International Journal of Innovative Technology and Exploring Engineering (IJITEE)
ISSN: 2278-3075, Volume-8 Issue-8, June, 2019

Secondary-Emission Signals in Plasma Above the Laser Beam Affected Zone during a Vacuum Laser Welding

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Abstract*:*Development and improvement of laser equipment used for welding allow increasing the share of laser welding in technological processes, especially for obtaining high-quality connections. The current problem of absorbing a portion of the laser beam power by a plasma cloud during laser welding with deep penetration can be solved by using laser welding in a vacuum. Laser welding in a vacuum compared to gas-shielded laser welding makes it possible to obtain a much greater penetration depth at the same power of the laser beam, and provides effective protection of the welding zone from the external environment, which is especially important in the welding of active metals. Thus, it is necessary to study the processes in the plasma cloud formed above the zone of action of the laser beam on the metal. Investigation of secondary emission processes in the plasma in the zone of the action of a laser beam on a metal in a vacuum made it possible to numerically simulate the processes in laser welding, depending on the focusing of the laser beam and other technological parameters of laser welding in vacuum. It also allowed recording of the secondary emission current for controlling geometrical parameters of penetration in laser welding. Varying the pressure in the vacuum chamber confirmed the collisional mechanism of damping of secondary-emission current oscillations. The registration of secondary emission signals of ion current is of particular interest, since the detected signal parameters are not associated with the excitation of plasma self-oscillations and, consequently, the magnitude of the ion current directly reflects the density fluctuations of metal vapors flowing out of the channel. The technique can be used in the construction of methods for the operational control of the welding process.

Index Terms*:*electron current, ion current, laser welding in a vacuum, numerical modeling, plasma, welding zone.

I. INTRODUCTION

Laser welding has been used for several decades in high-tech industries to produce high-quality welded joints of structural steel and non-ferrous metal alloys.

In the first decade, lasers on carbon dioxide were used as high-power laser light sources for welding, which had large dimensions, low (not more than 20%) efficiency and could not compete with such a highly concentrated source of energy as the electron beam used in machines for electron beam welding.

More extensive introduction of laser welding into industrial production was facilitated by the appearance of powerful fiber-optic technological lasers, which, in comparison with carbon dioxide gas lasers, are more reliable, relatively small and provide high optical quality of radiation. In addition, the wavelength of radiation from fiber-optic lasers is much smaller than that of carbon dioxide-based lasers, which leads to lower energy consumption, and their continuous improvement ensures lower costs and an increase in the efficiency of technological laser installations. Among the shortcomings of high-power fiber-optic lasers is decreasing of operating reliability of the resonator with increasing laser power, and the increasing sensitivity of the resonator to the reflection processes of the beam that occurs when laser radiation interacts with the material being processed.

In recent years, disk lasers have been used as powerful technological lasers. The operation principle of disk lasers is based on the use of a cooled active element in the form of a disk. A high efficiency of cooling the laser environment is ensured by a large surface area of the disk, so the radiation power in the laser beam can reach quite high values. Important advantages of disk lasers are the ability to adjust the value of the radiation power without changing other parameters, the lack of sensitivity of the resonator to the impact of reflected laser radiation, and the modular design of the laser, which allows replacing individual modules under maintenance service.

One of the significant problems in laser welding with deep penetration is the absorption of a part of the beam power by a plasma cloud formed above the zone of laser beam impact on the metal and the consequent substantial decrease in the penetration depth compared to an electron beam of the same power. At the same time, the efficiency of laser welding when joining thick-walled parts is inferior to the electron-beam welding process, which is widely used in the manufacture of critical products, which restrains the widespread introduction of laser welding into the industry.

To reduce the shielding effect of the plasma cloud and, correspondingly, to increase the penetration depth during laser welding, the following methods were used: application of special coatings on the metal before welding, misalignment of the laser axis from the normal in the

Revised Manuscript Received on June 16, 2019.

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The reported study was partially supported by the Government of Perm Krai, research project No. C-26/794 and was supported by the Russian Foundation for Basic Research (grant No. 16-48-590208).

direction opposite to the welding speed by 20°…30°, oscillations of the laser beam in different directions relative to the joint, the application of a pulse-periodic mode of operation of the laser, blowing off the gas-plasma cloud by various gases and their mixtures. [1]-[5].

