Study of the operating modes of the electrostatic lens of the welding electron gun

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Abstract. The paper presents the results of a study of the operating modes of a technological electron gun used in installations for electron beam welding. The design of an electron gun, which is part of the ELA-15I power complex, is considered, and the results of modeling the accelerating gap for a new design gun with an accelerating voltage of 120 kV are presented. The current-voltage characteristics of the gun operation were experimentally obtained at different temperatures of the main LaB$_6$ cathode. For this, the beam current was recorded at different values of the control electrode potential. A mathematical model of the accelerating gap was implemented, which makes it possible to analyze the shape of the electron beam in the region of the first lens. Using a mathematical model, the shapes of the electron beam were calculated for various operating modes of the gun, and the characteristic transverse size of the beam in the crossover was determined. The beam diameter and the angle of convergence in the area of focusing the beam on the product were determined experimentally. Conclusions were made about the equality of the crossover diameters of the full-scale and mathematical models, as well as about the sufficient coincidence of the experimental and calculated volt-ampere characteristics. The design of the accelerating gap of the ELA-15 gun was optimized with an increase in the accelerating voltage from 60 kV to 120 kV. The optimization results are shown for the original and modified design in the form of a comparison of the patterns of the distribution of the electrostatic field strength and a comparison of the current-voltage characteristics.

1. Introduction
Previously, various analytical tools were used to analyze structures [1,2], but with the advent of computers, it became possible to simulate three-dimensional structures, obtain more visual results [3] and take into account parameters that are closer to real conditions. For example, it became possible to simulate electron guns with solid bodies under various operating conditions and various geometric parameters [4,5]. However, not only methods of solving problems are developing, but also the industrial sectors themselves, in which these problems are formed. Thus, with the development of mechanical engineering, tasks have arisen to create new structures, from which there is a need to create technological equipment with new parameters. Electron beam equipment used for technological purposes is used in many industrial areas. The wide application is based on the advantages of electron-beam technology, thanks to which it is possible to obtain high-quality welded joints and connect parts with poor weldability [6]. Therefore, with the emergence of problems to increase the thickness to be welded to several hundred millimeters with the EBW method, an increase in the accelerating voltage at the gun is required while
maintaining a high beam current. Proceeding from this, the need arose for new technical solutions for structures for electron beam welding [7]. Improvement of equipment will improve the technological process and increase the number of high-quality welded joints, etc.

As a consequence, the purpose of this article was to develop the geometry of an electrostatic lens with an accelerating voltage of 120 kV and a power of 120 kW based on the optimized geometry of the cathode-anode gap of the existing ELA-15 electron-beam gun.

2. Methods

2.1 Carrying out an experiment to obtain current-voltage characteristics and building a mathematical model of the ELA-15 gun

The experiment to obtain the I – V characteristic was carried out on the ELA-15 gun of the ELA-15I energy complex in the following order. A target was placed in the vacuum chamber. Then the vacuum chamber was evacuated to 10^{-4} Pa, and the optimal bombardment current was set. ELA-15 is a gun with indirect cathode heating, that is, the cathode heating temperature and beam power are regulated by the bombardment current supplied to the filament so that the emitting electrons bombard the cathode and heat it (Figure 1(a)). After reaching the specified operating mode, the gun was warmed up at the specified parameters for 30 minutes in order to establish a stationary thermal process. After the establishment of a stationary thermal regime, the boundary of the locking of the gun was determined. This is the minimum absolute voltage at which the beam current is zero. For this, it was established at what value of the bias voltage on the target there is no spot from the beam. Then, by adjusting the potential at the control electrode, the beam current setting was gradually increased, starting from 2 mA with a step of 1 mA. At each setting, the pulse duration was 5 s. This is necessary to stabilize the bias voltage values. The current setting was increased until the gun was fully opened, the bias voltage was zero.

![System of indirect heating of the cathode](image1.png)

(a)

![3D model of the accelerating gap of the ELA-15 gun](image2.png)

(b)

Figure 1 – System of indirect heating of the cathode (a): 1 – heater, 2 – cathode; 3D model of the accelerating gap of the ELA-15 gun (b): 1 – control electrode, 2 – cathode holder, 3 – cathode, 4 – anode.

The determination of the optimal bombardment current was carried out as follows. The setting for the bombardment current was varied from 5 mA to 50 mA with a step of 1 mA. At each setting of the bombardment current, the maximum beam current was measured to determine the required I – V curve recording range. To obtain an I – V characteristic with an accurate set of measured values, it is necessary that the recorded currents are in the maximum range, and the maximum recorded current should be close to the limiting value obtained by the high voltage source. However, the heating temperature of the cathode is not constant due to the influence of temperature fluctuations on the emission. Based on this,
it was optimal to use the temperature range limiting the maximum beam current from 15 to 50 mA. With such a range, the parameters are accurately recorded, the stability of the operation of the cathode filament is increased. Thus, at a bombardment current of 10 mA, the filament source operated with minimal oscillations, and the maximum beam current was 30 - 31 mA. These parameters satisfy the criteria for taking the I–V curve.

