Characteristics of plasma generated during electron beam welding

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Electron beam is at the forefront of welding technology. The choice of optimal welding modes, monitoring the weld quality and/or detecting weld defects in real-time during the electron beam welding process using nondestructive, cost-effective and reliable methods is one of current challenges in this field. The plasma, generated in the keyhole and the plasma plume (in the space above the welding pool), provides an opportunity to study welding stability and optimal modes as well as the formation of weld defects.

The generation and the characteristics of the plasma in the keyhole and above the welding pool are measured and discussed. In the case of electron beam welding with beam oscillations, the method of coherent accumulation is applicable to analyze of the plasma fluctuation process by the plasma electron current. Computer simulation results for the distributions of the plasma parameters in the case of presence of positively polarized collector electrode and in the case without such electrode above the welding pool are also presented in this review paper.

Характеристики на плазмата, генерирана при електронно-лъчево заваряване (Георги М. Младенов, Димитрий Н. Трушников, Елена Г. Колева, Владимир Я. Беленский). *Електронният сноп е на предния фронт на заваръчните технологии. Изборът на оптимални заваръчни методи, мониторингът на качеството и /или детектирането на заваръчни дефекти в реално време по време на заваръчния процес използвайки неразрушаващи, евтини и надеждни процеси е едно от актуалните предизвикателства.Плазмата, генерирана в заваръчния кратер и в плазмения облак над заваръчната вана обезпечават една възможност за изучаване стабилността, оптимизирането и формирането на заваръчни дефекти.*

Генерирането и характеризирането на плазмата в заваръчния кратер и над заваръчната вана се измерват и дискутират. В случай на електронно-лъчево заваряване с колебания на снопа методът на кохерентно акумулиране се прилага за анализ на процеса на плазмени флуктуации чрез колекторния електронен ток. Резултати от компютърна симулация на разпределението на плазмените параметри в случаите на положително поляризиран колекторен електрод и без такъв електрод над заваръчната вана са включени също в тази обзорна работа.

Introduction

Electron beam welding is widely used technology for joining of metals due to numerous advantages in comparison to other welding technologies. However, certain problems arise in the welding process, related to instability of weld joint formation and difficulties in creating and controlling the optimal welding modes. One of the main concerns of the industry is to assure the weld quality in real-time using a cost-effective and reliable method. It would be significant for the industry to be able to find optimal welding modes and/or detect defects nondestructively in real-time during the welding process.

One of the phenomena that occur during interaction of concentrated energy beam with metal sample is generation of plasma in the welding zone. Study of plasma characteristics and their relation to process/product performance/quality could help increase knowledge of control of electron beam welding using concentrated energy beams and create approaches for its optimization. Due to the complex character of electron beam welding and lack of adequate models of physical processes in the crater in the welding bath optimization and quality improvement of electron beam welding are empirical and still need more research.

Parameters of plasma, generating in the interaction zone of intense electron beam with welded sample

During interaction between intense electron beam and metal low temperature plasma is generated in the welding zone [1 - 12]. Deep penetration electron beam welding is associated with absorption of beam energy (over 5.10^5 W/cm^{-2}) by a work-piece through a capillary crater in the work-piece referred to as the keyhole. The keyhole is filled with metal vapor, ionized atoms and electrons. Vapor pressures in the keyhole near the root of the weld are higher thereby creating a vapor flow to the space surrounding the sample. Generation of plasma inside and outside the keyhole is a result of collisions of vapor atoms with beam electrons, electrons reflected by the sample wall and the generated x-rays. It can be assumed that in the root part of the keyhole due to concentration of ions (there are beam electrons and free electrons and ions, created by the ionizing processes) of order of 10^{17} – 10^{20} m^{-3} a compensation and/or overcompensation of the beam negative charge takes place temporarily or continuously (free electrons are loosed off the wall). In the next keyhole part due to transportation of ions and mainly due to additional ionization of the ionized vapor flowing along the keyhole region, the electron concentration increases to 10^{22} - 10^{23} m^{-3} [3] and Debye radius becomes less than the keyhole radius - i.e. ionized vapor achieves plasma state. Due to maximum plasma concentration in this deep part of the keyhole plasma parameters such as plasma potential and electron temperature are determined here. The Debye layer around the liquid metal walls of the keyhole keeps the balance between the numbers of plasma electrons and ions in the rest of the keyhole propagation distance. The flow of a mixture of hot neutral atoms and cold plasma ions, directed towards the orifice of the keyhole on the sample surface is controlled by gas-dynamic conditions in the keyhole and the concentration of these particles decreases. Then vapor cloud and plasma plume are emitted in the space over the welding zone [6 - 8]. Note that neutral atom distribution and plasma particle distribution over the welding sample surface are different due to different nature of their ensemble expansion.

