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Modelling of the welded seam parameters at electron-beam welding

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Abstract. The article presents the results of technological parameters mathematical modeling when heating a titanium alloy by energy sources equivalent to an electron beam in electron-beam welding. Analysis and evaluation of simulation results was carried out using the criterion of optimality proposed by the authors. As a tool for calculations, the authors used a functional based on mathematical models of metal heating by a complex heat source consisting of mobile instantaneous point and linear energy sources. The results of calculations for a 0.12 cm thick plate are given in the paper. They were compared with the data obtained from prototypes from the VT-14 material using the design welding regimes carried out in the laboratory on an A306.13 electron beam unit.

1. Introduction

Electron-beam welding (EBW) is one of the promising and still actively developing methods of joining parts from various metals. Most often EBW is used for joining refractory, chemically active and dissimilar high-quality steels, as well as high-strength alloys based on aluminum and titanium. EBW allows connecting in one pass a material from 0.1 to 400 mm thick, while ensuring maximum plasticity and viscosity of welded joints.

Electron-beam welding is based on the use of thermal energy, which is released when the sharp-focused flow of electrons accelerated to high energies. The very phenomenon of the electron beams thermal impact on solid materials was already known in the XIX century, but this source of heating was developed only in the second half of the 20th century. This development is associated with the development of vacuum technology and electronic optics.

In work [1] the process of electron-beam welding as a whole is considered. It is proposed to conduct research on various metals and in various branches of engineering. Also, the authors note the promise of using electron-beam welding for joining dissimilar materials. A limited amount of available information on the connection of dissimilar materials stimulates research in this direction.

The promise of electron beam welding for joining different material alloys led to a new wave of research, for example, works [2-7]. The authors of these papers have studied electron-beam welding on various metal alloys. Also, in these works, the most suitable parameters of the technological process are selected, applied to the specific material selected by the articles authors.

In [8], an estimate of the heating source by the Levenberg-Marquardt algorithm is given. After this, a complete simulation of the heating process is presented. The Levenberg-Marquardt algorithm was used to analyze 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 is shown in [9] that with the help of the focusing parameter, the tuning of the welding process by an electron beam can be performed with high accuracy, in accordance with the desired values of the seam characteristics. The authors have obtained the recommended values of the focus position towards the surface of the welded material, which ensure the greatest efficiency or depth of welding. The same author in [10] carried out a statistical analysis of experimental data on electron-beam welding of stainless steel samples. Based on the results of statistical processing, a model is constructed on the basis of the distance between the electron gun and the plane of beam focusing, and also to the surface of the sample. The simulation results coincide with the obtained experimental data. The model makes it possible to predict the geometrical characteristics of a seam when working in a limited area of parameters of the electron beam welding technological process.

It was shown in [11] that electron-beam welding is suitable for joining various alloys in the most economical way. Within the framework of this work, a mathematical model of electron-beam welding was developed, on the basis of which the stability of the materials melting process being bonded is increased. By solving the equations of the given thermal process model using the finite element method, adequate parameters of the technological process are obtained depending on the materials to be connected.

In the process of manufacturing new products and structures using electron-beam welding, it is important to choose such technological process parameters that ensure the required characteristics of the welded seam. When welding products with a shallow penetration depth, there is a need to select the welding current, focal length and welding speed. To ensure minimum deformation of the welded parts bodies, the following conditions must be met: for the depth of the welded seam 0.1-0.2 cm, the ratio of the penetration depth to the width of the seam is greater than or equal to one. Often the duration of the welding process is measured in seconds, so experimenting with the required mode on samples under production conditions is a rather laborious operation. Currently, the choice of these parameters is carried out from available modes, or on the recommendation of literature sources [12].

2. Modelling method

Calculations of the technological regime parameters of electron-beam welding were performed by the authors of this article using the proposed functional, based on the source models from the thermal process theory. The process of metal heating during welding is non-stationary, so the calculation of the functional is carried out at fixed values of the integration time (*t*) and the heated volume of the material (*V*):

$$J = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(T_{Ii} - \overline{T}_I)^2}\Bigg|_{\substack{t=const \\ V=const}}; \tag{1}$$

where $T_{Ii} = \frac{T_{\sum i}}{T_{max}}$, $T_{max} = maxT_{\sum i}$, T_I – initial temperature of the material [^{0}C], t – integration time interval [sec.], V – the heated volume of the material [cm^3].

