Numerical modeling of the plasma parameters, generated during electron beam welding

Dmitriy N. Trushnikov, Georgi M. Mladenov

It is described a model of plasma formation in the crater in liquid metal as well as above electron beam welding zone. Model is based on solution of two equations for density of electrons and mean electron energy. The mass transfer of plasma heavier particles (neutral atoms, excited atoms and ions) is taken in the analysis by diffusion equation for multicomponent mixture. Electrostatic field is calculated by Poisson equation. On crater wall is calculated thermion electron emission. Ionization intensity of vapor by beam electrons and high-energy secondary and back-scattered electrons is calibrated using plasma parameters in the case of lack of polarized collector electrode above welding zone. The calculated data are in good agreement with experimental ones. The results of plasma parameters in the case of excitation of non-independent discharge are given. There is shown need to take in account effect strong electric field in the crater near the crater wall on electron emission (effect Schottky) at calculation of current non-independent discharge. Calculated electron draft velocities much bigger than velocity, at which is arising current instabilities. This confirm assumed idea for beginning ion-acoustic instabilities, observed also experimentally.

Числено моделиране на формирането и параметрите на плазмата, генерирана по време на електронно-лъчево заваряване (Д. Трушников, Г. Младенов). *Описан е модел на формирането на плазма в кратера в течния метал над зоната на заваряване с електронен лъч. Моделът се основава на решаване на две уравнения за електроните и за средната електронна енергия. Масовия пренос от тежките плазмени частици (неутрални атоми, възбудени атоми и йони) е анализиран от дифузионното уравнение за много-компонентна смес. Електростатичното поле се пресмята с уравнението на Поасон. Термоелектронна емисия от стените на кратера се отчита. Интензитета на йонизация на парите от електроните на снопа и от обратно-отразените електрони се калибрира, използвайки параметрите на плазмата в отсъствие на колектиращ електрод над зоната на заваряване. Пресметнатите данни са в добро съответствие с експерименталните данни. Дадени са плазмените параметри, пресметнати при възбуждане на не-самостоятелен разряд. Показана е необходимостта да се отчита силното електрическо поле около стените на кратера върху електронната емисия (ефект на Шотки) при пресмятане на несамостоятелния разряд. Пресметнатите дрейфови скорости на електроните са много по-високи от скоростите, при които възникват токови неустойчивости. Това подкрепя представата за възбуждане на йонно-акустични вълни, които са наблюдавани и експериментално.*

Introduction

Electron beam welding is wide distributed technology for joining of metals due to numerous advances in comparison with other welding technologies. In the same time, optimization and quality improvement are empirical or based on applications of statistical methods, due to complex character and lack of models of physical processes in the crater in welding bath. One of phenomena during interaction of concentrated energy beam with metal sample is generation of low temperature plasma in welding zone [1-10]. Study of plasma parameters and their relation with process product performances will help to extend knowledge for control of electron beam welding and approaches for its optimization. Difficulties of experimental measurement of plasma parameters in the crater in the welding bath forced the investigators to estimate plasma parameters in the crater based on few experiments in plasma plume above the welding zone [2,3] or using indirect data [9,11].

Electron current, collected from plasma, generated during electron beam welding

One application of plasma, generated in electron beam welding zone by powerful beam of accelerated electrons is to carry information for interaction of beam with material and to be used for control of the technology process. In the case of situated a polarized from +50V to +100V metallic collector electrode in the plasma plume above welding zone, the electro-conductive plasma provide conduction of enough big current. This current can be considered as non independent discharge with hot cathode (overheated spots of the crater walls on which beam transfer kinetic electron energy into heat) and anode-collector electrode.

The non independent discharge in metal vapor and removed gases during electron beam welding is dominated by intense electron beam, which play the next functions:

- provide quasi-steady input of the metal vapor in the discharge zone;
- stimulate generation of the low temperature plasma in welding zone by ionization of the metal vapor through electron-atom collisions;
- lead to intensive thermion electron emission from overheated areas liquid or solid metal surfaces.

In former time was achieved success in studies and use of non independent electron current for control of the beam focus during EBW [12-15]. In the same time some difficulties of interpretation of obtained results is existed. There is a lack of models, determining formation of non independent discharge.

Description of the mathematic model

In the last years a wide distribution have the packages of applied software. In this paper is described At simulation collecting electron current on positive electrode in plasma above welding zone was used package applied programs Comsol 4.3, Plasma Module, extension DC Discharge[16].

Scheme of registration non independent discharge current is shown on fig.1. Discharge glows between two electrodes – grounded sample (cathode) and ring collector of plasma electrons (anode). Collector 4 is situated bellows the end of electron gun in the grounded vacuum metallic chamber. In the outer collector circuit trough load resistor 6 of 50 Ω is connected positive voltage of 50 V.

