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

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Abstract. Currently, laser beam welding is widely used in engineering, especially in the production of responsible appointment. The implementation process of laser beam welding in the production gives such advantages as a high concentration of thermal effects, high growth rate and reducing the temperature in the processing zone, and the possibility of rapid formation of a welded bath in a given volume. In recent years, active development in laser beam technologies in the manufacture of general and special machine building products has been obtained by welding with a concentrated laser beam in a vacuum, which allows producing defect-free welds with a high seam depth to width ratio. Previously, these quality indicators could be observed only with the use of electron beam welding. Studies of physical processes during laser beam welding in a vacuum, in order to create efficient welding technology, is now just beginning. One of the research areas is the possibility of operative control of the process of formation of a welded seam, in order to ensure the absence of defects and high reproducibility of the quality of welded joints. The proposed method is based on registration of secondary emission signals of the welding zone with the use of a collector of charged particles. The amplitude-time characteristics obtained for the given registration can be used to estimate the value of the specific power introduced into the article to be welded. The change in the specific power was recorded during the experiments with a change in the focus of the laser beam relative to the surface being treated, which makes it possible to conclude that the emissivity has changed from the weld pool. The use of this technique for recording the secondary emission current recorded in the plasma over the laser welding zone in a vacuum provides the possibility of an operative control of the geometry of the penetration zone during laser welding in vacuum.

1. Theoretical justification of the energy impact of a laser beam

Laser welding of metals in vacuum is a promising technology, which, despite the need to place welded parts in the process vacuum chamber, allows obtaining, in comparison with laser welding in a protective gas environment, a much greater depth of metal penetration at the same laser beam power and providing a high degree of zone protection welding from the influence of the external environment [1-3]. The technological capabilities of laser welding in vacuum are comparable, and in some cases exceed the capabilities of electron beam welding, which also allows to provide a high concentration of power in the welding zone and for many decades has been a highly effective way of connecting parts of complex structural steels and alloys in aerospace and other high-tech industries.
The manufacture of critical products with the use of welding in a number of cases requires the operational control of the process of formation of the welded seam. This allows to ensure the absence of defects in the seam and high reproducibility of the quality of welded joints. Secondary-emission methods for controlling the interaction of the electron beam with a metal have found wide application in electron-beam welding. In this case, the parameters of electron fluxes leaving the welding zone are recorded [4-5].

The use of secondary emission signals to control the formation of the welded joint is also of considerable interest in laser welding in vacuum. In the zone of action of a powerful concentrated laser beam, processes similar to electron beam welding occur. Among these processes, one can single out thermionic emission from the condensed metal phase in the energy release zone, the formation of a low-temperature plasma above the welding zone, and the presence of vibrational gas- and hydrodynamic processes in a wide spectral region [4].

The process of interaction of a laser beam with a metal is explosive in laser welding with deep penetration. The energy introduced into the metal by the laser beam exceeds the energy expenditure for its explosive destruction. In this case some part of the laser beam energy is converted into internal energy of the plasma phase in the destruction zone, therefore the formation of intense pulses of current in the plasma zone over the laser beam can be regarded as a process of direct conversion of thermal energy into electrical [8-12].

Thus, the aim of the research was to confirm the relationship between the energy characteristics of secondary emission signals from the laser welding zone in vacuum and the power density of the laser beam and hence their influence both on the geometry of the fusion zones.

It is known that the main source of electromotive force in this process of energy conversion is the thermal energy of the products of metal destruction. Accordingly, the most complete information about the energy characteristics of the process of explosive destruction of the metal in the zone of action of the laser beam during laser welding in vacuum can be obtained by analysis of amplitude and time parameters of the current pulses in the plasma at a frequency of about $10^4$ Hz. These current pulses characterize the process of explosive destruction of the metastable condensed phase of the metal [13-16]. It is necessary to differentiate the arising oscillations with the oscillations associated with the occurrence of ion-acoustic instabilities and potential-relaxation instabilities. These instabilities are observed in a low-temperature isotropic plasma, in particular, as in the registration of secondary emission signals in electron-beam welding [16]. Both types of instabilities have similar excitation and propagation nature, and occur in the plasma density in excess of the current flowing in it a certain critical value.

