INFLUENCE OF THE SWIRLED ELECTROVORTEX FLOW ON THE MELTING OF THE EUTECTIC ALLOY IN-GA-SN

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Abstract
It was shown with experimental and computational methods that the process of metal melting essentially depends on the intensity and hydrodynamic structure of electrovortex flows (EVF) developing in smelting furnace. It was found that by controlling the EVF with an external longitudinal magnetic field one can reduce the melting time.

1. Introduction

The so-called electrovortex flow (EVF) is formed by the interaction of an electric current, spreding into the current-carrying fluid volume, with its own magnetic field [1]. It is assumed that in natural conditions electrovortex flow, as well as free convection [2], may be the cause of hydrodynamic structures similar to a tornado. In technology intensive EVF is observed in various high-current technological processes, for example, in the electroarc or electroslag remelting of metal [3]. Hydrodynamic structure of EVF was most fully investigated by numerical methods for working models of melting baths with axisymmetric geometry, in which the electrodes of different diameters were located at the butt-ends of the cylindrical shape container [3 - 5]. In [6] the pioneering measurements of the velocity fields of electrovortex flows were carried out in a cylindrical working section, the results of which indicate their complex multivortex structure. In subsequent studies [7 - 9], devoted to the study of the electrovortex flows formed at the axisymmetric spreading of the electric current from a point source in a hemispherical volume filled with liquid metal, it has been experimentally shown that the hydrodynamic structure of EVT is substantially determined by the intensity and orientation of the external, even relatively weak magnetic fields acting on the experimental setup. In particular, it has been proven by experimental and computational methods that the paradoxical spontaneous horizontal swirl of the axisymmetric electrovortex flow in the hemispherical bath is caused by interaction between spreading electric current in a liquid metal with the magnetic field of the Earth.

Furthermore it has been found that intensive swirling flow around the horizontal axis of the bath, due to the influence of the external longitudinal magnetic field leads to the formation of secondary vortices in the vertical plane and suppression the downward flow in the volume of current-carrying fluid, except a small region near the small electrode. Based on the results of earlier studies, one can assume that the presence of EVF and change of their hydrodynamic structure under the influence of the external magnetic fields affect the metal melting process. However, the analysis of literature revealed no studies on the quantitative characteristics of this effect.

Therefore, we have carried out additional experimental and computational studies on the influence of EVF on electrosmelting of metals, methods and the results are shown below.

2. Experimental setup, measurement and calculation methods

Experimental studies simulating EVF applied to electroarc remelting process were carried out at the setup shown in Fig. 1. An eutectic indium-gallium-tin alloy (weight content: Ga – 67%, In – 20.55, Sn – 12.5%, melting point +10.5 0C) was used as the working liquid in the experiments. Alloy filled copper hemispherical container with a diameter 188 mm which also served as a large electrode. Small electrode - copper cylinder with diameter 5mm with hemispherical end was immersed into the alloy in the middle of the working bath. Physical properties of the alloy are given in [10]. Power source developed on the basis of three-phase AC rectifier (I ≤ 1500A) was used to supply an experimental setup. To create an external longitudinal magnetic field the coil consisting of 15 turns of hollow copper tube (cooled with pumped water) was used. Coil power was supplied from a stabilized power source, providing smooth control of DC in the range from 0 to 100A. This system allowed to get the magnetic field with induction B = 5 × 10-3 T in the middle of the working area at a current of 100A.

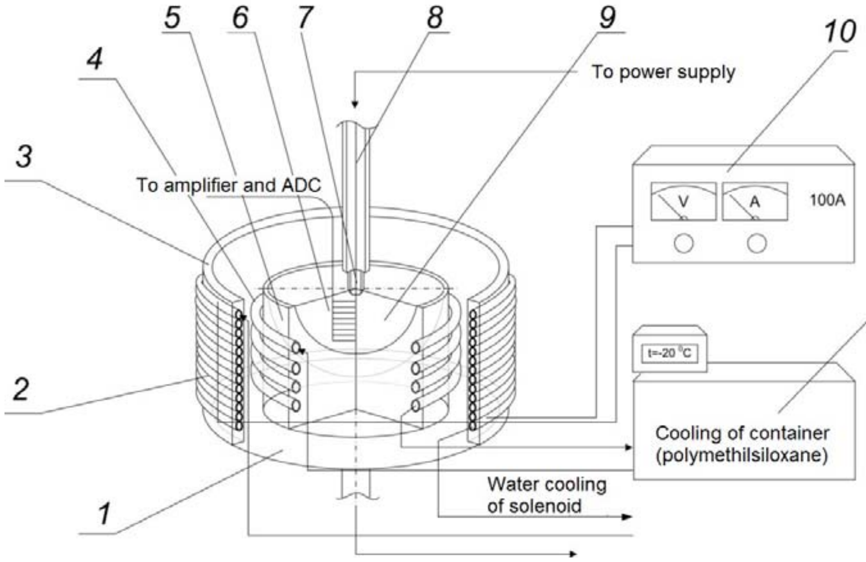

Fig. 1. Experimental setup. *1* — cooling vessel, *2* — water-cooled solenoid, *3* — heat insulation, *4* — heat exchanger, *5* — copper container, *6* — thermocouple probe, *7* — small electrode, *8* — current lead, *9* — eutectic alloy In-Ga-Sn, *10* — power supply of solenoid, *11* — refrigerator.