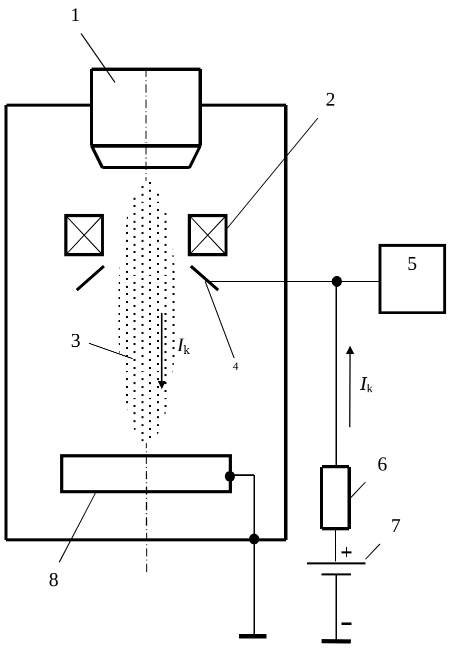

Fig.1. Scheme of registration of non independent discharge current in plasma, generated above the interaction zone during electron beam welding:1 – electron gun; 2 – focusing lens; 3 – plasma, generated above the welding zone; 4 – collector ; 5 – registration of data; 6 – load resistor; 7 – voltage source; 8– welded sample

Calculations are executed in axis-symmetrical cylindrical coordinate system. Plasma is generated due to vapor flow ionization by electron beam and by accelerated from outer electrostatic field thermion

The electron density and mean electron energy in plasma, generated during EBW are computed by solving drift-diffusion equations for the electron density and mean electron energy. [17-21]. Convection of electrons due to ion motion, drifted with gas flow is neglected.

$$\frac{\partial(n_e)}{\partial t}+\nabla\cdot\vec{\Gamma}_e=R_e \qquad (1)$$

$$\frac{\partial(n_\varepsilon)}{\partial t}+\nabla\cdot\left[-n_\varepsilon(\mu_\varepsilon\vec{E})-D_\varepsilon\nabla n_\varepsilon\right]+\vec{E}\cdot\vec{\Gamma}_e=R_e \qquad (2)$$

There n_e is electron density, μ_e – electron mobility, R_e – electron source intensity, n_ε - volumetric density of the electron energy and R_ε - energy loss due to inelastic collisions, E – electrostatic field intensity.

Electron flux $\vec{\Gamma}_e$ can be determined as:

$$\vec{\Gamma}_e=-n_e(\mu_e\vec{E})-D_e\nabla n_e \qquad (3)$$

Electron source R_e and energy loss due to inelastic collisions R_ε will be defined later.

The electron diffusivity D_e, energy mobility μ_ε and energy diffusivity D_ε are computed from the electron mobility μ_e using relations:

$$D_e = \mu_e T_e, \mu_\varepsilon = \frac{5}{3}\mu_e, D_\varepsilon = \mu_\varepsilon T_e. \quad (4)$$

The source coefficients in the equations (1, 2) are determined, using rate coefficients. In the case of rate coefficients, the electron source term in equation (1) is given by:

$$R_e = \sum_{j=1}^{M} x_j k_j N_n n_e \quad (5)$$

where x_j is the mole fraction of the target species for reaction j, k_j is the rate coefficient for reaction j (m^3/s), and N_n is the total neutral number density (1/m^3).

The electron energy loss is obtained by summing the collisional energy loss over all reactions:

$$R_\varepsilon = \sum_{j=1}^{M} x_j k_j N_n n_\varepsilon \Delta\varepsilon_j \quad (6)$$

where $\Delta\varepsilon_j$ is the energy loss from reaction j (eV).

The rate coefficients may be computed from cross section data by the following integral:

$$k_k = \gamma \int_0^\infty \varepsilon \sigma_k(\varepsilon) f(\varepsilon) d\varepsilon \quad (7)$$

where $\gamma = (2q/m_e)1/2$ ($C^{1/2}/kg^{1/2}$), m_e is the electron mass (kg), ε is energy (eV), σ_k is the collision cross section of molecule or ion (m^2) and $f(\varepsilon)$ is the electron energy distribution function. In this case a Maxwellian distribution of electron energy is assumed.

For the mass transport description of non-electron species in the plasma (ions, neutral atoms and excited neutral atoms), the diffusion equation for multi-component mixture is solved for the mass fraction of each species :

$$\rho \frac{\partial(\omega_k)}{\partial t} + \rho \vec{u} \nabla \omega_k = \nabla \cdot \vec{j}_k + R_k \quad (8)$$

where: $\vec{j}_k$ is vector of the diffusion flow; R_k - source intensity for component k (kg / (m^3 · s)); $\vec{u}$ –average velocity environment vector (m / s); ρ - denotes the density of the mixture (kg/m^3); ω_k – mass portion of k-component .

