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Determination of Critical Values for Parameters of Electron Beam Microprocessing of Optical Plates with Double Curvature

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The widespread use of electron beam technology in optoelectronic instrumentation is constrained by the limited data on the critical values of the parameters of the electron beam (density of thermal effect of the beam, the time of this effect, etc.) on the optical elements of devices of various geometric shapes (flat, rectangular and curvilinear elements, etc.), the excess of which leads to the destruction of their surface layers (the appearance of cracks, chips, cavities, violation of surface flatness, etc.). Currently, the ranges of change for these parameters for flat plates, rectangular bars, cylindrical and spherical elements have been determined. However, the studies mentioned are absent for optical elements in the form of plates of double curvature, widely used in integral and fiber optics, microoptics and other areas of optoelectronic instrumentation. The work is devoted to the development of mathematical models of the thermal effect of an electron beam on optical elements in the form of plates of double curvature, that allow with a relative error of 5... 7 % to determine the critical ranges of changes in its parameters (density of thermal effect, time of its action), the excess of which leads to a deterioration in the physical and mechanical properties of the surface layers in the elements up to their destruction. This allows to prevent possible deterioration of technical and operational characteristics at the stage of manufacturing devices with the usage of electron beam technology.

Keywords: Optoelectronic instrumentation, Elements made of optical glass and ceramics, Electron beam technology, Maximum permissible thermoelastic stresses in optical elements.

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1. INTRODUCTION

The current level of development of optoelectronic instrumentation puts forward increased requirements for the performance characteristics of their optical elements (microhardness of the surface, spectral transmission coefficient, resistance to external thermal and mechanical shocks, etc.), which affect the technical and operational characteristics of devices (pulsed laser rangefinders of devices of sighting complexes, laser medical devices, IR devices, etc.) [1-4].

The widespread use of traditional methods of preparation and surface treatment of optical elements (mechanical, chemical, chemical-mechanical) has shown that it is impossible to obtain simultaneously clean and defect-free surfaces, as well as defect-free surface layers, which leads to deterioration of the technical and operational characteristics of optoelectronic devices.

Fundamental researches that have been carried out in the field of development of new high-energy technologies for processing various materials, including optical materials, have revealed that the most promising sources of energy for such technologies are focused flows of ions and low-temperature plasma, laser radiation, etc. [5-8].

However, the application, for example, of ionic and laser surface treatment of elements revealed a number of obstacles that limit the possibilities of their widespread use in optoelectronic instrumentation (violation of surface microgeometry; formation of local high-temperature zones with large temperature gradients that lead to the emergence of critical thermal stresses in materials and destruction of the latter; the complexity of control (especially with a scanning laser beam), etc.).

As practice has shown [1, 3, 9-12], the most convenient, environmentally friendly and easily controlled method of processing optical elements is the electron beam method. The following possibilities were shown: using a movable electron beam of tape form for polishing elements from optical glass and obtaining surfaces of high purity with minimal roughness, as well as for strengthening elements from optical ceramics and obtaining 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 constrained by the limited data on the critical values of the parameters of the electron beam (density of thermal effect of the beam, the time of this effect, etc.) on the optical elements of devices of various geometric shapes (flat, rectangular and curvilinear elements, etc.), the excess of which leads to the destruction of their surface layers (the appearance of cracks, chips, cavities, violation of surface flatness, etc.) (Fig. 1). Currently, the ranges of change for these parameters for flat plates, rectangular bars, cylindrical and spherical elements [1, 3] have been determined: the distributions of temperatures and thermoelastic stresses along the thickness of the elements depending on the density of the thermal effect of the beam q_b (W/m^2) and the processing time t (s) have been found by calculation; by comparing the maximum values of thermoelastic stresses $|\sigma|_{max}$ with their maximum permissible values of σ^* for specific optical materials (optical glass K8, K108, K208, etc.) and optical ceramics (KO1, KO2, KO3, etc.)) the critical values of q_b^* and t^*, which were recommended for practical use in the electron beam processing of various optical materials, were determined. However, the studies mentioned are absent for optical elements in the form of plates of double curvature, widely used in integral and fiber optics, microoptics and other areas of optoelectronic instrumentation. Therefore, the purpose of this work is to develop nonlinear mathematical models of the thermal effect of the tape electron beam on optical elements in the form of plates of double curvature of different thicknesses, taking into account the temperature dependences of the thermophysical properties in the material (volumetric heat capacity $C_V(T)$ and the coefficient of thermal conductivity $\lambda(T)$) and allowing to find critical values of processing parameters.

