Experimental research on electron-beam welding technology with a scanning electron beam

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Abstract. In this paper the question of achievement of quality welded joints in electron-beam welding is considered. The welded seam is largely characterized by its depth, width and their relation. The parallelism of the sides of the penetration zone plays an essential role, as well as the radius of the root part and other geometric parameters that affect the nature and magnitude of the welding deformations and stresses in the welded products. Traditional welding regimes entail root defects, porosity, undercuttings and fissures, and these are unacceptable in the manufacture of critical products. To obtain the required seam geometry various technological methods are used, for example, various forms of electron beam scanning with the programming of energy along the trajectory; the use of welding with different focus positions; oscillation of the electron beam; programming of change of current and focus at the beginning and end of the welding process. Nine difference trajectory scans were programmed in order to manage the energy distribution of the electron beam across the heating spot.

The effect of various forms of energy distribution across the heating spot on the process of formation of a welded seam and its characteristics was studied in this research. The quality of welded joints was evaluated by the results of the x-ray control of welded joints and microsections of the cross-section and longitudinal section of the welded joints.

1. Introduction
The quality of a seam in the process of electron-beam welding is determined by a combination of the technological and energy parameters of the process. Maintaining the energy parameters of the welding process at the required level ensures the constancy of the geometric dimensions, as well as of parameters relating to structure and strength among others under the same technological conditions. However, the possibility of forming a unique close-range form with a minimal metal content of the bath comes into conflict with the achievement of stable operating parameters of the welded joint. Violation of the optimal mode of electron-beam welding often leads to the appearance of defects in the seams, even on well-welded materials. These violations are found in all methods of fusion welding and non-welds, undercuttings, sagging and increased spattering are all widely known. However, other specific defects also exist; there are root defects, extended cavities at the root of the seam, "median" cracks and seam deflections from the joint due to residual or induced magnetic fields [1]. The root defects of the seam are inherent in all methods of welding with highly concentrated energy sources. The root defects have a hydrodynamic nature of formation and they are connected with the peculiarities of the metal transfer in a weld pool.

To prevent root defects it is necessary to form a steam-dynamic channel with a sufficiently wide lower part and a rounded bottom. The form of the channel is changed by the form of power distribution of the electron beam along the heating spot [3-5]. A selected focus level of the beam [6, 7] is not able to completely suppress the root defects, and in any event the probability of incomplete fusion remains quite high. In addition, the triangular form of the deposit leads to considerable deformations and stress. In practice, welding with full penetration is used to eliminate root defects [8-10] but this method is not applicable for closed seams. The most efficient way to control the distribution of energy affecting the formation of the penetration channel is by scanning the electron beam. The following beam scans are widely used: longitudinal, transverse, X-shaped, circumferential, ellipse and arc [11]. The calculation methods for selecting the beam sweep shape have not yet been developed. At the same time, a rather large amount of experimental data is accumulated. However, the practical recommendations do not always coincide. The latter facts are largely determined by the specifics of the equipment used for scanning of the beam with limited capabilities and imperfections in the methods of investigation. The relationship between the scanning parameters and the beam focusing level, the geometry of the initial stationary...
electron beam, the welding speed, and the level and the pulsation frequency of the beam parameters are not taken into account.

The effect of the sweep is shown in the change in both the instantaneous distribution of the power density of the electron beam and this distribution averaged over a period. Accordingly, the nature of the hydrodynamic processes and the configuration of the weld pool change. When welding thick metal with a horizontal beam, it is possible to expand the diameter sharply and increase the stability of the channel in the weld pool, which has a favourable effect on the stability of the formation of seams, i.e. the spattering of molten metal decreases, and the melt is prevented from flowing out of the bath. As a result of changing the seam form, the likelihood of cracking, root defects and extended cavities decreases.

At relatively large scanning frequencies (1000-2000 Hz) the beam power is distributed along the scanning path uniformly without leading to fluctuations in the depth of penetration. Therefore, in practice such sweep frequencies are commonly used.

In the Siberian Research Centre for Electron Beam Technologies (SICELT) of Reshetnev Siberian State University of Science and Technology, an industrial sample of equipment for electron-beam welding has been developed and created with a converter source of accelerating voltage [12]. In this equipment new technological capabilities have been realized to control the energy distribution of the electron beam over the heating spot. In this equipment a microprocessor block for the functional scanning of the electron beam is used allowing the beam to be scanned along various programmable trajectories. In the functional scanning block high-speed channels of beam deflection are applied to the coordinates X, Y with a bandwidth of frequencies up to 60 kHz. The electron-beam equipment CEP-2 has been modernized in the replacement of deflecting and focusing systems by high-speed ones.

