Computer modeling of cyber-physical system based on digital twins of melt electric current treatment modes

Yuriy Zaporozhets[1], Artem Ivanov[1], Yuriy Kondratenko[2,3] and Volodymyr Tsurkin[1]

[1] Institute of Pulse Processes and Technologies of National Academy of Science of Ukraine, Bohoyavlensky Ave., 43-A, Mykolaiv, Ukraine
[2] Petro Mohyla Black Sea National University, 68-Desantnykiv St., 10, Mykolaiv, Ukraine
[3] Institute of the Artificial Intelligence Problems of the MES and NAS of Ukraine, Ukraine

Abstract

The paper expounds the main provisions of original author's devisings devoted to composing of a special information control system for automation of control processes in foundry production, where the problem of quality control of cast products is complicated due to the presence of many uncertain factors of production. To improve the quality of castings, in particular, electric current treatment (ECT) of the melt is used. ECT generates complex electromagnetic and other physical phenomena in the melt that make impossible the direct control of the technological process parameters. Based on the cognitive analysis of the physical content of these phenomena, the main factors influencing the results of treatment are determined. The article presents the innovative information and control system of computer modeling "ITIS", which implements the principles of integration of computing with physical processes of ECT. The algorithmic paradigm of ITIS system involves the formation of simulation models – digital twins of ECT modes, especially electromagnetic, that adequately reflect the real physical processes. ITIS de facto embodies the structure and functional scheme of the cyber-physical system (CPS) of "smart casting". The mathematical models and algorithms for calculating the parameters of melt treatment and filling the CPS databases with digital twins of ECT modes to predict its results are presented. Prospects for the application and development of "smart casting" CPS in foundry technologies are discussed.

Keywords

Computer modeling, digital twins, cyber-physical systems, controlled mode, electric current treatment, structure, casting.

1. Introduction

The trends of technological transformations formed at the current stage of industrial production development, aimed at achieving higher efficiency and productivity via the applied intelligent systems of machines and production processes, are embodied in the construction of unmanned "smart" factories, the creation of "smart" (unmanned) vehicles and other "Industrial Internet of Things" (IIoT) [1]. In this paradigm, based on the concept of automation, robotization, communication between machines and digitally supported product management, the effective processing and use of information, primarily digitalization and Big Data analytics, inter alia, with application of "Digital Twins", play a key role [2].

Therefore, these technological advances are successfully implemented in areas where comprehensive physical, technological and economic information is available, i.e., the certainty of the manufactured product and the determinacy of the production process [3]. Such industries, based on tightly integrated applied intelligent systems, are mostly suitable for creating modern high-tech cyber-physical systems (CPS), which include, for example, stamping, conveyor lines, mining and processing plants, fixed transportation networks, etc.

However, there are a large number of industries in which the characteristics of the final product depend on many uncertain and even undetected, but significant production factors. A typical industry of this kind is metallurgy and, in particular, foundry, whose technical assignment is to produce castings with predictable structural and mechanical quality indicators. The quality of the resulting castings is determined by the homogeneity and orderliness of the grain structure with a minimum of impurities and gas inclusions, which is formed spontaneously at the cooling stage and is revealed only by a posteriori examination of the structure of solidified castings [4].

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[1] *ICST-2024: Information Control Systems & Technologies, September, 23 – 25, 2024, Odesa, Ukraine*

✉ yurii.zaporozhets@nuos.edu.ua (Y. Zaporozhets); artiomsan@gmail.com (A. Ivanov); yuriy.kondratenko@chmnu.edu.ua (Y. Kondratenko); dpta@iipt.com.ua (V.Tsurkin);

0000-0002-3693-3844 (Y. Zaporozhets); 0000-0002-3247-6121 (A. Ivanov); 0000-0001-7736-883X (Y. Kondratenko); 0000-0003-2697-579X (V.Tsurkin)

2. The problems and tasks for creation of "smart casting" technology

2.1. The problems of controlling the modes of melt electric current treatment

It is ascertained that the quality of the casting structure can be influenced by external physical impacts on the metal in the liquid state before its solidification, due to the inheritance of physical features of the melt in the properties of castings [4,5,6]. A very promising method turned out the electromagnetic treatment of melts, in particular, straight with electric current (ECT) [7], which consists in the direct transmission of current of various modes through the melt, thereby creating conditions for obtaining better characteristics of the cast metal in the subsequent crystallization process [8,9]. The main task of this treatment is to promote the synchronous formation of the smallest possible crystallization grains and their uniform distribution in the casting volume.

