Mathematical modeling of electron beam deflection for welding in narrow gap

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Abstract. In this paper the technology of an electron beam deflection directly in the weld joint during the welding process is considered. The technique of mathematical simulation of the electron beam deflection in the gap between the magnetic circuit tips has been worked out. Mathematical modeling of the equipment operation was carried out using the materials of EP517 steel and ARMCO iron. According to the mathematical model, the magnetic induction distribution in the gap is constructed. The model passed a successful verification by experimental measuring the magnetic induction in the gap.

1. Introduction
Electron beam welding (EBW) is known as a flexible tool for materials processing. The possibility of modulation of electron beam current and simultaneously its deflection in magnetic or electric field (in fact, such deflection is non-inertial), allows creating complex forms of heating source and changing its location in space. However, the need of the heating source shape precise control during the process of EBW requires the development of various electron beam control technologies. The main problem in single-pass welding of large thicknesses is the provision of specified EBW parameters to avoid the formation of defects [1-3]. In case of dissimilar materials welding the formation of defects may be occurred due to the impact of thermo-electromotive force (thermal EMF). Thermal EMF creates intensive currents and magnetic fields, which deflect electron beam from the joint during the welding process. The beam deflection phenomenon is occurred at a penetration depth of 30 mm and more [4].

This problem is known to be solved using the EBW in a narrow gap with filler wire. However, in this case defects in the form of non-fusion can occur, and the probability of their appearance increases sharply with the increase in the welded products thickness. The deflection of the electron beam in the joint can simplify the welding of large thicknesses of dissimilar materials having a large influence of thermal EMF.

In this paper the technology of an electron beam deflection directly in the joint during the process of welding into a narrow gap is considered. This technology realizes bending of beam axis outside an electron beam gun, since only inclination or transfer of beam axis is possible inside the gun.

Welding in a narrow gap can be used instead of the welding with a barrier material for joining of restrictedly welded pairs of materials, as well as for dissimilar materials welding with a filler wire [1]. Application of a filler material will allow to achieve the necessary structure of welded joint with simultaneous increasing of the weld operating characteristics.
2. Research methods and equipment

To provide the stability of the formation of weld joints and to avoid the defects appearance in the seam root and the fusion zone, a special device was developed. This device allows to deflect the electron beam nearby the weld pool to produce a heat source of complex shape. When creating the device, the shortcomings of similar technologies for solving several problems were taken into account [5]. The device is a magnetic core with inductor and magnetic tips (figure 1), which form a gap and can move, creating by that a various active distance $H$. In the hole in the magnetic core the electron beam pass is mounted providing a shielding of the beam from the magnetic fields influence. Magnetic field is created by means of inductor and concentrated in the gap. Thus, electron beam passing through the device is deflected only in its lower part, which is in the area of the junction between welded parts.

![Figure 1. Magnetic conductor construction: $H$ – active distance; $B_x$ – magnetic induction.]

Welding process with the application of this device is carried out as follows. Magnetic tips, having a thickness less than the welding gap, are placed in the weld joint. An alternating magnetic field, concentrated in the gap between the magnetic tips, produces a deflection of the electron beam on the walls of the parts and the filler wire (figure 2) creating a weld pool. In the welding process, the whole device moves with the welding speed $V$ along the weld joint.

![Figure 2. Scheme of welding process: 1 – magnetic tips; 2 – welded item (the second one is not shown).]
With the use of numerical simulation of an electron beam motion in a magnetic field [6, 7], the design of the magnetic circuit was optimized, which made it possible to reduce dimensions of the magnetic tips with an angle of the beam deflection in the gap of at least 45°. In the next step, the device for welding in a narrow gap was manufactured and tested. EP517 steel (C ≈ 0.15%, Cr ≈ 12%, Ni ≈ 2%, Mo ≈ 1.5%, W ≈ 0.8%, V ≈ 0.2%, N ≈ 0.05%, Nb ≈ 0.25%) was used for making of magnetic core and magnetic tips.

The inductance coils can be fed with any form of signal through an operational amplifier, which provides sufficient output power to create a magnetic field. With the help of alternating magnetic field, an alternating deflection of electron beam on the walls of the welded parts was produced, and electron beam was split into several heating sources. The device was tested with a static magnetic field created by a direct current (DC) and in the absence of welded joint. In this operation mode the distribution of the $B_x$ magnetic induction component along the Z axis was obtained. It was assumed here that the magnetic permeability parameters of air and paramagnetic material are equal.

