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Determination of Optimal Modes of Electron-Beam Micro-Treatment of Surfaces in Optic Elements

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As practice has shown, the most erratic, environmentally friendly, and easily controllable way of optical element treatment is the electron-beam method. However, the widespread use of electron beam technology in optoelectronic instrumentation is hampered by the lack of methods for determining optimal modes of electron beam microprocessing of optical elements, representing a set of controlled parameters of the electron beam (current of the beam $I_b = 50…300$ mA, accelerating voltage $V_y = 4…8$ kV, distances to the treated surface $l = 6·10^{-2}… 8·10^{-2}$ m, beam movement speed $V = 5·10^{-2}…5·10^{-3}$ m/s, heat exposure time $t = 0.3…1.0$ s), excess of which leads to a number of undesirable phenomena, that harm the quality of the surfaces to be treated.There have been developed the mathematical models of the process of heating elements from optical glass and ceramics of various geometric shapes and sizes (thin film elements, thin plates of high size) by a moving belt electron beam, which allow to calculate the influence of its parameters on temperature fields in treated elements. It was established that the increase in the I_b and V_y parameters in the specified ranges leads to an increase in the maximum surface temperature of optical elements by more than 2 times, and the decrease in the parameters l and V by less than 1.5 times. Optimal values of the parameters of the electron beam are determined, the excess of which leads to the appearance of cracks and splits in the surface layers of elements, violation of their geometric shape and deterioration of the metrological characteristics of the devices up to their failure.

Keywords: Belt-type electronic beam, Elements from optical glass and optical ceramics, Temperature fields in optical elements, Optoelectronic instrumentation.

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1. INTRODUCTION

The modern level of development of optoelectronic instrumentation puts forward increased requirements for the operational characteristics of their optical elements: microhardness of the surface, spectral transmittance, resistance to external thermal and mechanical shocks, etc., which affect the technical-operational characteristics of devices (impulse laser rangefinders of sighting complexes, laser medical devices, IR devices, etc.) [1-5].

As practice has shown [3, 6, 7], the most erratic, environmentally friendly, and easily controllable way of optical element treatment is the electron-beam method. The possibilities of using the moving elementary beam of the tape form were displayed for polishing elements from optical glass and obtaining high purity surfaces with minimal roughness, as well as to strengthen elements from optical ceramics and obtain surfaces with increased microhardness and thickness of reinforced layers by tens of microns.

However, the widespread use of electron beam technology in optoelectronic instrumentation is hampered by the lack of methods for determining critical modes of electron beam microprocessing of optical elements, representing a set of controlled parameters of the electronic beam (current of the electric flow I_b (mA), accelerating voltage V_y (kV), distance to the processed surface l (m), the movement rate of the beam V (m/s), etc.), excess of which leads to a number of undesirable phenomena, that harm the quality of the surfaces to be treated.

Thus, for optical glass, the surface temperature begins to exceed the temperature of the liquid state T^* when its flow increases sharply (for example, for glass K8, K08, BK10 – $T^* = 1300... 1500$ K [8, 13]), which leads to intensive surface evaporation, significant deformation of the melt on the surface and, ultimately, to significant violations of the flatness and geometric shape. For optical ceramics, the surface temperature begins to exceed the temperature of intensive structural changes start in the surface layers of ceramics T^{**} (for example, for ceramics KO1, KO2, KO5 – $T^{**} = 1100... 1200$ K [2, 3, 8]), which cause a sharp increase in the absorption of radiation in the IR-area of the spectrum, that is, the reduction of their IR-transmission coefficient and deterioration of the technical and operational characteristics of devices.

Therefore, when using electron beam technology for micro-treatment of surfaces from optical elements, it is necessary to have methods for determining the influence of controlled parameters of the electron beam on the maximum processing temperature T_m in order to detect and control the critical change ranges in ray parameters that lead to exceeding the above-mentioned temperatures T^* and T^{**}. Today, the research in this direction is very limited: mathematical models have been developed and optimal change ranges in the parameters of the electron beam are determined only for the simplest elements in the form of flat layers and rectangular elements [10-14]. At the same time, these studies are absent for a wide class of other optical elements (for example, thin film elements, thin plates of large sizes, etc.), which are widely used in microoptics, integral and fiber optics, nanoelectronics (planar wave, substrates of optical integral circuits, window visibility of IR guidance and surveillance devices, etc.) [3, 10].

The purpose of this work is to develop mathematical models of thermal influence of a moving electron beam on thin-film elements, as well as large-size plates made of optical glass and ceramics to calculate the dependences of the maximum temperatures on their surfaces on the controlled parameters of the electron beam and determine the optimal ranges of their change.

