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Automatic control of positioning along the joint during EBW in conditions of action of magnetic fields

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Abstract. Positioning along the joint during the electron beam welding is a difficult scientific and technical problem to achieve the high quality of welds. The final solution of this problem is not found. This is caused by weak interference protection of sensors of the joint position directly in the welding process. Frequently during the electron beam welding magnetic fields deflect the electron beam from the optical axis of the electron beam gun. The collimated X-ray sensor is used to monitor the beam deflection caused by the action of magnetic fields. Signal of X-ray sensor is processed by the method of synchronous detection. Analysis of spectral characteristics of the X-ray sensor showed that the displacement of the joint from the optical axis of the gun affects on the output signal of sensor. The authors propose dual-circuit system for automatic positioning of the electron beam on the joint during the electron beam welding in conditions of action of magnetic interference. This system includes a contour of joint tracking and contour of compensation of magnetic fields. The proposed system is stable. Calculation of dynamic error of system showed that error of positioning does not exceed permissible deviation of the electron beam from the joint plane.

Introduction

Electron beam welding (EBW) is widely used in aerospace engineering, nuclear power, automotive, shipbuilding to create permanent connections, when other types of welding cannot provide the required weld quality.

Often the process of electron beam welding is accompanied by disturbances in the form of magnetic fields caused by the residual magnetization of equipment and parts to be welded, the work of various electromagnetic devices, and the thermoelectric currents flowing in the details during welding of dissimilar materials. As a rule, the effect of magnetic fields on the electron beam cannot be eliminated completely. These fields deflect the electron beam. This leads to formation lack of fusion. In addition, magnetic fields are nonstationary. They can change during the welding process. Therefore, the possibility of using of positioning systems with a preliminary record a trajectory is very limited.

The method of control and compensation of displacement of a scanning electron beam is designed to eliminate the effect of magnetic fields on electron beam during the welding process. The measuring device in the system is a collimated X-ray detector. The sensor is placed on the electron gun. The collimator slit of sensor is aimed at the optical axis of the gun. X-ray sensor signal is processed by the synchronous detection method, with frequency separation of first and second harmonics of frequency of scanning the electron beam across the joint [1].

Elimination the effect of magnetic fields on the electron beam deflection from the optical axis of electron beam gun is realized by introducing the compensating magnetic fields in the zone of action of magnetic interference. Special electromagnetic devices produce the compensating magnetic field directed towards the magnetic interference [1-2].

Analysis of the spectral characteristics of the X-ray sensor

The X-ray sensor includes X-ray detector and collimator. The collimator is made as slotted hood which limits the field of view of the sensor. The collimator is made of material which absorbs X-ray radiation. Slit of collimator must coincide with the optical axis of the gun and the direction of welding (Fig. 1). When the electron beam scans across the joint in the output of the X-ray sensor harmonic components appear. Harmonic components have frequencies that are multiples of the frequency of scanning ω.

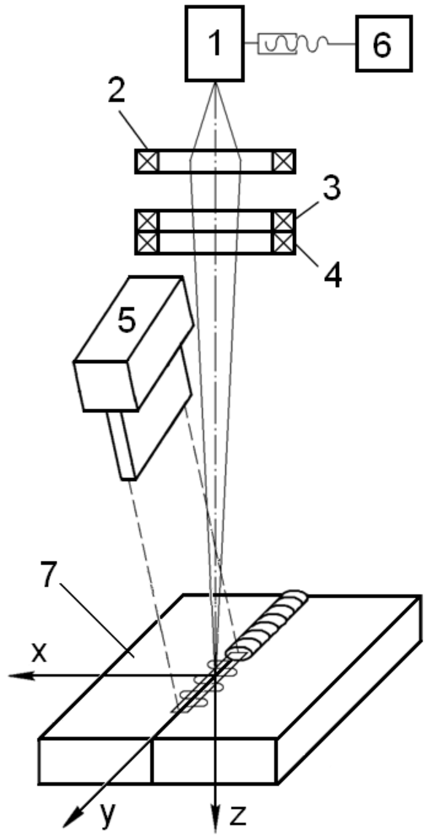


Figure 1. Scheme of control of the effect of magnetic interference on the deflection of the electron beam: 1 – electron beam gun; 2 – focusing system; 3, 4 – deflection system; 5 – collimated X-ray sensor; 6 – electric drive of the electron beam gun; 7 – welded product.

