Electron Beam Welding In-Process Control and Monitoring

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***Abstract*—This work presents the results of an investigation of processes in the melting zone during Electron Beam Welding (EBW) through analysis of the secondary current in the plasma.The studies show that the spectrum of the secondary emission signal during steel welding has a pronounced periodic component at a frequency of around 15–25 kHz. The signal contains quasi-periodic sharp peaks (impulses). These impulses have stochastically varying amplitude and follow each other in series, at random intervals between series. The impulses have a considerable current (up to 0.5 A). It was established that during electron-beam welding with the focal spot scanning these impulses follow each other almost periodically. It was shown that the probability of occurrence of these high-frequency perturbation increases with the concentration of energy in the interaction zone. The paper also presents hypotheses for the mechanism of the formation of the high-frequency oscillations in the secondary current signal in the plasma.**

***Keywords:* automation of welding processes; electron beam welding; focus control; focus spot scanning; weld formation monitoring**

I. INTRODUCTION

ELECTRON beam welding (EBW) is a fusion welding process often done in a vacuum. The process has a number of advantages: high power concentration in the electron beam, easy control of the energy flow into the metal, smaller heat-affected areas, equal strength of the weld joint and main metal, etc. These advantages allow the use of electron beam for welding reactive and nonferrous metals, high-tensile and heat-resistant alloys that are typically used in the production of critical products.

However, certain problems arise in EBW process, which are related to instability of weld-joint formation and difficulties in creating and controlling an optimal focus regime. A major limitation in controlling such a focus regime is the lack of understanding of the processes during EBW. The complex character and high speed of these processes make numerical modeling very difficult, forcing researchers to rely on experimental research methods.

The basic parameters of EBW are accelerating voltage, electron beam current, focusing-coil current, welding speed, operating gun-sample distance, vacuum level in the process chamber, etc. These parameters are chosen according to factors such as the operator's own experience, mathematical models [1, 2], or statistical analysis [3–4]. The most difficult parameter to identify and reproduce in EBW is the focusing position. The operator of an EBW needs to manually set the focus of the beam. The adjustment of the focusing-coil current is based on the subjective operator evaluation of luminosity brightness, emitted from the interaction area of the beam irradiating refractory target material, e.g. wolfram. When the luminosity brightness becomes maximal, the focusing mode is considered sharp [5].

The process of manual focus control is subjective and can lead to performance depreciation. Each operator interprets the luminosity brightness of the operational area differently and, therefore, the welding results could be not reproducible. Changing the focusing current by 1% may cause a 20–60% fluctuation of fusion depth. The focusing position also significantly influences the probability of various defects specific to EBW such as spiking, cavitations, medial cracks, etc. The difficulties in focusing control are aggravated by changes in the electronic and optical systems of an electronic beam gun due to cathode wear and tear or after planned maintenance.

In recent years, this problem has been partly solved by using a modified Faraday cup to control the electronic beam density distribution [6]. During circular scanning, the beam passes through a set of radial gaps in the wolfram disk. After the current passing through the gaps is measured, the density of the electronic-beam power, beam diameter, maximum specific power and other important metrics are calculated based on computer tomography algorithms. By controlling these basic parameters of the electronic beam, the parameters of the welding seams can be reproduced. It has also been reported that due to this measurement of beam characteristics, the concrete EBW technology can be migrated between various electron beam sets [7]. Some vacuum chambers do not support internal mounting of the required sensor (the modified Faraday cup). For welding operation modes, the focusing current should be adjusted based on experiments with various materials, thicknesses and types of electronic-beam guns. Moreover, the systems based on modified Faraday cup do not

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executed the real-time control and adjustment of the focusing mode during welding. Real-time adjustments are important for large objects welding especially when the cathode electron emission and thus the electronic and optic adjustments of the gun are significant.

Therefore, the control, monitoring and analysis of the processes in welding bath during EBW requires analysis of the secondary signal parameters, such as secondary electron or ion emission, optical emission, X-rays, etc.

