IMPROVEMENT OF TECHNICAL AND OPERATIONAL CHARACTERISTICS OF DEVICES WITH OPTICAL ELEMENTS BY PRELIMINARY ELECTRON BEAM TREATMENT OF THEIR SURFACE

УЛУЧШЕНИЕ ТЕХНИКО-ЭКСПЛУАТАЦИОННЫХ ХАРАКТЕРИСТИК ПРИБОРОВ С ОПТИЧЕСКИМИ ЭЛЕМЕНТАМИ ПУТЕМ ПРЕДВАРИТЕЛЬНОЙ ЭЛЕКТРОННО-ЛУЧЕВОЙ ОБРАБОТКИ ИХ ПОВЕРХНОСТЕЙ

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Abstract: *The results of experimental studies of the influence of electron beam parameters (density of heat action, the speed of movement) on the properties of the surface layers of the elements of optical ceramics (changes in the structure of the material through the thickness of the element, the amount of surface microhardness, values of residual thermal stresses in the layers, the thickness of the hardened layers, their stability to external thermal and mechanical stresses) are. The optimum range of parameters of the beam, within which there is improvement in the properties of the surface layers of the optical elements, which leads to the increase of the basic technical-operational characteristics of devices based on (reliability, lifetime) in the conditions of use of devices with the influence of external-heat are established.*

KEY WORDS*: optical ceramics, electron beam, elements of precision instruments*

1. Introduction

Modern devices with optical elements for measurement and thermal control of different physical nature objects (flat plates and cylindrical disks as substrates of IR instruments filters, the input protective windows in sight for observation in the visible and infrared regions of the spectrum and so on) in the conditions of their use are exposed to intense external-heat (higher heating temperature and external pressure, the shock-heat in a shot and the flight and so on. d.) [1 - 3]. Under these conditions, there is a substantial change in the properties of the surface layers of the optical elements up to their destruction (cracking, chipping and other defects), which leads to significant deterioration of the technical-operational characteristics of devices and their failure.

So actual is the prevention of these adverse events at the stage of design and manufacture of devices considered to optical elements. In many studies carried out by different authors in the direction [2 - 7], it was shown that one of the most promising directions in removing undesirable changes in the properties of the surface layers of the optical elements is their finishing movable electron beam. In particular, it shows the possibility of the electron beam method in the formation of surface layers of optical ceramics with changed physico-chemical properties [2, 4, 5, 7]. However, systematic studies of the effects of the electron beam on the surface layers of the elements is currently very limited.

Therefore, this paper presents the results of studies to determine the optimum range of parameters of the electron beam (of the heat exposure, the speed of movement), leading to the most significant improvement of the properties of the surface layers of the elements of optical ceramics (KO1, KO2, KO3, KO5, KO12) and the main technical -operational characteristics of devices based on them (reliability, durability) in terms of their application taking into account the impact of external-heat.

2. Results and discussion

The above electron-microscopic analysis of images of the surface and transverse sections of the elements of the optical ceramics showed that there is a marked change in the structure of their depth (up to 200 ... 250 microns), which depends significantly on the electron beam parameters (density of thermal exposure F_n and speed of movement *V).* It is noticed a rough terrain (of strain origin) with elements of "viscous" destruction, which indicates the ability of the optical material to create resistance to fracture at a load.

The optimal range of parameters of the electron beam (F_n= $5\cdot10^6…3\cdot10^7$ W/m^2, $V = 5\cdot10^{-3}…1,5\cdot10^{-2}$ m/s), within which there is the most significant (more than several times) improving the basic properties of the surface layers of the element: increasing surface microhardness (H_v, MPa); the emergence of them compressive stress ($|\sigma_C|$, MPa), leading to the emergence of hardened layers thickness Δ (microns) is established. Thus, an increase F_n to $3\cdot10^7$ Wt/m^2 leads to an increase in the microhardness of the elements surface treated by an electron beam 1,8 ... 6,3 times compared with the untreated elements; wherein a reduction moving speed of the beam from V = $1,5\cdot10^{-2}$ m/s to V = $5\cdot10^{-3}$ m/s also conducts to increase of the elements microhardness 1,3 ... 1,5 times (Fig. 1,2).