The output signal of the X-ray sensor can be presented as a Fourier series [3]. If ω=1, the output signal can be written as

$$I_d(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty}\left(a_n \cos nt + b_n \sin nt\right), \tag{1}$$

where coefficients of the series are given by the expressions:

$$a_0 = \frac{1}{\pi}\int_{-\pi}^{\pi} I_d(t)dt, \tag{2}$$

$$a_n = \frac{1}{\pi}\int_{-\pi}^{\pi} I_d(t)\cos ntdt, \tag{3}$$

$$b_n = \frac{1}{\pi}\int_{-\pi}^{\pi} I_d(t)\sin ntdt. \tag{4}$$

Here, the intensity of X-ray radiation from the surface of the work piece is determined by expression

$$I_d = kk_1 U_0^2 Z I_b \frac{1}{\sigma_x\sqrt{2\pi}}\int_{-\infty}^{\infty} f_d(x)\exp\left(-\frac{\left(x-\varepsilon_0-\varepsilon_m \sin\omega t\right)^2}{2\sigma_x^2}\right)dx, \tag{5}$$

where $f_d(x)$ – function of the view area of the collimator of X-ray sensor; k=1,5·10^{-9} B^{-1} – proportionality coefficient; k_1 – coefficient considering the orientation of the sensor in the space; I_b – electron beam current; Z – atomic number of the material of welded product;U_0 – accelerating voltage; σ_x – root mean square deflections of electrons from the axis of the beam along the x axis; ε_0 – deflection of the beam from the optical axis of the electron gun; ε_m – amplitude of the beam scanning across the joint.

Function of the view area of the collimator of X-ray sensor has the form

$$f_d(x) = \begin{cases} 0, & x < -\frac{l_2}{l_1}h - \frac{h}{2}, \\ \frac{l_1}{l_2 h}x + \left(1 + \frac{l_1}{2l_2}\right), & -\frac{h}{2} - \frac{l_2}{l_1}h \le x < -\frac{h}{2}, \\ 1, & -\frac{h}{2} \le x < -\frac{\Delta}{2}, \\ 0, & -\frac{\Delta}{2} \le x \le \frac{\Delta}{2}, \\ 1, & \frac{\Delta}{2} < x \le \frac{h}{2}, \\ -\frac{l_1}{l_2 h}x + \left(1 + \frac{l_1}{2l_2}\right), & \frac{h}{2} < x \le \frac{h}{2} + \frac{l_2}{l_1}h, \\ 0, & x > \frac{h}{2} + \frac{l_2}{l_1}h, \end{cases} \tag{6}$$

where h – width of the slit of the collimator of X-ray sensor; l_1 – length of the collimation channel; l_2 – distance from the collimator to the workpiece surface; Δ – width of gap at the joint.

The first harmonic of the scanning frequency allows determining the deflection of the electron beam from the optical axis of the electron gun caused by the action of magnetic interference.

Fig. 2 shows how the amplitude of the first harmonic as a function of displacement of the electron beam varies with different width of gap at the joint. The calculations were performed by the formulas (3) and (4) taking into account (5) and (6) for l_1 = 10 mm, l_2 = 15 mm, h = 0.3 mm.