Device MX-10, which is based on the Hall sensor, was used for measuring magnetic induction. The measurements were carried out according to the scheme shown in figure 1. Hall sensor was fixed to the movable bracket. Figure 1 shows the lowest position of the sensor. Zero point along the Z axis was measured from the bottom of the tips. Sensor was moved by means of helical transmission along the electron beam pass axis with a constant step of 1 mm, and at each point the magnetic induction $B_x$ was measured.

3. Results of research and discussion

Magnetic field parameters values required for electron beam deflection were determined by mathematical simulation of the motion of electrons in a local magnetic field in a narrow gap between welded parts. It was found that for deflection of electron beam by an angle of about 45° (with the following parameters: accelerating voltage in the electron beam gun is of 60 000 volts, a gap between magnetic tips is 7 mm) it suffices to induce a magnetic field in the gap of the order of 10-20 mT.

In the constructed mathematical model, in order to optimize and determine operating range for the tips, the following parameters were changed: current in the inductance coils and the active distance $H$ (figure 1). There was established from the results of mathematical modeling that magnitude of $H$ in the range from 30 to 100 mm does not affect the magnitude of inductance of magnetic field in the gap.

Several applications of the device with various materials that simulated welding parts were considered during the process of mathematical modeling. The following combinations of materials were considered: these are two paramagnetic parts and one paramagnetic and one ferromagnetic part. The main modeling results are shown in figures 3 and 4.

In the course of these calculations, “$B_x - Z$ coordinate” relations for EP517 steel (figure 3, graphs 5 and 6) and ARMCO iron (C < 0.035%; S < 0.03%; P < 0.02%; Mn < 0.3%; Cu < 0.3%; Si < 0.3%) (figure 3, graphs 2 and 3) were obtained. It can be seen from the graphs that it was more efficient to use ARMCO iron for this device due to its high magnetic permeability. Data obtained from the measurement of magnetic field using the Hall sensor (they are shown in figure 3, graph 1) correlate well with results obtained by modeling with similar parameters. This indicates the acceptable verification of the model, that allows further to improve the design without manufacture of intermediate equipment options.

Furthermore, the application of the developed device for welding materials with various magnetic properties was considered, namely the welding of paramagnetic materials and the welding of a paramagnetic material to a ferromagnetic material. Using of at least one part of ferromagnetic material is led to a sharp decrease of the magnetic induction in the gap between the tips (figure 3, graph 4). Ferromagnetic materials screen magnetic flux in whole or in part, which in turn reduces beam deflection efficiency (figure 4 (a)). The deflection method is the most effective when using parts made of paramagnetic materials. In this case, a sufficient magnetic field is created in the gap between the tips for deflection of the electron beam onto the walls of welded parts (figure 4 (b)).
Figure 3. “Magnetic induction $B_z$ – $Z$ coordinate” relations: 1 – experimental data, 0.1 A coils current; 2 – simulation data, 0.1 A coils current, ARMCO iron; 3 – simulation data, 0.15 A coils current, ARMCO iron; 4 – simulation data, 0.2 A coils current, ferromagnetic and paramagnetic parts; 5 – simulation data, 0.1 A coils current, EP517 steel; 6 – simulation data, 0.15 A coils current, EP517 steel.

Figure 4. Electron beam deflection between welded parts: paramagnetic part ($P$) and ferromagnetic ($F$) part (a); both parts are paramagnetic ($P$) (b).
4. Conclusions
Using of electron beam deflection in the joint during welding into a narrow gap opens up different possibilities of a complex shaped heat source formation on the walls of the welded parts. A device for this deflection method has been developed and tested.

Method of mathematical simulation of electron beam deflection in the gap between the tips of magnetic conductor has been worked out. The model passed a successful verification by measuring magnetic induction in the gap.

The results obtained make it possible to carry out further experiments on photo diagnostics of electron beam and welding with using different filler materials.

Acknowledgments
The research was carried out in the National Research University "Moscow Power Engineering Institute" with the financial support of the Ministry of Education and Science of the Russian Federation in accordance with base part of state assignment (project No. 11.8088.2017/8.9).

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