Achieving these goals provides a significant improvement in the quality of cast products, so when controlling the process of forming the castings structure, its characteristics, as well as the normalized operational properties of castings, become the parameters, which are being controlled. Then the controlling parameters in this technology are external factors that set the melt processing mode, namely the design of the reactor with the electrode system and the parameters of the electric current, variations of which determine the possibility of direct influence on the spatial distribution of the current density. At the same time, parameters of electric current, in particular, amplitude, frequency, pulse duration, electric current, in particular, amplitude, frequency, pulse duration, and processing time, set the energy spectrum of effects. This approach is the basis for the concept of a controlled mode of electric current treatment of melt described in the authors' works [10,11]. The tasks arising from it constitute the content of the innovative technology, which in the categories of Industry 4.0 should be defined as the technology of "smart casting" [1,3]. Controlling such a complex process in a tracking mode requires the collecting, processing, and monitoring of many data that differ in both physical nature and spatial and temporal characteristics. However, apart from the melt temperature and the integral parameters of current and voltage at the electrodes, it is physically impossible to obtain the mentioned data on the melt state directly during the processing. Therefore, the phenomena occurring during the treating and solidification of the casting are inaccessible for control, and therefore, the managing of such technological operations is more likely to be classified as heuristics and empirics than strict predetermination. In the specified circumstances, the possibility of ECT automation is determined by the fact that practically the only available means of "extracting" information (Data mining) about the object in the ECT process is to derive estimates of casting quality indicators by solving problems about the distribution of local parameters of internal processes in the melt using mathematical models.

2.2. The premises for creating a "smart casting" cyber-physical system

In such a situation, the high-tech strategy "Industry 4" [1] orients to creation of cyber-physical systems (CPS), the information technology concept of which involves the integration of computing systems with their physical environment by creating "Digital Twins" of production facilities and exchanging information between them using standardized networks and protocols [12]. In such a system, sensors and equipment for direct physical monitoring and control are connected to information systems, where the arrays of direct gauging and accumulated statistical data are intelligently processed [13]. For this purpose, methods of correlation analysis, fuzzy logic [14], pattern recognition [15] as well as the development of AI systems based on cognitive and conscience conceptions for identifying process parameters used to predict system states and to form control actions in automated technological chains are applied.

Thus, the tasks of constructing an automated system for the modes control of electric current melt treatment, which are reflected in the authors' works, fully correspond to the specified content of CPS. The Integrated Three-Component Information System (ITIS) presented in them is actually a prototype of CFS, since the procedures for the functioning of the ITIS and its components are fully identified with the main levels of cyber-physical interaction [16] and the architectural components of CFS [17]. In particular, CFS defines the interaction of components at the sensor, network, computing and information-control levels, and additionally distinguishes the service or intellectual level. In accordance with this scheme, the structural composition of both systems is revealed in Table 1.

The digital layouts of structure formation specified in clause 4 are used to synthesize prognostic archetypes of the structural properties of castings, on the basis of which the tasks are formed to ascertain the optimal parameters of the ECT mode for specific products.

Thus, the algorithmic paradigm of ITIS functioning [10] embodies the concept of "smart casting" in the main features of the CFS structure and, using the procedures for identifying the parameters of melts and castings, combines disparate information flows that reflect the specificity of the physical experiment, the statistical representativeness of prognostic archetypes selections, and the mathematical accuracy of computer modeling.

As a result of such a synthesis, the premises are created for considering the entire set of factors affecting structure formation and the forming of control influences that should ensure the optimal mode of melt ECT. That is, virtually, cyber, software and analytical components of the CPS are developed in detail in the ITIS structure, but its physical component, which is associated with the managing of processes, which are characterized by a high degree of uncertainty of the physical processes essence and their technological parameters, requires the use of the most effective methods of processing great arrays of data, such as Big Data Analyses, neural networks, machine learning, etc. [18].

At the same time, the use of this toolkit requires filling the CPS with a sufficient number of identification attributes of the controlled parameters of the modes of technological operation modes for the manufacture of products. So, the objective of this publication is to fill the physical component of the cyber-physical system of "smart casting" with models of the melt ECT process that can be used as digital twins (DT) – the simulators of melt processing modes, to identify controllable factors influencing the casting structure formation process to obtain the desired quality indicators. Setting the tasks to form a batch of models – simulators of processing modes, obviously, requires specifying the phenomenological content of the processes performed in the melt and the peculiarities of the structural elements of this environment behavior.

Table 1

The comparison of CFS and ITIS components

Components of CPS [17]	Components of ITIS [10,11]
1. Physical: objects, about which CPS collects information	1. EDB: Experimental Data Base of structural analysis of samples after ECT.
2. Cyber-technical: computing and communication equipment with appropriate data exchange protocols for processing and distribution of primary information.	2. NDB & BDIS: Normative Data Base with casting structure templates and a Data Base of Identified Samples for which quality indicators are determined.
3. Software: software for storing, processing and analyzing the information received from the second component sources.	3. CMB & SRB: Data processing algorithms in the computer modeling block and the sample recognition block with a database of template identification cards.
4. Analytical: algorithms for processing information needed to manage production processes.	4. DMDB: Algorithms for modeling ECT modes and determining quantitative estimates of the energy intensity of melt treatment and forming a Data Base of Digital Models (layouts) of structure formation.

3. The basic insight of liquid metals structure and factors affecting the casting structure formation

3.1. The cluster model of liquid metal

The cluster model represents a liquid metal as a heterogeneous substance consisting of partially ordered sibotactic groups and amorphous zones. Sibotaxis is believed to retain the particle placement inherent in the arrangement of atoms in crystals [19].

