INDUCTION SYSTEM FOR LOCAL TREATMENT OF SURFACES BY LIQUID METAL FLOWS

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Electrodynamic processes occurring in molten metal on the horizontal surface of metal product in the inductor magnetic field were studied. Conditions of intensification of liquid metal flows at local treatment of metal surfaces are determined. Formulas for calculation of induction system are given.

Keywords: *induction heating, metal treatment, intensified liquid metal flows, electrodynamic processes, calculations*

At local remelting of surface layer of metal products, elimination of defects on their surfaces, local alloying, surfacing of protruding elements and their repair, application of induction heating alongside the known electrometallurgical technologies of metal treatment and surfacing is promising and urgent [1–7].

Induction heating is a non-polluting process, allowing control of molten metal flows and of applied power at heating. So far, induction heating found only limited application for the above purposes, in view of the high power consumption. One of the effective methods to reduce power consumption and improve the efficiency of treatment of the surfaces of metal products at induction heating is intensification of molten metal flows in the crucible placed above the treated product. In this case heat exchange between the already molten metal in the crucible and metal of the product to be melted is increased, thus promoting a shortening of the melting time and input power.

PWI developed a method [8] of intensification of molten metal flows in the crucible, directed at the treated surface of metal product at induction heating.

The purpose of this work is investigation of electrodynamic processes in liquid metal, which is contained by the crucible on the horizontal surface of the metal product in the inductor magnetic field, and determination of the conditions for intensification of molten metal flows at local treatment of metal surfaces.

According to Helmholtz theorem, any continuous vector field can be presented in the form of a sum of potential and eddy components [9]. Thus, density of electromagnetic forces of vector **F** causing the motion of electrically-conducting liquid (molten metal) in an open crucible, has potential and eddy components, the ratio of which is different in different points of the liquid. In a closed volume (closed crucible) the motion of electrically-conducting liquid is affected only by the eddy component of the electromagnetic forces.

A characteristic of the magnetic field capability to induce melt motion around a certain contour of length l_i is circulation C_i of force vector **F** around this contour (without allowing for hydrodynamic features) [6]:

$$C_i = \oint_{l_i} \mathbf{F} dl = \int_{S_i} \mathrm{rot}_n\, \mathbf{F} dS,$$

where S_i is the area of a surface supported by a contour of length l_i; n is the index, which denotes quantity components normal to surface of area S_i.

In crucibles of classic induction furnaces (Figure 1, *a*) there exist two eddy flows of molten metal — upper and lower [5–7]. Directions of circulation of electrically conducting liquid in them are opposite, as directions of forces causing them are opposite. Intensity of motion of molten metal eddy flows depends on forces applied to it, hydrodynamic resistance to their motion and crucible shape. In the absence of mechanical obstacles, the region, covered by molten metal motion, can go beyond the zone of action of forces **F** inducing this motion.

At non-uniform distribution of volume density of the electromagnetic force, for instance, in the presence of magnetic field asymmetry, the intensity of molten metal flow will be greater in the region of action of large forces **F** and large C_i values. The cause for magnetic field asymmetry can be a non-uniformity of the gap between the inductor and liquid metal pool, asymmetry of current density distribution in the inductor, crucible shifting relative to the inductor and crucible shape. So, with the cylindrical inductor and crucible rounded from below the largest magnitude of magnetic induction is achieved in the crucible wide part, where the distance between the inductor and crucible is smaller. This increases relative value C_i and extent of eddy zone of the force field, acting in the crucible narrow lower part. Conditions for movement of molten metal flows are more favourable in the crucible broad upper part that is confirmed by experimental data [3]. However, at item treatment, just a change of crucible shape is insufficient for a significant intensification of molten metal flows.

