DOI: https://doi.org/10.15407/techned2018.02.017

COUPLED ELECTROMAGNETIC AND THERMAL PROCESSES IN THERMAL INSULATION OF INDUCTION CHANNEL FURNACES DURING CHANGES OF ITS DEFECTS CONFIGURATION

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The interrelated electromagnetic and thermal processes that occur during induction heating of metals in channel furnaces are investigated. A mathematical model and a technique for determining the size and shape of defects (leaks of liquid metal) in the thermo-insulation material (lining) of such furnaces are developed on the basis of determination of the regularity of the time variation of the inhomogeneous temperature distribution on the surface of furnace' body. Verification of the developed mathematical model was carried out by comparing the calculated results obtained with the results of the experiment on an induction furnace for the production of high-quality copper rolled wire for the cable industry. The regions of maximum temperatures on the furnace body and the maximum temperature gradients inside the lining are determined, as well as the dynamics of their changes on the surface of the furnace during the experiment, which lasts for more than 4.5 years. A relationship between the distribution of isotherms on the furnace body and the location, shape and depth of penetration of liquid copper into furnace thermal insulation masonry was found. On the basis of obtained relationship the hypotheses about the configuration of the currently existing defects were offered. The application of the proposed technique makes it possible to control the change in the state of the lining of induction channel furnaces and to develop recommendations for increasing their life time. References 15, figures 4, tables 2.
Key words: electromagnetic field, induction heating, temperature distribution, interrelated (multi-physical) processes, three-dimensional mathematical modeling, finite element method.

Introduction. At present the study of the disturbed electromagnetic field and the associated thermal and force effects on materials by means of mathematical modeling is a powerful tool for obtaining deeper knowledge about interrelated multi-physical processes. To develop new industrial equipment and improve existing one, the available information on the progress of physical processes and engineering intuition are not enough. Modern research is aimed at both identifying deeper interrelated mechanisms and taking into account previously unused material properties, which require the complexity of the real objects geometry at the micro- and nanoscale [4, 5]. The development of computational methods makes it possible to supplement and sometimes replace an expensive and sometimes impossible experiment with results obtained on mathematical models. And more and more new products are developed by leading world companies on the basis of such models [2]. Special attention is paid to interdisciplinary or multi-physical research [3, 6], in which the processes are described by laws from different areas of physics and they are studied simultaneously, rather than independently, as was done previously.

This class of problems also arises in the improvement of induction heating technologies. The phenomena of electromagnetic induction have been successfully used for heating and melting metals for more than a hundred years, and industrial equipment created for these purposes is continuously modernized [4, 8]. A lot of scientific research has been carried out, the results of which have been generalized in fundamental works [1, 4, 5]. Despite this, the problem of prolonging the life time of expensive induction equipment for the production of highly pure metal products, in particular electro-technical copper rolled wire (99.99 % purity), is still acute today. The leakage of liquid metal into thermal insulation materials of furnaces and inductors is the main cause of their planned and emergency stops [12].

Although numerical methods, including one of the most used of them – the finite element method, have developed rapidly in the past 20 years [1, 5, 7], the mathematical modeling of induction heating processes remains a task of increased complexity. This is due to the fact that the nonlinear properties of materials (the magnetization curve of the inductor core and the temperature dependence of the electrical conductivity of the metal) force the system of differential equations to be solved in the time domain, while the time constants of the electromagnetic and thermal subtasks can differ by a 4–6 orders of magnitude [1, 13]. In addition, the objects under consideration have a complex three-dimensional geometry, and the sizes of their in-

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ternal elements in different coordinates can differ by more than an order of magnitude. Besides, the change in their size or curvature often does not coincide with the change in the gradients of calculated values [9, 10].

Therefore, when solving many problems, you can not use a ready-made software product with pre-programmed solvers and automatic finite element mesh construction, but it is necessary to make changes based on specific features of the problem under consideration.

Such problems arise when analyzing the distribution of temperature inside the melt, in the lining and on the surface of the body of induction furnaces, taking into account the occurrence of liquid metal leakages into lining cracks, the configuration of which varies with time. An example of such a furnace is an induction channel furnace of the UPCAST type [12], used for oxygen-free melting of high-quality copper and the production of rolled wire for the cable industry. Structurally induction melting plant consists of a furnace and an inductor, and, at present time, there is a significant difference between their life times. The predicted life of the furnace is usually 3–4 years, and the inductor – 1–2 years. Consequently, in induction technology, there is a planned 2–3-fold inductor replacement with the same furnace [12].

