# ELECTRONICS. RADIO ENGINEERING. TELECOMMUNICATION FACILITIES

## ЕЛЕКТРОНІКА. РАДІОТЕХНІКА. ЗАСОБИ ТЕЛЕКОМУНІКАЦІЙ

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# EXPERIMENTAL AND STATISTICAL MODELS OF IMPACT DETERMINATION OF THE ELECTRON BEAM PARAMETERS ON SURFACE LAYERS PROPERTIES OF OPTICAL ELEMENTS IN PRECISION INSTRUMENTS BUILDING

*І.В. Яценко.* **Експериментально-статистичні моделі визначення впливу параметрів електронного променя на властивості поверхневих шарів оптичних елементів точного приладобудування.** Для запобігання руйнуванням оптичних елементів практичне значення мають електронно-променеві методи фінішної обробки їх робочих поверхонь на стадії виготовлення, які дозволяють покращувати властивості поверхневих шарів елементів і тим самим робити їх стійкішими до зовнішнього теплового і механічного впливу. ***Мета:*** Метою роботи є визначення оптимальних діапазонів зміни параметрів електронного променя, а також розробка експериментально-статистичних моделей, що дозволять автоматично в режимі реального часу формувати базу даних за покращеними властивостями поверхневих шарів оптичних елементів після їх попередньої електронно-променевої обробки. ***Матеріали і методи:*** Для дослідження впливу параметрів електронного променя на властивості поверхневих шарів оптичних елементів було використано пластини з оптичного скла і кераміки. Визначення властивостей поверхневих шарів оптичних елементів до і після електронно-променевої обробки проводилося за відомими методами фізико-хімічного аналізу. ***Результати:*** При дії електронного променя на поверхню оптичного елемента відбувається її помітне очищення від різних домішок, усуваються різні мікродефекти, що залишаються на ній після стандартних методів обробки, а також суттєво підвищується її гладкість, тобто зменшується висота залишкових мікронерівностей на цій поверхні. Також було встановлено, що при обробці електронним променем елементів з оптичного скла їх поверхневі шари змінюють свою структуру, яка стає близькою до кварцу. Показано, що поверхні елементів, попередньо оброблені електронним променем, здатні витримувати критичні значення зовнішніх теплових потоків у 1,3...1,5 разу більші, ніж до обробки. Встановлено, що при дії електронного променя на поверхню елементів з оптичних керамік відбувається значне збільшення мікротвердості їх поверхні у 1,3…1,7 разу та утворення зміцнених шарів товщиною 70…230 мкм. ***Висновки:*** За результатами проведеного дослідженo було розроблено експериментально-статистичні моделі визначення впливу параметрів електронного променя на основні властивості поверхневих шарів оптичних елементів і їх стійкість до теплових дій. Це дає можливість автоматично в режимі реального часу формувати керовану базу даних з покращених властивостей, що впливають на техніко-експлуатаційні характеристики оптичних елементів і приладів на їх основі.
*Ключові слова*: оптичний елемент, зовнішні термічні впливи, електронний промінь.

*I.V. Yatsenko.* **Experimental and statistical models of impact determination of the electron beam parameters on surface layers properties of optical elements in precision instruments building.** To prevent destruction of optical elements the electron beam methods of work surfaces finishing at the stage of manufacture has practical significance. These methods can improve the properties of the element surface layers and thus make them more resistant to external thermal and mechanical action. ***Aim:*** The aim is to determine the optimal ranges of parameters of the electron beam and the development of experimental and statistical models that will automatically generate database with improved properties of the surface layers of optical elements in real time mode after previous electron beam treatment. ***Materials and Methods:*** To study the influence of parameters of the electron beam on the properties of the surface layers of the optical elements used plates of optical glass and ceramics. Determination of the surface layers properties of the optical elements before and after electron beam treatment was carried out by known methods of physical and chemical analysis. ***Results*:** It was established that under the influence of the electron beam on the surface of the optical element there is visible clearing of various impurities take place, various micro-defects that remain on it after standard processing methods remove and also its smoothness significantly increases, i.e. height of residual asperities on the surface is reduced. It was also found that the processing of optical glass elements by electron beam their surface layers change their structure, which is close to the quartz. It is shown that the surface of the pre-processed electron beam elements able to withstand the critical value of external heat flows in 1.3...1.5 times higher than before treatment. ***Conclusions:*** As results of the research the experimental and statistical models to determine the impact of parameters of the electron beam on the basic properties of the surface layers of the optical elements and their resistance to thermal action have been developed. This makes it possible automatically in real time to form a managed database with improved properties that impact on the technical and operational characteristics of optical components and devices based on them.
*Keywords*: optical element, external thermal impacts, the electron beam.