The vector of diffusion flux can be calculated as:

$$\vec{j}_k = \rho \omega_k \vec{V}_k \quad (9)$$

where and $\vec{V}_k$ is the multicomponent diffusion velocity for species k.

The electrostatic field is computed using the Poisson equation:

$$\nabla^2 U = -\frac{\rho_0}{\varepsilon_0} \quad (10)$$

There U is potential of electrostatic field. The space charge density ρ_0 is computed based on the reactions specified in the model using the formula:

$$\rho_0 = q\left(\sum_{k=1}^{N} Z_k n_k - n_e\right) \quad (11)$$

The drift-diffusion equations (1) and (2) are applicable only in the cases of calculation for plasma with collisions between plasma particles (the effective cross-sections for collisions of electrons, ions and neutral atoms are leads to mean free paths smaller than container dimensions). These conditions are satisfied only at vapor densities in the crater in welding bath. At retirement from the crater output plasma becomes collisionless [7]. Expansion of the plasma there is described continuity equation:

$$\nabla \cdot \vec{j} = d\rho_0 / dt \quad (12)$$

After exchange $\vec{j} = qn\mu_e\vec{E}$ and dividing two sides by q is resulting to eq. (1) without diffusion, that together with Poisson equation (10) determine electron motion in collisionless conditions. In our case the values 0 was given to diffusion coefficient in equations (1) and (2).

Boundary conditions

The calculated geometry area is given on Fig. 2. The crater walls 1 are accepted as a cutted cone. The sign. 2 is the collector; 3 is the grounded technology vacuum chamber wall.

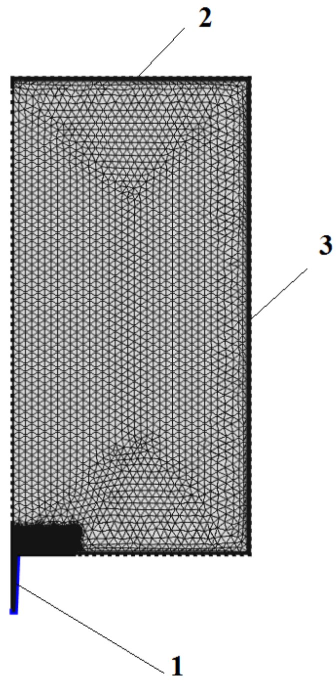

Fig. 2. The geometry of calculating space: 1- crater in the welding bath; 2 – collector of electrons; 3 – vacuum chamber walls

Non-independent discharge is connected with thermion electron emission from overheated by electron beam spots of crater wall. At polarized from +50 to +100 V collector and self-determinate detaining potential for keeping the plasma electrons of +1 V to +3 V all thermion emitted electrons are accelerated and can ionized vapor particles. In this way the charged particles near hot spots increased. The current in circuit with voltage source and any outer resistance is determined generally by the ratio of the difference between voltage of outer source and plasma potential to the sum of inner and outer resistances.

The electron are loosed on chamber walls, as well as on crater walls in result of random movement (transverse velocity bigger one threshold) and gained due to beam electron ionization, secondary emission effects, resulting in the following boundary conditions for electron flux:

$$-\vec{n}\cdot\vec{\Gamma}_e = (1/2\nu_{e,th}n_e) - \sum_p \gamma_p(\vec{\Gamma}_p\vec{n}), \qquad (13)$$

and for electron energy flux:

$$-\vec{n}\cdot\vec{\Gamma}_\varepsilon = (5/6\nu_{e,th}n_\varepsilon) - \sum_p \varepsilon_p\gamma_p(\vec{\Gamma}_p\vec{n}). \qquad (14)$$

$\nu_{e,th}$ is the thermal velocity. The second term in right hand side of equation (13) is describing electron generation due to secondary effects of discharge radiation, γ_p is coefficient of secondary emission. The second term in equation (14) is the energy flux of beam and secondary irradiations, ε_p – is average energy of electrons.

The ions are loosed on walls due to surface reactions (recombination) and that electrostatic field is directed to the walls.

$$-\vec{n}\cdot\vec{j}_k = M_\omega R_k + M_\omega c_k Z_k \mu_k(\vec{E}\cdot\vec{n})\left[Z_k\mu_k(\vec{E}\cdot\vec{n})>0\right] \quad (15)$$

Thermion electron emission from the overheated crater wall is determined by Richardson-Dushman equation $j = AT^2\exp(-e\varphi/kT)$, where $e\varphi$ is work function of the emitter, T is temperature, A is constant; k is Boltzmann constant.

The boundary conditions for electron flux in/from the crater are described

$$-\vec{n}\cdot\vec{\Gamma}_e = j/e \qquad (16)$$

Reaction of gaining electrons

During EBW of alloys in the vapor could be various chemical elements. As example at welding of chromium-nickel steel in the vapor there are similar portions iron, chrome and manganese [11].

