Electron-beam welding of large thickness parts in a narrow gap

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Abstract. The paper presents a method of large thickness parts welding in a narrow gap with filler wire. A modernized deflection magnet is proposed, which allows deflecting an electron beam directly in the zone of weld pool. The distribution of magnetic induction in a local magnetic field along the axis of electron beam guide was measured and the results obtained were compared to the calculated ones. A photographic recording of electron beam deviation in a local magnetic field created by the presented deflection magnet was carried out. The angle of electron beam deviation about electron beam guide axis is estimated.

1. Introduction

When creating modern products, the use of different welding technologies is now widespread. For example, electron-beam welding (EBW) is one of the most essential in obtaining of one-piece joints made of stainless steels, titanium alloys, non-ferrous and refractory metals or their alloys. Nowadays electron-beam welding is widely used in different power engineering industries, aircraft manufacturing, shipbuilding and in cryogenic equipment production. Such a various application of this process is associated with a number of its advantages. The production of welded structures using electron-beam welding technologies allows obtaining welded joints with mechanical properties almost at the level of parent metal properties. However, welding of large thicknesses (over 100 mm) parts always presents a number of difficulties, one of which is increased probability of defects formation and complexity of their correction. In addition, in this case, high demands are made on the power of the equipment used [1, 2].

The problem of obtaining high-quality welded joints during butt welding of large thickness materials is associated with the possible appearance of various defects, such as incomplete fusion due to electron beam deviation from the joint axis, defects formation in weld root, sagging of weld root, formation of undercuts, pores and cavities. The reason for these defects formation can be such factors as inaccurate beam guidance on the junction, instability of technological parameters during welding process, excessive heat input and some others [1-3].

The paper presents a method of large thickness parts electron-beam welding in a narrow gap using filler material (wire) to improve weld formation and reduce the probability of most these defects formation. Such approach allows combining the positive qualities of layer-by-layer welding and special features of electron-beam welding. Using this method, it is possible to carry out layer-by-layer control of welding process, create an optimal source of heating, and vacuum protection allows realizing high-quality welding of chemically active metals.
2. Description of proposed method

The proposed electron-beam welding method was tested on the ELA-15I plant. To realize this method, the deflection magnet used for electron beam deflection was modernized. For its making it was proposed to use a material with a higher magnetic permeability (09G2S steel (C~0.09%, Mn~2% Si~1%, Fe balanced) in the annealed state) compared to that used previously (EP 517 steel (C~0.16%, Mn~0.5%, Cr~12%, Si~0.5%, Ni~2%, Mo~1.6%, W~1%, Nb~0.3%, Fe balanced), because it was necessary to obtain larger values of magnetic induction (more than 10 mT) for realization the method of welding in a narrow gap. Such values were not possible to obtain with a deflection magnet made of EP 517 steel and used earlier.

Typical deflection magnets do not allow electron beam reaching directly the material treatment zone during the process of welding materials of large thicknesses in a narrow gap. This is due to the fact that electron beam does not enter the weld pool zone, but is scattered on the side walls of the parts being welded, and when they are heated, a significant part of its power is lost. This leads to a change in the beam parameters and disruption of the entire process as a whole.

Therefore, to ensure the stability of joints formation during electron-beam welding of large thicknesses parts in a narrow gap and to eliminate defects formation in the weld and fusion zone, the deflection magnet was developed, which allows deflecting electron beam in close proximity to weld pool for obtaining a heat source of complex shape (figure 1).

![Figure 1](image_url)

**Figure 1.** Scheme of electron-beam welding in a narrow gap: 1 – electron beam; 2 – deflection magnet; 3 – parts to be welded; 4 – electron beam extreme positions; 5 – filler material; 6 – scheme of melting isotherm; 7 – weld.
Design and operating parameters of the deflection magnet were selected using mathematical modeling of the process of electron beam deflection in a local magnetic field [1]. The Finite Integration Technique (FIT) [2] developed by Weiland in 1977 was used for the calculation. This numerical method provides a universal spatial discretization scheme applicable to various electromagnetic problems according to the equations

\[
\int \mathbf{H} \cdot d\mathbf{s} = \int \left( \frac{\delta \mathbf{D}}{\delta t} + \mathbf{J} \right) \times d\mathbf{A},
\]

(1)

\[
\int \mathbf{B} \cdot d\mathbf{A} = 0,
\]

(2)

where \( \mathbf{H} \) is magnetic field strength, A/m; \( s \) is closed contour (\( d\mathbf{s} \) is contour element, m); \( \mathbf{D} \) is electric induction, C/m²; \( t \) is time, s; \( A \) is the surface stretched over the contour \( s \) (\( d\mathbf{A} \) is vector of area element, directed outward from the considered volume); \( \mathbf{B} \) is magnetic field induction, T.

