Research of Plasma Parameters Formed in the Laser Welding Area in Vacuum

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Abstract. The use of laser technology in the manufacturing processes of mechanical engineering is gradually increasing. However, laser welding cannot compete with electron beam welding because the processes of the interaction of the laser beam with the plasma arising above the zone of the laser beam affecting the metal are not sufficiently studied. Of particular interest is the use of laser welding in vacuum. The study of the secondary emission signal in the zone of the laser beam affecting the metal allows one to obtain information about the plasma cloud in the zone of laser welding in vacuum. To study the secondary emission current in the laser welding zone, a computer system with an analog-to-digital interface can be used. The registered secondary emission current made it possible to estimate such parameters of the plasma arising in the laser welding zone in vacuum as the plasma concentration, electron temperature, and plasma potential.

1. Introduction
In recent years, laser welding has been increasingly used in industry in the manufacture of critical parts. A high concentration of heat exposure, high growth and temperature reduction rates in the treatment zone, as well as the possibility of rapid formation of a weld pool in a given volume, make it possible to efficiently use laser radiation to implement the welding process. Laser welding in shielding gases using powerful technological lasers is increasingly used in industrial production [1–3]. However, with a high power of the laser beam, the absorption of its energy by a plasma torch forming near the metal surface in the welding zone significantly reduces the efficiency of the thermal effect of the laser beam on the metal [4–6].

One of the promising directions of the development of laser technologies in the manufacture of critical large thickness products is welding with a concentrated laser beam in vacuum. This process has several advantages over its closest competitor by electron beam welding. The laser beam is not sensitive to magnetic fields and, consequently, the presence of residual magnetization in the object to be welded do not affect the quality of the process. The use of a laser beam for deep penetration also opens up fundamentally new possibilities for controlling the hydrodynamics of a weld pool using constant and variable magnetic fields at the same time. Electron beam welding requires a residual vapor pressure in the chamber $10^{-1} - 10^{-2}$ Pa. Laser welding in an environment with reduced pressure exerts its advantages already at pressures of about 1 kPa and pressures of about 100 Pa gives results almost indistinguishable from the results at 10$^4$ Pa [7–10]. This advantage allows you to abandon the use of molecular pumps and significantly increases the manufacturability of the process. In addition, it greatly simplifies the creation of mobile local forevacuum systems that can be used for welding large-sized products. Laser welding in vacuum allows you to get defect-free welds with a high ratio of the depth of the weld to its
width. It has been established that when conducting the welding process with a laser beam in a vacuum, the penetration depth can be increased by a factor of 2–3 compared with laser welding in the atmosphere. An additional factor holding back the development of vacuum laser welding technology is the need to verify the physical models of related processes.

The processes of plasma formation under the influence of a powerful laser beam on a metal at atmospheric pressure are quite well studied [11–13]. When laser welding in vacuum in the zone of exposure to the laser beam as a result of ionization of metal vapor, plasma also appears, which, unlike a plasma torch during laser welding in a protective gas medium, does not absorb the energy of laser radiation and, at the same time, is a conducting medium for secondary emission current arising in the zone of laser welding in vacuum as a result of intense thermionic emission from the zone of the laser beam affecting the metal [14–16].

The formation of the secondary-emission signal in the zone of the action of a powerful laser beam on a metal in a vacuum is of considerable interest from the point of view of implementing operational control of the laser process vacuum welding [15, 16]. The magnitude of this signal substantially depends on the conditions of current flow in the gap between the welded product and the charged particle collector installed above the welding zone to register the secondary emission signal. However, to date, there is no information on the parameters of the plasma cloud in the zone of laser welding in vacuum.

In accordance with this, the goal of this work was to study the plasma parameters in the zone of the laser beam affecting the metal in vacuum and the conditions for the passage of the secondary-emission current recorded in it to monitor the process of laser welding in vacuum.

2. Research Methodology

The study of plasma parameters was carried out by recording the magnitude of the secondary-emission current using a charged particle collector installed above the zone of the laser beam affecting the metal in vacuum and selecting current from the plasma when the positive collector potential changed. The experimental design is shown in Figure 1.

![Figure 1. The registration scheme of the secondary emission current during laser welding in vacuum: 1 – installation for laser welding model ALFA-300; 2 – vacuum chamber; 3 – collector of charged particles; 4 – welded product; 5 – load resistor; 6 – bias voltage source.](image)

The secondary emission current was recorded by creating an external electric circuit for plasma charges. This circuit contained an adjustable bias voltage source on the collector, which allowed changing the positive potential of the collector in the range 0…50 V and a resistor, the voltage drop on which was detected using a computer information-measuring system equipped with an analog-to-digital interface based on the multichannel analog-to-digital converter E20–10 from L–Card. The experiments were carried out on ALFA–300 laser welding machines equipped with a technological vacuum chamber with a quartz glass window in the upper lid of the laser beam input chamber. As the material of the processed product was used austenitic steel grade 12X18H10T.