One of the specific processes caused by the impact of the dense electron beam to the metal during EBW is the formation of plasma in the operational area [8–9]. The parameters of the plasma are closely connected with the electron beam thermal effect on the metal being welded. In [10–11], plasma current parameters are suggested for electron beam focusing control.

All the above methods use extreme correlations between the secondary emissions and the focusing lens current. These correlations are characterized by the dead zones and two values of the focusing lens current that ensure similar signal parameters, but various derivatives. The application of focal spot scanning (modulation of the focusing lens current) was required in this case for the embodiment of the methods of operational control. All known research has been based on the extreme of a signal function, obtained while slowly changing the focusing current. In this case, the execution of the operational control requires low-frequency scanning of the focusing current, which negatively affects the quality of the welded joint. High-frequency scanning of the focal spot for the purpose of improving the quality of the welded joint is known [12]. However, its applicability to the operational control of beam focusing has not been investigated until now.

In recent years, control and monitoring of electron beam and laser beam welding has become more and more popular [13–16]. Laser technologies and EBW are based on similar principles and used concentrated energy beams. New research opportunity provided by modern signal processing is finding an increased interest by researchers

One of the well-known ways to increase the signal/noise ratio for physical object analysis is periodic exposure of the object with subsequent analysis of its response at a given exposure frequency [17]. In [10,11,18], it is reported that periodic changes of the electron beam parameters (beam current modulation, oscillation or focus spot scanning) causes normalization of the processes in the keyhole created by the electron beam, thus making the series of impulses passing at constant interval`s proportional to the waveform frequency. However, obtained results are not sufficiently reliable, so further investigation is required. For example, simultaneous recording the focusing lens current and of the secondary current signals collected by the plasma was not performed. Also, the principles for generating harmonics proportional to the scanning frequency were not revealed.

This article studies the behavior of the current collected from the plasma, generated in the operational area of the electron beam, when using EBW with focal spot scanning (modulation of the focusing lens current), based on the coherent accumulation method (cross-correlation analysis) [17, 19]. This method can be used to obtain not only amplitude ratios, but also the phase ones, as well as determining how the current signals in the plasma are synchronized with the focusing lens signals during EBW. These results can be useful for focal spot scanning - parameters selection methods and methods to control EBW against the parameters of the plasma current.

II. . EXPERIMENTAL PROCEDURE

A ring electrode collector was used to measure the secondary current from the plasma. The collector was located over the zone of welding. The collector has a positive potential of 50 V. The loading resistance was 50 Ω. The signal from the collector was registered by a data acquisition system and further processed by a computer. The sampling frequency in the experiments was in a range from 100 kHz to 1 MHz per channel.

During the experiments, samples of chrome-molybdenum steel (0.15 % carbon, 5 % chrome and around 1 % of molybdenum) and high-alloy chrome-nickel steel (up to 0.12 % carbon, 18 % chrome and up to 0.8% titanium) were welded. The accelerating voltage in all experiments was 60 kV. The welding power was in the range from 2 kW to 4 kW.

During the experiments, the welding power P, welding speed, focus degree $\Delta I_f(\Delta I_f = I_f - I_{f0}$ is the difference between the average focusing lens current of the welding mode and the focusing lens current of sharp focus), the frequency f and amplitude of the focal spot scanning A were varied.

The current in the focusing lens was changed under a linear law. The limits of scanning frequency were from 90 to 12000 Hz. The amplitude of these oscillations was in a range from 3 to 25 mA.

Transverse metallurgical sections of the weld were made from all the welded samples. The focus regime was determined by the transverse sizes of the penetration depth. The sharp focus regime corresponds to the maximum penetration depth.