A. Plasma parameters in case of vacuum electron beam welding

The plasma plume above the welding pool has been studied because it is readily observable. Some research used Langmuir probe methodology (the Langmuir probe is shielded from direct back scattered electron current by a grounded metal shield) oscillations of measured values, unclean surface of the probe in electron beam welding conditions and presence of negative ions or charged droplets. On Fig. 2 to Fig. 4 electron part of volt-ampere probe characteristics is shown for three beam currents, three sample materials and two distances between welding pool and Langmuir probe. The ion part is not shown, because ion currents are more than 100 times smaller.

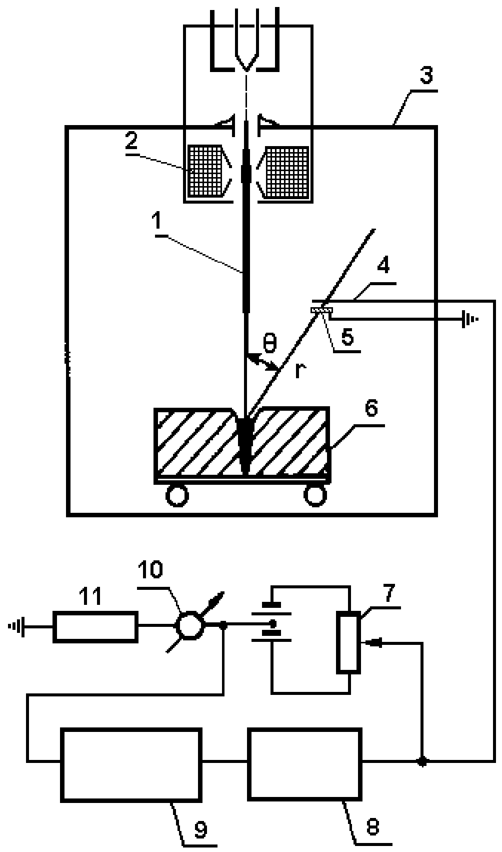

Fig.1. Measurements of plasma parameters during electron beam welding [4]

In ref. [5] electron temperature, density of charged particles and floating [1, 2, 4, 5, 8], as shown in Fig. 1. There: 1 is electron beam, 2 – focusing coil, 3 – vacuum chamber, 4 – Langmuir probe, 5 – grounded metallic shield, 6 – welded sample, 7 – two-polarity energy source, 8 – logarithmic amplifier, 9 – recorder, 10 – measuring device, 11 – resistor.

At distances of 3 - 10 cm from the interaction zone electron temperature is kTe ≈ 1 - 6 eV and electron density is of order of 10^{15} m^{-3} (note, here density of neutral vapor atoms is of order of 10^{15} - 10^{16} m^{-3}). In ref. [1, 2] for Cu, Ni, Fe and Mo and semi-spherical welding pool (no keyhole penetration: U = 13 kV; I = 44 mA) density of charged particles at distances of 3 - 4 cm from welding bath is more than 10^{14} - 10^{15} m^{-3}.

The measured electron temperature there was 80 000 K - 90 000 K. Plasma potential was 20 – 30 V. Langmuir probe method was not applicable at higher beam powers due to oscillations of the probe characteristic data.

