Доклади на Българската академия на науките
Comptes rendus de l'Académie bulgare des Sciences

Tome 73, No 9, 2020

PHYSICS

Applied physics

STUDY OF THE PROCESSES IN THE ELECTROSTATIC PART OF THE ELECTRON-BEAM GENERATOR

Peter Petrov, Manahil Tongov*, Maria Ormanova, Stefan Valkov

(*Submitted by Corresponding Member Ch. Stoyanov on June 19, 2020*)

Abstract

In this work, the electrostatic field results are presented in dependence on the voltage of the control electrode, construction, shape and size of the anode and the control electrode by numerical calculations via finite elements method (FEM).
Key words: electron-beam generator, electron-beam system

1. Introduction. In the electron beam welding (EBW), the energy of a flux of accelerated electrons is transformed into heat when they interact with the metal target. The main advantage of the EBW in comparison with the arc welding is the introduction of a high-intensity thermal source, leading to a formation of the gas canal „keyhole" when the energy introduced exceeds a certain critical value for the power density. This leads to low linear energies, small longitudinal and angular deformations, small sizes of the thermal influence zone, and short time of metal staying over-determined critical temperatures [1–5]. For the formation of a heat source with such a high concentration of the thermal flux, of major importance are the processes that occur in the electrostatic part and focusing system of the electron gun [3]. For a given voltage between the cathode and anode, the magnitude of the beam current is controlled by the temperature of the cathode (the current of warming up at direct heating), and the voltage between the cathode and control electrode. On the other hand, the geometry change of

This work was supported by the Bulgarian National Science Fund under Grant DN 07/26.
DOI:10.7546/CRABS.2020.09.05

the control electrode (Wehnelt) affects the structure of the electrostatic field in the space between the electrodes (anode, cathode, control electrode) [10].

The aim of this study is an investigation of the processes in the electrostatic part of the electron-beam generator (EBG) on equipment for electron-beam welding by the methods of mathematical modelling.

2. Geometry of electron-beam generator (EBG). A scheme of the electrostatic part of the electron-beam generator (EBG) on equipment for electron-beam welding, which is accepted in our investigations, is shown in Fig. 1 [3,7]. The sizes of the cathode centre, control electrode and anode are identical with those, described in [8,9]. The cathode is broad-strip with a thickness of 0.1 mm and a size of the active surface 2×2 mm [7–9] and it is with a direct heating (by passing current I_{beam}).

During this investigation, the curve of the control electrode surface (Wehnelt), pointed with the radius R is varied. The curvature is changed in dependence on the value of the parameter $p \in [-1; 1]$. When $p < 0$, the surface is concave, and if $p > 0$ – protuberant (Fig. 1).

3. Numerical model. The intensity of the electric field in front of the cathode surface depends on the geometry of the electrostatic area, anode potential, and the potential of the control electrode. The current density of emission from the active surface of the cathode is defined as follows [3,9,10]:

$$(1) \qquad j_{R-S} = \begin{cases} \beta A T^2 \exp\left(-\dfrac{\varphi - \Delta\varphi}{kT}\right) & E_n \geq 0 \\ 0 & E_n < 0 \end{cases},$$

where β is a coefficient, depending on the material (for tungsten according to it is $0.38 \div 0.40$); is the absolute temperature [°K]; $k = 1.380649 * 10^{-23}$ [J/K] is the Boltzmann constant; φ is the operation for emitting (for tungsten $\varphi = 4.3$ [eV]); $\Delta\varphi$ is a correction of Schottky, depending on normal component of the electric field intensity E_n [V/m] and is the quantum coefficient, determined as $A = \left(4\pi m_e k^2 e\right)/h^3$. Here $m_e = 9.10938356 \times 10^{-31}$ kilograms and $e = -1.602176634 \times 10^{-19}$C are the mass and charge of the electron, respectively; $h = 6.62607004 \times 10^{-34}$ [J*s] is the Planck constant.

The intensity of the electrostatic field in the EBG (cathode, the control electrode and the anode) are determined after transforming the Poisson equation into a Laplace equation by neglecting the volume charge. The equation used is:

$$(2) \qquad \nabla^2 V = 0, \quad E = -\nabla V$$

with the following boundary conditions: all surfaces that are electrically connected with the cathode have a zero potential; the outer anode surface and the control electrode have potentials U_a and $U_{wehnelt}$ ($U_{wehnelt} < 0$), respectively, and V and E are the potential and the intensity of the electrostatic field.