**Introduction.** Modern devices with optical elements used for measurement and thermal control of different physical nature objects are the subjects of intense external thermal actions such as high

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heating temperature, external pressure, thermal shock action in flight and firing, etc. [1…3]. In these conditions there is a significant change in the properties of the surface layers of the optical elements take place (the appearance of cracks and chips, deep surface melting of elements and form a nodule, wavy surfaces and change the geometry etc.) till their destruction.

This leads to a significant spoilage of technical and operational characteristics of devices and their failure. To prevent the damage of optical elements the electron beam methods of finishing of their work surfaces at the manufacturing stage have practical significance. These methods can improve the properties of the surface layers of elements and thus make them more resistant to external heat and mechanical stress [3, 4].

Bessmertnyi V., Kovalenko V., etc. [5…7] show that to improve the properties of the surface layers of different materials the concentrated flows of energy (laser and electron beam, the flow of low-temperature plasma, etc. nowadays are widely used. In his turn Mayer, Bauer and Engel [8…10] showed that for the optical glass and ceramic elements surface treatment the use of mobile strip electron beam is rational in terms of handling and economy. It is established that by control of the main parameters of the electron beam (density of heat exposure and rate of displacement) the surface layers of the optical elements can be specifically modified.

However, these important issues whose solution will improve the properties of the surface layers of the elements and make them more resilient to external thermal action remain unexplored:

1. It is not set the optimal ranges of parameters of the electron beam within which there is a substantial improvement of the properties of the surface layers of cells takes place and their thermal stability increases. Solution of this problem will prevent the destruction of optical elements and failure of devices based on them.

2. It was not designed the experimental and statistical model of determination of three-dimensional dependencies of the basic properties of the surface layers of elements from the e-beam parameters.

**The aim** is to determine the optimal ranges of parameters of the electron beam and the development of experimental and statistical models that will automatically generate database with improved properties of the surface layers of optical elements in real time mode after previous electron beam treatment.

**Materials and Methods.** To study the influence of parameters of the electron beam on the properties of the surface layers of the optical glass (K8, K108, etc.) and ceramics (KO1, KO2, etc.) used the plate of thickness $2...4\cdot10^{-3}$ m, width $3...5\cdot10^{-2}$ m and a length of $6...8\cdot10^{-3}$ m [3]. Author has developed a specialized electron-beam technological equipment for the study which are protected by patents of Ukraine [1, 3, 4], which allows realizing strip electron beam in width $5\cdot10^{-4}...5\cdot10^{-3}$ m, length 0.06...0.08 m, heat flux density $F_n = 5\cdot10^6…9\cdot10^8$ W/m$^2$ and rate of displacement $V = 0…0.1$ m/s.

Determination of the surface layers properties of optical elements before and after electron beam treatment (heights of residual microirregularities on the surface, micro hardness, thickness of reinforced layers, etc.) carried out by known methods of physical and chemical analysis — a method of atomic force microscopy, Vickers hardness test, methods of optical microscopy and micro-probe analysis, etc. [8…11].

For modeling the thermal effects on the studied optical elements under normal conditions ($T_0 = 273$ K, $P = 10^5$ Pa) and for finding the critical values of parameters (heat flow $q_n^*$ and time of action $t^*$) controlled infrared heating has been used quartz lamps of type KNM-220-1000-1 with RIF-101 sensors for temperature control of surfaces elements in the range of 300...1900 K and heat flow that come to them [3, 4].

For the modeling of high heating temperatures impact (1500 K) and external pressures ($10^7$ Pa) the specialized equipment was used, tests on which were held using methodic developed at SDP SE "Arsenal" (Kyiv) and Cherkasy State Technological University [1, 3].

In studies conducted to determine the properties of the surface layers of optical elements listed before and critical parameters of external influences, the relative error did not exceed 10 %.

To obtain the experimental and statistical models to determine the impact of parameters of the electron beam on the properties of the surface layers of the optical elements, the specially designed application package by regression and interpolation methods [1, 3] was used.

**Results.** As a result of experimental studies, the following optimal ranges of parameters of the electron beam have been set:

$$F_n^{opt} = 7\cdot10^6\ldots8\cdot10^8 \text{ W/m}^2,$$

$$V^{opt} = 5\cdot10^{-3}\ldots5\cdot10^{-2} \text{ m/s}.$$

Within these ranges there is the most significant improvement of the properties of the surface layers of the optical elements take place.