In [9] is proposed to use the mean values for the mass and for the ionization energy.

In Table 1 the accepted reactions and the values of energies loosed or gained during these reactions are given. The reactions between the electrons and the excited or ionized atoms are neglected due to their small quantity in the vapor. With A is signed the an average atom, participating in reactions governed plasma parameters.

Table 1.

Accepted reactions for calculations of the parameters of the non independent discharge

Reaction	Formulation	Kind interaction	energy Δε (eV)
1	e+A=>e+A	elastic	0
2	e+A=>2e+A+	ionization	7.35
3	e+A=>e+A*	excitation	3.084
4	A=>e+A+	Beam electron ionization	-7.35

Reactions on boundaries are listed in Table 2. Probability of de-excitation or de-ionization (recombination) of excited or ionized atoms is given by their sticking coefficients

Table 2.

Sticking coefficient of atoms on wall surfaces

Reaction	formulation	Sticking coefficient
1	A*=>A	1
2	A+=>A	1

Results of calculations in case without collector (collector is grounded)

Vapor ionization by the beam electrons is described with reaction 4 (Table 1), realized along the beam axis. The negative absorbed energy of created electrons is the accepted as their mean energy. Additionally important role take ionization of secondary and back scattered electrons. Distribution of these electrons was chosen as cosine one in respect on the local surface.

Intensities of reaction sources were chosen taking in account the cross section of these reactions at mean energy of the ionizing electrons, concentration of particles. The results were calibrated by the experimental data.

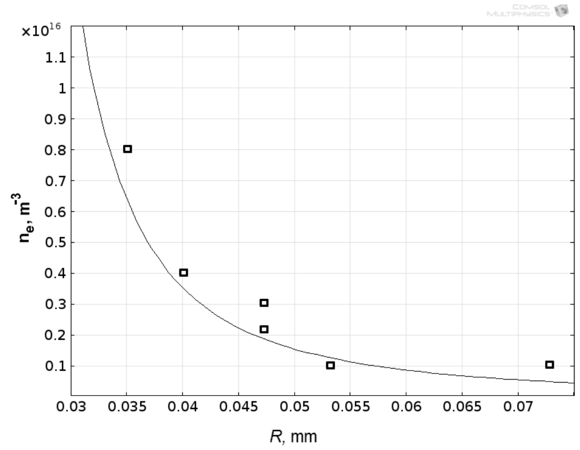

Fig.3. Dependence of plasma concentration on distance from interaction zone on welded sample surface

On fig.3 are shown the results of simulation the concentration of the plasma above welding bath. Points on the same figure are experimental values of dependence of the concentration of plasma on the distances from welding bath. There the distance $R=\sqrt{z^2+r^2}$ were changed in direction of 45^o respectively sample surface; *z* is distance between the collector electrode and sample surface and *r* is distance of center of the collector electrode and beam axis. On fig.4 are given the dependence of distribution of electron density on distance from welding zone R in log scale. The character of dependence is in good agreement with generalized experimental as well calculated data in [7] on expansion of the plasma column under electron beam metal interaction.

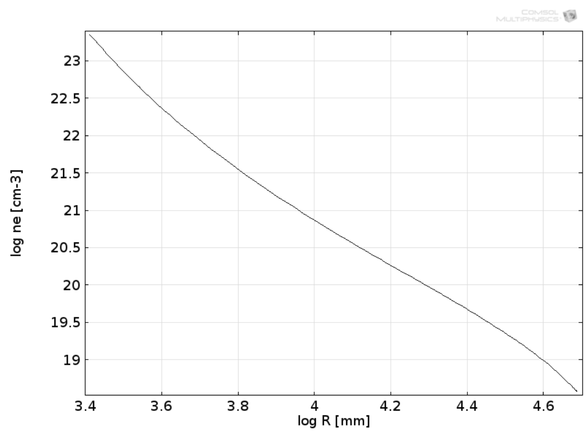

Fig. 4. Dependence of electron density above sample on distance R from welding zone