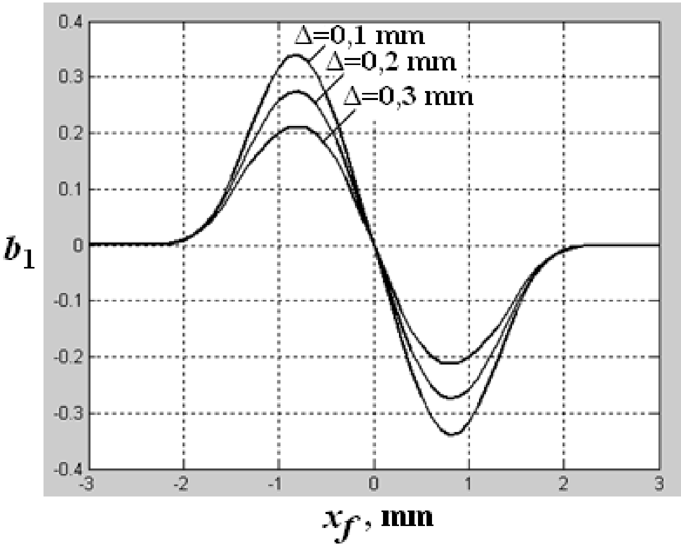


Figure 2. Dependence $b_1(\varepsilon_0)$ at ε_m=1.

Spectral characteristics indicate that an increase of width of gap at the joint leads to a decrease of the amplitude of the first harmonic. EBW is used for the production of important parts that have passed thorough preliminary processing before welding. Therefore, width of gap is constant during the welding process and does not affect the readings of the X-ray sensor.

If joint of welded details is displaced relative to the optical axis of the electron beam gun (Fig. 3), the beam deflection from the joint consists of joint displacement from the optical axis of the gun x_j and the beam deflection from the optical axis of the gun x_f:

$$\varepsilon_j = x_j + x_f.$$

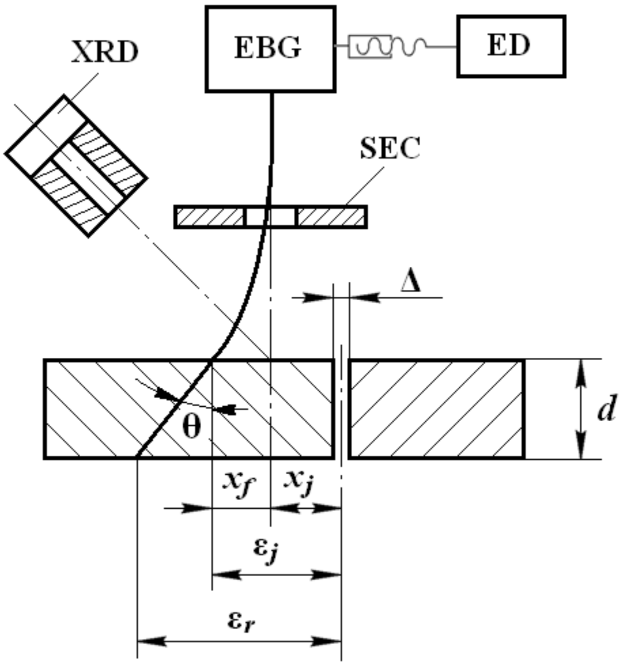


Figure 3. To analysis of the spectral characteristics of the X-ray sensor:
EBG – electron beam gun; ED – electric drive for gun; XRD – X-ray detector;
SEC – collector of secondary electrons; Δ – width of gap at the joint.

Dependencies of amplitude of the first harmonic from the beam deflection from the axis of the gun for different values of the joint displacement are shown in Fig.4.