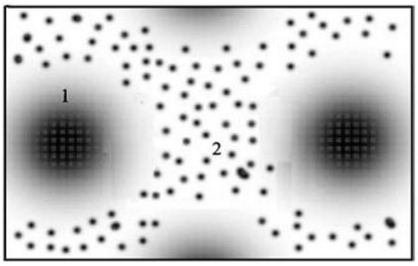

Figure 1: Scheme of the melt structure: 1 - sibotaxis (cluster), 2 - disordered zone

But clusters have no clearly delineated boundaries, they are dynamic formations that change in time continuously: the ordered arrangement of atoms within the sibotaxis is replaced by their disordered arrangement in the neighboring disordered microvolume. Collapsing in one place, the clusters arise in another, as it's shown in Figure 1. The ratio of the clusters' volume and disordered zone in the melt depends on temperature and is approximately (80% : 20%).

Clusters and disordered zones are thermodynamically unstable systems: the value of the Gibbs energy for clusters exceeds its level for entire melt, but in disordered zone is lower than it. Clusters arise and decay due to the shift of atoms through an amorphous zone from one to another. Owing to this, the microvolume are connected with each other. Nevertheless, the life expectancy of clusters, as well as disordered zone, is only $\tau_{cl} \approx 1{,}5 \cdot 10^{-9}$ s. However, it is vastly greater than the period of thermal oscillations of particles in liquid metals (10^{-14} s), as well as the duration of elementary acts of thermal conductivity, and diffusion. In the concept of a microinhomogeneous structure of a metallic liquid, the number of atoms in a cluster reaches several hundred. However, the size of the clusters is smaller than the critical size of crystals that can develop into a solid phase at the crystallization temperature, since the minimum radius of a crystal with an energetically formed surface is approximately $r_{\min}^{cr} \approx 25\text{Å}$. It is this order that makes up the size of a quasicrystalline formation in an aluminum (Al) melt, which can act as a nucleus that, under certain conditions, will reach the critical size r_{cr}. For Al, the radius of a cluster with the number of atoms $N_{cl} \approx 950$, reaches $r_{cl} \approx 16$ Å [20]. It should be noted that clusters as a material substance carry a positive charge, while the amorphous gap remains negatively charged. Under such conditions, the electromagnetic field can exert a significant effect on the cluster structure of the liquid and its dynamics. In the case of external energy impact on the melt due to the action of the above-mentioned elementary acts, the redistribution of Gibbs free energy and entropy of the system at all levels of its structural composition (electronic, atomic, cluster) occurs, which leads to a change in the thermodynamic state of metal system and the nature of its ordering. At the same time, its properties change at the atomic level, and at the cluster level, conditions are created for the emergence of the nuclei of the grain structure of castings [4]. The given information on the spatial and temporal parameters of elementary acts of physical processes at the atomic level and the characteristics of the dynamic behavior of large ordered groups of interacting atoms arising in a liquid-metal substance as a result of the inflow of energy from the external medium and its outflow indicate the presence of a certain hierarchy of levels of energy interactions of commensurate elements of the melt structure.

3.2. Phenomenological premises of external energy impact on the process of structure formation of castings

The concept of energy-metric levels of interaction of commensurate objects from the deep level of the substance structure to the inspiration of activity of the structure elements of the upper hierarchical level, which was introduced in [4], corresponds to the abovementioned notion regarding the structure of liquid metals. The designated levels reflect the interaction of elements which differ by orders of magnitude in space-time scales (metrics) and energy flow densities that characterize the nonequilibrium thermodynamic state of the casting substance. In particular, macro-, micro-, submicro-, meso- and atomic energy-metric levels of the interaction of commensurate objects are distinguished. The above phenomenological hypothesis should be understood in such a way that the nonequilibrium processes excited at the deepest level generate a response – the reaction of each layer to the upper levels of the system, producing the effect of structural fluctuations, which, according to current notions, impel the disturbed structure to self-organization, that is, to the formation of another – modified structure, with other properties. So the conditions of the precrystallization state, in which nucleation occurs, are formed, therefore it is considered as the incubation period of crystallization.