However, joint experimental studies by PJSC "Zavod Yuzhkabel"(Kharkov) and Institute of Electrodynamics of the National Academy of Sciences of Ukraine (Kiev) on the UPCAST US20X-10 installation showed that the inductor replacement procedure significantly shortens the life of the furnace [14, 15]. Because of the temperature drop on the surface of the lining of the furnace from 1150 °C (the temperature of the copper melt) to 300–400 °C (the highest possible temperature when heating by gas burners after draining the copper), new micro- and macro-cracks arise inevitably in the lining. After restart of the furnace with a new inductor and old lining, liquid metal leaks out into lining cracks.

In addition, the method currently used for control and diagnostics of the furnace state is integral and indirect method. It does not allow to indicate the location and size of the areas of incipient leaks [12], and as a result does not allow to optimize the operating conditions of the furnace in order to slow down the destructive processes in thermal insulation and prolong the life of the operated furnaces.

The aim of the work is to develop a mathematical model and technique for taking into account the relationship between the distribution of electromagnetic and thermal fields in the thermal insulation of induction channel furnaces with a changing configuration of defects in this insulation, as well as controlling the change in the size and shape of the liquid metal leaks into thermal insulation and verification of the developed mathematical model by comparison with the results of an experiment lasting 4.5 years.

Physical-mathematical formulation of the problem. The problem of induction heating of a metal consists of electromagnetic and thermal problems with strong mutual relations [5, 7]. Since the time constants of the electromagnetic and thermal processes considered in this paper differ by 6 orders of magnitude (period of electromagnetic oscillations is $2 \cdot 10^{-2}$ s and duration of heating is $1.8 \cdot 10^{4}$ s), then, as in [1, 15], the electromagnetic part of the problem was solved in the frequency domain in the linear approximation using the effective values of the relative permeability μ_{eff} obtained from the magnetization curve, and the thermal part in the time domain.

Electro-magnetic subtask. To calculate the distribution of the magnetic field and the current densities, the system of Maxwell equations with respect to the vector potential $\vec{A}$ was solved. The calculated equations for various elements of the inductor and furnace were derived as in [7, 15] and have the form:

a) for copper melt in the inductor channel and in the furnace:

$$\mathrm{rot}\,[\frac{1}{\mu_0}\mathrm{rot}\,\dot{\vec{A}}] + j\omega\sigma(T)\dot{\vec{A}} = 0, \tag{1}$$

b) for copper inductor buses:

$$\mathrm{rot}\,[\frac{1}{\mu_0}\mathrm{rot}\,\dot{\vec{A}}] - \dot{\vec{J}}_{ext} = 0, \tag{2}$$

c) for the steel core of the inductor:

$$\mathrm{rot}\,[\frac{1}{\mu_0\mu_{eff}}\mathrm{rot}\,\dot{\vec{A}}] = 0, \tag{3}$$

d) for the lining mixture of the inductor, the four-layer brick masonry of the furnace, and for the water in the tubes of the cooling system of the inductor and the furnace:

$$\mathrm{rot}\,[\frac{1}{\mu_0}\mathrm{rot}\,\dot{\vec{A}}] = 0. \tag{4}$$

Here $\vec{J}_{ext}$ is the current density vector in the inductor buses, $\sigma(T)$ is the conductivity of copper, which is a function of temperature T and is described by the following equation:

$$\sigma(T) = 1/[\rho_0(1+\alpha(T-T_{ref}))], \tag{5}$$

where $\rho_0 = 1.72 \cdot 10^{-8}$ Ω·m is the electrical resistivity of copper, $\alpha = 3.9 \cdot 10^{-8}$ K^{-1} is temperature resistance coefficient of copper, T_{ref}= 273.15 °K is the reference temperature.

The inductor is connected to a 50 Hz sinusoidal voltage transformer whose power is controlled automatically depending on the data of the melt temperature sensor. Commutation is possible between 14 power levels from 33 to 616 kW, and the operating range is usually 80–400 kW. The computational domain was three-dimensional and consisted of a volume both of an inductor and a furnace with a copper melt, whose contact with the ambient air was described by the boundary conditions on their bodies. Equations (1)–(4) were joined at the interfaces of the elements and supplemented by the Dirichlet conditions $\vec{n} \cdot \vec{A} = 0$ at the boundaries of the computational domain.