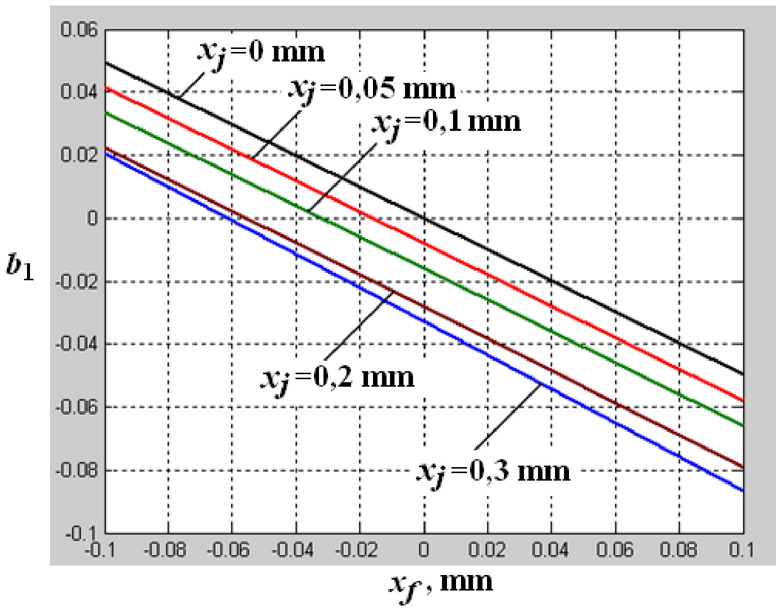


Figure 4. Dependence $b_1(\varepsilon_0)$ at ε_m=1, Δ=0.2 mm.

Analysis of presented characteristics shows that the displacement of joint from the axis of collimation hole of sensor leads to displacement of the spectral characteristics of the sensor respect to the origin. This displacement should be taken into account in the automatic system of tracking along the joint in conditions of action of magnetic fields.

Automatic system of tracking along the joint during EBW in conditions of action of magnetic fields

Structural diagram of dual-circuit system of tracking along the joint during EBW in conditions of action of magnetic fields is presented in Fig. 5. Due to the effect of displacement of joint on the signal of the collimated X-ray sensor of beam position relative to the optical axis of the gun the dual-circuit system becomes an interconnected.

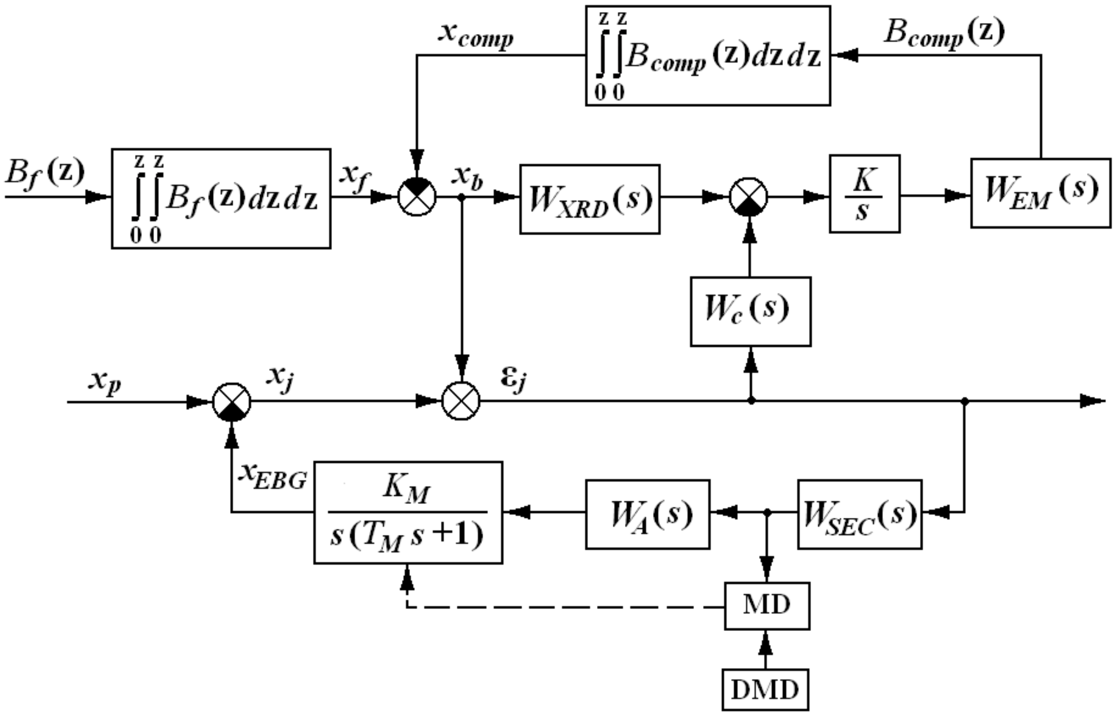


Figure 5. Structural diagram of dual-circuit system of tracking along the joint.

