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WELD FORMATION CONTROL AT ELECTRON BEAM WELDING WITH BEAM OSCILLATIONS

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Electron beam welding is used extensively to produce essential machine parts. The control of the basic beam parameters – beam power or beam current at constant accelerating voltage, welding speed, current of focusing lens and distance between electron gun and welded sample surface – is not enough to obtain at most of the regimes sound welds. Control of the focus position using analysis of the high frequency component of the current, collected by plasma, at periodic interactions on the beam (the oscillation of the beam or modulation of the focusing current) could be a way for the formation of non-defect welds at these conditions. The statistical analysis of weld geometry is shown.

Keywords: Electron beam welding, penetration control, focus control, beam oscillation, focus scanning.

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УПРАВЛЕНИЕ ФОРМИРОВАНИЕМ СВАРНОГО ШВА ПРИ ЭЛЕКТРОННО-ЛУЧЕВОЙ СВАРКЕ С ОСЦИЛЛЯЦИЕЙ ПУЧКА

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Электронно-лучевая сварка широко используется для производства ответственных изделий. Только контроля основных параметров пучка – мощности пучка или тока пучка при постоянном ускоряющем напряжении, скорости сварки, тока фокусирующей линзы и расстояния между электронной пушкой и поверхностью образца – не достаточно, чтобы получить качественные швы на большинстве режимов. Контроль положения фокуса, использующий анализ высокочастотной составляющей тока, собранного из плазмы, при периодических взаимодействиях на пучок (колебания пучка или модуляции тока фокусировки) может быть способом для формирования бездефектных сварных швов на этих условиях. Приведены результаты статистического анализа геометрии сварных швов.

Ключевые слова: электронно-лучевая сварка, управление проплавлением, контроль фокусировки, осцилляция луча, сканирование фокуса.

Introduction. Electron beam welding (EBW) is a fusion welding process performed in a vacuum. The process has a number of advantages: high power concentration in the electron beam, easy control of the beam energy flow, deeply penetrating beam producing narrow and deep welds, smaller heat-affected zones, equal strengths of the weld joint and the main metal, etc. These advantages allow the use of the electron beam for welding of reactive and non-ferrous metals, high-tensile and heat-resistant alloys that are typically used in the production of critical products.

However, certain problems arise in the EBW process, which are related to the instability of weld-joint formation and the difficulties in controlling the optimal focus regime. The complex character and the lack of understanding of the processes during EBW make numerical modelling difficult, forcing scientists 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 during EBW is the beam focusing position. The operator of an EBW machine needs manually to set the focus of the beam. The adjustment of the focusing-coil current is based on the operator's subjective 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 may not be 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 need for real-time focusing control results from changes in the electronic–optical systems of an electronic gun due to cathode wear and tear or after planned maintenance. For welding operation modes, the focusing current should be adjusted based on experiments with various materials, thicknesses and types of electronic-beam guns. Real-time adjustments are important for welding large objects, especially when the cathode electron emission and thus the adjustments of the gun are significant.

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

All the above methods use extreme correlations between the secondary emissions and the focusing lens current. These correlations are characterised by the dead zones and two values of the focusing lens current that ensure similar signal parameters, but various derivatives.

One of the specific processes caused by the impact of the intensive electron beam on the metal during EBW is the formation of plasma in the operational area [6; 7]. The parameters of the plasma are closely connected with the electron beam thermal effect on the metal being welded. In [8; 9], the plasma current parameters are suggested for electron beam focusing control.

A possibility to change from free to forced instabilities of the keyhole walls is to apply beam linear longitudinal oscillation.

The application of focal spot scanning (modulation of the focusing lens current) is another method for control of the keyhole wall instabilities. The low frequency scanning of the focusing current has negative effects on the quality of the weld. Application of high frequency scanning of the focal spot to improve the quality of the welded joint is known. However, its applicability to the operational control of the beam focusing has not been investigated until now.

A simultaneous recording of the deflection coil current or the focusing lens current and the secondary current signals collected by the plasma was realised using both approaches in order to affect the beam energy deposition processes in keyhole.