However, these techniques do not solve the problems connected with the loss of laser beam power in the plasma cloud over the welding zone. Therefore, in recent years, there has been an increasing interest in laser welding under vacuum, which, despite some limitations associated with the use of a vacuum chamber, makes it possible to obtain, in comparison with gas-shielded laser welding, a much greater penetration depth at the same laser power beam, as well as provides effective protection of the welding zone from the external environment, which is especially important when welding active metals [6]-[8].

Providing high-quality repeatability of the welded joints and the absence of defects in the weld seam in most cases requires the operational control of the process of formation of the weld. Electron-beam welding widely uses secondary-emission methods for controlling the interaction of an electron beam with a metal, at which the parameters of the secondary-emission signals from the interaction zone of the electron beam with the metal are recorded [9]-[12].

In the laser-welding zone in vacuum, the processes take place similar to those in electron-beam welding by a powerful electron beam: intense thermionic emission from the condensed metal phase, the formation of a plasma cloud above the welding zone, and the presence of a wide range of vibrational processes in the penetration channel formed by a powerful concentrated laser beam [13]-[15].

II. MODELING

The One of the purposes of this work was numerical modeling of secondary-emission processes in a plasma in the zone of action of a powerful concentrated laser beam on a metal in vacuum and an experimental study of the parameters of secondary-emission processes in a laser welding zone in a vacuum with the purpose of using these signals to control the formation process of a welded seam.

To simulate the formation of electron and ion current in plasma in laser welding in a vacuum, a model was developed [16], which is based on transport equations for the electron concentration and average electron energy in the plasma above the welding zone:

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

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

whereμ_ε – electron mobility, R_e – the intensity of the electron source, n_ε– the bulk density of the electron energy, R_ε– electron energy source (describes the energy loss as a result of inelastic collisions), $\vec{E}$ – electric-field strength vector, $\vec{\Gamma}_e$ –electron flux density.

To describe the mass-transfer of heavy plasma particles (ions, neutral unexcited and excited atoms), the model uses the mass transfer equation for a multicomponent mixture:

$$\rho\cdot\frac{\partial(\omega_k)}{\partial t} + \rho\cdot\left(\vec{u}\cdot\nabla\right)\cdot\omega_k = \nabla\cdot\vec{j}_k + R_k \qquad (3)$$

where $\vec{j}_k$ – the mass flux density of the k-th component; ω_k – the mass fraction of the k-th component; R_k– the intensity of the source of the k-th component; $\vec{u}$ – the average velocity vector of the medium; ρ – the density of the mixture.

The electric field was determined from the Poisson's equation.

To obtain a numerical solution, the authors used the COMSOL 4.4 software, Plasma Module. The problem was solved in an axisymmetric formulation in a cylindrical coordinate system.

Fig. 1 shows the geometry of the computational area. The annular collector of plasma electrons is located above the welding zone. The formation of plasma was considered as a result of ionization of the metal vapors flowing from the channel of penetration by a laser beam.

The diffusion coefficient for electrons D_e, the mobility factor μ and diffusion factor D for the energies are calculated under the assumption of the Maxwellian energy distribution in terms of electron mobility in expression

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

The density of the mixture is given by the equation of state of an ideal gas $\rho = p\cdot M_n/R_u\cdot T$, where R_u is the universal gas constant. In the general case, calculating the pressure of a gas mixture requires solving the Navier-Stokes system of equations considering the convective heat transfer. In this case, for regions in the penetration channel formed in a metal by a laser beam and above the zone of action of a laser beam, the continuous flow regime is replaced by an intermediate regime (Knudsen number 0.01<Kn<10). In the intermediate regime, the Navier-Stokes equations are also applicable, but special modified boundary conditions are used. Since the modeling is aimed primarily at understanding the physical processes occurring during the registration of signals of secondary emission currents in a plasma during laser welding in vacuum, a sufficient approximation will be the use of linear approximation of data (known from the literature) on the interaction of concentrated energy fluxes with matter [5], [14], [15].