2. RESULTS OF THE RESEARCH AND THEIR ANALYSIS

As practice shows [3, 10], when processing optical materials with a moving electron beam, mainly its single loop motion is used.

As a result of the conducted research on the probing of the electron beam [9-13], it was found out that the beam has a normal (Gaussian) division of energy flow density (or heat flow density) q within the thickness of the electron beam (Fig. 1):

$$q_v(x) = \frac{P_0(I_b, V_y)}{B \cdot H} \cdot \sqrt{\frac{k_0(I_b, l)}{\pi}} \cdot \frac{e^{-k_0(I_b,l)\cdot x^2}}{erf\left[b(I_b,l)\cdot\sqrt{k_0(I_b,l)}\right]}, \quad (1)$$

$|x| < b, \quad 0, \quad |x| > b$

where $P_0(I_b, V_y) = I_b, V_y$ – beam power in the center of impact, W; (2)

$k_0(I_b, l) = 9.367\cdot 10^7 - 7.8598\cdot 10^5 \cdot l - (5.10^4 - 1.3\cdot 10^2 \cdot l)\cdot I_b$ – beam concentration coefficient, m²; (3)

$$b(I_b, l) = \frac{3.46}{\sqrt{k_0(I_b, l)}} \cdot m . \quad (4)$$

In addition, when constructing mathematical models of thermal influence of the electron beam on optical elements, temperature dependences of thermal properties of optical materials (volumetric heat capacity $C_V(T)$ and thermal conductivity coefficient $\lambda(T)$) were taken into account [3, 11-14]:

$$C_V(T) = C_{V0} \cdot T^{\nu}, \quad \lambda(T) = \lambda_0 \cdot T^{\nu}, \quad (5)$$

where C_{V0}, λ_0, ν are empirical constants, which depend on the nature of optical material.

In this case, the geometric appearance of the model according to coordinates (one-dimensional, two-dimensional and three-dimensional) is determined by the ratio between the depth of the heat diffusion (depth of heat wave penetration $\delta = 2\cdot\sqrt{a_0^2 \cdot \tau}$ ($a_0^2 = \dfrac{\lambda_0}{C_{V0}}$ coefficient of temperature transmission, m²/s; τ is the average influence time of the beam on the optical element, s)) [8-11, 14], with the thickness of electron beam $2b$, thickness H and width B of the treated optical element. Thus, if $\delta < 2b$ and $\delta > H$, B, it comes that the temperature field in the element is one-dimensional (along the x coordinate); if $\delta < 2b$, H and $\delta > B$ – the temperature field is two-dimensional (along the x and z coordinates); and, at last, if $\delta < 2b$, H, B, then the temperature field is three dimensional (along the x, y, z coordinates). Further, if, for example, $\delta < H$, the heat exchange on the underside of the element does not affect the temperature field in the element, that is, the element along the Oz axis can be considered as a semiendless medium, and if $\delta \sim H$, then the indicated heat exchange already affects the temperature field and must be taken into account.

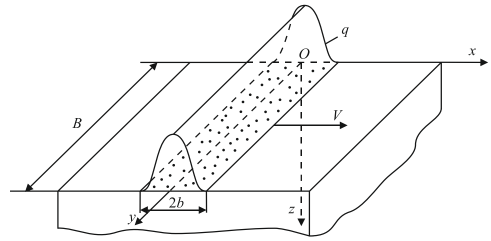

Fig. 1 – Scheme of thermal influence of moving belt electron beam on the optical element: q is the thermal flow normally distributed along the x and evenly along y axes, W/m²; $2b$, B are the thickness and width of the electron beam, m; V is the beam movement speed, m/s

The following is based on the well-known methods of thermal conductivity theory, taking into account small speeds of motion of the electron beam ($V << 10^3$ m/s, which allows to use a simpler equation of thermal conductivity of parabolic type to calculate temperature fields, instead of a much more complex equation of thermal conductivity of hyperbolic type) nonlinear mathematical models of the process of heating flat optical elements of small thickness by moving electron beam of tape form, temperature dependences of thermal properties (thermal conductivity coefficient, volumetric heat capacity) of the processed materials and allows to calculate the effect of these beam parameters on temperature fields in optical elements, in particular, on the above-mentioned temperatures T^* and T^{**}.