However, it is essential that the final quality indicators of cast products are influenced indirectly by any external impacts and melt treatment methods, so they can be considered as targeted only conditionally, because the aftereffect of any of them, being provided as the part of the complex effect on the metal, does not give an additive result, since the properties of the metal are formed not separately, but as a cooperative effect of competing processes [4]. From this the phenomenological basis of perceptions of the mechanism and methods of targeted influence on the process of casting structure formation is formed, which opens up the prospect of developing technological methods for managing the quality of cast products. So, the metal melt is a multilevel hierarchical system, the physical nature of processes in which are elementary acts [4]. The key role in the mechanisms of these processes is associated with the energy of the bonds of the structural elements inherent in the metal system (MS). However, the energy of these bonds is inevitably subject to fluctuations due to natural factors or external influences. In real technological processes, the MS exchanges energy and entropy with the surrounding medium, so such a system is open, and the processes that occur in it are thermodynamically non-equilibrium. Open systems in which the energy of ordered motion is transformed into the energy of disordered (chaotic) motion, resulting in an increase in entropy, are called dissipative. Non-equilibrium thermodynamics relates the formation of dissipative structures to the loss of stability and reformatting of energy bonds, and claims that the new structure is always the result of a transaction of instability due to fluctuations. Thus, the talk is about "the order through fluctuations" [21,22]. In particular, if the outflow of entropy in a nonlinear system exceeds its internal growth, then the large-scale fluctuations arise in it and they grow to a macroscopic level, which leads to the development of self-organization processes intended to create the ordered structures. Consequently, if an open thermodynamic system is unstable, the role of external influences in it changes, in particular, electromagnetic fields substantially transform energy bonds, and secondary fields enhance these effects. Thus, in the case of the external load of the MS by the electric field, which, in turn, generates secondary fields, their integral action causes the amplification of fluctuations and an extension of their duration in certain zones of the MS. Fluctuations correlate with each other, synchronize, and then a new structure or phase occurs in a hopping manner.

4. Cognitive analysis and mathematical foundations of ECT modes computer simulation

4.1 The cognitive model of ECT

According to the current notions of the essence of the ECT process, the totality of the described phenomena creates favorable conditions for the mass formation of crystallization nuclei, which improve the crystallization ability of the melt. However, there is no comprehensive and unambiguous understanding of this mechanism. In such circumstances, the use of cognitive analysis will be a natural approach for solving the problem of determining the factors of targeted control of ECT process mode [23, 24]. Cognitive analysis involves the synthesis of a cognitive model by causally structuring information about the processes that occur in the system under study. In a cognitive model, information about a system is represented by a set of terms (factors) that are connected by a causal network (cognitive map). Following this approach, the authors drew up a map of the investigated process of melt ECT, which is shown in Figure 2. This form allows to build the different scenarios of model behavior by changing factors input data on which this model depends.

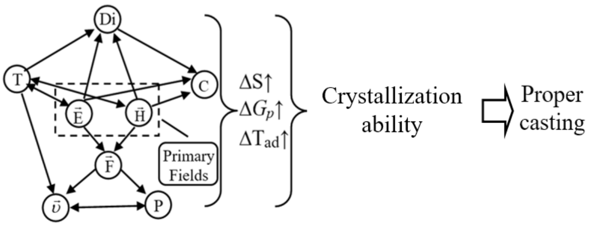

Figure 2: ECT cognitive map: $\vec{E}$ – electric field; $\vec{H}$ – magnetic field; $\vec{F}$ – force field; $\vec{\upsilon}$ – flow field; T – temperature field; Di – diffusion; P – pressure field; C – heat exchange; $\Delta S\uparrow$ – entropy export; $\Delta G_p\uparrow$ – Gibbs energy growth in the melt; $T_{ad}\downarrow$ – artificial undercooling

By the logic of interrelationships of factors that determine the content of physical processes of ECT, which is displayed on the map (Figure 2), it is necessary to have effective facilities for modeling the primary electric and magnetic fields, since they have the basic effect on the melt. At the same time, these fields generate secondary effects that also need to be accounted for in computer models of ECT for the sake to ascertain CPS reliability and survivability [25]. Thus, in accordance with the goal set in this paper, in order to fill the CPS of "smart casting" with DT – the models of melt ECT modes, it is necessary to determine such a mathematical toolkit and a range of tasks that would make it possible to analyze the relationship between the factors of castings structure formation and the parameters of processing modes in the most complete and adequate way. The variety of problems that arise when searching for optimal parameters derives from the physical conditions of the treatment: the material of the ladle – is it conductive or not, whether the ladle is insulated or not, is the ladle magnetic or not; the same applies to electrodes – they can be insulated or not, buried partially or completely, etc. These factors have necessitated a clear systematization of specified problems and formalization of methods for solving them.

4.2. Algorithmic and mathematical foundations of computer simulation of ECT modes in IT format

Being oriented to the maximum adaptation of mathematical models and computational algorithms for simulating ECT modes to the IT and CPS format, the authors compiled a taxonomic codifier of the mentioned tasks and methods for solving them – Taxstrum [11], on the basis of which a pattern-modular scheme for algorithmizing the procedures for simulating processes and obtaining digital twins (DTs) of ECT modes was developed.

The formulation of these DTs is based on structural and procedural patterns, which are unified abstract forms to compile algorithms for solving specific modeling problems. The mathematical apparatus, on which the described innovative scheme of computer modeling of ECT modes is founded, includes a number of traditional and original versions of finite element methods (FEM) and integral equations (IE). The integral formulation of the mathematical model of the primary electric field of the ECT process in its general form follows from Green's formula for the internal Dirichlet problem [26]. In this problem, the computational domain is given in the form of a closed surface S, inside which there are m_q primary field sources (free electric charges) q and m_σ some bodies, on closed surfaces of which $S^{(\sigma)}$ are induced the secondary sources (bound charges) σ. The primary sources create potentials $u^{(1)}$, and the secondary sources create potentials $u^{(2)}$.