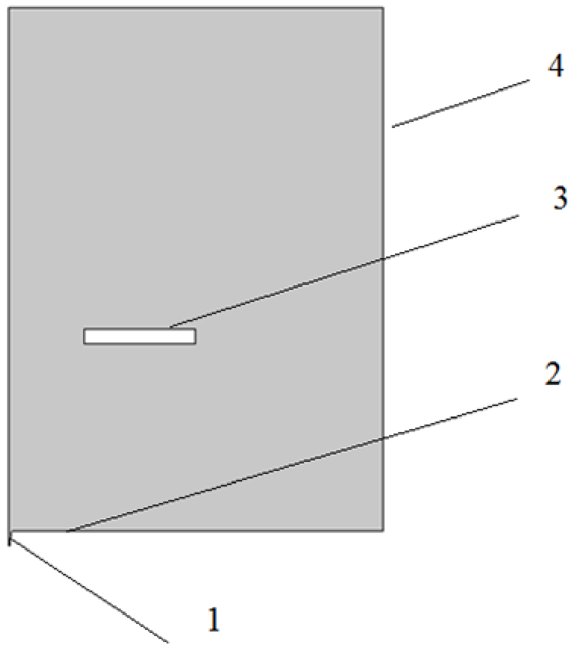

Fig.1. The geometry of the computational area:
1 - channel of penetration; 2 - a surface of a metal heated by a laser beam; 3 - collector of charged particles; 4 - boundaries of the computational domain

The values of pressure and temperature at the bottom of the penetration channel are set to be 7 kPa and 2700 K, respectively, in the upper part 3 kPa and 2200 K. Over the zone of action of the laser beam on the metal, the flow of metal vapors gradually passes into a freely molecular one. In this case, considering the constancy of the velocity, the vapor density can be estimated from the condition of unchanged mass flow $\rho \cdot R^2 = \rho_0 \cdot R_0^2$ = const, where R is the distance to the metal surface in the vicinity of the penetration channel ρ_0 and R_0 is the density and radius of the penetration channel in the upper part.

An important feature of the model is that it makes it possible to calculate plasma parameters not only above the welding zone but also directly in the emerging gas-vapor channel.

In addition, the described model allows calculating the change in the parameters upon initiation of a non-self-sustained discharge in a plasma above the zone of action of a laser beam on a metal in a vacuum by feeding a positive potential to the collector of charged particles. First of all, the changes are noticeable in the distribution of the potential. The potential practically in the whole region becomes close to the steady voltage on the collector. Near the cathode (a metal sample, which a laser beam affects), a layer appears on which this potential changes to zero (Fig. 2).

In the penetration channel, this layer becomes particularly thin, which leads to the appearance of a strong electric field at the surface. Calculations show, that along the entire length of the wall of the channel of penetration, the electric field strength equals the size of order $10^5 \dots 10^6$ V/m. Such a strong electric field significantly reduces the height of the potential barrier and the work function of the electrons.