Mathematical model of heating process of a thin film element. While considering a thin-film element, the following conditions are fulfilled: $\delta > B$, H and $\delta < 2b$, that is $\dfrac{\partial T}{\partial y} = \dfrac{\partial T}{\partial z} = 0$ (one-dimensional temperature field $T(x, t)$). In this case, the density of energy flow q becomes a dimensional heat source $q_v(x)$ (W/m³), that moves in the direction of the Ox axis at speed V (Fig. 2):

$$q_v(x) = \frac{P_0(I_b, V_y)}{B \cdot H} \cdot \sqrt{\frac{k_0(I_b, l)}{\pi}} \cdot \frac{e^{-k_0(I_b,l)\cdot x^2}}{erf\left[b(I_b,l)\cdot\sqrt{k_0(I_b,l)}\right]}, \quad (6)$$

$|x| < b, \quad 0, \quad |x| > b$

The equations of the mathematical model of the process of heating and rolling the considered element (in a moving coordinate system associated with the heat source) have the same representation [6, 14]:

$$C_V(T)\cdot\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left[\lambda(T)\cdot\frac{\partial T}{\partial x}\right] + C_V(T)\cdot V\cdot\frac{\partial T}{\partial x} + q_v(x) t > 0, \quad (7)$$

$$-\infty < x < +\infty , \quad (8)$$

$$T \to T_0, \frac{\partial T}{\partial x} \to 0, q_v(x) \to 0 \text{ at } x \to \pm\infty . \quad (9)$$

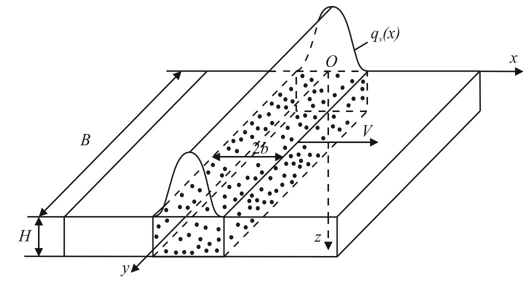

Fig. 2 – Scheme of the heating process of a thin film element by moving electron beam: $2b$ is the beam thickness, m; B, H are the width and thickness of the element, m; V is the beam movement speed, m/s; $q_v(x)$ is the dimensional function of thermal radiation, W/m³

Considering dependences $C_V(T)$ and $\lambda(T)$ and introducing new variables

$$\theta(x,t) = T^{\nu+1} - T_0^{\nu+1}, \quad \Phi_\nu(x) = \frac{\nu+1}{C_{V0}} \cdot q_\nu(x), \tag{10}$$

we get a system of equations:

$$\frac{\partial\theta}{\partial T} = a_0^2 \cdot \frac{\partial^2\theta}{\partial x^2} + V \cdot \frac{\partial\theta}{\partial x} + \Phi_\nu(x), \tag{11}$$

$$\theta\big|_{t=0} = 0, \tag{12}$$

$$\theta \to 0, \quad \frac{\partial\theta}{\partial x} \to 0, \quad \Phi_\nu(x) \to 0 \text{ at } x \to \pm\infty \tag{13}$$

Next, let us bring the system of equations (11)-(13) to the fundamental form (Fourier form) by substitution [13, 14]

$$\theta(x,t) = \bar{\theta}(x,t) \cdot e^{\mu \cdot x + \beta \cdot t}, \tag{14}$$

where $\mu = -\dfrac{V}{2a_0^2}, \beta = -\dfrac{V^2}{4a_0^2}$.

By substituting (14) into (11)-(13), we get a fundamental equation of thermal transmittance with initial and limit conditions:

$$\frac{\partial\bar{\theta}}{\partial T} = a_0^2 \cdot \frac{\partial^2\bar{\theta}}{\partial x^2} + \Phi_\nu(x,t), \tag{15}$$

$$\bar{\theta}\big|_{t=0} = 0, \tag{16}$$

$$\bar{\theta} \to 0, \quad \frac{\partial\bar{\theta}}{\partial x} \to 0, \quad \bar{\Phi}_\nu(x,t) \to 0 \text{ at } x \to \pm\infty, \tag{17}$$

where $\bar{\Phi}_\nu(x,t) = \Phi_\nu(x) \cdot e^{\frac{V \cdot x}{2a_0^2} + \frac{V^2 \cdot t}{4a_0^2}}$. (18)

To solve the system of equations (15)-(17), the method of integral Fourier integral transformation is used for unlimited environments [11-14].