2. THE RESULTS OF THE RESEARCH AND THEIR ANALYSIS

The considered plates are cut out elements with a curvilinear surface having a double curvature r_1, r_2 – the main radii of curvature of the surface of the element at $z = 0$) and thickness H (Fig. 2). At the same time, as a result of the thermal effect of the scanning electron beam, a uniformly distributed heat flow $q_b(t)$ enters the surface of the plate [18, 19].

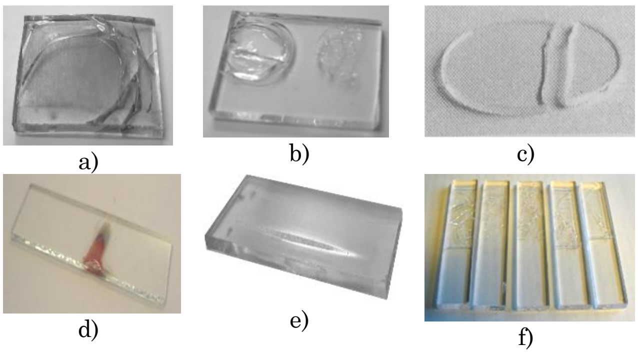


Fig. 1 – Different types of destruction of optical elements under the influence of an electron beam: cracks and chips (a, b, c), influxes (d), boiling (e) and wavy surfaces (f).

For the values used in practice H ($H = (6...12)\cdot 10^{-3}$ m), the condition $H >> \delta = 2\cdot(a_0^2\cdot\tau)^{1/2}$ is fulfilled δ – the depth of the thermal action zone (m) is satisfied; a_0^2 – coefficient of temperature conductivity of optical material (m^2/s); τ – time external thermal action (s)) [1, 13-15], which means that the depth of penetration of a heat wave into an element is much less than its thickness and can be considered as a semi-limited curvilinear environment ($\partial T/\partial x = \partial T/\partial y = 0$). At the same time, heat loss due to convection and radiation flow is not taken into consideration. In this case, the equations of the mathematical model of heat transfer in the plate are presented as [16, 17]:

$$C_V(T)\cdot(1+\frac{z}{r_1})\cdot(1+\frac{z}{r_2})\cdot\frac{\partial T}{\partial t}=\frac{\partial}{\partial z}[\lambda(T)\cdot(1+\frac{z}{r_1})\cdot(1+\frac{z}{r_2})\frac{\partial T}{\partial z}],$$

$$t > 0 \quad , \quad 0 < z < +\infty, \tag{1}$$

$$T|_{t=0}=T_0, \tag{2}$$

$$-\lambda(T)\cdot\frac{\partial T}{\partial z}|_{z=0} = q_b(t), \tag{3}$$

$$T\to T_0 \ , \ (\frac{\partial T}{\partial z})\to 0 \ , \text{ при } \ z\to +\infty. \tag{4}$$

Using dependencies $C_V(T)$ and $\lambda(T)$ [1, 3]

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

where C_{V0}, λ_0, υ – are empirical constants, and also taking into account that $q_b(t) = q_{b0} = const$, we get

$$(1+\frac{z}{r_1})\cdot(1+\frac{z}{r_2})\cdot\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}[\lambda(T)\cdot(1+\frac{z}{r_1})\cdot(1+\frac{z}{r_2})\frac{\partial\theta}{\partial z}],$$

$$t > 0 \quad , \quad 0 < z < +\infty, \tag{6}$$

$$\theta|_{t=0}= 0, \tag{7}$$

$$-\frac{\partial\theta}{\partial z}|_{z=0}=\bar{q}_n(t), \tag{8}$$

$$\theta\to 0 \quad , \quad (\frac{\partial\theta}{\partial z})\to 0 \quad , \text{ при } \ z\to +\infty, \tag{9}$$

where

$$\theta = T^{\nu+1} - T_0^{\nu+1} \quad , \quad \bar{q}_b(t) = \frac{q_{n0}\cdot(\nu+1)}{\lambda_0}. \tag{10}$$