Results of research of the microhardness measurement on depth of the optical ceramics elements treated by an electron beam, indicate that the microhardness of the material of all types of ceramics considered sufficiently rapidly decreases, tending to its value for the untreated material. The thickness of the hardened layer, where there are major structural changes and it increases the microhardness of the treated material for the parameter of the electron beam, changes in the range of 50...130 microns to 100...250 microns with thicknesses of workpieces 4...$6\cdot10^{-3}$ m. The value Δ depends strongly on the nature of the ceramic, and the parameters of the electron beam (Fig. 3): an increase F_n from $5\cdot10^6$ W/m^2 to $3\cdot10^7$ W/m^2 leads to an increase in the thickness of the hardened layer 1,6...3,1 times and increasing the moving speed the beam from $5\cdot10^{-3}$ m/s to $1,5\cdot10^{-2}$ m/s leads to a reduction in the thickness of the hardened layer 1,3...1,4 times.

As a result conducted X-ray studies have shown that regardless of the nature of ceramics (KO1, KO2, KO3, KO12, KO5) in the surface layers of the elements treated by an electron beam to considered range changes density of a thermal exposure and the moving speed of notable phase changes were not observed, but there is an increase in the size of the crystal grains of the material. In respect to the extension lines of the X-ray it is revealed that almost irrespective of the crystallographic directions in the crystal lattices of ceramics after electronic processing occurs a marked change microdistortions and size of the mosaic blocks: the value of the original mosaic blocks to processed by an electron beam optical element is increased in 3,9 times for the elements of the KO1, in 5,5 times for the elements of KO2, in 3,3 times for the elements of KO12, in 4,7 times for the elements of the KO3 and in 7,7 times for elements of KO5 and microstrain value decreases in 3,7 times for elements of KO1, in 5,4 times for the elements of KO2, in 4,2 times for the elements of KO12, in 5,5 times for the elements of KO3 and in 5,9 times for the elements of KO5.

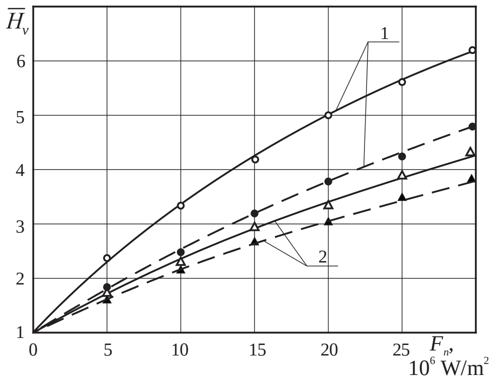


Fig 1. Dependence of the relative microhardness $\overline{H}_V$ ($\overline{H}_V = \dfrac{H_V}{H_{V0}}$, где H_V, H_{V0} – microhardness of the treated and untreated element, respectively) of the surface of the elements of the optical ceramics KO12 (1) and KO5 (2) from the density of the thermal exposure of the electron beam (H_{V0} = 1,18·10^3 MPa (KO12); 1,21·10^3 MPa (KO5)): —— – V = 5·10^{-3} m /s; – – – V = 1,5·10^{-2} m/s; Δ, ○, ▲, ● - experimental data.

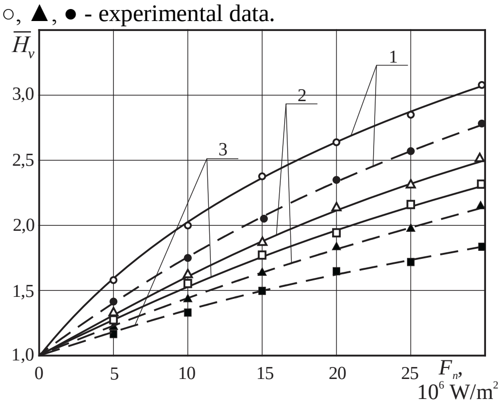


Fig. 2. Dependence of the relative microhardness $\overline{H}_V$ of the surface of the optical ceramics elements KO3 (1), KO2 (2) and KO1 (3) from the density of the thermal exposure of the electron beam (H_{V0} = 1,85·10^3 MPa (KO3); 2,17 · 10^3 MPa (KO2); 2,86·10^3 MPa (KO1)): —— – V = 5·10^{-3} m /s; - - - – – V = 1,5·10^{-2}m/s; Δ, ○, □, ▲, ■, ● - experimental data.