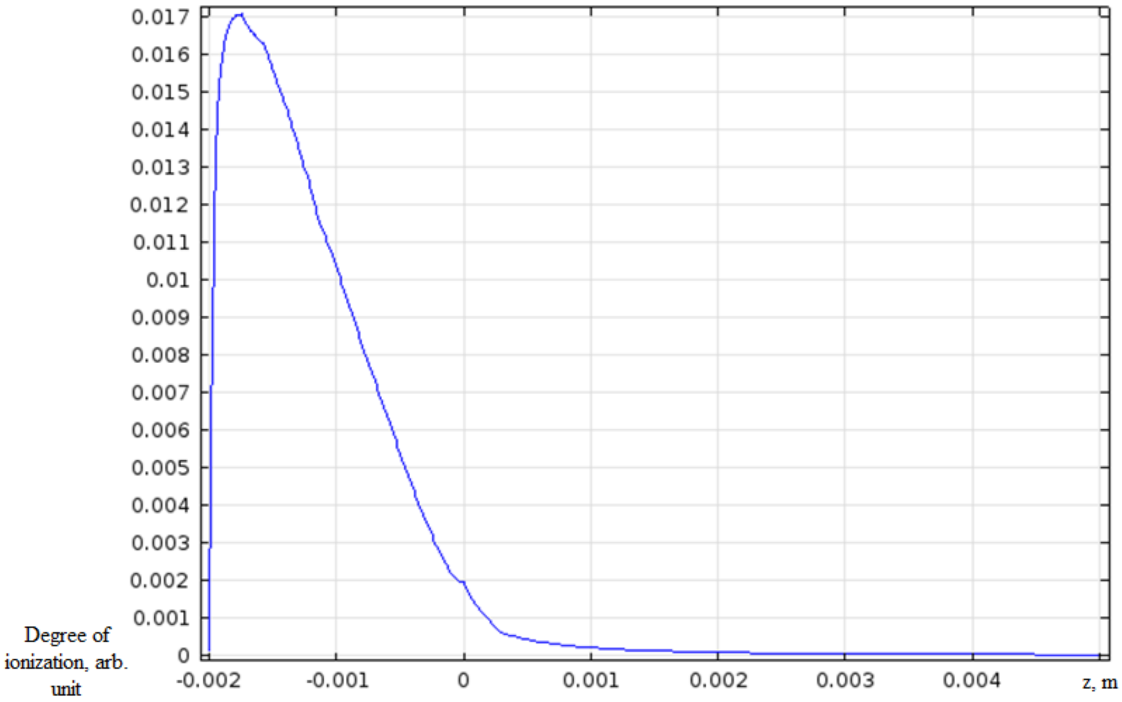

Fig. 2. The degree of plasma ionization during laser welding along the Z-axis in the penetration channel and above the welding puddle

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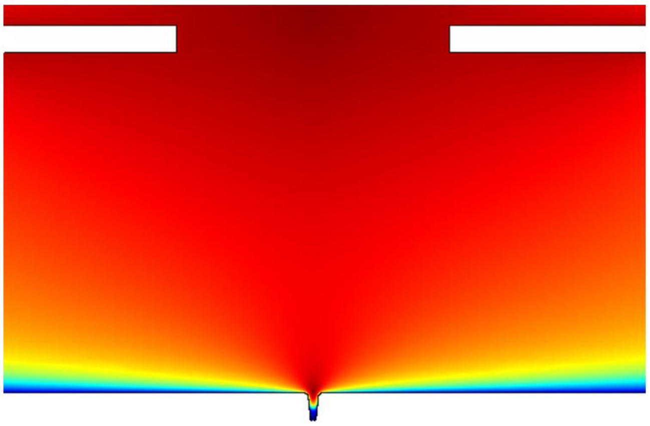


Fig. 3. The distribution of the potential in the plasma over the welding zone and in the penetration channel under the initiation of a non-self-sustaining discharge

This dependence causes the extreme nature of the change in the value of the secondary-emission signal depending on the focusing of the laser beam and other technological parameters of laser welding in a vacuum, which can be used in constructing methods for operational control of the welding process. When the external pressure changes, the magnitude of the signal monotonically decreases according to the law close to the inverse, which is satisfactorily consistent with the experimental data.

III. EXPERIMENTAL RESEARCH

Experimental studies of secondary-emission signals in the laser-welding zone in vacuum were carried out on a laser-welding machine ALFA-300 equipped with a process chamber that was evacuated by a vacuum sliding vane rotary pump ERSTEVAK PRM 54. Vacuum measurement was carried out using the Ertevak MTM-9D vacuum sensor. In carrying out experimental studies, the voltage of the storage ring of the solid-state Nd-YAG laser of the welding installation was regulated within the limits of 200-400 V. The sample material used was austenitic steel 12Cr18Ni10Ti.

The registration scheme for secondary-emission signals in the laser vacuum welding zone is shown in Fig. 4. Above the zone of action of the laser beam on the metal, a charged particle collector was installed into an external electric circuit for plasma charges containing a bias voltage source and a load resistor [17], [18]. The magnitude of the bias voltage was 60V. The signal from the load resistor was applied to the input of the analog-digital converter E14-440 of the company L-Card, connected to a computer information and measuring system. The measurement results were written to a file and processed in a MathCad environment.

