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REGULAR ARTICLE

Critical Values Determination of Parameters of Fixed Electron Flows System in the Processing of Oxide Coatings on Extended Optical Elements

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A mathematical model has been developed for the external uniformly distributed thermal effect on the surface of a flat bilayer element made of optical glass K108 and oxide coating with Al_2O_3, MgO, taking into account the temperature dependencies of their thermophysical properties (volumetric heat capacity and thermal conductivity). Critical values of external thermal impact parameters (heat flows and durations of their action) leading to the destruction of coatings (crack formation, detachment, delamination, etc.) have been determined. The problem of implementing a uniformly distributed thermal effect along the surface of the oxide coating using a system of fixed ribbon electron flows (REF) has been solved. These REFs are incorporated as a programmatically controlled module into the equipment of modern electron-beam devices. Permissible processing regimes for coating surfaces have been defined (the number of REFs, controlled parameters for each REF such as current, accelerating voltage, and distance to the processed surface). These regimes allow to improve their operational characteristics and prevent potential damage under extreme operating conditions of devices (elevated heating temperatures, thermal shock effects, etc.). Electron-beam processing of extended elements made of optical glass and ceramics, piezoceramic elements, as well as optical elements with coatings of metal oxides, is considered potentially capable of qualitatively processing their surfaces using a system of fixed REF. These REF can serve as the elemental basis in microoptics, integrated and fiber optics, functional electronics, and other fields of precision instrument engineering.

Keywords: Optoelectronic Instrumentation, Optical Elements, Nanoscale coatings of metal oxides, Electron beam processing, Thermal processes, Optimal control.

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1. INTRODUCTION

Currently, optical elements (made of optical glasses K8, K108, K208, etc., optical ceramics KO2, KO5, etc.) are widely used as individual components in purpose-specific optoelectronic devices (such as pulsed bearing range finders, sighting complexes, laser medical devices, infrared devices, etc.) [1-7].

To enhance durability and reduce the radiative and convective components of thermal losses on optical elements, nanoscale ($10^{-4}…5\cdot10^{-4}$ m) oxide coatings are applied, consisting of compositions of ZnO, Al_2O_3, TiO_2 etc. [8-12]. In this process, the obtained coatings are non-uniform, containing hidden defects (cracks, detachments, etc.), the surface has significant roughness and low hardness, and so on. All of these factors lead to a decrease in the operational characteristics of these coatings: reduced durability, decreased reflection coefficient in the infrared and visible spectra, etc.

To address the mentioned drawbacks and improve the quality of coatings, surface microprocessing using a moving ribbon electron beam (REF) has been employed [13-21]. As a result of the conducted research, it was determined that after the electron processing of oxide coatings, defects are no longer observed, and the roughness decreases from 30…35 μm to 9…15 μm. The surface microhardness increases from 13.1…9.3 GPa to 15.9…14.7 GPa (for ZnO coating), from 21.5…17.5 GPa to 24.9…23.7 GPa (for Al_2O_3 coating), and from 3.5…2.3 GPa to 7.1…6.3 GPa (for TiO_2 coating), etc. The influence of coating thickness on the surface microhardness diminishes by 30…40 %. The surface porosity of optical elements decreases by 5…10 %, and their durability increases by 7…12 %, along with a 20…30 % extension of their service life.

However, as technological experiments have demonstrated [4, 7], during electronic microprocessing of oxide coatings on extended elements (element length of $5\cdot10^{-2}…10^{-1}$ m and more), with a single moving REF alone is insufficient to improve the specified operational characteristics of coatings. To achieve a uniformly distributed thermal influence along the processed surface, it is necessary to control the speed of REF movement: at the ends of the element, the REF should move more slowly than at its center. This approach prevents overheating of the element in the central area, avoiding disruptions in surface flatness,

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changes in its geometric shape, and local damage (such as crack formation, detachments, delamination, etc.) due to large temperature gradients, etc. Currently, the problem of controlling the speed of REF movement has not been resolved, as it belongs to the class of invalid problems in mathematical physics [21-25]. Therefore, for the surface treatment of extended elements with oxide coatings of different geometric shapes (flat, cylindrical, spherical, etc.), it was proposed to use a system of fixed REFs with controlled parameters (current I_b (mA), accelerating voltage V_y (kV), distance to the treated surface l (m), and exposure time t (s)) [26, 27]. The possibility of technically implementing the treatment of extended objects using a controlled module with a system of individual electron streams (REF) has been demonstrated.

