Penetration shape control with correction of the state variables evaluation during electron-beam welding by the level of active disturbances

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Abstract. Penetration shape during electron-beam welding is determined in the first approximation by the vapour plasma crater shape formed by the energy source. The inability to measure the parameters of penetration shape during electron-beam welding leads to their estimation by regression equations that establish a relationship with mode parameters. However, when welding mode parameters are stabilized, the instability of penetration shape remains due to the action of uncontrolled disturbances, which in some cases lead to unacceptable deviations. A possibility of the state variables evaluation correction during electron-beam welding, namely the depth penetration and the weld shape factor, by determining the "noise component", is considered. Such correction is carried out by the discrepancy of any measured output variable, as the difference between its estimate according to a similar mathematical model and the measured value. As such output variable, the vapour plasma torch light intensity can be used. A control algorithm and a structural diagram of the automatic control system for weld penetration shape with correction of model assessment of the process state by the measured output have been developed.

1. Introduction

One of the main disadvantages of electron-beam welding is the lack of stability of the melt properties during non-through penetration, in particular, the depth penetration and the weld shape factor. Until now, attempts to improve the properties of the formed weld by controlling the process have mainly been reduced to the use of classical control schemes, in particular, single-circuit feedback systems. Joint tracking systems can serve as an example of such systems.

There are also known automatic control systems that control one of the process variables based on the measurement of various types of radiation from a vapor-plasma crater (X-ray, ion, electronic, etc.) [1–2] by a sensor. The remaining variables are ignored, the hidden relationship between them and the complex nature of their influence on the weld penetration shape are not taken into account. Naturally, such regulatory systems, with many advantages (ease of implementation, reliability, low cost), are ineffective and in most cases give unsatisfactory results for practice.

With an increase in the penetration depth, the correlation of charged particles emission and thermal radiation from the channel during electron-beam welding worsens, and regulation by feedback systems becomes impossible. Under these conditions, the stabilization of the mode parameters improves the
situation, reducing the spread of the properties of welds made by electron-beam welding. However, the practice has shown that welding with stabilization of the main mode parameters up to 1 ... 0.05% does not solve the problem of fluctuation of penetration area shape, which even in this case may exceed 10%. This is explained by the fact that the welding process as a control object has, to some extent, a probabilistic character, and its state vector contains a random component, the value of which is subject to uncontrolled dispersion due to the action of uncontrolled disturbances. Significant uncertainty is introduced by measurement errors, noise, and random disturbances, as well as by a violation of the adequacy of state variables estimation models [3–4].

2. Problem Statement
In control theory, there are methods of sequential or recurrent estimation that allow one to obtain estimates of states during the process by recalculating existing estimates when the next portion of measurement data arrives. Then the control algorithms use already updated estimates. In general, estimation is the problem of restoring the state of the system based on information about its inputs (controls and disturbances) and outputs. Usually, filtering is used for this, when the estimation of the state at time $t$ needs to be formed from information received at time $t = t_i$ or a forecast, an estimation of the state at time $t$ needs to be formed from information received before the moment of time $t_i < t$ [5].

The model of the electron-beam welding process can be represented as a multidimensional object of the state space, which is understood as an $n$-dimensional arithmetic (Euclidean) space $R^n$. Let some region $X \subseteq R^n$ be defined in this space, each element $x$ of which (column vector) completely determines the state of the process (Figure 1) [4].

![Figure 1. Diagram of the representation of the object model from the position of the state space: $u(t)$ – vector of controls; $w(t)$ – vector of disturbances; $x(t)$ – vector of states; $y(t)$ – vector of outputs; MD – measuring device; $\eta(t)$ – vector of measurement noise.](image)

The main geometric parameters of the crater, as a paraboloid, determining weld penetration area section shape, can be considered the depth $H$ and radius $R$ of the crater top part. The same parameters: depth and width $B = 2R$, are the main ones used in production to characterize the weld shape [6]. The process state variables will be the depth penetration $H$ and the weld shape factor $K = H/B$, as well as the brightness $E$ of the torch from the vapor-plasma crater, which can be measured during welding as an output variable. Linear regression equations for the parameters of electron-beam welding mode as components of the control vector, which are obtained by the experiment planning method, will be used as mathematical models for estimating state variables [7–9].

This model is very convenient for monitoring and controlling the process and allows to interpret of the physical side of the phenomenon. In this case, the response function, due to the action of disturbances, is taken as the mathematical expectation of a specific random state variable under the condition of the action of $m$ factors, that is, its average value is taken [7]:

$$\hat{x}(u) = M\left[x | u_1, u_2, \ldots, u_m\right] = \bar{x}(u),$$

(1)

where $x$ is the state variable; $u$ is the vector of factors (mode parameters $u_i$); $\hat{\ }$ is the evaluation symbol; $\bar{\ }$ is the averaging symbol; $\bar{x}(u)$ is a vector column of mode parameters (they are also factors) that are used as control actions. The regression equations include normalized values of the factors $u_i = (\bar{u}_i - u^0_i)/\delta u_i$, as the ratio of its deviation from the main level of the factor to its range of variation, that is, $|u_i|\leq1$. 