Using (10) and (18) and taking into account (6), finally, to solve the original problem, we obtain an expression for $T(x,t)$, that allows to calculate the effect of the electron beam parameters on the temperature field in a thin-film optical element:

$$T(x,t) = \Bigg\{ T_0^{\nu+1} + \frac{(\nu+1) \cdot P_0(I_b,V_y) \cdot \sqrt{k_0(I_b,l)} \cdot e^{-\frac{V \cdot x}{2a_0^2} - \frac{V^2 \cdot t}{4a_0^2}}}{2\sqrt{\pi} \cdot C_{V0} \cdot H \cdot B \cdot erf\left(b(I_b,l) \cdot \sqrt{k_0(I_b,l)}\right)} \cdot \int_0^t \frac{e^{\frac{V^2 \cdot \tau}{4a_0^2} - \frac{4a_0^2 \cdot k_0(I_b,l) \cdot x^2 - V \cdot [2x + V(t-\tau)]}{4a_0^2 \cdot [1 + 4a_0^2 \cdot k_0(I_b,l) \cdot (t-\tau)]}}}{\sqrt{1 + 4a_0^2 \cdot k_0(I_b,l) \cdot (t-\tau)}} \times$$

$$\times \left[erf\left(\frac{1}{2a_0 \cdot \sqrt{t-\tau}} \cdot b(I_b,l) \cdot \sqrt{1 + 4a_0^2 \cdot k_0(I_b,l) \cdot (t-\tau)} + \frac{x + V \cdot (t-\tau)}{\sqrt{1 + 4a_0^2 \cdot k_0(I_b,l) \cdot (t-\tau)}} \right) + \right. \tag{19}$$

$$\left. + erf\left(\frac{1}{2a_0 \cdot \sqrt{t-\tau}} \cdot \left(b(I_b,l) \cdot \sqrt{1 + 4a_0^2 \cdot k_0(I_b,l) \cdot (t-\tau)} - \frac{x + V \cdot (t-\tau)}{\sqrt{1 + 4a_0^2 \cdot k_0(I_b,l) \cdot (t-\tau)}} \right) \right) \right] dt \Bigg\}^{\frac{1}{\nu+1}}$$

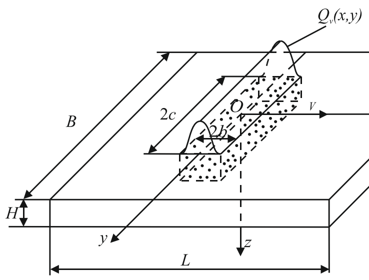

Fig. 3– Scheme of the heating process in a thin plate of large sizes with a moving electronic beam: B, H, L – width, thickness and length of the plate, m; V – beam movement speed, m/s; $Q_v(x,y)$ – dimensional function of heat emission, W/m³; $2b$, $2c$ – thickness and width of the beam, m

Mathematical model of the process of heating a thin large-size plate. For the considered thin large-size plate, the following conditions are met (Fig. 3): $\delta < 2b$, $2c$ and $\delta > H$, that is $\dfrac{\partial T}{\partial z} = 0$ (two-dimensional field $T(x,y,t)$). In this case, the energy density q becomes a three-dimensional heat source:

$$Q_\nu(x,y) = \frac{P_0(I_b,V_y)}{2 \cdot C \cdot H} \cdot \sqrt{\frac{k_0(I_b,l)}{\pi}} \cdot \frac{e^{-k_0(I_b,l) \cdot x^2}}{erf\left[b(I_b,l) \cdot \sqrt{k_0(I_b,l)}\right]}, \tag{20}$$

$|x| < b, \quad |y| < c, 0, \quad |x| > b, \quad |y| > c$

where parameters $P_0(I_b,V_y), k_0(I_b,l), b(I_b,l)$ are determined by formulas (2)-(4).

In this case, the heat source moves along the Ox axis at a speed V. The equations of the mathematical model of the heating process in the plate (in the moving coordinate system associated with the heat source) have a representation [2, 14]:

$$C_V(T)\cdot\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left[\lambda(T)\cdot\frac{\partial T}{\partial x}\right]+\frac{\partial}{\partial y}\left[\lambda(T)\cdot\frac{\partial T}{\partial y}\right]+$$

$$+C_V(T)\cdot V\cdot\frac{\partial T}{\partial x}+Q_\nu(x,y), \qquad (21)$$

$$t>0, \quad -\infty<x, \quad y<+\infty$$

$$T\big|_{t=0}=T_0, \qquad (22)$$

$$T\to T_0, \frac{\partial T}{\partial x}, \frac{\partial T}{\partial y}\to 0, Q_\nu(x,y)\to 0 \text{ at } x,y\to\pm\infty. \qquad (23)$$

