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ON THE PROBLEM OF MODELING TRANSVERSE MAGNETIC FIELD STRUCTURE IN WELDING POOL ZONE

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It was established experimentally that a normal component of induction along the side surfaces of rods of the input device of the transverse magnetic field is distributed almost uniformly (has the same values). A slight increase in the values of this induction component is observed only in the zones at the ends of rods and coils, placed on these rods. To study the distribution of transverse magnetic field induction in the welding pool zone (at the base metal surface), it was proposed to use the well-known assumption that there is an analogy between the structure of magnetostatic and electrostatic fields. On this basis, a procedure was proposed which allows calculating the distribution of transverse and longitudinal induction components of the magnetic field generated by the input device of the transverse magnetic field at the surface of welded plate of nonmagnetic materials. In this case, the known equations of electrostatics are used. It was assumed in the calculations that charges of electrostatic field on the side surfaces and rod ends of the input device of the transverse magnetic field are uniformly distributed. It is shown that the proposed method provides a satisfactory convergence of calculated and experimental data. 8 Ref., 6 Figures.

Keywords: *transverse magnetic field, induction, Coulomb's law, electrostatic field strength*

The use of a transverse magnetic field (TMF) in arc welding and surfacing provides the control of welds (beads) geometry, increase in the coefficient of electrode melting and refinement in structure of welds (deposits) [1–4].

The study of TMF structure in the weld pool zone has a theoretical and practical importance. However, there are no simple procedures for calculating the induction of the magnetic field, generated by two-rod systems of TMF input devices (ID) in the weld pool zone.

The well-known calculation program ANSYS provides determination of the induction values generated by the TMF ID in this zone. However, its use is hindered because of excessive complexity [5]. The excessive complexity is also inherent in a calculation procedure based on the use of a method of secondary sources, when a numerical solution of the problem by the finite element method is also required [6, 7]. It is necessary to develop a calculation procedure which is simpler in use.

According to the literature data [6], there is an analogy between the structure of the magnetic field generated by the TMF ID and the structure of the electrostatic field, if the latter field was generated by the similar charged bodies. According to the data presented, in particular, in work [6], at a certain point of the surrounding space, the induction *B* and the electric field intensity *E*, generated respectively by electromagnets and charged bodies, are summed as vectors. The mathematical apparatus for describing the structure of the electrostatic field was developed more fully unlike that for the electromagnetic field. It should be noted that as-applied to calculation of induction of the magnetic field generated by the TMFID, this method was not used.

The aim of this work is to analyze the feasibility of modeling a stationary magnetic field, generated by the TMF ID, using a stationary electrostatic field in the pool zone during arc welding and surfacing.

Below the developed calculation method of modeling the spatial distribution of the induction of the controlling TMF in the zone of the weld pool is presented by using the equations of electrostatics.

Investigated were the features of structure of the magnetic field generated by a single rod with winding. The cross-section of the rod of low-carbon steel was F_s = 26×16 mm, the rod length was L_r = 130 mm. On the rod a winding of a copper wire of 1.0 mm diameter was arranged with a number of coils W = 100. The winding was four-layered and had a height of 30 mm. The winding was positioned in the rod length center.