Thermal subtask. To calculate the distribution of the thermal field in the lining of furnace and inductor, the heat balance equation was solved as in [1, 7, 15]:

$$\rho C_p \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = Q_{eddy} + Q_{water} . \tag{6}$$

Here ρ, C_p and k are the density, heat capacity and thermal conductivity of materials, Q_{eddy}, Q_{water} are heat sources including eddy current heating of the metal Q_{eddy} and cooling of the buses and lining when water flows through the tubes of cooling system Q_{water}.

The heat rejection through the water was calculated according to the equation:

$$Q_{water} = M_t \cdot C_p \, (T_{in} - T)/V, \tag{7}$$

where M_t – water flow in kilograms, passing through the cross section of the tubes per time unit, T_{in} − incoming water temperature, V − internal volume of the system pipes.

The heating of copper by eddy currents realizes a multi-physical connection between the electromagnetic and thermal parts of the problem and it is specified in the form:

$$Q_{eddy} = \dot{\vec{E}} \cdot \vec{J}^* = \omega^2 \sigma(T) \dot{\vec{A}} \cdot \vec{A}^* . \tag{8}$$

The system of equations (6)–(8) was supplemented by the conditions for convective heat rejection from the inductor and furnace bodies using given heat transfer coefficient h according to the equation:

$$-k \frac{\partial T}{\partial n} = h(T - T_{ext}) , \tag{9}$$

where T_{ext} is the ambient air temperature, n is the normal vector to the outer boundary.

Systems of differential equations (1)–(4) and (6)–(8) were solved using the finite element method in the software package Comsol Multiphysics [2].

Features of mathematical modeling using the package Comsol Multiphysics. Despite the fact that the software package used for mathematical modeling is one of the most modern tools and has many opportunities and advantages, in order to solve the system of equations (1)–(9), it was necessary to change the algorithms used (mathematical solvers). Iterative solvers, which are used in the package by default [2], are based on the conjugate gradient method. Most often used method is the stabilized bi-conjugate gradient method (BiCGStab). The main advantage of these methods is the use of much less RAM in comparison with direct solvers, but the main their drawback is the lack of convergence in a number of problems with significant nonlinearities and strong multi-physical connections (including our problem).

Therefore, instead of the iterative method, a direct solver was used, in particular MUMPS (MUltifrontal Massively Parallel Sparse Direct Solver) [2], based on the Newton-Raphson relaxation method and LU-decomposition. Moreover, the advantages in the calculations algorithm, it can also use a hard disk in addition to RAM, creating a swap file. The coefficient of memory allocation for it increased from 1.2 to 2 in order to support more massive simultaneous computations.

In addition, when solving a multi-physical task in a package, a segregated approach is used by default, i.e. each physical process within single iteration is considered sequentially, using as input the results of solving the previous physical process [2]. After current iteration the input data is refined, approaching to the solution, and all physical processes are recalculated sequentially, one by one. With strong multi-physical connections of processes (including in our problem), this approach is inapplicable because it gives inaccurate, and in some cases incorrect solutions.

Therefore, in describing the mutual relationship between the electromagnetic and thermal subtasks, a fully-coupled approach [4], where all the physical processes within single iteration were considered simultaneously (within the same matrix of coefficients), was used instead of the separate approach. Also, the requirements for the relative error of the temporary solver and its fully interconnected part were increased accordingly by a factor of 10 (from 0.01 to 0.001) and a factor of 1000 (from 1 to 0.001), while the maximum number of iterations was increased from 4 to 25. Thus, a stable convergence of the mathematical solver was achieved and a numerical experiment on the calculation of the distribution of magnetic and thermal fields in the lined inductor and furnace during the long-term process of heating the copper melt was performed.

To verify the developed mathematical model, the results of the calculation were compared with the results of a physical experiment conducted over 4.5 years on the induction furnace of the industrial unit UPCAST US20X-10 at PJSC "Zavod Yuzhkabel".

Results of physical experiment. At present, diagnostics of the state of the furnace and inductor is performed by monitoring the temperature changes ΔT of running water in the cooling system and active R and reactive X resistances of the inductor. According to the technical documentation, the unit state is considered as normal if the difference in ΔT across all contours remains within 5 °C, and the resistance values lie within the permissible limits: $R_{perm\ min} > R > R_{perm\ max}$, $X_{perm\ min} > X > X_{perm\ max}$. This diagnostics method is indirect one. It allows to answer the question "the furnace can or can't operate", but it does not provide an opportunity to assess the degree of deterioration in furnace characteristics, i.e. does not allow to reveal the location and size of the leaks of liquid metal into thermal insulation materials, as well as the dynamics of change of such leaks.