III. RESULTS AND DISCUSSION

Fig. 1 shows a typical spectrum of the secondary current signal collected from plasma during welding of steel samples. It can be noted that there is a characteristic maximum in the signal at frequencies close to 15-20 kHz. Fig. 2a shows the secondary signal together with a signal of focusing lens. The processes in the keyhole become periodic with focal spot scanning s. Frequency perturbations in the secondary current start to periodically follow at multiples of the scanning frequency. More detailed consideration (Fig. 2b) shows that each perturbation represents a series of high-frequency quasi-periodic impulses. Their frequency 10–25 kHz is very stable and specific for different materials and welding regimes. The amplitude changes randomly. The spectrums and waveforms of the secondary current in a plasma during electron-beam welding are more fully described in [10,11, 18].

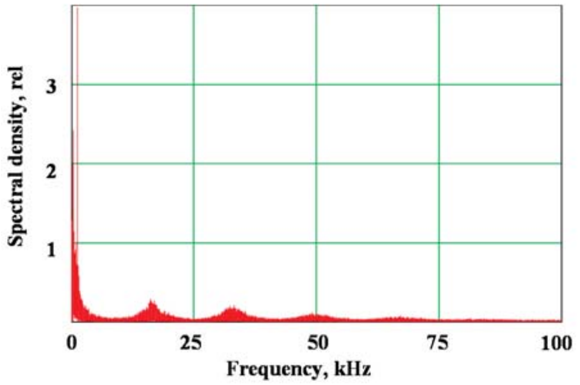

Fig. 1 A typical signal spectrum of the secondary current collected from the plasma during electron-beam welding with focus point oscillation (welding power: 2.5 kW, sharp focus regime (ΔI_f=0), scanning frequency: 561 Hz).

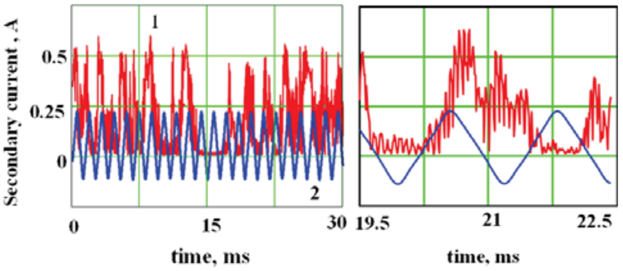

Fig. 2 Waveform of secondary current, collected from the plasma and the signal of the focus coil current during electron-beam welding with focus point oscillation. 1. *Data* (*t*): secondary current. 2.*Osc*(*t*): signal from the focusing lens current.

There is a hypothesis to explain the mechanism of the appearance of high-frequency oscillations in the secondary signal in the plasma. It deals with the assumption of the existence of explosive boiling in the keyhole [12, 20]. The rate of energy input in the interaction of the electron beam with the metal in the keyhole is much higher than the rate of heat removal through conduction. There is local overheating of the metal, followed by explosive boiling. The boiling metal vapor affects beam shielding, the beam is scattered by the metal vapor, and the power density is dramatically reduced. After the vapor evacuation from the keyhole, the beam power density is again above the critical and the process resumes. The frequencies predicted by this hypothesis are close to those observed experimentally (Fig. 1).

The described phenomena have important effect. They imply the extreme character of the probability of self-oscillation processes on the power density of the electron beam. The hypotheses do not disprove each other. Increasing the power density of the electron beam makes the difference between the velocities of the input energy in the metal and its removal even larger. This must increase the probability of local overheating of the metal.

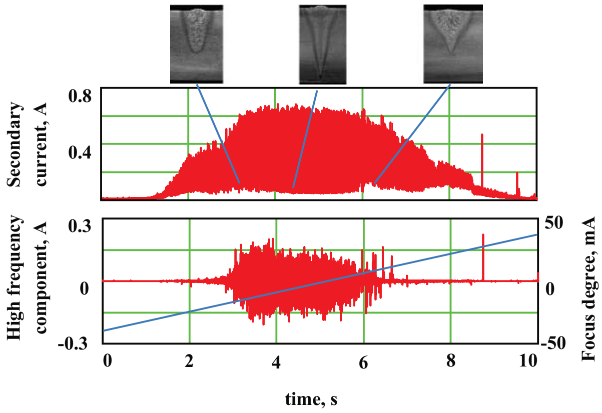

Fig. 3 The high-frequency component of the secondary current during the linear rise of the focusing lens current. (*P*=2 kW).

