need of a research of processes of hashing of liquid metal fusion for receiving homogeneous alloys is proved in this work. The mathematical model of processes of electromagnetic hashing of the fusions received the arc furnace is given. Statement of a special experiment for check of the offered model is considered. Results of calculations and the made experiments on the small-sized arc furnace are given. In the conclusion good coincidence of the offered theory and an experiment is emphasized and recommendations for improvement of the available processing equipment are made.

Keywords: modelling, experimental research, equations gidro- and electrodynamics, magnetic field, metal melt, arc furnace

1. Introduction
The relevance of research problems of processes of stirring of liquid metal fusion is dictated by requirements of modern production of the homogeneous alloys with special properties. Such tasks were set and solved in a varying degree today [1 – 6].
The first results of the experimental research, obtained on the small size arc furnace with the solenoid with the purpose of studying of influence of the external axial magnetic field on dynamics in a metal melt, and the results of the theoretical modeling of working processes at arc smelting in the electromagnetic crystallizer were reported by us at the conference on Plasma Physics and Plasma Technology (ВРП-4) [7].
The review of last experiments on the modified furnace as well as more detailed description of used theoretical model and the analysis of the received calculated results are presented in this paper.

2. Experimental research
The experiments on the modified arc furnace were carried out in argon medium at the pressures $p = 20, 200, 400, 760$ mm Hg, the arc currents were $I = 50–600$ A and the axial magnetic induction was $B_a = 0–11$ mT. The main attention was given to study the operational modes at the low pressure (20 mm Hg), which have the lot of technological advantages [8].
The optical diagnostics of a working zone including a videoshooting of the formed liquid metal mirror and simultaneous optical pyrometry of the melt surface (or the ingot) were used. The velocities of the
molten metal particles were determined by means of original method of graphite "floats". The graphite "floats" were preliminary placed on a working surface of an ingot and were well traced during a shooting.

It has allowed registering intensive rotation of the liquid metal bath. Then the distributions of azimuthal and radial velocities on a melt surface were obtained by further processing of the results of this shooting [7].

The important technological parameter in experimental metallurgy is the temperature condition of melt (ingot), and consequently obtained data of pyrometry of its surface (fig. 3) should be considered as one of the basic results used at formation of the general picture of dynamics of the processes at arc melting.

3. Theoretical research and comparison with experiment

The simulation of processes which are flowing past in fluxed metal included a numerical integration of a set of equations of motion, continuity and energy, that is, accordingly:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \bar{v} = -\nabla \cdot \rho \bar{g} + \nabla \cdot \mu \nabla \bar{v},$$

where $\rho$ - density of matter, $\bar{v}$ - velocity of the melt particles, $p$ - pressure, $\bar{g}$ - acceleration of a summary falling, $\mu$ - a dynamic viscosity, $\bar{j}$ - current density, $\bar{B}$ - induction of a magnetic field,

$\nabla \cdot \mu \nabla \bar{v}$ - force of internal friction, $H$ - enthalpy, $Kh$ - function of Kirchhoff $(Kh = \int_{0}^{T} \lambda \, dT$, where $\lambda$ - coefficient of heat conductivity). These equations were decided together with equations determining properties of medium:

$$\frac{\partial H}{\partial t} = \frac{1}{\rho} \nabla \cdot \rho \nabla H,$$

where $\rho$ - density of matter; with an equation of the Laplace: $\nabla \cdot \nabla \phi = 0$, where $\phi$ - electric potential; with an Ohm's law: $\bar{j} = \sigma \bar{E} = -\sigma \nabla \phi$, where $\sigma$ - conductance, $\bar{E}$ - electric field strength; with Maxwell equation: $\nabla \cdot \nabla \bar{B} = \mu_0 \bar{j}$, where $\mu_0 = 4\pi \times 10^{-7} \, \text{H/m}$.

