New approaches to the rational manufacturing of combined constructions by EBW

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Annotation. The paper derives a relation describing the shape of an electron beam axis affected by thermoelectric currents during welding of dissimilar materials. The treatise suggests a new method for determining the adjustment actions for preventing lack of penetration in the weld root and derives an expression for determining the critical degree of weld penetration during welding of dissimilar austenitic and pearlitic steels. The received results can be used to make high-quality welding connections of thick dissimilar materials by eliminating incomplete penetration and ensuring necessary penetration degree of welded edges along the whole part thickness.

1. Introduction
In the welding seam of dissimilar alloys made by different welding methods, including electron-beam one, the melting boundary undergoes formation of regions with transitional composition (crystallization layers), which properties differ from those of welded alloys and cladded metal. The reason is virtually absent mixing of the liquid metal in the melting pool near the interface of solid and liquid phases [1]. The dimensions of these sections depend on the penetration degree, intensity of liquid metal mixing in the melting pool and its life duration, i.e. on the welding technology. It is be believed that the width of crystallization layers during manual arc welding is 0.4–0.6 mm, in the case of automatic submerged arc welding it is 0.4–0.6 mm, while in the case of electron-beam welding it does not exceed 0.1 mm [2]. In the latter case, the dimensions of the layer with variable chemical composition turns out to be smaller as compared to arc welding, because of more intense mixing of metal in the melting pool and its reduced life.

If the welded connection is formed by steels of the same structural class and different alloying, the properties of the crystallization layers practically have no effect on the operation characteristics of the parts. Unlike such situation, the layers of welded connections of steels from different structural classes, for instance austenitic and pearlitic, can be expected to include brittle martensitic regions and for cracks during welding or operation. In the first place, the width of the regions will depend—under given welding conditions—on the weld seam composition. Reducing content of Ni in the weld seam metal increases the width of the martensitic layer in the fusion zone, while its exceedingly low content yields martensitic structure of the seam. Such a case appreciably increases the affinity to form cold cracks that, as a rule, arrange along the seam in its middle. Therefore, the structural nonuniformity, conditioned by the presence of layers with reduced ductility in the fusion zone, reduces the performance of combined welded structures from dissimilar metals and alloys.
In this connection, one of the important challenges in welding dissimilar metals and alloys is obtaining the required chemical composition of the seam metal determining the properties of the welded connection as a whole. The most widely spread methods for adjusting the chemical composition in welding dissimilar metals are based on the implementation of intermediate inserts between welded parts, which main purpose is alloying the seam metal. In addition, the chemical composition of the seam metal can be adjusted by beam displacement towards one of the parts.

However, welding of dissimilar steels gives rise to magnetic fields, which sources are residual magnetization of ferromagnetics and thermoelectric currents [3]. These fields interact with the electron beam and deflect it from the joint region. Hence, the required degree of edge penetration and seam composition are determined by the preset accuracy of beam positioning relatively to the joint.

The work is aimed at scientifically justifying the technological methods for stabilizing the spatial parameters of the beam relatively to the joint during electron-beam welding of dissimilar steels and alloys providing necessary chemical composition, structure and properties of welded connections in combined constructions.

2. Investigation Methods

Currently, different methods are used to reduce the action of magnetic fields on electron beam: demagnetizing the parts before welding, implementation of screens from high-permeability materials for transporting the electron beam from the gun anode to the part's surface, field compensation in the welding zone, introduction of additional materials into the welding zone or orientation of the beam oppositely to its deflection [4–9]. These methods can also be combined; for instance, demagnetizing with application of ferromagnetic shields considerably increase the EBW conditions. The effective implementation of such technological techniques is possible only in cases with known distribution of magnetic field induction in the region of electron beam propagation in the penetration channel [10].

In the absence of external high-current sources, for preliminarily demagnetized materials, the thermoelectric currents are the main source of magnetic field. The field lateral component distribution $B_{xm}(z)$ is practically linear along the depth of the gas-vapor channel ($0 \leq z \leq \delta$) and reaches extremums at its opposite ends. The longitudinal field induction component over the surface of welded parts in the electron drift space ($z \leq 0$) decreases almost exponentially. The direction of the thermoelectric current field magnetic induction vector, in this case, is determined by the sign of relative thermal EMF of the welded pair of materials. The magnetic field of thermoelectric currents $B_{xm}(z)$—while switching its sign along the thickness of the welded connection, deflects the electron beam up to the semi-thickness of the connection towards the material with positive thermoelectric potential, and then towards the opposite side (Fig. 1). In this case, the deflection angles of the beam axial electron relatively to the initial direction in the top and root of the penetration channel are equal ($\theta(0)=\theta(\delta)$), while the inflection point of its trajectory is at the middle of the channel depth. Such spatial parameters of the beam usually fail to provide necessary penetration degree and cause lack of penetration along the part thickness. Thus, the adjustment of the parameters is needed. The adjustment means providing such beam inclination angle to the joint $\varphi(0)$ (Fig. 2), at which there is no beam deflection in the weld top and root, i.e. $\psi(0) = \psi(\delta) \approx 0$. This condition is satisfied when turning line CD — connecting the point of entrance of a beam electron into the part and its exit point — around point C by angle $\Theta$ and displacing it by distance $\psi(0)$ up to the alignment with the joint.
Figure 1. Deflection of beam axial electron in magnetic field of thermoelectric currents: 1) welded part with positive thermoelectric potential; 2) welded part with negative thermoelectric potential; 3) welding bench of the electron-beam setup; 4) joint of welded parts; 5) vacuum chamber of the electron-beam setup; 6) electron-beam gun; 7) electron beam axis; 8) direction of the magnetic field induction $B_{xm}(z)$. 
In this case, angle $\Theta$ equals

$$\Theta \approx \tan \Theta = \frac{\psi(\delta) - \psi(0)}{\delta}.$$  

(1)

