Analytical characteristics of the electron beam distribution density over the heated spot for optimizing the electron-beam welding process

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Abstract. The control of the electron beam energy distribution density over the heated spot, realized by using different scanning trajectories, can significantly improve the quality of welded joints. Experimental research by the authors showed that the best quality of welded joints is provided by scanning the electron beam in the form of a raster. Therefore, to optimize the process of electron-beam welding, trajectories of the classical raster, sinusoidal raster and truncated raster were proposed, and by increasing the scanning amplitude along the joint, the vapour-gas channel of penetration transforms into a stable cavity, on the front wall of which the metal melts, with it then being transferred along the side walls to the tail end of the weld pool. It is advisable to investigate the effect of the formation of the penetration cavity in the EBW of various materials and different thicknesses. For this, an apparatus must be created that implements scanning in the form of various rasters. For optimizing the process of electron-beam welding, the trajectories of the classic sawtooth raster, sinusoidal raster and truncated raster are proposed. For these scanning trajectories, analytical expressions and calculated characteristics of the electron beam energy distribution density are obtained over the heated spot. The trajectory in the form of a sinusoid and a truncated raster makes it possible to obtain double-humped energy distribution over the heated spot. The obtained characteristics facilitate the optimization process of electron-beam welding of different materials.

1. Introduction
The combination of energy and technological process parameters determine the quality of the weld during electron-beam welding (EBW). A deep penetration by a focused electron beam is created by forming a vapour-gas channel. Thus, the welding joint has a dagger shape with a characteristic mushroom-shaped formation in the upper part. The mushroom expansion of the weld in the upper part is associated with the periodic dispersion of the beam in the metal vapour. The pointed shape of the weld in the root part leads to the formation of root defects, or voids, arising due to the displacement of liquid metal by the penetration channel. Thus, to prevent such defects from occurring, it is necessary to form a wider root part of the welding joint. The simplest way to form the radius in the root of the seam is by defocusing the electron beam being used but it does not lead to the complete elimination of root defects.

To prevent root defects, it is necessary to form a parodynamic channel with a fairly wide lower part. The most effective way to influence the formation of the channel of penetration is by scanning the electron beam. The current trend in the development of welding technology is to use complex-
shaped scanning for the formation of welding joints with a given cross-sectional shape. The use of
digital signal generators allows us to create rasters of any shape with a sufficiently high resolution of
up to 24 bits and also plays a major role in solving the problem of targeting the joint [1].

The method of choosing the scanning shape of the electron beam has not been developed yet. At
the same time, a rather large amount of experimental data has been accumulated [2]. The most widely
used forms of scanning beam trajectory are: longitudinal [3-4], x-shaped [5-7], circular and elliptical
[8-10], and arc and clamp [11-12]. The scanning amplitudes typically vary between 1-3 mm.

Electron-beam welding by rotating an electron beam along a circular trajectory makes it possible
to achieve a significant reduction in root defects and picoformation; however, since the power density in
the central part of the heating zone is small, the use of a circular scan reduces the penetration depth
compared to a stationary electron-beam welding beam.

In earlier published paper [13] present experimental research on the application of various scanning
trajectories by electron beam with the focus on the high-quality formation of welded joints. The
research showed that the best scanning trajectory for the quality of weld formation is a raster in which
scanning of electron beam along the coordinate across the joint is according to the one-sided sawtooth
law. For one scan along the junction, 16, 32 or 64 scans are carried across the junction along a two-
sided sawtooth path. The scan period along the junction is equal to 1-2 ms.

More detailed studies with scanning in the form of a raster revealed that with an increase in the
amplitude of scanning along the joint from 5 mm when welding small thicknesses to 15 mm when
welding medium thicknesses, the vapour-gas channel is transformed into a stable cavity to the full
depth of penetration [14]. The cavity shape was fixed by abrupt termination of the welding process by
switching off the accelerating voltage.