Fig. 3 shows the secondary current and the high-frequency component (f> 10 kHz) during the linear rise of the focusing lens current. The signal is appreciable in a certain range, accompanied by deep penetration. The high-frequency component appears in a narrow range. The dependence of the high-frequency component on the power density (the focus degree) is used to construct operational control methods.

In the given work, research into the secondary signal was conducted using coherent accumulation, which is an enhancement of coherent detection, and is widely applied to tracking an electronic beam on a seam, but it has been applied to research processes in the keyhole and welding control only recently. In this research, the high-frequency range 15–20 kHz was studied.

The coherent accumulation method is illustrated in Fig. 4. The small-width square-wave signal is formed from the signal from the current of the focusing lens ($Osc(t)$) - a basic signal $g(t)$. The basic signal $g(t+\tau)$ is shifted relative to the initial signal $Osc(t)$ for a set time τ (Fig. 4).

The signal of the secondary current, collected from the plasma $I_c(t)$ is processed by a digital or analog high-pass filter with a cutoff frequency around 10 kHz. The selected signal of the high-frequency component ($Data(t)$) is rectified and then multiplied by the basic signal, $g(t+\tau)$. The result is integrated over time. As a result, we have the function $S(\tau)$

$$S(\tau) = \int_0^{t_0} g(t+\tau)\cdot\left|Data(t)\right|dt\,,$$

where t_0 is the sampling time. This function $S(\tau)$ expresses the average amplitude of the high-frequency secondary signal for each value of the shift kV. The welding power was in the range from 2 kW to 4 kW.

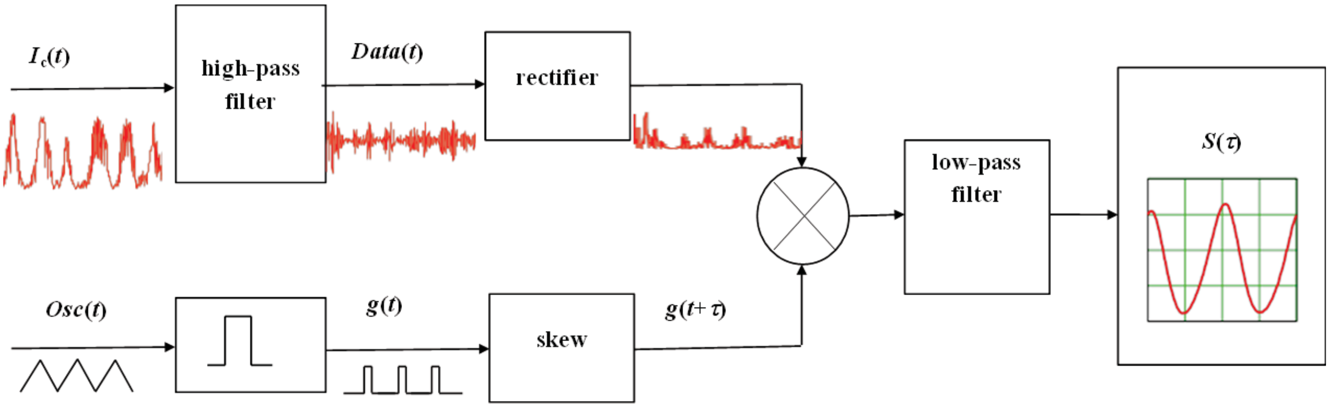

Fig. 3 Coherent accumulation method

In other words, for each value of focusing lens current, there is an average value of the amplitude of the high-frequency oscillations of the secondary signal.