To improve the diagnostic system, it was suggested to monitor not only the lumped parameters of the system (impedance Z and the temperature difference ΔT), but also the temperature distribution over the inductor and furnace bodies. For this purpose, a mathematical model and a technique for calculating the temperature distributions both on the surface of their bodies and inside lining in nominal and emergency operation modes have been developed. According to the developed method, the control temperature measurements are carried out regularly on the surface of the bodies of the inductor and furnace. If temperature distribution is not non-uniform, the areas of maximum heating are detected. Then, using a mathematical model, a mutual relationship between the distribution of the thermal field over the surface of the bodies and its distribution within the linings is found. Thus, the location, shape and size of the metal melt leaks are determined from the temperature isotherms on the furnace and inductor bodies. Using enumeration of possibilities of leaks configurations, the configuration that gives the temperature isotherms in the model, which coincide with the isotherms measured experimentally, is defined.

By means of this technique, diagnostics of both the instantaneous state of the furnace and the dynamics of state change is carried out. The developed model was verified by comparing the isotherms calculated on the body with the real isotherms measured on the operating equipment. For this purpose, an experiment with duration of 4.5 years (from 04.2013 to 09.2017) for measurements of the temperature distribution T on the inductor and the furnace bodies was planned and carried out. The main attention was paid to the furnace, since it contains the bulk of the melt (up to 10 tons). The furnace's body was divided into 72 control zones, as shown in Fig. 1 (36 zones in the place were copper cathodes for melting are charged and 36 ones in the place were the copper rolled wire is drown). In these zones the temperature T was measured with optical pyrometer every 2 weeks.

The results of the final measurements in September 2017 are presented graphically in Fig. 2, and in Table 1. Figure 2, *a* shows half of furnace's body in the cathode loading zone and Figure 2, *b* – in the rolled wire drawing zone. Comparing the experimental results in Fig. 2, *a* and *b*, we note that higher temperatures (both minimal and maximal values) are observed in the rolled wire drawing zone. If in the cathode charging zone $T_{\min}$ = 64 °C and $T_{\max}$ = 152 °C, then these values in the rolled wire drawing zone are $T_{\min}$ = 102 °C and T_{max} = 254 °C.

Table 1

	Zone of cathodes charging (09.2017), *T*,°C										Zone of rolled wire drawing (09.2017), *T*, °C								
	*x*1	*x*2	*x*3	*x*4	*x*5	*x*6	*x*7	*x*8	*x*9		*x*1	*x*2	*x*3	*x*4	*x*5	*x*6	*x*7	*x*8	*x*9
*z*1	95	78	77	96	95	95	98	65	95	*z*1	105	105	110	110	102	105	130	110	115
*z*2	105	90	105	105	105	105	70	69	64	*z*2	106	118	130	226	150	151	160	163	125
*z*3	105	91	135	152	124	120	79	80	68	*z*3	120	148	242	215	180	190	199	201	141
*z*4	95	96	91	108	90	88	83	82	79	*z*4	140	200	254	170	202	170	182	154	108