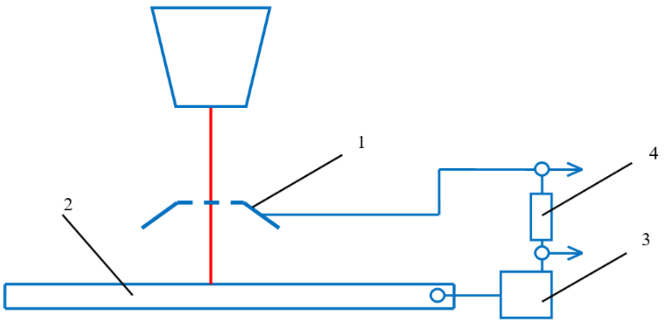


Fig. 4. The scheme of registration of the secondary-emission current during laser welding:
1 - collector of charged particles; 2 - the welded product; 3 - a source of bias voltage; 4 - load resistor

The preliminary analysis of the vibrational spectrum recorded by the collector of charged particles under the action of a laser beam on a metal in a vacuum showed that in the oscillation spectrum of the secondary-emission current, components with a frequency of the order of 10^4Hz are observed, related both to self-oscillations caused by local overheating of the metal in the zone of the laser beam action, and ion-acoustic and potential-relaxation instabilities in plasma. These high-frequency components of the current oscillation spectrum in plasma in the zone of laser welding in vacuum, are additionally modulated by oscillations with a lower frequency due to the capillary instabilities of the penetration channel, stochastic displacement of the interaction zone of the laser beam with the metal on the front wall of the channel, pulsations of steam flows from the channel and other periodic processes in the channel of penetration.

In accordance with this, the task was to differentiate the components of the oscillation spectrum of the secondary emission signal from the laser beam impact zone connected with various instabilities in plasma and the spectrum components due to auto-oscillatory processes in the penetration channel. Since the latter should be more correlated with the technological parameters of the laser welding in a vacuum and geometric parameters of the penetration zone in a metal under the action of a laser beam in vacuum.

Considering the fact that the nature of the self-oscillating processes in the plasma cloud above the zone of laser welding in vacuum, and connected with various plasma instabilities, is largely determined by the geometry of the plasma, the studies of the effect of the distance between the charged particle collector selecting the secondary emission current from plasma, and the surface of a metal exposed to a laser beam in a vacuum to the amplitude-time parameters of the secondary emission signal have been made.

Fig. 5 shows the frequency dependence of the component of the oscillation spectrum of the secondary emission current for laser welding in vacuum due to ion acoustic oscillations in the plasma from the distance between the collector of charged particles detected by the collector of charged particles under the action of a laser beam on a metal in vacuum with a change in the distance between the collector and metal surface [19].

As Fig. 5 shows, as the distance from the surface of the metal to the charged particle collectordecreases, the frequency of the recorded high-frequency components increases. In addition, the analysis of the vibration spectrum of these components shows that the spectral density of the components associated with the ion-acoustic and relaxation instabilities in the plasma decreases. This indicates that when registering the secondary emission current in order to control the geometric parameters of penetration in laser welding in a vacuum, it is necessary to place the charge collector electrode in the immediate vicinity of the surface of the metal to be welded.

The next stage in the research of secondary emission processes in laser welding in vacuum was to study the influence of the degree of process chamber evacuation on the amplitude-time parameters of the secondary emission current. Fig. 6 shows the oscillograms of the secondary emission current recorded by the collector of charged particles at different pressures in the process vacuum chamber.

