Experiments on the effect of thermoelectric current magnetic field on welding of 60-mm thick dissimilar steels

A P Sliva\textsuperscript{1}, A L Goncharov\textsuperscript{1}, E V Terentyev\textsuperscript{1}, I A Kharitonov\textsuperscript{1}, V K Dragunov\textsuperscript{1}

National Research University Moscow Power Engineering Institute, ul. Krasnokazarmennaya, 14, Moscow, 111250
E-mail: SlivaAP@mpei.ru

Abstract. The work describes a method for measuring the magnetic field induced by thermoelectric currents in control points above welded specimens and presents the measurement results. The dissimilar 60-mm thick steel samples are welded by electron-beam welding (EBW). The grades of the pairs of steels are 09Mn2Si + 12Cr18Ni10Ti, 09Mn2Si + 20Cr13 and 20Cr13 + 12Cr18Ni10Ti. The study shows that the electron beam in the weld root deflects towards the material with larger positive potential of integral thermal EMF. The deflection is uneven along the specimens, which necessitates taking into account the geometry of welding joints when elaborating the mathematical models of the process. Maximum deflection for the studied pairs of materials correspondingly amounts to 0.6, 2.8 and 3.8 mm, which is critical for producing a high-quality seam. In addition, the alteration of magnetic induction in control points during EBW was obtained.

1. Introduction
The electron-beam welding of dissimilar steels leads to the generation of thermoelectric currents inducing magnetic field in the processing zone due to different thermal EMF of the materials. The interaction of the beam electrons with the magnetic field leads to the deflection of the beam electrons from a set trajectory, occurrence of weld-seam defects (such as lack of penetration [1–7]) and alters the material penetration degree. This changes the chemical composition, structure and properties of the seam metal. The deflection from the weld joint can reach up to several millimeters and increases with both the thickness of welded parts and difference in absolute coefficient of thermal EMF of the materials. An appreciable impact is made by relative magnetic permeability and electric resistance of the materials [2, 3, 7]. According to the experimental background, a deflection of the weld root from the joint of 0.3–0.5 mm can lead to lack of penetration, while that of 0.1–0.3 mm can change the fraction of each of the welded metals in common molten pool by dozens of percent.

To compensate the deflection of the electron beam, several methods can be considered: preliminary inclination and displacement of the electron beam [2, 8], passing compensating electric current through the welding joint [9], induction of local magnetic fields [10].

The choice of electron beam correction parameters is often based on numerical models connecting the regimes and geometry of welded parts with a deflection of the electron beam. The development of precise numerical models is impeded, because the EBW of dissimilar materials causes interdependent factors to occur. Thermal field from the penetration channel conditions the generation of thermoelectric currents inducing the magnetic field also depending on the magnetic properties of the materials. The magnetic field affects the electron beam by deflecting it, changing the penetration
channel, altering the thermal field, thermoelectric current spreading and magnetic field distribution [1, 2].

Current study is aimed at developing the methods of experimental verification of a numerical model of electron beam deflection during EBW of dissimilar materials and studying the effects of the magnetic field induced by thermoelectric currents on the formation of welding seams of 60-mm thick dissimilar steels.

2. Experimental methods

For increased efficacy of the verification of numerical models, the most promising and feasible technique is the verification of the electron beam trajectory by both macrosections of the welding seams and magnetic field induction. The control points for magnetic field measurement should not introduce appreciable disturbance into the magnetic field induced by EBW. Therefore, they should reside away from the welded specimens. Fig. 1 presents the suggested scheme of magnetic field measurement above the welded specimens.

Figure 1. Scheme of magnetic field induction measurement during EBW of dissimilar materials: 1) and 2) welded specimens; 3) and 4) magnetic field induction sensors above the specimens; 5) magnetic field induction sensor in the weld root; 6) electron beam axis; 7) electron beam in the penetration channel; 8) gas-vapor channel; 9) molten pool; 10) tack welds.