3. Development of Algorithm and Structure of Control System

We shall construct a system of stabilization for the given geometric parameters of the weld shape, namely: the depth \( H_0 \) and the weld shape factor \( K_0 \) (the constants of the regression equations). They correspond to zero values of control action \( u_i = 0 \), and the welding mode corresponds to the center of the factor space \((u^0_1,u^0_2, \ldots, u^0_m)^T\). This is possible under the condition of a stable energy source when the level of disturbances does not exceed the error of the estimated model. The presence of disturbances \( w(t) \) leads to the fact that the current shape state variables will differ from the values calculated using the mathematical model (1) by the value of the second component:

\[
\hat{H}(t) = H + \alpha_H \xi(t),
\]

\[
\hat{K}(t) = K + \alpha_K \xi(t),
\]

where \( \xi(t) \) is the total level of disturbances acting in the circuit, \( \alpha_H \) and \( \alpha_K \) are coefficients of the disturbance vector influence on the state variables of weld penetration area shape.

It is known that to correct the calculated values of the state parameters according to (2), taking into account changes in the conditions of the process, it is possible to use the difference between calculated from the model value and measured value of any component of the object state vector, which can be directly measured [5]. The difference between these values will characterize the influence of the disturbance vector on the electron-beam welding process (Figure 2).

In general, it is assumed that the control object model includes a random component \( w(t) \) due to uncontrolled disturbances or inaccuracy of the model. The output \( y(t) \) is a function of the state vector \( h(x) \), it is measured with an error \( \eta(t) \). Thus, state and output are random processes, and it is assumed that statistical properties of the random processes generating them \( w(t) \) and \( \eta(t) \) are known. The magnitude of the estimation correction is regulated by the coefficient \( D(t) \), which depends on the properties of the disturbances.

As such output variable \( y(t) \), depending on the state of the electron-beam welding process, the light output \( E(t) \) of a vapor plasma torch can be taken, the regression equation of which, depending on the mode parameters, was obtained simultaneously with the dependencies for the shape parameters, according to a similar planning matrix. The light output was measured at a right angle to the beam axis at a point lying at a distance of 40 mm from the surface of the welding pool using a photoelectronic multiplier, but it is also possible to use a photodiode. Its value, similar to (2), can be represented by the equation:

\[
E(t) = \bar{E}(u) + \alpha_E \xi(t),
\]
where the second component represents the increment of the luminous flux due to disturbances, $\alpha_E$ is the coefficients of the disturbance vector influence on the light output of the vapor plasma torch.

Then from equation (3), it is possible to express the total level of disturbances:

$$\xi(t) = \frac{E(t) - \bar{E}(u)}{\alpha_E} = \frac{\Delta E(t)}{\alpha_E},$$

(4)

After substituting (4) into (2), it is possible to obtain the value of the depth and shape of the weld penetration area, taking into account the active disturbances estimated by the increment of the torch luminous flux:

$$\hat{H}(t) = \bar{H}(u) + \frac{\alpha_H}{\alpha_E}\Delta E(t) = \bar{H}(u) + \gamma_H\Delta E(t),$$

$$\hat{K}(t) = \bar{K}(u) + \frac{\alpha_K}{\alpha_E}\Delta E(t) = \bar{K}(u) + \gamma_K\Delta E(t).$$

(5)

The coefficients $\gamma_H$ and $\gamma_K$ are determined from equations (5), minimizing the sum of squared errors of the predicted values $\hat{H}(t)$ and $\hat{K}(t)$.

Based on equations (5), it is possible to record the deviation of the current geometric parameters from their values $H_0$ and $K_0$, which in this particular case it is necessary to provide by welding technology:

$$\Delta H(t) = \hat{H}(t) - H_0 = \bar{H}(u) + \gamma_H\Delta E(t) - H_0,$$

$$\Delta K(t) = \hat{K}(t) - K_0 = \bar{K}(u) + \gamma_K\Delta E(t) - K_0,$$

(6)

According to the deviations obtained, according to the accepted control goal, control actions are formed, as which the beam current and welding speed are selected, the focusing current is reserved for regulation in the electron beam control circuit. It can be shown that two control actions are sufficient.

The system of linear equations compensating for these deviations by incrementing the selected controls in the normalized form $\Delta i$ and $\Delta v$ at the time of states correction can be represented as:

$$\Delta H = \theta_1\Delta i + \theta_2\Delta v,$$

$$\Delta K = \theta_1\Delta i + \theta_2\Delta v,$$

(7)

where $\theta_i; \theta_i (i = 1, 2)$ are the coefficients of the regression equations $\bar{H}(u)$ and $\bar{K}(u)$ for the corresponding mode parameters. By resolving the system with respect to the increment of control actions, it is possible to obtain:

$$\Delta i = (\Delta H\theta_2 - \Delta K\theta_1) \big/ (\theta_1\theta_2 - \theta_2\theta_1),$$

$$\Delta v = (\Delta K\theta_1 - \Delta H\theta_2) \big/ (\theta_1\theta_2 - \theta_2\theta_1).$$