In the absence of residual magnetization field, the following expression was derived for determining the values of $\psi(\delta)$ and $\psi(0)$:

$$\psi(z) = \sqrt{\frac{e}{2m_e U}} B_m(0) \left[ \frac{1(1 + \alpha s) \exp(-\alpha s)}{\alpha^2} + \frac{1 - \exp(-\alpha s)}{\alpha} \frac{z^2}{2} - \frac{z^3}{3\delta} \right],$$

(2)
where \( e \) is the electron charge, \( C \); \( m_e \) is the electron mass, \( \text{kg} \); \( U \) is the accelerating voltage, \( \text{V} \); \( \alpha \) is the empirical coefficient characterizing the plasma density above the part, \( \text{m}^{-1} \); \( s \) is the distance between the gun and part, \( \text{m} \); \( \delta \) is the thickness of welded parts, \( \text{m} \).

The inclination angle between the electron-beam gun to the joint \( \varphi(s) \)—with due consideration of the beam deflection in the magnetic field above the part—will equal \( \Theta \). Neglecting the minuscule change in the magnetic field induction in \( X0Y \) plane (1) with due regard to (2) gives the following:

\[
\Theta \approx \sqrt{\frac{e}{2m_eU}} B_{xm}(0) \left[ \frac{1 - \exp(-\alpha \delta)}{\alpha} + \frac{\delta}{6} \right]
\]

(3)

Thus, depending on the welding regimes, the adjustment of the beam axis inclination to the joint can be used to set up the spatial beam position during EBW of thick parts, which ensures necessary penetration degree and reduces the possibility of lack of penetration.

Below is the experimental method for determining the deflection angle \( \Theta \) between the beam and joint. The ferromagnetic specimens were demagnetized before welding by alternating magnetic field at industrial frequency with gradual reduction of its strength. The induction of the residual magnetization field was ensured to be less than 0.05–0.06 mT. Then, trial welding was performed for the dissimilar materials to measure the beam deflection from the joint. The electron gun axis (electron beam) was aligned with the joint, and then the penetration was carried out. The welding process induced thermoelectric currents \( IT \) which magnetic field \( B_{xm}(z) \) was deflecting the electron beam from the joint by angle \( \theta(0) \) towards the metal with positive thermoelectric potential. To compensate such beam deflection, the electron-beam gun axis was revolved around the seam top by angle \( \Theta \) that was determined from eq. (3) and then, the gun was displaced towards metal 1 with negative thermoelectric potential and then the penetration was carried out. The welding process induced thermoelectric currents \( IT \) which magnetic field \( B_{xm}(z) \) was deflecting the electron beam from the joint by angle \( \theta(0) \) towards the metal with positive thermoelectric potential. To compensate such beam deflection, the electron-beam gun axis was revolved around the seam top by angle \( \Theta \) that was determined from eq. (3) and then, the gun was displaced towards metal 1 with negative thermoelectric potential so the beam axis (axial electron beam trajectory) was pointing to metal 2 with negative thermoelectric potential. The gun was displaced up to the alignment of the electron beam on the part's surface with the joint. This provided the angle between the beam axis and joint at the entrance and exit from the part to be \( \varphi(0)=\varphi(\delta)=\Theta \).

3. Results
The study established that if the angle of electron beam entrance into the part \( \varphi(0) \) is larger than \( \theta(0) \), then the electron beam axis at the exit from the part deflects towards the material 2 with negative thermoelectric potential. On the contrary, if \( \varphi(0)<\theta(0) \), the beam deflects towards the material 1 with positive thermoelectric potential. In both the cases, one of the materials is predominantly melted. In addition, the welding seam features defects of lack of penetration along the thickness.

4. Discussion
In the presence of the magnetic field of thermoelectric currents and with due account for the seam shape, the beam adjustment leads to melting of different alloys in the top and in the root of the seam, the penetration areas being not equal to each other. The suggested method for adjusting the spatial position of the beam in this case can increase the penetration degree of the edges of non-austenitic steel, which may negatively affect the properties of weld connections. Thus, this method is effective for welding different steels with austenitic steels, if the penetration degree for the austenitic steel is

\[
\gamma_1 = \frac{F_1}{F_1 + F_2} \geq \frac{13Cr_{s2} + 16Ni_{s2} - 416\%}{13(Cr_{s2} - Cr_{s1}) + 16(Ni_{s2} - Ni_{s1})},
\]

(4)

where

\[
Cr_{s} = \%Cr + \%Mo + 1,5\%Si + 0,5\%Nb + \%V
\]

and

\[
Ni_{s} = \%Ni + 30\%C + 0,5\%Mn + 30\%N_{er}
\]

are equivalent contents of chrome and nickel in the seam metal.
The specificities of the technological process presented above can be used to make high-quality welding connections of thick dissimilar materials by eliminating incomplete penetration and ensuring necessary penetration degree of welded edges along the whole thickness, thus forming necessary structure and properties of welded connections.

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