As a result, a periodically collapsing steam and gas channel, typical for traditional electron-beam welding technologies, is, with the appropriate scanning paths, transformed into a stable vapour-gas cavity, extending to a significant part of the penetration depth. This action leads to a change in the conditions for the formation of the welded seam, an increase in the efficiency of the welding process, a change in the shape of the welded joint, and an improvement in the quality of the welded joints [13].

2. Material and methods

Preliminary investigations based on the use of these technological capabilities have revealed the promise of new scanning paths in order to improve the technology of electron-beam welding and improve the quality of welded joints.

Experimental investigations were performed on an ELU-5 electron-beam unit with electron-beam equipment and a CEP-2 gun with a Ø 4.7 mm tablet. Welding was performed on annular specimens of Ø 300 mm with a thickness of 27 mm made of AMg-6-HH material. The welding speed was 30 m / hour.

The purpose of this experimental research was to study the influence of various forms of energy distribution on the heating spot on the process of formation of the welded seam and its characteristics.

The quality of welded joints was evaluated by the results of x-ray inspection of welded joints and microsections of the cross-section and longitudinal section of the welded joints.

For managing the distribution of the electron beam across the heating spot we programmed nine different scanning trajectories of electron beam scanning paths. The scan numbers correspond to the following images:

It was possible to change and control the scanning amplitudes by "x" and "y", by the scanning frequency and by defocusing the beam through the dynamic focusing channel.

Welding was executed at an accelerating voltage U = 25 kV, and the currents of the electron beam were $I_x = 100, 150, 200, 250 mA$. 

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To exclude the effect of heating of the sample on the formation of the welded joint, the following welding was performed on a cooled model. More than 200 models were welded.

Regime 1 - without scanning.

| № | 1  | 2  | 3  | 4  |
|---|----|----|----|----|
| The current defocus, mA | -16 | 30 | 30 | 20 |
| The beam current, mA  | 180 | 150 | 180 | 200 |

When scanning is not used, the welding was performed with different values for the beam current and with different defocusing currents along the dynamic focusing channel. As can be seen from the microsections, the form of the welded joint has a type of close-range penetration with a sharp root of the seam, with root defects and instable penetration.

Regime 2 – scanning № 1.

| № | 1  | 2  | 3  | 4  | 5  |
|---|----|----|----|----|----|
| The amplitude X, mm | 0,8 | 1,0 | 1,2 | 1,2 | 2,5 |
| The amplitude Y, mm  | 1,5 | 2,0 | 2,2 | 2,2 | 2,5 |
| The beam current, mA  | 150 | 150 | 200 | 250 | 250 |

The form of the seam is cosinusoidal with a radius of curvature at the root of the seam of 0.1-0.3 mm. In addition, there are root defects and significant instability in the penetration depth. This mode is also unsuitable for practical use.

Regime 3 – scanning № 8.

| № | 1  | 2  | 3  | 4  | 5  | 6  | 7  |
|---|----|----|----|----|----|----|----|
| The amplitude X, mm | 1,4 | 1,6 | 1,4 | 1,6 | 0,8 | 1,0 | 0,6 |
| The amplitude Y, mm  | 1,4 | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | 1,2 |
| The beam current, mA  | 250 | 100 | 150 | 150 | 200 | 200 | 200 |

The form of the seam is approaching a cylindrical form in its upper part, which is 2/3 of the penetration depth. The lower part of the seam is close to being conical with a rounding radius of 0.3-1 mm depending on the scanning amplitudes. This mode is of interest for further research and optimization of the welding process.

Regime 4 – scanning № 5.

| № | 1  | 2  | 3  | 4  | 5  | 6  |
|---|----|----|----|----|----|----|
| The amplitude X, mm | 0,6 | 0,8 | 1,0 | 1,2 | 1,2 | 1,6 |
| The amplitude Y, mm  | 1,2 | 1,6 | 2,0 | 2,0 | 2,0 | 2,5 |
| The beam current, mA  | 200 | 150 | 100 | 150 | 200 | 200 |

The form of the seam is from conical to nearly cylindrical with a radius of fillets from 0.3 to 1 mm. depending on the
scanning amplitude. It is possible to obtain welds without root defects. This regime is of considerable interest for further investigation.

