Research of thermoelectric effects and their influence on electron beam in the process of welding of dissimilar steels

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Abstract. The results of studies of magnetic and thermoelectric properties of pearlite, martensitic and austenitic steels are given. The magnetization curves for the materials under study, as well as dependences of absolute thermoelectric power on the material temperature are obtained. The data of magnetic induction changing at the control points above the welded samples during EBW are achieved. The simulation of the magnetic field distribution during electron beam welding of dissimilar steels under the conditions of the thermopower currents generation is carried out. The shape of the electron beam being deflected in the magnetic field of thermoelectric currents is calculated. The calculated values are compared to the experimental results.

1. Introduction

The process of electron beam welding is characterized by a large number of physical phenomena occurring in the interaction of the accelerated electrons beam with the material, namely thermal, deformational, hydrodynamic and plasmic. Most of these processes are connected, moreover, the arising physical fields affect the processing tool – the electron beam – in response.

During dissimilar materials welding process the greatest influence on the electron beam is exerted by magnetic fields formed as a result of thermoelectric currents. Thus, the existing variety of physical processes can be supplemented by the thermoelectric phenomena, which under certain conditions becomes decisive in the formation of a high-quality welded joint. That is because the beam deflection caused by the magnetic field of thermoelectric currents can cause the lack of penetration in the thickness of the product and lead to a serious defect [1-7].

The value of the magnetic induction of thermoelectric current is determined by a number of factors including the temperature distribution in the welding zone, the shape and thickness of the welded part, as well as electrical resistance, magnetic permeability and thermo-EMF of the joined materials [3].

One of the main reasons for the appearance of thermoelectric power in dissimilar alloys is the deviation of electron system from the equilibrium state in the presence of a temperature gradient. Since in this case the driving force is a diffusion flow of a charge carrier in the field of temperature gradient this kind of thermoelectric power is called diffusion [8, 9]. The magnetic permeability of the material is not constant and depends on the magnetic field strength, as well as on the type of material and temperature.

Mathematical models of thermoelectric phenomena in electron beam welding have been developed to predict the value of the electron beam deflection from the joint [2, 3]. However, the assumptions made in existing models cause significant limitations in their applicability, and the models themselves
are not sufficiently verified. There are no data on the values of thermoelectric and magnetic coefficients for most grades of structural materials, which are necessary for the quantitative assessment of trajectory changes in the conditions of thermoelectric current generation.

The aims of the work are:
- to study the thermo-EMF for steels of different classes
- to establish the dependence of the coefficients of thermo-EMF on temperature
- to estimate the magnetic permeability of materials in the fields which values are determined by the electric currents generating conditions
- to evaluate the shape of the thermo-EMF currents magnetic field in electron beam welding and its correlation with the calculated value obtained by mathematical modeling.

2. Research methods
Using thermocouples, the temperature dependences of thermo-EMF for different materials of various structural classes were obtained. Temperature gradient was provided by placing thermocouple in a high-temperature furnace.

The temperature dependence of thermo-EMF was determined by the integral method (figure 1) on thermocouples of the materials under study (table 1), in which one of the branches was made of chromel.

![Figure 1. Scheme for integral thermo-EMF study: 1 – chromel, 2 – material under study.](image)

| No. | Material | Chemical composition, % | Class | Thermo-EMF at 800°C |
|-----|----------|-------------------------|-------|---------------------|
| 1   | 12Kh18N10T | 0.12 17–19 9–11 – 2/0.8 | A     | –2.18               |
| 2   | 20Kh13    | 0.16–0.25 12–14 <0.6 – 0.6/0.7 | M+F   | 7.71                |
| 3   | 09G2S     | <0.12 <0.3 <0.2 /

Thermo-EMF was measured with a V7-22 voltmeter when the hot junction was heated in the temperature range of 50–1100°C. Further, the relative Seebeck coefficient for pairs of conductors was calculated by the expression

\[ S_r = \frac{dE_r}{dT}, \]  

where \( E_r \) was a measured relative thermo-EMF.

Then by the expression (2) the absolute Seebeck coefficient at each point was calculated:

\[ S_{abs} = S_r - S_{chr}, \]

where \( S_{chr} \) was a Seebeck coefficient for chromel.

According to expression 3, the absolute thermo-EMF was calculated for each material from table 1:
The combined PERMAGRAPHR® REMAGRAPHR®C-750 device, consisting of 2 EF5 fluxmeters, was used for receiving of magnetization curves. Measuring yoke is shown in Figure 2.

Thus, to receive the magnetization curve, three samples were made for each material under study with a cross-section of 10 x 10 mm (±0.02 mm); the length of each sample was 120 mm.

Before measurements, each of the samples was demagnetized in an alternating magnetic field with a decreasing amplitude. Then, for each of the samples the magnetization curve was received.

