Investigation of the characteristics of ion saturation current in plasma over the keyhole in the process of electron beam welding

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Abstract. The energy spectra of the ion saturation current of the Langmuir probe in the plasma formed over the keyhole directly during the process of electron-beam welding of steel 09G2S with the varied parameters (e.g., the welding speed and focus coil current) has been investigated. The presence of typical zones with the energy spectrum peaks in the low-frequency and high-frequency bands has been shown. It has been established that the peak location in the high-frequency range of the energy spectrum does not depend on the welding modes and the position of the probes relative to the keyhole. The low-frequency range of the energy spectrum depends on the vapor flow density of the keyhole and is rather sensitive to the welding modes. The use of electron beam oscillation makes it possible to control plasma flows and hydrodynamic processes in the penetration channel.

1. Introduction

Electron beam welding (EBW) is a complex technological process with many variable parameters that significantly affect both the geometric parameters of the weld – the width and depth of penetration, the shape of the weld, – and the quality characteristic – the presence of defects in the weld. The development of methods for managing the welding modes based on the information obtained during the investigation of the keyhole during the EBW process is an important task. These methods can contribute to the formation of welded joints with the desired geometric parameters.

One of the main conditions to form the deep penetration in beam welding methods is the transition of the most molten metal part into a gaseous state [1, 2]. Recoil pressure displaces the molten metal from the beam treatment area and allows the beam to penetrate deeper into the metal, creating conditions for the formation of a deep vapor-dynamic keyhole [2, 3, 4]. Vapor occurs at the interaction surface between the electron beam and the material and creates static and dynamic pressure on the keyhole wall. The recoil pressure causes transition of metal from the melting front of the keyhole to the crystallization one and prevents it from closing [5, 6].

There is a generally accepted model of the keyhole formation in the process of EBW [4, 6-10]. Interaction between an electron beam and a front wall of the keyhole leads to the formation of convexity and concavity on its surface (Figure 1). The intensity of heating, evaporation and metal transfer depends
on both the distribution of the power density over the electron beam cross-section and the angle between the electron beam and the front wall. This angle is influenced by the presence of convexities and concavities on the front wall surface. Vapor flow formed by the liquid metal evaporation from the front wall, pushes the melt pool and displaces it unevenly creating a vapor cavity. The most significant displacements occur in front of areas with the highest power density. When disturbance of the front wall temporarily disappears, vapor cavities will close. These cavities do not always have enough time to be filled with the liquid metal and this fact may result in the formation of large voids in the welds after crystallization.

![Diagram of the dynamic keyhole with labels for keyhole, beam axis, base metal, weld pool, metallic vapor, and vapor flow direction.]

**Figure 1.** Model of the dynamic keyhole.

The intense evaporation process alternates with the periods without any significant disturbances and steady material evaporation. This mechanism ensures self-regulation of the keyhole parameters and allows an electron beam to interact with it’s front wall along its height [4]. Meanwhile, the recoil pressure is the key factor in the process of the liquid phase transfer from the melting front to the melt pool. This periodicity explains a formation of defects such as the spiking at the weld root and the scaliness at the weld surface [11, 12].

It is obviously that the periodicity of intense evaporation from the front wall defines instability of the vapor flow from the vapor-dynamic keyhole. Moreover, it can be detected by surveillance of the electromagnetic radiation above the keyhole in the different spectral ranges [13, 14, 15, 16]. Several studies present the opportunity of the X-ray radiation application [17, 18] and secondary current in plasma which is formed above the electron beam welding treatment area for intensifying processes in the keyhole [13, 19, 20, 21, 22] and creating automatic-control systems [23, 24].

The flow of electrons with different energies is formed during the interaction between the electron beam: backscattered electrons, secondary electrons, and thermal electrons. The interaction of the metal vapor with the electron flows leads to partial ionization of the vapors and the formation of a low-temperature metal target plasma in the treatment zone [20, 25, 26]. Intense plasma flow from the keyhole to a vacuum chamber volume is formed due to the difference in pressure between the beam treatment area and a vacuum chamber, and in accordance with thermal velocities of neutral atoms and ions, and the keyhole shape.

