1. Introduction
The quality of the seam at EBW is determined by the combination of technological and energy parameters of the process. Maintenance of the welding process energy parameters at the required level ensures, under the same technological conditions, the constancy of the welded joint operational parameters, geometric dimensions, structural, strength and other parameters. However, the possibility of forming a unique "dagger" shape with minimal metal capacity of the welding bath comes into conflict with the achievement of stable operating parameters of the welded joint. Violation of the EBW optimal mode often leads to the appearance of defects in the seams, even on well-welded materials. Defects found in all fusion welding methods and are well known: lack of penetration, undercuts, sagging of the beam, as well as increased spatter. The root defects of the weld have a hydrodynamic nature of formation and are due to the peculiarities of metal transfer in the weld pool [1-4, 7].

To prevent root defects, it is necessary to form a steam-dynamic channel with a sufficiently wide lower part and a rounded bottom. The shape of the channel is changed with the electron beam power distribution shape in the welding zone. The most effective way to influence the formation of the penetration channel is the electron beam oscillation. Calculation methods for choosing the shape of the oscillations have not been developed yet.

The effect of the oscillations manifests itself in a change in the instantaneous and period-averaged distribution of the electron beam power density. The nature of the hydrodynamic processes and the configuration of the weld pool also change accordingly. When welding metals with a horizontal beam, it is possible to significantly widen the diameter and increase the stability of the channel in the weld pool, which has a positive effect on the stability of seams formation: the spattering of molten metal is...
reduced, and the melt is prevented from flowing out of the bath. Due of the change in the shape of the beam, the tendency to crack, root defects and extended cavities decrease.

At the Reshetnev Siberian State University of Science and Technology it was revealed that the periodically coagulating vapor-gas channel which is typical for the traditional electron-beam welding technology is transformed with appropriate scanning paths into a stable vapor-gas cavity that extends to a significant part of the penetration depth. This leads to a change in the conditions for the formation of the weld, an increase in the ECE of the welding process, a change in the shape of the weld and an increase in the quality of welded joints.

Preliminary researcher 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, improve the quality of welded joints. Welding was performed on annular specimens Ø300 mm with a thickness of 2.4 cm made of AMG-6 material [4].

The purpose of the experimental researcher was to study the effect of the different forms of energy distribution over the heating spot on the process of formation of the weld and its characteristics.

The quality of welded joints was evaluated by microsections of the transverse and longitudinal sections of welded joints.

Mathematical modeling of the thermal welding process based on the classical theory of the thermal field was conducted in parallel with the experimental research [1, 4, 8].

Comparing the results of many years of experimental research and the data obtained during the modeling of thermal processes, an algorithm has been developed to search for the optimal technological mode of electron beam welding, which can be recommended for testing the EBW technology of new structural materials or improving existing old technological processes. The algorithm consists of three stages [4]:

- Choice of the electron beam oscillations trajectory;
- Correction of the selected electron beam oscillations trajectory shape;
- Calculation of welding process parameters.

2. Choice of the electron beam oscillation path
Since the size of the scanning path always significantly exceeds the diameter of the electron beam itself, it is advisable to represent the electron beam in the form of an energy point source moving along the chosen trajectory at a rate proportional to the frequency of the electron beam oscillation. The method is based on the mathematical model of a moving point source on the surface of a semi-infinite body [1, 9, 10]:

$$T(x, y, z, q, v, t) = T_i + \frac{2q}{c_r \rho \sqrt{(4 \pi a)^3}} e^{-\frac{r^2}{2a}} \int_0^t \exp \left( -\frac{v^2 \tau}{4a} - \frac{R^2}{4a \tau} \right) dt,$$

(1)

Most beam scanners contain digital-to-analog converters, so it is easy to convert the scan form of an electron beam in the form of moving it along a grid.

As a measure for the analysis of trajectories, the next functional was chosen:

$$J = \left( \frac{1}{n} \sum_{i=1}^{n} \left( T_{i2}(x, y, z, q, v, t) - \overline{T}(x, y, z, q, v, t) \right)^2 \right)^{1/2},$$

(2)

where $T_{i2}(x, y, z, q, v, t) = T_{i2}(x, y, z, q, v, t)$ – initial temperature, calculated by (1), $\overline{T}(x, y, z, q, v, t)$ – arithmetic average of temperature, $T_{\text{max}}(x, y, z, q, v, t)$ – max of temperature. The minimum of the functional ($J_{\text{min}}$) is used for choice the trajectory of scanning.

