# IMPROVING THE RELIABILITY OF INSTRUMENTS FOR MEASURING AND THERMAL CONTROL OF OBJECTS OF DIFFERENT PHYSICAL NATURE BY THE FINISH ELECTRON-BEAM PROCESSING SURFACES OF OPTICAL ELEMENTS

# ПОВЫШЕНИЕ НАДЕЖНОСТИ ПРИБОРОВ ДЛЯ ИЗМЕРЕНИЯ И ТЕПЛОВОГО КОНТРОЛЯ ОЪБЕКТОВ РАЗЛИЧНОЙ ФИЗИЧЕСКОЙ ПРИРОДЫ ПУТЕМ ФИНИШНОЙ ЭЛЕКТРОННО-ЛУЧЕВОЙ ОБРАБОТКИ ПОВЕРХНОСТЕЙ ИХ ОПТИЧЕСКИХ ЭЛЕМЕНТОВ

Associate Professor Ph.D. Yatsenko I.[1], Professor dr. eng. Antonyuk V.[2], senior researcher dr. eng. Kyrychenko O.[3], Professor dr. eng. Vashchenko V.[4]

Department of Electrotechnical Systems[1], Department of Physics[4] - Cherkassy State Technological University, Ukraine

Faculty of instrument-making[2], National Technical University of Ukraine "Kiev Polytechnic Institute", Ukraine

Department of organization of technogenic-prevention work and health safety[3] - Cherkassy Institute of Fire Safety named after Heroes of Chornobyl of National University of Civil Protection of Ukraine, Ukraine

E-mail: irina.yatsenko.79@mail.ru

***Abstract:*** *The optimum ranges of the electron beam parameters change (density of heat exposure and speed of movement), within which there is a substantial improvement (more than 2 ... 3 times) of the basic properties of the surface layers of the optical elements are found. The tests of the optical windows of laser rangefinders under intensive external heating and hemispherical optical fairings of IR devices at supersonic blowing by air flow and axisymmetric rotation that simulate real operating conditions, have shown that in the case of processed by electron beam optical windows and fairings it reduces the number of their destruction and increases the reliability of the devices during the operation, taking into account the impact of external-heat.*

***KEY WORDS****: optical glass, optical ceramics, electron beam processing, elements of precision instrument-making*

## 1. Introduction

Modern devices with optical elements for measuring and thermal control of different physical nature objects (laser rangefinders sighting systems with optical windows of the transmitting and receiving channels, IR devices with optical hemispherical fairing for homing and surveillance, etc.) in operating conditions are exposed to intense external heat (higher heating temperature and external pressure, the shock-heat in a shot and a flight and so on).

Under these conditions a variety of negative defects (cracks, bumps, depressions, nodules etc.), further development of which leads to destruction of elements (detachment, chipped, undulating surface appear) are formed on the surface and in the surface layers of the optical elements. The result is a worsening of their basic properties, reduced resistance to external mechanical and thermal stresses, which results in reduction of reliability of devices during their operation to the influence of external-heat [1 - 7].

There fore relevant is the anticipation of these adverse events during the design and manufacturing of the considered devices with optical elements. In many studies carried out by different authors in the direction [8 - 12], it was shown that one of the promising areas in removing undesirable changes in the properties of the surface layers of the optical elements is their finishing by movable electron beam. In particular, it shows the possibility of an electron beam method in the formation of the surface layers elements of the optical glass and ceramics with modified physical and chemical properties [2, 9, 10, 12].

However, there has not been established the optimum ranges of the parameters changes of the electron beam, within which there is the most significant improvement in properties of the surface layers of the elements that affect the reliability of devices during their operation.

Therefore, this paper presents the results of studies to determine the optimal ranges of change of the electron beam parameters (density of heat exposure, movement speed) that lead to the most significant improvement in properties of the surface layers of the elements of the optical glass (K8, K108, K208, and others) and ceramics ( KO1, KO2 and others) and increase the reliability of devices during their operation.