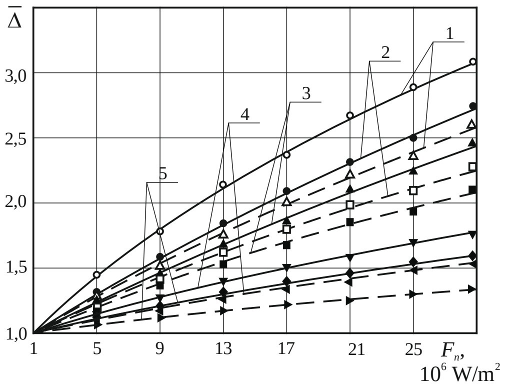


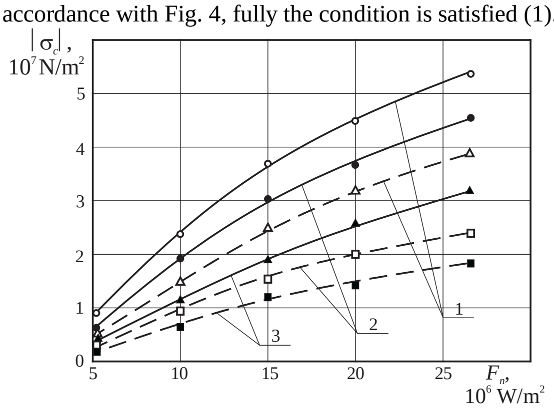
Fig. 3. Dependence of the relative thickness of hardened layers by electron beam $\overline{\Delta}$ ($\overline{\Delta} = \dfrac{\Delta}{\Delta_0}$, where Δ, Δ_0 - the thickness of hardened layers, respectively at the current value F_n and at F_n = 10^6 W/m^2) of optical ceramics elements KO5 (1) KO3 (2) KO1 (3), KO2 (4) and KO12 (5) on the values of its thermal effects density (Δ_0 = 80 microns (KO1), 121 microns (KO2), 67 microns (KO3), 49 microns (KO5), 129 microns (KO12)): —— – V = 5·10^{-3} m/s; - - - - V = 1,5 · 10^{-2} m/s; Δ, ○, □, ▲, ■, ♦, ▼, ●, ►, ◄ - experimental data.

The analysis of received changes of the crystal lattice parameters of elements after the electronic treatment in accordance with known methods for calculating these radiographs [2], which are based on the direct analytical dependence between the residual stresses in the surface of the element and change of the period of the main components crystal lattice of the considered ceramics, showed the presence of compressive stresses in thin surface layers of the elements of the depth of 40 ... 60 microns to the center of the treated areas (portions size 4·10^{-2}...5·10^{-2} m) in the considered range of parameters changes of the electron beam (Fig. 4). It is determined that the increase F_n from 5·10^6 W/m^2 to 2,7·10^7 W/m^2 leads to the increase of compressive stress in the surface layers of the elements in 2...6 times; thus the increase moving speed electron beam from 5·10^{-3} m/s to 1,5·10^{-2} m/s leads to the reduction of compressive stresses in 1,6...2,3 times.

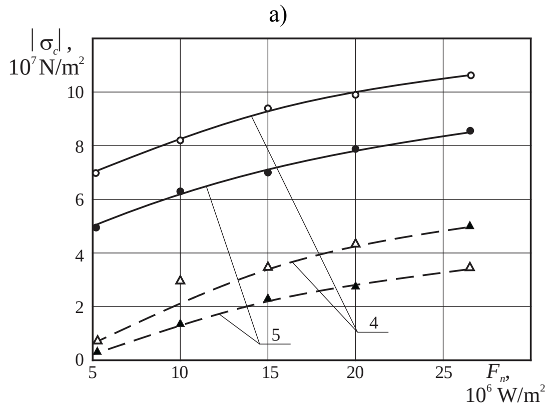
In addition, the change for the selected ranges F_n= 5·10^6…2,7·10^{7}W/m^2 and V = 5·10^{-3}…1,5·10^{-2}m/s the following condition is performed

$$|\sigma_c| < \sigma^*, \quad (1)$$

where σ^* – the maximum permissible thermoelastic stresses in the surface layers of the considered elements, the excess of which leads to their destruction (cracks, chips and other defects). For example, under normal conditions (T_0 = 300 K, P = 10^5 Pa) for the considered ceramics σ^* = 8·10^7 N / m^2 (KO1), 7,5·10^7 N / m^2 (KO2), 5,7·10^7 N / m^2 (KO3), 1,4·10^8 N / m^2 (KO5), 1,18·10^8 N / m^2 (KO12) [2], that is, in accordance with Fig. 4, fully the condition is satisfied (1).



a)



b)

Fig. 4. Dependence of module of the compressive thermoelastic stresses $|\sigma_c|$ in the surface layers of the elements from optical ceramics KO1, KO2, KO3, KO5 KO12 from the density of the thermal exposure of the electron beam: —— – V = 5·10^{-3} m/s; – – – – V = 1,5·10^{-2} m/s; a) - the elements of the optical ceramics KO5 (1), KO1 (2) and KO3 (3); b) - elements of optical ceramics KO12 (4) and KO5 (5); Δ, ○, □, ▲, ■, ● - experimental data.