The following notation is used in the diagram: x_p – coordinate of weldment; x_{EBG} – coordinate of gun; $B_f(z)$ – magnetic induction of the field of interference; $B_{comp}(z)$ – magnetic induction of compensating field; x_f – displacement of electron beam from the action of the field of interference; x_{comp} – displacement of electron beam from the action of compensating field; x_b – displacement of the electron beam from the optical axis of the gun; x_j – displacement of the joint from the optical axis of the gun; $\varepsilon_j=x_j+ x_b$ – electron beam deflection from the joint; $W_{SEC}(s)$ – transfer function of measurement device the position joint; $W_{XRD}(s)$ – transfer function of the measuring device of the beam deflection; $W_c(s)=K_c\cdot W_{XRD}(s)$ – transfer function of communication, where $K_c<1$ – coupling coefficient; $W_{EM}(s)$ – transfer function of the electromagnet; $W_A(s)$ – the transfer function of the amplifier; K – transfer coefficient of the integrator; K_M – transfer coefficient of the motor; T_M – time constant of the motor; s – Laplace operator; MD – memory device; DMD – motion sensor of product.

Secondary emission sensor (collector) is used as a measuring device of the joint position. Secondary emission sensor (collector) collects electrons which are reflected from the surface of the product during scanning the joint by an electron beam [4].

SimuLink MatLAB was used to analysis of stability and the quality of the tracking system along the joint. Functional diagram of dual-circuit tracking system for calculations in SimuLink is presented in Fig. 6.

