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A method of measuring the depth of the penetration channel during electron-beam welding

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Abstract. Penetration depth control is an important scientific and technical problem and the quality of welded joints largely depends on its solution. A mathematical model of the method of measuring the depth of the penetration channel during electron-beam welding has been developed. In order to determine the depth of penetration, the thickness of the solid metal under the keyhole produced by an electron-beam is measured. The measurement method is based on the use of X-ray radiation from the processing zone. The use of harmonic components of the signal, which are multiples of the scanning frequency, is a distinctive feature of the presented mathematical model of the X-ray sensor to monitor the thickness of the solid material under the cavity.

1. Introduction

Producing reliable welds with predetermined geometric parameters is the main objective of electron beam welding (EBW). The depth of the penetration channel is one of the main geometrical parameters characterizing the weld. Stabilization of the penetration depth in the process of EBW makes it possible to get rid of defects in the root of the weld seam, porosity and metal loss that occur during unwanted melting across the product.

The task of determining the optimal parameters of the welding process for given properties of the material being welded and the depth of the weld always arises in practice. As a rule, these parameters are the result of experimental studies or calculations using analytical expressions for the geometry of the penetration channel. Another solution to this problem is the direct control of the depth of penetration by means of measuring equipment and its stabilization.

The lack of appropriate sensors makes it impossible to directly measure the depth of the penetration channel. Therefore, the thickness of the layer of solid material under the cavity is measured by X-ray radiation from the treatment area using an X-ray sensor located on the back side of the weld.

Experimental studies by the authors of this work have revealed that the transformation of a dynamic channel of penetration into a stable vapour-gas cavity for the entire depth of penetration is possible by selecting appropriate trajectories and amplitudes of scanning of the electron beam. In this case, the quality of welded joints is improved [1]. If the depth of the penetration channel is stable, then information on the thickness of the layer of solid material under the cavity can be obtained more qualitatively and with a minimum of interference. This technique is used in this work.

2. Mathematical model of the X-ray sensor for penetration depth

As is known, as a result of the interaction of the electron beam with the surface of the welded parts, X-ray radiation appears. The intensity of the X-ray radiation from the surface of the welded product can be determined from the following expression [2]

$$I_0 = kk_1 I_b Z U_0^2, \tag{1}$$

where k =1,5·10^{-9} V^{-1} is the coefficient of proportionality [3]; k_1 is the coefficient reflecting the spatial orientation of the sensor; I_b is the electron beam current; Z is the atomic number of the material to be welded; U_0 is the accelerating voltage.

Considering that the current density of the electron beam is distributed unevenly over the surface of the parts, the expression (1) can be written in the following form

$$I_0 = kk_1 U_0^2 Z I_b \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f_d(x,y) j_b(x,y) dx dy, \tag{2}$$

where $f_d(x, y)$ is the X-ray sensor review function; $j_b(x, y)$ is the normalized distribution of the beam current density on the part of the surface in x, y coordinates; here

$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} j_b(x,y) dx dy = 1.$$

A number of studies have shown that the normalized electron beam current density is described by a normal distribution law with sufficient accuracy [4, 5, 6]

$$j_b(x,y) = \frac{1}{\sigma_x\sqrt{2\pi}} \exp\left(-\frac{(x-\varepsilon_x)^2}{2\sigma_x^2}\right) \cdot \frac{1}{\sigma_y\sqrt{2\pi}} \exp\left(-\frac{(y-\varepsilon_y)^2}{2\sigma_y^2}\right), \tag{3}$$

where σ_x, σ_y are the standard deviations of electrons from the beam axis along the corresponding axes; ε_x, ε_y is the position of the beam axis in x and y coordinates.

If the joint is oriented along the y axis, then the X-ray sensor review function is independent of y. Then

$$f_d(x,y) = f_d(x).$$

If the current density distribution is also independent, then

$$j_b(x,y) = j_b(x) j_b(y).$$

In this case, the beam current density along the y axis is

$$\int_{-\infty}^{\infty} j_b(y) dy = 1,$$

and the expression (2) takes the following form:

$$I_0 = kk_1 U_0^2 Z I_b \int_{-\infty}^{\infty} f_d(x) j_b(x) dx \tag{4}$$

or

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$$I_0 = kk_1U_0^2ZI_b \frac{1}{\sigma_x\sqrt{2\pi}} \int_{-\infty}^{\infty} f_d(x)\exp\left(-\frac{(x-\varepsilon_x)^2}{2\sigma_x^2}\right)dx. \tag{5}$$

If the angle of incidence of the beam on the surface of the workpiece is 90°, then the X-ray radiation intensity distribution diagram has the shape of a circle. [7]. Thus, X-rays are distributed both in the space above the surface of the product, and in the material of the parts being welded.