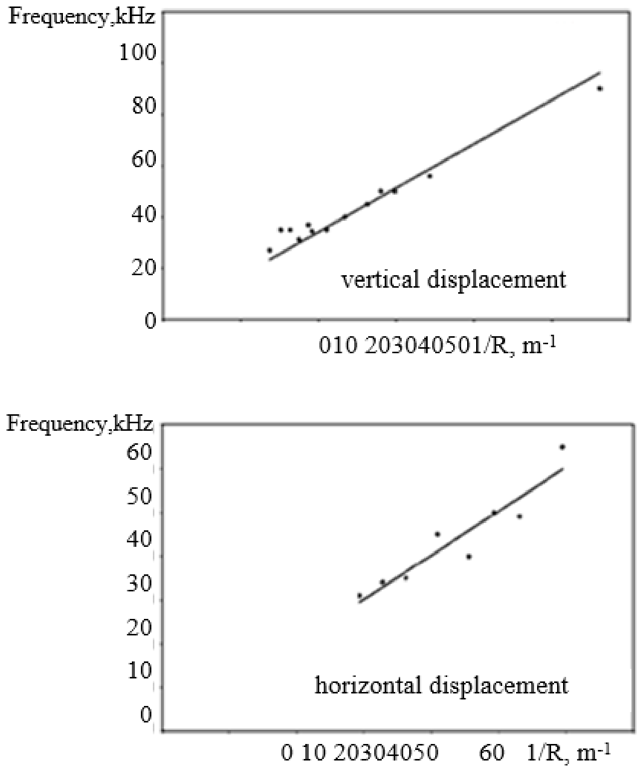
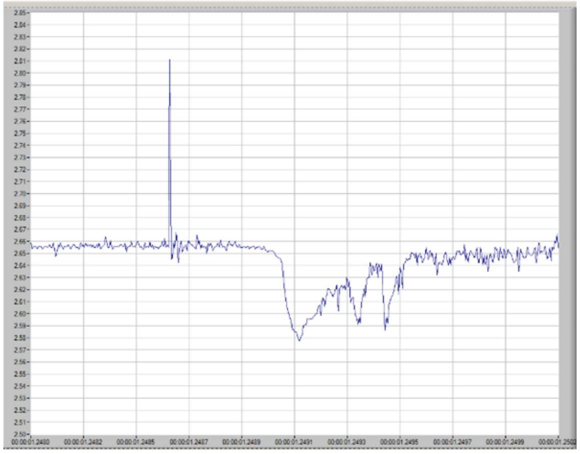
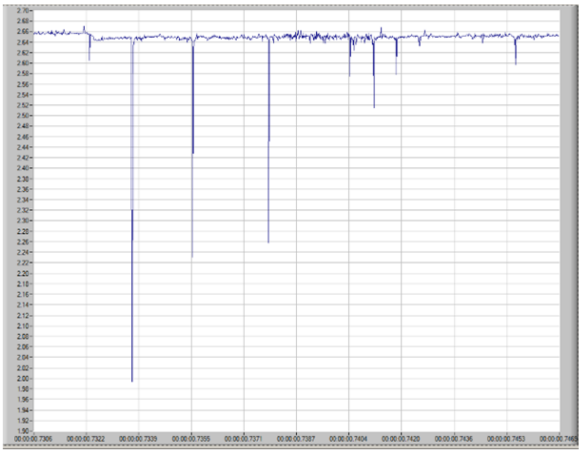


Fig. 5. The dependence of the frequency of the oscillation spectrum components of the secondary-emission current during laser welding in a vacuum on the distance between the collectors of charged particles



a)



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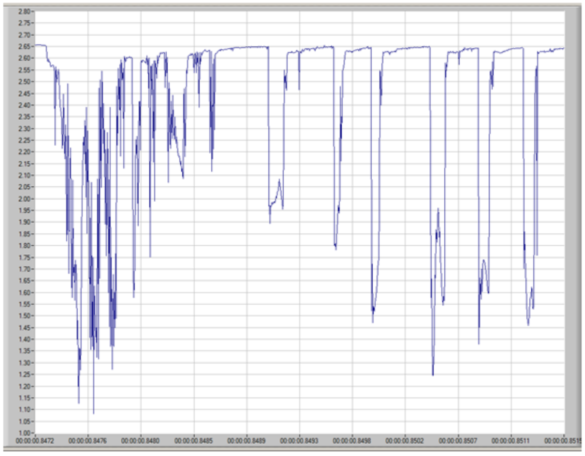

c)

Fig. 6. The oscillograms of the secondary-emission current in the plasma at different degrees of the evacuation of the process chamber for laser welding in a vacuum: the pressure in the chamber a) 4000 Pa, b) 100 Pa, c) 10 Pa

The results of the experiments showed that when the pressure in the vacuum process chamber of the laser installation increases, the amplitude of the pulses of the secondary emission current in the plasma decreases and becomes zero at a pressure in the chamber close to atmospheric.

With respect to the vibrational processes in the plasma in the zone of vacuum laser welding, arising as a result of the formation of different types of instabilities, this is due to the fact that at a pressure close to atmospheric, due to the collision damping mechanism known in plasma physics, at high concentrations of neutral particles the probability of collision of plasma particles during the period of oscillations arises. The number of these collisions at a pressure close to atmospheric is large, and the oscillations decay rapidly enough.