Regime 5 – forward plane scanning №4

| №  | 1   | 2   | 3   | 4   | 5   | 6   |
|----|-----|-----|-----|-----|-----|-----|
| The amplitude X, mm | 0.6 | 0.8 | 1.0 | 1.2 | 1.4 | 1.4 |
| The amplitude Y, mm  | 1.2 | 1.6 | 2.0 | 2.4 | 2.8 | 3.2 |
| The beam current, mA  | 150 | 150 | 150 | 220 | 220 | 200 |

The form of the seam is mostly conical. The asymmetry of the seam relative to a vertical line with a pronounced slope is observed. There are root defects. This scanning mode is not of practical interest in terms of its use.

Regime 6 – scanning №2.

| №  | 1   | 2   | 3   | 4   | 5   | 6   |
|----|-----|-----|-----|-----|-----|-----|
| The amplitude X, mm | 0.6 | 0.8 | 1.0 | 1.2 | 1.2 | 1.2 |
| The amplitude Y, mm  | 1.2 | 1.6 | 2.0 | 2.4 | 2.8 | 3.2 |
| The beam current, mA  | 200 | 200 | 200 | 250 | 250 | 200 |

The form of the seam is nearly triangular with an acute angle in its root. There are root defects and an instable penetration depth. This mode is not of interest for further analysis or optimization.

Regime 7 – scanning №4 angle forward.

| №  | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| The amplitude X, mm | 0.6 | 0.8 | 1.0 | 1.0 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |
| The amplitude Y, mm  | 1.2 | 1.6 | 2.0 | 2.0 | 2.4 | 2.8 | 3.2 | 3.2 | 3.6 |
| The beam current, mA  | 150 | 200 | 250 | 200 | 250 | 250 | 200 | 200 | 250 |

The form of the seam is clearly triangular with a sharp apex at the root. There are root defects and instable penetration. This regime is of no interest for further research.

Regime 8 – scanning №3.

| №  | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|----|-----|-----|-----|-----|-----|-----|-----|-----|
| The amplitude X, mm | 1.6 | 1.2 | 1.2 | 1.2 | 1.6 | 1.0 | 0.8 | 0.6 |
| The amplitude Y, mm  | 3.2 | 3.2 | 2.8 | 2.4 | 2.0 | 2.0 | 1.6 | 1.2 |
| The beam current, mA  | 250 | 250 | 250 | 250 | 200 | 200 | 200 | 150 |
The form of the seam is irregular. There are root defects and discontinuities. This mode is of no interest in practice.

Regime 9 – scanning №6.

| №  | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| X  | 0,8 | 1,4 | 2,0 | 0,8 | 1,6 | 0,6 | 0,8 | 0,8 | 0,8 |
| Y  | 2,0 | 2,4 | 2,8 | 3,2 | 3,2 | 1,4 | 3,2 | 2,0 | 3,2 |
| mA | 0   | 0   | -20 | 0   | 0   | 0   | -15 | 5   | -5  |
| mA | 150 | 200 | 250 | 200 | 250 | 250 | 200 | 250 | 250 |

The form of the seam is triangularly peaked asymmetric. There are root defects. The regime is of no practical interest.

Regime 10 – scanning №7.

| №  | 1   | 2   | 3   | 4   | 5   | 6   | 7   |
|----|-----|-----|-----|-----|-----|-----|-----|
| X  | 2,0 | 1,6 | 0,8 | 0,8 | 0,8 | 0,8 | 0,8 |
| Y  | 2,0 | 2,4 | 2,8 | 3,2 | 3,2 | 3,2 | 3,2 |
| mA | 0   | 0   | 0   | 0   | -5  | -10 | -15 |
| mA | 150 | 200 | 200 | 200 | 150 | 250 | 250 |

The form of the seam varies from triangular peaked to triangular blunted. The weld walls are almost parallel with through penetration. However, when the beam is taken out at the end of welding, there exists a possibility of root defects appearing.

Regime 11 – scanning №9.

| №  | 1   | 2   | 3   |
|----|-----|-----|-----|
| X  | 1,6 | 1,6 | 0,8 |
| Y  | 3,2 | 3,2 | 3,2 |
| mA | 250 | 250 | 300 |
| \(v_{\text{cm}}/\text{hour}\) | 60  | 60  | 60  |
The form of the seam is triangular with a rounding at the root of a seam. It can possibly be used with through penetration. Further research is required.

3. Discussion of results

The results of the first phase of the experimental research confirmed the prospects of new technological methods for improving the quality of welded joints. The most promising are the electron beam scans according to the forms (5), (8) and (9). In certain modes of the technological process, a more optimal form of the welded seam, a lack of root defects and a decrease in porosity are observed.

To achieve optimal technological processes it is suggested to continue the experiments with the electron beams denoted by these three scans, while varying the welding speed.