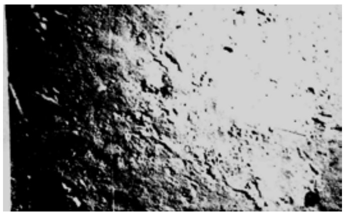
## 2. Results and discussions

The following optimal ranges of electron beam parameters: the density of heat exposure $F_n = 7{\cdot}10^6 \ldots 8{\cdot}10^8$ W/m$^2$ and the moving speed $V = 5{\cdot}10^{-3} \ldots 5{\cdot}10^{-2}$ m/s, within which there is the most significant improvement of the properties of the surface layers of the optical elements (more than 2 ... 3 times) are established.

Electron microscopic study of surfaces of optical glass elements (fig. 1, 2) showed that after machining the most characteristic there is the presence of various microroughness - small cracks of 0.1 ... 0.7 microns depth, fine scratches of 2 ... 5 microns length and bubbles of $10^{-3}$...$10^{-2}$ microns size. After electron beam treatment the bubble sizes (diameters) are reduced in 2 ... 4 times on the surface elements, while other microroughness of less than 1 ... 2 microns are not observed, that is by treating the surface with an electron beam elements like "purified "small defects are eliminated. Thus, the area which is occupied by these defects decreases in 1.8 ... 2.7 times with increasing $F_n$ from $5{\cdot}10^6$ W/m$^2$ to $7{\cdot}10^7$ W/m$^2$ .

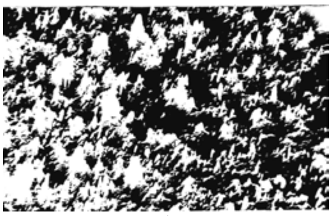
Study of scans of thin elements surfaces of chips before and after electron beam treatment indicates that in the first case microroughness height of 30 ... 40 nm, and in the second it is reduced to a level of 0.5 ... 1.2 nm. The following effect of an electron beam parameters on the height of the residual microscopic irregularities: an increase in the density of an electron beam heat exposure from $10^7$ W/m$^2$ to $8{,}5{\cdot}10^7$ W/m$^2$, for example, used in practice, the speed of its movement $V = 8{\cdot}10^{-3} \ldots 5{\cdot}10^{-2}$ m/s leads to a reduction of residual microroughness height from 3...5 to 1.0...1.5 nm (Fig. 3a) is defined.

*a)*

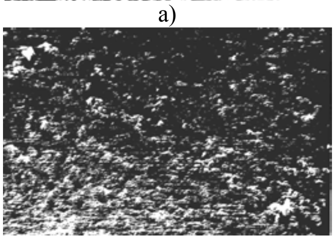


*b)*

***Fig. 1.*** *An electron microscopic images of the surface of optical glass elements K8: a) - a surface after mechanical processing, × 3700; b) - a surface after electron beam processing, × 4500.*



a)



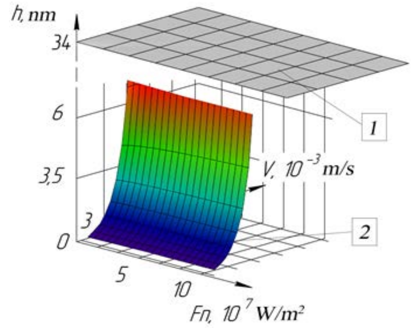
b)

***Fig. 2.*** *The scans of the element surface of the optical glass K208: a) - a surface to electron beam processing, Y-modulation, × 610; b) - a surface after electron beam processing, Y-modulation, × 610.*

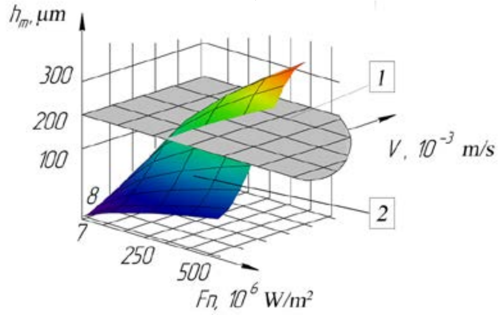
It is found that the maximum thickness $h_m$ of the molten layer can reach values of 250 ... 300 microns, which can exceed the maximum allowable value $h^*$ = 150…200 microns, which leads to disruption of flatness and geometrical shape of the optical element (Fig. 3b). Thus $h_m$ value depends essentially on the values of $F_n$ and its movement speed $V$: an increase of $F_n$ from $7{\cdot}10^6$ W/m$^2$ to $8{\cdot}10^8$ W/m$^2$ are used in practice, the values of V increases the melted layer thickness from 25 microns to 230 microns; increasing the speed of movement of an electron beam from $10^{-3}$ m/s to $10^{-2}$ m/s when in practice, the used values of $F_n$ already lead to a reduction of depth in fusion from 200 microns to 30 microns.

