The device with fluxgate sensor for joint tracking

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Abstract. The possibility to evaluate electron beam deflection from joint by magnetic field strength of the current flowing through the welded part of joint is studied. The differential flux gate is utilized as a sensor of electron beam and joint displacement. The concept of the proposed way of electron beam position control relatively to joint is that welding current is divided into two components. Value of beam deflection is defined due to value and direction of vertical magnetic field strength component. At the same time magnetic field strength over welded part of joint is measured.

Introduction. Since the moment when electron beam welding was applied in industry first time the large experience of such type of welding has acquired. On the other hand the problems connected with assurance of accuracy of beam position along joint have not had perfect solutions. This task is a subject of the paper and other issues [1–7]. One reason of poor quality of welded joints is low accuracy of automatic tracking system that directs electron beam along joint. There are many mentioned control systems where sensor is located with some distance from welding place. Therefore deflection between sensor is measured and result has difference from deflection between sensor and joint where last one is needed. Due to such measuring conditions the inaccuracy of overlapping joint and beam can appear in case of curvilinear joint, for example. Moreover, there is high level of electromagnetic interference, which disturbs electronic control system operating. The analysis has shown the following. To improve accuracy of the beam control system information about beam and joint positional relationship can be extracted from electromagnetic field behavior, as electromagnetic processes accompany welding process.

The way of beam and joint positional relationship definition. Proposed technique is based on magnetic field of welding current (I_B) and beam coordinates identification. Principle of this way is that under beam deflection from the joint redistribution of welding current components and current-induced magnetic fields happens [8, 9].

Due to current collectors electron beam current I_B is divided into two components I_1 and I_2 (Fig. 1). In case when electron beam is located strictly over the joint then magnetic-fields strength H_1 and H_2 have equal values and opposite directions (Fig. 1, a). In such case total magnetic field is defined by current I_B, and vector of magnetic-field strength is located in horizontal plane. Under beam deflection (-ε) from the joint (Fig 1, b) current I_2 flows through welded part of the joint, and magnetic-field strength produced by current I_2 is changed on value H_V. The total magnetic field over welded part of the joint is defined by vertical component of magnetic field strength H_V from current I_2, flowing through welded part of the joint, and horizontal component of magnetic field strength from beam current I_B. In case of
beam deflection to opposite direction, current $I_1$ flows through the welded part of the joint and magnetic field strength produced by current $I_1$, is changed on value $-H_V$ (Fig. 1, c). So the total magnetic field over welded part of the joint is defined by vertical component of magnetic field strength $-H_V$ from current $I_1$, flowing through welded part of the joint, and horizontal component of magnetic field strength from beam current $I_B$. Therefore vertical component of magnetic field strength over welded part of the joint gives information about beam position relatively to joint. In case of magnetic field sensor (for example flux-gate meter) utilizing under condition that sensitive axis located in plane of the joint but perpendicularly to plane of weldment, vertical components $H_V$ and $H_V$ can be measured. It is sufficient information to define electron beam position.

**Figure 1.** Dependence of magnetic field vertical component on electron beam position relative:

a) – $X=\varepsilon=0$ (no displacement); b - $X=-\varepsilon$ (left displacement); c – $X=+\varepsilon$ (right displacement)

**Experimental analysis.** The magnetic field alteration depending on electron beam position relatively to the joint is proved with help of physical model. In the capacity of conducting medium (the simulation of weldments material) electrolytic solution is used. The joint was simulated by dielectric sheet. So voltage source, current contacts, electrolytic solution and electrode drowning to electrolytic solution in border between joint and weld generate model of welding current electrical network.

With the help of the probe and meter the family of equipotential lines on the surface of electrolytic solution has been received.

Thereto it is necessary to define set of points with equal potential as Fig.2 shows. Then current lines of force are plotted taking to account that lines of force must be normal to equipotential lines in each point (Fig. 2).
As Fig 2,b shows, under beam deflection from the joint the symmetry of current distribution is disturbed. Therefore, total magnetic field differs from the field under coincidence of beam and joint positions. (Fig. 2, a).

**Theoretical analysis.** Analytical definition of magnetic field strength dependence from electron beam deflection relatively to joint was done with 3D model, which allows simulating of welding process from the position of electromagnetic properties of space restricted in plane of weldment by coordinates that were defined due to two-dimension model analysis.

Mentioned dependence can be presented as:

\[ H_V = F(x, y, h_S, I), \]

where \( H_V \) – vertical component of magnetic field; \( x, y \) – beam coordinates; \( h_S \) – height of the flux-gate meter; \( I \) – welding current.

The simulation is based on Maxwell equations calculation:

\[ \text{rot}\vec{H} = \vec{j} + \frac{\partial\vec{D}}{\partial t}, \]
\[ \text{rot}\vec{E} = -\frac{\partial\vec{B}}{\partial t}, \]
\[ \text{div}\vec{D} = \rho, \]
\[ \text{div}\vec{B} = 0, \]
where $E$ – electric field strength, $D$ - displacement field (electric flux), $H$ – magnetic field strength, $j$- current density, $\rho$ – volume charge density, $B$ – flux density.