Three pairs of structural steel specimens were studied: 12Cr18Ni10Ti + 20Cr13, 12Cr18Ni10Ti + 09Mn2Si and 09Mn2Si + 20Cr13. The dimensions were 60×50×200 mm, the former being the thickness. The specimens were welded on an AELTK-344-12 automatic EBW setup with an accelerating voltage of 60 kW. In the first place, the following EBW parameters were defined for burn-through welding: electron beam current of 250 mA, welding rate 15 m/h.

To measure the magnetic field induction during EBW, an experimental setup was elaborated based on the ACTest Pro automatic measuring complex (Laboratory of Measuring Systems (AC), Russia). The package includes a working station with sockets for electrically isolated LTR-modules, a ADC LTR 11 universal module for multi-channel data collection and a signal synchronization unit with DSCA40-03 DataForth signal normalizers with electrical isolation. The complex allows recording measured values, processing results and compiling measurement reports.

To measure the magnetic field parameters, the following sensors can be used: Hall sensors, ferroprobes, magnetoresistive sensors and magnetic-induction sensors. The anticipated values of magnetic field induction in the control points during EBW of dissimilar materials stay within a range of 0.1–10 mT. The magnetic field is almost unchanged in time. Therefore, the testbed was equipped with Hall sensors, because they cover the necessary measurement range, can be used for constant magnetic fields and have wide operating temperature range. The testbed was integrated with the
Automatic measurement complex using an AD22151 magnetic field sensor (Analog Devices). The sensor outputs a voltage proportional to the magnetic field applied in perpendicular to the top surface of its body. The sensors have high magnetic sensitivity and thermal stability of the main parameters in a wide temperature range. It can be adjusted for the necessary measurement range.

Sensors 1 and 2 (Fig. 1) should be positioned as closely as possible to the weld joint, though stay out of the action of the electron beam and liquid metal of the molten pool during EBW. Thus, the distance from the joint was 15–20 mm at the surface of the welded specimens. According to the preliminary estimates, the magnetic field induction in this region should not exceed 1.5 mT [4, 7]. Sensor 3 is located in the weld root and in the case of burn-through can be damaged by the electron beam, and the magnetic field induction in this region can be appreciably higher. The sensors were mounted on a breadboard and sealed by an epoxy-resin compound. The actual values of amplification coefficient and magnetic field induction measurement limit for sensors 1 and 2 were $K_a = 251$ and $B_{\text{max}} = \pm 2.49$ mT, correspondingly; for sensor 3 they were $K_a = 46.46$ and $B_{\text{max}} = \pm 13.45$ mT. The sensors were calibrated using a verified MX-10 magnetometer.

The weld specimens were mounted in a vacuum chamber as per the elaborated scheme (Fig. 1). The sensors were mounted directly on the welded specimens using special paramagnetic clamps (Fig. 2). The arrangement of the sensors was recorded for each of the experiments. The electron beam deflection was assessed by burn-throughs and macroscale polished sections of the specimens.

**Figure 2.** Arrangement of weld specimens and Hall sensors:

a) general view; b) weld root sensor; c) specimen surface sensors; d) specimens after EBW

1) and 2) welded specimens; 3) and 4) clamps for Hall sensors; 5) and 6) Hall sensors on the specimen surface; 7) weld root Hall sensor; 8) weld joint; 9) electron-beam gun.
3. Investigation Results

Measured magnetic field induction for 12Cr18Ni10Ti + 20Cr13 pair is presented in Fig. 3. After enabling the electron beam, the sensor above the 12Cr18Ni10Ti specimen failed, so its readings are not presented. The maximum magnetic field induction reached 0.89 mT in the weld root and 0.77 mT above 20Cr13 steel. The electron beam deflects in the weld root to 20Cr13 steel and demonstrates unsteady behavior: increases from 1.8 mm in the beginning of the seam up to 3.8 in the middle and decreases down to 1.6 mm in the end (Fig. 3). In the experiment, the electron beam crossed the location of the weld root sensor and damaged it, so in the rest of the experiments we decided to work without them.

![Figure 3. Magnetic field induction from thermoelectric currents during EBW and electron beam deflection in the weld root of 12Cr18Ni10Ti and 20Cr13 steels](image)

During EBW of 12Cr18Ni10Ti and 09Mn2Si steels, the distance from the sensor sealing edge to the weld joint was increased up to 20 mm. The noise in Hall sensors caused by electron beam lead to inadequate values of the magnetic field induction, so this data is not presented. The electron beam in the weld root deflects towards 09Mn2Si (Fig. 4) and again has nonuniform character: in the beginning of the seam it is 0.64 mm, then reduces and almost disappears in the end.

