Method for determination of technological mode parameters of electron-beam welding based on the application of optimality criterion with the view on the weld pool uniform heating

Yu. N. Seregin, V. D. Laptenok, A. V. Murygin, V. S. Tynchenko

Reshetnev Siberian State University of Science and Technology, 660037, Krasnoyarsk, Russia

E-mail: vadamond@mail.ru

Abstract. The paper presents the results of mathematical modelling of temperature fields when the AMG-6 alloy is heated with energy sources equivalent to an electron beam in electron-beam welding. The evaluation of the results was performed using the criterion of optimality proposed by the authors. Used as a functional for calculations was the normalized standard deviation of the temperature from heating by a complex heat source consisting of mobile instantaneous point and linear energy sources. Proposed in this work are both an algorithm for finding solutions using an optimality criterion and the results of calculations for plates with thicknesses of 0.12cm and 1.2cm from the AMG-6 material, which were compared with experiments carried out under laboratory conditions.

1. Introduction

Welding is one of the most important technologies in industrial production. Depending on the production requirements, various methods of welding have been developed and are now being widely used. Among these, electron-beam welding (EBW) provides a solution to most of the problems regarding the design and manufacturing of structural metallic materials [1-5].

In the heart of electron-beam welding lies the ability of an electron beam to create on a small area of a surface high heat flux densities sufficient for heating, melting or vaporizing practically any material. This is due to the thermal effect of the radiation absorption by opaque solid materials.

The main advantages of electron-beam welding are provided by the achievement of a high energy density in the electron beam, the controllability of its parameters and the possibility of fully automating the welding process.

Reasons for the wide application of electron-beam welding include high welding speed, ability to create deep and narrow welds and a minimal value for the thermal influence zone.

2. Physical modelling of processes in electron-beam welding

Despite the fact that electron-beam welding has been used in industrial production for a long time, the physical processes in the interaction of an electron beam with metal have not been fully studied. There are several factors which have led to the creation of simplified physical models of the electron-beam welding process. These include the complex nature of interaction between the intense energy flow and the material being welded in the interaction zone in solid, liquid and gaseous states; insufficiently studied mechanism of electron beam penetration into the metal; as well as the complex dynamics of the liquid bath in the metal and the vapour-plasma flows. In most cases, instead of an accurate description in existing models, a crude approximation of the processes is used. The actual distribution of the electron beam power in the zones where it interacts with metal is the function of coordinates and time. The reason for this is the complex nature of the processes occurring during electron-beam welding.

The sufficient description of all the processes associated with welding is further complicated by the fact that there is no formulation of the processes as completely adequate general equations or statement of the corresponding initial and boundary conditions. As a result, the physical models proposed in the literature are greatly simplified and are based on the assumption of the quasi-stationary existence of the penetration channel and the weld pool.

Analysis of the processes of energy distribution injected by the electron beam into metal during welding is the basis of most attempts to relate the parameters of electron-beam welding to the geometric characteristics of
welded seams. However, since the dimensions of the weld pool are small, the heat field in the rest of the welded part can be calculated as an approximation of heat propagation in solid metal heated by a point source or a linear source of heat, which gives fairly accurate results for practical use.

Based on the general theory of Rosenthal-Rykalin, in which an infinite body is heated by a moving point or linear heat source, taking into account characteristics of the electron beam, formulas and nomograms were obtained to calculate the geometrical parameters of welded seams for the electron-beam welding of thin plates [6], as well as for the depth of the liquid metal layer with an electron-beam thermal modification of the surface [7]. In this case, a high level of correlation between the calculated data and the experimental results was obtained.

The necessity of increasing the complexity of physical models and determining characteristics of an electron beam, as well as that of controlling real heat transfer in the welded part, requires creation of adequate statistical models for electron-beam welding. Statistical approach can provide a choice of process parameters for a particular welding mode and the material of the unit to be welded. A model approach to improve the accuracy of calculations applied to the conditions of mass production is given in [8].

