# Influence Patterns Of The Finishing Electron-Beam Treatment Of The Surface Of Optical Parts On Their Physical-Mechanical Properties

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***Abstract:*** **It has been established that, with the optimum parameters of the electron beam (thermal pressure density, speed) in the result of the surface flowing of optical parts, there is an improvement in the physical and mechanical properties of their surface layers: the purity and smoothness of the surface increases; microfirmity is increasing; hardened layers with compressive stresses appear; the changes in the structure of the surface layers and their homogenization occur; flint-oxygenic grid becomes similar to the quartz glass. This results into the increase of the resistance of the elements to the external thermal and mechanical effects and ultimately improves the reliability of the appliances when they are operated under extreme conditions (elevated heating temperatures, supersonic airflow, axisymmetric rotation, etc.).**

***Keywords— optical instrument-making, optical glass, optical ceramics, electron beam, physical-mechanical properties***

## I. INTRODUCTION

The use of modern optical-electronic devices under extreme conditions acutely arise the problem of increasing their reliability in operation.

The optical parts of the instruments under these conditions are subjected to intense thermal and mechanical effects (elevated heating temperatures, external pressures, shock thermal actions under the conditions of supersonic airflow and axisymmetric rotation, etc.).

These external influences result in the formation on the surface of the optical parts of cracks, chipsing, and breaking of the surface geometry. At the same time, the physical and mechanical properties of surface layers of optical parts get worse, that affect their optical characteristics and resistance to external influences, leading to a decrease in accuracy up to their failure under extreme operating conditions [1-6].

New possibilities for improving the physical and mechanical properties of optical parts are opened by their surface electron-beam treatment, that allows to modify their surface layers [7-13].

Phenomena related to the modification of the physical-mechanical properties of the surface layers of optical parts by the electron beam are not fully studied or systematized.

This makes the relevance of studies of influence patterns of finishing electron-beam treatment (FEBT) on the properties of the working surfaces of optical parts.

The purpose of this work is to investigate the impact of the finishing electron-beam treatment of the surface of optical parts on their physical-mechanical properties.

## II. CHARACTERISTICS OF OPTICAL PARTS AND METHODS OF THEIR INVESTIGATION

In order to investigate the influence of electron beam parameters on the properties of detail surface layers from optical glasses (К8, К208, БК10 (ВК10)) and optical ceramics (КО1, КО2, КО3, КО5, КО12), $3\text{-}10^2$ discs were used with diameter... $3{\cdot}10^{-2}...5{\cdot}10^{-2}$ m and thickness $4{\cdot}10^{-3}...6{\cdot}10^{-3}$ m [8, 14].

Modern methods of physical-chemical analysis [14-16] have been used for pilot studies: the methods of the raster electron microscopy (REM) and the transfused electron microscopy (TEM) to study the surface structure and surface layers of optical parts, as well as to determine the thickness of the char layers; the methods of atomic-power microscopy (APM) and micro dimpling by Vickers to measure the residual microbends on the surface of the optical elements as well as its micro-firmness; methods of filming in X-rays on diffractometres DRON 2.0 and DRON 3.0 to measure termotensions values in surface layers of optical parts; contact methods (chromel-alumel thermocouples, ranges of temperature measurement to 1600 K) and proximity methods (photoresistors, ranges of temperature measurement to 1600 K) to measure the surface temperature of the optical parts.

For the finishing electron-beam treatment of surface layers of optical parts to improve their physical and mechanical properties, they used an advanced installation in part of the developed technological set up to automatically measure and control the temperature of the processed surface, and electronic beam sensing, which is protected by patents (Ukrainian patent №57551, Ukrainian patent № 91523).