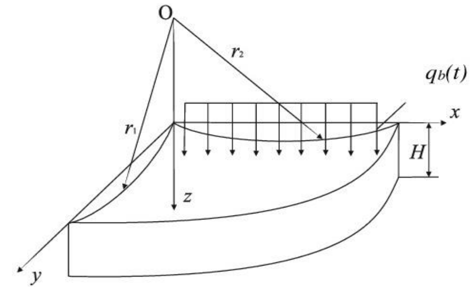


Fig. 2 – Scheme of heating of the double curvature plate by external thermal action from the electron beam: r_1, r_2 – radii of curvature of plate surface , m; H – plate thickness, m; $q_b(r, t)$ – surface density of thermal effect, m^2

Used for solving (6)-(9) the method of integral transformations (Laplace transform by variable t) [16]:

$$\bar{\theta}(z,s)=\int_0^{\infty}\theta(z,t)\cdot e^{-s\cdot t}dt. \tag{11}$$

We get the differential equation in the images

$$\frac{d}{dz}[(1+\frac{z}{r_1})\cdot(1+\frac{z}{r_2})\cdot\frac{\partial\bar{\theta}}{\partial z}]-\frac{s}{a_0^2}\cdot(1+\frac{z}{r_1})\cdot(1+\frac{z}{r_2})\cdot\bar{\theta}=0, \tag{12}$$

the solution of which for arbitrary radii r_1 and r_2 cannot be represented in elementary or special functions.

In the case of a sharp change in heat exchange conditions on the surface of the plate at $z = 0$ in the first period of time, large temperature gradients may occur, which cause significant thermal stresses, especially dangerous for optical materials with increased fragility. These gradients usually exist for a short period of time when the perturbations of the initial temperature distribution in the plate extend to the depth z, small compared to the absolute values of the radii of curvature r_1 and r_2. If, after differentiating by z in equation (6), the absolute values z/r_1 and z/r_2 are neglected in comparison with the unit, then it will take the form of

$$\frac{d^2\bar{\theta}}{dz^2} + 2\chi\cdot\frac{d\bar{\theta}}{dz} - \frac{s}{a_0^2}\cdot\bar{\theta} = 0, \quad (13)$$

where $\chi = \frac{1}{2}\cdot(\frac{1}{r_1}+\frac{1}{r_2})$ – medium surface curvature at $z = 0$;

$$-\frac{\partial^2\bar{\theta}}{\partial z^2}\Big|_{z=0} = \frac{\bar{q}_n}{s}, \quad (14)$$

$$\bar{\theta} \to 0\ ,\ (\frac{\partial\bar{\theta}}{\partial z}) \to 0\ ,\ \text{при}\ \ z \to +\infty. \quad (15)$$

The general solution of the boundary value problem (13) – (15) has the form [43]

$$\bar{\theta}(z,s) = \frac{\bar{q}_b\cdot a_0}{s}\cdot\frac{e^{-\frac{z}{a_0}\cdot(a_0\cdot\chi+(a_0^2\cdot\chi^2+s)^{1/2})}}{a_0\cdot\chi+(a_0^2\cdot\chi^2+s)^{1/2}}. \quad (16)$$

Denote $\tilde{\beta} = a_0\cdot\chi$ and estimate its value for optical glass (ceramics). For $a_0^2 = 0.6\cdot10^{-6}\ m^2/s$, r_1, r_2 = $10^{-2}\ m$ (corresponds to the real radii of curvature of the plate surface (curvilinear rasters, etc.)) and get that $\tilde{\beta} = 10^{-2}$, that is, for the elements under consideration $\tilde{\beta} \ll 1$.