Figure 3 shows an example of an arbitrary region with above conditions. The boundary of the area may consist of mu sites $S^{(u)}$, at which the potential values u^0, are given, but the values of the normal component of the electric field strength are unknown, and m_E sites $S^{(E)}$, at which the normal component of the electric field strength $E_n{}^0$, are given, but the values of the potentials $u^{(b)}$ are unknown. The values $u^{(b)}$ and $E_n^{(b)}$ are to be determined by solving the given problem. Then the general expression for the potential at any point M inside the region bounded by the surface S, will have, according to Green's formula, the following form:

$$u(M)=u^{(1)}(M)-\frac{1}{4\pi}\sum_{i=1}^{m_u}\int_{S_i^{(u)}}\left(E_{n,i}^{(b)}\frac{1}{r_{b,M}}+u_i^0\frac{\partial}{\partial n_b}\frac{1}{r_{b,M}}\right)ds-$$

$$-\frac{1}{4\pi}\sum_{i=1}^{m_E}\int_{S_i^{(E)}}\left(E_{n,i}^0\frac{1}{r_{b,M}}+u_i^{(b)}\frac{\partial}{\partial n_b}\frac{1}{r_{b,M}}\right)ds+\sum_{i=1}^{m_\sigma}u_i^{(\sigma)}, \quad (1)$$

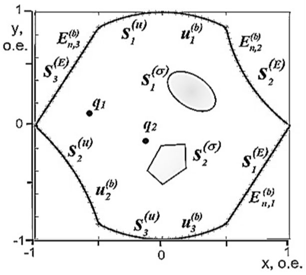

Figure 3: The computational domain for potential (1)

Here $r_{b,M}$ is the radius vector drawn from the point *b* on the boundary to the point *M* :

$$r_{b,M}=\sqrt{\left(x_b-x_M\right)^2+\left(y_b-y_M\right)^2+\left(z_b-z_M\right)^2}. \quad (2)$$

The mathematical model (1) – (2) covers any boundary conditions, which may be used to calculate the fields in ladles with melt. In most cases, the numerical solution of the IE is carried out with replacing of integrals by finite sums by means of discretization of integration surface (contour) and reducing them to systems of linear algebraic equations (SLAE). For the successful solution of these equations, the primary point of methodological importance is the procedure of rational representation of the geometric parameters of the surfaces, adapted for using in algorithmic procedures the explicit expression of mathematical operations of differentiation and integration on curved surfaces.

For this purpose, a universal geometric platform (GP) is created, based on the approximation of surface contours with arcs of circles, which provides the possibility to specify various configurations of boundary surfaces and is fully adapted to the computational operations of integral field equations according to (1) [27].

However, in the conducted experiments the ladle with the melt had a simple cylindrical shape, so for the calculation of DTs with proper accuracy it turned out to be sufficient to split the boundary contour just into 4 arcs with a total number of discrete elements not more than 200. In doing so the calculation time of separate DT did not exceed 2 minutes, that makes it quite possible to play out various scenarios of ECT modes on conventional PCs (with 2–4-core processors).

5. Exploration of electromagnetic fields in the multyelectrode system and formation of a database of ECT modes digital twins

5.1. Exploration of electric fields and currents on ECT reactor simulation models

The study was carried out by computer modeling of ECT multiphysical processes on simulation models of a reactor with replaceable electrode systems. A long cylindrical vessel with several thin electrodes parallel to the cylinder walls is taken as the main type of the spatial shape of the melt reactor. With regard to the extended length of the reactor, it is reasonable to represent the computational model of such a system as a set of its cross-sections and consider for them the two-dimensional problems. Figures 4 shows some results of such calculations for a variant with 2-electrode system in a non-insulated and insulated metal ladle, as well as a non-metallic one. Next, in Figure 5 there are shown the results of calculating the flux function lines and equipotentials for 2-electrode system in the insulated ladle and a non-metallic ladle. In Figure 6 it is given the results of calculations for 4-electrode system in the non- insulated metal ladle. And Figure 7 show the results of calculating the electric field strength in a non-metallic ladle with four electrodes.

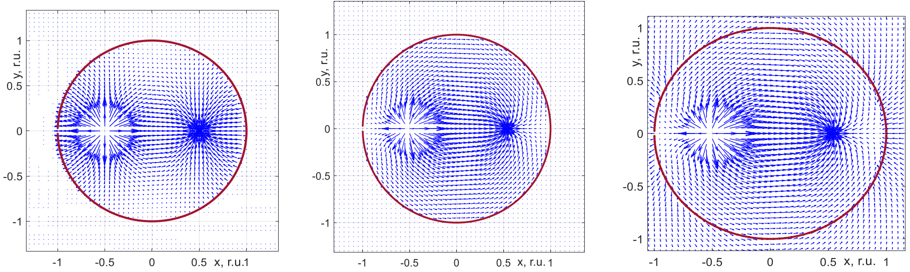

Figure 4: Distribution diagrams of vector field of currents in a non-insulated metal ladle (left), insulated one (middle) and a non-metallic ladle (right) with 2-electrode systems