However, at present, there is a lack of mathematical justification and software for implementing the specified method through an automated control system. Mathematical models of the thermal impact of these ribbon electron beams (REFs) on the mentioned multilayer elements (optical element + oxide coatings) have not been developed, which would allow calculating temperature distributions and thermoelastic stresses through their thickness depending on REB parameters. By comparing the maximum values of thermoelastic stresses in the elements with their permissible limits for the considered optical materials (optical glass and ceramics) and oxide coatings, critical values of REF parameters (I_b^*, V_y^*,l^*,t^*) can be determined. Exceeding these critical values leads to the deterioration of operational characteristics of oxide coatings and subsequent failure. Therefore, the aim of this work is to develop mathematical models of the thermal effect of a system of fixed beams on extended bilayer elements: a layer of optical material with an oxide coating. These models should enable the determination of critical values of REF parameters for preventing the deterioration of coating operational characteristics, their failure, and the malfunction of devices during uniformly distributed thermal influence along the processed surface.

2. THE RESULTS OF THE RESEARCH AND THEIR ANALYSIS

The two-layered plate consisting of different materials is considered (one made of optical material, and the other with an oxide coating) (Fig. 1). As a result of the thermal influence of the fixed REF system on the plate's surface, a uniformly distributed heat flow $Q_n(I_b, V_y, l)$ is introduced. Ideal thermal contact is observed between the layers, and in the first approximation, radiation and convective heat losses are not taken into account due to their small magnitude [4].

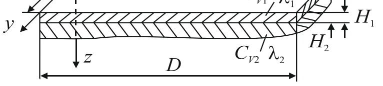

Fig. 1 – The scheme of heating an optical plate with an oxide coating by a system of fixed REBs with an influence density Q_n: B, D – width and length of the plate, m; C_{V1}, λ_1, H_1, C_{V2}, λ_2, H_2 – volumetric heat capacity (J/m^3·K), thermal conductivity coefficient (W/m^2) and the thickness (m) of the oxide coating (1) and the optical material of the plate (2), respectively

For commonly used metal oxides (ZnO, Al_2O_3) for nanoscale coatings and optical materials (K8, K108 optical glasses and KO1, KO2 optical ceramics), and the values of H_2 ($H_2 = (5\ldots10)\cdot10^{-3}$ m), the conditions [28] are met:

$$\delta_1 = 2\cdot(a_{01}^2\cdot\tau)^{1/2} \sim H_1$$
$$\delta_2 = 2\cdot(a_{02}^2\cdot\tau)^{1/2} \ll H_2 \tag{1}$$

where δ_1, a_{01}^2, δ_2, a_{02}^2 – are the depth of the thermoaction zone (m) and the coefficient of thermal conductivity (m^2/s) for the oxide coating and the optical element, respectively; τ – time of external thermal action (s). Therefore, the plate is considered as a semi-confined environment, on the lower side of which heat exchange conditions are not taken into account ($\frac{\partial T}{\partial x} = \frac{\partial T}{\partial y} = 0$)

In this case, the equations of the mathematical model of heating a two-layer plate have the form [29]:

$$C_{V1}(T_1)\cdot\frac{\partial T_1}{\partial t} = \frac{\partial}{\partial z}\left[\lambda_1(T_1)\cdot\frac{\partial T_1}{\partial z}\right],\ t > 0,\ 0 < z < H_1, \tag{2}$$

$$C_{V2}(T_2)\cdot\frac{\partial T_2}{\partial t} = \frac{\partial}{\partial z}\left[\lambda_2(T_2)\cdot\frac{\partial T_2}{\partial z}\right],\ t > 0,\ H_1 < z < +\infty, \tag{3}$$

under the following conditions

$$T_1|_{t=0} = T_2|_{t=0} = T_0,\ -\lambda_1(T_1)\cdot\left.\frac{\partial T_1}{\partial z}\right|_{z=0} = Q_n,$$

$$T_1|_{z=H_1} = T_2|_{z=H_1},\ \lambda_1(T_1)\cdot\left.\frac{\partial T_1}{\partial z}\right|_{z=H_1} = \lambda_2(T_2)\cdot\left.\frac{\partial T_2}{\partial z}\right|_{z=H_1},$$

$$T_2 \to T_0,\ \left(\frac{\partial T_2}{\partial z}\right) \to 0\ at\ z \to +\infty$$