The main problem of electron-beam welding is to obtain a reproducible cross-section of the welded seam. At present, in most cases this is achieved by the empirical selection of welding modes on control samples with cutting, preparation of sections and analysis of the weld cross section. After selecting the necessary modes for the same setting of the electron beam welding installation and on the same material, the required welds are performed. In this case, reproducibility is provided only at a specific welding installation and until the scheduled maintenance work (for example, changing the cathode).

At present, various models of thermal sources are used to calculate the dimensions of the weld pool and the heat-affected zone, which are still used to a greater extent for research purposes. Existing models include a large number of difficulties to determine parameters that depend on the welding mode. Determination of these dependencies is possible by solving the optimization problem using the appropriate experimental data. Such calculations require a lot of time and highly-qualified researchers.

The publications of Russian and foreign researchers reflect models of volumetric energy sources, which propose to predict the shape of the melting channel. The proposed models are presented both in the form of regular geometric shapes [9-16], and in more complex ones that take into account the convection in the weld pool and a functional-analytical technique for calculating temperature fields [17-19]. In [20], the model was built on the basis of collection and statistical evaluation of the experimental data for the EBW process. The task was to minimize the area of the weld. This problem was solved using a binary genetic algorithm with penalties. The solution turned out to be close enough to the global optimum. In [21] the heating source was estimated with the Levenberg-Marquardt algorithm. After this, a complete simulation of the heating process was presented. The Levenberg-Marquardt algorithm was used to analyse the sensitivity of measurements. The sensitivity analysis showed that measuring the temperature at a distance of 2.5 mm from the heating source line does not make it possible to identify the parameters of the electron beam. The study showed the expediency of using the Levenberg-Marquardt method to identify the source of heat.

It should be noted that the disadvantages of existing thermal models require current design approaches and computer modelling to be improved, and also experimental techniques for monitoring and controlling the electron-beam welding process to be developed.

When creating new products and structures from new materials using electron-beam welding, it is important to choose such parameters of the technological process that ensure the required characteristics of the welded seam. In cases of welding products with small penetration thicknesses, not so many parameters need to be selected to ensure the required characteristics of the welded seam. Such parameters include welding amperage, focal length and welding speed. Often such welding processes last for seconds and determining the required mode on analogue samples under production conditions is a rather laborious operation. Currently, the choice of these parameters is based on available modes, or on the recommendation of literature sources [9].

3. The method electron-beam welding modes finding

The authors propose a method for finding electron-beam welding modes based on the classical representation of an electron beam in the form of moving point and linear instantaneous energy sources. Together with the models of the thermal process accepted for consideration, their limitations are taken into account and the temperature limitation is introduced, at which the appropriate thermal coefficients are used. The essence of the proposed method is application of the optimality criterion for calculating the basic parameters of the electron-beam welding technological mode. As a functional in the criterion, the mean-square deviation function [22] of the normalized temperature of metal heating $\frac{T_r}{T_{E}}$ at the final moment of time $t = t_f$ is proposed:
where \( n \) is a sample in the fixed volume of heated metal.

The criterion of optimality is the minimum of the functional (1) in the fixed volume of heated metal with a variation of the parameter for which the solution is being searched.

From a physical point of view, the minimum of the proposed functional is proportional to the minimum scattering of the heating temperature in the fixed volume of metal. If we introduce volume restrictions on this function, then we can assume the following: in the case of uniform heating of the material, i.e. minimum temperature scattering in the volume under consideration, the probability of uniform melting of metal will be the highest. This will entail the formation of the seam with the best quality indicators. The introduction of normalized indicators increases the sensitivity of the criterion, which is especially important for temperatures not exceeding the temperatures of the phase transitions of the welded materials.