In the result of the conducted research on sensing of electron beam by a known method of the rotating probe, the following empirical dependencies of thermal pressure density in its centre from the managed parameters of the electron-beam installation (relative error 5 ... 8%) are established:

$$F_n(x)=\sqrt{\frac{k_0(I_л,l)}{\pi}}\cdot\frac{I_л\cdot V_y}{B\cdot erf\left[b(I_л,l)\cdot\sqrt{k_0(I_л,l)}\right]}, \qquad (1)$$

$$k_0(I_л,l) = 1,237\cdot10^7-6,587\cdot10^5 l-3,725\cdot10^4 I_л+1,518\cdot10^2 I_л l, \qquad (2)$$

$$b(I_л,l)\frac{1,75}{\sqrt{k_0(I_л,l)}}, \qquad (3)$$

where $F_n$ – density of thermal action in the centre of the electron beam , Wt/m$^2$; $k_0$, $2b$ – coefficient of concentration (fineness of heat wave ) and thickness of electron beam, m; $I_n$ – electron beam current, mA; $V_y$ – external voltage, *kV; l* – distance from the processed surface of optical part, m.

It is determined, that for the working ranges of change of the stated parameters of installation ($I_n$ = 50…300 mA, $V_y$ = 6...8 *kV*, *l* = 0, 04...0,08 m) the following ranges of change of the energetic characteristics of electron beam are realized: $k_0$ = (0,5…5)·10$^7$ m$^{-2}$; *2b* = (0,5…1,5)·10$^{-3}$ m; $F_n$ = 10$^6$…10$^9$ Wt/m$^2$. At the same time the travel speed of the beam has changed within V = 0…0, 1 m/s.

## III. THE RESULTS OF INVESTIGATIONS AND THEIR ANALYSIS

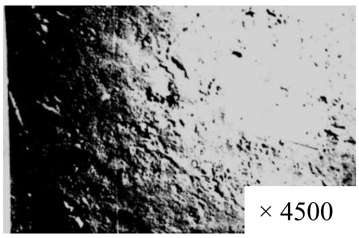
Electronic microscopic studies of surfaces of the optical glass parts (Figure 1, 2) showed that, after machining, the most characteristic is the presence of microdefects –fractures with depth to 0,1 ... 0,7 μm, scratches up to 2 ... 5 μm, and also bubbles in size of 10$^{-3}$...10$^{-2}$ μm.

After the electron-beam processing, the bubble sizes (diameters) on the surface of the elements become reduced by 2 ... 4 times, thus other wavinesses smaller than 1 ... 2 μm are not observed, that is, it means in the result of the electronic beam treatment of the surface the elements as if become "cleaned", minor defects are eliminated.

At the same time, when the density of heat pressure *Fn* is increased from 5·10$^6$ Wt/m$^2$ to 7·10$^7$ Wt/m$^2$, the area of these defects is reduced by 1,8...2,7 times.

The study of scans of surfaces of glass joints from detail chips before and after electron-beam processing indicates that in the first case the height of the wavinesses is 30 ... 40 nm and in the second is reduced to 0,5 ... 1,2 nm.


a)

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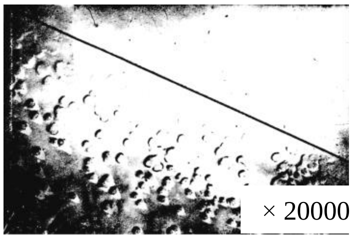
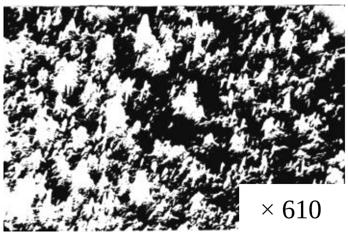



c)

*Fig.1. Electron-microscopic shots of the surface of the detail made of optical glass K8: surface after machining (a); surface after electron-beam treatment (b); from optical glass K108 (c): after abrasive polishing (1) and after electron-beam treatment (2).*

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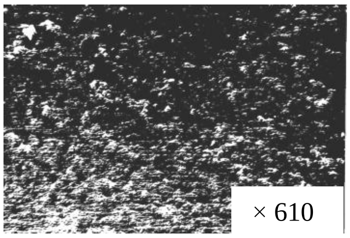