Further, based on the real design of ELA-15, a solid geometric model was designed in the Comsol Multiphysics program (Figure 1(b)). For modeling, the potentials on the electrodes and their materials were set, an area surrounding the three electrodes was added to indicate the properties of the vacuum on it. Potentials and materials: anode from M06 - 0 kV, cathode from lanthanum hexaboride – -60 kV and control electrode from 12Kh18Н10T – from -64 to -60 kV. The thermal emission model was used to calculate the trajectories. For this model, the temperature was set, calculated using the Richardson - Deshman equation at a beam current from the experiment of 30 mA (1476 K). To refine the results, the calculations of the accelerating gap were carried out with an additional element - a cathode holder. The cathode holder reduces the emitting surface of the cathode and, as a result, significantly affects the operating conditions of the gap. Also, when calculating, it is necessary to take into account that the potentials on the cathode holder and on the cathode itself are equal, the material of the holder is molybdenum. The calculation of the electrostatic field was carried out. Then the electron trajectories were calculated [8]. The current-voltage characteristics of the model are constructed.

2.2 Verification of the mathematical model of the ELA-15 gun by the beam profile

In this subsection, an experiment was carried out to obtain images of the beam profile by the method [9].

Photographing was carried out at stationary parameters of the electron beam. The main parameters of the experiment: beam current – 100 mA, focusing current – 748 mA, bombardment power – 16 kW.

A photograph of the profile of an electron beam in the focal region with a current of 100 mA was obtained. By mathematical processing of the profile image, it was found that the minimum beam diameter in the focal plane is 0.88 mm.

To determine the size of the beam crossover, it is necessary to determine the relative position of the crossover plane, focal plane and midplane of the magnetic lens. The distance between the focal plane and the middle plane of the magnetic lens is determined by the sum of the distance from the middle of the magnetic gap of the focusing magnetic lens to the gun cut and the distance from the gun cut to the position of the focal plane. For the ELA-15 gun, the first is 95 mm, the second is 153 mm. As a result, the distance from the mid-plane of the lens to the focal plane is 248 mm. Based on the fact that the region of the accelerating gap is an order of magnitude smaller than the distance from the assumed plane of the crossover to the plane of the focusing lens, it was assumed that the crossover of the beam is in the middle of the accelerating gap between the anode and the cathode. As a result, the distance between the crossover and the center plane of the focusing lens is 137 mm. Based on the obtained values, the crossover radius according to formula (1) is 0.243 mm.

\[ r_{cr} = \frac{r_f \cdot a}{b}, \]

where \( r_{cr} \) – beam radius in the crossover, mm; \( r_f \) – focused beam radius, mm; \( a \) – distance from crossover plane to lens plane, mm; \( b \) – distance from the plane of the lens to the plane of focusing of the electron beam, mm.

Next, the parameters for the mathematical model of the accelerating gap of the ELA-15 gun were determined. The required cathode temperature was calculated from the condition that when the gun was operating in the diode mode (bias voltage is 0 V), the beam current should be equal to 250 mA. This is necessary to provide conditions equivalent to a full-scale experiment on recording the beam profile. As a result, the required cathode temperature was 1626 °C. A beam current of 100 mA was also provided. The parameters were entered into the mathematical model and the trajectory calculation was performed.
To determine the crossover dimensions, the resulting profile was processed in Autodesk AutoCAD. The resulting profile image was scaled. Next, the envelope line of the beam profile was constructed and the cross section with the minimum size was determined.

2.3 Transition from the geometry of the original design of the ELA-15 gun to an improved shape based on the analysis of the electrostatic field

At the initial stage, a solid-state geometric model of the gun, potentials and materials from paragraph 2.1 were taken, the cathode temperature was set at 1748 K. The electrostatic field was calculated, the electric strength of the accelerating gap was exceeded [10]. With an increase in the accelerating voltage to 120 kV, areas with an overvoltage of the electrostatic field were more clearly observed. They are located on the surface of the anode and gate and are centered on the shortest distance between the gate and the anode. The field strength also accumulated on the angular parts of the surfaces in the areas or near them. There are two possible ways to solve the problem: moving the anode at a sufficient distance from the cathode and the control electrode, the disadvantage is a decrease in the rate of acceleration of electrons; rounding of angular areas and optimization of geometric parameters. The places where rounding is feasible, as well as the main geometric parameters, excluding the diameter of the hole in the anode, the diameter of the cathode, and the distance from the cathode to the control electrode, were identified. One parameter was selected and varied within the possible limits, with the other parameters unchanged. Next, the distance from the cathode to the anode was selected. 2 iterations were performed.