Taking into account dependencies [7]

$$\tilde{N}_{vi} = \tilde{N}_{v0i}\cdot T_i^v,\ \lambda_i = \lambda_{0i}\cdot T_i^v,\ (i = 1, 2), \tag{4}$$

where ($\tilde{N}_{v0i}$, λ_{0i}, v – empirical constants) and substitution of variables

$$\theta_i(z,t) = T_i^{v+1} - T_0^{v+1},\ (i = 1, 2), \tag{5}$$

we get a system of equations:

$$\frac{\partial\theta_1}{\partial t} = a_{01}^2\cdot\frac{\partial^2\theta_1}{\partial z^2}, \tag{6}$$

$$\frac{\partial\theta_2}{\partial t} = a_{02}^2\cdot\frac{\partial^2\theta_2}{\partial z^2}, \tag{7}$$

under the following conditions

$$\theta_1|_{t=0} = \theta_2|_{t=0},\ -\left.\frac{\partial\theta_1}{\partial z}\right|_{z=0} = \bar{q}_{n0},\ \theta_1|_{z=H_1} = \theta_2|_{z=H_1},$$

$$\lambda_{01}\cdot\left.\frac{\partial\theta_1}{\partial z}\right|_{z=H_1} = \lambda_{02}\cdot\left.\frac{\partial\theta_2}{\partial z}\right|_{z=H_1}$$

$$\theta_2 \to 0,\ \left(\frac{\partial\theta_2}{\partial z}\right) \to 0\ at\ z \to +\infty$$

where $a_{0i}^2 = \frac{\lambda_{0i}}{C_{v0i}}$, $\bar{q}_{n0} = \frac{v+1}{\lambda_{01}}\cdot Q_n$.

We look for a solution to the problem in the class of functions for which the Laplace transform of a variable can be applied [30]. We consider

$$\bar{\theta}_i(z,p) = \int_0^{\infty} e^{-pt} \cdot \theta_i(z,t)dt. \quad (8)$$

The operational solution of the problem is presented in the following form:

$$\bar{\theta}_1(z,p) = \frac{\bar{q}_{n0} \cdot [\tilde{n}h(\frac{H_1 - z}{a_{01}} \cdot \sqrt{p}) + d_0 \cdot sh(\frac{H_1 - z}{a_{01}} \cdot \sqrt{p})]}{p \cdot \sqrt{p} \cdot [\frac{\lambda_{01}}{a_{01}} \cdot sh\left(\frac{H_1 \cdot \sqrt{p}}{a_{01}}\right) + \frac{\lambda_{02}}{a_{02}} \cdot ch\left(\frac{H_1 \cdot \sqrt{p}}{a_{01}}\right)]}, \quad (9)$$

$$\bar{\theta}_2(z,p) = \frac{\bar{q}_{n0} \cdot e^{\frac{(z - H_1)}{a_{02}} \cdot \sqrt{p}}}{p \cdot \sqrt{p} \cdot [\frac{\lambda_{01}}{a_{01}} \cdot sh\left(\frac{H_1 \cdot \sqrt{p}}{a_{01}}\right) + \frac{\lambda_{02}}{a_{02}} \cdot ch\left(\frac{H_1 \cdot \sqrt{p}}{a_{01}}\right)]}, \quad (10)$$

where $d_0 = \frac{a_{01} \cdot \lambda_{02}}{a_{02} \cdot \lambda_{01}}$.

The solution of the original problem has the following form:

$$T_1(z,t) = \left\{T_0^{v+1} + \frac{2(v+1) \cdot 2Q_n \cdot a_{01} \cdot \sqrt{t}}{\lambda_{01}} \cdot \left[\sum_{n=0}^{\infty} b^n \cdot i \cdot erfc\left(\frac{2H_1 n + z}{2a_{01} \cdot \sqrt{t}}\right) - \sum_{n=0}^{\infty} b^n \cdot i \cdot erfc\left(\frac{2H_1 n - z}{2a_{01} \cdot \sqrt{t}}\right)\right]\right\}^{\frac{1}{v+1}}, \quad (11)$$

$$T_2(z,t) = \left\{T_0^{v+1} + \frac{4(v+1) \cdot Q_n \cdot a_{01} \cdot \sqrt{t}}{\lambda_{01} \cdot (1 + d_{0)}} \cdot \sum_{n=0}^{\infty} b^n \cdot i \cdot erfc\left(\frac{H_1 n}{a_{01} \cdot \sqrt{t}} + \frac{z}{2a_{01} \cdot \sqrt{t}}\right)\right\}^{\frac{1}{v+1}}, \quad (12)$$

where *erf, i·erf* - are special functions [30].

To find thermoelastic stresses in the considered plate $\sigma_i(z,t)$ ($i = 1$, 2 – are the coating and plate numbers, respectively) the following standard ratio is used to calculate stresses in flat layers [31]:

$$\sigma_i(z,t) = \frac{a_T \cdot E_i}{1 - v_i} \cdot \left[-T_i(z,t) + \frac{2}{H_1^2} \cdot (2H_1 - 3z) \int_0^{H_1} T_1(z,t)dz \cdot \frac{6}{H_1^3} \cdot (H_1 - 2z) \int_0^{H_1} T_1(z,t) \cdot zdz\right], \quad (13)$$

where a_{T_i}, E_i, v_i - coefficient of thermal expansion (K^{-1}), Young's modulus (N/m^2) and Poisson's ratio of the oxide coating and the optical element, respectively.