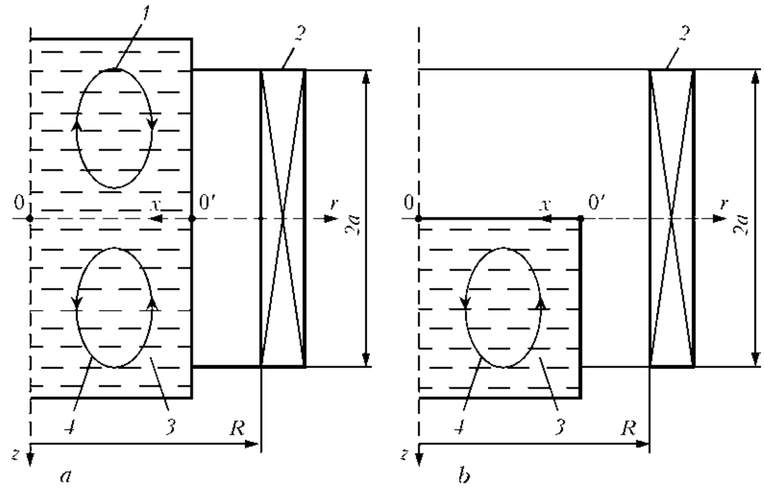

Figure 1. Schematic of motion of molten metal flows at classical (*a*) and proposed inductor position (*b*): *1*, *4* — the upper and lower vortex of the flow, respectively; *2* — inductor; *3* — molten metal

For a more effective utilization of molten metal eddy flows at treatment of metal products it is necessary to ensure the presence of one powerful flow (single-contour motion of the melt) in the crucible, directed to the crucible axial part (axis z in Figure 1, *a*) towards the item being treated. Single-contour motion of the flow arises in the case, when there exists only one eddy zone of the force field in the molten metal volume that is the case in the liquid pool at ingot solidification in induction furnaces with a cold crucible or in electromagnetic mould.

It is experimentally established that the single-contour motion of molten metal can be realized in the simplest and most effective way at the expense of relative displacement of the inductor and crucible along their vertical axis of symmetry. Here, the first eddy contour is enhanced and increased, and the second is weakened and decreased down to complete disappearance. The lower contour can be enhanced even further by rounding the crucible bottom (Figure 2). This Figure shows the schematic of the crucible shaped as the paraboloid of revolution, the open narrow lower part of which is resting on the treated item. Circular cylindrical inductor, acting by its variable electromagnetic field on the molten metal in the crucible, is placed in its upper wide part.

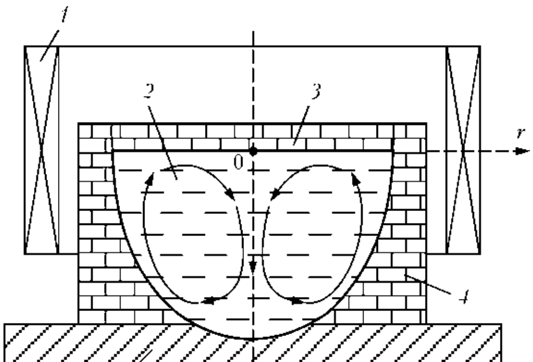

Figure 2. Schematic of motion of molten metal flows in the crucible at treatment of items by the proposed method: *1* — inductor; *2* — molten metal; *3* — crucible cover; *4* — crucible; *5* — item

From [6] it follows that the tangential electrodynamic forces are of secondary importance at metal circulation (less than 3 % contribution to C_i), while the main contribution is made by forces directed normal to the surface, the presence of which is due to electromagnetic pressure of inductor filed on the metal. Proceeding from this fact, let us apply Maxwell–Lorentz law, which is used to find the dependence of density of forces **F** in the form of vector product of current density **J** and magnetic induction **B** [10]:

$$\mathbf{F} = [\mathbf{JB}],$$

where $\mathbf{J} = \mathbf{E}/\rho$; $\mathbf{B} = \mu\mathbf{H}$; **E**, **H** is the intensity of electric and magnetic fields, respectively; ρ is the specific electric resistance; μ is the magnetic permeability of metal (above Curie point it is equal to magnetic constant μ_0).