Maxwell equations are added with constitutive equations that connect vectors $E$, $D$, $H$ and $B$ to quantities characterizing electrical and magnetic medium properties:

$$D = \varepsilon_0 \varepsilon \vec{E},$$
$$\vec{B} = \mu_0 \mu \vec{H},$$
$$\vec{j} = \gamma \vec{E},$$

where $\varepsilon$ – relative dielectric constant, $\mu$ – relative permeability, $\gamma$ – electric conductivity, $\varepsilon_0$- electric constant, $\mu_0$ – space permeability. The current injects to the network through the beam and is taken off from the side of non welded part of the joint.

The weldment is zoned by cylindrical air layer. In this region magnetic field should be calculated under $x$ coordinate of the beam variations. Obtained calculations were produced under following assumptions: the medium is isotropic, $\varepsilon$ and $\mu$ parameters are real numbers. The voltage is applied to upper edge of the element - “beam” to provide welding current 250mA.

Two parameters were modeled - direct current in conducting medium and electromagnetic field. The equations were calculated due to finite elements method.

The calculations were produced for aluminum alloy and steel materials under beam deflection variations. In Fig. 3 results of calculations for welding process of parts from aluminum alloy with thickness 10 mm under $I_B = 250 m\text{A}$ and speed of welding process $S_W = 0,5 sm/s$ are presented. The lines show currents and full tones correspond to distribution of magnetic fields.

It shows that in case when beam deflection is zero, the distribution of welding current components $I_1$ and $I_2$ and magnetic fields produced by them are symmetrical relatively to the joint (Fig. 3, a).

In case of beam deflection from the joint the symmetry is disturbed (Fig 3, b), and some current component flows through the welded part. The stronger the beam deflection is, the larger the beam deflection is. The same effect is occurred under the physical simulation that was described earlier. As a result the balance of currents $I_1$ and $I_2$ is disturbed. The vertical component of the magnetic field $H_V$ appears. The value $H_V$ depends on value and direction of beam deflection from the joint (Fig 3).

All in all, the calculation results have shown that beam deflection from the joint converts to deviation of vertical component of magnetic field.

The dependence $H_V$ from $\varepsilon$ can be represented approximately as

$$H_V \approx \frac{1}{4\pi r_0} \cdot \frac{I_B \cdot \varepsilon}{\sqrt{r_0^2 + \varepsilon^2}},$$

where $r_0$ – average distance from magnetic field source to point of measuring, $I$ – average beam current value. The calculations have shown, that magnetic field strength $H_V$ is almost proportional to beam deflection from the joint (Fig. 4).

The research results authenticate the possibility of beam position definition relatively to joint by value and direction of magnetic field vertical component. Meanwhile, the sensor (flux gate) can be located with some distance from the beam but it doesn’t lead to procedure error of measurement, as vertical component of magnetic field $H_V$ appears only under beam deflection from the joint.
Figure 3. Magnetic fields distribution: a – $\varepsilon = 0$; b – $\varepsilon = 0.1\text{mm}$

Figure 4. Dependence of magnetic field vertical component from beam deflection relatively to joint
The system for joint tracking. In Fig. 5 the simplified diagram of the system for automatic joint tracking with flux gate as a sensor of beam position relatively to joint of welding parts is given. The system consists of flux gate $S$, converter-amplifier $T$ to provide standard electrical signal from the flux gate, beam-deflection system $DS$ to shift beam position in the line perpendicularly to joint line.

![Diagram of the system for automatic beam control](image)

**Figure 5.** Structural diagram of the device for automatic beam control: $S$ – sensor; $DS_X$ – deflection system for $X$-axis; $T$ – transducer; $EB$ – electron beam; $EBG$ - electron beam gun

The sensor is fixedly connected with electron-beam gun under welded part of the joint. Sensitive axis is located in plane of the joint but perpendicularly to plane of weldment. When the beam is located on the joint (Fig. 1, $a$), sensitive axis projection of the magnetic field strength is produced by welding current under welded part of joint equal to zero. So output signal from the sensor is also equal to zero.

Under beam deflection from the joint (Fig. 1, $b$) component of current welding $I_2$ flows through the welded part of joint. So, sensitive axis projection of the magnetic field strength characterizes value and direction of beam deflection from the joint. In this case the measuring coil of the flux gate generates the signal that is converted and gained by device $T$ and becomes $DC$ voltage that is proportional to beam deflection value from the joint. The mark of voltage defines direction of the beam deflection. The voltage signal enters the input of deflection system $DS$, which compensates displacement of beam location from the joint.

The proposed system was tested in real conditions and received error of beam and joint overlap was less than 0,2mm.

**Conclusions**

1. The method of electron beam location relatively to joint, based on identification of magnetic fields and coordinates of the electron beam, is proposed.
2. The proposed technique allows controlling of electron beam location and correcting it with help of automatic system for joint tracking with low error.
3. The noise immunity of the proposed system is very high, because in the proposed system the welding current is information source whereas in the known similar systems the welding current is the source of electromagnetic noise.
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