Considering the following, we get

$$\bar{\theta}(z,s) = \frac{\bar{q}_b}{a_0^{-1}}\cdot\frac{e^{-\frac{z}{a_0}\cdot(\tilde{\beta}+s^{1/2})}}{s\cdot(\tilde{\beta}+s^{1/2})}. \quad (17)$$

Now on the table of images [16] we find:

$$\theta(z,t) = \frac{\bar{q}_b}{\chi}\cdot\{e^{\chi\cdot z}\cdot[1\text{-}erf(\frac{z}{2a_0\cdot t^{1/2}})]\text{-}e^{a_0^2\cdot\chi\cdot t}\cdot[1\text{-}erf(a_0\cdot\chi\cdot t+\frac{z}{2a_0\cdot t^{1/2}})]\}. \quad (18)$$

Taking into account (10), (11) we get

$$T(z,t) = \{T_0^{\nu+1} + \frac{(\nu+1)\cdot q_{n0}}{\lambda_0\cdot\chi}\cdot[e^{\chi\cdot z}\cdot[1\text{-}erf(\frac{z}{2a_0\cdot t^{1/2}})]\text{-}e^{a_0^2\cdot\chi^2\cdot t}\cdot[1\text{-}erf(a_0\cdot\chi\cdot t^{1/2}+\frac{z}{2a_0\cdot t^{1/2}})]\}^{\frac{1}{\nu+1}}. \quad (19)$$

Determination of thermoelastic stresses in the surface layers of the plates. A non-stationary temperature field in a plate with a thickness of " H: $T(z,t)$, where $z \in [0,H]$ that is, the temperature field in the plate changes only in its thickness. At the same time, as shown in [17], for an unlimited, surface force free plate with the ends free from fastening, the components of the stress tensor have the form of:

$$\sigma_{zy} = \sigma_{zz} = \sigma_{xy} = \sigma_{xz} = 0\ \ ,\ \ \sigma_{yy} = \sigma_{xx} = \sigma(z,t) = -\frac{\alpha_T\cdot E}{1\text{-}\nu}\cdot T(z,t)+C_1+C_2\cdot z, \quad (20)$$

where the axes of coordinates x, y lie on one of the boundary surfaces of the plate, for example, the lower, and $x \in [0, H]$; the constants C_1 and C_2 are derived from the following conditions: for any temperature field $T(z, t)$ the resulting force and the resulting moment per unit of length that are conditioned by these stresses at the edges of the plate equal to zero, i. e.

$$\int_0^H \sigma(z,t)dz = \int_0^H z\cdot\sigma(z,t)dz = 0. \quad (21)$$

Determining from here the constants C_1 and C_2 and substituting in (20), we get

$$\Sigma(z,t) = \frac{\alpha_T\cdot E}{1-\nu}\cdot(-T(z,t)+\frac{2}{H^2}\cdot(2H-3z)\cdot\int_0^H T(z,t)dz - \frac{6}{H^3}\cdot(H-2z)\cdot\int_0^H z\cdot T(z,t)dz), \quad (22)$$

The obtained formulas (19), (22) allow, with the help of known physical and technical characteristics of optical glass and ceramics, as well as the developed application packages [1, 3, 5, 6], to carry out calculations in dialogue mode and real-time mode on modern PCs of temperature distributions and thermoelastic stresses in the surface layers of optical plates of double curvature of different sizes depending on the main parameters of the electron beam (the value of thermal flow q_b and the time of its action t) and determine their critical values of q_b^* and t^* from the condition

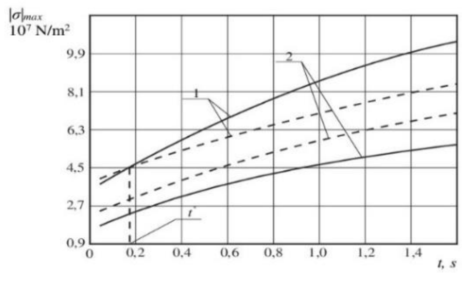
$$|\sigma|_{max} > \sigma^*, \quad (23)$$

where σ^* is the tensile strength of optical materials.