This article studies the behaviour of the current collected from the plasma, generated in the operational area of the electron beam, when using EBW with oscillating beam or with focal spot scanning (modulation of the focusing lens current), based on the coherent accumulation method [10–12]. This method can be used to obtain not only amplitude ratios, but also the phase ones, as well as determining how the current signals collected by the plasma are synchronised with the deflection current or the focusing lens signals during EBW. These results on the probability of the generation of the high frequency component of the non-independent gas discharge current (namely the instabilities of electron emission from the super-heated spots on keyhole walls) can be useful as methods to control the EBW focus position against the parameters of the plasma current.

Experimental procedure. A ring electrode collector was used to measure the secondary current from the plasma. The collector was located over the welding zone. 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) were welded. The accelerating voltage in all experiments was 60 kV. The welding power was 3 kW and the welding speed was 5 mm/s for experiments of beam oscillations and the welding power was in the range of 2 kW to 4 kW in the case of focusing spot scanning.

During the experiments, the welding power P, welding speed, focus degree ΔI_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 the sharp focus), the frequency f and the amplitude of the focal spot scanning A were varied.

The current in the focusing or deflection lenses was changed under a linear law. In the case of beam deflection oscillations experiments, the deflection oscillation frequency ranged between 50 Hz and 1.400 Hz and the range of the duplicated maximal amplitude of the beam deflection oscillation was 0.4 mm to 3.5 mm.

In the case of beam focus scanning, the limits of the scanning frequency were from 90 to 12,000 Hz. The amplitude of these oscillations was in the range of 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.

Measured results. Fig. 1 shows the spectrum of the secondary current signal, generated from the plasma plume over the work-piece from studied chrome-molybdenum steel at EBW with the electron beam oscillations.

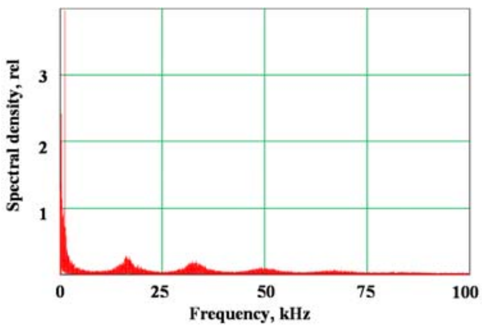


Fig. 1. Spectrum of secondary current signal, extracted from plasma at EBW with the oscillation of electron beam: electron beam power P = 2.5 kW, lens focusing current at position of 'sharp focus' (I_f = 840 mA), oscillation frequency f = 561 Hz, sweep size of the duplicated amplitude of deflection oscillations 2A = 0.9 mm

The main part of the signal oscillations is in the low frequency range up to 5 kHz. Apart from that, a peak of oscillations of the plasma signal is observable at the frequency of 15–20 kHz and its multiple harmonics, which characterises high frequency processes in the system electron beam-penetration channel-plasma.

Fig. 2 shows a typical spectrum of the secondary current signal collected from plasma during the welding of steel samples. It can be noted that there is the same characteristic maximum in the signal at frequencies close to 15–20 kHz. The collected from the plasma signal record (fig. 3) looks like a series of high frequency impulses that follow each other (curve 1). For comparison, the record of deflection oscillations current (curve 2) is shown. The impulses of the series of the secondary signal appear with frequency of order 10–30 kHz and have considerable values (impulses value depends on the current selection conditions and reached 1 A in the performed experiments).