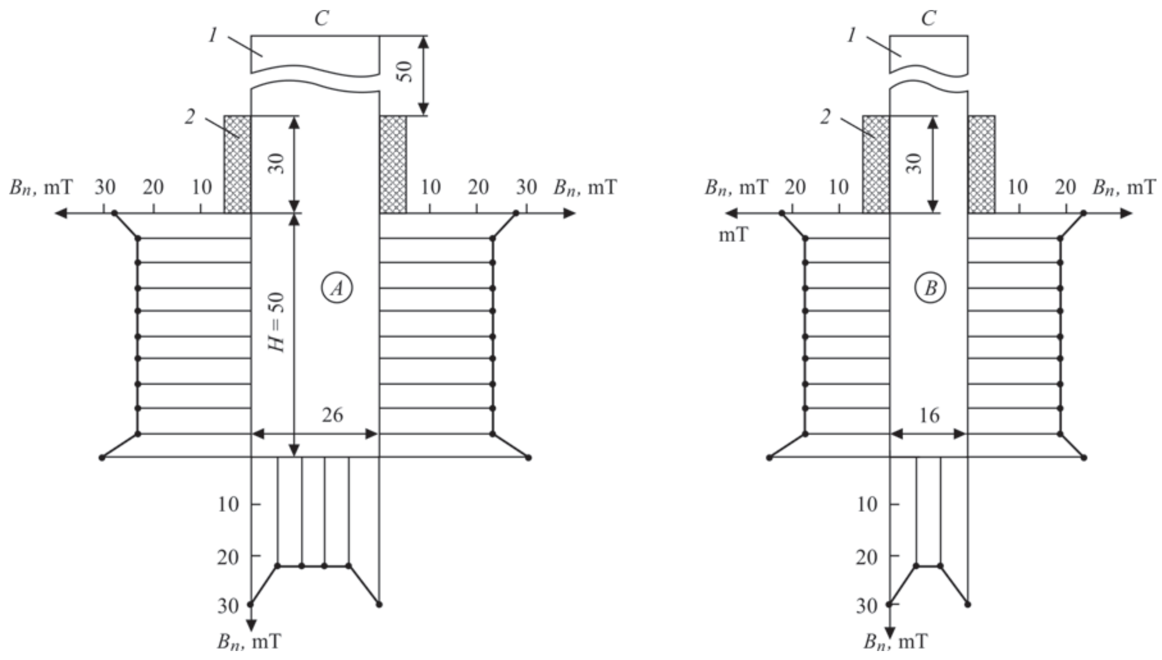

Figure 1. Distribution of induction B_n along the surfaces of rod (W = 100, I_c = 8 A): *1* — rod; *2* — winding

The normal induction component B_n and also the induction component B_n normal to the rod end at the section below the winding were measured along the side surfaces of the rod. In the coil, a direct current I_c = 8 A was passed. The measurements of induction B_n were performed applying a milliteslameter of type 43205 with a Hall sensor having a measuring base of 0.9×0.9 mm. The measurement data are shown in Figure 1. The data demonstrated a «splash» of induction B_n only at the winding end and below at the rod end. A «splash» of B_n was observed in the sections of about 5 mm length, while along the entire length of the rod and at its end the induction B_n was distributed rather uniformly. The tangent component of magnetic field induction on all the rod surfaces was almost equal to zero. The similar data were obtained using rods of 26×32 mm and 32×52 mm section. With a decrease in the distance from the coils up to the rod ends from 60 to 20 mm, the nature of change in the induction components corresponded to that preset for the rod of 26×16 mm section (Figure 1). This statement was also preserved for the rods, made as a set of plates of electrical steel E42 of 0.5 mm thickness.

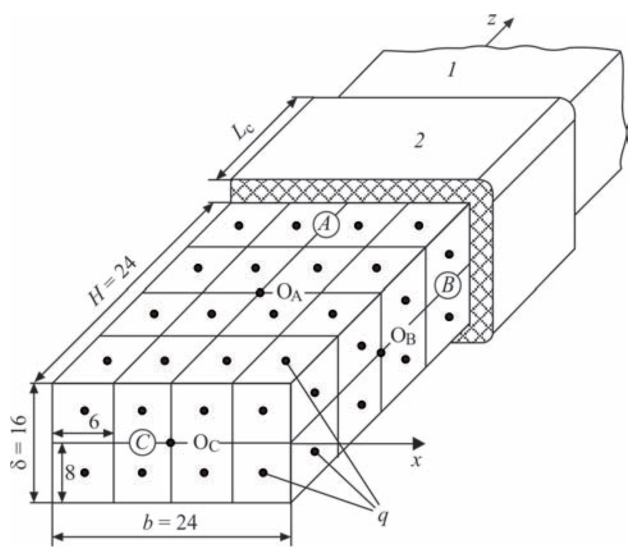

Figure 2. Scheme of distribution of charges at the surfaces *A*, *B*, *C* of the rod (*1*) below the level of the coil (*2*): *H*, *b*, δ — dimensions of the rod area (m); L_c — length of the coil (m); (points — places of charges arrangement)

