Investigation of the effect of electron beam parameters on the characteristics of the steam-gas channel during welding of nickel and titanium alloys

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Abstract. The article presents the developed technique of high-speed video recording of the combined-cycle gas channel and subsequent frame processing to obtain the dimensional characteristics of the combined-cycle gas channel. On the basis of this technique, dependences of the width of the weld at different depths were obtained depending on the current and welding speed. A pattern of dimensional characteristics of the steam-gas channel depending on the running energy and the dependence of the frequency of collapse of the steam-gas channel on the electron beam current at a constant welding speed of 40 m/h by the example of nickel and titanium alloys was revealed.

1. Introduction

Electron beam welding (EBW) is a promising welding method, as it has a number of technological advantages over other types of welding. EBW is used for welding refractory, hard-to-weld metals and products of large thicknesses, which is used in such promising areas of mechanical engineering as the aerospace industry, military industry, shipbuilding, etc. However, when using EBW, specific defects occur at the root of the seam, such as penetration peaks and voids. The formation of these voids is often explained by hydrodynamic phenomena in the welding bath, which lead to the periodic collapse of the neck of the steam-gas channel [1–2].

For more than 50 years, scientists from different countries have been investigating the regularities of the mechanism of formation of a combined-cycle gas channel and the accompanying processes that occur during EBW. In this way, the physical processes occurring in the steam-gas channel during electron beam welding are of interest to study from the point of view of creating optimal conditions for the formation of a high-quality welded joint. The scientific interest is the study of the parameters of the electron beam on the characteristics of the steam-gas channel, which is presented in this article on the example of nickel and titanium alloy [3–6].

2. Materials and methods

In order to fix the electron beam welding process in the visible range of the spectrum, high-speed video shooting was used, conducted using a high-speed camera [2, 7].

Shooting with a high-speed video camera was carried out with the following parameters presented in Table 1. The remaining settings were used with default values.
The experiment was carried out according to the scheme shown in Figure 1. The video camera is mounted on a tripod opposite the porthole of the welding chamber. The combination of the focus of the video camera and the point of electron beam exposure to the target was carried out by means of a mirror. After pointing the lens of the video camera at the target, the vacuum chamber was pumped out to a working pressure of $1 \times 10^{-1}$ Pa.

Table 1. Shooting parameters of a high-speed camera.

| Name                      | Meaning        |
|---------------------------|----------------|
| Input speed, FPS          | 1000–2000      |
| Exposition                | 350–494        |
| Signal gain               | 30–150         |
| Input area, pixels: X × Y | 1280 × 250     |

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The video obtained as a result of the shooting was presented as separate frames (Figure 2) in the “png” format. Then the frames were cut and processed in the Matlab software environment.

In a specially written program, further processing of frames was carried out using the “Canny” boundary detection algorithm. This algorithm has good detection and localization of boundaries and has a single response to one boundary. Applying the “Canny” algorithm for detecting boundaries to the image shown in Figure 2 at the output, a contrasting image of the boundaries of the brightness changes of pixels in the frame was obtained (Figure 3, a).

Figure 1. High-speed video shooting scheme.
Next, the measurement of the major and minor axes of the ellipses describing the boundaries of the steam-gas channel and the welding bath was carried out in images with contrasting borders according to the scheme shown in Figure 3 (b).

![Figure 2](image2.png)

**Figure 2.** The resulting image of the welding bath and the steam-gas channel.

![Figure 3](image3.png)

**Figure 3.** Processing of the frame of the steam-gas channel: (a) the boundaries of the welding bath and the steam-gas channel; (b) the measurement scheme of the major and minor axes of the ellipse.

The frequency of changes in the size of the combined-cycle gas channel was determined according to the scheme shown in Figure 4.