The obtained formulas (11) – (13) allow, with the help of known physical and technical characteristics of the oxide coating and optical material of the element, as well as standard software [7, 31, 32], to perform calculations in interactive and real-time mode on modern PCs. These calculations involve temperature distribution and thermomechanical stress throughout the thickness of the oxide coating and optical element, depending on the controlled parameters of the stationary REF system (the magnitude of uniformly distributed heat influence Q_n along the processed surface and the duration of its action, t). It also enables the determination of their critical values Q_n^* and t^* based on the condition

$$|\sigma|_{max} > \sigma^*, \quad (14)$$

where σ^* - is the strength limit of the oxide coating.

The results of calculations of thermomechanical stresses $\sigma_i(z,t)$ throughout the thickness of the oxide coating using the known physical and mechanical properties of Al_2O_3, MgO oxides, and optical glass K108 [7-10], under thermal influences $Q_{n1} = 3.5 \cdot 10^7$ W/m^2 and $Q_{n2} = 4.7 \cdot 10^8$ W/m^2, that are practicaly implemented during electron-beam processing of various optical materials, are presented in Fig. 2-5.

It is determined that the maximum tensile stresses occur near the surface of the coating ($z = 0$), and the maximum compressive stresses occur in its middle (at $Q_{n1} = 3.5 \cdot 10^7$ W/m^2) (Fig. 2, 4). With an increase in the external heat influence Q_n from $3.5 \cdot 10^7$ W/m^2 to $4.7 \cdot 10^8$ W/m^2, the maximum values of thermomechanical stresses $|\sigma|_{max}$ increase by 1.7… 1.9 times (for Al_2O_3), 2.1 … 2.8 times (for MgO). In this case, the max values $|\sigma|_{max}$ shift from the middle of the coating (~ $0.5H_1$) closer to its end (~ $0.75H_1$).

It is also established that with an increase in the duration of the thermal influence t (up to 1.8…2.0 seconds) on the oxide coating, the max values $|\sigma|_{max}$ decrease by 1.5 … 1.7 times (for Al_2O_3), by 2.5 … 2.7 times (for MgO) for $Q_n = 3.5 \cdot 10^7 \ldots 4.7 \cdot 10^8$ W/m^2 due to a sharp rise in the temperature of the heated coating (more than 5…8 times) (Fig. 3, 5). Critical modes of thermal influence by a set of fixed REF on oxide coatings are achieved (critical values Q_{ni}^* and t_i^*, where $i = 1, 2,\ldots$), where $|\sigma|_{max}$ exceeds the material strength limit σ^*, leading to its destruction (appearance of cracks, splits, etc.) (Table 1).

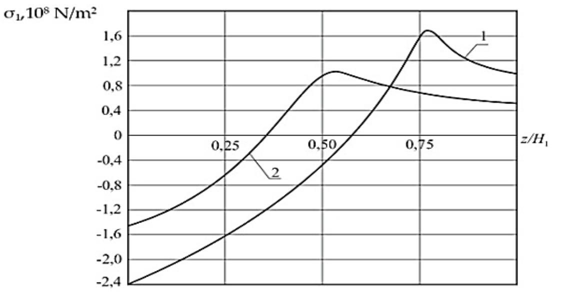

Fig. 2 – Distribution of thermal stresses across the thickness of an element made of optical glass K108 with an oxide coating of Al_2O_3 depending on the external thermal influence Q_n ($T_0 = 300$ K; $H_1 = 3 \cdot 10^{-4}$ m; $t = 0{,}1$ s): 1 – $Q_n = 4{,}7 \cdot 10^8$ W/m^2; 2 – $Q_n = 3{,}5 \cdot 10^7$ W/m^2.

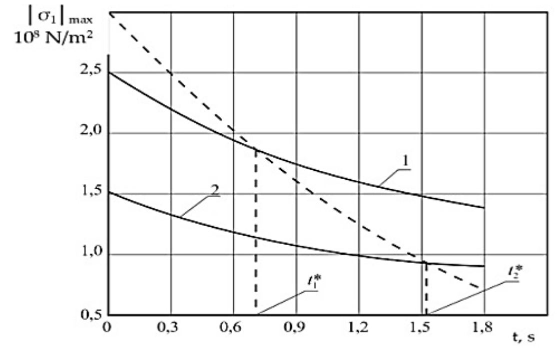

Fig. 3 – Dependence of the module of maximum thermal stresses $|\sigma|_{max}$ in the oxide coating with Al_2O_3 on the surface of the K108 optical glass element on the time of external thermal action for different values of Q_n ($T_0 = 300$ K; $H_1 = 3 \cdot 10^{-4}$ m): 1 – $Q_n = 4{,}7 \cdot 10^8$ W/m^2; 2 – $Q_n = 3{,}5 \cdot 10^7$ W/m^2); t_1^*, t_2^* – critical times of thermal action, s; ——– – calculation results; – – – – strength limit of the oxide coating σ^* [33-35]

For preventing mentioned critical modes in the electron-beam processing of oxide coatings on optical elements, it is necessary to determine the critical values of the controlled parameters of the fixed REF system that implement external thermal influence.

