Analysis of the amplitude-time parameters of current pulses in a plasma during laser beam welding

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Abstract. The share of application of laser processing of materials in technological processes of mechanical engineering has increased over the past few years. In this regard, there is a need for reliable control of the technological parameters of the laser welding process. In deep penetration laser welding, part of the beam power is absorbed by the plasma cloud. As a result, a significant decrease in the penetration depth is observed. Using amplitude-time pulse of current in the plasma in the zone of impact of the laser beam on the metal is one of the directions of the work necessary for the control of the processes in the melting channel. The study of the processes of secondary emission in the plasma in the zone of impact of the laser beam on the metal allowed carrying out numerical simulation of the processes during laser welding. The models took into account the dependence on the focusing of the laser beam and other technological parameters of laser welding. The registration of the secondary emission current was also carried out in order to control the geometric parameters of penetration during laser welding. This technique can be used to build methods for the operational control of the welding process.

1. Introduction

The application of laser material processing continuously expands in high-technology industries to produce high quality welds of parts of the structural steels and non-ferrous metal alloys.

As a first source of high-power laser radiation, a carbon dioxide laser was used for welding. They had large dimensions, low (not exceeding 20%) efficiency and could not compete with electron-beam welding equipment.

The emergence of high-power fiber-optic process lasers has contributed to the wider introduction of laser welding into industrial production. These lasers can be compared to carbon dioxide lasers. Lasers have higher reliability, relatively small size and provide high optical quality of radiation. In addition, the radiation wavelength of fiber-optic lasers is an order of magnitude smaller than that of carbon dioxide lasers. This causes less energy consumption. Their continuous improvement ensures lower cost and increased efficiency of technological laser systems. Powerful fiber-optic lasers have drawbacks: the operational reliability of the resonator decreases with increasing laser power, the sensitivity of the resonator increases to beam reflection processes, which arise as a result of the interaction of laser radiation with the material being processed.

In recent years, as high-power industrial lasers, disk lasers began to be applied. The principle of operation of these lasers is based on the use of cooling the active element in the form of a disk. High cooling efficiency of the laser medium is provided due to the large surface area of the disk. Consequently, the radiation power in a disk laser beam can reach quite high values. Important
advantages of disk lasers are the ability to control the radiation power without changing other parameters, the lack of sensitivity of the resonator to the reflected laser radiation, as well as the modular design of the laser, which allows replacing individual modules during service.

Currently, one of the major 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 action on the metal. This is associated with a significant decrease in the depth of penetration compared to the electron beam of the same power. The efficiency of laser welding when joining thick-walled parts is significantly inferior to the process of electron-beam welding, which is widely used in the manufacture of critical products at the same time. This hinders the widespread introduction of laser welding in industrial production.

Certain technological methods are used to reduce the screening effect of the plasma cloud and accordingly to increase the penetration depth during laser welding. Technological methods are known: the application of special coatings on the metal before welding; the deviation of the axis of the laser beam from the normal to the side opposite to the welding direction by 20°…30°; oscillations of the laser beam in different directions relative to the joint; the use of a pulse-periodic mode of the laser; blowing the gas-plasma cloud with various gases and their mixtures [1-5].

However, these technological methods do not solve the problems associated with the power loss of the laser beam in the plasma cloud over the welding zone. Interest in laser welding in vacuum has increased in recent years. This method of welding has some limitations associated with the use of a vacuum chamber. It allows getting a much greater penetration depth at the same power of the laser beam as compared to gas-shielded laser welding. The use of a vacuum chamber provides effective protection of the welding zone from the external environment, which is especially important when welding active metals [6-8].

Operational control of the weld formation process can ensure high reproducibility of the quality of welded joints and the absence of defects in the weld seam. Secondary emission methods for controlling the process of the interaction of an electron beam with a metal have found wide application in electron beam welding. The parameters of the secondary emission signals from the zone of interaction of the electron beam with the metal are recorded with these methods of control [9-12].

Processes similar to processes in electron beam welding with a high-power electron beam occur in the area of laser welding in a vacuum. The following processes are known: intense thermionic emission from the condensed metal phase, the formation of a plasma cloud over the welding zone and the presence of a wide range of oscillatory processes in the melting channel formed by a powerful concentrated laser beam [13-15].

The purpose of this work is to analyze the amplitude-time parameters of plasma current pulses in the zone of influence of a powerful laser beam on a metal surface. Experimental work is carried out to evaluate secondary emission processes in the laser welding zone in order to use these signals to monitor and control the process of weld formation.

2. Research and experiments
The registration of the secondary emission current in the plasma in the laser welding zone was carried out by installing a collector of charged particles above the welding zone (Figure 1). It was included in an electrical circuit containing a load resistor and a source of bias voltage. The signal from the load resistor was fed to a computer information-measuring system with an analogue-digital interface based on an analogue-digital converter U-14-140M of the company L-CARD.

The experiments were carried out on the laser welding machine model ALFA-300, supplemented by a vacuum chamber with variation of the maximum drive voltage from 200 V to 400 V, pulse duration from 4 ms to 20 ms and their repetition rate 1 Hz.
Experimental studies have shown that the spectrum of the recorded signal contains a high-frequency component ($f > 10$ kHz) and its harmonics (Figure 2).

This component of the secondary current in the plasma was measured using a collector of charged particles; it reflects the oscillatory processes in the plasma column when applied to the collector of positive potential.