As for the oscillations of the secondary-emission current caused by periodic processes in the zone of action of the vacuum laser beam on the metal, a significant decrease in their amplitude is caused by a decrease in the plasma conductivity as a result of a decrease in the mean free path of the charge carriers and a decrease in their drift velocity in the plasma.

The ion current in the

plasma was also recorded in the laser-welding zone in a vacuum whena negative potential was created at the charged particle collector in the circuit shown in Fig. 7.

Fig. 7 shows an oscillogram of the ion current in the plasma produced by the action of a vacuum laser beam on a metal.

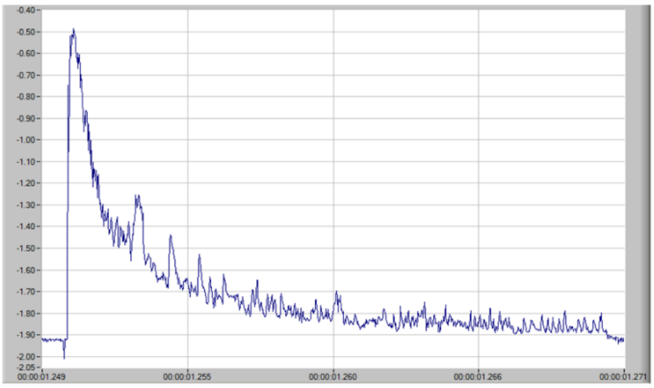

Fig. 7. The oscillogram of the ion current in the plasma produced by the action of a vacuum laser beam on a metal

With respect to the use of secondary-emission signals to control the geometric parameters of penetration in laser welding in vacuum, the registration of the ion current is of particular interest, since in this case the recorded signal parameters are not associated with the excitation of plasma self-oscillations, and the magnitude of the ion current directly reflects the density fluctuations of the metal vapors flowing out of the channel [20], [21].

IV. CONCLUSION

A model of secondary-emission processes in a plasma for laser welding in a vacuum has been developed, and numerical simulations of these processes have been performed. The experimental studies of parameters of secondary-emission processes in pulsed laser welding in vacuum have been carried out, the results of which will be the basis for the development of methods for secondary-emission control of the seam formation process in vacuum laser welding.

