Installation for Treatment of Metal Surfaces by Low Energy Electron Beam[1]

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Abstract – This paper describes the design of a facility for surface treatment of metal specimens and presents the results of studies of a source which produces a low-energy high-current electron beam. An electron beam of current up to 300 A and pulse duration 30 μs is generated in a gas-filled diode with a plasma cathode at a pulse repetition rate of up to 10 Hz and at an accelerating voltage of up to 20 kV. The space-charge-compensated electron beam is transported in a longitudinal magnetic field for a distance of 20 cm to the region of its interaction with a solid. At a current density of up to 100 A/cm^2, the beam power density proves to be sufficient for melting the metal surface within one or several pulses.

1. Introduction

Dense energy flows in the form of electron beams with a high power density are rather widely employed in different technological processes, such as welding of critical parts, remelting of refractory and reactive metals and surface modification by hardening [1]. In the majority of cases, technological high-current electron sources incorporate cold cathodes based on explosive [2, 3], arc [4–6] and glow [7–9] discharges of low pressure. In such sources, a high beam current density should be attained at a comparatively low energy of accelerated electrons. Under these conditions it is difficult to obtain a high electric strength of the acceleration gap because of gas desorption, back ion flows, and high-power vapor flows from the surface of the treated material. Moreover, the problems arise with respect to the formation and transportation of a beam with the required parameters and without considerable losses to the region of its interaction with a solid.

This paper describes a pulsed e-beam facility which is based on a plasma cathode with grid stabilization of the emission plasma boundary. The design of this facility has made it possible to solve a number of the above problems and to produce an electron beam to study pulsed thermal treatment of materials and articles in a new range of parameters.

2. Design of the System and Electron Beam

The general view of the facility is shown in Fig. 1. It consists of a vacuum chamber with a pumping unit, an electron source, transportation and measuring system, an accelerating voltage source, and a control rack of the vacuum system and electron source.

Fig. 1. General view of the facility

The setup of the electron source with a plasma emitter located in the upper part of the facility is shown in Fig. 2. In essence, the gas-discharge system of the plasma emitter consists of two gas-discharge systems. The first system is formed by cylindrical hollow cathode I of internal diameter 10 mm and length 50 mm and cylindrical anode 3 of diameter 40 mm and length 50 mm and is a system of a trigger glow discharge which operates at a comparatively high (~ 1 Pa) pressure within a short (2–5 μs) pulse duration.

To decrease the initiating voltage of the trigger discharge, the cylindrical hollow cathode 1 is placed in a 0.1-T magnetic field induced by circular permanent magnets 2. The main discharge is ignited between the cylindrical electrode 3 and hollow anode 6 with subsequent switching to emission grid electrode 7. The duration of the main discharge is 30 μs. In the system of the main discharge, the electrode 3 plays the role of a hollow cathode. Stable transition of the main discharge to an arc is due to magnesium electrode 4 with a cathode spot operating on it. To create a pressure difference between two discharge systems and to decrease the pressure in the acceleration gap, there is a small 6-mm diameter constriction channel in the electrode 3. The grid electrode 7 has a 50-mm diameter emission orifice covered with a grid of transparency

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50–60%. The electrode 7 is located at the face plane of a hollow anode of diameter 80 mm and length 100 mm and is connected to the hollow cathode through a resistor $R = 50\ \Omega$.