Figure 1 shows the microsections of the welded joints obtained during scanning № 9

\[
x = 1.6\text{mm}; y = 5\text{mm}; \nu_{\text{weld}} = 100\text{m/hour}; I_{\text{beam}} = 0...300mA
\]

The form of the seam is similar to the one received earlier (mode 11) for the same scan. The form of a seam approaches a triangular form with a radius of 0.5-1mm at the root of the joint.

Figure 2 shows the microsections of the welded joints obtained during scanning № 8

\[
x = 1.6\text{mm}; y = 5\text{mm}; \nu_{\text{weld}} = 100\text{m/hour}; I_{\text{beam}} = 200...250mA
\]

In the microsection the instability of the formation of the seam at a specified speed is clearly visible.

Figure 3 shows the microsections of the welded joints obtained during scanning № 8

\[
x = 1.6\text{mm}; y = 5\text{mm}; \nu_{\text{weld}} = 60\text{m/hour}; I_{\text{beam}} = 0...290mA
\]

Figure 4 shows the microsections of the welded joints obtained during scanning № 8

\[
x = 1.6\text{mm}; y = 5\text{mm}; \nu_{\text{weld}} = 45\text{m/hour}; I_{\text{beam}} = 150...270mA
\]
Figure 5. The microsections of the seam obtained in the following regimes:

$$a) \ x = 2.0 \text{mm}; \ y = 10 \text{mm}; \ v_{\text{weld}} = 30 \text{m/hour}; \ I_{\text{beam}} = 178 mA$$

$$b) \ x = 2 \text{mm}; \ y = 10 \text{mm}; \ v_{\text{weld}} = 30 \text{m/hour}; \ I_{\text{beam}} = 228 mA$$

$$c) \ x = 2.0 \text{mm}; \ y = 10 \text{mm}; \ v_{\text{weld}} = 30 \text{m/hour}; \ I_{\text{beam}} = 245 mA$$

Figure 5 shows microsections of the welded joints obtained by scanning No. 5 at a welding speed of 30 m/h.

Analysis of the conducted investigations showed that the best results were obtained by scanning No. 5. This form of scanning makes it possible to obtain a form of the welded joints close to rectangular with almost parallel walls, while the number of stresses and deformations in the welded joints decrease. The rounding radius is 1-2 mm. In the welded seams there are no root defects at all; porosity is reduced, which is confirmed by the results of the x-ray inspection of the welded joints. Longitudinal sections of welded seams showed that the processes of formation of the welded joint proceed more stably. In comparison with traditional technology, the instability of the penetration depth is decreased by 2-3 times, shown in the form of vibrations of penetration in the root of the seam.

The output of the electron beam at the completion of the welding process can be realised only in the case of a linear decrease in the welding current without changing the parameters of the beam focusing and the scanning amplitudes. Root defects do not occur.

Experiments were conducted to stop the EBW process abruptly as a result of the switching off the accelerating voltage. In addition, the experiments have shown that at amplitudes of scanning along a joint of more than 5 mm, the vapour-gas channel is transformed into a stable cavity along the entire depth of the weld, while the thermal efficiency is increased by reducing the energy expended on the evaporation of the material.

One defect that is difficult to control in EBW with a thickness of more than 10 mm is the root defect that forms at the root of the seam as voids of different forms. With x-ray control this defect manifests itself as a chain of pores of various forms with superposition and contact. This phenomenon is not connected to the habitual pore formation and depends only on the energy distribution in the heating spot. Poor weld formation with a distorted heat spot, as a rule, leads to the formation of a root defect and the more concentrated the heating spot is, the less weldable thickness is that is affected by this defect. A welding thicknesses of over 12 mm is not guaranteed against varying intensities of damage due to this defect. In order to eliminate this defect it is necessary to control the energy distribution law in the beam heating spot and form the seam in such a way that the root of the seam will be blunted with a radius of at least 1 to 2 mm., with the voids formed by the vapour-gas channel being filled with molten metal.

4. Conclusion
The following results were achieved in the research:

1. Programming the distribution of the energy of the electron beam in the weld pool by means of corresponding sweeps of the beam allows the formation of the welded seam in electron-beam welding to be controlled.
2. An asymmetric sweep relative to the vector of the welding speed leads to the asymmetry of the seam along the depth of penetration.
3. By choosing the sweep of the electron beam, the quality of the welded joints is improved by eliminating root defects, thus reducing the porosity and instability of melting and reducing stresses and deformations in welded joints.

The reported study was funded by Russian Foundation for Basic Research, Government of Krasnoyarsk Territory, Krasnoyarsk Region Science and Technology Support Fund to the research project № 17-48-240098

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