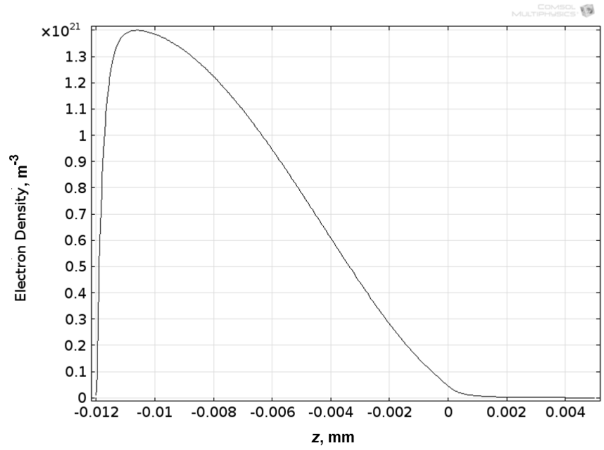

Fig. 5. Dependence of the electron density on beam axis z in the welding crater

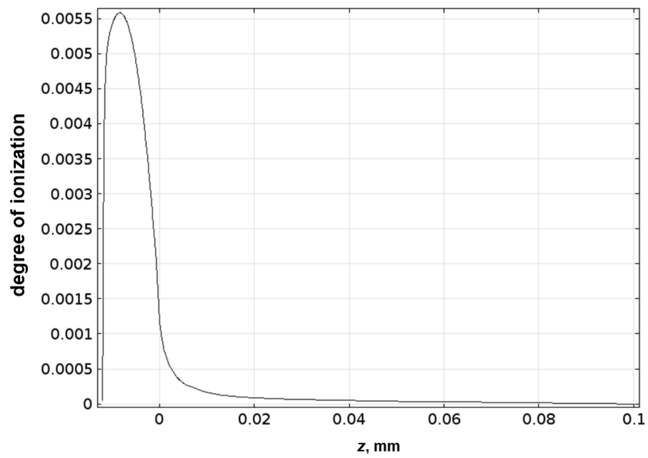

Fig. 6. Ionization degree from coordinate z in the crater and above sample surface

On fig. 5 and fig.6 are shown the plasma density and ionization degree along beam axis. The origin of the coordinate z (z=0) is situated on sample surface. The positive values of z are above the sample surface (respectively above the welding zone). The ionization degree in the crater in liquid welding bath is of order of 10^{-2}, that is in good agreement with experimental data [2]. Above the crater in welding bath the ionization degree decreases quickly.

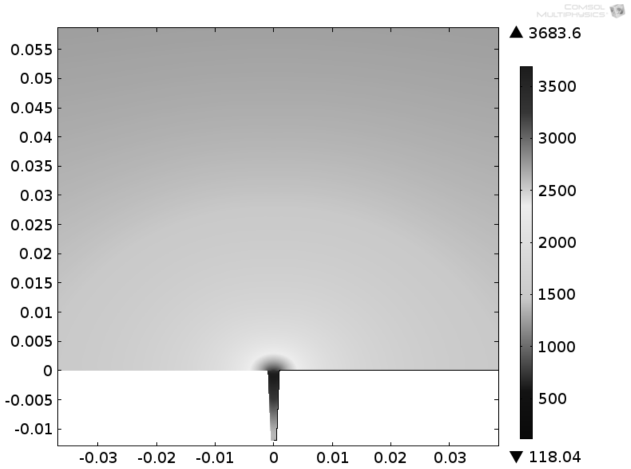

Fig.7 Electron temperature in the crater and above the welding zone

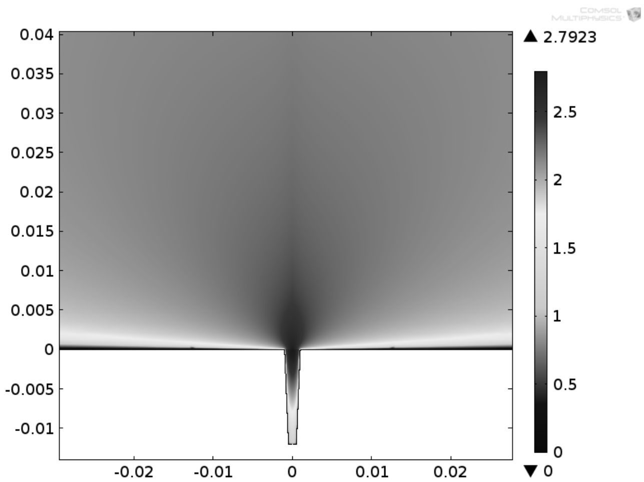

Fig. 8 Potential distribution in the crater in welding bath and above the welding zone

On fig. 7 and fig.8 are shown the results of calculation of the electron temperature distribution and respectively the plasma potential distribution in the case of electron beam welding with grounded collector. The plasma potential values and the electron temperature values becomes maximal in the upper part of the crater, near the crater orifice. Above the crater the plasma is around 1V and electron temperature is of order of 3 000 K, that is in good agreement with data in [2, 3, 7].

Calculation results of the plasma parameters in the case of non-independent discharge

The computer simulation results in the previous part are presenting the case of usual situation of electron beam welding. The obtained results for lack of positively polarized collector are also results of lack of non-independent discharge and a calibration of the following calculations. At excitation of non-independent discharge by polarization the collector with positive potential of + 50 V. This case is situation in experimental papers studying the oscillations of the collecting by plasma current [13, 14, 15], when the collector was connected to a voltage source through a load resistor of 50 Ω.