To find parameters in models (1) and for calculation them, it is necessary to solve the inverse task, which is unrealizable due to their complexity, so the solution has obtained graphically. To determine the welding speed, the integration time and the boundaries of the heating volume, is used an optimality criterion, which take the minimum of the functional. The final values of the calculated parameters are determined at the points where the following condition is satisfied:
\[
\rho \frac{d^4 \psi}{dt^2} + \frac{d^2 \psi}{dx^2} + \frac{d^2 \psi}{dy^2} = 0,
\]

Taking into account the time, coordinates and sequence of positioning of the electron beam when reproducing the scanning path (Figure 1), the temperature field was calculated by varying the distances between the adjacent points of scanning path $\delta = 0.001 \div 0.035$ cm. This interval was chosen for reasons of the minimum diameter of the electron beam and the effective feasibility of the selected scanning method.

![Figure 1. Plot of electron beam positioning sequence for scan form «Raster».](image)

Other beam scans were obtained when calculating thermal fields according to model (2). In the earlier published paper [4], present experimental research on the calculation of the value the functional against the intervals $\delta$ for the studied scanning paths. It was revealed that the trajectory of scanning the electron beam in the form of a raster has the least functional. Therefore, this form is the most prefer.

2.1. Correcting the shape of the selected path of oscillation of the electron beam

Having chosen the shape of the electron beam scanning path, it is necessary to evaluate the influence of each segment of this trajectory shape on the functional (2) value. If the segment leads to an increase in the functional, then it should be removed from the shape, redistributing the energy input to the remaining parts.

After performing these actions, a new shape of the scan path was obtained (figure 2).
2.2. Calculation of the welding process parameters

This stage of work is the most time-consuming, as it uses the calculation of massive models of the thermal process with a sufficiently small integration step.

The parameters of the welding process are taken:
- welding speed;
- welding current;
- scanning amplitude along the established path of the electron beam;

To simulate the electron beam, taking into account the thickness of the welded product, a heating source was considered, representing the following expression:

$$T_1(x, y, z, q, v, t) = T_1(x, y, z, q, v, t) + T_2(x, y, z, q, v, t),$$

where $T_1(x, y, z, q, v, t)$ and $T_2(x, y, z, q, v, t)$ are the formulas for the spatial state of the temperature field exposed to a fast-moving linear (4) and point source (1). Both formulas are used due to the need to take into consideration the effect on the thermal field of the thickness of the product.

$$T_2(x, y, z, q, v, t) = T_i + \frac{q}{4\pi\lambda\delta} e^{\frac{-x^2}{2a}} \int_0^t \exp \left( -\frac{v^2}{4a} - \frac{2\lambda}{c\rho \delta} \frac{(x^2+y^2)}{4a^2} \right) \frac{dr}{\tau}.$$  

The welding speed is explicitly present in formulas (1) and (4), so it can be found by solving the inverse problem:

$$v = \min_{v_{\text{min}}, v_{\text{max}}} f,$$

To this purpose, by modeling the behavior of the selected functional by variation welding speeds, we determine the solution of the problem at the point where the functional achieves the minimum value. Figure 3 shows the result of such a simulation.
The welding current is not represented in the formulas of the thermal process, but it is related to the energy of the heating source $Q$ by the following expression:

$$I = \frac{Q}{U \eta_{0.89}}$$

(7)

where $U$ – accelerating voltage, $\eta = 0.89$ – energy conversion efficiency, $Q$ – the effective power.

In earlier published paper [4], proposes an algorithm developed by the authors. The purposed developed algorithm is based on the following assumption: since the heat welding process is not stationary, it is advisable to select the source energy (or welding current), at which the value of the functional did not change in the event of an increase in the integration time at some limit.

The scanning amplitude of the electron beam is determined at the stage of choosing the geometric parameters of the integration volume for mathematical models (1) and (4). First, the value of the temperature threshold defining the boundaries of the investigated volume of the heated material is calculated:

$$T_{\text{threshold}} = \min_{T_{\text{min}} \rightarrow T_{\text{max}}} J$$

(8)

Figure 4 shows the calculation.

**Figure 3.** Plot of curve of modeling the functional against from variation of welding speed

**Figure 4.** Plot of functional against from heating temperature.
3. Conclusions
The proposed method for calculating the focal length of an electron beam relative to the surface of a welded product is applicable for developing a technology for welding new designs of products from varying materials.

Numerical calculation of the thermal processes for determining the parameters of EBW will significantly reduce the cost of developing technologies for structures made of new materials.

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