The number of half-periods in which the size of the major axis of the ellipse fell below the average value for several frames was determined. The frequency of collapse of the steam-gas channel was determined by the formula:

$$f = \frac{n}{\Delta T},$$  \hspace{2cm} (1)
where \( n \) is the number of half-cycles of oscillations, \( \Delta T \) is the time during which \( n \) oscillations were performed.

During the periodic overlap of the steam-gas channel with liquid metals, an increase in brightness in the area of the welding bath was established, and the frequency of such overlaps was also determined.

Based on the results obtained, the average size of the ellipse axes was calculated, as well as the dependence of the average size of the ellipse axes on the linear energy at the EBW.

![Figure 4](image-url)

**Figure 4.** Diagram of measuring the number of half-periods.

![Figure 5](image-url)

**Figure 5.** Photos of the steam-gas channel at different points in time: (a) the steam-gas channel is opened, time – 2.5025; (b) the steam-gas channel is blocked by liquid, time – 2.505.
Collapses can also be recorded in photographs, along the channel boundaries and changes in the intensity of radiation from the welding area. During deep melting (Figure 5, a), there is a decrease in the intensity of radiation, and during the overlap of the vapor-gas channel with liquid, the intensity of radiation increases (Figure 5, b), and there is also no clear boundary of the vapor-gas channel.

3. Results and Discussion
Based on the conducted experiments, dependences of the width of the weld at different depths were obtained depending on the current and welding speed. Figure 6 shows the dependence of the seam width at a depth of $Z = 0.5$ and $1.25$ mm, respectively, on the parameters of electron beam welding at a constant penetration depth of $3$ mm.

![Figure 6](image)

**Figure 6.** The dependence of the seam width on the welding parameters for the EP648 alloy at (a) $Z = 0.5$ mm, (b) $Z = 1.25$ mm.

It can be seen that within the same section of the seam depth, with an increase in the welding speed and current, the width after reinforcement does not change significantly. Also, the influence of the EBW parameters on the seam width in depth decreases at a constant penetration depth.

![Figure 7](image)

**Figure 7.** The dependence of the size of the axes of the ellipse, the steam-gas channel at a constant penetration depth for the EP648 alloy.
At a constant penetration depth of 3 mm on the EP648 alloy, a decrease in the size of the upper part of the steam-gas channel is observed, which is shown in Figure 7. The compression ratio of the ellipse describing the boundary of the steam-gas channel was in the range of 0.62–0.65, which indicates the elongated shape of the ellipse in the direction of welding. It is worth noting that with a constant penetration depth in different welding modes, the compression ratio did not change significantly in the range of 0.62–0.65.

With a constant welding speed and adjustment of the electron beam current, an inverse pattern is observed Figure 8, with an increase in linear energy, the size of the small and large axes of the ellipse describing the vapor-gas channel increases. The compression ratio of the ellipse with such welding parameters varies in a wider range of 0.8–0.92, which indicates the shape of the vapor-gas channel closer to the circle.

![Figure 8](image)

**Figure 8.** The dependence of the size of the axes of the ellipse, the steam-gas channel at a constant welding speed for Ti.

![Figure 9](image)

**Figure 9.** The dependence of the frequency of collapse of the steam-gas channel on the welding current at a constant welding speed, Ti.

The steam-gas channel in the welding process changes the size of the major and minor axes of the ellipse due to the unevenness of the process, but periodically the steam-gas channel collapses and fills
it with liquid metal. Figure 9 shows the dependence of the collapse frequency of the vapor-gas channel on the electron beam current at a constant welding speed of 40 m/h.

It can be seen that with an increase in the electron beam current, the frequency of collapse of the vapor-gas channel decreases, which is associated with more intense vaporization.

4. Conclusion
The technique of high-speed video recording and processing of video files to obtain the parameters of the combined-cycle channel has been worked out. Experimental dependences of the parameters of the vapor-gas channel on the parameters of the electron beam effect on nickel and titanium alloys are obtained. The experimental dependence of the frequency of collapse of the vapor-gas channel on the electron beam current is obtained.

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