Before the experiments special coolant - polymethylsiloxane (PMS-5) at a temperature of 250C was poured into a cylindrical cooling tank, located in the gap between the working section and a solenoid. In addition, polymethylsi-loxane was pumped through the heat exchanger - tube wrapped around the copper container filled with alloy. These preliminary procedures allowed to cool alloy In-Ga-Sn up to 0^0C (at the air temperature 25^0C), i.e. substantially below its freezing temperature of ~ 10^0C. After liquid solidification in the whole volume of the hemispherical container, polymethylsiloxane was poured from the bath cooling system. Then an electric current was passed through the working area and heating and melting of liquid metal happened The probe-comb consisting of 8 chromel - alumel thermocouples with diameter of junction 0.5 mm was used to get thermograms in the volume of the alloy. The width and depth of the molten zone were measured with a special probe.

In a numerical study of the influence of EVF on the metal melting process, so-called enthalpy-porous model built-in software package ANSYS Fluent was used [11]. In this model two-phase zone liquid - solid is considered as a porous medium with a porosity equal to the propor-tion of the liquid phase, and the pressure loss caused by the presence of not molten material was taken into account by introducing of an additional dissipative term into the motion equation. The conservation equations system of momentum, enthalpy and continuity was solved in inductionless approximation, i.e., consideration of the influence of magnetic field on the velocity field and the temperature was taken into account by addition of the Ampere force **F** = **j** × **B** in the motion equation.

To determine the current density **j** in all elements of the working area, including both electrodes, the equation for the electric potential Φ (div(σgradΦ) = 0) was solved with boundary conditions at the upper and lower end of the current leads $\Phi=\Phi_0$ and Φ=0 corresponding to a complete electrical current flowing through the setup. Current density **j** was calculated from the equation **j** =-gradΦ. More complete description of the calculation of the magnetic fields and forces acting on the electroconductive liquid is presented in [12]. At solving the motion equation, no-slip conditions were set on all surfaces, including open surface of metal because solid oxide film has been formed on it. For the energy equation on the borders with the air free convection conditions were set, and the temperature of the environment was considered 25^0C.

3. Results

Typical results of experimental studies on the spreading of the melting front deep down into the bath and the metal surface are shown in Fig. 2. Shapes of the melting curve boundary at different times in the whole volume of the metal shown in Fig. 3. Experiments were carried out at a current I = 400 A at the presence of the Earth's natural magnetic field (EMF), and adding there an artificially created longitudinal (relative to axis of the setup) magnetic field of solenoid with induction B = 5 × 10^{-3} T. The table below shows some data on rate and time of melting.

As seen from these graphs, there is a significant difference in the shape of the melting front with the presence of artificially generated external magnetic fields, and its absence.

In the first case, the shape of this curve follows the shape of the melting pool, and under the influence of EMF melting front has a typical shape elongated along the axis of the bath. Also the time of complete melting of the metal in the bath under the influence of an external magnetic field was 12% lower than in its absence.

Analyzing presented results one can assume that the process of melting in the processing bath is as follows. At the start of heating of the metal with the electric current, a small portion of metal near small electrode melts.

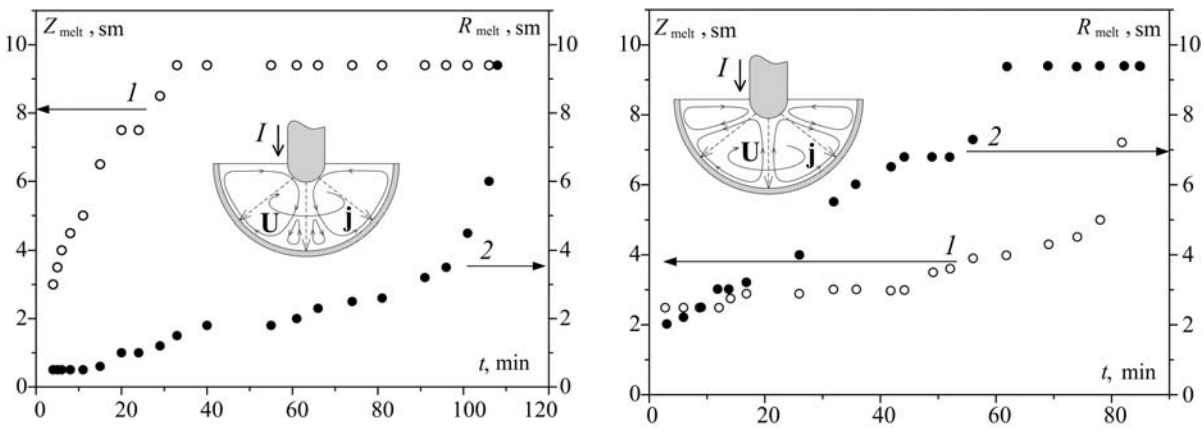

Fig 2. Moving the melting front in the direction of the axis of the metal bath and radially on its surface.
I = 400A. Influence of (a) – Earth's magnetic field (EMF) (B~5×10^{-5}Тл); (b) – EMF and solenoid B= 5×10^{-3} Тл.
1 и *2* – coordinates of melting point on axis and radius of the bath.