As is known [12], one of the main factors causing plasma formation in the zone where a powerful laser beam acts on a metal is the ionization of metal vapors when interacting with powerful laser radiation due to inhibitory absorption when an electromagnetic wave interacts with free electrons. The emission of these electrons from a metal occurs both as a result of thermionic emission from a metal heated by a laser beam, and due to photoelectron emission when the metal is absorbed by laser radiation.
In this case, the charged particle collector can be considered as an electrode placed in a “foreign” plasma, and the current-voltage characteristic of the collector – work piece gap can be analyzed as a curve of the current to the Langmuir probe in the plasma. Using such a curve constructed on a logarithmic scale, the plasma concentration and electron temperature can be calculated using the expressions valid for the Maxwellian electron energy distribution [17]:

\[ T_e = \frac{e}{k} \left[ \frac{d}{dU} \left( \ln j_p \right) \right]^{-1} \]

\[ n_e = \frac{j_{pm}}{e} \left( \frac{2\pi m_e}{kT_e} \right)^{1/2} \]

where \( U \) – is the voltage between the products in contact with the plasma electrode; \( j_p = I_p S^{-1} \) is the density of the recorded current in the plasma; \( I_p \) – detectable secondary emission current; \( S \) – is the surface area of the electrode (in this case, the collector of charged particles) in contact with the plasma; \( j_{pm} \) – is the saturation current density (at the electrode potential equal to the plasma potential).

When a powerful laser beam acts on a metal in a vacuum, the current recorded by the charged particle collector is oscillatory in nature [16] In accordance with this, the average value (constant component) of this current was determined by processing the secondary-emission current registration files recorded during the experiments using the Mathcad program. During processing, the recorded signal was cleaned from associated interference by filtering at a frequency of 50 Hz. The direct and inverse Fourier transforms were performed. The received filtered signal was divided into sections. For each plot, extremes were determined with further calculation of the average amplitude.

3. Results and discussion

In Figure 2 shows the dependence of the average value of the secondary emission current recorded by the collector of charged particles in the zone of the laser beam affecting the metal in vacuum on the voltage between the collector and the product, built on a semi-logarithmic scale \( \ln(I_p) \) when this voltage varies in the range of 5...30 V. The area of the charged particle collector was 180 mm².

![Figure 2. The semi-logarithmic dependence of the average value of the secondary emission current on the voltage between the work piece and the charged particle collector.](image)

This dependence was analyzed as an electronic branch of the probe characteristic. The saturation of the electron current from the plasma characterizes the equality of the potentials of the collector of charged particles, taking current from the plasma, and thus, the plasma potential is 30...33 V.

The graph shows that the dependence of the density of the average value of the secondary emission current on the voltage between the charged particle collector and the electron current product being
processed has a character close to linear. However, the fact that the secondary-emission signal is practically absent at a positive potential of the charged particle collector of less than 4...8 V indicates a violation of the linearity of the electron current curve and, accordingly, a deviation of the electron energy distribution function in the plasma from the Maxwellian one in the high energies. These deviations may be due to a distortion of the plasma parameters due to the selection of current from the plasma to the charged collector electrode or to the presence of a high-energy “tail” in the distribution function. Nevertheless, as shown in [18], the effective temperature of plasma electrons can also be estimated if the energy distribution function of electrons deviates from the Maxwellian one. In this case, to estimate the effective plasma temperature, a part of the electron branch of the probe characteristic corresponding to potentials close to the plasma potential should be used.

As a result of calculating the plasma parameters in the zone of influence of a powerful concentrated laser beam on a metal in vacuum using expressions (1) and (2), \( T_e = 1.2 \times 10^{10} \) K and \( n_e = 6 \times 10^9 \) m\(^{-3}\). It should be noted that the estimates made are of a qualitative nature, since the collector of charged particles has a significant area of contact with the plasma and selects the current, acting on the plasma and changing its parameters. High electron plasma temperatures are caused in this region by heating as a result of energy dissipation during the interaction of the electromagnetic wave of laser radiation with free plasma electrons.