It has been shown that exposure of an electron beam on the ceramic optical elements of ($F_n = 10^6...2{\cdot}10^7$ W/m$^2$, $V = 10^{-3}...2{\cdot}10^{-2}$ m/s) increases the microhardness of their surface depending on electron beam parameters: $F_n$ increase from $10^6$ W/m$^2$ to $1.5{\cdot}10^7$ W/m$^2$ increases the microhardness of the ceramic surface in 1.5...1.7 times, and a reduction from $1.5{\cdot}10^{-2}$ m/s to $10^{-3}$ m/s results an increase in the microhardness of ceramic surface in 1.3 ... 1.4 times (Fig. 4a).

It is found that the thickness of the hardened layer ($\Delta$,microns), where there are major structural changes and it is increased the microhardness of the treated material examined for electron beam parameters that is changed in the range from 70...90 microns до 210...230 microns in thickness of processed workpieces $4...6{\cdot}10^{-3}$ m (Fig. 4b). Value of $\Delta$ also depends essentially on the electron beam parameters: increase $F_n$ from $10^6$ W/m$^2$ to $2{\cdot}10^7$ W/m$^2$ results in an increase in the thickness of the hardened layer of 1.8 ... 2.6 times, and increasing the speed of movement of the beam from $1.5{\cdot}10^{-3}$ m/s to $2{\cdot}10^{-2}$ m/s leads to a reduction in the thickness of the hardened layer in 1.7 ... 2.5 times. The presence of compressive stresses up to 25 ... 90 MPa in thin surface layers of the elements of 40 ... 60 microns depth for the central part of the processed areas (size portions $4{\cdot}10^{-2}...5{\cdot}10^{-2}$ m) in these ranges of electron beam parameters change is determined.




a)



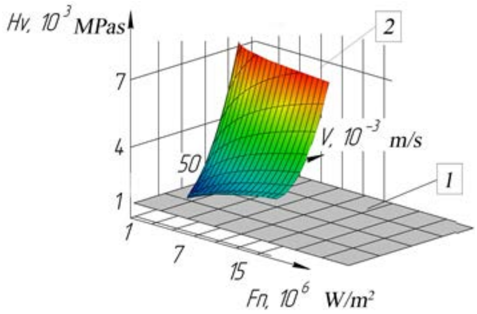

b)

***Fig. 3.*** *The dependence of the height of the residual microroughness h (a) on the surface of the optical glass element K108 (a) and a maximum thickness of its melted layer $h_m$ (b) from the electron beam parameters: 1 - the maximum permissible values $h^*$; 2 - $h_m$ values that were obtained when processing by an electron beam.*

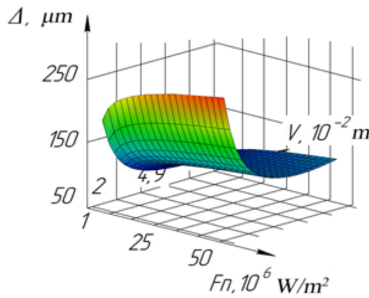
In addition, it was found that, after finishing electron-beam processing of the optical elements, resulting in improvement of the above properties of surface layers, there is an increase of elements resistance to external influences: increasing the critical values of the external heat flows $q_n^*$ and $t^*$, the excess of which leads optical elements to fracture and failure of devices in 1.4…1.5 times for optical glasses and in 1.3…1.7 times for optical ceramics; an increase of the external pressure to $10^7$ Pa reduces the values of $t^*$ and only in 1.4 ... 1.5 times for the optical glass and in 1.3 ... 1.7 times for optical ceramics.

It was also shown that the limit values $\sigma^*$ of thermoelastic stresses at different heating temperatures T = 300...1200 K for optical elements, processed by electron beam, in 1.7 ... 2.3 times higher for the optical glasses, in 1.8 ... 2.7 times - for optical ceramics.