Considering dependences $C_V(T)$ and $\lambda(T)$ and using the famous method of Fourier integral transformations (first along the x coordinate, and then along the y coordinate) [2, 14] and taking into account (22), we get the final expression for $T(x,y,t)$, that allows to calculate the impact of electron beam parameters in the thin large-soze plate:

$$T(x,y,t)=\left\{T_0^{\nu+1}+\frac{(\nu+1)\cdot P_0(I_b,V_y)\cdot\sqrt{k_0(I_b,l)}\cdot a_0^2}{8\sqrt{\pi}\cdot c\cdot H\cdot\lambda_0\cdot erf\left[b(I_л,l)\cdot\sqrt{k_0(I_л,l)}\right]}\cdot e^{\frac{V\cdot x}{2a_0^2}\frac{V^2\cdot t}{4a_0^2}}\cdot\int_0^t\frac{e^{\frac{V^2\cdot\tau}{4a_0^2}\frac{4a_0^2\cdot k_0(I_b,l)\cdot x^2-V\cdot[2x+V\cdot(t-\tau)]}{4a_0^2\cdot[1+4a_0^2\cdot k_0(I_b,l)\cdot(t-\tau)]}}}{\sqrt{1+4a_0^2\cdot k_0(I_b,l)\cdot(t-\tau)}}\times\right.$$

$$\times\left[erf\left(\frac{c+y}{2a_0\cdot\sqrt{t-\tau}}\right)+erf\left(\frac{c-y}{2a_0\cdot\sqrt{t-\tau}}\right)\right]\cdot\left[erf\left(\sqrt{\frac{1+4a_0^2\cdot k_0(I_b,l)\cdot(t-\tau)}{4a_0^2\cdot(t-\tau)}}\cdot\left(b(I_b,l)+\frac{x+V\cdot(t-\tau)}{1+4a_0^2\cdot k_0(I_b,l)\cdot(t-\tau)}\right)\right)+\right. \qquad (24)$$

$$\left.\left.+erf\left(\sqrt{\frac{1+4a_0^2\cdot k_0(I_b,l)\cdot(t-\tau)}{4a_0^2\cdot(t-\tau)}}\cdot\left(b(I_b,l)-\frac{x+V\cdot(t-\tau)}{1+4a_0^2\cdot k_0(I_b,l)\cdot(t-\tau)}\right)\right)\right]dt\right\}^{\frac{1}{\nu+1}}.$$

Determination of the influence of electron beam parameters on temperature fields in elements made of optical glass and ceramics, selection of critical heating modes and correlation with experimental data. When choosing the critical modes of processing optical glass and ceramics by a moving electron beam, it is necessary to be able to predict the effect of controlled beam parameters on the maximum processing temperature T_m in order to determine and control the ranges of critical changes in these parameters, the excess of which leads to the excess of the specified temperatures above T^* (for optical glass) and T^{**} (for optical ceramics), that is, the fulfillment of the following conditions:

1) For optical glass: $T_m\le T^*$ at $I_{b1}^*\le I_b\le I_{b2}^*$, $V_{y1}^*\le V_y\le V_{y2}^*$, $l_1^*\le l\le l_2^*$, $V_1^*\le V\le V_2^*$, $t_1^*\le t\le t_2^*$, (25)

2) For optical ceramics: $T_m\le T^{**}$ at $I_{b1}^{**}\le I_b\le I_{b2}^{**}$, $V_{y1}^{**}\le V_y\le V_{y2}^{**}$, $l_1^{**}\le l\le l_2^{**}$, $V_1^{**}\le V\le V_2^{**}$, $t_1^{**}\le t\le t_2^{**}$. (26)

Using the well-known physical and mechanical properties of widely used elements of optical glass K8 and optical ceramics KO1 [3, 10-13], as well as with the use of special application programs [2, 3, 14] in dialogue and real time modes on the up-to-date computers, calculations were performed for the maximum processing temperature T_m (temperature in the zone of influence of the moving electron beam) from the beam parameters under consideration. For a clearer idea of the existence of optimal ranges of changes in electron beam parameters for optical elements of geometric shapes under consideration (thin-film element, thin large-size plate), the results of calculations are shown in a three-dimensional form in Fig. 4 and Fig. 5.

The calculation results presented in Fig. 4 and Fig. 5 show that for treatment times $t\ge t^*$ ($t^*=0.3...0.4$ s for glass K8; $t^*=0.5...0.6$ s for ceramics KO1) the heating process for optical glass as well for optical ceramics enters the quasi-state regime, meaning that T_m does not change with time; thus t^* value practically does not depend on beam parameters. By the level of influence of T_m value, beam parameters are arranged as such a series: I_b, V, V_y and l. Quantitatively, the degree of their impact on T_m is assessed in such a way: at increasing I_b from 50 to 300 mA, the value of T_m increases (for glass K8 by 2.5...2.7 times; for ceramics KO1 by 1.5...1.9 times); an increase in V from $5\cdot10^{-3}$ to $5\cdot10^{-2}$ m/s leads to the decrease in T_m (for glass K8 by 1.4...1.6 times; for ceramics KO1 by 1.3...1.4 times); an increase in V_y from 4 to 8 kV responds to the increase in T_m (for glass K8 by 1.3...1.5 times; for cersmics KO1 by 1.2...1.4 times); an increase in l within the limits of $6\cdot10^{-2}...8\cdot10^{-2}$ m leads to the decrease in T_m by less than 1.2 times.