The above results show that, as applied to the conditions for recording the secondary emission current generated by thermionic emission into plasma during laser welding in vacuum, the charged particle collector can be considered as an electrode operating in the probe mode. The magnitude of the potential drop in the space charge layer near this electrode is determined by the ratio of the density of the recorded secondary emission current \( j_p \) to the total current density from plasma \( j \) [19]:

\[
\Delta U = \frac{kT}{e} \cdot \ln \frac{j_p}{j}
\]

When a potential equal to the plasma potential is applied to the electrode, the detected secondary emission current is saturated, associated with the complete selection of the current from the plasma.

### 4. Conclusion

For research, a technique was used to register the secondary emission current between the charged particle collector and the surface of the workpiece during laser welding in vacuum. A charged particle collector can be considered as an electrode operating in probe mode. The magnitude of the secondary emission current is dependent on the voltage between the charged particle collector and the product. This site is analyzed as an electronic branch of the current-voltage characteristics of the Langmuir plasma. A change in the potential applied to the electrode made it possible to saturate the secondary-emission current, therefore, to fix the plasma potential above the processing zone of the product with a laser beam in vacuum. Thus, the study of the dependence of the secondary emission current in plasma during laser welding in vacuum on the voltage between the charged particle collector and the workpiece made it possible to determine the parameters of the plasma arising in the laser welding zone in vacuum: concentration, electron temperature, and plasma potential.

### References

[1] Gapontsev V P 2003 Fiber lasers burst a laser industry Proc. of the 12th International Laser Physics Workshop

[2] Holzer M, Rominger V and Havrilla D 2010 Latest Results in Industrial Welding of Thick Sheets with High Power Trudisk Lasers and Optimized Peripheral Components Physics Procedia of Lasers in Manufacturing

[3] Schlüter H 2005 Advances in Industrial Power Lasers Proc. SPIE 5777 8–15

[4] Weiler S 2009 Disk lasers for industry Photonics 3 10–13

[5] Petrovskiy V N, Prokopova N M and Shcheglov P Yu 2010 Spectral diagnostics of a vapor-plasma plume produced during welding with a high-power ytterbium fiber laser Laser Phys.
Lett. 7 396

[6] Harutyunyan R V, Baranov V Yu, Bolshov V A 1985 The effect of laser radiation on materials (Moscow: Science)

[7] Arata Y, Abe N, Oda T and Tsujii N 1985 Fundamental phenomena during vacuum laser welding Proc. of ICALIEO ’85 Materials Processing Symp. Laser Inst. of America 44 1–7

[8] Katayama S, Abe Y, Mizutani M and Kawahito Y 2011 Deep Penetration Welding with High-Power Laser under Vacuum Transactions of JWRI 40(1) 15–19

[9] Katayama S, Yohei A, Mizutani M and Kawahito Y 2011 Development of deep penetration welding technology with high brightness laser under vacuum Physics Procedia 12 75–80

[10] Reisgen U, Olschok S and Jakobs S 2013 A comparison of electron beam welding with laser beam welding in vacuum 9th International Conference Beam Technology

[11] Scheglov P Yu and Uspensky S A 2011 Investigation of the vapor-plasma torch during welding with a high-power fiber laser Scientific session of MEPhl 2

[12] Petrovsky V N and Uspensky S A 2011 Investigation of a vapor-plasma welding torch when welding with a powerful ytterbium fiber laser Nuclear Physics Engineering 2 159–165

[13] Ishide T, Shono S, Ohmae T, Yoshida H and Shinmi A 1987 Fundamental Study of Laser Plasma Reduction Method in High Power CO2 Laser Welding Proc. of the Int. Conf. on Laser Advanced Materials Processing 187-191

[14] Letyagin I Yu, Belenkiy V Ya and Trushnikov D N 2018 On the connection between the energy parameters of secondary emission signals from the laser beam welding zone in vacuum with the parameters of metal penetration Journal of Physics: Conference Series 1109(1) 012013 1–9

[15] Letyagin I Yu, Trushnikov D N, Belenkiy V Ya 2018 Investigation of secondary emission signals from the laser beam exposure zone during laser welding in vacuum Bulletin of Perm National Research Polytechnic University. Engineering, Mechanical engineering, materials science 20 3 106–114

[16] Letyagin I Yu, Belenkiy V Ya, Lyamin Y V, Erikov A P 2019 The study of processes in the area of the laser beam on the metal during laser welding in vacuum Bulletin of the Perm Federal Research Center 3 20–29

[17] Kozlov O V 1969 An electric probe in a plasma (Moscow: Atomizdat)

[18] Ershov A P, Dovzhenko V A, Kuzovnikov A A 1981 On processing the current-voltage characteristics of a Langmuir probe in a non-Maxwellian plasma Physics of plasma 7(3) 609–613

[19] Granovsky V L Electric current in the gas (Moscow: Science)

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