To develop the calculation procedure, the magnetized section of the rod (below the winding) was replaced by a dielectric body, having charges on its surface. The dimensions of such a dielectric body are the same as the considered section of the electromagnet rod. Moreover, the charges on the surfaces (*A*, *B*, *C*) of the indicated body were distributed uniformly.

As an example, Figure 2 shows dividing of surfaces into sections of the same area, at the center of which the charges q are arranged. It is necessary that all the small sections (after dividing) on all the side surfaces and ends of the rods (*A*, *B*, *C* in Figure 2) have the same area. It is rational to start dividing of the rod (*C*) ends area into sections. The sufficient quantity of areas on the surfaces *C* is 8–12. The larger the quantity of sections, the more accurate the results of calculations will be in future. However, the amount of calculation works will increase.

As is known [6], according to Coulomb's law, the intensity of the electrostatic field E from the charge q in a point at the distance R from the charge:

$$E = \frac{q}{4\pi\varepsilon_0 R^2}, \quad (1)$$

where ε_0 is the electric constant; $\varepsilon_0 = 8.85\cdot10^{-12}$ F/m.

Since $q/(4\pi\varepsilon_0)$ = const, then in the formula (1) to estimate (calculate) E, generated by a charge on the side surface of the TMF ID, any numerical value $q/(4\pi\varepsilon_0) = K$ (convenient for calculations) can be taken.

Then the formula (1) will take the form:

$$E = \frac{K}{R^2}. \qquad (2)$$

The calculation by formula (2) is convenient, because in order to finally evaluate the character of distribution, the field intensity E (E_x, E_y, E_z) along any direction (axes X, Y, Z) should be expressed in relative units, for example, through the parameter $E_x/E_{x\max}$. In this case, the distribution of the electrostatic field component $E_x/E_{x\max}$ can be compared with the distribution of induction components of the magnetic field generated by the real structure of the TMF ID ($B_x/B_{x\max}$). In addition, the values of components of field E (E_x, E_y, E_z) along any direction allow evaluating numerically (in divisions, units, obtained during the calculation) the influence of dimensions and arrangement of the TMF ID rods in space, the inclination of rods to the vertical axis on the value of field components E (E_x, E_y, E_z), and, thus, allows determining the optimal parameters of the TMF ID, providing the maximum values of components of the field E_x, E_y, E_z at a certain point (analogues of values of components of the magnetic field B_x, B_y, B_z in the point).

It was established earlier [8] that the structure of a controlling TMF generated by different structures of П-type ID in relative units does not depend on how the magnetic force lines of are closed at the upper part of the two-rod TMF ID systems. This was the basis for modeling the magnetic field by the electrostatic field for the TMF ID from two rods (with windings), not connected by a jumper at the top.

In the calculations, the lower part of two rods with a section $F_s = b\times\delta = 26\times16$ mm, of length $H = 50$ mm in the zone below the coils was considered. On the surfaces of rods, the point-like charges of the same size were arranged (in Figure 3, in the form of points the charges are indicated arranged on the vertical surfaces of each of the two rods, but the similar charges are also arranged on the lower ends of rods).

The vectors E of each charge are decomposed in space into three components directed along the coordinate axes OX, OZ, OY through the cosines of direction angles α, β, γ of vector E with respect to these axes (Figure 4).

It was assumed that from each charge on the surface A of the rod, positive pole (+), the vector of the field intensity E «comes out», and the vector E' «comes in» the same point of the rod B, negative pole (–) (see Figure 3).