Changing in the plasma volume density above the keyhole and velocities of the plasma flux can be promising parameters to estimate processes in the keyhole during the electron beam welding. This can be explained by the fact that the changing in the flux velocities and plasma density above the keyhole depends directly on the intensity of metal evaporation from the front wall. This process is accompanied by the frequency registration during the similar processes of the beam energy absorption by the front wall, partially by gas-vapor phase, and the scattering. In turn, the evaporation on the front wall defines...
the intensity and frequency of the liquid metal transfer from the melting front to the weld pool. Thus, the study of plasma flows from the penetration channel and their fluctuations in time describe the dynamic state of the vapor-gas channel. Such information can be used to predict the development of processes in the penetration channel and control the formation of welded joints.

The main purpose of this study was to establish the relationship between the parameters of the electron beam welding and the plasma density above the keyhole. The main object of this research was a low-temperature nonequilibrium plasma formed when the high-power density electron beam \((q_2 = 10^6–10^7 \text{ W/cm}^2)\) interacts with the material during the electron beam welding with the deep penetration.

2. Methods

2.1. Registration of ion saturation currents

The Langmuir probe was used to study the plasma parameters when the electron beam interacted with a target [19, 20, 27, 28, 29]. The probe method allows to obtain reliable results in case of a vacuum atmosphere while the mean free path of charged particles is greater than the probe dimensions and the perturbed plasma region around it [30]. Namely, this occurs when high-power electron beams interact with metallic materials [20, 26-29] during an electron beam welding. The probe method allows to study the plasma in the following range of parameters: the ambient pressure \(p \sim 10^{-3}–10^4 \text{ Pa}\), and particle concentration \(- n_e\sim 10^6–10^{14} \text{ cm}^{-3}\) [30].

Experimental conditions determine the shape and probe design. A probe size is generally about \(10^{-1} \text{ cm}\) [20, 30, 31]. The spherical probe with a diameter of \(1.5\pm0.1\ mm\) was used for this research (Figure 2). The isolation of the probe was performed by aluminosilicate ceramics with the external diameter of \(2\ mm\) and length of \(105-125\ mm\).

Figure 2. Schematics and the probe image.

Due to the significant pressure gradient and the difference in the volumes between the keyhole and the vacuum chamber, the plasma flow density should decrease in proportion to the distance from the electron beam processed area in the keyhole [25]. Consequently, considering its characteristic dimensions – \(10\ mm\), diagnostics of the plasma parameters should be carried out near the keyhole.

The ion density is proportional to the saturation current \(i_s\) [23, 30, 32]:

\[
n_i = \frac{i_s}{C \cdot S \cdot e \cdot \sqrt{\frac{k \cdot T_e}{m_i}}},
\]

where \(C = 0.8\) for the spherical probe, \(S\) – the area of collecting surface of the probe, \(e\) – electronic charge, \(k\) – Boltzmann’s constant, \(T_e\) – electronic temperature, \(m_i\) – ionic mass.

Thus, it is possible to estimate the fluctuations in the ion density at the location of the probe by changing the ion saturation current. Figure 3 shows a scheme of the ion current determination that occurs during the material processing by an electron beam.
Figure 3. Test rig scheme for investigation of ion saturation current.
1 – electron beam; 2 – electron gun; 3 – processed specimen (target); 4 – spherical probe; 5 – probe isolation; 6 – surge protector; 7 – shunt resistor; 8 – vacuum chamber wall; 9 – vacuum feed-through; 10 – stabilized power source

The test rig included an electron beam equipment, a probe mounting system, a data acquisition system and stabilized power supplies for setting the potential to the probes. The probe was connected to the negative potential of the power supply using a shunt resistor (Figure 3). The positive potential of the power supply has been electrically grounded. The ion saturation current was measured by the voltage drop on the shunt resistor. The voltage on the probes was applied by the stabilized power source and it was constant during all the experiments and equal to 100 V with respect to the grounded specimen (target). A surge protector was installed between the probe and the grounding to prevent the failure of the power supply of the data acquisition system.