The test analysis of the optical ceramics elements hardened by electron beam, for resistance to external mechanical impacts according to standard techniques (it was defined critical height $H_{кр}$ from which a steel ball of diameter $d = 4{\cdot}10^{-3}...5{\cdot}10^{-3}$ m, freely falling, destroys the element surface, Fig. 5) showed (for $F_n = 10^8...5.5{\cdot}10^8$ W/m$^2$, $V = 10^{-2}... 5{\cdot}10^{-2}$ m/s) that for unprocessed elements - $H_{кр}$ = 0.18...1.1m, and for processed - $H_{кр}$ = 0.37...1.35 m.




*a)*




b)

***Fig. 4.*** *The dependence of the surface microhardness $H_v$ (a) of an optical ceramics element of KO1 (a) and the thickness of its hardened layers Δ (b) of the electron beam parameters: 1 - unprocessed surface; 2 - the electron beam processed surface.*

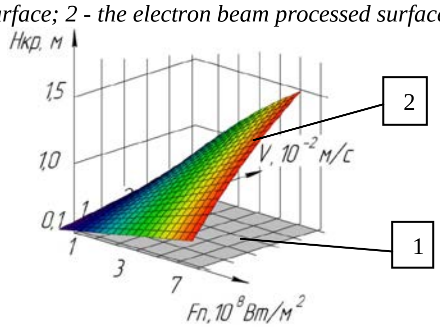



***Fig. 5.*** *The dependence of critical value $H_{кр}$ for the optical ceramics elements of KO2 from the electron beam parameters: 1 - unprocessed surface; 2 - surface-processed by electron beam.*

Thus, the finish electron beam processing of optical elements leads to an improvement in their surface layer properties, which ultimately increases their resistance to external mechanical and thermal impacts, and can enhance reliability of devices during their operation under conditions of external-heat.

Indeed, carried out tests of optical windows of laser rangefinder under intense external heating and hemispherical fairings IR devices at supersonic blowing air flow and axisymmetric simulating actual operating conditions have shown that in the case of processed by electron beam input windows and fairings in the zones of maximum external-heat (most dangerous areas on their surfaces where the fairings may undergo to destruction) occurs in 1.7 ... 2.3 times less damage than unprossed windows and fairings (Table 1).

Table 1

The effect of electron beam processing of the optical windows surfaces of laser sights and hemispherical fairing of IR devices targeting and observation on the number of their destruction $\overline{k}$ *) (%) depending on the parameters of the external-heat (heating rates $V_1$ (K/s) for windows from optical glass K8; airflow speed $V_2$ (m/s) for the fairings from optical ceramics KO2)

| Input window / $V_1$, K/s | $\overline{k}$, % | |
|---|---|---|
| | Before electron-beam processing | After electron-beam processing |
| 100…200 | 40…50 | 20…30 |
| 200…300 | 50…60 | 30…40 |
| 300…400 | 60…70 | 40…50 |

| Fairing / $V_2$, K/s | $\overline{k}$, % | |
|---|---|---|
| | Before electron-beam processing | After electron-beam processing |
| $5\cdot10^2…10^3$ | 30…40 | 10…20 |
| $10^3…1.5\cdot10^3$ | 40…60 | 20…40 |
| $1.5\cdot10^3…2\cdot10^3$ | 60…80 | 30…50 |

*) Note. $\overline{k} = \dfrac{k}{k_0}$, where $k_0$, $k$ – the total number of test input windows and fairings and their number accordingly subjected to destruction. The angular speed of an axisymmetric rotation of fairings in this range of variation (up to $4\cdot10^3$ rad/s) is not affected much the number of their destruction.

The coefficient of reliability as a criterion of laser rangefinders performance at different speeds of external heating, as well as IR-devices at supersonic air flow blowing is determined by the following formula [12]:

$$W(V_i) = 1 - \frac{N(V_i)}{N_0}, \; i = 1, 2, \qquad (1)$$

where $W(V_i)$ - the probability of working capacity preserving of the considered devices under the external heat conditions; $N(V_i)$ - the number of devices that deny for the given parameters of external-heat (destruction of the input windows and fairings was taken as the failure of the device as a whole); $N_0$ - the total number of input windows and fairings which are tested.