For these optimal ranges of parameters $F_n$ and $V$ the experimental and statistical models are developed to determine the impact of parameters of the electron beam on the basic properties of the surface layers of the optical elements and their resistance to thermal activity (relative error is 5...9 %):

$$h(F_n,V) = a_0 \cdot F_n^{a_1+a_2\cdot V+a_3\cdot V^2} \cdot V^{a_4},$$

$$h_m(F_n,V) = b_0 \cdot F_n^{b_1+b_2\cdot V+b_3\cdot V^2} \cdot V^{b_4},$$

$$H_v(F_n,V) = c_0 \cdot F_n^{c_1+c_2\cdot V+c_3\cdot V^2} \cdot V^{c_4},$$

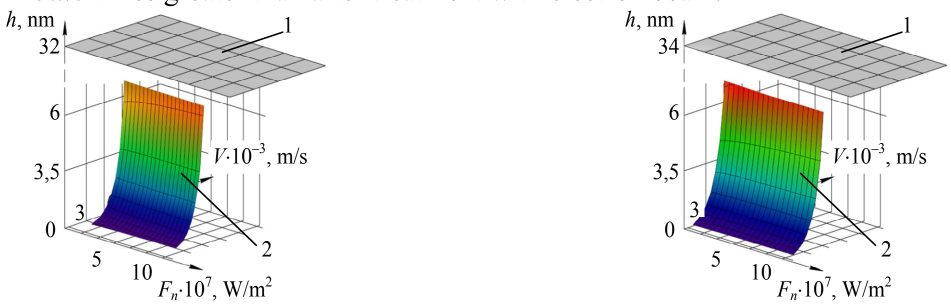
$$\Delta(F_n,V) = d_0 \cdot F_n^{d_1+d_2\cdot V+d_3\cdot V^2} \cdot V^{d_4},$$

$$q_n^*(P,t^*) = (m_0 + m_1\cdot P + m_2\cdot P^2)\cdot(t^*)^{n_0+n_1\cdot P+n_2\cdot P^2},$$

where $h(F_n,V)$, $h_m(F_n,V)$, $H_v(F_n,V)$, $\Delta(F_n,V)$ — dependencies of heights of residual micro irregularities on the surface, melted layer thickness, microhardness, thickness of reinforced layers, from electron beam parameters respectively;

$a_k$, $b_k$, $c_k$, $d_k$ $(k=\overline{0,4})$, $m_l$ and $n_l$ $(l=\overline{0,2})$ — empirical constants whose values depend on the nature of the optical material.

It is established that under the influence of the electron beam on the surface of the optical element there is its noticeable clearing from various impurities, eliminating of various micro-defects that remain on it after standard processing methods (mechanical, chemical, etc.) take place and also significantly increases its smoothness, i.e. height of residual asperities is reduced on this surface. Three-dimensional images of dependencies $h(F_n,V)$ (Fig. 1) give visual presentation of recent regularities for optimal ranges of parameters of the electron beam. It is shown from these dependences that even in the deep mechanical grinding-polishing of optical elements the residual microscopic are significant and can be in 5...6 times greater than after treatment with electron beam.




*a* *b*

*Fig. 1. Dependencies $h(F_n,V)$ for elements of optical glass K8 (a) and K108 (b):*
*1 — unprocessed element; 2 — element processed by electron beam*

It is necessary to control the parameters of the electron beam. This occurs because a thickness of the molten layer $h_m(F_n,V)$ formed on the surface of the element that smoothes the asperities, at some

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critical parameters of $F_n^*$ and $V^*$ may exceed the maximum allowable $h_m^*$ value at which the wave-like surfaces start forming, so-called “formation of ribs” that leads to loss of the original form of optical element (Fig. 2).