The data acquisition system included a workstation with four LTR 210 ADC oscilloscope modules, and a signal synchronization unit based on normalizers with galvanic separation Dataforth 8B50-01. The system recorded the measured values through four independent channels with an acquisition frequency of up to 10 MHz.

The measurement of the ion current was carried out during the EBW process. Welded samples were made of steel 09G2S and had dimensions 40x50x25 mm. The EBW process was carried out using AELTK-344-12 electron beam equipment (JSC "Scientific Research Technological Institute "Progress") with accelerating voltage of 60 kV. Table 1 shows the EBW modes. The focus coil current equaled to 825 mA and corresponded to the maximum depth of the vapor-gas channel. The electron beam oscillation in the type of “sawtooth” along the welding direction [33] with the amplitude of 1.5 mm was used in modes 9-12 to study the effect of the electron beam oscillation on the metal transfer intensity. The start of recording the values of the ion saturation current of the probe began 4-5 seconds before the start of the welding process. After the electron beam current was turned off, the recording also stopped. This made it possible to obtain the dependence of the ion saturation current of the probe over the keyhole on time with a sampling rate of 500 kHz during the EBW process.

Data was simultaneously recorded from the four probes installed at different points above the keyhole in each experiment to increase reliability of acquiring data (Figure 4). This proved the fact that the obtaining signal fluctuations are truly generated by the process in the keyhole. The tips of the probes formed a tetrahedron with a side of 25 mm. The lowest probe N4 was located above the sample at 10 mm. The uppermost probe N1 was over the sample at 35 mm. Probe N2 was located on the right side toward the welding direction, and probe N3 was located on the left side.
Figure 4. Probes positioning above the keyhole (a), top view (b), electron gun equipped with the probes (c).

1 – electron beam; 2 – probes; 3 – specimen (target); 4 – weld, 5 – electron gun, 6 – probe mount system.

2.2 Processing of ion current signals

The energy spectrum of the ion current signal for each of the studied welding modes was analyzed to estimate the characteristic fluctuation frequencies. Discrete Fourier transformation is usually used to construct the energy spectrum. However, discrete time-limited signals calculated the spectral density using the DFT is equivalent to a window Fourier transformation with a rectangular window function. The width of the window is similar to the time of recording the signal. This method of calculating the spectral density has the effect of spreading the spectrum [34]. Various weight functions are used in the window Fourier transformation to eliminate this effect:

$$F(t, f) = \int_{-\infty}^{+\infty} x(\tau)w(\tau - t)e^{-2\pi if\tau}d\tau,$$

(2)

The $\beta$ parameter of the Kaiser window weight function was defined to configure the procedure for calculating the ion current spectrum:

$$w_k(n) = \frac{I_0(\beta\sqrt{1 - \frac{2n}{N-1}})}{I_0(\beta)}, \quad -\left(\frac{N-1}{2}\right) \leq n \leq \left(\frac{N-1}{2}\right),$$

(3)
where \( I_0 \) – zero-order Bessel function, \( N \) – the number of counts in the window, \( n \) – reference number of the count. The window width was in addition determined using the frequency \( f_r \) at which the resolution of two adjacent peaks in the signal occurs. Model signals consisted of 3 sinusoids with specified frequencies \( f_j \) and located at a certain distance \( \Delta f \) from each other were compiled for the selection of \( \beta \) and \( f_r \). The value of \( \Delta f \) determines the frequency resolution that must be achieved when analyzing experimental ion current signals. In other words, it determines the desired minimum distance of the peaks in the spectrum so that they can be identified as different frequencies.