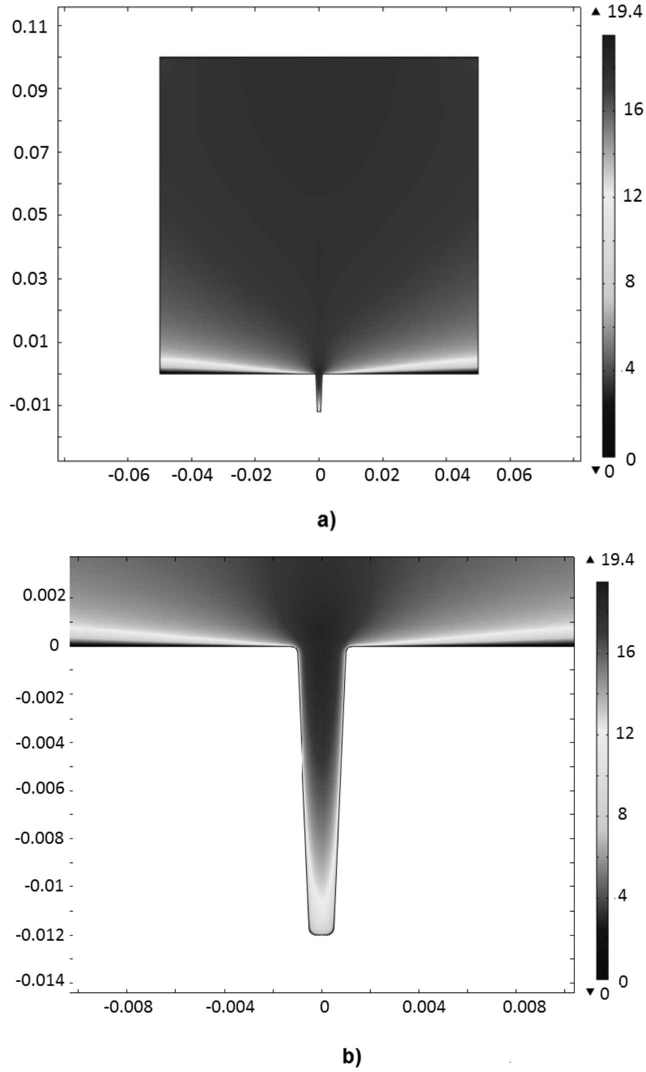

Fig.9 Potential distribution at excitation of non-independent discharge: (a) in the vacuum chamber space (b) magnified fragment

The changes are seen in plasma potential distribution (Fig. 9). The plasma potential practically in the whole space becomes similar to the collector potential. In concrete simulation plasma potential is 20 V that is corresponding to the collected current of 0.6 A. The plasma potential value decreases due to voltage drop on load resistor in the collector circuit serially to voltage source.

Near sample surface there is a layer, were the potential is falling to zero. On the upper part of the crater this layer becomes very thin, that leads to a strong electrostatic field there. The calculations show, that in this part of the crater wall the intensity of electrical field can reach 10^6 V/m. This strong electric field decrease the height of potential barrier on liquid metal surface and electron emission in this case is described by Richardson- Schottki

$$j = AT^2 \exp(-e(\varphi - \sqrt{eE_k} / kT) \qquad (17)$$

where E_k – electrostatic field intensity. The thermion current value increases from about three way near the crater bottom and about 7 way around the crater orifice.

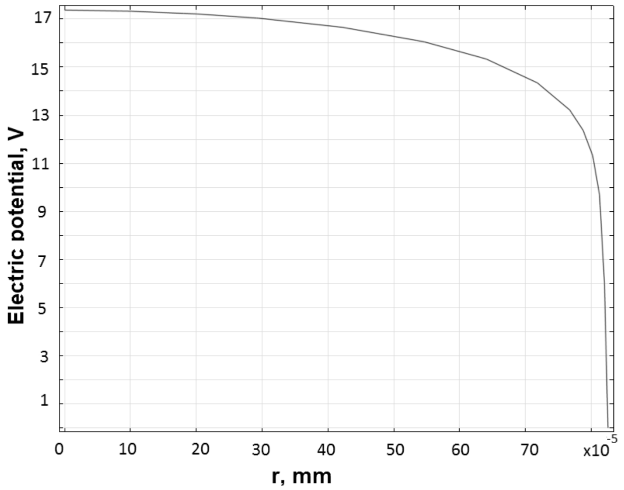

Fig. 10 Potential distribution on radius of the crater in one half of the crater cross-section in the middle part of the depth of the crater

On Fig. 11 is given distribution of the electron temperature at excitation in the plasma non-independent discharge. разряда. One can see, that temperature is about 10^4 K (about 1 eV). Near the crater orifice have a drop of electron temperature and a increase near the vacuum chamber walls.

At this position of collector the increase of non-independent discharge current is limited from transformation of plasma state to an anomalous resistance state and excitation of current high frequency oscillations [21].