The magnetic field strength $H$ in the considered measurement device was determined using a C-shaped coil (Rogowski belt) which was installed directly on the sample surface. With this coil, a magnetic voltage was measured as the potential difference between two points on the sample surface.

The magnetic field strength (in the SI system being measured in amperes) was calculated by dividing the obtained value of the magnetic voltage by the distance between these points:

$$ H \approx \frac{U_{ab}}{l}. $$

In addition to the magnetic field strength, the polarization $J$, [T] was also determined when the magnetization curve was received. Knowing the polarization $J$ and the magnetic field strength $H$, the magnetic induction $B$ was determined as

$$ B = J + \mu_0 H. $$

The electron-beam welding is characterized by small values of magnetic field induction induced by thermoelectric current, therefore for further analysis they were limited to an induction value not exceeding 100 mT. As in this section the magnetization curve is nonlinear, a high-order polynomial was used to represent the results of measurements.

An improved numerical model of the Seebeck effect in electron beam welding was created on the basis of the obtained data on thermoelectric and magnetic properties.

The model consists of four submodels: thermal problem, electric problem, magnetic and trajectory problem. The thermal problem was solved on the basis of the non-stationary heat equation

$$ c(T)\rho(T)\mathbf{\nabla} \cdot \mathbf{\nabla} T = \mathbf{\nabla} (\lambda(T)\mathbf{\nabla} T) + Q(x,y,z), $$

where $c(T)$ is the specific heat at constant pressure, $\mathbf{J}$ / (kg · K); $\rho(T)$ is the density of the material, kg / m$^3$; $\lambda(T)$ is the thermal conductivity of the material, W / (m · K), $Q(x,y,z)$ is the volumetric heat
source, W / m³. The heat source in the EBW (vapor-gas channel) was adopted in the form of a cylinder acting on the entire welded depth. Then, the action of the volume source in equation (6) can be specified as the boundary condition on the cylindrical boundary of the penetration channel with radius \( r_k \) in the form of the specific heat flux \( q_{bh}(x, y, z) \).

The resulting temperature distribution during welding was used to solve the electrical problem which was formulated as Ohm’s law in differential form

\[
\vec{j} = \sigma \vec{E} + j_e, \tag{7}
\]

where \( j_e = -\sigma S \nabla T \), \( \vec{j} \) is the current density vector, \( \vec{E} \) is the electric field strength vector, \( \sigma \) is the conductivity of the material, S / m; \( S \) - thermoelectric coefficient, V / K.

The magnetic problem was solved regarding the vector potential \( \vec{A} \). The magnetic induction distribution was found:

\[
\nabla \times \left( \frac{1}{\mu(T) \mu_0} \nabla \times \vec{A} \right) = \vec{j}, \tag{8}
\]

\[
\vec{B} = \nabla \times \vec{A} \tag{9}
\]

In the calculations, the formation of the paramagnetic zone in the region of the penetration channel was taken into account. For this, the dependence of magnetic permeability was set in the form:

\[
\mu(T) = \mu_m (1 - h(T - T_c)), \tag{10}
\]

where \( \mu_m \) is the magnetic permeability of the material at room temperature, \( T_c \) is the Curie temperature, \( h(x) \) is the Heaviside function.

And finally, for the obtained distribution of magnetic induction, the trajectory problem of the motion of a charged particle (electron) in a stationary magnetic field was solved:

\[
\frac{d^2 x}{dz^2} + \frac{2e}{m \mu} B_z(x, y, z) \frac{dy}{dz} = \frac{2e}{m \mu} B_y(x, y, z), \tag{11}
\]

\[
\frac{d^2 y}{dz^2} - \frac{2e}{m \mu} B_z(x, y, z) \frac{dx}{dz} = -\frac{2e}{m \mu} B_x(x, y, z), \tag{12}
\]

gде \( x(z), y(z) \) – electron trajectories in the XOZ and YOZ planes, respectively, \( B_x(x, y, z), B_y(x, y, z), B_z(x, y, z) \) – the projection of the magnetic induction vector on the corresponding coordinate axis; \( U \) – accelerating voltage in an electron gun.

Due to the complexity of the developed numerical models, their verification should be carried out on several parameters. In addition to the assessment of the electron beam trajectory, the estimation of the magnetic field induction is promising and feasible.

In this case, the control points for measuring magnetic fields should not introduce significant perturbations into magnetic field induced during the EBW; therefore, they should be located outside the body of the welded samples. Figure 3 shows the proposed scheme for measuring magnetic field in the welded samples.

The studies were taken for three pairs of constructional steels – 12Cr18Ni10Ti + 20Cr13 and 09Mn2Si + 20Cr13 – on the samples of 60 mm thick in a form of plates with 60 × 50 × 200 mm dimensions. The welding was carried out on electron beam installation AELTK-344-12 with accelerating voltage of 60 kV. Preliminarily the EBW mode was determined for a weld with point penetration (beam current of 250 mA, welding speed of 15 m/h).