The functional calculating is based on the classical theory developed by N.N. Rykalin in the middle of the 20th century, suitable for analyzing the temperature fields in bodies when they are heated by various sources of heat. When deriving expressions describing the temperature fields of mobile sources, we use the principle of superposition [13].

$$T_{\sum i} = T_{1i} + T_{2i}; \tag{2}$$

where T_{1i} – point heating source [^{0}C], T_{2i} – linear heating source [^{0}C].

$$T_{1i} = T_H + \frac{2q}{c\rho\sqrt{(4\pi a)^3}} e^{-\frac{vx}{2a}} \int_0^t exp\left(-\frac{v^2\tau}{4a} - \frac{R^2}{4a\tau}\right)\frac{d\tau}{\tau^{3/2}}; \tag{3}$$

$$T_{2i} = T_H + \frac{q}{4\pi\lambda\delta} e^{-\frac{vx}{2a}} \int_0^t exp\left(-\frac{v^2\tau}{4a} - \frac{2\lambda\tau}{c\rho\delta} - \frac{(x^2+y^2)}{4a\tau}\right)\frac{d\tau}{\tau}; \quad (4)$$

where T – material temperature [^{0}C], (x, y, z) – coordinates [cm], q – heating source energy [J], v – heating ratio [cm/sec.], t – integration time interval [sec.], $c\rho$ – bulk heat capacity of the material [J/(cm^{2}K)], a – thermal diffusivity of material [cm^2/sec.], R – radius [cm] ($R=(x^2+y^2+z^2)^{1/2}$), τ – current integration time [sec.], δ – interval [cm], λ – coefficient of thermal conductivity [W/(cm K)].

The representation of the heating source in the form of two instantaneous moving sources is caused by the need to take into account the effect on the thermal field of the material thickness.

To determine the welding speed, the integration time and the limits of the heating volume, an optimality criterion is used, which is the minimum of the functional (1):

$$t = F_t \to \min_J; V = F_V \to \min_J; v = F_v \to \min_J. \quad (5)$$

Functions F_v, F_t, F_V are formed from the values of the functional (1) with the variation of the corresponding values:

$$F_t = \frac{var(t_{min} \div t_{max})}{J}; F_V = \frac{var(T_{min} \div T_{max})}{J}; F_v = \frac{var(v_{min} \div v_{max})}{J}. \quad (6)$$

The proposed optimality criterion has the following features: the criterion's nature has a physical semantic orientation; the criterion has extrema at characteristic values of variable parameters.

From a physical point of view, the minimum of the proposed functional is proportional to the minimum scattering of the metal heating temperature. If we introduce volume restrictions on this function, then we can assume the following: in case of uniform heating of the material, i.e. minimum temperature scattering in the volume under consideration, the probability of the metal uniform melting will be the highest. What will entail the formation of the seam by 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 models of thermal sources (3,4) contain not only the characteristics of the material being welded, but also the energy parameters of the electron beam. These models are valid for metals and alloys, provided that the physical characteristics of the material do not change when heated.

3. Experimental study

Based on the results of numerous studies of the functional behavior for various materials and their thicknesses, the authors developed an algorithm for calculating the parameters of the technological process, recommended for use in electron beam welding.

At the first stage, the values for (5) are searched. To do this, the graphs of the functions (6) are successively formed. For example, in figure 1, the definition of the time coordinates in which the function F_t undergoes an extreme value (minimum) is presented. This time is subsequently accepted for calculations.

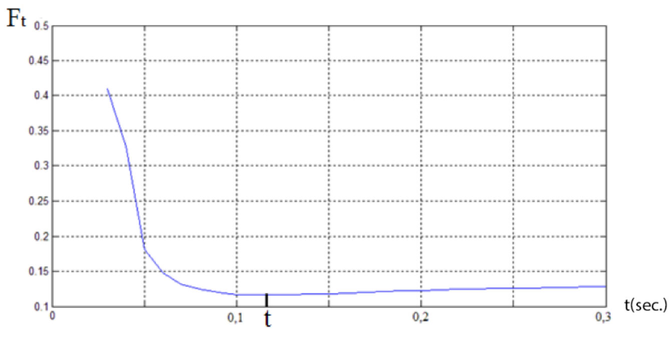


Figure 1. The graph of the dependence of the function F_t on the integration time t.

Using the integration time obtained in the calculations, the dependence graphs of the functions F_V and F_v on temperature are plotted in the same way, according to which the coordinates of the optimum temperature of the threshold and the welding speed are determined, respectively.