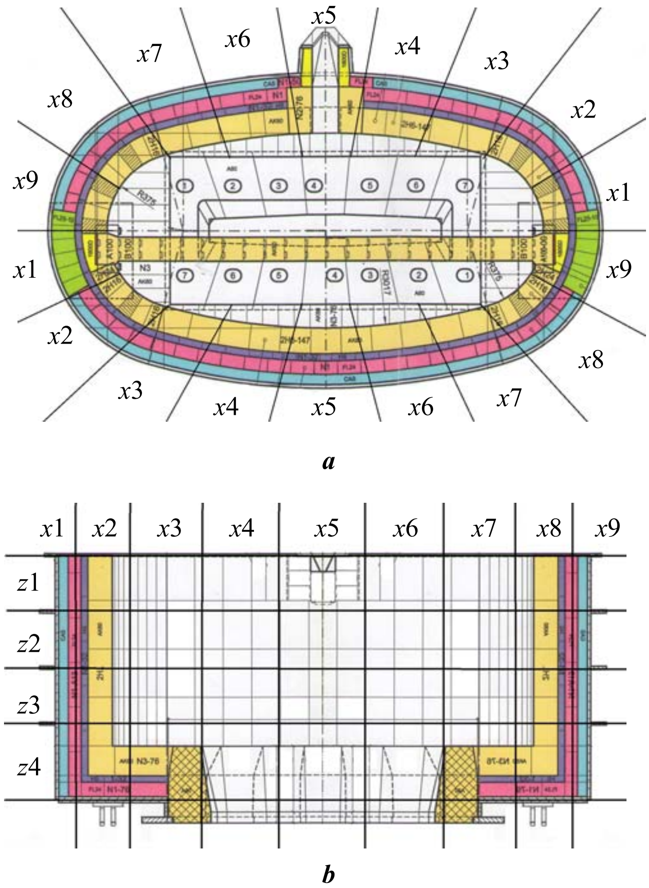


Fig. 1

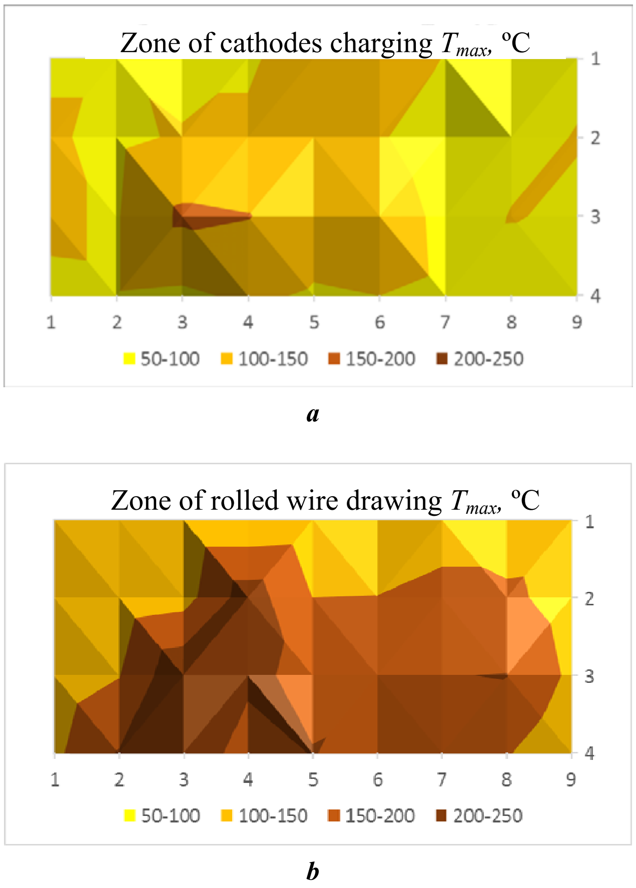


Fig. 2

It was revealed that during the long operation of the furnace, the average temperature on its body increased significantly. For a furnace with a new lining, the temperature T on its body is 70–100 °C, and under operating conditions, $T < 132$ °C is considered as normal temperature. After continuous operation of the furnace for 42 months, 7 regions with $T > 200$ °C (zones $z2x4$, $z3x3$, $z3x4$, $z3x8$, $z4x2$, $z4x3$ and $z4x5$) are observed, and even $T_{max} = 254$ °C is achieved in zone $z3x4$.

A physical explanation for the appearance of these zones is the leaks of the metal melt through the lining to the furnace body. Lining is formed by four layers of bricks, where first and second layers operate as armor, which keeps the metal melt from leaks, and the third and fourth layers are used for a heat insulation providing a basic temperature drop of about 900 °C [12]. However, in the case of penetration of the melt through the armor, the metal is actively absorbed because of the porous structure of the third and fourth layers of bricks, and the irreversible degradation process of the lining is intensified with time. As a result, even droplets of liquid copper may leak through the technological holes of the furnace body. If, at any place of body, a temperature is 300–350 °C, then such a furnace is considered unsuitable for operation and requires disconnection and replacement.

