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IMPROVING THE RELIABILITY OF PULSED LASER RANGEFINDER AND INFRARED DEVICES OF HOMING AND SURVEILLANCE BY FINAL ELECTRON BEAM PROCESSING OF THEIR OPTICAL COMPONENTS

І.В. Яценко, *В.І. Гордієнко*, *В.В. Холін*. **Підвищення надійності імпульсних лазерних далекомірів та ІЧ-приладів самонаведення і спостереження шляхом фінішної електронно-променевої обробки їх оптичних деталей.** Для запобігання негативного впливу зовнішніх термічних впливів на надійність приладів для вимірювання і теплового контролю об'єктів різної фізичної природи практичне значення має фінішна електронно-променева обробка поверхонь їх оптичних елементів, яка запобігає виникненню дефектів на поверхні елементів, що призводять до різкого погіршення характеристик приладів та їх відмов при експлуатації. ***Мета:*** Метою роботи є розробка методу підвищення надійності приладів для вимірювання і теплового контролю об'єктів різної фізичної природи шляхом фінішної електронно-променевої обробки їх оптичних елементів. ***Матеріали і методи:*** Для дослідження впливу параметрів електронного променю на властивості поверхневих шарів елементів з оптичного скла марок К8, К208, БК10 та кераміки марок КО1, КО2, КО3, КО5, КО12. Для проведення досліджень було використано розроблене спеціалізоване електронно-променеве обладнання, що дозволяє реалізувати стрічковий електронний промінь шириною $5\cdot10^{-4}\ldots5\cdot10^{-3}$ м, довжиною $6\cdot10^{-2}\ldots8\cdot10^{-2}$ м, густиною теплової дії $F_n = 5\cdot10^{6}\ldots9\cdot10^{8}$ Вт/м^2 та швидкістю переміщення $V = 3\cdot10^{-3}\ldots10^{-1}$ м/с. ***Результати:*** Проведено експериментальні дослідження та встановлено критичні значення параметрів зовнішніх термодій (теплового потоку, швидкості надзвукового обдуву потоком повітря, часу їх дії), перевищення яких призводить до утворення на поверхні елементів негативних дефектів, що спричиняє їх руйнування. Встановлено оптимальні діапазони зміни параметрів електронного променю ($F_n = 7\cdot10^{6}...8\cdot10^{8}$ Вт/м^2 і $V = 5\cdot10^{-3}...5\cdot10^{-2}$ м/с), в межах яких спостерігається найістотніше покращення властивостей поверхневих шарів оптичних елементів.

Ключові слова: точне приладобудування, електронний промінь, оптичне скло, оптична кераміка, надійність.

I.V. Yatsenko, *V.I. Hordienko*, *V.V. Kholin*. **Improving the reliability of pulsed laser rangefinder and infrared devices of homing and surveillance by final electron beam processing of their optical components.** To prevent the negative impact of external thermal actions on reliability of devices for measurement and thermal testing of objects of various physical nature the practical importance has electron beam processing of surfaces of optical elements has practical importance, because it prevents appearance of defects on the surface of elements which lead to a sharp degradation of performance of devices and their failures during operation. ***Aim:*** The aim of this research is to develop a method for improving the reliability of devices for measurement and thermal control of various physical nature objects by final electron-beam processing of optical elements. ***Materials and Methods:*** To study the influence of parameters of the electron beam on the properties of the surface layers of the optical glass elements of marks K8, K208, BK10 and ceramics marks KO1, KO2, KO3, KO5, KO12 used discs with a diameter of $3\cdot10^{-2}\ldots5\cdot10^{-2}$ m and thick $4\cdot10^{-3}\ldots6\cdot10^{-3}$ m, hemispherical cowl with diameter $4\cdot10^{-2}\ldots8\cdot10^{-2}$ m. For research was used developed specialized electron-beam equipment; the main characteristics of strip electron beam were as follows: width – $5\cdot10^{-4}\ldots5\cdot10^{-3}$ m, length – $6\cdot10^{-2}\ldots8\cdot10^{-2}$ m, density of thermal action – $F_n = 5\cdot10^{6}\ldots9\cdot10^{8}$ W/m^2 and velocity – $V = 3\cdot10^{-3}\ldots10^{-1}$ m/s. ***Results:*** Experimental studies were held and found the critical values of external thermal actions (heat flux, time of action, etc.), the excess of which leads to the formation on the surface of negative defects that lead to their destruction. The results of the research determined the optimal range of change of parameters of the electron beam ($F_n = 7\cdot10^{6}...8\cdot10^{8}$ W/m^2 and $V = 5\cdot10^{3}...5\cdot10^{-2}$ m/s) within which observed substantial improvement of the properties of the surface layers of the optical elements.

Keywords: precision instrumentation, electron beam, optical glass, optical ceramics, reliability.