The tests for resistance to external thermal influences untreated and treated by an electron beam optical elements are conducted on the equipment that protected by patents of Ukraine [1, 2], simulating the effect of external heat fluxes and high pressure on their working surfaces. It is established (Fig. 5) that for the elements treated by an electron beam, the critical values of external thermal flows q_n^* (the time of their impacts t^*) for the studied range of parameters change of the beam are increased in 1,5 ... 1,7 times; thus the increase of the external pressure from 10^5 Pa to 10^7 Pa leads also to the decrease of the value q_n^* in 1,3 ... 1,5 times.

That is, after the electron beam treatment of the working surfaces of the optical ceramics elements (KO1, KO2, KO3, KO5, KO12) their resistance to external thermal effects on 30 ... 70% for the whole range of variation of external pressure P = 10^5...10^7 Pa is increased.

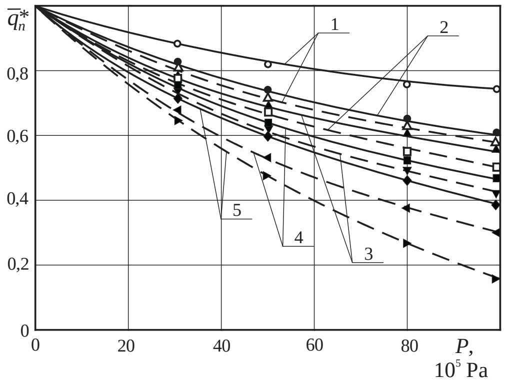


Fig. 5. Dependence of relative critical values of the external thermal flow $\bar{q}_n^*$ ($\bar{q}_n^* = \dfrac{q_n^*}{q_{n0}^*}$, where q_n^* and q_{n0}^* - the current value q_n^* and its value at P = 10^5 Pa, respectively) from pressure for different times of its exposure to the optical ceramics elements KO5 (1) KO1 (2), KO12 (3) KO3 (4) and KO2 (5): ——— – t = 20 s; – – – – t = 10 s; Δ, ○, □, ▲, ■, ♦, ▼, ●, ►, ◄ - the experimental data.

The tests for resistance to external mechanical influences of optical elements untreated and treated by an electron beam were carried out in a known method "Autoglass" [2] it was found the critical values of the height $H_{кр}$ from what the steel ball of diameter d = $4\cdot10^{-3}$...$5\cdot10^{-3}$ m, free falling on the element surface destroys it (the appearance of cracks, chips and other defects).

Table 1

The influence of the electron beam processing of working surfaces of optical cylindrical disks on the dependence of the relative amount of their damages (k) from the heating rate *) (discs from the optical ceramics KO2 of diameter $3\cdot10^{-2}$…$5\cdot10^{-2}$ m and thickness $4\cdot10^{-3}$…$6\cdot10^{-3}$ m, T_0 = 300 K, P = 10^5 Pa)

Disc / Speed of heating disc K/s	k, %	
	Untreated by electron beam	Treated by electron beam
200…250	30…40	10…20
250…300	40…50	20…30
300…400	50…60	30…40

*) Note. $k = k_p / k_0$, where k_0, k_p - the total number of the tested plates and the number of plates that were destroyed, respectively.

It is established (Fig. 6), that the elements treated by an electron beam, the values of $\overline{H}_{cr}$ 1,4...3 times higher than the values for untreated elements.

Thus, their resistance increases to the external mechanical stresses after the electron beam treatment of working surfaces of optical ceramics elements (KO1, KO2, KO3, KO5, KO12) in some times. It was shown that pre- electron beam treatment of the working surfaces of cylindrical optical discs used, for example, as substrates of diffusing screens, input protection windows, sighting systems for observation in IR spectrum, and so on and under conditions of variable external heating, which simulates their actual operating conditions, taking into account the effect of external thermal influences, heat, leads to reducing the amount of damage of the plates in 2,5...3 times (Table 1) and increases the service life in 2...2.5 times.