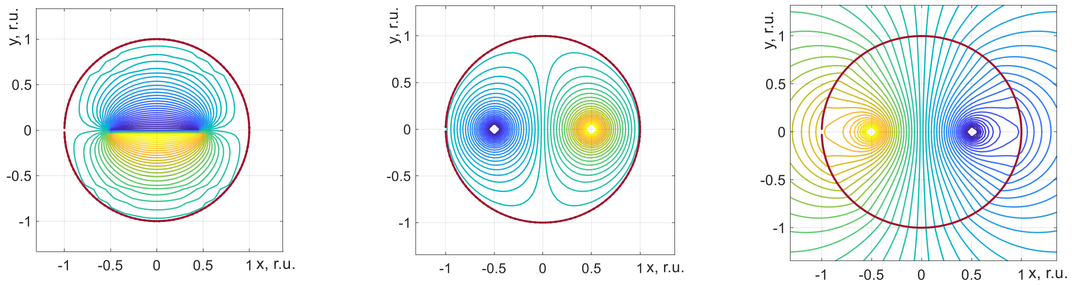

Figure 5: Flux lines (left) and equipotentials of current field in the insulated ladle (middle) and a non-metallic ladle (right) in the 2-electrode system

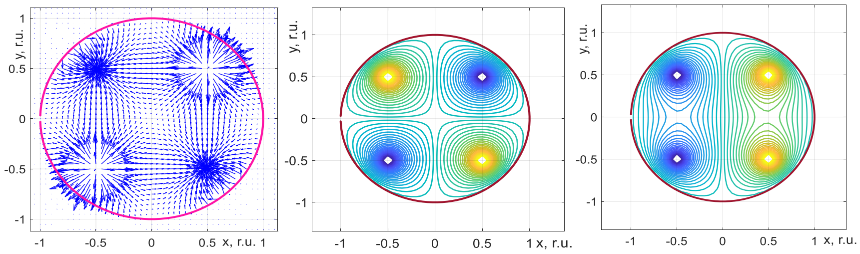

Figure 6: Distribution diagrams of vector field of the spreading currents (left), and equipotentials with crossed arrangement of electrodes (middle) and parallel arrangement (right) in the non-insulated metal ladle with the 4-electrode system

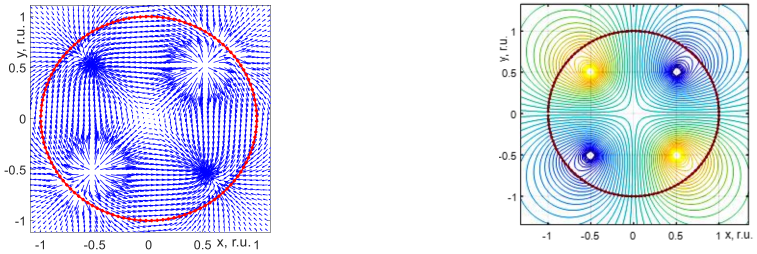

Figure 7: Distribution of the electric field strength vectors (left) and equipotentials (right) in the space of a non-metallic ladle in the 4-electrode system

5.2. Modeling and calculations of the magnetic field in a cylindrical ladle at direct current

In general, the direct calculation of the magnetic field components H for a given current density distribution δ requires the use of a vector potential formula with its subsequent differentiation:

$$\boldsymbol{A}(P)=\frac{\mu_a}{4\pi}\int_V \frac{\boldsymbol{\delta}(M)}{r_{PM}}dV_M, \tag{3}$$

$$\text{rot}\,\boldsymbol{A}=\boldsymbol{B}\rightarrow \boldsymbol{H}=\boldsymbol{B}/\mu_a, \tag{4}$$

where μ_a – absolute magnetic permeability, r_{PM} – radius vector according to (2), and B – magnetic induction. Performing the calculations according to (3) and (4) is a very cumbersome procedure even in a two-dimensional statement of the problem, as in our version. However, in the plane-parallel (2D) case, which in our study is taken as the basis for spatial approximation of the problem, the solution of the outlined task is significantly simplified. Indeed, if the potential is a function of only x and y, i.e., $U = f(x, y)$, then the induced magnetic field have only one component $H_z = H$, and from the equation $\text{rot}\boldsymbol{H}=\boldsymbol{\delta}=-\sigma\,\text{grad}U$ follows [28]:

$$\frac{\partial H}{\partial y}=-\sigma\frac{\partial U}{\partial x}=-\frac{\partial(\sigma U)}{\partial x},\quad \frac{\partial H}{\partial x}=\sigma\frac{\partial U}{\partial y}=-\frac{\partial(\sigma U)}{\partial y}.$$