Let us consider the processes occurring at quasistationary in time variable electromagnetic field, at which the method of complex amplitudes can be used.

Complex components of intensity of magnetic $\underline{H}_e$ and electric $\underline{E}_e$ fields of a wave, propagating in-depth of the metal, can be expressed with sufficient accuracy through complex values of magnetic field intensity $\underline{H}$ that are generated by the inductor in the ambient space and on liquid metal surface [10]:

$$\begin{cases} \underline{H}_e \approx 2\underline{H}\ \exp(-jkx); \\ \underline{E}_e = 2\underline{H}\ \underline{Z}_e \exp(-jkx), \end{cases}$$

where $j = \sqrt{-1}$; $jk = (1 + j)\sqrt{\omega\mu_0/(2\rho)} = (1 + j)b$; $b = \sqrt{\omega\mu_0/(2\rho)}$; $\underline{Z}_e = \sqrt{j\omega\mu_0\rho}$ is the normal surface impedance or wave resistance of metal; x are the current coordinates of points, lying on the normal aimed from the surface in-depth of the metal (see Figure 1); ω is the angular frequency of magnetic field variation.

If for instant values of intensity of magnetic and electric fields of a wave passing in-depth of the metal initial phase H_e is selected so that amplitude value of complex quantity $\underline{H}_m$ was equal to scalar value H_m, then they can be presented in the following form [10]:

$$\begin{cases} H_e = 2H_m \exp(-bx) \sin(\omega t - bx); \\ E_e = 2H_m \sqrt{\omega\mu_0\rho} \exp(-bx) \sin(\omega t + \pi/4 - bx). \end{cases}$$

Force $F_{e,\,x}$ acting on a unit of metal surface is equal [10] to

$$F_{e,\,x} = E_e\mu_0 H_e/\rho = \\ = 4H_m^2\mu_0\sqrt{\omega\mu_0/\rho} \exp(-2bx) \sin \times \\ \times (\omega t - bx) \sin(\omega t + \pi/4 - bx).$$

Average value of force F_e over $2\pi/\omega$ period is equal to

$$F_e = \frac{\omega}{2\pi} \int_0^{2\pi/\omega} F_{e,\,x} dt = H_m^2\mu_0\sqrt{2\omega\mu_0/\rho} \exp(-2bx).$$

Considering that presence of exponential factor in this expression leads to a fast decrease of force density with increase of x, these forces can be regarded as concentrated on the metal surface (presence of skin-effect), and they can be replaced by pressure p_e, applied to the surface:

$$p_e = \int_0^{\infty} F_e dx = H_m^2\mu_0\sqrt{2\omega\mu_0/\rho}/2b = \mu_0 H_m^2.$$

In the derived expressions it is rational to move from magnetic field intensity H having two components — axial and radial — to electric field intensity E and vector potential of magnetic field A, having in this case one azimuth field component $\underline{E} = -j\omega\underline{A}$ for circular closed current [4].

Considering that

$$\underline{H}_e \approx 2\underline{H} \approx 2\underline{E}/\underline{Z}_e = -2j\omega\underline{A}/\underline{Z}_e,$$

hence $\underline{H} \approx -j\omega\underline{A}/\underline{Z}_e$, at the assumed above initial phase of variation of instant values of magnetic field intensity for their scalar values (amplitudes) we write can as $H_m \approx \omega A_m/Z_e = A_m\sqrt{\omega}/(\mu_0\rho)\}$. Here, force F_e and pressure p_e are calculated by formulas [5]

$$F_e = (\omega A_m^2\sqrt{2\omega\mu_0/\rho}/\rho) \exp(-2bx), \quad p_e = \omega A_m^2/\rho.$$