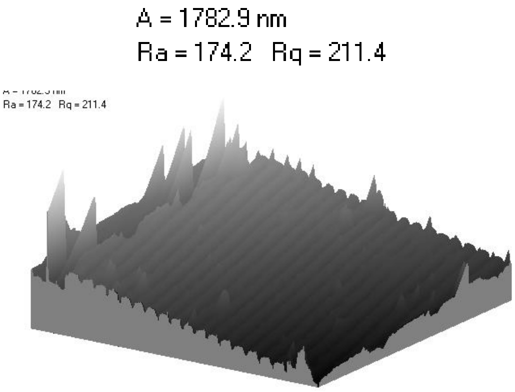

b)

*Fig.2. Scans of the detail surface made of optical glass K208 after machining (a) and after electron-beam treatment (b), Y-modulation.*

Typical microphotographs of the results of the study of surfaces of parts from optical glass by AFM methods (e.g. for optical glass K8) are presented in Fig. 3a (after standard mechanical polishing) and Fig. 4a (after the electronic beam polishing), and the typical profile of the cross section of the surface under study is in Fig. 3b (after mechanical polishing) and Fig. 4b (after the electronic beam polishing). Research of the morphology of the surface of optical parts after standard machining and electron beam polishing showed that in the first case the surface is significantly heterogeneous in terms of residual wavinesses (rough spots).

At the same time, the average of the profile's deviation $R_a$ from the base plane and the mean-square deviation of profile $R_q$ from the specified plane (values $R_a$ and $R_q$ were defined by profiles (type of fig. 3b, 4b) using standard techniques) at different points of the observed surface may differ in several times, and in the latter case the specified obstacles are noticeably smoothed and the differences in meanings of $R_a$ and $R_q$ for different patches of the surface are not greater than 10 ... 15%. In addition, the values of $R_a$ and $R_q$ for the surface of optical parts polished by the standard mechanical method is even higher than for a surface that has been polished by an electronic beam.

Therefore, within this error, the height of the residual wavinesses *h* on the processed by electron beam details' surface of the optical glass was defined, for example, as the average value $R_a$ ($h \approx \overline{R_a}$) for several randomly selected patches of the surface (usually 3…4 patches were studied).

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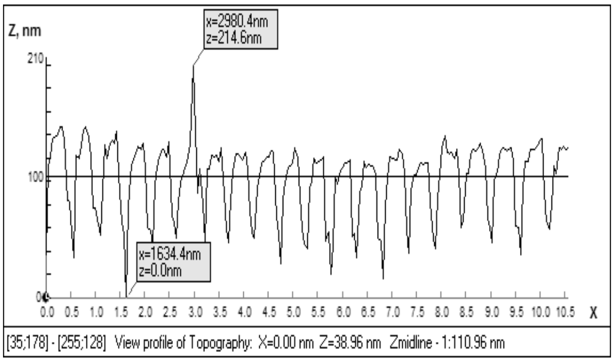
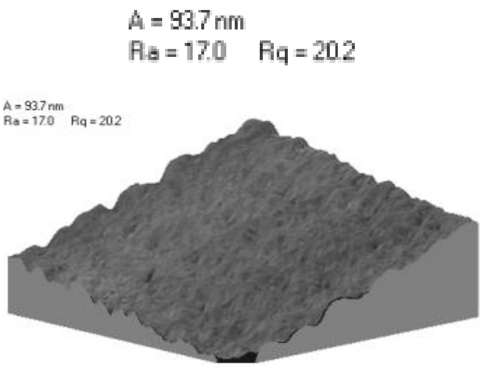



b)

*Fig3. Three-dimensional (a) AFM-image of the part processed by mechanical polishing method of detail surface from optical glass К8, along which the scanning of the measure probe is realized, and also a также cross section profile of the scanned surface (b).*

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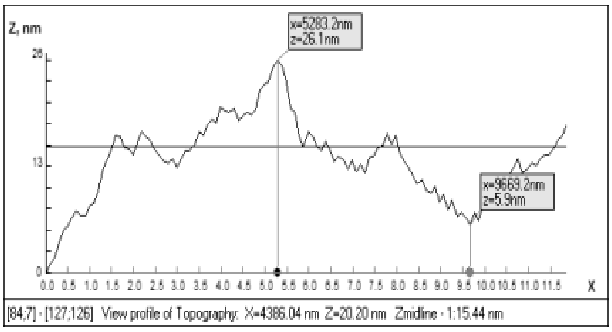



b)