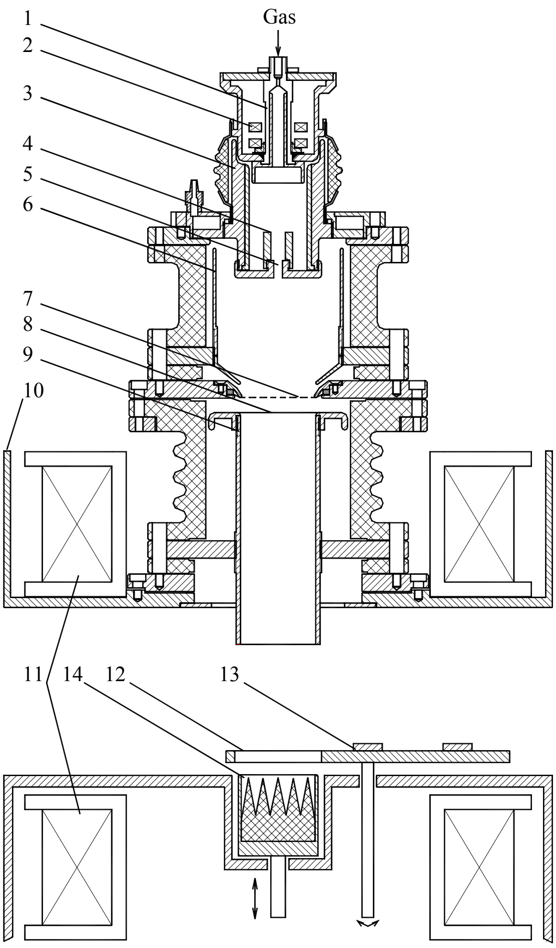

Fig. 2. Design of the electron source with a plasma emitter

A high DC voltage (0–20 kV) is applied between the emission grid electrode 7 and accelerating electrode 8 made in the form of a diaphragm. Accelerating gap is 5–8 mm. Electrons are extracted from the plasma through grid meshes and accelerated to an energy corresponding to the applied voltage. The grid forms and stabilizes the plasma boundary and allows producing a beam with a reasonably uniform distribution of the emission current density. The extracted and accelerated electrons ionize the gas in the acceleration gap and in the drift space. The plasma produced in the drift channel due to ionization of the gas by the electron beam acquires a potential close to the anode potential. Thus, after a time ($\tau = 3–5\ \mu s$) a system consisting of the cathode plasma emission surface stabilized by the grid and the plasma anode with a movable plasma boundary (set according to the Child-Langmuir law for the ion current in the acceleration gap) appears in the gas-filled diode. The electrons emitted by the plasma cathode are accelerated in the layer between the cathode and anode plasmas and find their way to the drift space where the space charge of the beam is neutralized by the ions resulting from gas ionization. The use of different electrodes makes it possible to vary the orifice diameters of the emission and accelerating electrodes from 10 to 50 mm, thus varying the beam diameter. Vacuum chamber 10 of volume 0.1 m^3 is evacuated with a turbomolecular pump at a rate of 800 liter/s. The pump produces an ultimate vacuum of no worse than $1 \cdot 10^{-3}$ Pa. The facility is provided with a vacuum pumping control system which allows operation in the automatic and manual modes. In the automatic mode, emergency conditions are controlled, which are associated with cooling or with deterioration of the vacuum in the chamber, and in the manual mode special measures are realized to protect attending personnel from improper operations.

3. Transportation and Measuring System

With a neutralized space charge, the beam may experience contraction under the action of its self-magnetic field. To stabilize the electron beam in the acceleration gap and in the drift space, the entire system is placed in a longitudinal magnetic field induced by magnetic coils 11. The design of the working chamber has been optimized taking into account that the magnetic coils should necessarily be located outside the evacuated volume of the chamber. To accomplish this, the coils are located inside special cups which enter the working chamber volume at the bottom and at the top and produce either a uniform alongitudinal magnetic field (up to 0.03 T) in the region where the electron beam is formed and transported or, with an independent control of the current in each coil, a magnetic field of specified configuration to vary the beam diameter on the specimen. The suppress the "winding" instability, the beam is transported in metal tube 9 of diameter 52 mm and length 160 mm.

The specimens are placed on rotating manipulator table 12 in the working chamber through a side loading hatch. The manipulator table has several fixed positions that allows quick replacement of specimens 13 without failure of vacuum in chamber. One of the positions of the working table is used to measure the parameters of the electron beam with graphite collector 14. The collector is fixed on a movable rod and is capable of moving along the axis of the e-beam source. The e-beam current is measured with Rogowskii coils which are in the circuits of the main electrodes. Both the collector and the manipulator table is provided with a water cooling system, since up to 1.5-kW average power can be absorb on them, when operated at a pulse repetition rate of 10 Hz.