Inductor electromagnetic field can be described using scalar value of magnetic field vector potential A, the source of which is current I, distributed with linear density $\delta = wI/2a$ along the surface of thin-walled solenoid with turn number w of radius R and length $2a$ (at $r \le R$) [11, 12]. In this case, magnetic field vector potential A has the following form:

$$A = \frac{\mu_0 RwI}{\pi a} \int_0^{\infty} I_1(\lambda r) K_1(\lambda R) \sin(\lambda a) \cos(\lambda z) \frac{d\lambda}{\lambda},$$

where λ is the integration variable, equivalent to spatial frequency of harmonics of solenoid electromagnetic field; I_1, K_1 are the modified Bessel's functions of the 1st and 2nd kind of the first order; r, z are the coordinates of observation point from the origin of axes r, z. At $r \ge R$ the arguments of Bessel's functions should be interchanged.

Axial and radial components of the vector of magnetic field intensity are found from equation $\mathbf{H} = \mu_0^{-1}$ rot $\mathbf{A}$, written in the cylindrical system of coordinates (at $r \le R$) [11, 12]:

$$H_a = \frac{RwI}{\pi a} \int_0^{\infty} I_0(\lambda r) K_1(\lambda R) \sin(\lambda a) \cos(\lambda z)\, d\lambda,$$

$$H_r = \frac{RwI}{\pi a} \int_0^{\infty} I_1(\lambda r) K_1(\lambda R) \sin(\lambda a) \cos(\lambda z)\, d\lambda.$$

To avoid calculation of improper integrals, the kernel of integral in these expressions can be approximated with not less than 1 % error by the following formula (at $r \le R$) in the entire range of variable change [11, 12]:

$$I_1(\lambda r) K_1(\lambda R) = \\ = \frac{1}{2}\left\{\frac{r}{R} \exp\left(-0.4\lambda R\right) + \frac{1}{\lambda R}\left(1 - \exp\left[-\lambda R\left(1 - \frac{r}{R}\right)\right]\right)\frac{\sqrt{r}}{R}\right\}.$$

Having used this approximation, we obtain the following expression for calculation of scalar value of magnetic field vector potential A (at $r \le R$) [11]:

$$A = \frac{\mu_0 RI}{4\pi a}\left\{\frac{r}{R}\left(\text{arctg}\,\frac{a+z}{0.4R} + \text{arctg}\,\frac{a-z}{0.4R}\right) + \frac{1 - r/R}{\sqrt{r/R}} \times \right. \\ \times \left[\text{arctg}\,\frac{a+z}{R-r} + \text{arctg}\,\frac{a-z}{R-r} + \frac{a+z}{2R} \times \right. \\ \left.\left. \times \ln\left[1 + \left(\frac{R-r}{a-z}\right)^2\right] + \frac{a-z}{2R} \ln\left[1 + \left(\frac{R-r}{a-z}\right)^2\right]\right]\right\},$$

and for intensity of inductor magnetic flow (at $r \le R$)

$$H_r = \frac{wI}{2\pi a}\left\{\frac{0.8Razr}{[(0.4R)^2 + (a-z)^2][(0.4R)^2 + (a+z)^2]} + \right. \\ \left. + \frac{1}{2}\sqrt{\frac{r}{R}}\left[\ln\left(1 + \left(\frac{R-r}{a-z}\right)^2\right) - \ln\left(1 + \left(\frac{R-r}{a+z}\right)^2\right)\right]\right\}.$$

At $r \ge R$, R/r and $r - R$ should be written in the derived formulas instead of r/R ratio and $R - r$ difference.