The calculation of draft electron velocity shows, that its value in all studied space is about 0,8-1.10^6 m/s . This is much more than critical values of phase velocity at which the anomalous conductivity of the plasma is observable [21-24]. As a result, some impulses instead a steady current are observable.

For ionic-acoustic oscillations, in the case of large wavelengths, the dispersion relation takes the form of a linear dependence, which is characteristic of sound waves. If a consistent frequency and arbitrary velocities are typical for Langmuir ionic oscillations, then in ionic-sonic waves the speed is constant, but the frequencies may take on a wide range of values, depending on the wavelength. We will assume a wavelength equal to the typical size of the system (a working distance of 100 mm). In this case, the frequency turns out to be equal to $f=V_s/\lambda$~16 kHz, что хорошо согласуется с работами [25, 26].

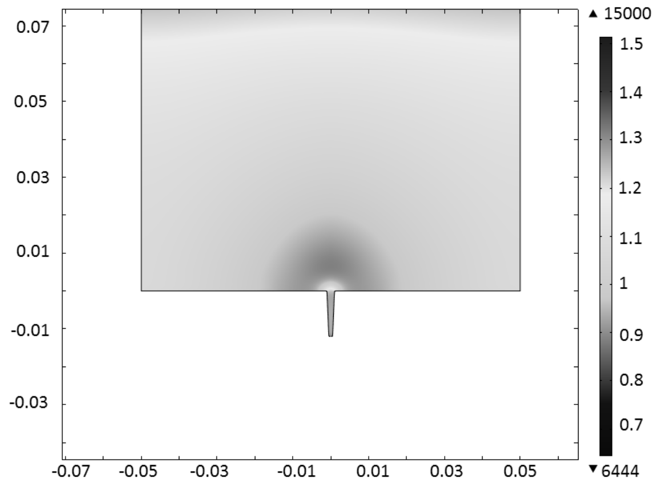

Fig.11. Distribution of the electron temperature in crater in welded sample and vacuum chamber at excitation in the plasma a non-independent discharge.

Conclusion

1. It is described a model of plasma formation in the crater in liquid metal as well as above electron beam welding zone. Model is based on solution of two equations for density of electrons and mean electron energy. The mass transfer of plasma heavier particles (neutral atoms, excited atoms and ions) is taken in the analysis by diffusion equation for multicomponent mixture. Electrostatic field is calculated by Poisson equation. On crater wall is calculated thermion electron emission.
2. Ionization intensity of vapor by beam electrons and high-energy secondary and back-scattered electrons is calibrated using plasma parameters in the case of lack of polarized collector electrode above welding zone. The calculated data are in good agreement with experimental ones.
3. The results of plasma parameters in the case of excitation of non-independent discharge are given. There is shown need to take in account effect strong electric field in the crater near the crater wall on electron emission (effect Schottky) at calculation of current non-independent discharge. Calculated electron draft velocities much bigger than velocity, at which is arising current

instabilities. This confirms assumed idea for beginning ion-acoustic instabilities, observed also experimentally.

Acknowledgements

The authors would like to express gratitude for the financial support by RFBR 13-08-00397, 14-08-96008_a_ural and by Ministry of Perm district Education.

REFERENCES

[1] Ледовской В., Г.Младенов. Учет влияния плазменых явлений на взаимодействие мощных электронных пучков с веществом, Ж Т Ф, т 40, N 10, 1970, 2260

[2] Ледовской В., Г.Младенов. О параметрах плазмы, генерируемой электронным лучом в технологической камере, Известия ЛЭТИ, в. 126, 1972, 96.

[3] Dyakov T., M.Bielawski, M.Kardjiev, B.Djakov, G.Mladenov. Electronic Probe Studies of the Metal Vapour accompaning Electron Beam Welding, Intern. Conf. on Electron Beam Technol., EBT-85, Varna, BAS Publ. Hause, 1985, 199.

[4] Г.И.Лесков, В.М.Нестеренков, Управление электронными пучками по параметрами плазмы, Вторая международная конференция по ЭЛТ, Варна, 31 мая-4 июня 1988, ИЕ БАН,София, 1988,стр.106-112

[5] V.O.Tokarev, O. E. Ostrovskii, V .A . Kazakov and I .V. Alekseev, Control of low-temperature plasma when electron beam welding non-ferrous metals and their alloys in an intermediate vacuum, Welding International, 9,12,1995, pp. 987-988

[6] G. Mladenov and S. Sabchevski: Potential distribution and space-charge neutralization in technological intense electron beams — an overview // Vacuum, v. 62, 2001, 113–122.

[7] I.A.Krinberg, G.M.Mladenov, Formation and expansion of the plasma column under electron beam-metal interaction, Vacuum, 77, 2005, pp.407-411.