The amplitude-time parameters of the pulses of the secondary emission current in the plasma determine the energy of these pulses per unit resistance:

$$E_i = \int_0^t I^2(t) \, dt = \psi \cdot I_m^2 \cdot t,$$

(1)

where $\psi$ – the current pulse shape of the current, $I(t)$ – the current in the load; $I_m$ – the amplitude of the current pulse; $t$ – the pulse duration.

The interval "welded article - the collector of charged particles" (the charged particle collector is an electrode and takes a current from the plasma) can be considered as a nonlinear active two-terminal network in the secondary emission current detection circuit. In this case, external sources of electromotive force are considered as factors that change the distribution of the potential in the layers of space charge and determine the conditions for the passage of the secondary emission current in the plasma. The pulses of the secondary emission current in the plasma above the zone of laser welding in vacuum with a frequency of the order of $10^4$ Hz in the load of the measuring circuit can be considered as pulses of the thermoelectromotive force generated during the thermal explosion of the condensed phase of the metal in the zone of action of the laser beam. The energy of these pulses is proportional to the thermal energy $Q$ emitted by the products of metal disruption.
(2)

where \( \eta \) - the coefficient of efficiency taking into account the thermodynamic losses and losses in the electric circuit, and which constitutes, with regard to the registration conditions secondary emission current in the plasma on the laser welding zone in vacuum value 0.1 \( \ldots \) 0.01%.

The energy released during the thermal explosion of the condensed phase of the metal is determined in the adiabatic approximation by the excess enthalpy of the superheated metal

\[
Q = m \cdot c \cdot (T - T_0),
\]

(3)

where \( m \) - mass of superheated metal undergoing explosive destruction; \( c \) - the specific heat of the condensed phase of metal; \( T \) - temperature of the metal at the moment before the explosive destruction; \( T_0 \) - boiling point of the metal.

The mass of the metal that is destroyed by the action of the laser beam is

\[
m = q \cdot L^{-1} \cdot \tau,
\]

(4)

where \( q \) - power released by the laser beam; \( L \) - specific fracture energy; \( \tau \) - time of energy accumulation during which the temperature rises from \( T_0 \) to \( T \).

The heating of a metal with a laser beam of high power causes a significant overheating of the metal above the boiling point, the magnitude of which is determined by the rate of increase in the temperature of the metal. This rate can be estimated by neglecting the loss of thermal conductivity by formula

\[
\frac{dT}{dt} \equiv -\frac{q_s}{c \cdot \rho \cdot \delta},
\]

(5)

where \( \rho \) - density of the condensed phase of metal; \( \delta \) - depth of superheated metal layer; \( q_s \) - specific power of the laser beam in the energy release zone.

If we approximate the dependence of the superheat value on the rate of temperature rise by the power function

\[
T - T_0 = \alpha \cdot \left( \frac{dT}{dt} \right)^\gamma,
\]

(6)

where \( \alpha \) and \( \gamma \) - constant coefficients, and \( T \) is bounded above by the spinodal temperature, which determines the limiting stable state of the metastable liquid, then, from expressions (5) and (6), in the approximation of a constant rate of temperature rise in the temperature range of superheating,

\[
T - T_0 = \alpha \cdot \left( \frac{q_s}{c \cdot \rho \cdot \delta} \right)
\]

(7)

\[
\tau = \alpha \cdot \left( \frac{q_s}{c \cdot \rho \cdot \delta} \right)^{\gamma-1}
\]

(8)

Then the energy released during the explosive destruction of the metal in the zone of action of the laser beam in vacuum is approximately equal to

\[
Q \approx \frac{\alpha^2 \cdot c \cdot q}{L} \cdot \left( \frac{q_s}{c \cdot \rho \cdot \delta} \right)^{2\gamma-1},
\]

(9)
and the interrelation of the energy of the pulses of the secondary emission current recorded in the plasma above the laser welding zone in vacuum and the specific power of the laser beam at a constant value of the total power is given by

\[ E_l \equiv A \cdot \eta^z \cdot \tau^{-1}, \tag{10} \]

where \( A \equiv \frac{a^2 \cdot c \cdot \eta}{l} \cdot \left( c \cdot \rho \cdot \delta \right)^{1-2 \cdot \gamma} \) – constant factor.