The nature of these self-oscillation processes is associated with the onset of ion-acoustic instability. The observed instability is similar to the potential-relaxation instability, characterized by large amplitude of oscillations on the positive electrode located in the plasma. Both types of instabilities have similar excitation and propagation nature. These instabilities in the plasma appear when the discharge current density exceeds a certain critical value. The critical current density $j_c$ is expressed through the threshold value of the drift velocity of electrons.
\[ V_D = \frac{J}{n_e e} \]  
(1)

where \( n_e \) – the electron concentration, \( e \) – the electron charge.

The minimum value of the velocity \( V_D \) at which ion-sound instabilities arise coincides with the velocity of ion sound in plasma

\[ V_s = \sqrt{\frac{\gamma_e k_b T_e + \gamma_i k_b T_i}{m}} \]  
(2)

where \( k_b \) – the Boltzmann constant; \( \gamma_e \) – the coefficient, which for electrons is taken to be unity, for ions, \( \gamma_i = 3 \); \( T_e \) and \( T_i \) – respectively, the temperature of electrons and ions; \( m \) – the mass of ions.

The critical current density is \( \sim \) 3 mA / m², with an ion temperature above the welding zone of about 2400 K, an electron temperature of \( \sim 10000 \) K and a plasma density \( n_e \approx 10^{16} \) m⁻³, which corresponds to a collector current of charged particles of about 4 mA for an area of about 2...4 cm².

The experimentally observed pulses of the electron current in the plasma have a magnitude greater than the threshold value.

Dispersion ratio for ion-sound waves is

\[ \omega(k) = k V_s / \sqrt{1 + k^2 \lambda_D^2} \]  
(3)

where \( \omega \) – the frequency, \( k \) – the wave number, \( V_s \) – the phase velocity of the ion-sound waves in the plasma, \( \lambda_D \) – the Debye screening radius.

The dispersion relation takes a linear form \( \omega(k) = k V_s \) for ion-sound oscillations in the case of large wavelengths (\( \lambda >> \lambda_D \)). The speed in ion-acoustic waves is constant, and the frequencies can take on a wide range of values, depending on the wavelength. This is possible if the ionic oscillations of the Langmuir are characterized by a constant frequency and arbitrary velocity values. If we take the quantity \( L/n \) as the wavelength of the n-th harmonic (\( L \) is the characteristic size of the system, i.e. the distance between the metal surface and the collector of charged particles), we obtain the expression for harmonic frequencies

\[ f_n = n V_s / L \]  
(4)

The frequency of the high-frequency component depends on the distance between the weld zone and the collector of charged particles. This agrees well with the experimental data. In this case, the evaluation of the phase velocity of the corresponding ion-acoustic waves gives a value of 1650 m/s.

Arisign self-oscillations in the plasma above the welding zone modulate the oscillations in the spectrum of the secondary signal in the range of 100 Hz – 10 kHz. They arise due to: capillary instability of the penetration channel, stochastic movement of the zone of interaction of the laser beam with the metal on the walls of the penetration channel, local overheating in the penetration channel, pulsations of steam flow from the penetration channel and other periodic processes in the penetration channel.

The mechanism of collisional damping of oscillations is known in plasma physics. The probability of collisions of plasma particles during the oscillation period increases in the zone of laser welding at atmospheric pressure at high concentrations of neutral atoms. The number of these collisions is large enough, and the oscillations decay very quickly.

The task was to differentiate the oscillatory processes in the plasma associated with various types of instabilities and self-oscillations caused by periodic processes in the channel of melting. It is assumed that self-oscillations should correlate to a greater degree with the technological parameters of laser welding in vacuum and with the geometry of the melting zone in the metal when exposed to a laser beam.
The studies were conducted with the registration of the signal of amplitude-time parameters of the current of the secondary emission. The influence of the distance between the collector of charged particles, which produces a secondary current from the plasma and the surface of the metal exposed to the laser beam, was evaluated. This made it possible to take into account the nature of self-oscillations in plasma associated with various instabilities largely determined by the geometry of the plasma cloud formed in the zone of laser welding in vacuum.

Figure 3 shows the dependence of the frequency of the spectrum component due to ion-acoustic oscillations in the plasma in the zone of laser welding in vacuum, on the distance between the charged particles collector and the metal surface.

![Figure 3](image_url)

**Figure 3.** Dependence of the frequency of the spectrum component due to ion-acoustic oscillations in the plasma in the zone of laser welding in vacuum on the distance between the charged-particle collector and the metal surface.

Figure 4 shows the oscillation spectra obtained by mathematical processing in the MathCad medium of the results of recording the signals of secondary emission in the zone of laser welding in vacuum. The data correspond to different distances from the collector of charged particles to the metal surface.

The spectral density of the high-frequency components of the secondary-emission current spectrum in the laser-welded zone decreases in vacuum, and their frequency increases as the distance from the metal surface to the collector of charged particles decreases, as can be seen from Figure 3 and Figure 4. Consequently, the high-frequency components of the spectrum of the secondary emission current in the zone of laser welding in vacuum are associated with ion-acoustic and relaxation instabilities in the plasma.

This proves that the electrode-collector of charged particles must be placed in close proximity to the surface of the welded metal. This will ensure the registration of the secondary emission current in order to control the geometric parameters of penetration during laser welding. Additionally, in the course of the experiments, an experimental dependence was obtained, which determines the extreme nature of the change in the magnitude of the secondary emission signal depending on the focusing of the laser beam and other technological parameters of laser welding.
Thus, on the basis of experimental studies of the amplitude-time parameters of current pulses in plasma with pulsed laser welding, the results were obtained. These results will be the basis for the development of methods for the secondary emission control of the process of weld formation during laser welding in vacuum.

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