(8)

Finally, taking into account the accepted normalization, the actual values of the controls increments necessary to compensate for deviations in the weld geometric parameters can be written as:

$$\Delta I = \Delta i \cdot \delta I,$$

$$\Delta V = \Delta v \cdot \delta V,$$

(9)

where $\delta I$ and $\delta V$ are the various intervals of beam current and welding speed when determining the factor space. Based on the algorithm considered, it is possible to form the structure of the process control system (Figure 3).
However, the presence of such deterministic instability as the loss of cathode emission requires correction of the beam diameter, which will increase over time while maintaining the same beam current. The solution to this problem can be reduced to the stabilization of the beam diameter, which determines its melting ability. The current change in the serial source is carried out by changing the potential of the electron gun control electrode \( U_{ce} \). At the same time, the size of the electron escape zone from the heated cathode surface changes and, as a consequence, the size of the focal beam spot changes too [8; 10; 11]. In this regard, current control leads to a change in the beam diameter. A similar situation is observed with the loss of cathode emission.

At stable values of the filament current and cathode bombardment, the beam diameter is affected by such factors as beam current, control electrode potential, and focusing current. A complete factorial experiment was conducted for these three factors. The dimensions of the identified area of these factors space were \{40 mA; 0.6 kV; 10 mA\} centered at the working point \( (I^0; U^0_{ce}; I^0_f) = (80 \text{ mA}; 2 \text{ kV}; 0.99I_{ext}) \), where \( I_{ext} \) is the focusing current value corresponding to the maximum of penetration depth. The beam diameter was measured using the straight edge method [8]. As a result of the study, the dependence of the diameter in mm was obtained, adequately describing the experiment with a confidence level of 0.95:

\[
\bar{d}(u) = 0.69 + 0.096i - 0.046i_{ce} + 0.1i_f + 0.06i_f, \quad (10)
\]

where normalized values of factors are used. The variance of the experiment reproducibility was \( \sigma^2[d] = 0.002 \text{ mm}^2 \).

The beam diameter stabilization is carried out as follows. Welding is carried out with an electron beam, which diameter is \( d_0 \); it is somewhat unfocused to a minimum value. This allows adjusting the beam diameter enlargement by changing the focusing current until it reaches the value \( I_{ext} \). The control loop is organized without taking into account the influence of the remaining disturbances \( w_1(t) \). We note that the electron gun output parameters, including the considered beam diameter, are the input effects of the EBW process, and moreover they are perturbations (see Figure 3).

The system works as follows. The welding process is carried out, which is determined by an electron beam with a given beam current, welding speed, and degree of focusing, set by the focusing current magnitude. These current values of the mode parameters are also received at the input of the process model, which, according to equations (1), determines the assessment of the current values of the welding zone state variables, as well as the vapor plasma torch light intensity.

At the same time, the vapor plasma torch light intensity is measured directly by radiation from the area of the beam and metal interaction. The difference between the estimated and measured brightness is determined by the two values of the variable on the comparison element. Using the data obtained, as well as the values \( H_0 \) and \( K_0 \) required by the technology, which determine the purpose of control, deviations of the state variables current values from the set ones are calculated using equations (5) and (6). Moreover, these deviations are adjusted taking into account the effect of uncontrolled disturbances determined by the formula (4).

Based on the equations (7–9), the corresponding values of the control actions required increment for the beam current and welding speed are calculated. The beam current increment is fed to the regulator, which converts it into a corresponding potential change on the control electrode of the electron gun, which provides the required change in the beam current of the EBW process.

In addition to the potential of the control electrode, the current of the focusing system is also supplied to electron gun input as a control signal; it is used for beam diameter stabilization. Its deviation is determined based on a comparison of the current estimate according to the mathematical model (10) with the required value of \( d_0 \) on the corresponding comparison element.
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Figure 3. The control system scheme for weld penetration shape with correction of model assessment of process state by measured output: 1 – EBW process; 2 – electron gun; 3 – EBW process model; 4 – unit for calculating the weld geometry deviation; 5 – EBW process control calculation unit; 6, 8 – controller; 7 – electron beam model.

All the characteristics of the actual energy source are perturbations for the ELS process. For the operability of such system structure, their level should be very insignificant, so as not to go beyond the scope of the model definition.

4. Conclusion
Penetration shape during electron-beam welding is determined in the first approximation by the vapor plasma crater shape formed by the energy source. The inability to measure the parameters of penetration shape during electron-beam welding leads to their estimation by regression equations that establish a relationship with mode parameters.

A possibility of the state variables evaluation correction during electron-beam welding, namely the depth penetration and the weld shape factor, by determining the “noise component”, was considered. Such correction is carried out by the discrepancy of any measured output variable as the difference between its estimate according to a similar mathematical model and the measured value. As such output variable, the vapor plasma torch light intensity can be used.

A control algorithm and a structural diagram of the automatic control system for weld penetration shape with correction of model assessment of the process state by the measured output have been developed.

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