[8] C.Y.Ho, M.Y.Wen, and C.Ma, Plasma from EB evaporation of a Metal Target, Advanced Materials Research, v.83-86, 2010, pp.1190-1196

[9] V. V. Novokreshchenov, R. V. Rodyakina, Yu.V.Myakishev and A.P.Sliva, Determination of the degree of ionization of the vapour phase of the penetration channel in electron beam welding, Welding International,v.27, No3, PP.238-242, 2013

[10] V.M. Yazovskikh, D.N. Trushnikov, V.Y. Belen'kii. The mechanism of secondary emission processes in electron beam welding with the modulation of the electron beam //«Welding International», 2004, v. 8, № 9, p. 724-729.

[11] Trushnikov, D. N., E. S. Salomatova, and V. Ya Belenkiy. "Estimation of the Temperature in the Weld Penetration Channel in Electron Beam Welding." Journal of Power and Energy Engineering 1 (2013) p. 51-54.

[12] Беленький В.Я., Язовских В.М. Контроль электронно-лучевой сварки с использованием плазменных явлений в области сварочной ванны // Сварочное производство, 1997. - № 1, с.7-9.

[13] Trushnikov D.N., Belenkiy V.Ya., Mladenov G.M., Portnov N.S., Secondary – Emission signal for weld formation monitoring and control in electron beam welding (EBW) // Materialwissenschaft und Werkstofftechnik. 2012. Vol. 43. Iss.10. p.892-897.

[14] D. Trushnikov, V. Belenkiy, V. Schavlev, A. Piskunov, A. Abdulin and G. Mladenov. Plasma charge current for control and monitoring at electron beam welding with the beam oscillation // Sensors. 2012, 12(12), 17433-17445; doi:10.3390/s121217433.

[15] D.N. Trushnikov, V.Ya. Belen'kii. Investigation of the formation of the secondary current signal in plasma in electron beam welding with oscillations of the electron beam // Welding International. Volume 27, Issue 11, 2013, pages 877-880. doi:10.1080/09507116.2013.796645.

[16] COMSOL Plasma Module reference guide.

[17] Teng, W. A. N. G., G. A. O. Xiangdong, Katayama Seiji, and J. I. N. Xiaoli. «Study of dynamic features of surface plasma in high-power disk laser welding.» Plasma Science and Technology 14, no. 3 (2012): 245.

[18] Ho, C. Y., M. Y. Wen, Y. H. Tsai, and C. Ma. "Potential and electron density calculated for freely expanding plasma by an electron beam." Journal of Applied Physics 110, no. 1 (2011): 013306-013306.

[19] Raizer, Y.P., Gas Discharge Physics, Springer (1991).

[20] M.A. Lieberman and A.J. Lichtenberg, "Principles of Plasma Discharges and Materials Processing," Willey, Hoboken, New Jersey, 2nd edition, 2005.

[21] D. N. Trushnikov, G. M. Mladenov, V. Ya. Belenkiy, E. G. Koleva, and S. V. Varushkin. Current-Driven Ion-Acoustic and Potential-Relaxation Instabilities Excited in Plasma plume during Electron Beam Welding. AIP Advances 4, 047105 (2014); doi: 10.1063/1.4870944

[22] V. Kadomtsev, Collective phenomena in plasma. Russia, Moscow (In Russian) (1976).

[23] A. Artsimovich, R.Sagdeev, Plasma physics for physicists. Russia, Moscow (In Russian) (1979).

[24] A. Akhiezer, Ion-acoustic oscillations. Electrodynamics plasma. Moscow: Russia, Nauka (In Russian) (1974).

[25] S. Iizuka, K. Takada, N. Sato,A relation between current-driven ion-acoustic instability and potential-relaxation instability excited by a positive biased electrode in a plasma, J. Plasma Fusion Res. Series4, 492495 (2001).

[26] H. Tanaca, A. Hirose, M. Koganex, Ion-wave instabilities in mercury-vapor plasma, Phys. Review161(1), 94-101 (1967).

Dr. Dmitriy N. Trushnikov *- Department of Applied physics, Department of Welding production and technology of construction materials, Perm National Research Polytechnic University, Perm, Russian Federation; Education - 1999 Department of Aerospace, Perm National Research Polytechnic University; Research Areas – control, monitoring and simulation of electron beam welding;*

tel.: +79194785031, e-mail: trdimitr@yandex.ru

Corr. Memb. of BAS, Prof. DSc. Georgi M. Mladenov *- Institute of Electronics – Bulgarian Academy of Sciences, Bulgaria*

Technological Center on Electron Beam and Plasma Technologies and Techniques, Bulgaria

He is the author of 10 books, 26 inventions and more than 200 articles. His research interests include electron beam microscope accelerators, electron beam technologies, electron devices physics, electron beam welding, melting and refining metals in vacuum, electron spectroscopy simulation, electron lithography, vacuum technology.

Tel. +359 899902510, e-mail: gmmladenov@abv.bg

.