In ref. [4] at beam current of 10 - 70 mA and accelerating voltage of 25 kV, as in [4, 5] at beam current of 40 - 80 mA at accelerating voltage of 60 kV and welding velocity of 5 – 20 mm/s the density of charged particles is 10^{16} m^{-3}, the electron temperature is 4 000 K at distances of 1 - 2 cm from the welding pool and the plasma potential is 3 - 4 V. Data accuracy is not high (with rate of mistake from 20% to 50%) due to plasma potential are measured using the same Langmuir probe methodology at various beam parameters (beam current 40 mA, 50 mA and 60 mA; accelerating voltage 60 kV) and using various welding samples (Al, Ni, Cu). The results were as follows: electron temperature of plasma above the interaction zone Te was from 4 eV to 6 eV; density of charged particles in plasma plume Ne was from 10^{13} m^{-3} (for Cu), 10^{14} m^{-3}(for Ni) and to 10^{15} m^{-3} (for Al); plasma potential Upl = 4 V.

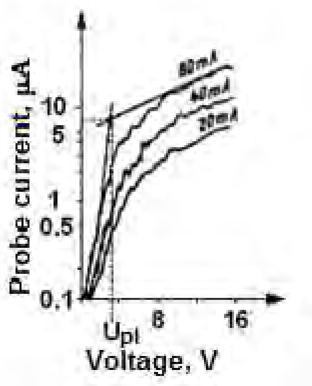

Fig.2. Probe characteristics for three beam currents. The distance to welding pool is 3 cm [4].

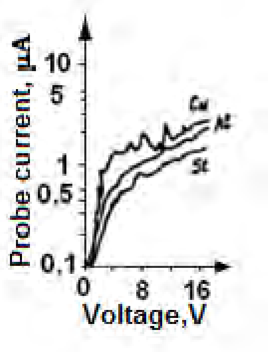

Fig.3. Probe characteristics for three sample materials. I_b=40 mA [4]

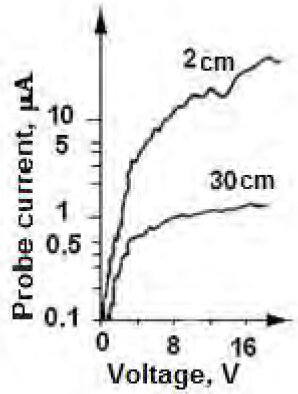

Fig.4. Probe characteristics for two distances from welding pool. I_b = 40 mA [4].

Discussing the two models – namely, hemispherical or cylindrical sources of free plasma expansion in the space over the beam-work piece interaction zone [6 - 8], it has been concluded [6] that a cylindrical plasma column in the region traced by the electron beam over the welding zone is formed. In ref. [8] oscillations of potential in the radial direction was predicted, due to different velocities of ions and electrons in the expanding plasma.

The relative distribution of the electron density and the electrostatic potential in the welding vacuum chamber were compared to experimental results and they showed good agreement.

B. A comparison of plasma parameters during electron beam and laser beam welding

Note, that during vacuum electron beam deep penetration welding the generated plasma is weak low temperature plasma (measured using Langmuir probe) and during atmospheric pressure keyhole laser welding plasma is isothermal (light emission from exiting neutral atoms or ions is observed). The average plasma temperature in keyholes is found to be considerably higher than that in plumes in both types of energy sources. Plasma parameters in the keyhole are experimentally evaluated only for welds that are not very deeply penetrating.

Plasma plume outside the keyhole has been studied extensively in both types of concentrated energy beams because it is readily observable. Plasma above the welding bath in electron beam welding (EBW) is collisionless [6], because the mean free paths le > 10^3 cm and li > 10^2 cm even for maximal values of neutral and charged particle densities. In the beam region weak light emission from exiting vapor or residual gas atoms is sometimes observed. Plasma plume above the keyhole in case of laser welding is a bright, often bluish or green flash from isothermal light emitting plasma.

During deep penetration welding the plasma in the keyhole is in the temperature range of 4 000 – 80 000 K. In ref. [13] as was mentioned above it was found that laser power of 5 kW is a turning point for plasma characteristics during laser welding. After laser power reaches 5 kW, the plume changes from metal vapor dominated weakly ionized plasma (ionization degree about 1%) to strongly ionized plasma (ionization degree reach 25%). Corresponding phenomena are the dramatic increase of the value of characteristic parameters and the appearance of a strong plasma shielding effect. Calculation of effective laser power density demonstrated that the plasma shielding effect is dominated in this case by inverse Bremsstrahlung absorption. The finding suggested that the plasma shielding effect must be considered in fiber laser welding of aluminum alloys, rather than ignored as claimed in several references concerning laser welding with laser power less than 5 kW.