The similarity of these records of the high frequency current signals, collected by the plasma at periodic interaction on beam energy absorption in the keyhole in the welding bath, can be seen. There is a hypothesis to explain the mechanism of the appearance of high frequency oscillations in the collected current by the positive electrode in the plasma. The collector plays the role of an anode in a non-independent discharge. The plasma in the keyhole and the plasma plume over the interaction zone is an electrically conductive media in that discharge. The electron emission occurs from over-heated spots on the walls or in the bottom part of the keyhole. These spots are explained with the assumption of the existence of electron beam ablation (explosive boiling) [13–15]. The rate of the energy input in the interaction zone of the electron beam with the metal in the keyhole is much higher than the rate of heat removal through conduction. There is local over-heating of the metal, followed by explosive boiling. The boiling metal vapour affects the beam structure, the local beam part is scattered by the metal vapour and by the blow-up ablation products, and the power density is dramatically reduced. After the vapour 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 the high frequency component, observed experimentally (fig. 1 and fig. 2). The local over-heating of the metal walls of the keyhole is a result of the local areas with lower angle in respect to near to vertical walls of the front side of the keyhole in the welding bath. Some blow-up droplets also absorb additional energy and are for a short time over-heated. As a result the thermal electron emission from over-heated spots plays the role of an impulse cathode emitter in non-independent gas discharge with an anode – the collector electrode.

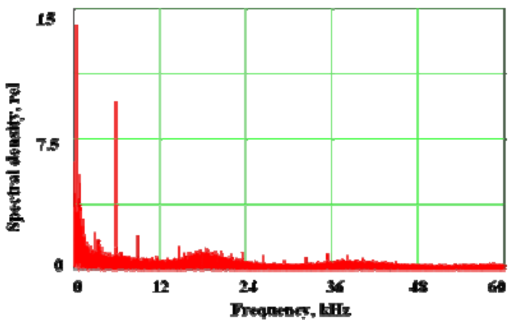


Fig. 2. A typical signal spectrum of the secondary current collected from the plasma during EBW with focus position oscillation (welding power: 2.5 kW, sharp focus regime (ΔI_f = 0), scanning frequency: 1.523 Hz)

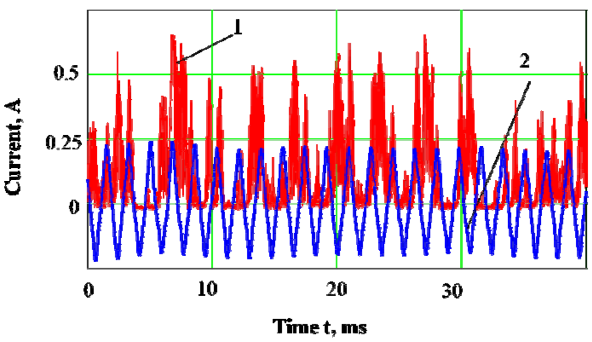


Fig. 3. Records of the secondary current, generated by plasma and of the current in the deflection coils. Welding of steel with the oscillation: P = 2.5 kW, sharp focus (I_f = 840 mA), oscillation frequency f = 561 Hz, sweep size 2A = 0.9 mm. Curve 1 presents high frequency impulses (packed in low frequency oscillation signal) and curve 2 is deflection coils current

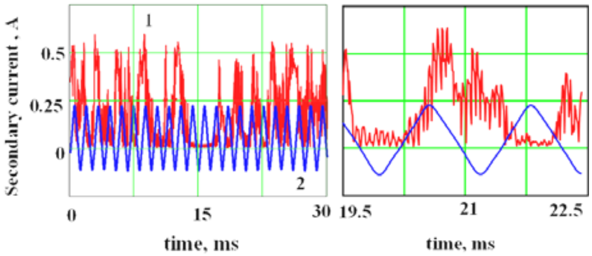


Fig. 4. Waveform of secondary current, collected from the plasma and the signal of the focus coil current during EBW with focus position oscillation: 1 – Secondary current; 2 – Signal from the focusing lens current

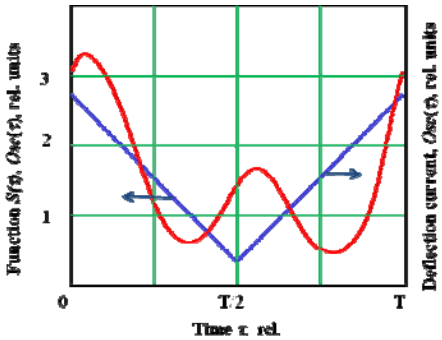


Fig. 5. Record of deflection coils current signal Osc(t) (two straight lines) and function $S(\tau)$ obtained by the coherent accumulation method during the steel welding with oscillation along the joint (P = 3 kW, beam current 50 mA, oscillation frequency f = 630 Hz, oscillations sweep size 2A = 1.5 mm); $S(\tau)$ is for low frequency (up to 2 kHz) oscillations and for focusing current 825 mA (low focused beam)