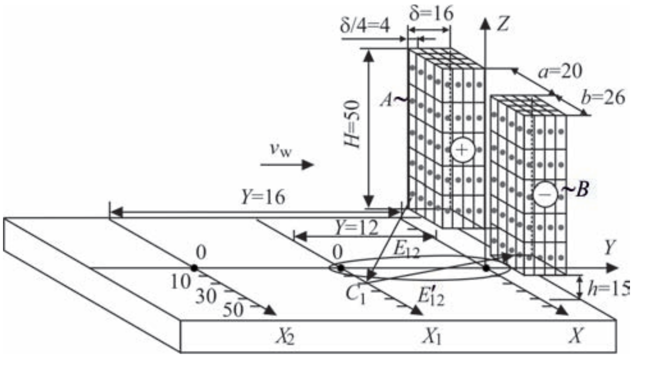

Figure 3. Scheme for the calculation of vector E in the point C_1 at the plate surface

For each vector of intensity, the following equations can be composed:

$$E_{Y_i} = E\cos\beta = E_i\frac{y_i}{R_i}, \qquad (3)$$

$$E_{Z_i} = E\cos\gamma = E_i\frac{z_i}{R_i}, \qquad (4)$$

$$E_{X_i} = E\cos\alpha = E_i\frac{x_i}{R_i}, \qquad (5)$$

where E is the value of the field intensity at the point considered,

$$E = \frac{q}{4\pi\varepsilon_0\varepsilon_r R^2}, \qquad (6)$$

y_i, z_i, x_i is the length of vector E projection to the corresponding axis, m; R_i is the distance from the charge q_i to the point considered C_1, m.

Further, the calculation was carried out according to the formula (2), where K is a constant value:

$$K = \frac{q_i}{4\pi\varepsilon_0\varepsilon_r} = \text{const}. \qquad (7)$$

To obtain the numerical values of the vectors E_x, E_y, E_z, at a given point of space (in particular, at the point C_1), the summation of all the components E'_{xi}, E'_{yi}, E'_{zi} was performed at this point from each charge q_i arranged on the surfaces A and B of rods and at the end C.

Moreover, the bodies (rods A and B in Figure 3) are considered conditionally opaque, i.e. it is necessary to take into account the action of only those charges q on

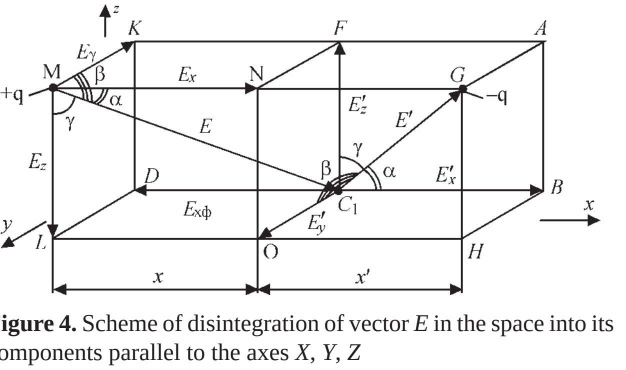

Figure 4. Scheme of disintegration of vector E in the space into its components parallel to the axes X, Y, Z