These equations represent the Cauchy-Riemann conditions for harmonically conjugate functions H and σU. Therefore, in the complex plane $z = x + jy$ a complex analytical function $W(z)$ can be introduced as that: $W(z)=H(x,y)+j\sigma U(x,y)$, where the real and imaginary parts characterize the magnetic field strength and electric field potential of plane-parallel systems, respectively. This function is a complete analogue of the same function used to calculate the electric field distribution of the electrode system. Therefore, if the complex potential of the electric field of the spreading currents is known, then the flow function in it is an analogue of the magnetic field, that is, if $W(z)\,\square\, V+jU$, then $V\,\square\, H/\sigma$. So:

$$H_z=\sigma V. \tag{5}$$

5.3. The revealing of phenomenological ground of emerging the volumetric electromagnetic forces in the ECT process

Figure 4 (left) presents the chart of calculated vectors of the spreading current density $\delta(x,y)$ from non-insulated electrodes in horizontal sections of the ladle, and Figure 8 – the distribution profile of x-component of this current δ_x, which corresponds to this chart. Actually, it's this one that determines the nature of the distribution of the vertical (z-) components of the magnetic field strength formed by the current Hz, the main feature of which is a pronounced unevenness of change δ_x by coordinate y, which is clearly shown in Figure 8.

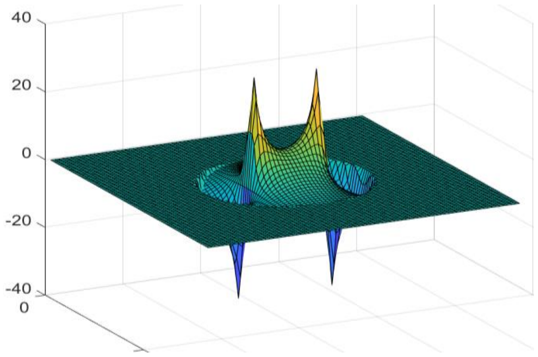

Figure 8: Distribution of vertical component of current-generated magnetic field strength H_z

Figure 9 (left) shows the orientation of z-component of the magnetic field H_z of spreading currents (5) relative to the plane of currents flows between the electrodes. When currents flow in the melt with a density $\boldsymbol{\delta}$, a volumetric electromagnetic force is formed with a density

$$\boldsymbol{f}_{em} = \boldsymbol{\delta} \times \boldsymbol{B} \ . \tag{6}$$

It creates an internal pressure p in the medium, and the diagram in Figure 9 (right) explains the occurrence of this pressure. Thus, based on (4) and (6) $\boldsymbol{f}_{em}$ and p are determined. Figure 10 clearly illustrates the spatial distribution of these forces. It should be noted that these forces in ECT differ from magnetohydrodynamic (MHD) stresses, because in the MHD process, the current originates from the magnetic field stresses, because in the MHD process, the current originates from the magnetic field when the fluid moves, but in ECT, on the contrary, the current generates a magnetic field, so the physical laws of their influence on the state of the fluid are different from each other.

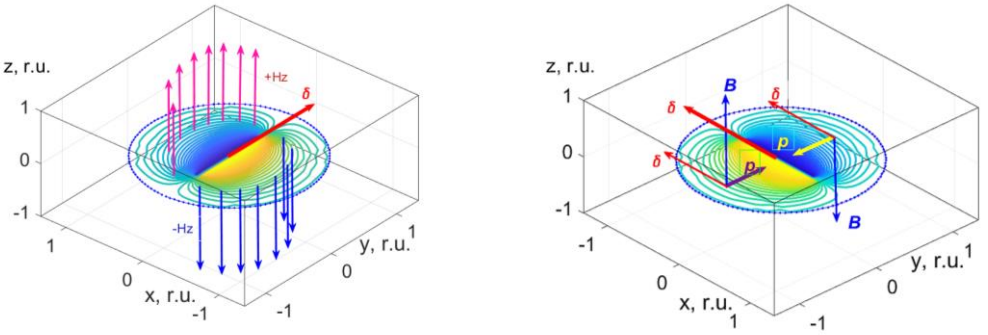

Figure 9: Orientation of z-component of magnetic field H_z of spreading current (left) and the vector diagram of the volumetric electromagnetic force $\boldsymbol{f}_{em}$ and internal pressure p (right)

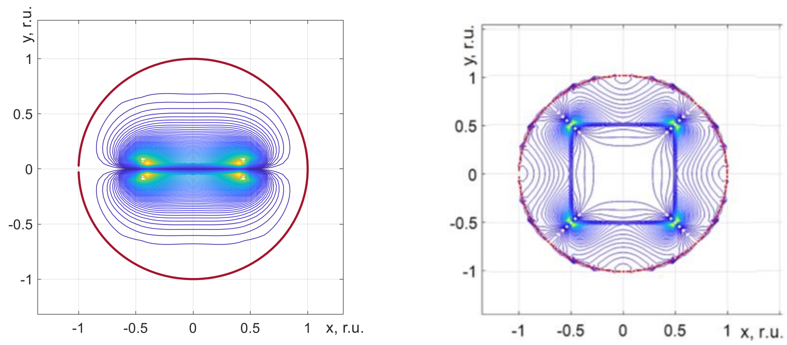

Figure 10: Level lines of the vector modulus of volume electromagnetic force $\boldsymbol{f}_{em}$ in 2-electrode (left) and 4-electrode (right) systems