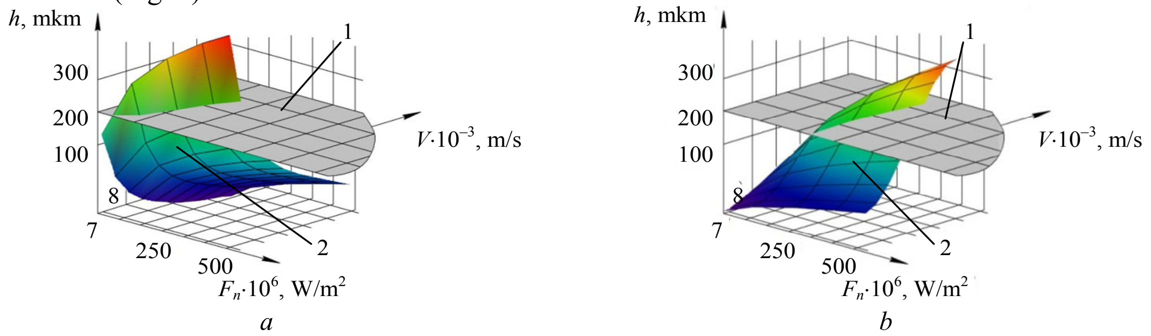


*Fig. 2. Dependencies $h_m(F_n, V)$ for elements of the optical glass K8 (a) and K108 (b): 1 — the maximum permissible values $h_m^*$; 2 — $h_m$ values obtained in electron-beam processing*

It was found in the research that during processing the optical glass elements by electron beam their surface layers change their structure, which become close to the quartz. In other words it is happening so-called “quartz formation” on the treated surface. As a result, the optical elements are becoming more resistant to external influences. This confirmed by experimental studies of dependencies of critical values of external heat flows from the time of their actions — namely, the excess of critical values leads to fractures. However, it was found that the surface layers of the elements that have been processed by electronically beam can withstand the critical value of external heat flows in 1.3...1.5 times higher than before treatment (Fig. 3).

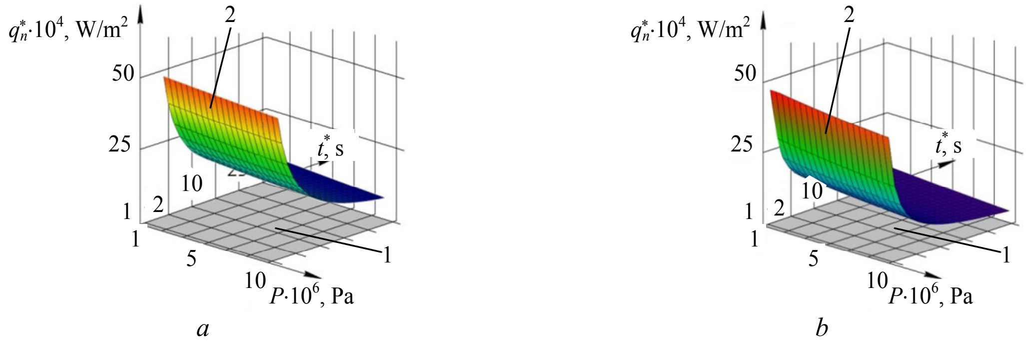


*Fig. 3. Dependencies $q_n^*(P, t^*)$ for elements of the optical glass K8 (a) and K108 (b): 1 — unprocessed element; 2 — element processed by electron beam*

It is established that under the action of the electron beam on the surface of the optical elements of ceramic there is an appreciable increase of micro hardness of the surface in 1.3...1.7 times as well as the formation of hardened layers with thickness 70...230 mm (Fig. 4, 5). Thus optical elements become more resilient to external shock thermal stress, as evidenced by a specially conducted experimental research on finding critical values of external heat flows and their impact on the time element surface (Fig. 6): element surface, which processed by electron beam requires for its destruction in 1.3...1.7 times more of heat flow already.

Studies have shown that prior electron beam processing of work surfaces, such as thin optical plates for input windows of laser thermovision sights and optical fairing infrared aiming devices and observation of objects [1, 12, 13] leads to the improvement of basic technical and operational characteristics of these devices: the resistance of the surface layers of the optical elements to external thermal action increases in 1.3...1.7 times; the service life of devices increases in 1.3...2 times; the amount of destruction of fairing infrared devices decreases in 1.3...1.5 times.

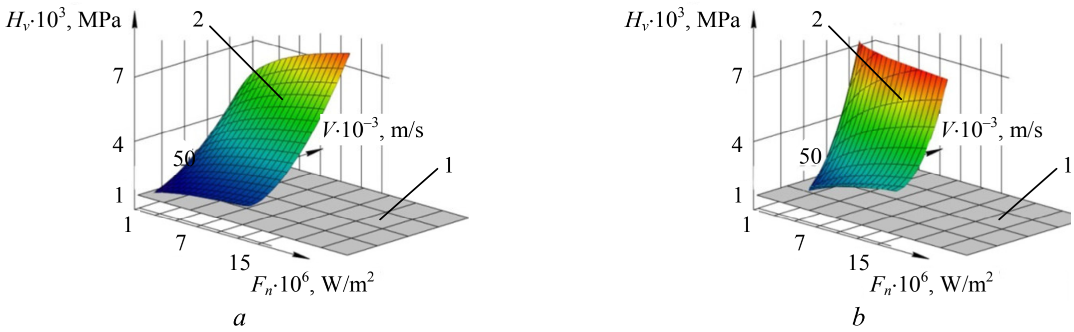


*Fig. 4. Dependencies $H_v(F_n, V)$ of the optical elements of ceramics KO1 (a) and KO2 (b):*
*1 — unprocessed element; 2 — element processed by electron beam*