A result of the treatment of the secondary signal by the method of the coherent accumulation, at the welding process with deflection oscillation along the joint, is presented on fig. 5. There is also shown a record of the deflection coil current Osc(τ). The differences in the maximal amplitudes on fig. 5 and the small shift of the positions of the maximal values of S(τ) in comparison with the positions of the changes of the deflection coil's current directions can be found.

Fig. 6 shows the results of the analysis of the high frequency component of collected by plasma current at modulation of the focusing current, when the beam is over-focused. The change in the sign of the phase shift at changes of the beam focusing position is of major interest. When the beam is under-focused, the phase shift is positive. As the focusing current is increased, the phase shift magnitude decreases monotonically, becoming zero in the region of sharp focus. A similar phenomenon has been observed in the entire range of investigated conditions as well as in the case of oscillating beam studies.

It can be concluded that the time shift and amplitude changes of the maximums in the created by coherent accumulation method curves of probability of excitation of high frequency current component $S(\tau)$ could be a base for new control methods for adjustment of the beam focus position during welding with periodic interactions on the electron beam (the oscillation of the beam or scanning the beam focus). Such method of focus position control, due to monotonic relation of the feedback signal with the focusing lens current, is faster than any known methods, which need the application of an additional focus exploratory scanning.

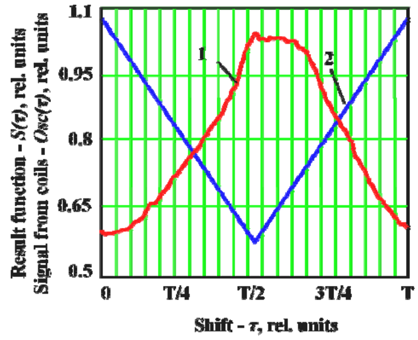
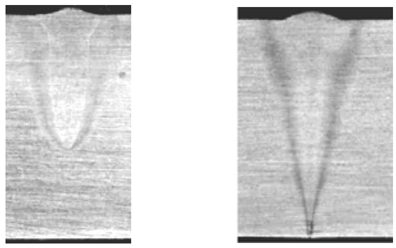


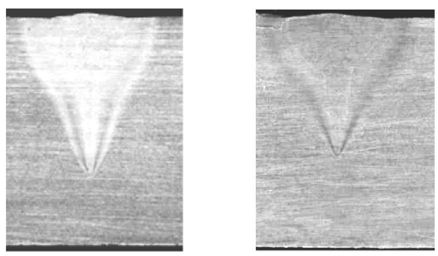
Fig. 6. Curve 1 – Function $S(\tau)$, obtained using the coherent accumulation method on τ, as a result of analysis of the high frequency component of collected from plasma current; Straight lines 2 – Osc(τ) is the record of the focusing lens current (P = 2.5 kW, over-focusing regime (ΔI_f = +17 mA), oscillation frequency f = 966 Hz)

On the weld cross-section control. The metallographic cross-sections of the welds, produced by beam longitudinal oscillations (630 Hz, A=1 mm), shown on fig. 7, *a* and fig. 7, *b* as fig. 8, *a* and fig. 8, *b* are compared.



a *b*

Fig. 7. Metallographic transverse cross-sections of the welds, obtained at focusing currents: 825 mA (*a*); 833 mA (*b*)

