Mathematical models of beam input and output in the process of electron beam welding of thin-walled structures

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Abstract. The article considers the problem of mathematical modeling of the electron beam welding process at the stages of input and output of an electron beam. A conceptual model is proposed, developed using the mathematical apparatus of the thermal process theory. The models allow the calculation of the individual stages of the process that affect the formation of a welded joint in the vicinity of the “zero point”. The proposed models will be used in the future and will be subjected to verification processes by comparison with the results of field experiments.

1. Introduction

Currently, a lot of research is being conducted on the formation of the weld optimal quality [1-4]. But little attention is paid to the quality of the joint formation. In this paper, it is proposed to study the process of input-output of an electron beam. As a rule, in electron beam welding (EBW), the optimal quality of the welded joint is a uniform penetration depth and the so-called “dagger” shape, which is currently difficult to achieve due to defects near the “zero point” of the weld, namely, the insertion point - output of the electron beam. The authors of this work carried out the simulation of thermal processes in an EBW, in order to obtain optimal technological parameters for the formation of an optimal weld [5, 6]. Point and linear fast-moving sources were used as models, a functional was obtained by which the optimal parameters were determined, but the source was accepted as ideal \( Q = 299 \, J \). It should be noted that the selected formula dependences contain not only the characteristics of the material being welded, but also the energy parameters of the electron beam. Instant source models are valid for metals and alloys, provided that the physical characteristics of the material do not change when heated.

However, the results obtained did not give optimal values and required refinement of the mathematical models.

In particular, the authors conducted experiments in which different welding modes were set and a proportional change in width was obtained. Thus, a correlation was found between the effective heating zone and the width of the weld. Effective heating refers to such heating, which is more consistent with the geometric parameters of the weld.

Figure 1 shows a graph of the change in the width of the weld for titanium alloy VT-14 with a thickness of 0.12 cm.
Figure 1. Correlation of width with effective heating zone, where: \( Y_{\text{max}} \), \( Y_{\text{min}} \) - width of the welded joint relative to the process parameters, \( \text{Temp} \) - heating curve during the process.

It should also be noted that when introducing EBW systems at aerospace enterprises, due to the need to adjust the technological parameters of the welding process for each specific product, it causes difficulties.

Currently, this problem is being solved by experimental selection of technological parameters of EBW process, increasing the total cost of products.

Thus, it is relevant to develop mathematical models that describe the beam extraction process, EBW process control algorithms implemented on the basis of the created mathematical models, as well as subsequent testing of the research results in experiments on industrial samples of thin-walled aerospace structures.

2. Mathematical models and methods

2.1. General statement of the problem
To solve this problem, namely, the study of the process at the stages of input and output of the beam, it is necessary to have mathematical models that allow an accurate measure of the accuracy of the thermal processes occurring in the weld joint area during electron beam welding. Thus, a number of models are needed, each of which will describe a separate process step. Ultimately, the superposition of the thermal fields obtained for each of the models will form a complete picture of the thermal field in the weld joint area. Then the general field can be defined as the sum of the fields describing each of the stages of the process separately.

2.2. Mathematical models
Next will be presented the models from which the general modeling scheme is built. The basis, as mentioned above, is taken from the models proposed in [7, 8], which allow one to obtain a temperature field when an electron beam passes through a workpiece and are mathematically substantiated in [9]. Moreover, these calculation methods have received empirical confirmation [10].

The calculation formula for an instantaneous point source on the surface of an infinite body is as follows:
\[ T_1(x, y, z, q, v, t) = T_i + \frac{2q}{cp\sqrt{4\pi a}} e^{-\frac{vx}{2a}} \int_0^t \exp \left( -\frac{v^2\tau}{4a} - \frac{R^2}{4a\tau} \right) \frac{d\tau}{\tau^{3/2}}, \]  
\[ (1) \]

where \( T_i \) – initial temperature of the product;
\( c \ast \rho \) – heat capacity of the steel;
\( q \) – effective beam power;
\( a \) – thermal diffusivity;
\( v \) – welding speed;
\( t \) – time counted from the moment the source passes through the section at which the point in question is located;
\( R \) – distance from the direction of movement of the source to the point in question.