No published data was found regarding plasma parameters in non-vacuum electron beam welding and in vacuum laser keyhole welding.

C. Secondary charged particles measurement in electron beam welding

From the beginning of application of the powerful electron beam for welding there were attempts to use the signals collected from charged particle flows above the welding zone to control the technological process. More clearly described was the research concerning detecting high-energy back-scattered electrons [14 - 17] or ions [18 - 20], collected above the melting pool. In many cases these studies were connected with measuring currents, collected at small positive potentials of a few volts. Many authors investigated the collector signal, located above the welding pool and positively polarized. This collected current has for a long time been called secondary electron or thermionic emitted electron signal. On Fig. 5 examples of signals [17] are given that were measured during EBW of steel at zero, small positive or negative potential (curves 1, 2 and 3). As usually these signals are distinguished by the authors of ref. [17] as back-scattered electrons, secondary electrons and ions. Note, that so-called secondary electrons signal 2 exhibits behavior of collected back-scattered electrons 1 (there is a sharp minimum at good beam focus and deep beam penetration. Explanation is that deep beam penetration in the welding sample leads to more difficult flow back of back-scattered electrons through the narrow keyhole). In the author's (of this review paper) opinion signal 2 is from the collected plasma electrons. At deep beam penetration distribution of plasma plume becomes more narrow (distribution around the beam being proportional to $\cos^3$ instead of cos from angle to vertical) and the ring collector electrode is situated in the periphery region of the plasma plume above the welding pool. Curve 3 (signal from collected ions) in case of sharp focusing has fluctuations at establishing keyhole. Vapor flow from the keyhole is wider and denser and the ions generating in the space above the welding pool in periphery of plasma plume are transported easily to the collector ring electrode (by collector electrical field and plasma boundary electrical potential drop). Here it is important that ion current signal is small and a small increase causes a big change.

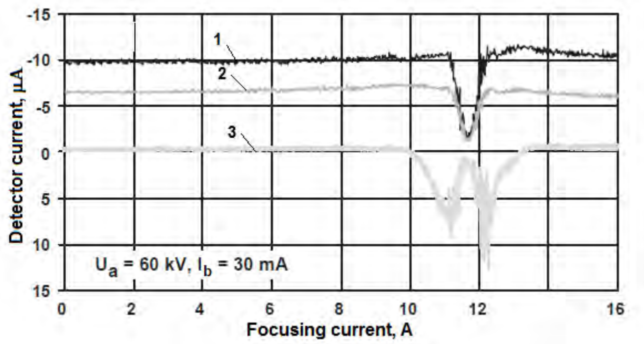

Fig.5. Component 0 - 50 Hz of charged particles' signals vs. focusing current: 1 - back-scattered electrons; 2 - secondary (plasma plume) electrons; 3 - ions [17].

Fig.6 present the spectra of signals, measured at conditions of Fig.5.

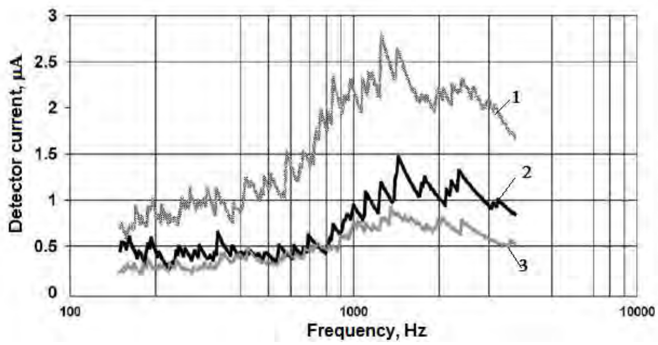

Fig.6. Frequency spectrum (component 150 Hz - 3 000 Hz of collected charged particles current at EBW for carbon steel (U_a = 60 kV, I_b = 30 mA):1 - back-scattered electrons; 2 - plasma plume electrons; 3 - ions [17].