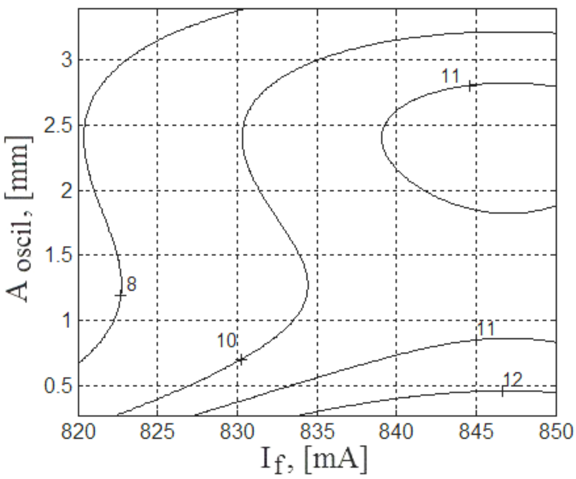


a *b*

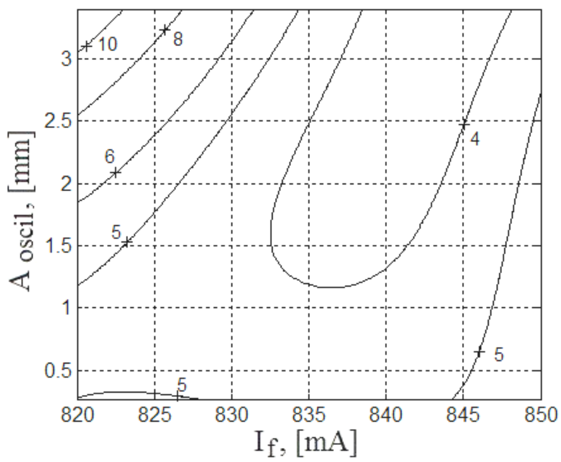
Fig. 8. Metallographic transverse cross-sections of the welds, obtained at focusing currents: 847 mA (*a*); 852 mA (*b*)

It can be seen that deflection oscillation prevents the appearance of root defects (spiking) only in the case of a low-focused beam, but there the penetration depth is lower than in the case of a sharp-focused beam.

The contour plots of the dependence of the weld depth H and of the weld width at sample surface B on the focusing current I_f and on the amplitude of deflection sweep A_{oscil} under linear longitudinal oscillations of the beam for the chosen oscillation frequency F_{osc} = 745 Hz are presented in fig. 9. The deflection oscillation amplitudes do not affect the weld depth at small focusing currents (fig. 9, *a*). An increase of the focusing current in this region extends slowly the weld depth. In fig. 9, *a* the region of the deepest welds (i. e., the sharp focus) can be seen at higher focusing currents in the range of 840–855 mA (in comparison with the static beam case, where a sharp focus was observed at 833–835 mA) and at amplitudes between 2 and 2.7 mm.



a



b

Fig. 9. Contour plot of dependence of weld depth H from focusing current I_f and amplitude of beam deflection oscillations A_{oscil} (*a*); contour plot of dependence of weld width on the sample surface from focusing current If and amplitude of beam deflection oscillations A_{oscil} (*b*)

In this case of longitudinal oscillations, as shown in fig. 9, *b*, it can be seen that narrower welds appears at oscillation amplitudes greater than 1.2–1.5 mm and focusing currents higher than 833–840 mA. In the case of down focusing position an increase of the oscillation amplitude extends the surface width of the seam.

Fig. 10 presents the dependences of weld depth H on oscillation amplitude A_{oscil} at constant F_{osc}. The focus position is on 13 mm (sharp focusing of the beam at which maximal weld depth was obtained). At small amplitudes (A_{oscil} < 1 mm) a maximal weld depth is shown, better for frequency of F_{osc} = 200 Hz. At F_{osc} = 1,000 Hz an invariant weld depth can be obtained, in the range of amplitudes of oscillations (1–2.5) mm. The weld depth at F_{osc} = 200 Hz and at amplitudes A_{oscil} < 2.5 mm is higher, than in higher frequencies of oscillations F_{osc} = 1.000 Hz or F_{osc} = 1.400 Hz.