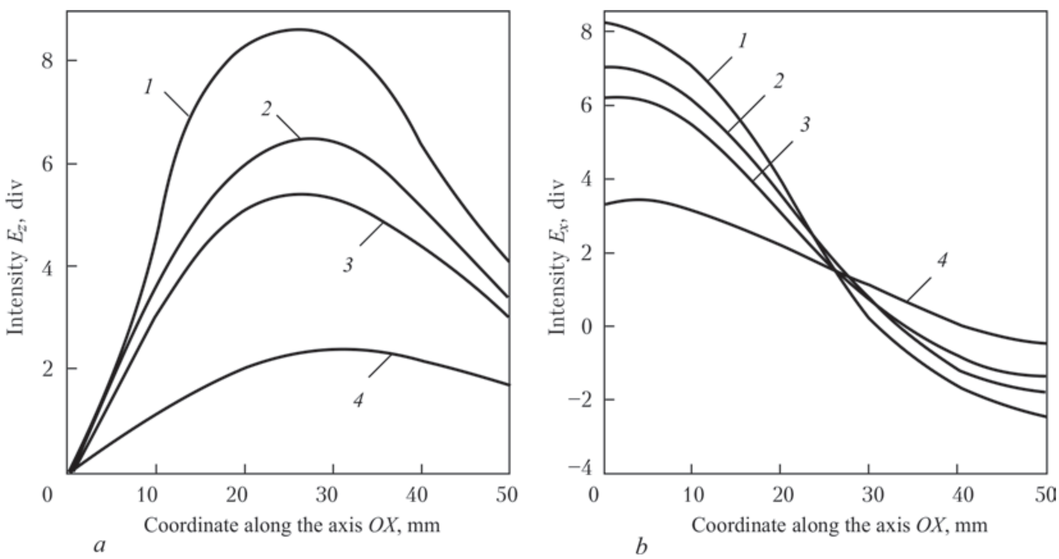

Figure 5. Distribution of calculation values E_z (*a*) and E_x (*b*) along the axes *OX*: *1–4* — respectively, at *y* = 0; 12; 16; 32 mm

the surfaces *A*, *B* and *C* of rods which are «visible» from the point C_1.

To evaluate the feasibility of practical application of the proposed calculation procedure, it is necessary to compare the calculated data with the corresponding experimental data. For this purpose, the distribution of components B_z, B_x of the magnetic fields, generated by the real TMF ID, were investigated. In the investigations, the electromagnets with a cross-section of rods of low-carbon steel $F_s = b \times \delta = 26 \times 16$ mm, length $L = 130$ mm with windings of length $l = 30$ mm were used. The distance from the windings to the rod end is $H = 50$ mm. Through the coils a direct current $I = 8$ A was passed. The induction was measured by a universal 43205 teslameter with a Hall sensor having a base of 0.9×0.9 mm.

To evaluate the structure of the magnetic field in the pool, a calculation scheme of two rods $F_s = 26 \times 16$ mm and a conditional distribution of charges along the side surfaces were taken, shown in Figure 3. The distance between the rods was $a = 20$ mm; between the axis *OX* (surface of the product) and the rod ends it was $h = 15$ mm. The inclination angle of rods to vertical was $\alpha = 0°$. The calculations were carried out taking into account the actions of all charges on the surfaces of all the rods (*A*, *B* and *C*), which are «visible» from the point C_1. To accelerate the calculations the program Mathcad 15 was used.

The absolute values of the field intensity *E* at the points arranged along the axis *OX* with a step of 10 mm, with the coordinates along the axis *OY* in the direction opposite to the welding direction, $Y_0 = 0$ mm, $Y_1 = 12$ mm, $Y_2 = 16$ mm and $Y_3 = 32$ mm were determined (Figure 3). In the calculation, the dependence $E = 16/R^2$ (R was measured in cm) was used. In this case, the numbers are obtained which are