The calculation formula for an instantaneous linear source on the surface of an endless plate is as follows:
\[ T_2(x, y, z, q, v, t) = T_i + \frac{q}{4\pi \lambda \delta} e^{-\frac{vx}{2a}} \int_0^t \exp \left( -\frac{v^2\tau}{4a} - \frac{2\lambda \tau}{cp\delta} - \frac{(x^2+y^2)}{4a\tau} \right) \frac{d\tau}{\tau}, \]
\[ (2) \]

where \( T_i \) – initial temperature of the product;
\( \delta \) – thickness;
\( \lambda \) – coefficient of thermal conductivity;
\( b \) – plate heat transfer coefficient;
\( v \) – welding speed;
\( t \) – heat propagation time.

The model describing the input process will correspond to a superposition (1) and (2), but with a variable source power:
\[ T_2(R, q(t_0), v, t) = T_1 + T_2, \]
\[ (3) \]

where \( T_1 \) and \( T_2 \) corresponds to (1) and (2);
\( R \) – coordinates;
\( q(t_0) \) – heating source energy;
\( v \) – heating ratio;
\( t \) – integration time interval.

Also, a superposition of models (1) and (2) will be a description of the free cooling process of the workpiece, after the step of introducing the beam, i.e. it is necessary to obtain a temperature field that describes the heating of the workpiece in the direction opposite to the welding direction. In this case, the field is calculated for the moment of the beam extraction stage beginning:
\[ \sum_{i=0}^J \Delta T_i(\Delta t, \Delta R_I), \]
\[ (4) \]
\[ \Delta T_i(\Delta t, \Delta R_I) = \frac{2q}{cp\sqrt{4\pi a\Delta t}} e^{-\frac{R^2}{4a\Delta t}} \int_{t_1}^{t_2} (T_1 + T_2) dt, \]
\[ (5) \]

where \( t_1 \) – starts from 0 to the beginning of the beam output;
\( t_2 \) – the end of the process;
\( \Delta T_i \) – instant heat source;
\( \Delta t \) – offset from \( t_0 \);
\( t_0 \) – input time;
\( R_0 \) – input coordinate;
\( \Delta R_i \) – sum of previous \( R \).

A simplified view of the calculation scheme is shown in figure 2.

Figure 2. The design scheme of the field’s superposition before the stage of beam output, where \( R_0 \) and \( R_i \) – the space of "zero point", \( \Delta T_i \) and \( \Delta T_j \) – the number of elementary sources that are taken into account.

The calculation of the field for the beam output will correspond to (3), with the exception of the nature of the form; in the case of input, the function increases according to output.

By setting the optimization criterion proposed in [5], it is possible to achieve the correspondence of the temperature field obtained with the optimal process parameters for a particular case, the results of which are empirically confirmed, and use them for field experiments. This, in turn, will give an answer regarding the suitability of the proposed method for evaluating and choosing the modes of the electron beam input and output.

3. Conclusions
The authors propose the use of a mathematical apparatus that allows us to describe and study the process of formation of a weld near the “zero point” of a welded joint. Conducting model experiments will allow the conceptual formation of methods for selecting the modes of input and output of the beam, which must be verified experimentally. This in turn will allow either to abandon the proposed concept, or to complement and clarify it in further studies.

The proposed models will potentially allow a conscious approach to the selection of technological parameters at the stages of input and output of an electron beam.

As a result of the study, mathematical models have been formed that allow us to describe the stages of input and output of the electron beam, as well as consciously approach the issues of their formation both in form and in intensity. The proposed models will be used in further studies and verified by comparison with the results of field experiments.

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