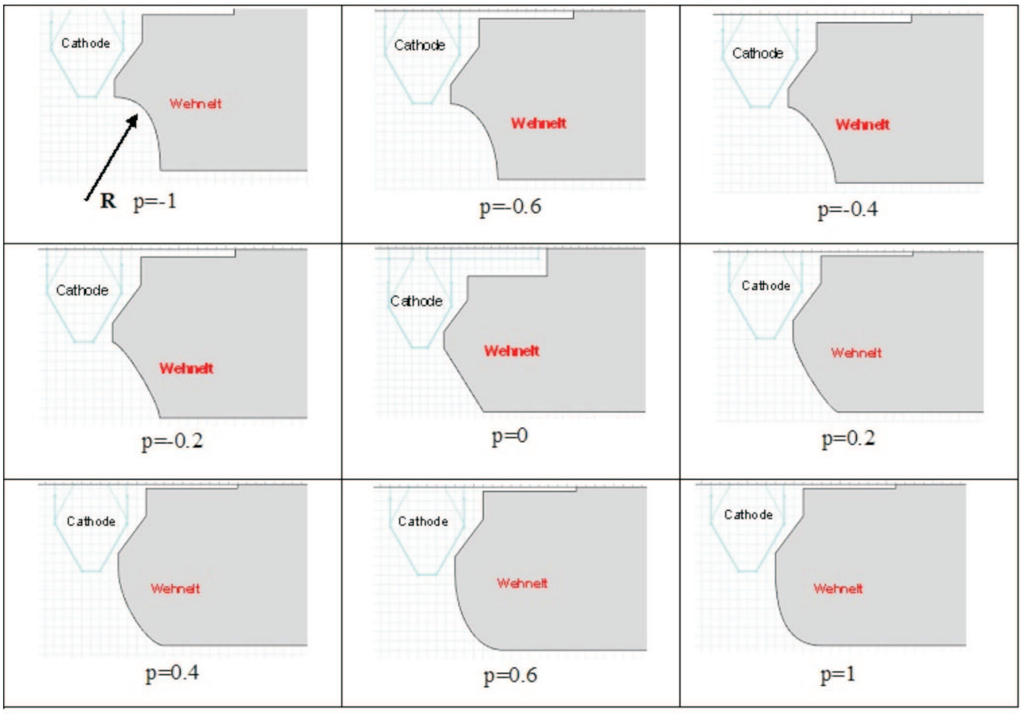

Fig. 1. Schemes of the geometry of a control electrode (Wehnelt) in dependence on the curvature radius

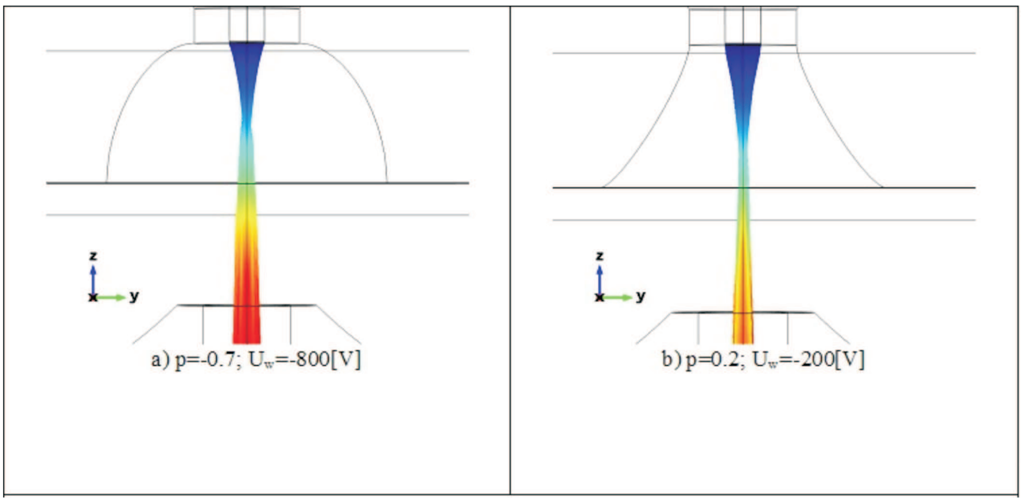

Fig. 2. Electron beam geometry in the electrostatic at control electrode curvature at $p = -0.7$ a) and $p = 0.2$ b)