In ref. [20, 21] numerical simulations of plasma generation and transport during electron-beam welding process are presented and discussed. There is clear description of plasma formation in the case of polarization with positive potential (about + 50 V) of a collector, set above the keyhole in the welding pool as well as the cases of zero or negative polarization of this collector. Positive collector potential due to plasma conductivity becomes plasma potential and plasma electrons are going to that electrode. At the same time thermionic emission occurs from keyhole walls pre-heated by the beam and that is keeping the balance between plasma electrons and plasma ions. In this case one could accept a non-independent discharge in the collector circuit [22 - 25]. In the cases of zero or negative collector potential the collector current is just the result of thermal diffusion of plasma particles in zone around the collector.

The spectrum of secondary current, collected by plasma could be divided into frequency ranges of 0 - 50 Hz; 50 - 3000 Hz and from 3 - 10 kHz to 100 and more kHz. The first ranges are connected with keyhole wall axial and radial instabilities. The latter high frequency range is caused by generation of ion-acoustic instabilities in the plasma plume [26] between the keyhole orifice and the collector and is a subject of another discussion. Important conclusion from this study is that in order to avoid occurrence of ion-acoustic oscillations in plasma plume the collector must be situated at a small distance to the welding pool.

D. Experimental investigations of fluctuations of the collector signal of plasma plume electrons, generated during EBW

During electron beam deep penetration the keyhole shape is continuously influenced by the beam/work-piece metal interactions, leading to oscillations of the keyhole walls and instabilities of the melt pool. Experimental investigations show [27, 28] that the beam-keyhole system is a multi-parametric oscillating system with various feedbacks. This leads to local changes of heating and vaporization intensities, of angle of front keyhole wall, of channel shape and depth, and creation of such weld defects as pores and spiking. The fluctuations influence the expanding plasma parameters [30]. The fluctuations influence the expanding plasma dynamics and oscillations of the collecting plasma electrons. The frequency range below 5 kHz is associated with radial keyhole oscillations, and the range of up to 30 kHz with axial-azimuthal oscillations of the keyhole, mostly related to weld penetration.

Experiments in a series of papers were executed utilizing a standard electron beam welding machine (Fig. 7). Accelerating voltage was 60 kV, beam current was 50 mA, and welding speed was 5 mm/s.

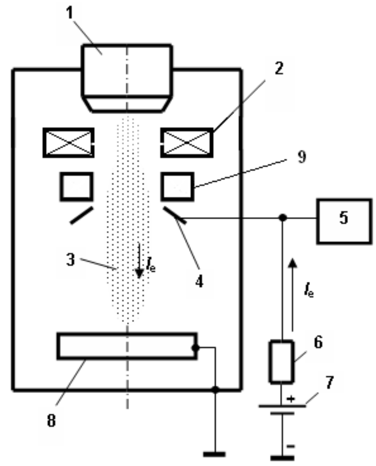

Fig.7. Diagram of secondary electron current registration in plasma formed above the area of electron beam welding: 1 - electron gun, 2 - focusing lens, 3 - plasma formed over the area of electron beam welding, 4 - electron collector, 5 - a system of registration, 6 - load resistor, 7 - a source of bias, 8 – work-piece, 9-deflection coils

Graphic representation of the plasma current collected by a metal ring electrode with potential of + 50 V, situated above the beam interaction zone (Fig. 7) during electron-beam welding with a continuously operating beam can be seen on Fig. 8. It looks as a series of high-frequency impulses which are modulated by low-frequency instabilities and follow each other in series almost regularly, reflecting focusing status of the beam.

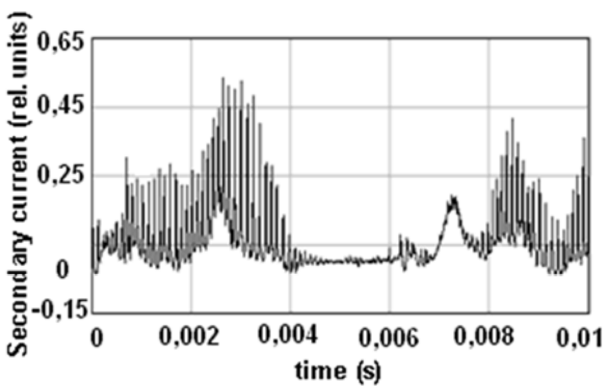

Fig.8. Typical record of the collector current, generated by plasma during EB welding. The focusing current provides sharp focusing of beam; beam power is 6 kW [24]

On Fig. 9 spectrum of the plasma current (Fig. 8) collected by the metal ring electrode 4 (see Fig. 7) is shown. This spectrum could be divided on the frequency ranges of: 0 - 5 kHz and 5 kHz - 100 kHz.