REFERENCES

1. A.A. Vedenov, and G.G. Gladush, "*Fizicheskie protsessy pri lazernoy obrabotke materialov*" [Physical processes in the laser processing of materials]. Moscow:Energoatomizdat, 1985.
2. A.G. Grigoryants, "*Osnovy lazernoy obrabotki materialov*" ["Fundamentals of laser processing of materials"]. Moscow: Mashinostroenie, 1989.
3. B.A. Vinogradov,V.N. Gavrilenko, and M.N. Libenson, "*Teoreticheskie osnovy vozdeystviya lazernogo izlucheniya na materialy*" ["Theoretical bases of the influence of laser radiation on materials"]. Blagoveshchensk: Izd-vo BPI, 1993.
4. I.V. Zuev, "*Obrabotka materialov kontsentrirovannymi potokami energii*" ["Processing materials with concentrated energy flows"]. Moscow: Izd-vo MEI, 1997.
5. L.I. Mirkin, "*Fizicheskie osnovy obrabotki materialov luchami lazera*" ["Physical basis of material processing by laser beams"]. Moscow: Izd-vo MGU, 1975.
6. I.Yu. Letyagin, "Tekhnologicheskie perspektivy lazernoy svarki v vakuume" ["Technological prospects of laser welding in vacuum"]. *Materials of the international STC in welding and related technologies*. Ekaterinburg,2016, pp. 6-7.
7. V.Ya. Belenkiy, D.N. Trushnikov,and I.Yu. Letyagin, "Lazernaya svarka v vakuume – perspektivnaya svarochnaya tekhnologiya izgotovleniya izdeliy otvetstvennogo naznacheniya" ["Laser welding in a vacuum is a promising welding technology for the manufacture of critical products"].*Vestnik Permskogo natsionalnogo issledovatelskogo politekhnicheskogo universiteta. Mashinostroenie, materialovedenie, vol. 16*(4), 2014, pp. 71-81.
8. I.Yu. Letyagin, V.Ya. Belenkiy, and D.N. Trushnikov, "Benefits and Prospects of Laser Welding Application in Vacuum".*IV Sino-Russian ASRTU Symposium on Advanced Materials and Processing Technology: ASRTU conf. proc.* Knowledge E, Dubai, 2016. Available: http://knepublishing.com/index.php/KnE-Materials/article/view/568/1818
9. V.Ya. Belenkiy, and D.N. Trushnikov, "Issledovanie formirovaniya signala vtorichnogo toka v plazme pri elektronno-luchevoy svarke s ostsillyatsiey elektronnogo puchka" ["Investigation of the formation of a secondary current signal in a plasma in electron-beam welding with electron beam oscillation"].*Svarochnoe proizvodstvo, vol. 11*, 2012, pp. 9-13.
10. V.A. Boyko, "Rentgenovskaya spektroskopiya lazernoy plazmy" ["X-ray spectroscopy of laser plasma"].*Itogi nauki i tekhniki. Radiotekhnika, vol. 27*, 1980, pp. 264.
11. D.N. Trushnikov, V.Ya. Belenkiy, and E.S. Salomatova, "Formation of a Secondary Current Signal in Electron Beam welding of Dissimilar Materials".*Global Journal of Pure and Applied Mathematics, vol. 12*(1), 2016, pp. 657-676.
12. V.Ya. Belenkiy,and D.N. Trushnikov, "Issledovanie formirovaniya signala vtorichnogo toka v plazme pri elektronno-luchevoy svarke s ostsillyatsiey elektronnogo puchka" ["Investigation of the formation of a secondary current signal in a plasma in electron-beam welding with electron beam oscillation"].*Svarochnoe proizvodstvo, vol. 11*,2012,pp. 9-13.
13. I.Yu. Letyagin, D.N. Trushnikov, and V.Ya. Belenkiy, "The studies of plasma torch processes by laser beam welding". *Mechanical Engineering.Materials Science and Civil Engineering IV (4th ICMEMSCE)*, 2016.
14. M.A. Lieberman, and A.J. Lichtenberg,"Principles of plasma discharges and materials processing".*MRS Bulletin, vol. 30*, 1994, pp. 899-901.
15. D.M. Gureev, and S.V. Yamshchikov, "Osnovy fiziki lazerov i lazernoy obrabotki materialov" ["Fundamentals of the physics of lasers and laser processing of materials"]. Samara: Samarskiy universitet, 2001.
16. D.N. Trushnikov,and G.M. Mladenov, "Numerical model of the plasma formation at electron beam welding".*Journal of Applied Physics, vol. 117*(1), 2015, pp. 013301.
17. D.N. Trushnikov, V.Ya. Belenkiy, and N.S. Portnov, "Secondary – Emission signal for weld formation monitoring and control in electron beam welding (EBW)". *Materialwissenschaft und Werkstofftechnik, vol. 43*(10), 2012, pp. 892-897.
18. D.N. Trushnikov, "Izuchenie fizicheskikh protsessov pri elektronno-luchevoy svarke po parametram vtorichnogo toka v plazme" ["The study of physical processes in electron-beam welding with respect to secondary current parameters in plasma"].*Fizika i khimiya obrabotki materialov, vol. 5*, 2015, pp. 36-45.
19. G.M. Mladenov, E.G. Koleva, S.V. Varushkin, D.N.Trushnikov,and V.Y. Belenkiy, "Current-driven ion-acoustic and potential-relaxation instabilities excited in plasma plume during electron beam welding".*AIP Advances, vol. 4*(4), 2014, pp. 047105.
20. L.M. Yanchuk, I.V. Zuev, and A.A. Uglov, "O vliyanii stepeni zaglubleniya fokusa v materiala na parametry proplavleniya pri elektronno-luchevoy svarke" ["On the influence of the degree of penetration of the focus into the material on the parameters of penetration in electron-beam welding"].*Svarochnoe proizvodstvo, vol. 12*,1974, pp. 3-4.
21. I.Yu. Letyagin, and E.M. Fedoseeva, "Otsenka skvoznogo proplavleniya pri lazernoy svarke na osnove registratsii plazmennogo fakela" ["Evaluation of through penetration in laser welding based on registration of a plasma torch"].*Vestnik Permskogo natsionalnogo issledovatelskogo politekhnicheskogo universiteta. Mashinostroenie, materialovedenie, vol. 18*(1),2016, pp. 84-100.