Derived expressions lead to the conclusion that magnetic flow intensity H_r is equal to zero along its horizontal plane of symmetry, irrespective of the distance, at which the observation point is located from the inductor (see Figure 1, *a*). In any other place the magnetic flow intensity rises from zero to maximum (closer to inductor), and then decreases at increase of value r. Therefore, electromagnetic pressure due to forces related to magnetic field intensity H_r, above the inductor horizontal plane of symmetry (see Fi-

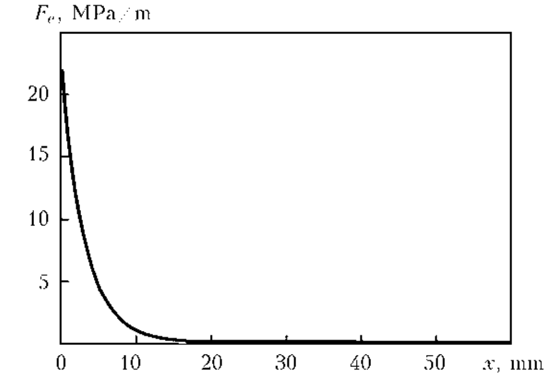

Figure 3. Change of force F_e by the billet depth along axis x

gure 1, *a*) rises from zero on the vertical plane of symmetry of the crucible with the melt up to maximum value on its edge. Here, molten metal motion takes place along the crucible walls downwards and along the crucible vertical axis of symmetry upwards. In the studied process of metal treatment such a direction of molten metal motion is unfavorable. In order to suppress it, the inductor should be placed so that its horizontal plane of symmetry coincided with molten metal surface (see Figure 1, *b*). Here, only one useful eddy flow of molten metal remains, which is aimed along the vertical plane of symmetry of the crucible downwards onto the treated item and upwards along the crucible walls.

Such a location of the inductor leads to intensification of molten metal eddy flows in connection with absence of upper vortex metal pressure onto that of the lower one. Here, the electric power consumed by the induction system is spent only on creation of one useful eddy flow of molten metal. Heat exchange between molten metal in the crucible and metal of item to be melted is enhanced due to intensification of these flows, thus promoting a reduction of melting time and input power.

Electromagnetic pressure to the melt is also applied by forces directed from the crucible side surface to its vertical axis of symmetry z, related to inductor magnetic flow intensity H_a. As the intensities of the magnetic and electric fields have maximum values in this case, the electromagnetic forces will also be the highest. They are exactly the factors that promote formation of eddy flows in the crucible in the axial direction, forming a menisk on the molten metal surface. To enhance the pressure of eddy flows on the treated item, it is rational to place a limiting wall in the form of crucible cover at the melt surface (see Figure 2) that prevents rising of molten metal. To lower the relative value of magnetic field intensity H_r in the crucible zone it is rational to apply an inductor of the length not less than its diameter. All this enhances the energy effectiveness of the induction system.

This work did not deal with forces applied to molten metal upper surface, which are caused by the magnetic field of inductor upper part protruding above the surface. These forces decrease essentially in the direction of the vertical axis of inductor symmetry z, whereas the length of the inductor proper should be greater than its diameter. The influence of these forces can be neglected in the first approximation in inductor design.

At induction system design we will use the above formulas and procedure of inductor design at heating of pipe end parts from [11]. In our case this is a short pipe section with very small internal diameter simulating a continuous cylindrical metal billet, which is heated by the inductor in the crucible.

Two inductors were designed and manufactured — single-turn consisting of four parallel conductors (windings) (four-winding), and two-turn consisting of two parallel conductors (two-winding [8]), of (80 ± ± 5) mm height, 190 mm diameter, in which the conductors are made from copper tubes of 10 × 15 mm section. The conductors of each of the inductors were connected in parallel and as aiding connection. Voltage of 8 kHz frequency was equal to 80 V for the first inductor, and to 160 V for the second inductor. Inductor power was practically unchanged at 170–180 kW. Such inductor designs allowed variation of product weight in a broad range at melting and of inductor position relative to molten metal.

Change of calculated force F_e at $z = 0$ by molten metal depth along axis x from 0 to R_n (at crucible inner radius $R_n = 60$ mm) is given in Figure 3, from which it is seen that F_e decreases from molten metal edge to its center. Figure 4 shows the change of calculated pressure p_e on molten metal surface at $x = 0$ by crucible height along axis z from 0 to 42.5 mm. Pressure p_e has the highest value in inductor center at billet upper edge and decreases towards its lower end face (see Figure 1, *b*), that promotes formation of molten metal eddy flows in the crucible.