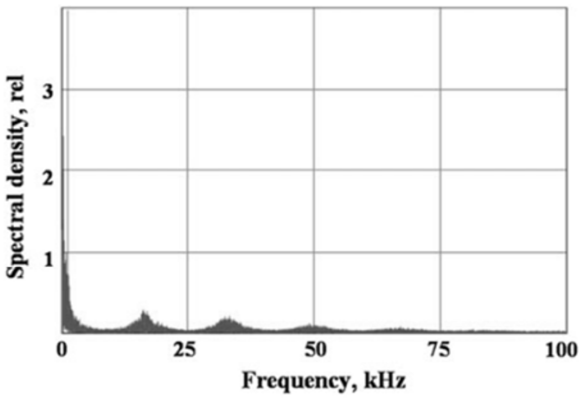

Fig.9. Spectral density of the signal of collector current at frequencies f from 0 Hz up to 100 kHz (steel welding with static beam); power 3 kW; sharp focus mode [24]

In [23 - 25] frequency range below 5 kHz is associated with mechanical radial and axially-azimuthal keyhole wall oscillations, and the range from 5 kHz up to about 15 kHz with processes such as vapor-plasma flows through keyhole and electrical and thermal non-linear interactions of the beam with these flows and keyhole walls. In [22] this signal range of oscillations is explained by local energy deposition and superheating of the metal surface, bombarded by the powerful beam and by consequent explosive destruction (ablation) of metal, as well as by instable electron emission from the bombarded surfaces on the keyhole walls. The spectral component with peaks of spectral density of the signal above 10 kHz as previously mentioned is caused by plasma ion-acoustic waves [26].

Such type of spectrograms is found almost at all welding modes with deep power penetration of beam with of 2 kW and more, for all the researched materials in several electron-beam systems (including systems without inverter power supply units).

E. Study of plasma plume density oscillations by measuring the signal, collected during EBW with beam deflection oscillations

An example of signal recording, collected from polarized to + 50 V collector electrode by plasma plume (Fig. 10) in the case of EBW with oscillations of the beam looks similar to recording on Fig. 8 (curve 1). For comparison a recording of deflection coils current (curve 2) is also shown in the figure.

Frequency spectrum of the current measured through the collector electrode polarized with + 50 V shows that low-frequency oscillation component (0 - 3000 Hz) could be observed. It is assumed [30 - 32] that this mixture of random peaks (with amplitude reaching to 0.5 A) and low frequency signal fluctuations represents the free and the forced instabilities of the keyhole walls and plasma-vapor flows, and determines the plasma parameters near the collecting ring electrode.

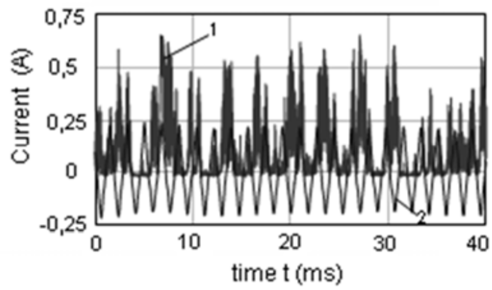

Fig.10. Recordings of the current collected by plasma and of the current in the deflection coils are shown. Welding of steel with oscillation across the joint: P = 2.5 kW, sharp focus (I_f = 840 mA), oscillation frequency f = 561 Hz, sweep size 2A = 0.9 mm. Curve 1 presents high frequency series of impulses, packed in low frequency oscillation signal) and curve 2 is deflection coils current [32].

For analyses of these signal oscillations in ref. [30 - 32] method of coherent accumulation is applied. The coherent accumulation method is illustrated on Fig. 22. The small-width square-wave signal formed from the signal from the deflection coils current (Osc(t)) is less than a basic signal g(t). The basic signal g(t + s) is shifted relative to the initial signal Osc(t) by a set time s.

Conclusions

Designed for the “Electromask Series 6000” machine installation software allows us to manage all systems from a PC and convert data from other formats. We obtain accurate mechanical movements of 0.20 micrometers in the field of 250mm x 250 mm.

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