Tracking electron's movement is based on the discretization of electric and magnetic forces by means of the following equations:

\[
m \frac{d\mathbf{v}}{dt} = q\left( \mathbf{E} + \mathbf{v} \times \mathbf{B} \right),
\]

(3)

\[
m^{n+1}\mathbf{v}^{n+1} = m^n\mathbf{v}^n + \Delta t \left( \mathbf{E}^{n+1/2} + \mathbf{v}^{n+1/2} \times \mathbf{B}^{n+3/2} \right),
\]

(4)

where \( m \) is particle mass, kg; \( q \) is its charge, C; \( \mathbf{v} \) is speed vector, m/s; \( \mathbf{E} \) is electric field vector, V/m; \( \Delta t \) is discrete time step, s; \( n \) is index of time step, at which the parameter is determined (speed, electric intensity and induction).

In the calculation, vacuum was defined as the medium for electron motion. In order to determine the magnetic induction in the gap of deflection magnet made of 09G2S steel, a magnetization curve was set, from which the magnetic permeability was determined depending on the magnetic field strength. The electron beam in the calculation has a fixed current value, which is equal to 100 mA. The main input data for the deflection magnet parameters selection were current and number of turns in inductors, as well as magnetic properties of the materials, specified in the form of magnetization curves.

Scheme of the proposed method of large thickness parts welding in a narrow gap with filler wire is shown in Figure 1. A deflection magnet is placed in a narrow gap between the parts to be welded of non-magnetic material 3. An alternating magnetic field, which deflects electron beam to position 4, is created in the magnetic gap between the tips. To fill the technological gap between the parts to be welded 3, a filler wire 5 is fed, which is melted by electron beam, when its axis coincides with the axis of deflection magnet. Electron beam deviation in the zone of weld pool is carried out to ensure the stability of joints formation during electron-beam welding of large thicknesses parts in a narrow gap and to eliminate defects formation in the weld and fusion zone. Thus, to obtain a more even temperature isotherm 6, a heat source is created that acts on the walls of weld joint and surface of the weld.

Other authors previously obtained results related to electron beam deflection in an electrostatic field in in close proximity to treatment zone. This made it possible to expand the technological capabilities of EBW [4-7], but using of an electrostatic mirror requires to select the shape of reflecting surface individually for different shapes of joints. In addition, the application of this method is difficult during welding in a narrow gap and does not allow use of large beam currents.

To determine the magnitude of resulting magnetic field and the nature of its distribution, magnetic induction was determined along electron beam guide axis [8-12]. Its measurement was carried out according to the scheme shown in figure 2, using the Hall sensor (model AD2251). During the measurement of magnetic induction, the current in the inductance coils was recorded (its values are
presented in the explanation to figure 3). The obtained current values were used for numerical simulation of electrons motion in a magnetic field.

To fix the deflection trajectory of electron beam by deflection magnet, there was used method of recording the glow of residual gases in the visible range of spectrum [13].

3. Results of studies
The distribution of magnetic induction in the gap between magnetic tips was obtained at various current values. The distribution of magnetic induction along electron beam guide axis in deflection magnet is shown in figure 3. Figure 3 shows the experimental data and calculated values obtained using numerical simulation. It can be seen from the graphs that the curves have a similar form and, with increasing current strength, the experimental data have values higher than the calculated ones.

During the tests, photographs of electron beam deviation in a local magnetic field were obtained (figure 4). Using the characteristic trace of electron beam on the target, the deviation angle from the axis of electron-beam gun was further determined; it was approximately 13°. According to the calculated data, the deviation angle was 11°.

4. Conclusion
The results of deflection magnet testing have good repeatability. The graphs of magnetic induction distribution in the gap have a similar form. The data obtained experimentally are slightly larger than the calculated ones. This fact can be explained by the presence of unaccounted parameters in the calculation, such as external magnetic field and structural features of the material.

The experimentally obtained value of inclination angle for electron beam corresponds to the calculated value. Since the magnetic deflection system is designed to operate in a narrow gap of about 6 mm, the obtained declination values are sufficient for realization of the technological process according to the scheme shown in figure 1.

Figure 2. Scheme of magnetic induction measurement: 1 – beam axis; 2 – electron-beam guide; 3 – magnetic core; 4 – magnetic tip; 5 – inductor; 6 – Hall sensor.
Figure 3. Distribution of magnetic induction along electron beam guide axis in deflection magnet. Calculated values: 2 – current is 0.123 A; 3 – current is 0.234 A; 5 – current is 0.342 A; 7 – current is 0.444 A. Experimental data: 1 – current is 0.123 A; 4 – current is 0.234 A; 6 – current is 0.342 A; 8 – current is 0.44 A.

Figure 4. Photography of electron beam deviation in a local magnetic field: 1 – magnetic tips; 2 – electron beam, deviated in a magnetic field.
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