Results of testing the induction systems at treatment of metal plates of different thickness are described in [8].

Thus, conducted research was the basis for determination of the method of intensification of eddy flows in the crucible, enhancement of heat exchange between the latter and treated surface of the item at its local treatment, as well as penetrability and reduction

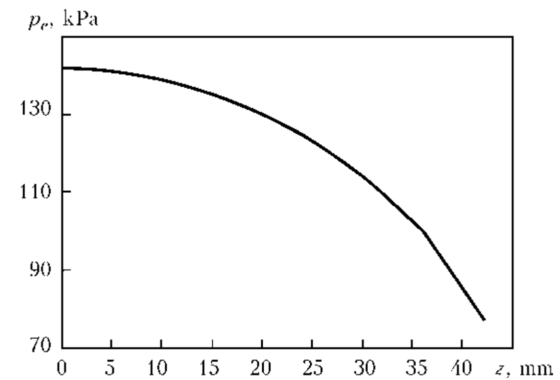

Figure 4. Change of pressure p_e on molten metal surface by billet height along axis z

of power consumption. For this purpose, the inductor should be placed so that the inductor horizontal axis of symmetry coincided with the upper surface of molten metal in the crucible with a rounded bottom, rising of liquid metal should be prevented at the expense of application of limiting cover and inductor of length not less than its diameter should be used.

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STUDYING THE FEATURES OF MASS TRANSFER IN THE PROCESS OF FRICTION STIR WELDING USING PHYSICAL MODELLING

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Model of the process of friction stir welding was used to study the influence of structural dimensions of working surfaces of tool shoulder and tip on the features of material displacement in the thermodynamic impact zone. It is shown that a permanent joint forms due to displacement of a certain amount of ductile material by the tool tip and its mixing across the entire thickness of edges. Shape of working surface of tool shoulder end face predetermines the displacement trajectory, movement speed, uniformity of mixing and degree of compaction of the materials being joined at solidification.

Keywords: *friction stir welding, process modelling, mass transfer, tool tip design, shoulder working surface*

Permanent joints began to be produced in the solid phase by friction stir welding (FSW) for fabrication of welded structures already in 1990s. This welding process became widely accepted in joining aluminium and magnesium based alloys, which feature a high ductility under the conditions of low-temperature heating [1–4].

Weld formation at FSW takes place at metal heating in the welding zone at the expense of friction to plastic condition and displacement at high pressure in a volume limited by working surfaces of the tool and substrate. FSW main parameters are design features and dimensions of tool working surfaces, its location relative to vertical axis and surfaces of billets being welded, tool pressing and depth of penetration of its tip into the butt, as well as speed of rotation ω and linear displacement of the tool at a certain speed, equal to welding speed v_w [5, 6]. These parameters determine the conditions of metal friction heating in the welding zone and essentially influence the magnitude and orientation of forces acting on plasticized metal, as well as the speed and trajectory of its displacement. Understanding of the features of mass transfer in the zone of permanent joint formation is very important for determination of optimum structural dimensions of the tool and welding process parameters, which will ensure production of dense sound welds.

First idea of the nature of plasticized metal displacement at FSW was obtained through experiments, which are based on instant stopping of the moving material flow [7]. The trajectory of its motion in the characteristic zones of the joint was assessed by the change of the position of special markers (very fine steel balls, copper pins, copper or titanium foil, thin tungsten wire, composite material interlayer, etc.), which were placed in the butt between the edges being welded or on the sections adjacent to it [7–10]. Data on the features of metal displacement can be also obtained in welding aluminium alloys of different alloying systems with different etching to each other [11], or of dissimilar materials differing greatly by their colour [12]. However, all the above methods to assess the mass transfer occurring at FSW are quite labour consuming, as their application requires testing of the produced welded joints by X-ray radiation or prepa-