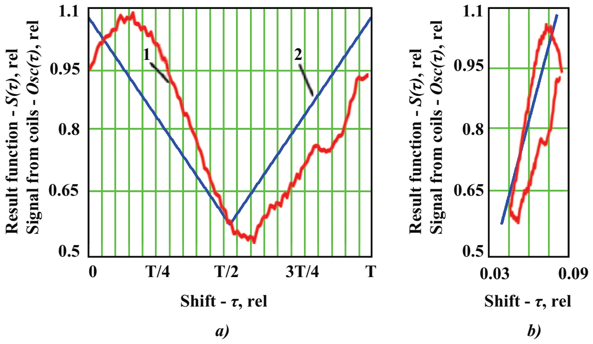

Fig. 5 1- Function $S(\tau)$, obtained using the coherent accumulation method on τ, is the result of secondary processing of the high-frequency component signal. 2- $Osc(\tau)$ is the record of the focusing lens current (P=2.5 kW, underfocus regime (ΔI_f= -10 mA), oscillation frequency f=966 Hz).

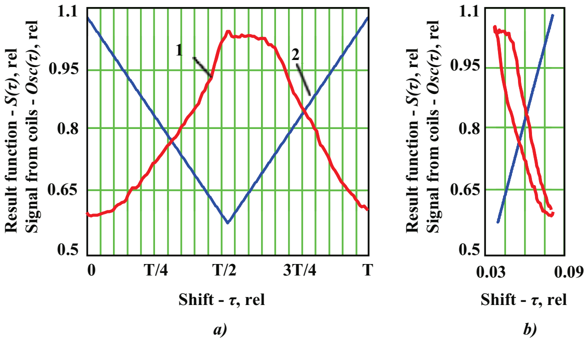

Fig. 6 1- Function $S(\tau)$, obtained using the coherent accumulation method on τ, is the result of secondary processing of the high-frequency component signal. 2- $Osc(\tau)$ is the record of the focusing lens current (P=2.5 kW, overfocus regime (ΔI_f= +17 mA), oscillation frequency f=966 Hz).

Fig. 5a shows the results of processing the secondary current signal using coherent accumulation with focal spot scanning . The underfocus regime was used. The frequency was 966 Hz and the amplitude of the focusing lens current oscillations was 7 mA. It is possible to present this function in phase space. For this purpose, on a horizontal axis we postpone the current of the focusing lens (Fig. 5b).The characteristic lag of the high-frequency component signal relative to the deflection coil current signal may be noted. A similar phenomenon has been observed in [21] and may be explained by thermal effects in the melting zone.

Fig. 6 shows the results when the beam is over-focused. The change in sign of the correlation coefficient when the beam is focused is of major interest. When the beam is under-focused the coefficient's sign is positive. As the focusing current is increased, the coefficient's magnitude decreases monotonically, becoming zero in the region of sharp focus. A similar phenomenon has been observed in the entire range of investigated conditions. The total number of observations in the multi-factor experiment was 107.

The change in the sign of the correlation coefficient during a change in the focusing current is highly significant. The existence of an extreme in the amplitudes of the high-frequency oscillations of the secondary current in the plasma as a function of the focusing current as it is slowly changed may be explained by the existence of an extreme in the welding parameters (weld penetration, width of the melting zone, etc.). In the experiments described, the frequency of change of the focusing current was several orders of magnitude larger than the frequencies characterizing the geometry of the melting zone. The results obtained confirm the hypothesis that the probability of the occurrence of high-frequency oscillations as well as the amplitude of those oscillations in the secondary waveform, increase monotonically given an increase in the concentration of energy in the area of interaction between the electron beam and the metal in the melting zone.

The function described makes it possible to detect focus conditions and directly control them in the process of EBW. To do this while welding with an oscillating beam, the electron gun's focusing lens current is modulated by frequency f. The current of the charged-particle collector installed over the electron beam weld zone is recorded during the welding process.