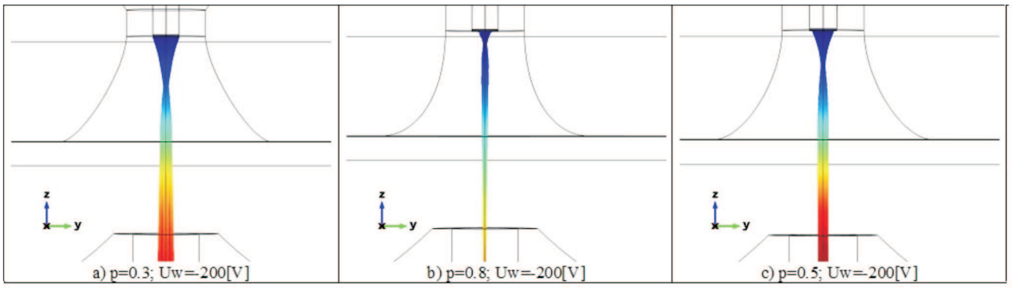

Fig. 3. Electron beam geometry in the electrostatic at control electrode curvature at $p = 0.3$ a), $p = 0.8$ b) and $p = 0.5$ c)

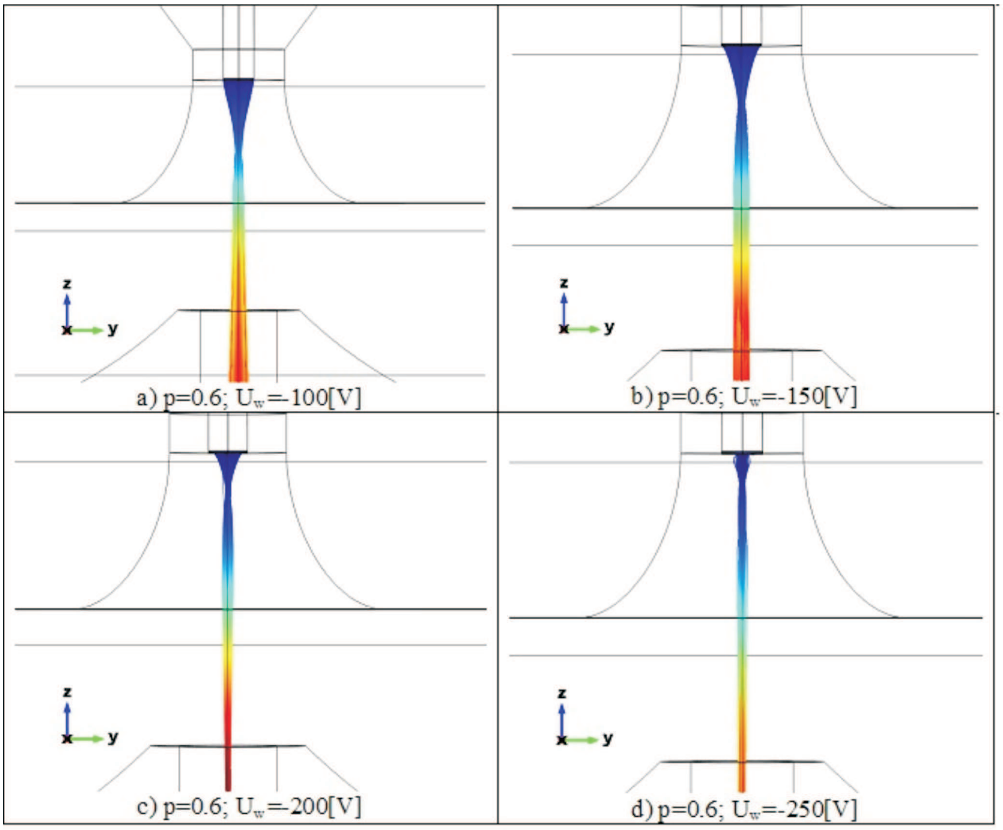

Fig. 4. Electron beam geometry in the electrostatic at control electrode curvature at control voltage $U_w = -100$ V a); $U_w = -150$ V b); $U_w = -200$ V c); $U_w = -250$ V d)

Solution of Eq. (1)—(2) is described in details in works [8–10]. The calculations were performed using a Comsol Multiphysics package [11], which is suitable for solving such type of equations.

The factors governing the electron emission and the beam quality in terms of physical processes are as follows: temperature distribution on the active cathode surface; shape and size of the spot through which the electrons are emitted; structure of the electrostatic field in front of the cathode. Information about the control characteristics of the EBG is also important, namely the dependence of the beam current on the control electrode voltage for different values of the heating current and the anode voltage [10].