*Fig.4. Three-dimensional (a) AFM-image of the part of the detail surface processed by electron beam that is made of optical glass К8, along which the scanning of measure probe is observed, and also the cross section profile of the scanned surface (b).*

Detailed studies of the surface structure of the details from optical glass made it possible to determine the following effects of electron beam parameters on the height of residual wavinesses (Figure 5, 6): increase of the density of the heat exposure of the electronic flow of $F_n$ from $3{\cdot}10^6$ Wt/m$^2$ до $7{\cdot}10^8$ Wt/m$^2$, for example, for the speed of its displacement used in practice of $V$ = $3{\cdot}10^{-3}$ m/s leads to the reduce of the height of the residual wavinesses from 5 ... 6 nm to 0,7...1,2 nm; However, the nature of the impact of $F_n$ and $V$ on $h$ does not depend to the glass mark.

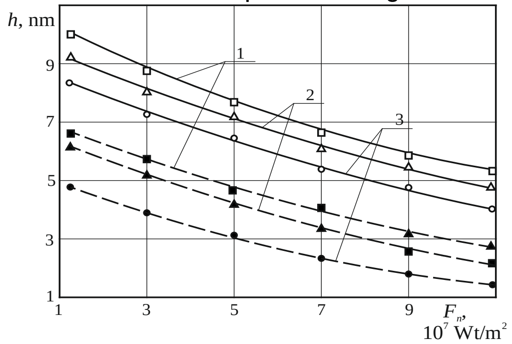
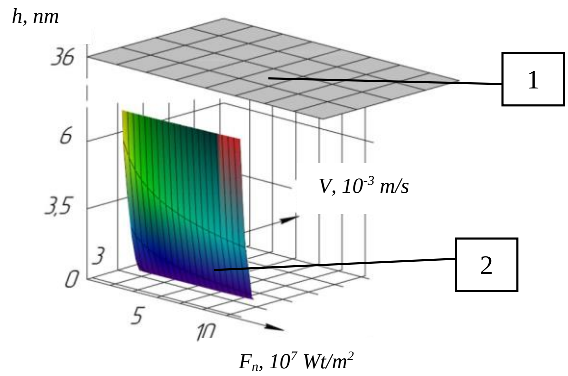



*Fig.5. Dependence of the height of residual wavinesses of detail surface of optical glasses К8 (1), TF 110 (ТФ110) (2) and BK10 (БК10) (3) from density of heat effect of the electron beam: ——— – travel speed of the electron beam $V = 7{\cdot}10^{-2}$ m/s; – – – – travel speed of the electron beam $V = 5{\cdot}10^{-3}$ м/с; ∆, ○, □, ▲, ●, ■ – experimental points.*



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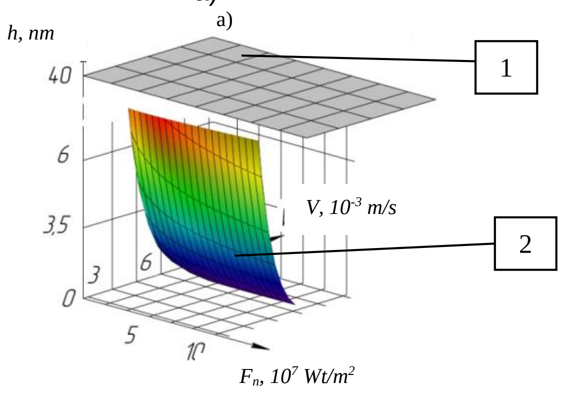



b)

Fig.6. Dependencies for the elements of optical glass K208 (a), BK10 (БК10) (b): 1 – details, not processed by the electron beam; 2 – details processed by the electron beam.