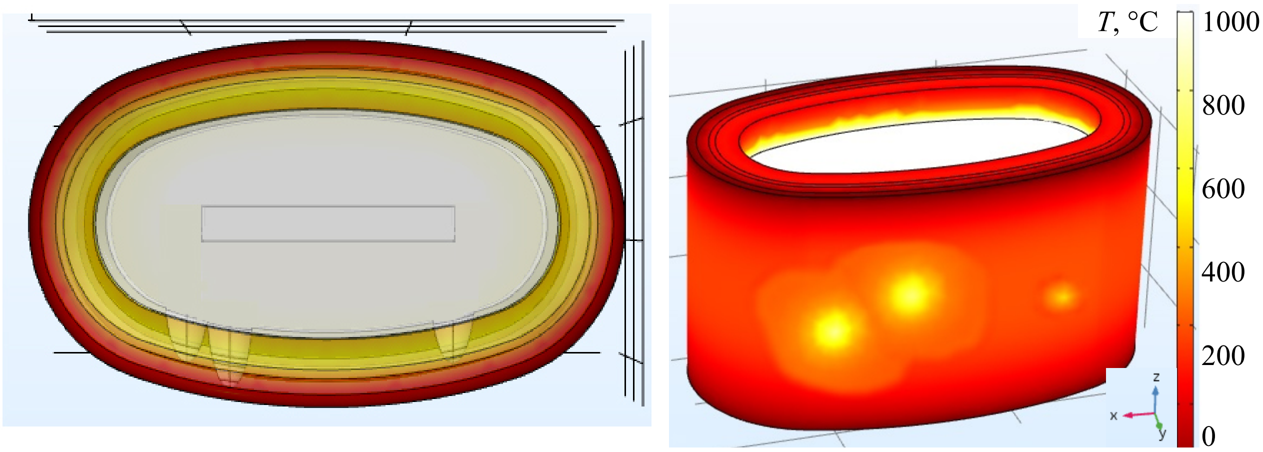
The study of the rate of penetration of the melt into the lining as the function of dynamics of the temperature change in the control zones of body was carried out. The results of the measurements are given in Table 2.

Table 2

	Zone of cathodes charging (2014-2017), ΔT,°C										Zone of rolled wire drawing (2014-2017), ΔT, °C								
	$x1$	$x2$	$x3$	$x4$	$x5$	$x6$	$x7$	$x8$	$x9$		$x1$	$x2$	$x3$	$x4$	$x5$	$x6$	$x7$	$x8$	$x9$
$z1$	25	0	2	18	0	0	1	0	24	$z1$	30	45	33	29	20	18	39	15	5
$z2$	4	1	0	0	0	0	0	0	8	$z2$	44	56	55	107	31	40	31	45	20
$z3$	13	5	45	22	0	21	0	1	8	$z3$	49	60	99	88	65	75	71	56	24
$z4$	25	11	6	13	0	0	3	2	5	$z4$	48	91	130	95	80	50	81	55	37

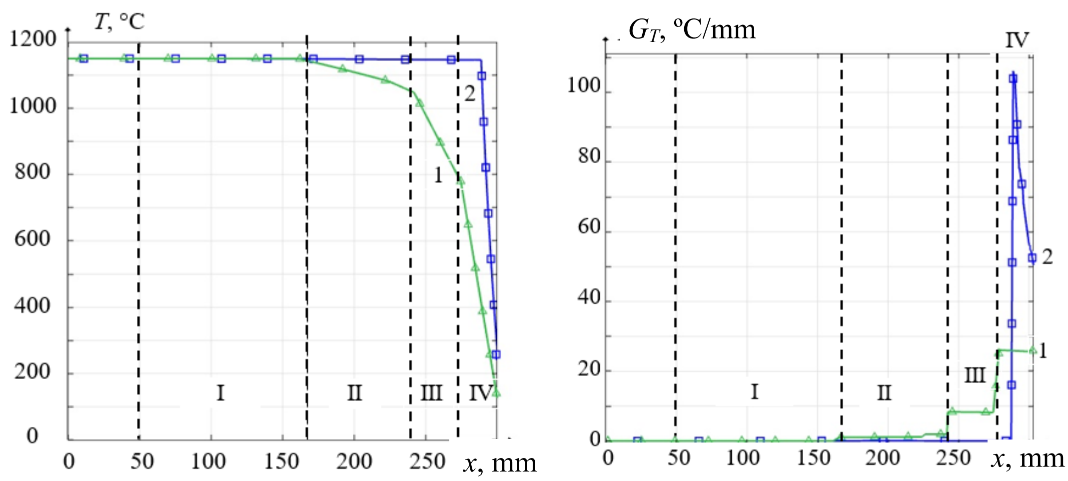
So after 42 months of continuous operation on the half of the furnace body in the zone of rolled wire drawing, the average temperature increased by 58 °C (from 96 °C to 154 °C). The greatest increase in temperature in five zones was 130, 107, 99, 95 and 91 °C, respectively. Thus, in the hottest zone on the surface of the body, the temperature increases at the average by 3 °C every month. While maintaining such dynamics (without optimization of technological modes), it will soon accept inadmissible values for further operation.