Carrying out similar calculations, changing the welding current, it is possible to reduce the extremums obtained in the calculations in the form of welding speed dependence graphs (figure 2) and the equivalent width of the weld (figure 3) from the corresponding welding current for a titanium alloy with a thickness of 0.12 cm.

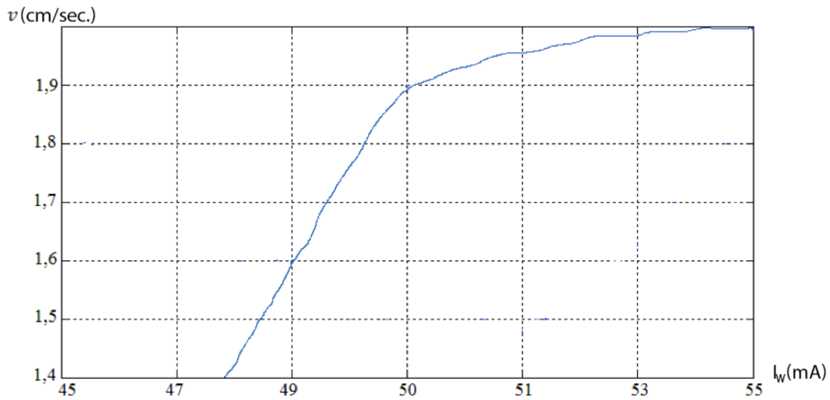


Figure 2. Graph of welding speed on the welding current dependence.

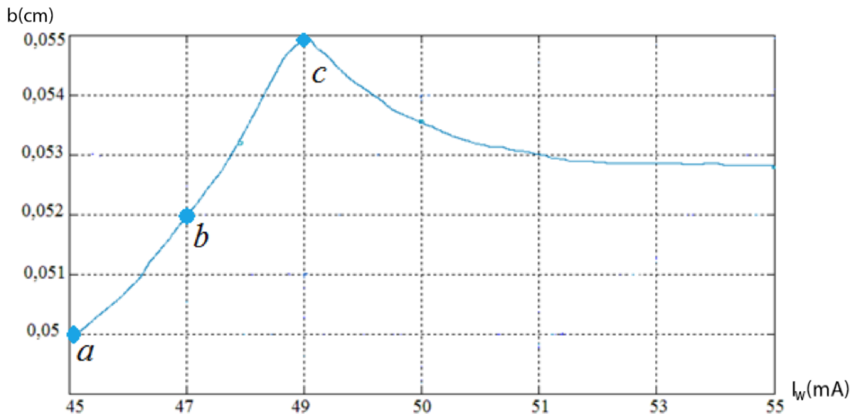


Figure 3. Graph of channel width equivalent on the welding current dependence.

These two 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.

Figure 4 shows photos of macrosections of welded joints with dimensions obtained experimentally on the modes selected from the graph in figure 3 (points a, b, c).

Experimental data confirm the possibility of selecting the welding mode according to the calculated schedule (figure 3) to obtain the expected seam dimensions.

Thus, it can be assumed that the selection of the welding speed for products of other thicknesses or in the case of complex configurations of joints can be carried out by the calculation method presented in this work. The application of the thermal field theory and the criterion of the proposed functional minimum 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 welding process, only adjust these parameters.

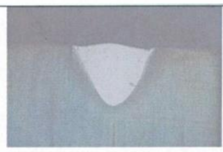
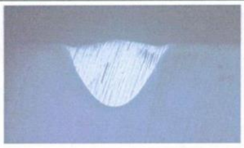
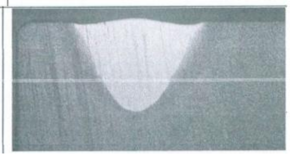
Regime	Depth of penetration, mm	Seam width, mm	Photo
a	1,32	1,84	
b	1,20	2,00	
c	1,76	2,48	

Figure 4. Photos of welded joints macrosections with dimensions obtained experimentally under the "a, b, c" regimes.

4. Conclusion

The article proposes a method for calculating the current and speed of welding, as well as the focal length of the electron beam relative to the welded surface, which is applicable for the development of welding technology for new designs of products from various materials. Numerical modeling of thermal processes for determining EBW parameters has also been carried out, which makes it possible to significantly reduce the costs of developing technologies for structures made of new materials.

The results of the calculations and experimental studies formed the idea of the possibility of using the above method to optimize not only the welding and focusing speed of an electron beam by computational method, but also other parameters to minimize the costs of electron-beam welding.

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