The calculations using formula (1) revealed that the increase in the heating rate of the input windows of laser rangefinders (from 100 K/s to 400 K/s) and blowing by air flow fairings of considered IR devices (from $7\cdot10^2$ m/s to $2\cdot10^3$ m/s), implemented in practice in terms of actual operation, lead in the case of their finish electron-beam processing of surfaces to the increase of these devices reliability in 1.3 ... 1.9 times (Fig. 6, 7).

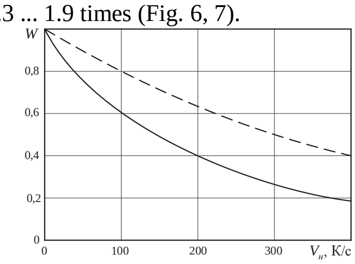



***Fig. 6.*** *The dependence of the probability of failure-free operation of laser sights in external heat conditions from the external heating rate of the optical windows: ——— – optical windows, not processed by electron beam; – – – – optical windows, which surface is processed by electron beam (the beam parameters $F_n = 5\cdot10^8$ W/m², $V = 5\cdot10^{-3}$ m/s).*

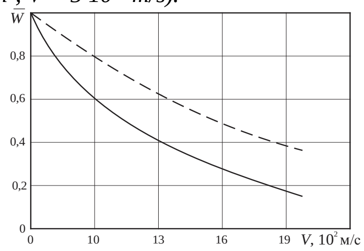



***Fig. 7.*** *The dependence of the probability of failure-free operation of IR devices under terms of the shot and the flight on the supersonic airflow speed by air flow of their hemispherical fairings: ——— – fairings, not processed by electron beam; – – – – fairings processed by electron beam (beam parameters $F_n = 2\cdot10^7$ W/m², $V = 10^{-3}$ m/s).*

## 3. Conclusions

1. It is found that in the result of finish electron-beam processing of element surfaces of the optical glass (K8, K108, K208) and ceramics (KO1, KO2) for optimal ranges of change of the electron beam parameters (density of heat exposure $F_n = 7\cdot10^6…8\cdot10^8$ W/m² and the speed of movement $V = 5\cdot10^{-3}…5\cdot10^{-2}$ m/s) there is a significant improvement in the properties of their surface layers:
- various negative defects disappear on the surface (scratches, fine bubbles, cracks, etc.) remaining after the standard machining processing, it becomes atomically smooth;

- height of residual microscopic irregularities on the surface is reduced from 30 ... 40 nm to 0.5 ... 1.2 nm, and the thickness of the molten layer is 250 ... 300 microns, which may exceed the maximum permissible values of 150 ... 200 microns, not breaking the flatness and geometric forms of the elements;
- the surface micro-hardness increases in 1.5...1.7 times, the thickness of the hardened layers reaches 210 ... 230 microns with compressive stresses up to 25 ... 90 MPa.

2. It is shown that in a result of improving the properties of surface layers of the elements after ttheir electron beam processing, the optical elements resistance increases to external mechanical and thermal impacts:

- the critical value of the external heat fluxes and the times of their actions increases in 1.5 ... 4 times, that leads to the destruction of the elements; the increase of external pressure to $10^7$ Pa reduces the listed critical values in 1.3 ... 1.7 times;
- increase in 1.7 ... 2.7 times the maximum permissible values of thermal stress in the temperature range 300 ... 1200 K, the excess of which leads to the destruction of the elements;
- the critical height of a steel ball fall on the surface of elements, leading to their destruction, rise from 0.18 ... 1.1 m to 0.37 ... 1.35 m.

3. It is found that after finishing electron-beam processing of the optical elements, resulting in improved properties of their surface layers and increasing the resistance of the elements to external influences, with increasing heating rates of the input optical windows of the laser rangefinders (up 400 K/s) and the speed of air blowing flow (up $2{\cdot}10^3$ m/s) and axisymmetric rotation (angular speed of up to $4{\cdot}10^3$ rad/s) fairings of IR devices, increasing their reliability in 1.3 ... 1.9 times.