Results of numerical experiment. To determine the configuration of internal defects of the furnace lining by the surface temperature distribution, a numerical experiment was carried out. The leaks of metal melt were modeled by three ellipsoids of rotation with semi-axes *a*, *b* and *c*, the centers of which were located at a height z = 550, 650 and 750 mm from the bottom of the furnace (at the height of melt of 950 mm). The coordinates of the ellipsoids centers in the *xy*-plane (which parallel to the bottom of the furnace) were chosen in such a way that the temperature in three hot zones (*z*4*x*3, *z*2*x*4 and *z*3*x*8) on the furnace body corresponded to the experimental data, namely, 254, 226 and 201°C. The main characteristic affecting the maximum value of T is the penetration depth of the melt into the lining, i.e. defect size along the *y*-axis. Fig. 3, *a* shows the temperature T distribution in the furnace lining volume (top view), and Fig. 3, *b* represents the distribution on the surface of furnace body (view from the side of rolled wire drawing). There are three melt leaks that create the region with temperature T > 200 °C on the body surface.



a **Fig. 3** *b*

According to the results of the simulation, it can be concluded that if the temperature at the furnace body reaches 200–250 °C, the metal melt has passed through the first three brick layers and it is located in the volume of the last fourth layer (Fig. 3, *a*). If the total thickness of the four brick layers is 275 mm, then in our case the length of the largest melt "tongue" of the three ones is 250 mm, which corresponds to a maximum temperature on the furnace body T_{max} = 254 °C. This situation is extremely dangerous, since the distance to the furnace body is only 25 mm.



a **Fig. 4** *b*

Let us consider the change in temperature T (Fig. 4, *a*) and its gradient G_T (Fig. 4, *b*) in the volume of the new lining of the furnace (curves 1) and in the presence of a melt leak in the old lining (curves 2). The graphs are plotted along the normal line ***n*** to the side surface of the furnace body, which simultaneously passes through the central axis of the largest of the three "tongues" of the melt. In the absence of melt leaks, the main temperature drop of 900 °C occurs on the III and IV layers of the brick with a total thickness of 115 mm (Fig. 4, *a*). The gradients of the temperature in these layers are $G_{T\,\mathrm{III}}$ = 9 °C/mm and $G_{T\,\mathrm{IV}}$ = 26 °C/mm, which corresponds to the normal operation of the furnace. When there are the metal leakages such temperature drop occurs only on a part of the IV brick layer of 25 mm thickness, which leads to an increase in the temperature gradient G_T by 4 times up to the value $G_{T\,\mathrm{IV}}$ = 105 °C/mm. Such high temperature gradients have an extremely negative effect on the lining material and substantially reduce its life time.

The use of the proposed technique allows to carry out more accurate control and diagnostics of the state of the lining of induction channel furnaces, and to create the basis for forecasting and recommendations for increasing their life. Analyzing the degree of leakage of metal into the lining, it is possible to correct the technological modes of furnaces, aimed at optimizing the production capacity and slowing the degradation processes in thermal insulation.

Also, the information obtained is useful for more accurate prediction of the remaining time before the emergency and makes it possible to prepare equipment and materials for a planned replacement of the furnace.

Conclusions. The interrelated electromagnetic and thermal processes that occur during induction heating of metal in channel furnaces are investigated. A technique and a three-dimensional mathematical model for determining the location, size and shape of defects (leaks of liquid metal) in the thermo-insulation material (lining) of such furnaces by analyzing the inhomogeneous temperature distribution over the surface of their bodies are developed. A relationship between the distribution of isotherms on the furnace body and the location, shape and depth of penetration of liquid copper into furnace thermal insulation masonry was found. On the basis of obtained relationship the hypotheses about the configuration of the currently existing defects were offered.