4. Result and discussion. Figure 2 presents results from numerical calculation of the electron beam geometry in the electrostatic part of the electron-beam generator (EBG) at the electron beam current $I_{beam} = 28.9$ [mA]:

(i) control electrode curvature $p = -0.7$ and control electrode potential $U_w = 800$ V, Fig. 4a and;

(ii) control electrode curvature $p = 0.2$, and control electrode potential $U_w = 200$ V Fig. 4b.

Figure 4 clearly shows the essential influence of the shape of the control electrode on the electrostatic focus of the electron beam. It demonstrates that the shape of the electron beam in both cases is almost the same.

Figure 3 presents results of calculations at a different shape of the electron beam, in case of the protuberant surface of the control electrode ($p = 0.3$; $p = 0.5$; $p = 0.8$) at a control electrode potential $U_w = -200$ V. It is evident that at $p > 0.5$ the electron beam diameter d_b tends to decrease.

The change of the electron beam geometry in dependence on the control voltage is shown in Fig. 4. The numerical experiments were carried out at p=0.6 and a control voltage $U_w = -100$ V to $U_w = -300$ V: when $U_w = -100$ V, the shape of the electron beam after electrostatic focus is conic, at $U_w = -150$ V – cylindrical, and at $U_w > -800$ V, the beam is shrunk after passing an area with enlarged radial size.

5. Conclusion. In this study, we presented a numerical model which is based on the finite element method of the processes in the electrostatic part of the electron-beam generator.

The numerical calculations indicated that with a change of the control electrode potential the shape of the electron beam after electrostatic focus is changed from conic to cylindrical, leading to diminishing in the diameter of the electron beam after passing an area with an enlarged radial size.

The protuberant shape of the control electrode surface ($p = 0.3$, $p = 0.5$, $p = 0.8$) allows the use of lower values of the control electrode potential, leading to formation of conditions for a decrease of electron beam radial sizes after electrostatic part of the electron beam generator.

REFERENCES

[1] Rikalin N., A. Uglov, A. Zuev (1978) Basics of electron beam material processing, Moscow, Mashinostroene (in Russian).

[2] Arata Y. (1986) Plasma, Electron and Laser Beam Technology: Development and use in materials processing, American Society for Metals.

[3] Schiller S., U. Heisig, S. Panzer (1972) Elektronenstrahltechnologie, Forschungsinstitut Manfred von Ardene, Dresden, VEB Verlag Technik, 528 pp.

[4] Sabchevski S., G. Mladenov, S. Wojcickiz, J. Dabek (1996) An analysis of electron guns for welding, J. Phys. D: Appl. Phys., **29**, 1446–1453.

[5] Sabchevski S., G. Mladenov, A. Titov, I. Barbarich (1996) Modelling and simulation of beam formation in electron guns, Nucl. Instruments Methods Phys. Res., Sect. A Accel. Spectrom., Detect. Assoc. Equip., **381**, 185–193.

[6] Petrov P., S. Sabchevski (2010) Parameters used for electron beam welding – A comparative study, Proc. 8th Int. Conf. Beam Technology, Halle, 92–94.

[7] Jánský P., J. Zlámal, B. Lencová, M. Zobač, I. Vlček, T. Radlička (2009) Numerical simulations of the thermionic electron gun for electron-beam welding and micromachining, Vacuum, **84**, 357–362.

[8] Wei Y. X., M. G. Huang, S. Q. Liu, B. L. Hao, P. K. Liu (2013) Numerical simulation of TWT electron gun, Vacuum, **92**, 90–94.

[9] Fan J., Y. Peng, J. Xu, H. Xu, D. Yang et al. (2019) Numerical simulation of beam current control mechanism in the thermionic electron gun, Vacuum, **164**, 278–285.

[10] Petrov P., M. Tongov (2020) Study of the Cathode Emissivity in Generators for Electron Beam Systems, Optik, **209**, 164358.

[11] COMSOL Multiphysics® v. 5.4. `www.comsol.com`. COMSOL AB, Stockholm, Sweden.

Institute of Electronics
Bulgarian Academy of Sciences
72, Tsarigradsko Shosse Blvd
1784 Sofia, Bulgaria
e-mail: `peterpitiv@gmail.com`
`maria_mecheva@abv.bg`
`stsvalkov@gmail.com`

* *Technical University of Sofia*
8, St. Kliment Ohridski Blvd
1756 Sofia, Bulgaria
e-mail: `tongov@tu-sofia.bg`