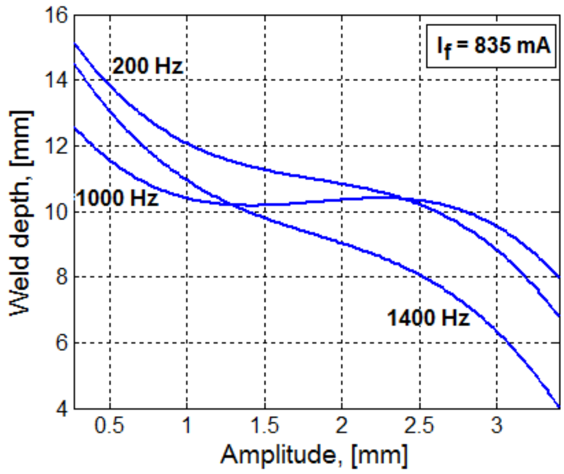


Fig. 10. Dependences of weld depth H on oscillation amplitude A_{oscil} at some frequencies F_{osc} = const of the longitudinal deflection oscillations

In the case of very big oscillation amplitudes (A_{oscil} ≥ 2.5 mm) the weld depth decreases, due to lower values of the beam power density.

On fig. 11 is shown dependences of weld depth from oscillation frequency at three amplitudes of deflection oscillations. In the range of frequencies of oscillations 400–1.000 Hz the weld depths are invariant. In the range of frequencies F_{osc} < 400 Hz small amplitudes lead to higher weld depths. Frequencies F_{osc} ≥ 1.000 Hz and oscillations amplitudes A_{oscil} ≥ 1.5 mm lead to decrease of the weld depths.

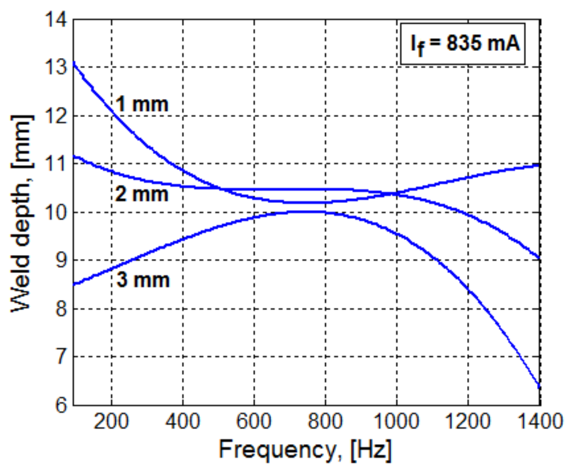


Fig. 11. Dependences of weld depth H on oscillation frequency F_{osc} at some longitudinal amplitudes A_{oscil} = const of the longitudinal beam deflections

In the case of scanning the focusing position along the beam axis at welding chrome-nickel steel the cross-section have a big head and narrow and deep weld (fig. 12). In some applications a more thick shaft and proportionally smallest head can be acceptable (fig. 13).

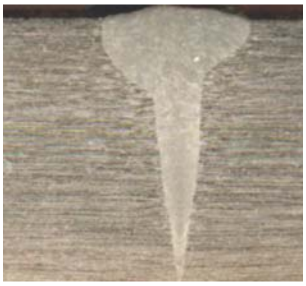


Fig. 12. Weld cross-section at 35 mA beam current, 835 mA focusing current and focus scanning: 9 mA, 960 Hz v = 5 mm/s

Fig. 13. Weld cross-section at 31 mA beam current, 826 mA no focus scanning, welding velocity 5 mm/s

On fig. 14 is shown contour plot of dependences of the weld depth on amplitude of focus scanning A and on focusing coil current If. The weld depth has weak dependence from focus scanning amplitude A and known considerable dependence from beam focus position.

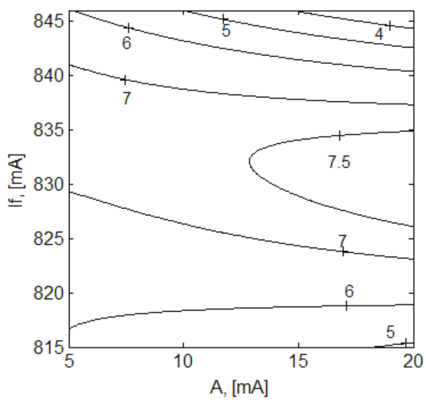


Fig. 14. Contour plot of weld depth on A and If at frequencies of focus scanning F = 1.116.5 Hz

On fig. 15 is shown contour plot of weld width on surface (namely width of weld-head) on amplitude of scanning and focusing lens current. One can see the same more strong dependence on position of focus on weld width, as well as that at small amplitudes of focus scanning are the regions of more width welds at down-focused and over-focused beams.