EVF occurs in the molten liquid volume, and in the ideal case, the absence of an external magnetic field EVF is a single axisymmetric toroidal curl, creating a jet axial flow under a small electrode [1]. Influence of EMF leads [8] to the azimuthal rotation developing in the current-carrying liquid. This movement of the melt in the horizontal plane leads to the generation of secondary vertical vortex near the bottom area which, although directed opposite EVT, but because of its relatively low intensity has no significant effect on the original structure of EVF (see Fig. 2a). Hot melt flow causes intense melting of the metal in the direction of axis Z, and melting in axis R direction became appreciable only when the liquid phase of the metal reaches bath bottom. Under influence of external longitudinal magnetic field of the solenoid, azimuthal swirl of the liquid also occurs in the horizontal plane in the working bath, but this swirl is more intense than under the influence of EMF. This rotation leads to generation of the strong secondary vortex in the vertical plane moving the melt upward along the axis of working area, and to weakening of primary EVF (Fig. 2b). Moreover intense azimuthal motion of the fluid enhances heat and mass transfer processes in the horizontal plane, thereby increasing metal melting rate in a radial (in the cylindrical coordinates) direction.

The results of numerical calculations (see Fig. 3) are qualitatively consistent with the results of experiments and confirm the melting flow processes described above. The observed quantitative differences can be explained, in particular by to some uncertain parameters (e.g., the value of effective porosity in the mushy zone). Also it should be noted the considerable complexity of calculations because the duration of calculation of one melting mode on the PC with 4-cores processor was more than one month.

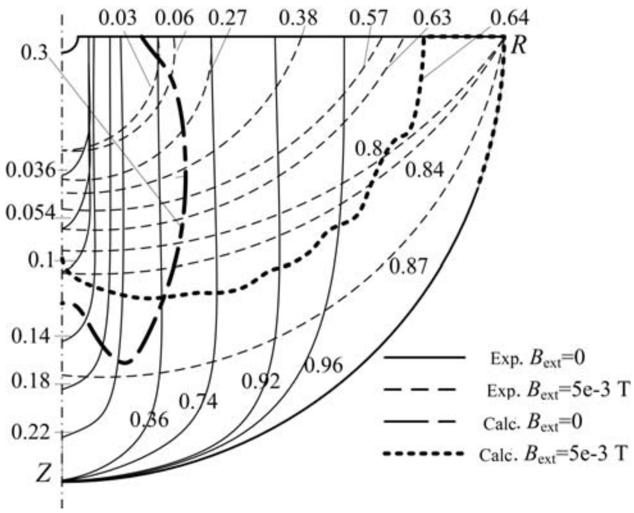

Fig.3. Melting front spreading with an external magnetic field and without. I = 400 A. The numbers on the lines - time from the beginning of the experiment, divided by the time of full molten of metal.

	Total melting time	Average melting rate along Z-axis	Average melting rate along R-axis
With magnetic field $B=5\times10^{-3}$ T	1 h 38 min	0.10 sm/min	0.14 sm/min
Without magnetic field	1 h 50 min	0.24 sm/min	0.09 sm/min

4. Conclusions

As a result of experimental and numerical studies there was found that the impact of constant axial (longitudinal) magnetic field leads to an intensification of the processes of melting and reduction of melting time. The mechanism of this phenomenon is connected with the occurrence of the azimuthal swirl of melt metal in these conditions and the radical transformation of the flow in a hemispherical bath with a central electrode. Hydrodynamic structure of flows formed in the working bath leads to more intensive (due to the formation of additional reverse flows) removal of heat from the hot region near the small electrode deep into melt. Furthermore, due to occurrence and interaction of additional large eddy formations, the direction of the prevailing EVF changes. For this reason the melting front loses axial and gets a radial direction.

Let note two important practical circumstances. First, the way to create external magnetic fields near the melting units with a solenoid is the most simple method. Second, many baths of industrial arc furnaces has a horizontal orientation (ratio of diameter to depth ~ 5:1) Therefore, it can be assumed that the effect described above can be used in these devices to intensify the melting process in the radial direction and increasing its energy efficiency.

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LIST OF SYMBOLS

B — magnetic field induction, T;
F — Ampere's force, N/m^3;
j — electric current density, A/m^2;
I – electric current, A;
t – time, min;
σ – conductivity, S/m;
Φ – electric potential, V.

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