Analysis of the calculation results from the point of view of the above-mentioned optimal change ranges in the electron beam parameters shows that such ranges exist in the process of electron beam processing of elements from both optical glass and optical ceramics:

glass K8: for $t=0.7$ s, $V_y=8$ kV, $l=6\cdot10^{-2}$ m and $V=3\cdot10^{-2}$ m/s we have $I_{b1}^*=53$ mA $\le I_b\le I_{b2}^*=167$ мA; for $t=0,7$ s, $V_y=5$ kV, $l=6\cdot10^{-2}$ m and $V=3\cdot10^{-2}$ m/s we have $I_{b1}^*=55$ mA $\le I_b\le I_{b2}^*=290$ mA; for $t=0,7$ s, $I_b=300$ mA, $V_y=5$ kV and $l=6\cdot10^{-2}$ m we have $V_1^*=6\cdot10^{-3}$ m/s $\le V\le V_2^*=1,8\cdot10^{-2}$ m/s; for $t=0,7$ s, $I_b=100$ mA, $V=7\cdot10^{-2}$ m/s and $l=6\cdot10^{-3}$ m we get $V_{y1}^*=5.2$ kV $\le V_y\le V_{y2}^*=7.4$ kV;

ceramics KO1: for $t=0.8$ c, $V_y=8$ kV, $l=6\cdot10^{-2}$ m and $V=3\cdot10^{-2}$ m/s we get $I_{b1}^{**}=65$ mA $\le I_b\le I_{b2}^{**}=185$ mA; for $t=0.8$ s, $I_b=300$ mA, $V_y=5$ kV and $l=6\cdot10^{-2}$ m we get $V_1^{**}=5\cdot10^{-3}$ m/s $\le V\le V_2^{**}=3\cdot10^{-2}$ m/s.

Thus, the developed complex of nonlinear mathematical models of the heating process of the considered optical elements allows at the stage of working out the technological modes of their electronic processing with an accuracy of 8...12 % to determine the optimal