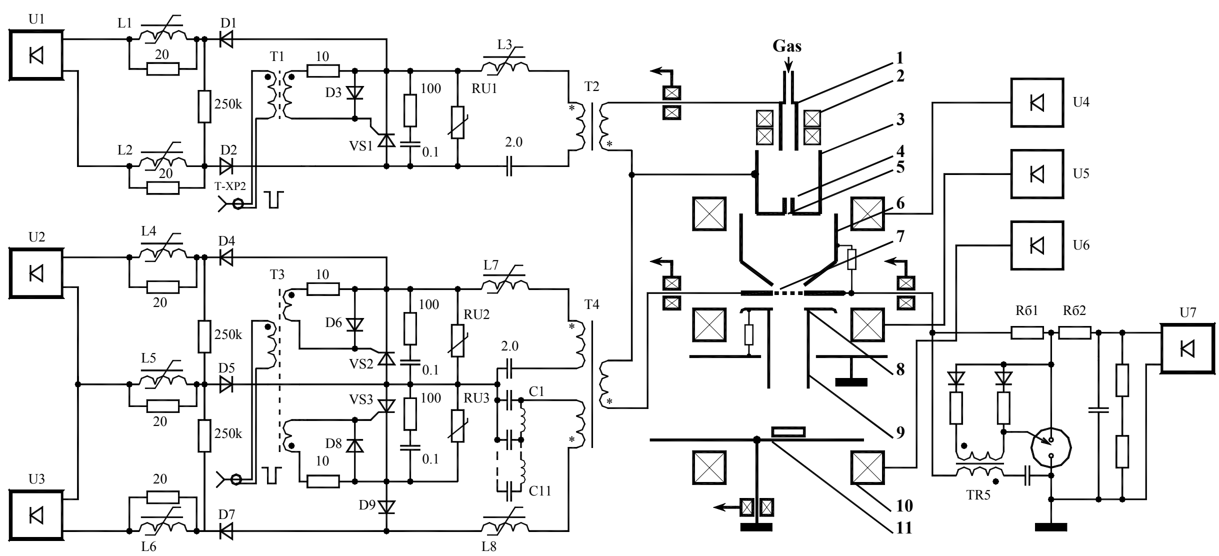

Fig. 3. Power supply circuit of the discharges and acceleration gap

4. Power Supply Circuit

The trigger discharge of the electron source (Fig. 3) is powered by a single-channel circuit based on a controllable rectifier *U*1 (0–300 B), a capacitor *C*2, a high-voltage isolation transformer *T*2 and a power thyristor switch *VS*1 which is triggered by the pulse generator through an isolation transformer *T*1. The protective *RC* circuit limits the rate of increase of the voltage across the switch and the variable resistor *RU*1 protects it from overvoltages. The saturable reactor *L*3 limits the rate of increase of the current through the power switch in the open state. The circuit forms a voltage pulse of up to 10 kV on the secondary winding of the transformer *T*2 in the no-load conditions and a discharge current of amplitude up to 30 A and pulse duration 5 μs in the operating conditions.

A peculiar feature of the power supply circuit of the main discharge is the presence of two channels. The first channel is composed of a thyristor switch *VS*2. When powered from a ~ 300-V uncontrollable rectifier *U*2, the channel ensures the formation of a high-voltage (up to 2.5 kV) pulse on the secondary winding of the transformer *T*4 and rapid ignition of the main discharge in the glow mode. The second channel is composed of a switch *VS*3 and provides operation from the storage line with a high discharge current upon transition to the arc mode wherein the current amplitude of the main discharge ranges from 50 A to 500 A. The discharge current is controlled by varying the voltage of the rectifier *U*3. The protective diode *D*9 precludes the passage of the current though the switch *VS*3 at the moment the switch *VS*2 is open. The elements *L*1, *L*2, *L*4, *L*5, *L*6 are used to decrease the pulse noise.

The accelerating voltage source *U*7 is composed of a step-up transformer with a regulating autotransformer in the primary winding circuit and a multiplier-rectifier which provides charging of the storage capacitor C_S during the operation of the source with a pulse repetition rate of up to 10 Hz and simultaneous protection of the high-voltage source from current overloads. In the operating conditions of the source the mode with a partial discharge of the storage capacitor is realized that ensures a near-constant electron beam energy within a pulse. In the case of a breakdown of the acceleration gap, the current is limited by ballast resistors *R*б1, *R*б2. A peculiarity of the circuit is that a unit composed of the transformer *TR*5, storage capacitor, and power switch based on an ignitron switch IRT-6 is incorporated into it to protect the emission grid from damages when the acceleration gap is broken down.