The calculation of the functional is based on the classical theory developed by N.N. Rykalin in the middle of the 20th century, suitable for analysing the temperature fields in bodies when they are heated with various sources of heat. In the derivation of expressions describing the temperature fields of mobile sources, we use the principle of superposition [23].

\[
J = \frac{1}{n-1} \sum_{i=1}^{n} \left( T_{\text{eff}}(Q, v, t_i) - T_0 \right)^2 \rightarrow \min_{Q, v, t_i}
\]  

(1)

where \( T_{\text{eff}}(Q, v, t_i) = \frac{T_i(Q, v, t_i)}{T_{\text{max}}} \)

The representation of the heating source in the form of a sum of two instantaneous moving sources (2): point \((T_i(Q, v, t_i))\) and linear \((T_2(Q, v, t_i))\), is due to the need to take into account the effect of the product thickness on the thermal field.

The chosen formulas depend not only on the characteristics of the material being welded, but also on the electron beam energy parameters. Instant source models are valid for metals and alloys, provided that the physical characteristics of the material do not change when heated. To this end, as the initial temperature of the search for the integration time and the limits of integration of the thermal models we take the one to which the numerical values of the thermo-physical coefficients of the alloy correspond. For example, for aluminium alloy AMG-6, the thermal conductivity coefficient \( \lambda = 1.17 \text{ W/cm}^2\text{K} \) and the volumetric heat capacity \( cp = 2.43 \text{ cm}^3 \text{g}^{-1} \) are determined for the temperature 100°C.

The thermal field generated by the heating of the material is by nature not stationary. Therefore, in order to prove the proposed functional to be an optimization criterion, it is necessary to determine the integration time, the parameters of the fixed volume of the metal, and the integration step for calculating the thermal field when the material is heated with the selected complex energy source.

It is important to choose the step in calculating the integrals in the models of the thermal field. Studies have shown that in order to find the region of variation of the investigated parameters, where the functional undergoes extreme value, the integration step is chosen so that the lines of the graphs are smoothed out. Thus, for example, for the AMG-6 alloy, the integration step was selected as \( \Delta = 0.0005 \text{cm} \). In the future, with refined calculations, in order for the graphs of calculated dependences to be uniform, the integration step had to be reduced to \( \Delta = 0.00025 \text{cm} \). This greatly increased the computing resource, however, it increased the accuracy of calculations.

Based on the results of long-term studies of the functional behaviour of various materials and their thicknesses, the authors developed an algorithm for computing the parameters of technological process, which are recommended for the future use in electron-beam welding.

4. Experimental study

At the first stage, the integration time is searched. To do this, we limit the heating temperature for the AMG-6 alloy to 100°C and compute the values of the functional (1) for the selected heating source. As a result, we obtain a dependence graph of the functional for the integration time (Fig. 1). On the graph, we determine the time coordinate in which the functional undergoes the extreme value (minimum); this time is subsequently taken for calculations.
This graph is a curve constructed for the fixed value of energy of the heating source $Q$. The analysis of families of such curves constructed for different $Q$ sources allowed us to localize those energy values for which the optimization criterion of the chosen functional was apparent. For this purpose, the slopes of the right branch of the curve were compared (Fig. 1).

The graph of coefficients is presented in Fig. 2.

The graph (Fig. 2) is constructed for a plate 0.12 cm thick with the AMG-6 material. In the range of the energy source $Q = 70 \ldots 95 \, \text{j}$, the energy value $Q = 85 \, \text{j}$ was determined, for which the selected optimization criterion is effective. For an accelerating voltage of 30 kV, this energy corresponds to welding amperage of 13 mA.

There can be more than one local extremum since the energy of the source ensuring effective heating of the metal is not always known. Therefore, when specifying a sufficiently wide range of energy changes in the calculations, there may be several extrema on the graph. For example, when calculating for a plate with a
thickness of 1.2 cm, there were two local extrema (Fig. 3). However, further calculations showed that not all local regions have solutions for the chosen optimization criterion. For a plate 1.2 cm thick, the functional became a minimum at the extremum point only in the energy region of the source $Q = 700 \, \text{J}$. And in the field $Q = 840 \, \text{J}$ the functional changed monotonically.