The boundary conditions on velocities were set, proceeding from conditions of attachment and nonpassage on firm borders and from a condition of equality of a stress tensor to an external pressure tensor on a free surface. The boundary conditions on electric potential guessed: equipotentiality of the crystallizer walls, count of a transient layer resistance, and also normal Gaussian distribution of a current density on a melt surface (ingot). The boundary conditions on a function of Kirchhoff were set with allowance for of heat -transfer coefficients from metal through a wall accretion and the wall to cooling water. Density of a heat flow on a melt surface was received of a proportional current density with a some factor of concentration.

The modular condition of matter was determined on value of an enthalpy $H$ (function $T (H)$ takes into account heat of phase change).

In the basis of the applied numerical approach to the solution of a problem the method of markers and cells with a number of additions lied [9, 10]. In this way, in the works [11 - 14] processes in a metal bathtub taking into account impurity were modelled.

The calculations were carried out for the melting with a wall accretion of titanium in a copper water-cooled crystallizer of diameter $2R = 100$ mm for a received ingot by an altitude $h = 12$ mm (fig. 1). The melting at an argon medium pressure of 20 mm Hg and at a cathode - anode gap of 23 mm was looked. The current arc modes $I = 400$ A and 500 A were researched at presence and in absence of an external magnetic field with induction $B_0 = 11$ mT.
As display the calculations and the experiment results, at superposition of the axial magnetic field the melt begins fast (with a velocity 10-16 cm/s) (fig. 2) to rotate around of the crystallizer axis. The velocities of meridional rotation of a arising curl in the melt are considerably increased. If the vertical motion velocity of a liquid phase under an operation of gravitational forces and Ampere forces in a owner magnetic field made about 0,3-0,5 cm/s, at imposing of an external field it has increased up to 2-6 cm/s, that can provide intensive enough stirring of a melt in a bath with depth ~ 1 cm. The fast rotation of the vortexes results in equalization of a temperature field in the melt, decrease of an overheating of a metal surface. At the expense of convective effects the area of a melt mirror is considerably augmented, however the temperature in regions of upward currents (in center) is reduced. The last result, however, is not essential in high-current modes (more than 500 A), when practically all ingot was uniformly melted. On fig. 3 the calculated temperature curves of the melt surface are presented at a current 500 A at presence of the magnetic field (1) and without the field (2) accordingly, in the same place in the form of separate points the values of temperature measured by the pyrometer are put.

The Fig. 4, growing out the numerical analysis, gives representation about dynamics of the processes proceeding both inside of the ingot (melt), and on its free surface. Here arrows designate directions and modules of velocities of the melt particles, and continuous lines define corresponding isotherms (the line 1940 K defines border of liquid and firm phases of the given alloy). It is possible to explain ascending of meridian velocities by a non-uniformity of a current diffuence on the ingot and, as a corollary, originating of a non-uniformity in operation of the Ampere forces.
4. Resume and recommendations

Thus, having in metal the inhomogeneous diffluence of a current and imposing an axial magnetic field, is possible considerably to intensify process of azimuthal and meridional intermixing of a melt are resulting in for equalization of temperatures in a melt, decrease of temperature of a surface both increase of homogeneity of a ingot composition and its structure.

At rotation of a melt its free surface is deformed (fig. 4), forming the funnel, owing to what the anodic binding of an arc displaces from center of an ingot and begins under an operation of an axial magnetic field “to run» on edges of this funnel. And this displacement is more, than more rotation rate of a melt (and, hence, depth of the funnel). Such motion of an arc results in dispersion of a heat flow on a surface of metal, to formation of the azimuthal kvazysymmetrical distributions of current densities and velocities, to originating near to center of an ingot the force that is raising metal from the depth of an ingot on the surface.

However, as shows the preliminary theoretical analysis by a technique stated in work [15] if in addition to axial influence to displace an arc by means of a cross-section magnetic field it is possible:

first, to achieve a more homogeneous heat flow on a surface that is especially important at the melting of refractory metals (W, Mo); secondly, arbitrary to displace a vortex of liquid metal in a horizontal plane, and, that, it is more effective to melt a metal on periphery of a crystallizer and to eliminate “cold” zones in the center of an ingot.

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