5. Results of Tests

Fig. 4 shows the current-voltage characteristic of the electron source. The source is characterized by a weak dependence of the beam current on the accelerating voltage that is mainly determined by the emissivity of the plasma cathode (by the discharge current) and is associated with mobility of the anode plasma boundary. As the accelerating voltage is decreased, the length of the acceleration gap decreases due to the motion of the anode plasma and the electron current in the gap is thus kept constant. Another peculiarity of the electron source is the high coefficient of electron extraction (up to $\eta = 0.9$, $\eta = I_e/I_d$ is the ratio of the emission current I_e to the discharge current I_d) from the plasma of the main discharge at a 60% geometric transparency of the emission grid.

Characteristic waveforms of the discharge current and emission current are presented in Fig. 5.

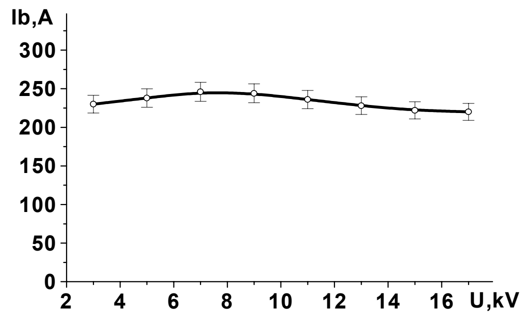

Fig. 4. Current-voltage characteristic of the electron source

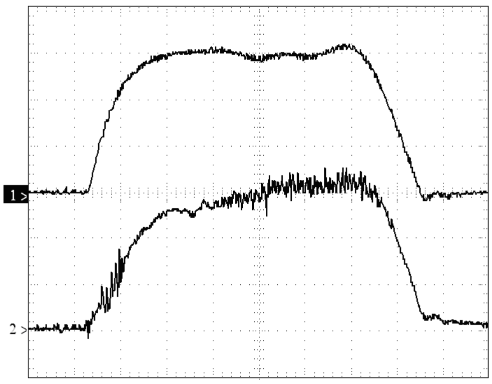

Fig. 5. Typical waveforms of the discharge current (upper trace) and emission current (lower trace); scale: 100 A/div, 5 μs/div

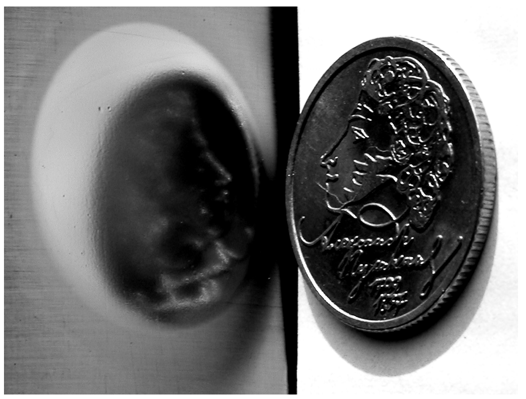

Fig. 6. Trace of the beam on the Ti surface

At a pressure in the vacuum chamber $p = 1 \cdot 10^{-2}$ Pa, the electron beam is transported with small losses in the drift Al tube and in an axial magnetic field $B = 0.02 – 0.03$ T for a distance of 20 cm. Varying the ratio of currents in some magnetic coils makes it possible to vary the beam diameter from 40 to 10 mm and to obtain an energy density on the specimen up to 30 J/cm^2. The trace of the beam on the Ti surface at an electron energy of 18 keV and a beam current density of ~ 50 A/cm^2 is shown in Fig. 6.

The long pulse duration allows melting the metal to a great depth. So, at a pulse duration of 30 μs, an energy density of 15–20 J/cm^2, and a power density of (5–7) · 10^5 W/cm^2 the Ti surface was melted to a depth of 50 μm. When acted upon by an electron beam of ~ 15 J/cm^2, the prehardened 38CrHi3MoVN-type steel surface reveals an about 1.5-fold increase in microhardness.

6. Conclusion

1. The independence of the bean current from the accelerating voltage makes it possible to control the beam current in a wide range and to study the interaction of high-power energy flows at a constant electron energy. The beam current is easily varied by varying the discharge current and the accelerating voltage by varying the charging voltage of the capacitor bank.

2. At a high beam power density, the low electron energy provides a low radiation level that simplifies the radiation shielding, which plays an important role in technological systems.

3. With a low accelerating voltage, the dimensions and weight of the power supply circuits of the facility are markedly decreased, the protection from high voltages becomes cheaper and the overall dimensions of the facility are reduced.

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