2. Experimental testing

To estimate the value of the power parameter \( \gamma \), an experimental study was made of the relationship between the pulses secondary-emission current recorded in the plasma above the laser welding zone in vacuum and the specific power of the laser beam when the laser beam was applied to flat samples 4 mm thick made of 321S12 steel. To reduce the reflectivity, surface cleaning of the samples was not carried out. For experiments used a setup ALFA-300 with a maximum variation of the drive voltage from 200 V to 400 V, a pulse duration of 4 ms to 20 ms, pulse repetition rate of 1 Hz.

To monitor the process of interaction of the laser beam to the metal by laser welding in a vacuum in the parameters of secondary emission signals of the welding zone installed charged particle collector (Fig. 1) to which is supplied a positive potential and create external electrical circuit for recording the current flowing in plasma, formed over the welding zone [6, 7].

During experiments carried out changing the focus point of the laser radiation within \( \pm 1.6 \) mm, which resulted in a change in power density of the laser beam. The specific power of the laser beam was calculated in the approximation of its uniform distribution along the diameter of the beam, which was determined by burning the foil under the pulsed action of the laser beam.

To determine average values of pulse energy by the formula (1) used in the experiments received the average value of amplitude and frequency of secondary-emission current pulses, the average pulse width is approximately taken equal \( t \equiv 0.5 \cdot f^{-1} \), where \( f \) - average oscillation frequency.

![Figure 1. Recording scheme of the secondary emission current at laser welding: 1 - collector of charged particles; 2 - the product to be welded; 3 - bias supply; 4 - termination resistor.](image)

In Figure 2 is a graph of pulse energy depending on the secondary-emission current on the specific power of the laser beam. As can be seen from the graph, in the first approximation, the energy dependence of the secondary-emission current pulses is proportional, and the power parameter in expression (10) can be assumed to be \( \gamma \equiv 1 \).
When the focus of the laser beam penetrates the product, the values of the amplitude-time characteristics and their frequency distribution change (Figures 3-4). This process can be explained by the increase in explosive destruction of metal in the weld pool and the increase in the emission of electrons from the zone of action on the metal of laser radiation [17, 18].

Analysis of the amplitude-time characteristics showed an increase in the number of recorded peaks of the secondary emission current, which confirms an increase in emission from the plasma phase in the destruction zone. In the spectrum of the recorded signal there is a high-frequency component (f>
10 kHz) and its harmonics. This component of the secondary current in the plasma, measured by the collector situated at a positive potential reflects oscillatory processes in the plasma column at the excitation of a non-self-sustained discharge in it. The magnitude of the signal increases as the amount of penetration of the focus of the laser beam into the article increases. The nature of these autooscillatory processes is associated with the onset of ion-acoustic instability. In this case the observed instability potentially similar relaxation instability characterized by large amplitude oscillations at the positive electrode, which is located in the plasma. Both types of instabilities have similar excitation and propagation nature. The resulting self-oscillations in the plasma above the welding zone modulate the oscillations in the spectrum of the secondary signal in the range from 100 Hz to 10 kHz caused by the capillary instabilities of the penetration channel, the stochastic displacement of the interaction zone of the laser beam with the metal on the walls of the penetration channel, local overheating in the penetration channel, from the channel of penetration and other periodic processes in the channel of penetration.

Experimental studies of the dependence of the shape coefficient of the penetration zone (the ratio of the depth of the zone to its width) on the specific power of the laser beam showed that this dependence is close to linear in the first approximation (Figure 5).

Thus, the energy of the pulses is in the first approximation proportional to the ratio of the depth of the penetration zone to its width. This allows the operative control of the geometry of the penetration zone during laser welding in vacuum with respect to the amplitude-time parameters of secondary emission current pulses recorded in the plasma above the laser welding zone in vacuum.

Figure 4. Recording secondary emission signal when the focus is shifted deep into the product by 0.6 mm
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