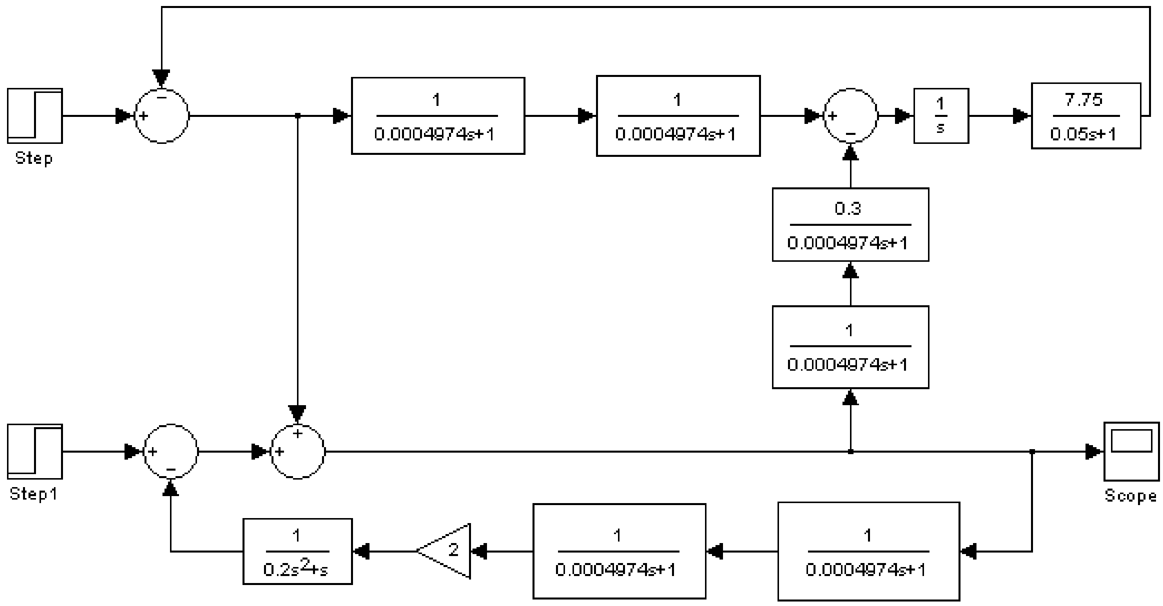
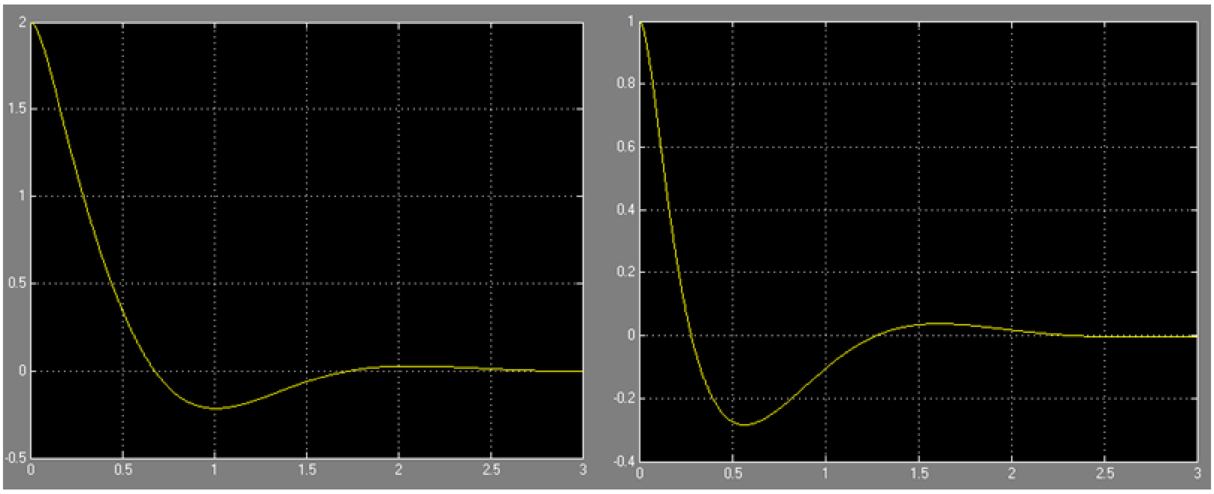


Figure 6. Model of dual-circuit tracking system in SimuLink.

Fig. 7 shows the transient processes in the system. Analysis of transient processes shows that the system is stable and the required performance of quality of control process can be achieved.



(a) (b)

Figure 7. Transient processes in the system (a) at a deviation the joint and in the presence magnetic interference, (b) in the presence of magnetic interference and absence of deviation the joint.

The error of alignment the electron beam with the joint in the root of weld will be

$$\varepsilon_r = \varepsilon_j + \theta \cdot d.$$

Dynamic error of the system is determined by the formula

$$\varepsilon_\nu = \frac{\nu_{max}}{K_v},$$

where ν_{max} – maximum rate of change of the input signal; K_v – transfer coefficient of the system.

Preparation of joints connection for electron beam welding is performed with the use of highly accurate processing equipment. Therefore change of joint position is usually associated with an error of the installation of parts in welding manipulator. When performing circumferential welds error of joint positioning is described by a sinusoidal function $x(t)=A_{max}\cdot\sin\omega t$, where A_{max} – maximum amplitude of the input signal, ω – frequency of the input signal.