Implementation of uniformly distributed heat influence Q_n along the processed surface of the oxide coating. The heat influence Q_n is realized on modern electron-beam equipment [4, 7] using a system of discretely located fixed REFs along the processed surface (s_1, s_2, ... s_N, N – amount of REFs). Mathematical processing of probing results [26] demonstrates that the distribution of the heat influence density of the j-type REF along the x coordinate of the processed surface in the optical element with an oxide coating is described by the Gaussian law (relative error 5…7 %) (Fig. 6):

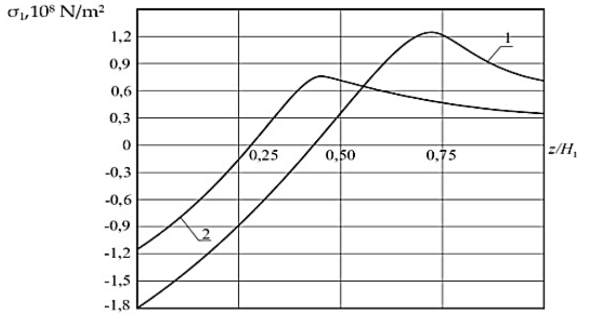

Fig. 4 – Distribution of thermal stresses across the thickness of an element made of K108 optical glass with an oxide coating of MgO depending on the external thermal influence Q_n ($T_0 = 300$ K; $H_1 = 3\cdot10^{-4}$ m; $t = 0{,}1$ s): 1 – $Q_n = 4{,}7\cdot10^8$ W/m²; 2 – $Q_n = 3{,}5\cdot10^7$ W/m²

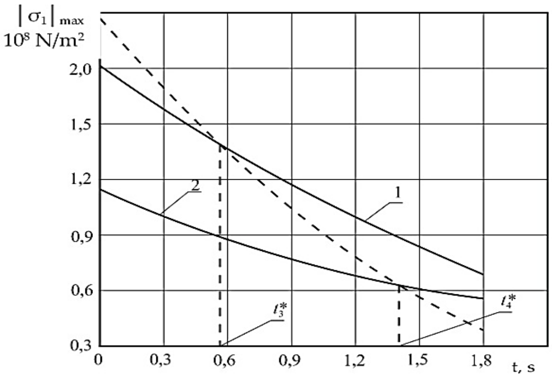

Fig. 5 – Dependence of the modulus of the maximum thermal stresses $|\sigma|_{max}$ in the oxide coating with MgO on the surface of the K108 optical glass element on the time of external thermal action for different values of Q_n ($T_0 = 300$ K; $H_1 = 3\cdot10^{-4}$ m): 1 – $Q_n = 4{,}7\cdot10^8$ W/m²; 2 – $Q_n = 3{,}5\cdot10^7$ W/m²); t_3^*, t_4^* – critical times of thermal action, s; ——— – calculation results; – – – – strength limit of the oxide coating σ^*

Table 1 – The ranges of changes in the critical values of heat flows Q_{ni}^* ($i = 1, 2,...$) and their action times t_i^* ($i = 1, 2,...$) on an element made of K108 optical glass with an oxide coating

Parameter / Material coating	Q_{ni}^*, 10⁸ W/m²	t_i^*, s
Al_2O_3	0,35	$t_2^* > 1{,}52$
	4,7	$t_1^* > 0{,}74$
MgO	0,35	$t_4^* > 1{,}37$
	4,7	$t_3^* > 0{,}59$

$$q_{nj}\left(V_{yj}, I_{лj}, l_j\right) = \frac{I_{лj}\cdot V_{yj}}{B}\cdot\sqrt{\frac{k_{0j}\left(I_{лj}, l_j\right)}{\pi}}\times$$
$$\times\frac{e^{-k_{0j}\left(I_{лj}, l_j\right)\cdot x^2}}{erf\left(b_j\left(I_{лj}, l_j\right)\cdot\sqrt{k_{0j}\left(I_{лj}, l_j\right)}\right)} \qquad (15)$$

where

$$k_{0j}\left(I_{лj}, l_j\right) = 9{,}367\cdot10^7 - 7{,}859\cdot10^5\times$$
$$\times l_j - \left(5{,}1\cdot10^4 - 1{,}3\cdot10^2\cdot l_j\right)\cdot I_{лj} \qquad (16)$$

$$b_j\left(I_{лj}, l_j\right) = \frac{1{,}73}{\sqrt{k_{0j}\left(I_{лj}, l_j\right)}} \qquad (17)$$