The intensity of X-ray radiation passed through the layer of material and reached the X-ray sensor installed on the back side of the weld, as shown in Fig. 1, and decreases exponentially as a function of the distance travelled in the absorbent layer:

$$I = I_0 e^{-\alpha\delta},$$

where I_0 is the X-ray intensity above the surface of the product; δ is the thickness of the absorbent layer; α is the coefficient depending on the nature of the substance of the absorbing layer and the wavelength.

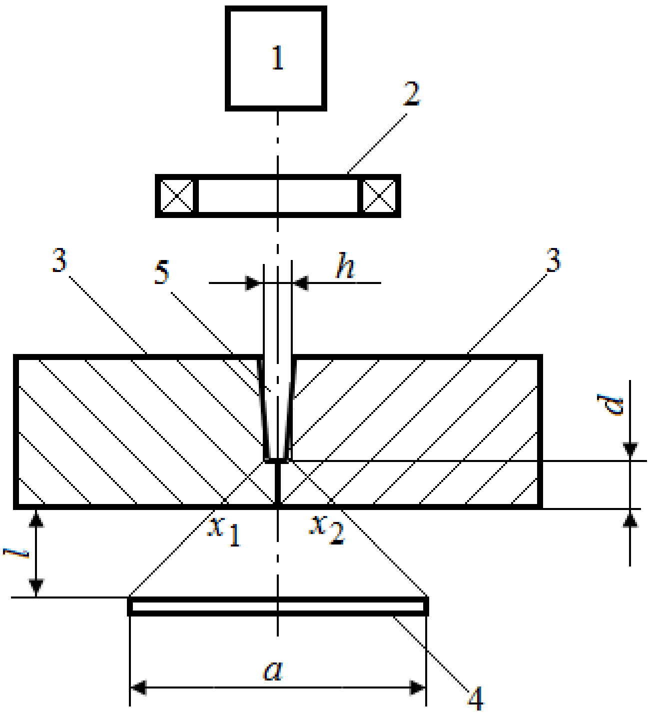

Figure 1. The scheme of installation of the X-ray sensor for monitoring the depth of the penetration channel: 1 - electron beam gun; 2 - deflection system; 3 - work piece; 4 - X-ray sensor; 5 -cavity.

This makes it possible to control the depth of the penetration channel by the magnitude of X-ray radiation from the treatment area.

When welding thick sheet metals, penetrating X-ray radiation from the surface of the parts decreases practically to zero to the opposite surface of the product. While penetrating, X-ray radiation from the lower surface of the penetration channel reaches the sensor and increases with decreasing thickness of the layer of solid material under the cavity. Since the walls of the penetration channel are close to being parallel, the penetration channel can be viewed as a kind of collimator limiting the sensor's field of view. Then the X-ray sensor review function will be as follows:

$$f_d(x) = \begin{cases} 1, & -\frac{h}{2} < x < \frac{h}{2}, \\ 0, & -\frac{h}{2} > x > \frac{h}{2}, \end{cases} \tag{6}$$

where h is the width of the penetration channel.

The X-ray intensity above the surface of the product in this case is determined by the expression

$$I_0 = kk_1 U_0^2 Z I_b \frac{1}{\sigma_x \sqrt{2\pi}} \int_{-\frac{h}{2}}^{\frac{h}{2}} \exp\left(-\frac{(x-\varepsilon_x)^2}{2\sigma_x^2}\right) dx. \tag{7}$$

The intensity of the penetrating x-ray radiation reaching the sensor is determined by the formula

$$I_d = I_0 \int_{x_1}^{x_2} \exp\left(-\alpha\sqrt{x^2 + d^2}\right) dx, \tag{8}$$

where d is the thickness of the layer of solid material under the cavity, as shown in Fig. 1; x_1 and x_2 are determined by the formulas:

$$x_1 = -\frac{da + lh}{2(l+d)}, \qquad x_2 = \frac{da + lh}{2(l+d)}. \tag{9}$$

Substituting the expressions (7) and (9) into (8), we get

$$I_d = kk_1 U_0^2 Z I_b \frac{1}{\sigma_x \sqrt{2\pi}} \int_{-\frac{h}{2}}^{\frac{h}{2}} \exp\left(-\frac{(x-\varepsilon_x)^2}{2\sigma_x^2}\right) dx \int_{-\frac{da+lh}{2(l+d)}}^{\frac{da+lh}{2(l+d)}} \exp\left(-\alpha\sqrt{x^2 + d^2}\right) dx. \tag{10}$$

The formula (10) allows the static characteristic (Fig. 2) of the X-ray sensor of penetration depth to be calculated.