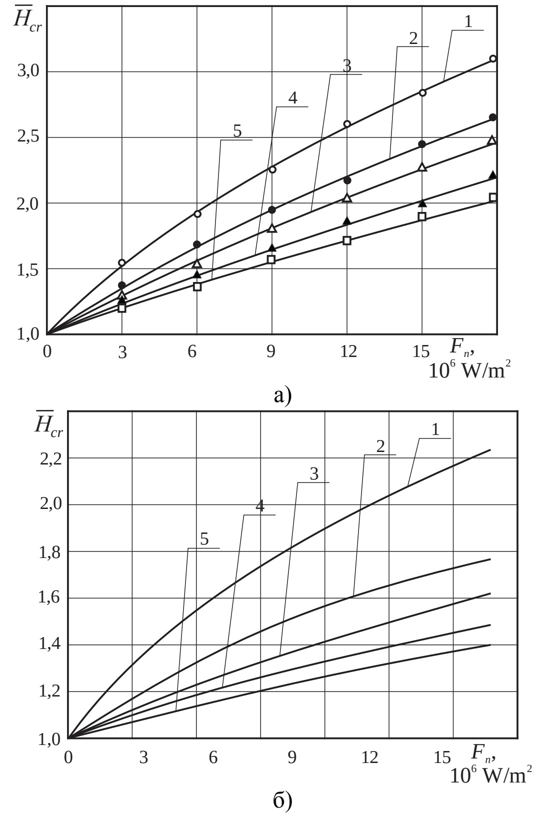


Fig. 6. Dependence of the relative values of the critical height of fall of a steel ball $\overline{H}_{cr}$ ($\overline{H}_{cr} = \dfrac{H_{cr}}{H_{cr0}}$, where H_{cr}, H_{cr0} - the elevation of the height of the elements, treated and untreated by an electron beam, respectively (0,42 m (KO1), 0,33 m (KO2), 0,25 m (KO3), 0,51 m (KO5), 0,48 m (KO12) [2])) on the surface of the optical ceramics elements KO3 (1), KO2 (2) KO5 (3), KO12 (4) and KO1 (5) from the density of the thermal exposure of the electron beam for different speeds of its movement (T_0 = 300 K, the thickness of the element 4...6 · 10^{-3} m): a) - V = 5 · 10^{-3} m/s; b) – V = $1,5\cdot10^{-2}$ m/s; Δ, ○, ▲, ●, □ - experimental data.

3. Conclusions

1. It is found that by pretreating the working surfaces of the optical ceramics elements (KO1, KO2, KO3, KO5, KO12) by movable belt electron beam by adjusting its parameters in the optimal range of variation (density of thermal exposure (F_n= $5\cdot10^6$…$3\cdot10^7$ W/m^2 and beam movement speed V = $5\cdot10^{-3}$…$1,5\cdot10^{-2}$ m/s), it is possible to improve the basic properties of the surface layers of the elements:
– increasing F_n to $3\cdot10^7$ W/m^2 and decreasing V from $1,5\cdot10^{-2}$ m/s to $5\cdot10^{-3}$ m/s leads to the increase of the microhardness of the surface elements that are processed by an electron beam 1,5...6,3 times compared with untreated elements;
– increasing F_n from $5\cdot10^6$ W/m^2 to $3\cdot10^7$ W/m^2 leads to the increase of the thickness of the hardened layer in 1,6...3,1 times; thus increasing the moving speed of the beam from 5 · 10^{-3} m/s to 1,5 · 10^{-2} m/s already leads to decreasing value Δ in 1,3... 1,4 times;
– compressive stresses in thin surface layers of elements of depth of 40...60 microns with increasing F_n from $5\cdot10^6$ W/m^2 to $2,7\cdot10^7$ W/m^2 increase in 2...6 times, and the increase V from $5\cdot10^{-3}$ m/s to 1,5 · 10^{-2} m/s leads to their reducing in 1,6...2,3 times.
2. The tests of optical elements in their resistance to external thermal and mechanical stress are shown:
– the elements treated by an electron beam are subjected to fracture at the critical values of the external thermal flows q_n^*

(since their impact t^*), which are 1,5... 1,7 times greater than in the case of untreated elemets; thus, increasing the external pressure from 10^5 Pa to 10^7 Pa in both cases leads to decreasing q_n^* (or t^*) in 1,3...1,5 times;

– for elements untreated by an electron beam, the critical height drop of the steel ball on their surface, leading to the destruction of the elements 1,4 ... 3 times lower than for treated elements.

3. It was found that pre- electron beam treatment of cylindrical disks of optical ceramics used as working parts of instruments for measurement and thermal control of different physical nature objects, leads to reducing the amount of destructions in 2,5 ... 3 times under conditions of variable external heating and also increases their resistance to external mechanical stress (more than some times), thereby increasing the service life of the instrument in 2...2,5 times.

4. Literature

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