The examination of fracture patterns of surface layers from optical glass before and after electron beam treatment showed that the maximum depth of the main area of thermal action or the thickness of the melted layer $h_m$ can reach 300...350 μm and is strongly dependent on the value $F_n$ and the speed $V$ of its displacement (Figure 7 – 9), which exceed the maximum permissible values of wavinesses $h_m^*$ = 150... 200 μm under some critical values $F_{ni}^*$ and $V_i^*$ ($i$ = 1, 2,…) which results in inflows on the surface of the parts, the violation of its plane and eventually the violation of condition of the surface layers of the optical parts and their screening.

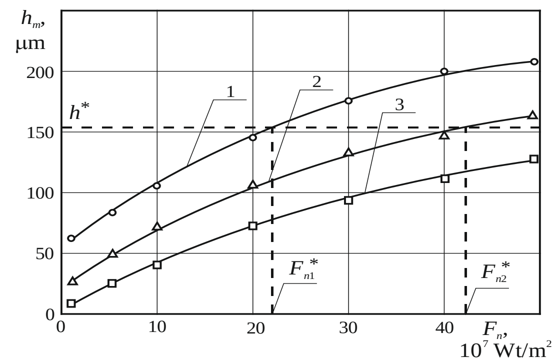



Fig.7. Dependence of the thickness of the melted layer $h_m$ in details from optical glass from the thickness of thermal action of electron beam ($V = 5{\cdot}10^{-3}$ m/s): 1 – detail from optical glass K8; 2 – detail from optical glass K108; 3 – detail from optical glass K208; Δ, ○, □ – experimental points.

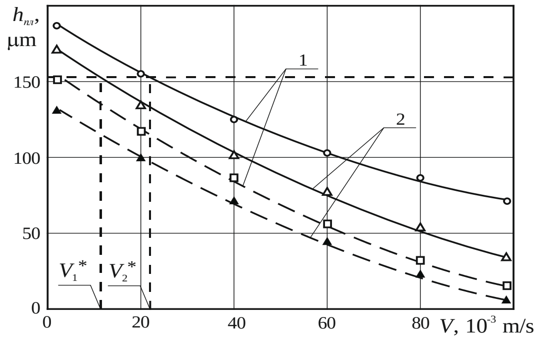
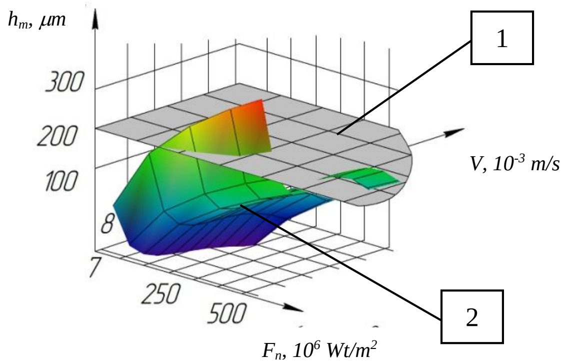



Fig.8. Dependence of the thickness of melted layer $h_m$ in details from optical glasses BK110 (БК10) (1) and TF110 (TФ110) (2) from travel speed of electron stream: ———— – $F_n = 5{\cdot}10^8$ Wt/m²; – – – – – $F_n = 3{\cdot}10^8$ Wt/m²; Δ, ○, □, ▲ – experimental points.

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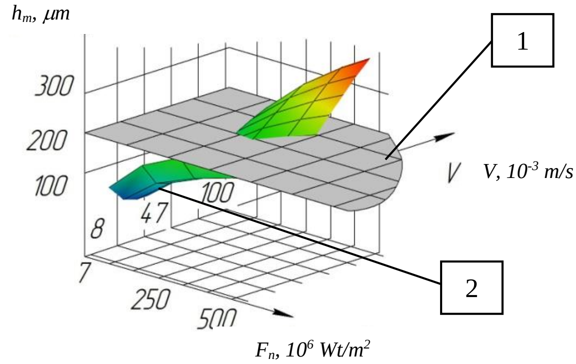



b)