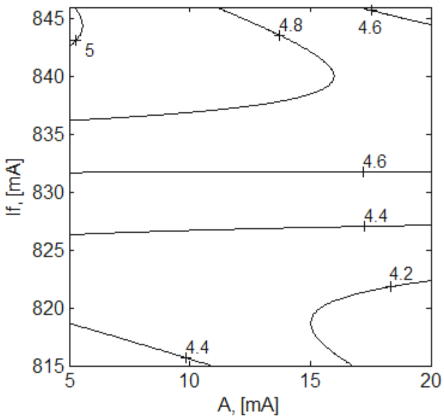


Fig. 15. Contour plot of weld width on surface on A and If at focus scanning frequencies F = 1.116.5 Hz

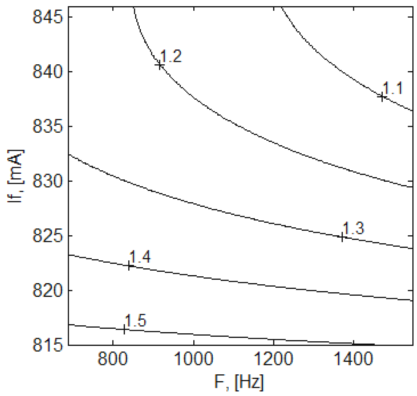


Fig. 16. Contour plot of weld width measured on one-half of the weld depth versus F of focus scanning and focusing current If at scanning amplitude A = 12.5 mA

On fig. 16 is shown the contour plot of weld width, measured on one-half of weld depth on focus scanning frequencies and focusing current at constant scanning amplitude A = 12.5 mA. For over-focused beam an increase of scanning frequency decrease of weld width, as well as at down-focused beam the scanning frequency is practically not affects the weld width, measured at one-half of the weld depth.

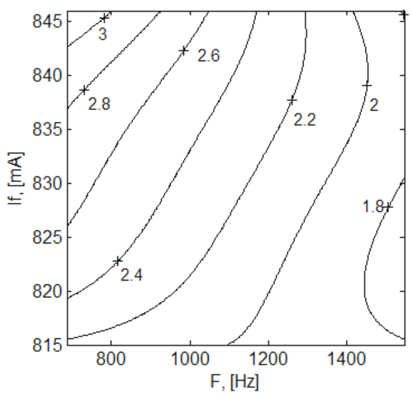


Fig. 17. Dependences of the depth of the weld-head on F of focus scanning and on focusing current If at scanning amplitude A = 12.5 mA

On fig. 17 is shown contour plot of the depth of head (more wider upper part of the weld on *F* of scanning and focusing position at constant amplitudes of scanning and welding speed). Smallest depths of the weld-heads is observable at down-focused beam and higher scanning frequencies.

The study demonstrates the possibility to research of processes in the keyhole at electron-beam welding according to parameters of secondary current in plasma. The signal spectrum of the secondary current at electron beam welding contains a characteristic high-frequency (15…25 kHz) component. The secondary current signal at electron-beam welding with electron beam oscillation presents a series of high-frequency impulses which follow each other with frequency to multiple oscillation frequency. The obtained by coherent accumulation method function $S(\tau)$ has a lag (time shift) in relation to the signal of deflection coils. The Lag value is depended on welding regime and it can be used to in-process control at electron-beam welding. There are three characteristic frequency areas at EBW. In the range up to 100 Hz, from two hundred hertz to two kilohertz, and five kilohertz and more. When the oscillation frequency changes in these ranges, the formation of a secondary signal and weld formation are significantly different, too.

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