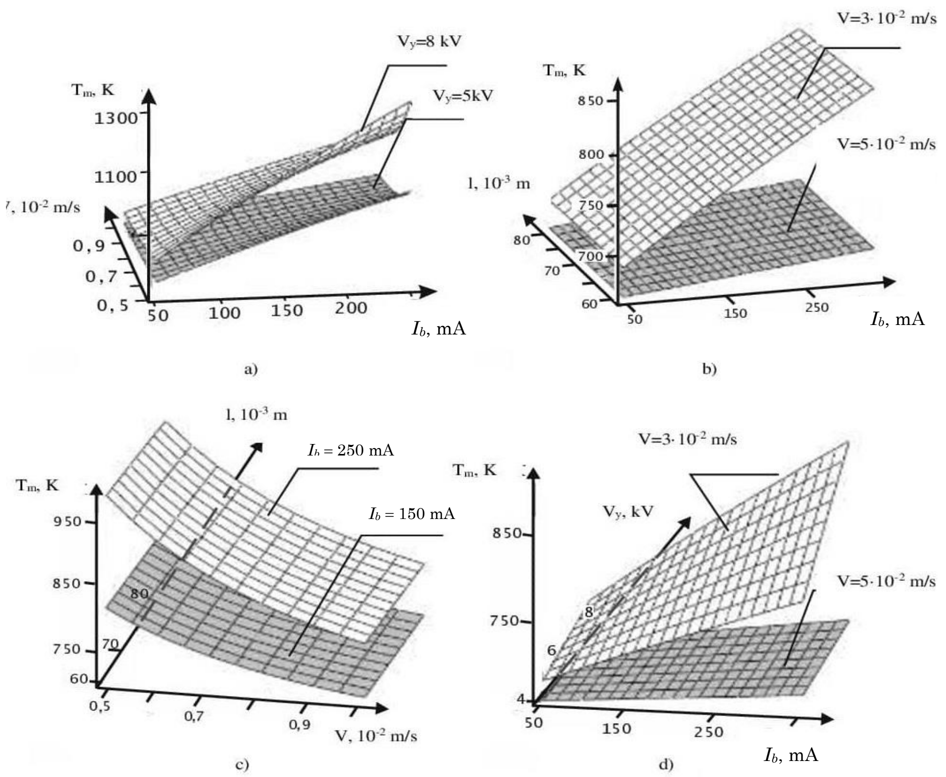

Fig. 4 – Three-dimensional image of the function $T_m = f_1\left(I_b, V_y, l, t\right)$ for a thin-film element from optical glass K8: a) $t = 0{,}7$ s, $l = 6{\cdot}10^{-2}$ m; b) $t = 0{,}9$ s, $V_y = 6$ kV; c) $t = 0{,}3$ s, $V_y = 8$ kV; d) $t = 0{,}8$ s, $l = 6{\cdot}10^{-2}$ mm

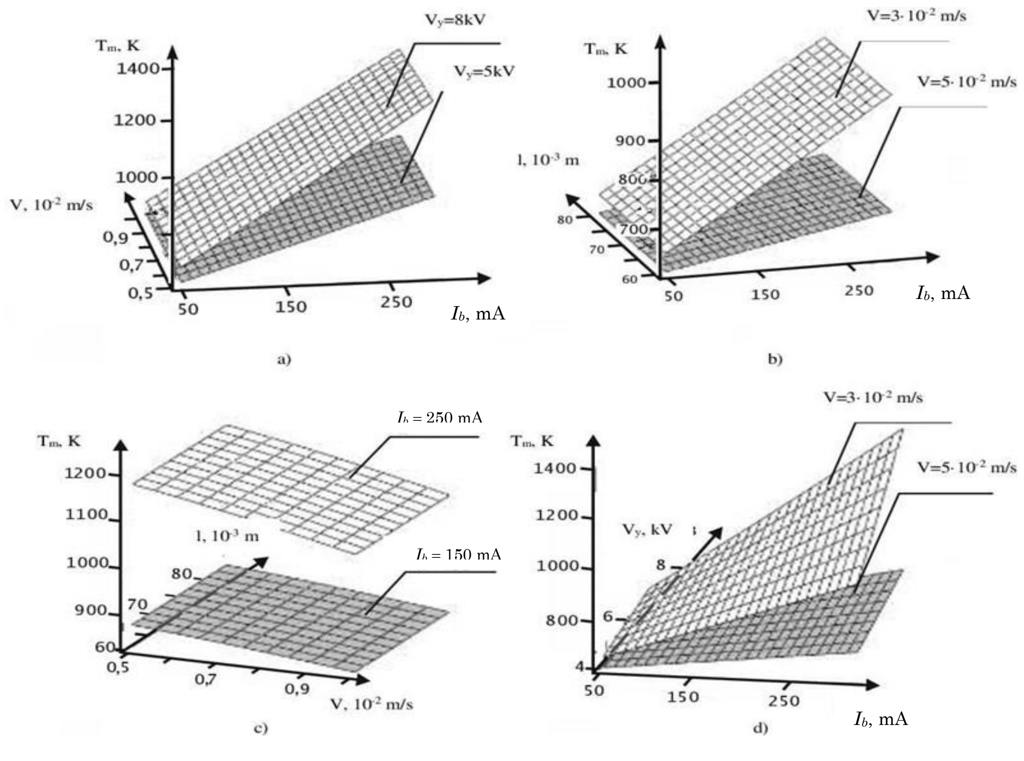

Fig. 5 – Three-dimensional presentation of the function $T_m = f_2\left(I_b, V_y, l, t\right)$ for a thin large-size plate from optical ceramics KO1: a) $t = 0.5$ s, $l = 6{\cdot}10^{-2}$ m; b) $t = 0.8$ s, $V_y = 5$ kV; c) $t = 0.3$ s, $V_y = 8$ kV; d) $t = 0.$ s, $l = 6{\cdot}10^{-2}$ m

change modes of the controlled parameters of the electron beam, the excess of which leads to a sharp deterioration in the properties of the surface layers of the treated elements up to their destruction (the appearance of cracks, chips, etc.) and the failure of optoelectronic devices.