The analysis of the spectra of the model signals allowed to define the parameters of the window for processing the signals obtained in the experiment. The processing of experimental signals was carried out at values \( \beta = 6 \) and \( f_r = 5 \) Hz.

3. Results and discussion

Figure 5 shows typical signals recorded during the single experiment. The start of the signal registration had occurred before the EBW process began. The amplitude of the recorded noise has been two or more orders of magnitude lower than the amplitude of the general signal. The graph of the noise amplitude distribution is close to normal, and the autocorrelation functions of noise are close to the delta function. This allows to conclude that the overwhelming part of the noise component of the signal is the flat noise.

The value of the SNR indicator which determines the ratio of the useful signal power to the noise power for the vast majority of signals was in the range of 45-55 dB. The noise spectrum practically does not contain a deterministic component and is continuous. Thus, the presence of noise in the experimental signal does not lead to distortion of the spectrum.

In the energy spectrum of the ion current signal (Fig. 6) there is a peak at a frequency of about 16 kHz (I\( \text{H} \)) and an increase in the background level of the spectral density in the frequency range of 13-20 kHz, as well as a less obvious peak at a multiple frequency in the region of 32 kHz (II\( \text{H} \)) in all experiments.

![Figure 5. Typical ion current signals from 4 probes in the experiment N6: a – in the process of EBW in the local interval, b – noise signal in the local interval, Probe N1 – red, N2 – green, N3 – blue, N4 – cyan.](image)

The lack of such a peak of spectral density in the noise signal and its presence through all the spectra of the useful signal indicates that the excitation of vibrations in the frequency range of about 16 kHz occurs due to processes in the keyhole and the weld pool. In this case, the period of such processes will be about \( 6.25 \times 10^{-5} \) s and it correlates well with the characteristic time of energy accumulation before flash evaporation of the metal on the surface of the keyhole [35] and intense evaporation [36]. It is noted that for all the studied EBW modes, the I\( \text{H} \) peak frequency was observed in a rather narrow range of 15894 - 16040 Hz. Furthermore, it is identical for all probes, regardless of their location.
Figure 6. Characteristic energy spectrum of the ion current signal in the frequency range of 0 - 50 kHz for mode N1 (a) and mode N9 with the beam oscillation (b).

The spectrum contains spectral density peaks which are multiple of oscillation frequencies in the 9 - 12 EBW modes where the electron beam oscillation was used. Moreover, in some cases the IH peak is lost against the background of peaks caused by oscillation (Fig. 6b).

It is more convenient to represent spectrum in dimensional units, rather than in dB, for a more visual representation of it in the low-frequency region up to 500 Hz. The spectra of the saturation ion current signals from different probes within the single experiment are identical (Fig. 7). This is a consequence of the same processes - the absorption and conversion of energy.

Figure 7. Characteristic energy spectrum of the ion current signal in the frequency range of 0-500 Hz, the mode N8, probes N1 (a), N2 (b), N3 (c), N4 (d).

The frequency fluctuations for the 1 – 8 modes without the beam oscillation are in the range of 40 – 200 Hz. Moreover, it is quite difficult to define the specific frequency in some cases. There is the whole group of peaks, for example, in the spectra of modes 3 and 4 (Fig. 8). However, it is possible to distinguish the typical first low frequency (peak IL), or frequency band. This fact is in a good agreement with the ideas about the nature of liquid metal transfer processes in the EBW [11, 12].
Figure 8. The energy spectrum of the ion current signal in the frequency range of 0 – 500 Hz for the probe N4 with different welding speeds: 

- a - 5 mm/s (mode N1),
- b - 10 mm/s (mode N2),
- c - 15 mm/s (mode N3),
- d - 20 mm/s (mode N4).

The low-frequency range of the spectrum differs significantly for different welding modes. Figure 8 shows the spectra of modes 1-4 in order to increase the welding speed. At the speeds of 5, 10 and 15 mm/s, the first peak $IL$ is clearly highlighted as well as the frequency band from 120 to 200 Hz at the speed of 20 mm/s. Table 1 shows the values of the first frequency peaks. If there is a frequency band, the frequency of the initial part of the band is given. The frequency of the first peak increases with a growth in the welding speed (Fig. 9 a).