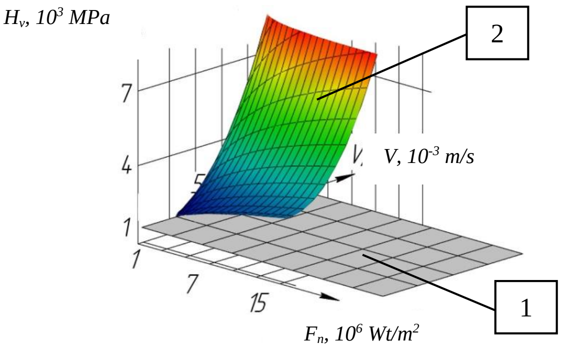
Fig. 9. Dependencies $h_m(F_n, V)$ for details from optical glass K208 (a), BK10 (БК10) (b), TF 110 (TФ110) (c): 1 – exposure limits $h^*$; 2 – values $h_m$, that are obtained at electron beam treatment of the.

It is established that the layers formed by electronic beam on the detail surface from the optical glass has changed chemical composition to various extent. Thus, an analysis of the change in the elemental composition of layers on the surface of elements from the optical glass K8, K108, K208, carried out using the wave dispersion spectrometer, showed a decrease in the concentration of Na and O, increase of Si concentration and constant concentration of K. At the same time, using the method of the X-ray-spectral analysis of the raw and processed by electron beam parts from the optical glass BK10 and TF110 shows that there is no noticeable quantitative change in the chemical composition of the layers on their surface, but it can be concluded that the homogeneity of the distribution of elements in the microvolumes of the surface layer is improved after the electron-beam treatment.

It is also established that the electronic beam treatment of parts from optical glass by welding leads not only to homogenization of the surface, but also to the orient alteration of grid of glass, which becomes approximate to the structure of the quartz glass. This is mainly due to the removal of the K ions, and other elements – modifiers, simultaneous effects of high temperatures on the surface, up to 1300...1600 K, resulting in an increase in the resistance of the optical parts to external thermal actions and decrease of the number of device failures on their basis under extreme conditions.

Electron microscopic analysis of the images of surfaces and sections of optical ceramics before and after electronic beam treatment shows that there is a noticeable change in structure at the depth of the material (up to 200...250 μm), which is most dependent on the parameters of the electron beam ($F_n$, $V$). In this case, the coarse topography is noticeable (of the distorted nature) with the elements of "viscous" destruction, indicating the ability of the material to resist the destruction at the load.

It has been determined that the effects of electron beam on the parts from the optical ceramics ($F_n$ = $10^6...2\cdot10^7$ Wt/m$^2$, $V$ = $10^{-3}...2\cdot10^{-2}$ m/s) increases the microfirmity of its surface, depending on the parameters of the electron beam: an increase in the $F_n$ from $10^6$ Wt/m$^2$ to $1,5\cdot10^7$ Wt/m$^2$ leads to the increase of the microfirmity of the ceramics surface by 1,5...1,7 times, and a decrease of $V$ of from $1,5\cdot10^{-2}$ m/s до $10^{-3}$ m/s increases the microfirmity of the ceramics surface by 1,3... 1,4 (Figure 10).

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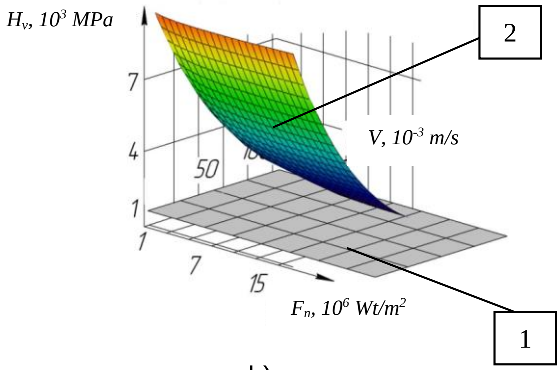
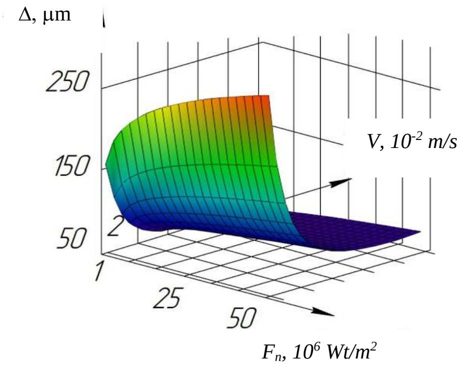



b)