## *4. References*


1. Vashchenko V. A., Kotelnikov D. I., Lega Y. G., Krasnov D. M., Yatsenko I. V., Kirichenko O. V. Teplovye protsesy pri elektronnoi obrabotke opticheskich materialov i ekspluatatsii izdelii na ich osnove (Thermal processes in the electronic processing of optical materials and use of products based on them) Kiev: Naukova Dumka, 2006, 368 p.

2. Vashchenko V. A., Yatsenko I. V., Lega Y. G., Kirichenko O. V. Osnovy elektronnoi pbrobky vyrobiv z optychnych materialiv (The basics of electronic processing of optical materials) Kiev: Naukova Dumka, 2011, 562 p.

3. Yatsenko I., Antonyuk V., Bondarenko M., Vashchenko V. Influence of parameters by electronic ray on properties of superficial layers of optical elements of exact instrument-making // International journal for science and innovations for the industry “Innovations in discrete productions”, ISSN 114-8907, YEAR III, ISSUE 1/2015, Sofia. – P. 13 – 15.

4. Yatsenko I. V., Antonyuk V. S., Vashchenko V. A. Упреждение возможных разрушений оптических обтекателей ИК-приборов в условиях выстрела и полета (Anticipation of possible damage fairings optical infrared devices in a shot and the flight) // Monthly scientific-technical and industrial journal "Nanoengineering", 2015. – № 12(54). – P. 26 – 31.

5. Yatsenko I. V., Antonyuk V. S., Vashchenko V. A. Попередження можливих руйнувань оптичних елементів точного приладобудування в умовах зовнішніх термодій (Prevention of possible damage optical elements precision instrument in terms of external thermal action) // Journal of Nano- and Electronic Physics, 2016. – Volume 8. – № 1. – P. 01027 – 01032.

6. Yatsenko I. V. Experimental and statistical models of impact determination of the electron beam parameters on surface layers properties of optical elements in precision instruments building // “Pratsi. Odes’kyi politechnichnyi universytet”, 2016. – Issue 1(48). – P. 63 – 69.

7. Yatsenko I., Antonyuk V., Kiritchenko O., Vashchenko V. Improvement of technical and operational characteristics of devices with optical elements by preliminary electron beam treatment of their surface // International journal for science and innovations for the industry “Machines. Technologies. Materials”, ISSN 1313-0226, YEAR X, ISSUE 6/2016, Bulgaria. – P. 47 – 50.

8. Dudko G. V., Kulov, S. K., Rose Y. A., Maksimova N. G. Issledovanie elektronno-luchevych protsessov v sozdanii bazovych technologii ELEFP (Investigation of electron-beam processes in the creation of basic technologies ELEPP) Electronnaya promyshlennost, 1991, Vol. 1, P. 41 – 45.

9. Vashchenko V. A., Dubrovskaya G. N., Kanashewich G. V., Pozdeev S. V. Opticheskie svoistva podlozhek OIS iz stekla posle nizkoenergeticheskoi elektronno-luchevoi obrabotki (Optical properties of substrates OIC of glass after low-energy electron-beam processing). Proceedings of the 3rd International Symposium vacuum technology and equipment, Kharkiv, 22 – 24 September 1999, P. 115 – 118.

10. Dubrovskaya G. N., Kanasewich G. V., Vashchenko V. A., Kotelnikov D. I., Yatsenko I. V. Poluchenie funktsyonalnych sloev v opticheskom stekle i keramike metodom elektronnoy obrabotki (Obtaining functional layers in the optical glass and ceramics by means of electronic processing). Collection of reports of International scientific-practical Symposium “Functional coatings on glass”, Kharkiv: NTC HFTI “Konstanta”, 2003, P. 135 – 137.

11. Yatsenko I. V. Дослідження залежностей енергетичних характеристик СЕП від його керованих параметрів при впливі на вироби мікрооптики і інтегральної оптики (Investigation of dependence of the BEB (belt electron beam) energy performance of its controlled parameters when exposed to mikrooptyky products and integrated optics) // “Pratsi. Odes’kyi politechnichnyi universytet”, 2009. – Issue 2(32). – P. 143 – 149.

12. ДСТУ 2860-94. Надійність техніки. Методи оцінки показників надійності за експериментальними даними. (Reliability engineering. Methods for assessing the reliability indices for the experimental data.)