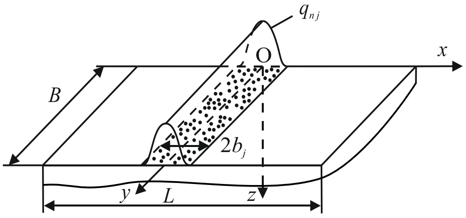

Fig. 6 – Scheme of the thermal effect of the j-th fixed REB on the optical element: q_{nj} – heat flow, normally distributed along x and uniformly along y, W/m²; 2_{bj}, B – thickness and width of the electron flow, m; L is the length of the processed element, m

Based on the obtained empirical formulas (15) – (17), dependencies $k_{0j}\left(I_{лj}, l_j\right)$, $2b_j\left(I_{лj}, l_j\right)$ and $q_{nj}\left(V_{yj}, I_{лj}, l_j\right)$ were received, from which it follows that with an increase in the electron beam current from $I_{bj} = 50$ mA to $I_{bj} = 200$ mA , the concentration coefficient k_{0j} decreases by 1.25 … 1.30 times, and the electron beam thickness $2b_j$ increases by 1.15 … 1.25 times. Additionally, with an increase in the distance to the processed surface from $l_j = 4\cdot10^{-2}$ m to $l_j = 6\cdot10^{-2}$ m, the value of k_{0j} decreases, while the value of $2b_j$ increases by 1.35 … 1.40 times and 1.2 … 1.25 times, respectively. It has been established that the heat influence density (heat flow) q_{nj} of the electron beam on the surface of processed optical elements depends on the controlled parameters of the electron beam: the electron beam current I_{bj}, accelerating voltage V_{yj}, and distance to the processed surface l_j. Changes within the range of 50...300 mA for I_b, 4...8 kV for V_{yj}, and l_j – $4\cdot10^{-2}$... $8\cdot10^{-2}$ m for l_j result in a quantitative change of the q_{nj} value (for example, $(q_{nj})_{max} = q_{nj}(0)$ increases by 1.9 times with an increase in I_{bj} and by 2.3 times with an increase in V_{yj}. Conversely, with an increase in l_j, the value of $(q_{nj})_{max}$ decreases by 2.5 times). In general, the conducted experimental studies on probing the electron flow for working ranges of its controlled parameters ($I_{bj} = 50$…300 mA, $V_{yj} = 4$...8 kV, $l_j = 4\cdot10^{-2}$...$8\cdot10^{-2}$ m) allowed establishing the following ranges of changes in its most important energetic characteristics: concentration coefficient (sharpness of the thermal impact of the electron flow) $k_{0j} = 0{,}5\cdot10^{-7}$...$5\cdot10^{-7}$ m⁻²; thickness of the electron flow (width of the thermal influence zone) $2b_j = 5\cdot10^{-4}$...$1{,}5\cdot10^{-3}$ m; maximum value of the heat flow (magnitude of the heat flow at the center of its influence) $(q_{nj})_{max} = 0{,}7\cdot10^{-1}$... $8{,}5\cdot10^7$ W/m², which fully corresponds to the level of values of these parameters for other types of electron flows, for example, electron flows that have a normal distribution of heat flow radially (so-called circular sources of thermal influence) [25].

According to the results of probing, the overall distribution of the heat effect density *N* of individual REB along the x coordinate of the processed surface of the element has the following form:

$$F_n(x)=\sum_{j=1}^{N} q_{nj}=\frac{1}{B\cdot\sqrt{\pi}}\cdot\sum_{j=1}^{N} I_{лj},V_{yj}\sqrt{k_{0j}\left(I_{лj},l_j\right)}\cdot\frac{e^{-k_{0j}\left(I_{лj},l_j\right)\cdot x^2}}{erf\left(b_j\left(I_{лj},l_j\right)\cdot\sqrt{k_{0j}\left(I_{лj},l_j\right)}\right)} \quad (18)$$

The number of discrete REF and the parameters I_{bj}, V_{yj} and l_j (j = 1, 2,…N) are chosen in such a way that the approximation to the specified distributed heat impact $Q_n(x)$ along the surface of the optical element with oxide coating, by a set of discretely located stationary electron flows s_j (j = 1, 2,…N) of Gaussian-type thermal influence $F_n(x)$ was minimized:

$$S=\sum_{i=1}^{M}\left[F_n\left(x_i\right)-Q_n\left(x_i\right)\right]^2\to\min_{\substack{N,I_{лj},\\ V_{yj},l_j}}. \quad (19)$$

As a result of the conducted numerical experiments for uniformly distributed heat impact $Q_n(x) = Q_n$ = const, it has been established that, for example, for N = 5…7, the approximation of the total $F_n(x)$ from individual REF to the specified Q^*_{ni} (i = 1, 2) is achieved within the range of 3…5 % in real-time mode. It is also demonstrated that by increasing the number of REF (up to 50…70), high accuracy can be achieved (relative error up to 10^{-4}…10^{-5}).