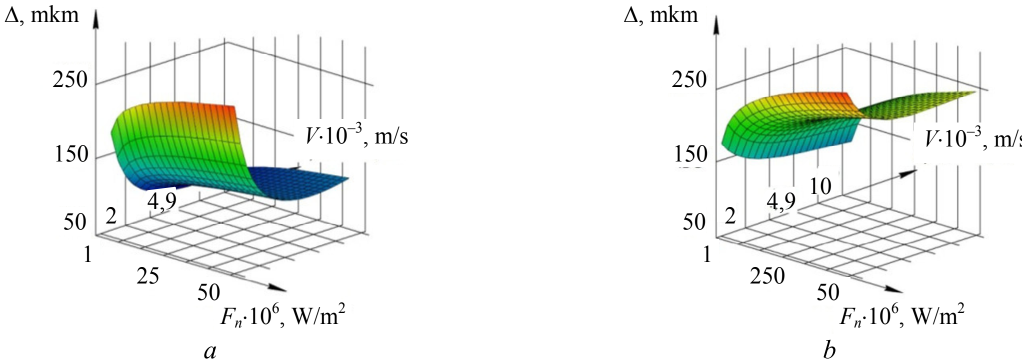


*Fig. 5. Dependence $\Delta(F_n, V)$ for the optical elements of ceramics KO1 (a) and KO2 (b)*

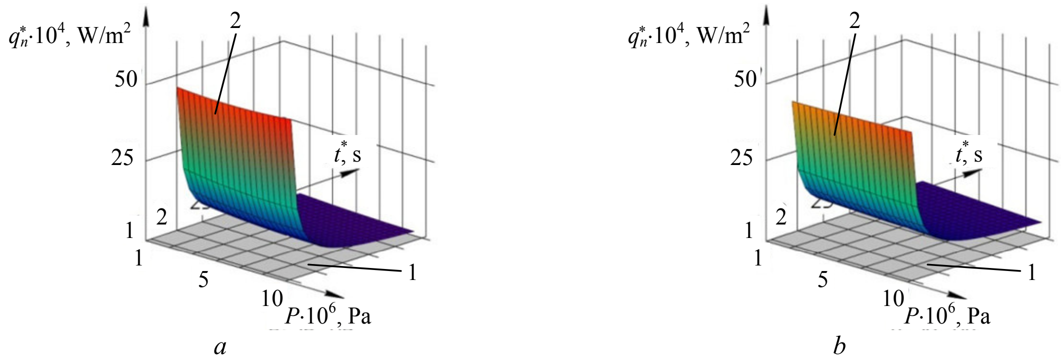


*Fig. 6. Dependencies $q_n^*(P, t^*)$ for the optical elements of ceramics KO1 (a) and KO2 (b):*
*1 — unprocessed element; 2 — element processed by electron beam*

**Conclusions.** Using the results of the research the experimental and statistical models were developed to determine the impact of parameters of the electron beam on basic properties of the surface layers of the optical elements and their resistance to thermal action. This makes it possible (with a relative error of 5...9 %) to automatically form in real time the managed database with improved properties that influence the technical and operational characteristics of optical components and devices based on them.

The first time shown that by pre-processing of hazardous areas on the surface of optical elements by movable electron beam with adjusting of its optimum settings $F_n^{opt}$, $V^{opt}$, could greatly improve the basic properties of the surface layers of the optical elements that influence the technical and operational characteristics of devices based on them. Thus, for the optical glass elements it is possible to reduce the height of the residual asperities on the surface in 5...6 times, and to keep the thickness of

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melted layer in the allowable range of 150...200 mm. For the optical ceramic elements it is possible to increase a surface microhardness in 1.3...1.7 times and form consolidated layers with thickness of 70...230 mm.

It was established that increasing of external pressure from $10^5$ to $10^7$ Pa leads to a reduction of critical values $q_n^*$ and $t^*$ in 1.2...1.7 times for the elements of the optical glass and in 2...2.5 times — for elements of the optical ceramics; while for optical elements that processed by electron beam, the critical values $q_n^*$ and $t^*$ in 1.3...1.7 times higher than unprocessed elements.

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