3. Research results

Figure 4 shows the experimental values of the absolute thermo-EMF and the coefficient of thermal EMF for the steels under study.
Figure 3. Scheme of magnetic field induction measuring during the EBW of dissimilar materials: 1, 2 – welded samples, 3, 4 – magnetic induction sensors above the samples surface, 5 – magnetic induction sensor in the weld root, 6 – electron beam axis, 7 – electron beam in the penetration channel, 8 – vapor-gas channel, 9 – weld pool, 10 – tack welds.

Figure 4. Experimental dependences of absolute integral thermo-EMF and the coefficient of therm-EMF on temperature. 1–3 – number of steels in Table 1

In addition, as a result of the research, experimental tabular and graphical dependences of the magnetic properties for the studied materials were obtained (Figure 5). The obtained results are well approximated by a third-order polynomial. The error in this case ranges from 2% to 9% for various materials (Table 2), which indicates the correctness of the choice of approximating curve.

The results of magnetic field induction measured for such pair of dissimilar steels as 12Cr18Ni10Ti and 20Cr13 are shown in figure 3. The maximum value of magnetic field induction reaches the value of 0.89 mT at the weld root and the value of 0.77 mT above 20Cr13 steel. Electron beam deflection does occur at the weld root of 20Cr13 steel. It is uneven: increasing from 1.8 mm at the beginning of the weld up to 3.8 mm in its middle and then decreasing up to 1.6 mm at the end of the weld (Figure 6). The peak value of the induction at the root is rated at 0.98 mT in the numerical model. It is rated at 0.83 mT above the 20Cr13 steel sample.
Figure 5. Experimental dependences of the magnetic induction (a) and the magnetic permeability of the material (b) on the magnetic field strength for the area up to 100 mT. 1–3 –number of steels in Table 1.

Figure 6. Experimental (a) and numerical (b) magnetic field induction values of thermoelectric currents during the EBW and electron beam deflection in the weld root for 12Cr18Ni10Ti and 20Cr13 steels. 

During the EBW of 20Cr13 and 09Mn2Si steel samples the sensors were also installed at a distance of 20 mm from the welded joint and shielded with several layers of aluminum foil. The results of magnetic field induction measuring are shown in figure 5. The maximum values of magnetic field induction were 0.54 mT and 0.47 mT above 20Cr13 and 09Mn2Si steels respectively, having been observed simultaneously. Electron beam deflection at the weld root (Figure 7) is not uneven: it increases from 2.1 mm at the beginning of the weld, reaches a peak of 2.8 mm in the middle of the weld and then decreases towards the end. In the mathematical model the values of the magnetic field induction above the 09Mn2Si steel sample and 20Cr13 steel sample are rated at 0.51 mT and 0.58 mT respectively.
Figure 7. Experimental (a) and numerical (b) Magnetic field induction values of thermoelectric currents during the EBW and electron beam deflection in the weld root for 09Mn2Si and 20Cr13 steels.

4. Conclusion

Thus, the magnetic field induction in the numerical and physical models shows a good correlation. While the EBW modeling of the 12Cr18Ni10Ti and 20Cr13 steels where a significantly greater deflection is observed, the magnitude of the magnetic field also increases compared to the pair of 09Mn2Si and 20Cr13 steels, which indicates the adequate reaction of the numerical model to the welded pair of materials thermo-EMF increasing.

The proposed method of magnetic field measuring at the control points above the welded parts (during the EBW) allows obtaining the data on the magnetic field induction distribution to verify the numerical process models.

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References
[1] Wei P S and Lii T W 1990 J. Heat Transfer 112(3) 714-20
[2] Ziolkowski M and Hartmut B 2009 COMPEL: Int. J. for Computation and Math. in Electrical and Electronic Eng. 28(1) 140-53
[3] Dragunov V K and Chepurin M V 2001 Welding Production 12 8–16
[4] Blakeley P I and Sanderson A 1984 Welding J. 63(1) 42–9
[5] Nazarenko O K 1982 Automatic welding 1 33–9
[6] Watanabe K, Shida T, Susuki M et al. 1975 J. Jap. Welding Soc. 44(2) 121–7
[7] Dragunov V K, Myakishev Y V, Goncharov A L and Sliva A P 2006 Welding Int. 20(10) 811–5
[8] Goncharov A L 2010 Welding Production 4 12-17
[9] Dragunov V K, Sliva A P, Goncharov A L and Chepurin M V 2014 Method of dissimilar metallic materials electron-beam welding (Russian Federation: Patent No 2534183)
[10] Laptenok V D, Druzhinina A A, Murygin A V and Seregin Yu N 2016 IOP Conf. Ser.: Mater. Sci. Eng. 122 012021