Measuring the depth of penetration makes sense only at the working current when the joint is scanned by an electron beam. In this case, the parameter ε_x acquires harmonic oscillations in accordance with the expression

$$\varepsilon_x = \varepsilon_0 + \varepsilon_m \sin \omega t, \tag{11}$$

where ε_0 is the difference between the positions of the beam and the optical axis of the electron beam gun; ε_m is the amplitude of beam scanning across the joint; $\omega = 2\pi/T$ is the scanning frequency across the joint; T is the scanning period.

Expression (5), taking into account formula (11), will have the form

$$I_0 = kk_1 U_0^2 Z I_b \frac{1}{\sigma_x \sqrt{2\pi}} \int_{-\infty}^{\infty} f_d(x) \exp\left(-\frac{(x-\varepsilon_0-\varepsilon_m \sin\omega t)^2}{2\sigma_x^2}\right) dx. \tag{12}$$

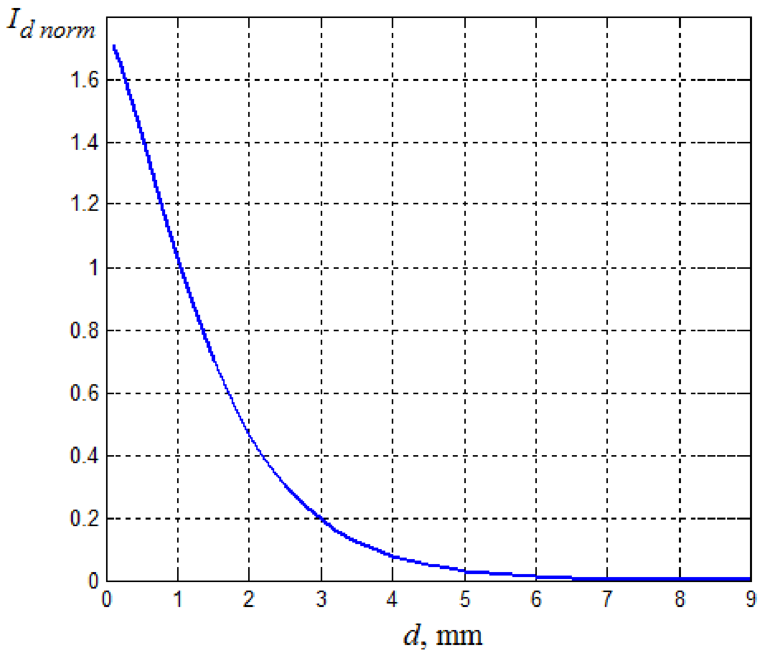

Figure 2. The normalized static characteristic of the X-ray sensor of penetration depth.

Then the intensity of the x-ray radiation reaching the sensor can be described by the expression

$$I_d = kk_1U_0^2ZI_b \frac{1}{\sigma_x\sqrt{2\pi}} \int_{-\infty}^{\infty} f_d(x)\exp\left(-\frac{(x-\varepsilon_x-\varepsilon_m \sin\omega t)^2}{2\sigma_x^2}\right)dx \times \\ \times \int_{-\frac{da+lh}{2(l+d)}}^{\frac{da+lh}{2(l+d)}} \exp\left(-\alpha\sqrt{x^2+d^2}\right)dx. \tag{13}$$

Changing the intensity of X-ray radiation in time can be represented in the form of a multiple Fourier series:

$$I_d(\omega t) = \sum_{n=-\infty}^{\infty} C_n e^{jn\omega t}, \tag{14}$$

where C_n are the coefficients of the Fourier series.