3. CONCLUSIONS

1. Non-stationary, nonlinear mathematical models of the process of heating elements from optical glass and ceramics of different geometric shapes and sizes are developed (thin film elements, thin large-size plates), taking into account the temperature dependences of the thermal properties of the material (volumetric heat capacity, thermal conductivity coefficient) that allows to calculate the influence of the electron beam parameters (beam current I_b, accelerating voltage V_y, distance to the treated surface l and beam movement speed V on temperature fields in the treated optical elements (in particular, at the maximum surface temperature of the element T_m) with a relative error of 8... 12 %.
2. It is found out, that by the level of influence on T_m value electron beam parameters arrange as a sequence (time of the thermal effect of the beam $t = 0.3…1.0$ s) $I_b > V > V_y > l$: during the increase in I_b from 50 to 300 mA the value of T_m increases (for glass K8 by 2.5…2.8 times; for ceramics KO1 by 1.5…1.9 times); an increase in V from $5{\cdot}10^{-3}$ to $5{\cdot}10^{-2}$ m/s leads to the decrease in T_m (for glass K8 by 1.4…1.6 times; for ceramics KO1 by 1.3…1.4 times); the increase in V_y from 4 to 8 kV responds to the increase in T_m for glass K8 by 1.3…1.5 times; for ceramics KO1 by 1.2…1.4 times); an increase in l within the limits of $6{\cdot}10^{-2}…8{\cdot}10^{-2}$ m leads to the decrease in T_m by less than 1.2 times (for glass K8 and ceramics KO1).
3. For the first time, the optimal change ranges of the electron beam parameters during surface micro-treatment of elements of optical glass and ceramics were determined: for optical glass K8 at $t = 0.7$ s; $V_y = 5…8$ kV; $V = 3{\cdot}10^{-2}$ m/s; $l = 6{\cdot}10^{-2}$ m we get $I_{b1}^{*} = 53$ mA $\le I_b \le I_b^{**} = 290$ mA; at $t = 0.7$ s; $I_b = 300$ mA; $V_y = 5$ kV; $l = 6{\cdot}10^{-2}$ m we have $V_1^{*} = 6{\cdot}10^{-3}$ m/s $\le V \le V_2^{*} = 1.8{\cdot}10^{-2}$ m/s; and at $t = 0.7$ s; $I_b = 100$ mA; $V = 7{\cdot}10^{-3}$ m/s; $l = 6{\cdot}10^{-2}$ m we get $V_{y1}^{*} = 5.2$ kV $\le V_y \le V_{y2}^{*} = 7.4$ kV; for optical ceramics KO1 at $t = 0.8$ s, $V_y = 9$ kV, $V = 3{\cdot}10^{-2}$ m/s, $l = 6{\cdot}10^{-2}$ m we get $I_b^{**} = 64$ мА $\le I_b \le I_b^{**} = 185$ mA; and at $t = 0.8$ *s*; $I_b = 300$ mA; $V_y = 5$ kV; $l = 6{\cdot}10^{-2}$ m we get $V_1^{**} = 4{\cdot}10^{-3}$ m/s $\le V \le V_2^{**} = 3{\cdot}10^{-2}$ m/s.

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Визначення оптимальних режимів електронно-променевої мікрообробки поверхонь оптичних елементів

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Як показала практика, найбільш зручним, екологічно чистим та легкокерованим способом обробки оптичних елементів є електронно-променевий метод. Однак широке використання електронно-променевої технології у оптико-електронному приладобудуванні стримується відсутністю методів визначення оптимальних режимів електронно-променевої мікрообробки оптичних елементів, що являють собою сукупність керованих параметрів електронного променю (струм електронного потоку $I_b = 50…300$ мА, прискорююча напруга $V_y = 4…8$ кВ, відстань до оброблюваної поверхні $l = 6{\cdot}10^{-2}$-

$8 \cdot 10^{-2}$ м, швидкість переміщення променю $V = 5 \cdot 10^{-2}$-$5 \cdot 10^{-3}$ м/с, час теплового впливу t = 0,3…1,0 с), перевищення яких призводить до цілого ряду небажаних явищ, які погіршують якість оброблюваних поверхонь. Розроблено математичні моделі процесу нагріву елементів з оптичного скла та кераміки різної геометричної форми та розмірів (тонкоплівкові елементи, тонкі пластини великих розмірів) рухомим стрічковим електронним променем, що дозволяють розрахувати вплив його параметрів на температурні поля у оброблюваних елементах. Встановлено, що збільшення параметрів I_n та V_y у вказаних діапазонах призводить до зростання максимальної температури поверхні оптичних елементів більше, ніж у 2 рази, а зменшення параметрів l та V – менше, ніж у 1,5 рази. Визначено оптимальні значення параметрів електронного променю, перевищення яких призводить до появи тріщин та відколів у поверхневих шарах елементів, порушення їх геометричної форми та погіршення метрологічних характеристик приладів аж до їх відказів.

Ключові слова: Електронний промінь стрічкового типу, Елементи з оптичного скла та оптичної кераміки, Температурні поля у оптичних елементах, Оптико-електронне приладобудування.