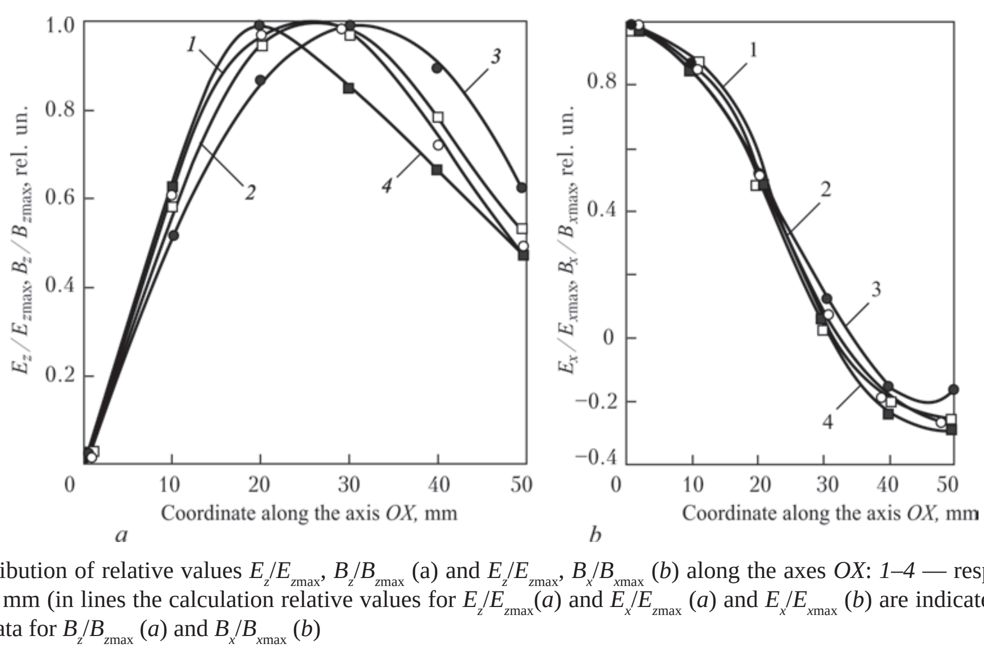

Figure 6. Distribution of relative values E_z/E_{zmax}, B_z/B_{zmax} (a) and E_z/E_{zmax}, B_x/B_{xmax} (*b*) along the axes *OX*: *1–4* — respectively, at *y* = = 0; 12; 16; 32 mm (in lines the calculation relative values for E_z/E_{zmax}(*a*) and E_x/E_{zmax} (*a*) and E_x/E_{xmax} (*b*) are indicated; in marks the experimental data for B_z/B_{zmax} (*a*) and B_x/B_{xmax} (*b*)

analogs to the values of the components of electrostatic field intensities E_z, E_x. In principle the numerical values E_z, E_x (in divisions) correspond to the values E_z, E_x, having the dimension B/m.

The data showed that the nature of distribution of calculated values of the longitudinal and transverse components E_z and E_x (analogs of the components of inductions B_z and B_x) along the axes *OX* is preserved with increasing distance along the axis *OY* (see Figure 3) in the direction opposite to the direction of welding (Figure 5, *a* and *b*). The calculated relative values $E_z/E_{z\max}$ and $E_x/E_{x\max}$ shown in Figure 6, *a* and *b*, corresponding to the experimental relative ratios of inductions $B_z/B_{z\max}$ and $B_x/B_{x\max}$ for real rods of the TMF ID almost coincide with each other.

Thus, the proposed method provides a satisfactory convergence of calculation data on the distribution of components of intensity of the modeling electrostatic field and the experimental data on the distribution of the magnetic field induction components in the weld pool zone. The method can be used to optimize the structure of the TMF ID to provide maximum values of the transverse induction component in the weld pool zone at a constant value of the magnetizing force of windings at the rods of this ID.

It should be noted that all the results of investigations mentioned above relate to the case when the product is not made of ferromagnetic material. To obtain the numerical values of the induction components shown in Figure 6 in the form of their relative values, it is necessary to know their numerical values for at least one point in this diagram. The method of calculated determination of numerical values of induction components, generated by the TMF ID, will be presented in the next publication.

Conclusions

1. A calculation procedure was proposed using the equations of electrostatics, which adequately reflects the structure of the magnetic fields generated by real TMF ID and allows estimating the distribution of the MF induction components in the weld pool zone.

2. The proposed method can be used to optimize the structure of the TMF ID to provide the maximum values of the transverse induction component in the weld pool zone at the unchanged value of magnetizing force of windings at the rods of this ID.

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