![Figure 4. Electron beam deflection in the weld root of 12Cr18Ni10Ti and 09Mn2Si steels](image)

The EBW of specimens from 20Cr13 and 09Mn2Si steels, the sensors were arranged at 20 mm from the weld joint and shielded by several layers of aluminium foil. Measured magnetic field induction values are presented in Fig. 5. The maximum magnetic field induction above 20Cr13 steel amounted to 0.54 mT and to 0.47 mT above 09Mn2Si steel. Interestingly, the maximums are observed simultaneously. The deflection of the electron beam in the weld root (Fig. 5) is nonuniform: increases from 2.1 mm in the weld beginning up to maximum of 2.8 in the middle and decreases in the end.
4. Discussion
For all welded specimens, the electron beam deflection along the joint length is nonuniform. This is caused by the changed resistance between welded specimens and altered conditions of thermoelectric current spreading in the course of welding seam formation: going farther from and closer to the boundary of the welded specimens. Besides, during EBW the temperature distribution changes: the high-temperature region increases, which changes the thermal EMF source power, hence, increases the thermoelectric currents, magnetic field induction and electron beam deflection from the weld joint. Taking into account the above, the deflection character during EBW of closed and open weld seams should be appreciably different. Thus, the numerical models that do not account for the geometry of welded parts, the change of thermal regime and contact resistance between the welded specimens during EBW yield incorrect results.

Figure 5. Magnetic field induction from thermoelectric currents during EBW and electron beam deflection in the weld root of 09Mn2Si and 20Cr13 steels

Absolute thermal EMF (E800) of the steels under study are as follows: minus 2.2 mV for 12Cr18Ni10Ti, plus 7.6 mV for 20Cr13 and minus 0.4 mV for 09Mn2Si. Thus, the deflection occurs towards the material with more positive thermal EMF potential, which agrees with [2, 3].

Fig. 6 presents the lateral macrosections and trajectories of the electron beam. The trajectories of the beam were determined by the coordinates of the weld seam middle measured on macrosections. The difference in thermal EMF (E800) of 20Cr13 + 12Cr18Ni10Ti and 20Cr13 + 09Mn2Si pairs equals 9.8 and 8.0 mV, correspondingly, which during the welding of 60-mm thick parts leads to lack of penetration in the weld root with a magnitude of more than a half of the joint thickness (Table 1).

Even with small difference in the thermal EMF (E800) for 12Cr18Ni10Ti + 09Mn2Si (only 1.8 mV), the lack of penetration in the weld root amounts to about 10 mm. Thus, welding of thick dissimilar materials should take into account the deflections of the electron beam from the joint even at negligible difference in thermal EMF.

Table 1. Deflection of the electron beam during EBW of dissimilar steels

| Position of the section from the seam beginning | Deflection of beam from joint / lack of penetration in weld root [mm] |
|-----------------------------------------------|---------------------------------------------------------------------|
| 25 mm On surface                              | 20Cr13 + 12Cr18Ni10Ti - 0.51 / -                                   |
| (Fig. 6a) In weld root                        | 12Cr18Ni10Ti + 09Mn2Si - 0.12 / -                                  |
| 95 mm On surface                              | 20Cr13 + 09Mn2Si - 1.98 / -                                        |
| (Fig. 6b) In weld root                        | 20Cr13 + 12Cr18Ni10Ti + 09Mn2Si - 1.33 / -                         |
|                                               | 20Cr13 + 09Mn2Si - 2.4 / 42                                       |