Table 2 – Critical values of the parameters of the REF system, which implement the critical values of external thermal influences

Parametr / Ordinal REF number	Q^*_{ni}, 10^8 W/m²	I^*_{bj}, mA	V^*_{yj}, кV	l^*_j, 10^{-2} m
1	0,35	62	5,3	6,8
	4,7	255	7,4	4,8
2	0,35	56	4,9	6,9
	4,7	254	6,9	4,9
3	0,35	33	4,8	7,2
	4,7	252	6,8	5,1
4	0,35	51	5,0	7,4
	4,7	248	7,0	5,4
5	0,35	54	5,1	7,1
	4,7	249	7,1	5,2
6	0,35	56	5,4	6,7
	4,7	251	7,3	5,1
7	0,35	59	5,6	6,6
	4,7	256	7,5	4,7

Eventually the following critical modes of electronic treatment of oxide coatings with Al_2O_3, MgO on elements made of optical glass K108 are obtained using a system of fixed REF that implement uniformly distributed heat effects along the processed surface. Exceeding these critical modes leads to a deterioration of the operational characteristics of the coatings, their destruction (appearance of cracks, splits, detachment, etc.), and device failure (Table 3).

The following critical values of the REF system parameters were established (I^*_{bj}, V^*_{yj}, та l^*_j, j = 1, 2,…7), which realize the critical values Q^*_{ni} (i = 1, 2) (Table 2).

In conclusion, it should be noted that in the light of modern advanced technologies used in optoelectronic instrumentation, electron-beam processing of extended elements made of optical glass and ceramics, piezoceramic elements, as well as optical elements with coatings of metal oxides, is considered potentially capable of qualitatively processing their surfaces using a system of fixed REF. These REF can serve as the elemental basis in microoptics, integrated and fiber optics, functional electronics, and other fields of precision instrument engineering. Furthermore, the undeniable advantages of electron-beam technology include its environmental cleanliness and the ability to obtain, on a common substrate of optical material in a unified technological cycle, microelements with improved operational characteristics. Such microelements usage in optical components of optoelectronic devices contributes to their flawless operation.

Table 3 – Critical ranges of changes in REF parameters (I^*_{bj}, V^*_{yj}, та l^*_j, j = 1, 2,…7) and their action times (t^*_i, i = 1, 2) implemented along the surface of an element made of K108 optical glass with an oxide coating of Al_2O_3, MgO

Parametr / Coating	Number REF	t^*, c					
		I^*_{bj}, mA	V^*_{yj}, кV	l^*_j, 10^{-2} m	I^*_{bj}, mA	V^*_{yj}, кV	l^*_j, 10^{-2} m
Al_2O_3	$t^*_1 > 0{,}74$				$t^*_2 > 1{,}52$		
	1	255	7,4	4,8	62	5,3	6,8
	2	254	6,9	4,9	56	4,9	6,9
	3	252	6,8	5,1	53	4,8	7,2
	4	248	7,0	5,4	51	5,0	7,4
	5	249	7,1	5,2	54	5,1	7,1
	6	251	7,3	5,1	56	5,4	6,7
	7	256	7,5	4,7	59	5,6	6,6
MgO	$t^*_3 > 0{,}39$				$t^*_4 > 1{,}37$		
	1	255	7,4	4,8	62	5,3	6,8
	2	254	6,9	4,9	56	4,9	6,9
	3	252	6,8	5,1	53	4,8	7,2
	4	248	7,0	5,4	51	5,0	7,4
	5	249	7,1	5,2	54	5,1	7,1
	6	251	7,3	5,1	56	5,4	6,7
	7	256	7,5	4,7	59	5,6	6,6
	6	251	7,3	5,1	56	5,4	6,7
	7	256	7,5	4,7	59	5,6	6,6

3. CONCLUSIONS

1. For the first time, a mathematical model has been developed for the uniformly distributed heat impact density Q_n implemented by a system of fixed REF onto the surface of an extended element (length greater than 10^{-1} m) made of optical glass (K8, K108, etc.) with coatings (thickness not exceeding 300…500 μm) of metal oxides (Al_2O_3, MgO, ZrO_2 etc.). This model takes into account the temperature dependencies of their thermophysical properties (volume heat capacity $C_V(T)$ and thermal conductivity λ(T)), allowing to calculate distributions of thermomechanical stresses

across the thickness of the coating and the element.