Figure 1 shows a scheme of scanning by electron beam in the coordinate system associated with the
weld pool. The shape of the resulting weld joint has almost parallel walls and a significant radius at
the root, which allows root defects to be eliminated. The instability of the depth of penetration
decreased by three to four times. The openness and stability of the penetration cavity leads to the
degassing of the weld pool and a decrease in porosity. By reducing the proportion of energy spent on
the evaporation of the material, the penetration capacity of the EBW process increases.

It is advisable to investigate the effect of the formation of the penetration cavity when welding
various materials and different thicknesses. For this purpose, equipment should be created that
implements scanning in the form of various rasters. In this paper, we consider three types of scanning:
classic raster, sinusoidal raster and truncated raster. The issue of this research is to obtain the density
of the energy distribution of the scanning by electron beam over the heated spot. It characterizes
the distribution of energy in the weld pool.

2. Modelling method
The energy distribution in an electron beam is usually described by a normal distribution law
characterized by the probability density of the species [15]:

\[ f(x) = \frac{1}{\sigma \sqrt{2 \pi}} \exp\left(-\frac{(x-m)^2}{2\sigma^2}\right), \]

where \( x \) is the abscissa, \( m \) is an expected value, and \( \sigma \) is a standard deviation characterizing the
diameter of the electron beam and the concentration of energy in it. This value is determined by the
electron-optical system of the gun and its focusing system. It depends on the welding current and is
usually determined within \( \sigma = 0.05 - 0.5 \) mm. The smaller the diameter of the electron beam, the
better the beam forms the gun.

In order to disregard the specific value of the standard deviation when constructing the
characteristics of the energy distribution density over the heated spot, we introduce dimensionless
coordinates and amplitudes of the beam scanning:
where $y$ – a coordinate along the junction, $\sigma$ – a standard deviation, $\bar{y}$ – a dimensionless coordinate along the junction. In a system of dimensionless coordinates $\sigma=1$.

$$\bar{x} = \frac{x}{\sigma},$$

(3)

where $x$ – a coordinate across the junction, $\bar{x}$ – a dimensionless coordinate across the junction.

$$\bar{A} = \frac{A}{\sigma},$$

(4)

where $A$ – an amplitude, $\sigma$ – a standard deviation, and $\bar{A}$ – a dimensionless amplitude.

The maximum ordinate of the normal distribution law (1), corresponds to the point $x=m$; the distance from point $m$ of the distribution density decreases. The centre of symmetry of the distribution is the centre of dispersion $m$. The centre of diffusion characterizes the position of the distribution on the abscissa axis [15]. Therefore, by changing the centre of scattering according to the corresponding law, it is possible to obtain the density of energy distribution along the corresponding coordinate.

The electron beam energy is described by the following formula:

$$W(x, y) = U \ast I \ast \int_{-\infty}^{\infty} W(x)W(y)dxdy,$$

(5)

where $U$ – an accelerating voltage, $I$ – a beam current, $W(x)$ and $W(y)$ – normalized energy distribution functions for the corresponding coordinates, $\int_{-\infty}^{\infty} W(x)dx = 1$, $\int_{-\infty}^{\infty} W(y)dy = 1$.

Scanning in the form of a classical raster while moving along the coordinate across the joint is carried out by a one-sided saw described by a piecewise linear function:

$$y = k \ast t + m,$$

(6)

where $t$ – an independent variable, $k$ and $m$ – numbers, and provided that $k = 1$ for the time $t = [-1;1]$ with period $T$, the following graph will be in the form of the saw in Figure 2.
It is known that when we change the expectation in the formula (1), the graph shifts relative to its centre. Therefore, instead of the expected value, in the formula (1), we can enter the formula (6) and integrate it to get the energy distribution curve. We get the following mathematical formula:

$$W(y) = \int_{-\sigma - \frac{\pi}{2}}^{\sigma + \frac{\pi}{2}} \frac{1}{\sigma \sqrt{2\pi}} \exp\left(-\frac{(y - \hat{A} \* k \* t + m)^2}{2 \* \sigma^2}\right) dt,$$

where $\hat{A} \in [0;25]$, $k = 1$, $m = 0$, $y \in [-30;30]$.