09Mn2Si

20Cr13

Sensor above

20Cr13

Sensor above

09Mn2Si

B, mT

0

0,1

0,2

0,3

0,4

0,5

0,6

0

20

40

60

80

100

120

140

160

180

200

l, mm

20Cr13

09Mn2

joint

root

Table 1. Deflection of the electron beam during EBW of dissimilar steels

| Position of the section from the seam beginning | Deflection of beam from joint / lack of penetration in weld root [mm] |
|-----------------------------------------------|---------------------------------------------------------------------|
| 25 mm On surface                              | 20Cr13 + 12Cr18Ni10Ti - 0.51 / -                                   |
| (Fig. 6a) In weld root                        | 12Cr18Ni10Ti + 09Mn2Si - 0.12 / -                                  |
| 95 mm On surface                              | 20Cr13 + 09Mn2Si - 1.98 / -                                        |
| (Fig. 6b) In weld root                        | 20Cr13 + 12Cr18Ni10Ti + 09Mn2Si - 1.33 / -                         |
|                                               | 20Cr13 + 09Mn2Si - 2.4 / 42                                       |
A substantial difference of the electron beam trajectory during EBW for 20Cr13 + 12Cr18Ni10Ti and 20Cr13 + 09Mn2Si should be noted. Despite the lower difference in thermal EMF (E800) and deflection in the weld root of 20Cr13 + 09Mn2Si pair, the dimensions of lack of penetration in the weld root are significantly larger: 42 and 39 mm versus 27 and 35 mm. This is caused by appreciable deflection of the electron beam during welding of 20Cr13 + 09Mn2Si pair above the welded parts. It is also uneven, similarly to the deflection in the weld root, while the character of changes is contrary: minus 1.98 mm at 25 mm from the seam beginning and plus 1.33 mm at 95 mm (Table 1).

It should be regarded that above the pair of ferromagnetic 20Cr13 and 09Mn2Si, the field is much larger than above the pair of ferromagnetic 20Х13 and paramagnetic 12Х18Н10Т. This estimation cannot be unambiguous using the magnetic field strength, because of different distance of magnetic induction sensor mounting from the joint in the experiments.

5. Conclusions
During EBW of dissimilar materials, the deflection of the electron beam from the joint plane alters. This is due to the geometry of the weld joints, change in the thermal field, field of electric potentials and thermoelectric current spreading, change in the electric contact between welded edges under welding stresses and strains. For instance, during EBW of 60-mm thick 20Cr13 + 12Cr18Ni10Ti pair, the deflections changed from 1.8 mm in the weld seam beginning up to maximum value of 3.8 mm in the middle. This should be taken into account when elaborating numerical models of the process and methods for preventing the beam deflection from the weld joint.

During EBW of 60-mm thick dissimilar steels, the deflection of the electron beam from the weld joint was found to cause lack of penetration in the weld root. Even with the difference in thermal EMF (E800) of 1.8 mT for 12X18H10T + 09Mn2Si pair, the detected lack of penetrations amounted up to 10 mm.

The electron beam deflection from the joint plane in the weld root of considered sections of ferromagnetic + paramagnetic pair (20Cr13 + 12Cr18Ni10Ti) with the difference in thermal EMF (E800) of 9.8 mV amounts to 2.2 and 3.4 mm. For the pair of ferromagnetic materials...
(20Cr13 + 09Mn2Si), with the difference in thermal EMF (E800) of 8.0 mV it amounted to 2.4 and 2.8 mm. Despite these facts, the lack of penetration in the joint for ferromagnetic materials is bigger: 42 mm versus 27, and 39 mm versus 35. This means strong deflection of electron beam over the pair of ferromagnetic parts, which is confirmed by the measurements of deflection on the weld top.

The suggested method for measuring magnetic field in control points over welded parts during EBW allows obtaining data on distribution of magnetic field induction for verification of numerical models of the process. A special attention should be paid to the protection from noise in sensitive components.

Acknowledgments
The research was carried out at National Research University Moscow Power Engineering Institute with the financial support of the Russian Science Foundation (project No. 18-19-00652).

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, Myakishhev Y V, Goncharov A L and Sliva A P 2006 Welding Int. 20(10) 811–5
[8] 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)
[9] Laptenok V D, Druzhinina A A, Murygin A V and SereginYu N 2016 IOP Conf. Ser.: Mater. Sci. Eng. 122 012021
[10] Murphy J T 2009 Method of electron-beam welding and weldments, constructed by this method (Russian Federation: Patent No. 2346795)