2. As a result of the conducted calculations, it has been established that: maximum tensile stresses ($\sigma < 0$) appear near the surface of the coating ($z \cong 0$), while maximum compressive stresses ($\sigma > 0$) occur within its middle ($z \cong 0{,}5H_1$, H_1 – is the thickness of the coating) at $Q_n = 3{,}5\cdot10^7$ W/m^2. With an increase in Q_n from $3{,}5\cdot10^7$ W/m^2 до $4{,}7\cdot10^8$ W/m^2 the values of maximum thermomechanical stresses increase by 1.7…2.8 times, and the position of $|\sigma|_{max}$ shifts from the middle of the coating towards its end ($z = 0{,}75H_1$). Increasing the duration of external thermal influence t leads to a decrease in $|\sigma|_{max}$ by 1.5…2.7 times. By comparing the value of $|\sigma|_{max}$ with the material strength limit σ^*, critical values of external thermal impact parameters (Q_n^* та t^*), have been determined. Exceeding these critical values leads to the destruction of the coating (cracks, splits, detachment, etc.).

3. For the operative control of the electronic processing modes of oxide coatings, the task of implementing a uniformly distributed heat impact Q_n along the processed surface of an optical element with an oxide coating using a system of fixed REF has been solved. The following new regularities have been established: for each individual REF, increasing the current I_b from 50 mA to 300 mA, accelerating voltage V_y from 4 kV to 8 kV, and decreasing the distance to the processed surface l from $8\cdot10^{-2}$ m to $4\cdot10^{-2}$ m leads to an increase in the maximum thermal flow from REF $(q_n)_{max}$ by 1,9…2,5 times; for the working ranges of controlled parameters of REF (I_b = 50…300 mA, V_y = 4…8 kV, $l = 4\cdot10^{-2}…8\cdot10^{-2}$ m), the following ranges of changes in its energy characteristics have been obtained: concentration coefficient $k_0 = 5\cdot10^{-8}…5\cdot10^{-7}$ m^{-2}, electron flow thickness $2b = 5\cdot10^{-4}…1{,}5\cdot10^{-3}$ m, and maximum values $(q_n)_{max} = 5\cdot10^{-1}…8{,}5\cdot10^7$ W/m^2; for a uniformly distributed thermal impact $Q_n = const$, it has been found that with the number of electron flows N = 5…7, the approximation of the aggregated total F_n from individual beams to the specified Q_n is within 3…5 % in real-time mode. Increasing the number of REF to 50…70 achieves a relative error of $10^{-4}…10^{-5}$; critical values of REF parameters controlled by electron-beam equipment (I_{bj}^*, V_{yj}^* and l_j^*, j = 1, 2,…7) have been determined, implementing critical values Q_{ni}^* (i = 1, 2). Exceeding these critical values leads to a deterioration of coating operational characteristics, their destruction, and device failures.

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Визначення критичних значень параметрів системи нерухомих електронних потоків при обробці оксидних покриттів на протяжних оптичних елементах

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Розроблено математичну модель зовнішнього рівномірно розподіленого теплового впливу на поверхню плоского двошарового елемента з оптичного скала К108 та оксидного покриття з Al_2O_3, MgO, що враховує температурні залежності їх теплофізичних властивостей (об'ємної теплоемності та коефіцієнта теплопровідності). Визначено критичні значення параметрів зовнішніх теплових впливів (теплових потоків та часів їх дії), які призводять до руйнування покриттів (поява тріщин, відколів, відшарувань та ін.). Вирішено задачу реалізації рівномірно розподіленого теплового впливу вздовж поверхні оксидного покриття за допомогою системи нерухомих стрічкових електронних потоків (СЕП), що входять у вигляді програмно керованого модуля у оснастку сучасного електронно-променевого обладнання. Визначено допустимі режими обробки поверхонь покриттів (кількість СЕП, керовані параметри кожного СЕП (струм, прискорююча напруга та відстань до оброблюваної поверхні)), що дозволяють покращувати їх експлуатаційні характеристики та попереджати можливі руйнування у екстремальних умовах експлуатації приладів (підвищені температури нагріву, термоударні впливи та ін.). Електронно-променева обробка протяжних елементів з оптичного скла та керамік, елементів з п'єзокерамік, а також оптичних елементів з покриттями з оксидів металів визначається як потенційно спроможна для якісної обробки їх поверхонь за допомогою системи нерухомих СЕП, які можуть бути використані як елементна база у мікрооптиці, інтегральній та волоконній оптиці, функціональній електроніці та інших галузях точного приладобудування.

Ключові слова*:* Оптико-електронне приладобудування, Оптичні елементи, Нанорозмірні покриття з оксидів металів, Електронно-променева обробка, Теплові процеси, Оптимальне керування.