Figure 9. The dependence of the first frequency peak $f_{IL}$ on welding speed $V$ (a) and on focus current (b).

Thus, the presence of a deterministic component of the frequency spectrum of the ion saturation current at low welding speeds confirms the existence of a dominant pulsation frequency of the plasma flow from the keyhole. Due to the transfer of metal from the melting front to the weld pool is determined by the vapor pressure in the keyhole the frequency of its pulsation will correlate with the frequency of metal transfer. An increase in the dominant frequency and its spreading into the band (Fig. 8, 9 a) with an increase in the welding speed indicates a transition to chaotic metal transfer. An increase in the frequency of the first $IL$ peak is observed with an increase in the focus coil current from the values of 810 to 830 mA (the position of the focal plane is closer to the surface) (Fig. 9, 10). In the range of 815-825 mA, the frequency is almost constant - about 48 Hz (Fig. 9 b). Thus, the frequency of the first peak responds to the change in the position of the focal plane.
Figure 10. Energy spectrum of saturation ion current signals in the frequency range of 0-500 Hz of the probe N1 with different focus current: a - 810 mA (mode N5), b - 815 mA (mode n6), c - 820 mA (mode N7), d - 830 mA (mode N8).

Figure 11. Energy spectrum of ion saturation current signals of the probe N3 with the different oscillation frequencies: a – 27 Hz (mode N9), b – 54 Hz (mode N10), c - 108 Hz (mode N11), d - 216 Hz (mode N12).

The spectrum of the mode with the sawtooth beam oscillation and the frequency of 27 Hz has only forced fluctuations of the ion current correlated with the beam oscillation frequency (Fig. 11 a). At the beam oscillation frequency of 54 Hz, the fluctuation peaks appear between the beam correlated oscillation peaks with a frequency that is half the beam oscillation frequency (Fig. 11 b). When the beam
oscillation frequency constitutes 108 and 216 Hz, the low-frequency peaks arise before the first beam fluctuation peak. Moreover, they are typical to modes without beam oscillation. This behavior of the spectra with an increase in the beam oscillation frequency suggests that own vibrations of the melt pools at a frequency of 27 Hz are completely suppressed and hydrodynamic processes occur at the beam oscillation frequency. As the beam oscillation frequency increases, its influence on the metal transfer becomes less and at a frequency of more than 216 Hz there is practically no effect at all. The frequency of the first low-frequency peak is not clearly detected in welding modes with oscillations with a frequency of 108 and 216 Hz. However, a group of peaks which may indicate a chaotic metal transfer process in the frequency bands of 40 ... 70 Hz and 35...100 Hz is detected in the frequency range.

4. Conclusions
Two characteristic zones are distinguished in the energy spectrum of the saturation ion current signal during the electron beam welding of 09G2C steel: high-frequency in the 16 kHz region and low-frequency in the 40-200 Hz band. The fluctuation period in the high-frequency region does not depend on the welding mode and numerically correlates with the energy accumulation time before the flash evaporation of the metal on the surface of the keyhole.

There is a dominant frequency of the plasma flow pulsation from the keyhole in the low-frequency region of the energy spectrum. This frequency depends on the welding speed and the position of the focal plane along the keyhole depth. An increase in the welding speed leads to the growth in the frequency and width of the peak. This fact indicates a rise in the randomness of metal transfer.

The external impact on the weld pool using the sawtooth oscillation of an electron beam affects the pulsations of the plasma flow and the frequency of hydrodynamic processes. Thus, at a low oscillation frequency of 27 Hz, this effect is maximum for the studied modes; and at a frequency of 108 Hz and higher, the effect of the oscillation is not observed at all. This confirms the possibility of controlling the metal transfer in the EBW process using special electron beam oscillations.

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