*Fig.10. Dependencies $H_v\left(F_n,V\right)$ for details of optical ceramics КО3 (a), КО5 (b): 1 – details not processed by electron beam; 2 – details treated by electron beam.*

It is determined that the thickness of hardened layer (Δ), where the main structural changes occur and the microfirmity of processed detail increases, changes within the rage from 70...90 μm to 210...230 μm at the thicknesses of processed objects $4...6\cdot10^{-3}$ m (fig. 11).

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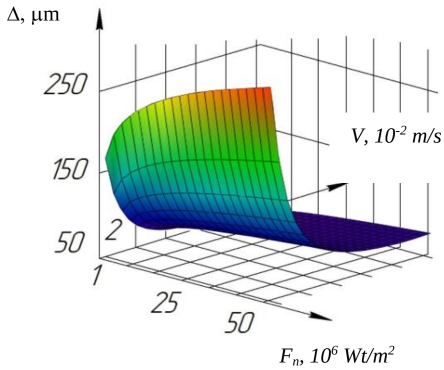


b)

*Fig.11. Dependencies for details from optical ceramics КО3 (a), КО5 (b).*

In the result of the conducted researches it was shown, that irrespective of the ceramics nature (КО1, КО2, КО3, КО12, КО5) in the surface layers of details, that are processed by electron beam, for the observed ranges of change of the thickness of thermal action (to $1,5\cdot10^7$ Wt/m$^2$) and travel speed (to $2\cdot10^{-2}$ m/s) noticeable phase changes are not observed, but the increase in the size of crystalline granules takes place.

With relative extension of the lines in X-ray patterns it is established that, almost independently from the crystallographic directions in the crystalline grilles of the ceramics after electron beam treatment there appears a noticeable change of micro-distortions and size of the mosaic blocks.

Analysis of the resulting changes in the parameters of the crystalline parts, after electron-beam treatment, showed compressive stresses in thin surface layers of parts at depths of 40...60 μm for the central part of the processed sections (size of sections $4\cdot10^{-2}...5\cdot10^{-2}$ m in the observed ranges of electron beam change: for parts from the optical ceramics КО1 – to 30...40 MPa; for parts from the optical ceramics КО2 – to 60...70 MPa; for parts from the optical ceramics КО3 – to 25...30 MPa; for parts from the optical ceramics КО5 – to 55...65 MPa; for parts from the optical ceramics КО12 – to 75...90 MPa.

## IV. CONCLUSION

For the first time the dependencies of finishing electron-beam treatment (FEBT) of the optical parts are defined. By regulating the optimal range changes of the beam parameters (the thickness of heat $F_n$ = $7\cdot10^6...8\cdot10^7$ Wt/m$^2$, travel speed $V$ = $5\cdot10^{-3}...5\cdot10^{-2}$ m/s), it is possible to improve physical and mechanical characteristics of its surface layers:

- the sizes of the defects decrease on the detail surface by 2…4 times, and the their occupied area – by 1,8…2,7 times;
- высоты остаточных микронеровностей на поверхности деталей уменьшаются от 30…40 нм до 0,3… 5 нм;
- the structure of surface layers changes, homogenization takes place, silicon-oxygen grid becomes closer to quartz glass;
- the thickness of the melted layer can reach to 300…500 μm, exceeding the maximum allowed values 150…200 μm, at which the geometry of parts and the state of their surface layers is violated;
- compression stresses are generated to 25…90 MPa in the surface layers of details from optical ceramics at depth to 40...60 μm, microthickness of their surfaces increases by 1,3...1,7 by, and the thickness of hardened layers increases from 70…90 μm to 210…230 μm.

Consequently, finishing electron-beam treatment (FEBT) leads to the increase of detail resistance to the external heat and mechanical effects and, after all, to the increase of realibility of devices by their under extreme conditions.

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