3. Experimental study

Figure 3 shows curves with a normal energy distribution for the case of a scanning electron beam trajectory along the junction in the form of a raster.

Figure 4 shows a sinusoidal electron beam scanning trajectory. The sinusoidal trajectory is described by the following formula:

$$F(\varphi) = A \* \sin(\varphi),$$

where $\varphi \in [0;\frac{\pi}{2}]$ - the phase.

Therefore, instead of the expected value, in the formula (1) we can enter the formula (8) and integrate it to get the energy distribution curve when applying the normal distribution law on the sinusoidal scanning trajectory (Figure 5). We get the following mathematical formula:

$$W(x) = \int_{-\sigma - \frac{\pi}{2}}^{\sigma + \frac{\pi}{2}} \frac{1}{\sigma \sqrt{2\pi}} \exp\left(-\frac{(x - \hat{A} \* \sin(\varphi))^2}{2 \* \sigma^2}\right) d\varphi,$$
where $\overline{A}_x \in [1;10], \overline{x} \in [-15;15], \varphi \in [-\pi;\pi]$ - the phase.

Figure 4. The shape of the controlling signal in the form of a sinusoid

Figure 5. Energy distribution for the case of a scanning trajectory in the form of a sinusoidal:

$A_{1} = 1; A_{2} = 2; A_{3} = 3; A_{4} = 4; A_{5} = 5; A_{6} = 6; A_{7} = 7; A_{8} = 8; A_{9} = 9; A_{10} = 10$

When scanning with a truncated raster on certain areas for a certain period, the amplitude takes a fixed value. In formula (7) we add expressions with the help of which the peaks arising on values of equal amplitudes are described. We get the following formula:

$$W(\overline{x}) = \frac{T - 2 * M}{T} \frac{1}{\sigma * \sqrt{2 * \pi}} * \exp \left( - \frac{(\overline{x} - (A * k * t + m))^2}{2 * \sigma^2} \right) dt + \frac{M}{T} * \left[ \exp \left( - \frac{(\overline{x} - (A))^2}{2 * \sigma^2} \right) + \exp \left( - \frac{(\overline{x} + (A))^2}{2 * \sigma^2} \right) \right]. \tag{10}$$

where, $m = 0, k = 1, M$ - a saturation time, $T$ - a period of scanning.

Figure 6 shows curves with a normal energy distribution for the case of a scanning electron beam trajectory across the junction in the form of a truncated raster.

In order to use the obtained design characteristics, it is necessary to move from the dimensionless coordinates to dimensional coordinates, and for this, it is necessary to carry out the following steps:

$$y = \overline{y} * \sigma; x = \overline{x} * \sigma; A = \overline{A} * \sigma; W(x) = \frac{W(\overline{x})}{\sigma}; W(y) = \frac{W(\overline{y})}{\sigma}$$
Figure 6. Energy distribution for the case of a scanning trajectory in the form of a truncated raster: \( A_1 = 1; A_2 = 2; A_3 = 3; A_4 = 4; A_5 = 5; A_6 = 6; A_7 = 7; A_8 = 8; A_9 = 9; A_{10} = 10 \)

4. Conclusions

For research on the optimization of the process of electron-beam welding, it is advisable to use scanning by electron beam in the form of a raster, which allows a stable penetration cavity and high quality of welded joints to be obtained.

Sinusoid and truncated raster allow a double-humped distribution of energy along the coordinate across the joint to be obtained, which is necessary for the formation of a weld with parallel walls and a significant radius in the root, which excludes the appearance of root defects.

It is advisable to program the proposed scan forms in the control unit for electron beam scanning.

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