3 Results

3.1 Current-voltage characteristics obtained experimentally and by calculation method

Figure 2 shows the current-voltage characteristics without taking into account thermal expansion (a) and taking it into account (b). In Figure 2(a), the obtained characteristics are displaced relative to each other. This can be seen from the position of the gun blocking boundary: for the real characteristic, the blocking voltage is 3.2 kV, for the calculated one it is 2.8 kV. Also, the positions of the boundary for stopping the regulation of the beam current differ: for the real one, it is 1.6 - 1.8 kV, for the calculated one, it is 1.4-1.6 kV. After the performed thermal calculation, it was found that the difference in characteristics is associated with the thermal expansion of the elements of the cathode assembly during the heating of the cathode, in particular, the main thermal expansion occurs at the elements of the cathode: the cathode holder and the cathode holder glass. By modeling thermal processes, it was found that there is a significant lengthening of the cathode assembly by about 0.2 mm. As a result, the cathode holder and cathode were shifted by 0.2 mm towards the anode, and repeated trajectory calculations were performed. In Figure 2.b, the calculated and experimental I – V curves converge quite well, the discrepancy is no more than 5%. For both modes, the calculated and experimental I – V curves have the same blocking voltages equal to 3.2 kV. For the I – V curves with a bombardment current of 10 mA, the value at which the beam current regulation stops is consistent with the calculated value; regulation stops at a bias voltage of 1.8 kV. Taking the error between the experiment and the calculation in 5% permissible, it is concluded that the mathematical apparatus is reliable.

3.2 Beam profile of the mathematical model

Figure 3 shows the processed beam profile of the mathematical model. The minimum beam size is 0.47 mm. The crossover is located 1.9 mm from the cathode. As a result, the crossover radius is 0.235 mm. In the course of the experiment, a crossover radius of 0.243 mm was obtained. Thus, the difference between the experiment and the mathematical calculation is 8 μm, that is, the deviation of the calculated result from the real one is 3%.
Figure 2 – Calculated and experimental current-voltage characteristics for a bombing current of 10 mA without taking into account thermal expansion (a) and taking it into account (b).

Figure 3 – The trajectory of electrons at a current of 100 mA of the ELA-15 gun (a) and the Processed profile of the electron beam of the mathematical model of the ELA-15 gun (b).

3.3 Comparison of the patterns of electrostatic fields for the original model and for the modified
Figure 4 shows the distribution of the electrostatic field strength for the original design of ELA-15 at an accelerating voltage of 60 kV (a) and 120 kV (b) and modified (c). In the original model, a dark red color is observed on the anode surface on the line of the shortest distance from the anode to the control electrode. This suggests that in this area the permissible value of 15 kV / mm was exceeded, which does not correspond to the dielectric strength of the gun. With an increase in the accelerating voltage to 120 kV, the dark red area increased, that is, the dielectric strength of the gap decreased. In the modified model, the field strength does not reach critical values, which ensures a stable operation of the equipment. Based on this, conclusions are drawn about the achievement of a positive result in the optimization of the design and the need for further optimization to obtain better results. Without optimization, the anode would have to be removed from the cathode at a distance 2 times greater than that of the resulting modified design. Thus, the minimum and permissible field strength is demonstrated with a sphere-in-sphere geometry.

3.4 Comparison of I - V characteristics for the original and modified shape of the anode-cathode gap
Figure 5 shows the I – V curves of the original model and the modified one. They have two sections: with an unregulated beam current and an adjustable one. The transition from one section to another for
two guns occurs close to each other in the region of the bias voltage value of 2 kV. However, they have different locking voltages: the original model has 3400 V; in the modified model - 3860 V. This means that the current values will be regulated more smoothly, since the rate of their increase or decrease has decreased, which indicates an improvement in the operating conditions of the equipment.

![Distribution of the electrostatic field strength for the original structure at an accelerating voltage of 60 kV (a) and 120 kV (b) and modified structures (c).](image)

**Figure 4** – Distribution of the electrostatic field strength for the original structure at an accelerating voltage of 60 kV (a) and 120 kV (b) and modified structures (c).

![Current-voltage characteristics for the original and modified designs](image)

**Figure 5** – Current-voltage characteristics for the original and modified designs/4.

### 4. Conclusions

On the basis of experimental data, a mathematical model of the ELA-15 gun was developed and confirmed with a difference in results not exceeding 5%. The possible discrepancy between the results of modeling and experiment in connection with the thermal expansion of equipment components has been substantiated. On the basis of electrostatic calculation and comparison of current-voltage characteristics, the necessity of optimizing modern electron-beam equipment in favor of the “sphere in sphere” geometric scheme is substantiated.
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