If the signal $x(t)=A_{max}\cdot\sin\omega t$ arrives at the input of the system then the rate of change of the input signal is

$$\nu = \frac{dx(t)}{dt} = A_{max}\,\omega\cos\omega t,$$

and maximum rate of change of the input signal is

$$\nu_{max} = A_{max}\,\omega.$$

For the contour of tracking along the joint at the welding speed 30 m/h and the diameter of the product 1 m (length of weld is 3.14 m) frequency of the input signal is ω = 0.0167 radian/second. At the maximum deviation of joint from the optical axis of the gun A_{max} = 2 mm dynamic error of contour of tracking along the joint is

$$\varepsilon_j = \frac{A_{max}\,\omega}{K_v} = \frac{2\cdot 0.0167}{2} = 0.0167 \text{ mm.}$$

For the contour of compensation of magnetic fields at the welding speed 30 m/h and the length of weld 500 mm the frequency of magnetic field is ω = 0.1 radian/second. Magnetic fields that accompany welding process can reach values which deflect the electron beam up to 5 mm [5]. In this case the dynamic error in the contour of compensation of magnetic interference is

$$\varepsilon_\nu = \frac{A_{max}\,\omega}{K_v} = \frac{0.1\cdot 5}{7.75} = 0.0645 \text{ mm.}$$

This error occurs at the full compensation of disturbing magnetic fields. This is performed in the center of the penetration channel (at a depth of d/2). Given the shape and dimensions of the channel penetration, in the worst case, full compensation is possible at depth of d/3. Angle of deflection of electron beam from the optical axis of the gun leading to such displacement is

$$\theta = \varepsilon_\nu \frac{3}{d} = \frac{0.0645\cdot 3}{d} = \frac{0.194}{d}.$$

At the root of the weld such an angle will cause an error

$$\theta\cdot d = 0.194 \text{ mm.}$$

Thus, error of alignment the electron beam with the joint in the root of weld would be

$$\varepsilon_r = \varepsilon_j + \theta\cdot d = 0.0167 + 0.194 = 0.2107 \text{ mm.}$$

Error of the method equals 0.2107 ≤ 0.3 mm and does not exceed permissible deviation of the electron beam from joint plane.

The contour of compensation of the magnetic field allows reducing by two orders the deflection of the electron beam from the optical axis of the gun as well as angle of inclination of trajectory. This is especially important when welding products of large thickness. In systems with preliminary record of joint trajectory the contour of compensation of the magnetic field should operate in the recording mode as well as in playback mode of joint trajectory during the welding. This allows increasing accuracy positioning along a joint in the case of changing magnetic fields. High reliability of the system is preserved. In the welding mode the joint is melted. Therefore, the deviation of joint does not change the signal of the measuring device of the electron beam deflection from the axis of the gun. In this case, the coupling coefficient is equal to zero.

Conclusions

1. Automatic compensation of the magnetic field of interference allows significantly improving the accuracy and reliability of positioning along the joint during electron beam welding.
2. Due to the contour of compensation of magnetic field the system of positioning along the joint becomes a dual-circuit and an interconnected.

References

[1] Laptenok V D, Druzhinina A A, Murygin A V and Seregin Yu N 2016 Method to eliminate the impact of magnetic fields on the position of the electron beam during EBW *IOP Conf. Series: Materials Science and Engineering* Volume **122**, p. 012021

[2] Druzhinina, A A, Laptenok, V D, Murygin, A V 2014 Improvement of the positioning accuracy along the joint connection of details with the residual magnetization in electron beam welding *Vestnik SibGAU* No. **5** (57) pp. 168-173

[3] Druzhinina, A A, Laptenok V D, Murygin A V, Seregin Yu N 2012Method for monitoring of impact of magnetic fields in the process of electron-beam welding by X-ray radiation from treatment area. *Vestnik SibGAU* No. **5** (45) pp. 158-163

[4] Laptenok V D, Murygin A V, Seregin Yu N, Braverman V Ya Control of electron beam welding. Krasnoyarsk, 2000, 234 p.

[5] Wei P S, Chih-Wei Wen 2002 Missed joint induced by thermoelectric magnetic field in electron-beam welding dissimilar metals *Experiment and scale analysis. Metallurgical and Materials Transactions B* Volume **33** Issue 5 pp 765-773