Figure 3. The plot of energy dependence of the $Q$ source on the slope of the right branch of the curve $k$ (for a plate 1.2 cm thick)

From the energy parameter $Q$ found it is not difficult to calculate the necessary values of accelerating voltage $U$ and welding amperage $I$ using the formula:

$$Q = 0.24 \cdot U \cdot I \cdot \eta$$  \hspace{1cm} (3)

where $\eta$ is the efficiency (for EBW $\eta \approx 0.84$).

The second stage includes the search for temperature threshold that specifies a fixed volume in the material that ensures manifestation of the functional properties as an optimization criterion. Using the integration time obtained at the first stage, we plot the dependence of the functional on temperature (Fig. 4). On the graph, we determine the coordinate of the threshold temperature, in which the functional undergoes the extreme value (minimum). At this stage, we also calculate the width of the limited heating zone, which is equivalent to the width of the welded seam. This parameter can be used to predict the width of the seam for the case of changing technological welding modes, such as welding speed, welding amperage and change in focal length.

Figure 4. The plot of the functional $J$ dependence on temperature threshold $T_{\text{thm}}$ of $^{\circ} \text{C}$
For a greater manifestation of the extreme properties of the functional at the first and second stages of the calculation, at each step of integration the variation of welding speed in the realizable range of the investigated material was used: $t = 0.1 \ldots 3.0 \text{ cm/s}$.

Having obtained the integration time and boundaries for calculating the welding parameters using the extreme properties of the functional, we proceed to direct determination of these parameters. Figure 5 shows the graph of the functional dependence on the welding speed. On the graph, we determine the velocity coordinate, at which the functional undergoes the extreme value (minimum).

![Figure 5. The dependence of the functional $J$ on the welding speed $v$](image1)

By performing analogous calculations and changing numerical energy values of heat sources $Q$, we can consolidate the extrema obtained in the calculations in the form of amplitude dependence graphs of the functional $J$ extrema (Fig. 6) for an AMG-6 alloy with the thickness of 0.12 cm.

![Figure 6. The dependence graph of the functional $J$ on the energy source $Q$](image2)

These three graphs are of the greatest practical interest when choosing welding modes for a particular material with a fixed penetration depth or the corresponding thickness of the welded plate.
The extremum of the functional is obtained only for fixed parameters of variation intervals of coordinates \( x \) and \( y \), which are characteristic for a particular thickness and the material to be welded. Currently, studies are under way to develop a search algorithm for these quantities.

Thus, it can be assumed that the welding speed for products of other thicknesses or in the case of complex configurations of joints can be selected using the calculation method presented in this paper. The application of the theory of the thermal field and the criterion of a minimum of the functional proposed by the authors allows us to calculate not only the welding speed and optimize the power of the electron beam, but also to select these parameters according to the expected width of the weld for products of various materials and their combinations (bimetals), and in the process of welding only adjust this parameter.

The authors also proposed a method for modelling the effect of the focal plane position of the electron beam on the thermal process relative to the heated material surface. The effect of the focus of the electron beam on the thermal process of heating can be modelled if the instantaneous point source along with the linear source is moved along the entire depth of metal \( z_f \) in the selected combined energy source. The graph of dependence of the functional \( J \) on the depth of the electron beam penetration \( z_f \) is shown in Fig. 7.

![Figure 7. The dependence graph of the functional \( J \) on the depth of the electron beam penetration \( z_f \) [cm]](image)

In case with a work piece thickness of 0.12 cm, the minimum value of the functional indicates the practical coincidence of the focal spot of the electron beam with the surface of the part.

Calculations showed that when the amperage and the welding speed change on the part with the same thickness, the position of the focal spot does not change.

When modelling a thermal heating process, the calculations used characteristics and test results of the samples obtained with electron beam equipment with an accelerating voltage of 30 kV.

5. Conclusion

Application of the optimality criterion, taking into account the uniformity of heating the weld pool, allows to determine the main parameters of the technological mode of electron beam welding: the welding amperage, focal length and welding speed.

Numerical modelling of thermal processes to determine EBW parameters will significantly reduce the cost of technology development for structures from new materials.

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