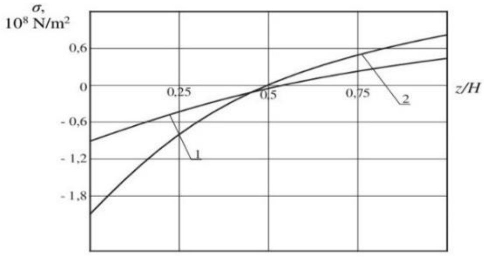
As a result of the conducted calculations (Fig. 3-5), it was found that at the thickness of the plate thermal stresses are located in the following way: compressive stresses take place near its surface ($\sigma < 0$, $|\sigma|_{max} = 4{,}3\cdot10^7 \ldots 4{,}8\cdot10^7$ N/m² – for optical glass К208 та $|\sigma|_{max} = 2{,}1\cdot10^8 \ldots 2{,}9\cdot10^8$ N/m² – for optical ceramics КО1).

A mutually unambiguous correspondence has been established between the parameters q_{b0}^* and t^*: for optical glass – an increase in the values of t^* from 0,1 c to 1,2 s leads to a decrease in the values of q_{b0}^* from $2{,}5\cdot10^7$ W/m² to $1{,}5\cdot10^7$ W/m², and for optical ceramics – an increase in the values of t^* from 0.5 s to 1.9 s leads to a decrease in the values of q_{b0}^* from $2{,}6\cdot10^7$ W/m² to $2{,}2\cdot10^7$ W/m².

Comparison of the results of calculations (see Figs. 4, 5) with experimental data showed that the differences between them do not exceed 5 ... 7 %.

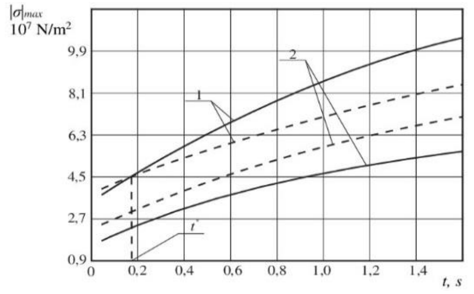


a)

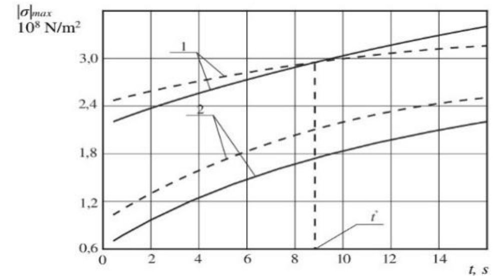


b)

Fig. 3 – Distribution of thermal stresses over the thickness of the plate of double curvature from optical glass K208 (a) and ceramics KO1 (b) depending on the external heat flow q_{b0} (T_0 = 300 K; H = 0,04 m; r_1, r_2 = 0,02…0,03 m; t = 0,5 s): 1 – q_{b0} = 2,5·10⁷ W/m²; 2 – q_{b0} = 7,3·10⁷ W/m².

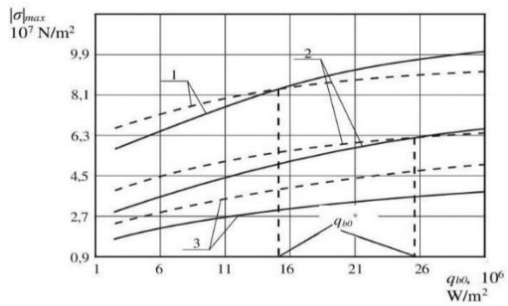


a)

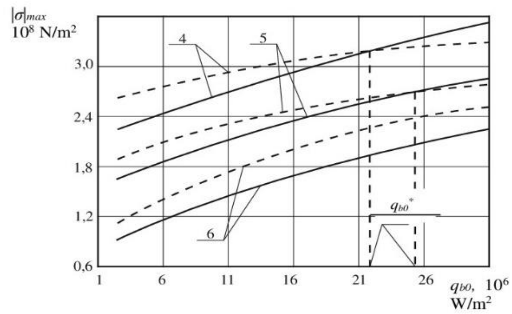


b)

Fig. 4 – Dependence of the module of maximum thermoelastic stresses $|\sigma|_{max}$ in a double curvature plate made of optical glass K208 (a) and optical ceramics KO1 (b) from the time of external thermal action for different values of external heat flow(T_0 = 300 K; H = 0,04 m; r_1, r_2 = 3·10⁻³…9·10⁻² m): 1 – q_{b0} = 7,3·10⁷ W/m²; 2 – q_{b0} = 2,5·10⁷ W/m²; t^*– critical action time, s; ———— – calculation results; – – – – – strength limit of optical material σ^*



a)



b)