In this case the focusing current can be written as:

$$I_{\text{f}}(t) = \langle I_{\text{f}} \rangle \cdot (1+\xi \cdot \cos\omega \cdot t)] \quad , \qquad (1)$$

where$\langle I_{\text{f}} \rangle$ is the current average value of the focusing current; ξ is the modulation depth of the focusing lens current, ω=2πf is the focus's scanning frequency (modulation of the focusing system's current).

The waveform of the secondary current in the plasma, which was captured by the electron collector, is subjected to high-frequency filtering and then rectification. In the process, the amplitude of the high-frequencies of the current captured by the electron collector will change according to the following law:

$$I_{\text{км}} = \varphi[I_{\text{fo}} - I_f(t)] \, ,$$

where$\varphi[I_{\text{fo}} - I_{\text{f}}(t)]$ – is the function described above which expresses the dependence of the amplitude of the high-frequency oscillations of the secondary current on the level of focus ($\Delta I_{\text{f}}=\langle I_{\text{f}} \rangle$ -I_{fo}).

As shown above, in the absence of modulation of the focusing lens current (ξ = 0) the function $\varphi[I_{\text{fo}} - I_{\text{f}}(t)]$ has an extreme(maximum) when $I_{\text{f}} = I_{\text{fo}}$, and the vicinity of this point may be roughly approximated by the quadratic function

$$I_{\text{км}} = \varphi(I_{\text{fo}} - I_{\text{f}}) = a - k \cdot \Delta I_f{}^2 = a - k \cdot (I_{\text{fo}} - I_{\text{f}})^2 \quad , \qquad (2)$$

where a, k are certain coefficients.

Inserting (1) into (2)

$$I_{\text{к}m} = a - k \cdot (\Delta I_{\text{f}}{}^2 - 2 \cdot I_{\text{f}} \cdot \xi \cdot \Delta I_{\text{f}} \cdot \cos\omega \cdot t + {} + I_{\text{f}}^2 \cdot \xi^2 \cdot \cos^2 \omega \cdot t) \qquad (3)$$

If the waveform of (3), which expresses the amplitude of the high-frequency oscillations of the secondary current are synchronously demodulated at frequency ω then, after synchronous demodulation and low-frequency filtering in order to remove modulation oscillations, we obtain a waveform proportional to the expression:

$$I_{k\omega} = I_{\text{f}} \cdot \xi \cdot (I_{\text{f}} - I_{\text{fo}}) \qquad (4)$$

This waveform makes it possible with high accuracy to determine and adjust the focusing current of an electron beam providing either the maximum weld penetration of the metal (a sharply focused beam) or a penetration value close to the maximum (over-focused or under-focused beams).

IV. CONCLUSION

1. In this paper, the ability to study processes in the penetration channel (keyhole) during electron-beam welding was demonstrated. A combination of an application of focus beam oscillation and an analysis of the instabilities of the secondary current, collected from the plasma over the welded samples was used for this purpose.

2. The experimentally obtained secondary current signal, collected from plasma during electron-beam welding with electron beam oscillation contains a series of high-frequency perturbations, which follow each other at certain frequencies that are multiples of the deflection scanning frequency.

3. It was shown that the probability of occurrence of these high-frequency perturbations increases with the concentration of energy in the interaction zone. Hypotheses for the emergence of high-frequency oscillating processes in the “beam-keyhole-plasma” structure were considered. The local overheating of the metal is possible during electron-beam welding with a subsequent vapor explosion and defocusing of the latter, when the vapor density reaches a critical value.

4. A method has been developed to adaptively focus an electron beam during EBW. The method provides highly accurate control of the focus of an electron beam during welding with an oscillating focus in conditions of deep weld penetration. The method is based on the use of synchronous demodulation and makes it possible to determine and adjust the focusing current of an electron beam during EBW, which during the welding process provides either maximum weld penetration of the metal (a sharply focused beam) or a penetration value close to the maximum (over-focused or under-focused beams).

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