To simplify the calculations, it is assumed that the scanning period T = 2π. Then, the expression (14) takes the form

$$I_d(t) = \sum_{n=-\infty}^{\infty} C_n e^{jnt}, \tag{15}$$

where the coefficients of the Fourier series are determined by the formula

$$C_n = \frac{1}{2\pi}\int_{-\pi}^{\pi} I_d(t)e^{-jnt}dt, \quad (n = 0, \pm1, \pm2, \ldots). \tag{16}$$

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Taking into account the expression (13) we get

$$C_n = \frac{1}{2\pi} k k_1 U_0^2 Z I_b \frac{1}{\sigma_x \sqrt{2\pi}} \int_{-\frac{da+lh}{2l+d}}^{\frac{da+lh}{2l+d}} \exp\left(-\alpha\sqrt{x^2+d^2}\right) dx \times$$
$$\times \int_{-\pi}^{\pi} \int_{-\infty}^{\infty} f_d(x) \exp\left(-\frac{(x-\varepsilon_0-\varepsilon_m \sin t)^2}{2\sigma_x^2}\right) dx \cdot e^{-jnt} dt. \quad (17)$$

Expressions (15) and (17) describe a mathematical model of an X-ray sensor as an element that has a frequency spectrum of the output signal in the presence of a periodic scanning signal of the joint by an electron beam. The mathematical model allows the components of the sensor signal with frequencies $n\omega t$ to be calculated.

In trigonometric form, the series (15) will have the following form

$$I_d(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} \left(a_n \cos nt + b_n \sin nt\right), \quad (18)$$

where the coefficients of the series are defined by the expressions:

$$a_0 = \frac{1}{\pi} \int_{-\pi}^{\pi} I_d(t) dt, \quad (19)$$

$$a_n = \frac{1}{\pi} \int_{-\pi}^{\pi} I_d(t) \cos ntdt, \quad (20)$$

$$b_n = \frac{1}{\pi} \int_{-\pi}^{\pi} I_d(t) \sin ntdt. \quad (21)$$

In this case,

$$C_n = \frac{a_n - jb_n}{2}.$$

Thus, the intensity of X-ray radiation can be represented by the sum of the constant component (19) and the harmonic components (20), (21).

If the scanning of the electron beam is absent, then $\omega = 0$. Then expressions (15) and (18) are converted into the equation of static characteristic (10).

When scanning the electron beam, harmonic components with frequencies that are multiples of the scanning frequency appear in the output signal of the X-ray sensor. The harmonics presented in figure 3 were calculated by formulas (20) and (21), taking into account expressions (13) and (6).

Calculations showed that, in the absence of displacement of the joint from the axis of the gun, the amplitudes of the odd harmonics are zero, and the absolute values of the amplitudes of even harmonics a_n with frequencies that are multiples of 2ω decrease exponentially with increasing thickness of the layer of solid material under the cavity. The second harmonic with a frequency of 2ω, which has the greatest amplitude, is most suitable for controlling the depth of penetration.

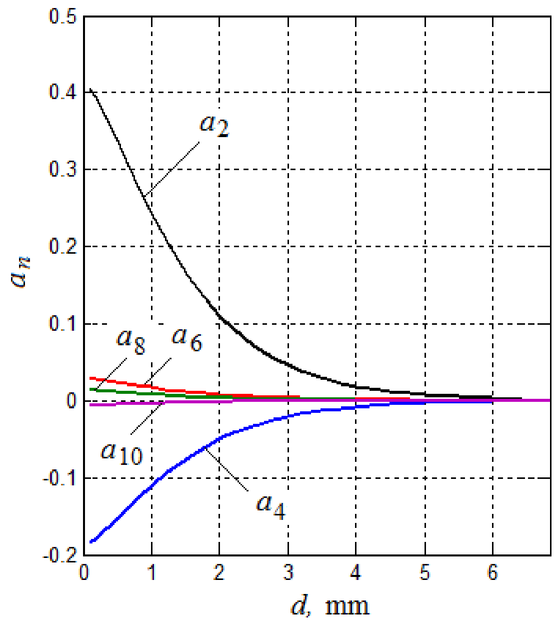

Figure 3. Dependence of $a_n(d)$ when ε_m=2.

3. Conclusions

A new frequency method for measuring the depth of penetration using X-ray radiation from the processing zone during electron-beam welding is proposed.

In accordance with the developed mathematical model of an X-ray sensor, a harmonic with a frequency that is a multiple of the scanning frequency of the electron beam across the joint of the parts to be welded, allows the depth of the penetration channel to be determined.

Using the frequency component of the signal in conjunction with selective amplification allows immunity to interference in the measurement method to be increased.

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