5.4. The secondary fields and effects modeling

Determination of the basic electric and magnetic field distribution allows to build models and explore secondary fields and effects associated with them. As an example, Figures 11 shows the results of modeling the thermal field in the volume of the A357 alloy melt during its treatment

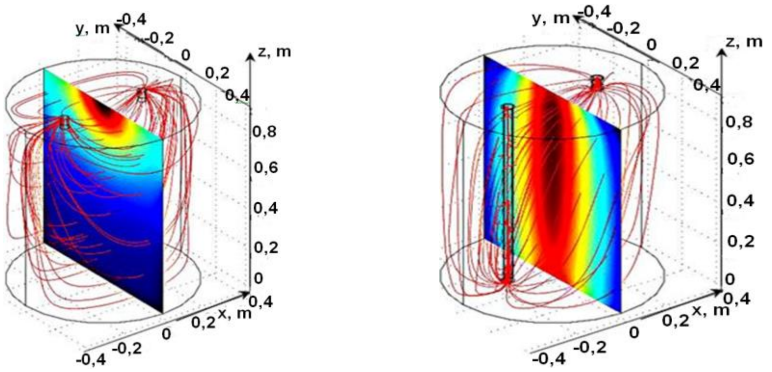

Figure 11: Flow lines of electric current and temperature distribution (color) in the volume of Al alloy melt with two types of electrode systems: equally deep non-insulated electrodes (left) and differently deep electrodes with an insulated side surface (right) with the direct current calculated by the classical equation of non-stationary thermal conductivity [29].

5.5. Practical application of digital twins – ECT mode simulators

The objective of the developed digital twins – ECT mode simulators – is to identify the zones of their most heterogeneous concentration, which, given the peculiarities of the behavior of the liquid metal structure, are most likely to become places of localization of fluctuations that inevitably arise in a cluster melt medium arise in a cluster melt medium. Based on the analysis of the information obtained, it becomes possible to specify purposefully the configuration of the ECT electrode systems and current parameters, which should synchronize the appearance and ensure the most uniform distribution of fluctuation centers in the melt volume, supposedly triggering the process of self-organization of a favorable casting structure through the formation of crystallization nuclei in these locations.

Thus, in spite of the fact that presented in fig. 4 –1 diagrams of the electric field vectors and electromagnetic force density level lines demonstrate the solutions for stationary problems, they explicitly serve as the “maps” of the probable distribution of pressure fluctuations locations and thermoacoustic waves excited by electric currents that occur at the meso- and submicroscopic levels of the EMLM. With an appropriate intensity of the external energy impact, these fluctuations are capable to initiate the processes of dissipative systems formation at the micro- and macrolevels of the liquid-metal system, which results in the self-organization of a favorable precrystallization state of the melt. The availability of such “maps” makes it possible to build scenarios for the influence of ECT modes on the formation of the casting crystallization nuclei distribution by varying of the construct data and parameters of electric current in the simulation model of the reactor with an electrode system, which specify the treatment mode, that is, to synthesize a predictive prototype of the proposed structure and properties that corresponds to the given processing options.

Hence, the solutions for stationary problems introduced in the paper as examples of the particular variant of ECT mode also serve the basis for non-stationary processes modeling. In particular, the solutions for various types of stationary, harmonic and transient processes obtained by the authors were introduced in [4]. However, as the ECT method is relatively new and poorly explored but the problems of optimization of processing modes are very versatile and intricate, the efforts on developing the digital twins of physical processes of melt treatment that comprise the ground for creating the CFS of "smart casting", are continuing.

6. Conclusions

1. According to the modern tendencies of AI development in the part related to foundry technologies the concept of filling the physical component of ECT of melt as a subsystem of "Smart Casting" intelligent systems on the basis of digital twins (DT) of process models formed by means of mathematical simulation of melt treatment modes has been developed.

2. Based on the analysis of the phenomenological ground of the notion about the ECT content, a cognitive model and a map of the cause-and-effect structuring of information about the processes, that occur in the melt, were developed that determined the logic of algorithmic paradigm of the CPS "smart casting" and the task for creating a database of ECT modes DT. Thus there are established the premises to study CPS from the standpoint of reliability and survivability.

3. The use of a unified mathematical apparatus and a pattern-module scheme of ECT modes DT calculation ensured the representativeness of filling the database of physical components of the CPS "smart casting" and the possibility to build scenarios of the influence of ECT modes on the crystallization nuclei formation in the casting.

4. The conjugation in CPS Big Database of the ITIS information flows, which display the experimental basis, the adequacy of mathematical models and the representativeness of DT, ensures the reliability of the results of electric current effect on the liquid metal system study in a wide range of variations of ECT modes parameters.

5. The relevance and perspective of further work in the direction of the development of the technology of "smart casting" with ECT of melts within the CPS-ITIS algorithmic paradigm framework is determined by the fact that it allows to predict and obtain the specified indicators of the quality of castings with a high degree of probability.

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