As a result of the planned experiment (duration 42 months), the temperature measurements in 72 control zones on the surface of the furnace body of industrial unit UPCAST US20X-10 for production copper rolled wide were made. It was revealed that 7 regions with a temperature $T > 200$ °C (instead of 130 °C recommended for the nominal operating mode) appeared in the course of its continuous operation, and in one zone the temperature is reached $T_{max} = 254$ °C. At the same time, the gradient of temperature G_T within the lining increased by 4 times (from 26 °C/mm to 105 °C/mm). The dynamics of temperature increase is investigated and the zones of its greatest growth, where ΔT reaches 130 °C, and the maximum rate of temperature rise is 3 °C per month are found. This indicates the presence of several zones of metal melt leaks in the furnace lining and requires of technological modes optimization to prevent the onset of emergency situations.

The use of the proposed technique allows to carry out more accurate control and diagnostics of the state of the lining of induction channel furnaces, and to create the basis for forecasting and recommendations for increasing their life.

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УДК 621.365.5

ВЗАИМОСВЯЗЬ РАСПРЕДЕЛЕНИЯ ЭЛЕКТРОМАГНИТНОГО И ТЕПЛОВОГО ПОЛЕЙ В ТЕРМОИЗОЛЯЦИИ ИНДУКЦИОННЫХ КАНАЛЬНЫХ ПЕЧЕЙ С ИЗМЕНЕНИЕМ КОНФИГУРАЦИИ ВОЗНИКАЮЩИХ В НЕЙ ДЕФЕКТОВ

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Исследованы взаимосвязанные электромагнитные и тепловые процессы, возникающие при индукционном нагреве металла в канальных печах. Разработана методика определения размеров и формы дефектов (протеканий жидкого металла) в термоизоляционном материале (футеровке) таких печей путем анализа неоднородного распределения температуры по поверхности их корпуса. Проведена верификация разработанной математической модели посредством сравнения с результатами эксперимента длительностью 3,5 года на индукционной печи промышленной линии литья. Определены области максимальных температур на корпусе печи и величины максимальных градиентов температуры внутри футеровки, а также динамика их изменения во времени. Установлена связь между распределением изотерм на корпусе печи с расположением, формой и глубиной проникновения жидкой меди в ее термоизоляционную кирпичную кладку, а также сделаны предположения о конфигурации существующих на данный момент дефектов. Использование предложенной методики позволяет проводить более точную диагностику состояния футеровки индукционных канальных печей, создавая основы для прогнозирования и рекомендаций по увеличению их ресурса. Библ. 15, табл. 2, рис. 4.

Ключевые слова: электромагнитное поле, индукционный нагрев, распределение температуры, взаимосвязанные (мультифизические) процессы, трехмерное математическое моделирование, метод конечных элементов.

УДК 621.365.5

ВЗАЄМОЗВ'ЯЗОК РОЗПОДІЛУ ЕЛЕКТРОМАГНІТНОГО І ТЕПЛОВОГО ПОЛІВ У ТЕРМОІЗОЛЯЦІЇ ІНДУКЦІЙНИХ КАНАЛЬНИХ ПЕЧЕЙ ЗІ ЗМІНОЮ КОНФІГУРАЦІЇ ДЕФЕКТІВ, ЩО ВИНИКАЮТЬ У НІЙ

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Досліджено взаємопов'язані електромагнітні та теплові процеси, які виникають при індукційному нагріванні металу в канальних печах. Розроблено методику визначення розмірів і форми дефектів (протікань рідкого металу) у термоізоляційному матеріалі (футеровці) таких печей шляхом аналізу неоднорідного розподілу температури на поверхні їхнього корпусу. Проведено верифікацію розробленої математичної моделі шляхом порівняння з результатами експерименту тривалістю 3,5 року на індукційній печі промислової лінії лиття. Визначено області максимальних температур на корпусі печі і величини максимальних градієнтів температури всередині футеровки, а також динаміку їхніх зміни у часі. Встановлено зв'язок між розподілом ізотерм на корпусі печі з розташуванням, формою і глибиною проникнення рідкої міді в її термоізоляційну цегляну кладку, а також зроблено припущення щодо конфігурації існуючих на даний момент дефектів. Використання запропонованої методики дозволяє проводити більш точну діагностику стану футеровки індукційних канальних печей, створюючи основи для прогнозування і рекомендацій щодо збільшення їхнього ресурсу. Бібл. 15, рис. 4, табл. 2.

Ключові слова: електромагнітне поле, індукційний нагрів, розподіл температури, взаємопов'язані (мультифізичні) процеси, тривимірне математичне моделювання, метод скінченних елементів.

Надійшла 05.12.2017
Остаточний варіант 08.12.2017