Fig. 5 – Dependence of the module of maximum thermoelastic stresses $|\sigma|_{max}$ in a plate of double curvature made of optical glass K208 (a) and optical ceramics KO1 (b) from the external heat flow for different times of its action(T_0 = 300 K; H = 0,06 m; r_1, r_2 = 3·10⁻³…9·10⁻² m): 1 – t = 1.2 c; 2 – t = 0.2 s; 3 – t = 0.1 s; 4 – t = 9 s; 5 – t = 6 c; 6 – t = 0.5 s; q_{b0}^* – critical values of the external heat flow, W/m² ;———— – the results of calculations; – – – – – – – tensile strength of optical material σ^*

In conclusion, it should be noted that the developed mathematical models and methods for determining the critical values of the parameters of the electron beam (density of thermal exposure q_{b0}^* and the duration of its action t^*) by the microprocessing of surfaces of optical elements allow to create a scientifically based method for determining the optimal modes of finishing electron beam processing of elements in optoelectronic devices at their production stage. The practical use of this method allows to prevent possible deterioration of the technical and operational characteristics of the devices during their operation.

3. CONCLUSIONS

Nonlinear mathematical models of thermal influence of the electron beam on optical plates of double curvature have been developed, which take into account the temperature dependences of the thermophysical properties of materials (volumetric heat capacity, thermal conductivity coefficient) and allow to determine the distributions of temperature and thermoelastic stresses through their thickness with a relative error of 5 ... 7 %.

For the first time, the following influence of the parameters of the electron beam (heat flow q_{b0} and the time of its action t) on the value of the maximum thermoelastic stresses in the considered elements was determined: an increase in q_{b0} from 1,5 · 10⁷ W/m² to 2,5 · 10⁷ W/m² and t from 0,1 s to 1,9 s leads to an increase in maximum thermoelastic stresses of 1.2 ... 1.4 times for optical glass and 1.5 ... 2.4 times – for optical ceramics.

For the first time, critical ranges for changing the parameters of the electron beam have been determined (q_{b0}^*, t^*). These ranges depend on the nature of optical materials, the excess of which leads to the destruction of the surface layers of optical elements and the deterioration of the technical and operational characteristics of the devices up to their failure.

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Визначення критичних значень параметрів електронно-променевої мікрообробки оптичних пластин двоякої кривизни

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Широке використання електронно-променевої технології у оптико-електронному приладобудуванні стримується обмеженістю даних про критичні значення параметрів електронного променю (густини теплового впливу променю, часу цього впливу та ін.) на оптичні елементи приладів різної геометричної форми (плоскі, прямокутні та криволінійні елементи та ін.), перевищення яких призводить до руйнування їх поверхневих шарів (поява тріщин, відколів, западин, порушення площинності поверхні та ін.). На даний час визначено діапазони зміни вказаних параметрів для плоских пластин, прямокутних брусків, циліндричних та сферичних елементів.Однак вказані дослідження відсутні для оптичних елементів у вигляді пластин двоякої кривизни, широко використовуваних у інтегральній та волоконній оптиці, мікрооптиці та інших направленнях оптико-електронного приладобудування. Робота присвячена розробленню математичних моделей теплового впливу електронного променю на оптичні елементи у вигляді пластин двоякої кривизни, що дозволяють з відносною похибкою 5…7 % визначати критичні діапазони зміни його параметрів (густини теплового впливу, часу його дії), перевищення яких призводить до погіршення фізико-механічних властивостей поверхневих шарів елементів аж до їх руйнування. Це дозволяє на стадії виготовлення приладів з використанням електронно-променевої технології попереджати можливі погіршення їх техніко-експлуатаційних характеристик.

Ключові слова*:* Оптико-електронне приладобудування, Елементи з оптичного скла та кераміки, Електронно-променева технологія, Гранично допустимі термопружні напруження у оптичних елементах.