Introduction. Modern devices with optical elements for measurement and thermal control of

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various physical nature objects (laser range finders of sighting complexes with optical window of transmitting and receiving channels, IR devices with hemispherical fairings of optical materials for homing and surveillance, etc.) in conditions of exploitation are exposed to intense external thermo actions (higher heating temperature and external pressure, thermal shock action in firing and flight, etc.) [1...5].

In these conditions on the surface and in the surface layers of the optical elements form various negative defects (cracks, bumps, hollows, flows, etc.), further development which leads to the destruction of elements (appearing detachment, chips, undulating surfaces, etc.). The result is a deterioration of their basic properties – micro hardness of surface, which leads to lower their resistance to external thermal and mechanical loads, more.

So, with scientific standpoint developing of methods to improve equipment reliability in operation is urgent. Based on the study [6...13], it can be concluded that such methods should mainly be based on electron beam final processing of optical elements, what will affect the reliability of the device operation by improving the properties of the surface layers and increasing of resistance to external thermal actions.

Some issues concerning the prevention of negative defects on the surface of optical elements in terms of external thermal action studied not enough. One of the current issues investigation of which devoted to this work is to establish the optimal ranges of changes in the parameters of the electron beam within which to expect to get a significant improvement of properties of the surface layers of the elements that in turn affect their reliability in operation.

The aim of this research is to develop a method for improving the reliability of devices for measurement and thermal control of various physical nature objects by final electron-beam processing of optical elements.

Materials and Methods. To study the influence of parameters of the electron beam on the properties of the surface layers of the optical glass elements of marks K8, K208, BK10 and ceramics marks KO1, KO2, KO3, KO5, KO12 used discs with a diameter of $3\cdot10^{-2}…5\cdot10^{-2}$ m and thick $4\cdot10^{-3}…6\cdot10^{-3}$ m, hemispherical cowl with diameter $4\cdot10^{-2}…8\cdot10^{-2}$ m [9, 14].

For research was used developed specialized electron-beam equipment that protected by patents of Ukraine [8, 9]. The main characteristics of strip electron beam were as follows: width – $5\cdot10^{-4}…5\cdot10^{-3}$ m, length – $6\cdot10^{-2}…8\cdot10^{-2}$ m, density of thermal action – $F_n = 5\cdot10^{6}…9\cdot10^{8}$ W/m^2 and velocity – $V = 3\cdot10^{-3}…10^{-1}$ m/s.

For modeling the thermal effects on the studied optical elements under normal conditions ($P = 10^5$ Pa, $T = 293$ K) has been used quartz lamps of KGM-220-1000-1 type with RIF-101 sensors for temperature control of surfaces elements in the range of 300...1500 K and external heat flow in the range of $1.5\cdot10^{5}…2.3\cdot10^{6}$ W/m^2 [9].

For the simulation of effect of high speed supersonic blowing by air flow (up to $2\cdot10^3$ m/s) and the angular velocity of axisymmetric rotation of hemispherical cowls ($4\cdot10^3$ rad/s) (the conditions of the shot and flight of products with infrared devices) used specially designed installation [3, 9]. Schematic diagram of the installation is shown in Fig. 1.

The air stream that blows the sample during test is created by leakage from the nozzle subsonic or supersonic jets, pre-heated to compensate for the cooling stream flow on the nozzle. The diameter of the air jet (diameter nozzle edge) is $4\cdot10^{-2}...6\cdot10^{-2}$ m. Nozzles are variables, and can vary the flow rate to $V = 2\cdot10^3$ m/s. Installation includes the chamber with nozzles mounted on the frame. Heating the air occurs in the chamber where the cold air and the hot gases generated by the heater are mixing. From the tank of fuel the gasoline is supplied through atomizer into the heater combustion chamber. The oxidant (air) is supplied where also. Both components are being supplied through shut-off valves, operated by electric pneumatic valves. On the frame there are fixed aligned with nozzle a node of rotation with rotation speed sensor and the DC motor with capacity of 2.7 kW, voltage of 27 V, and nominal angular speed of 995 rad/sec. Transfer of torque from the motor to the shaft of the element sample holder carried out by means of a special flexible flat belt. Speed sensor consists of a metal disc with a slot mounted on the shaft of holder, a photodiode and light sources which are mounted on a stationary frame.

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Light pulses are perceived by photodiode, converted to electric, amplified and fed to an electronic frequency meter. The distance from the end of the tested sample to nozzle selected on the basis of Schlieren photographic research of flow on the IAB-451 shadow device and measuring of the pressure at the front end of the sample. For qualitative evaluation of flow formation, visualization of flow about, determination of the optimal distance from the nozzle to the obstacles that the sample simulates and for definition of a site of the direct jump depending on the distance and type of obstacles we held survey of flow during the flow around the model of sample by air flow (Fig. 2, 3).

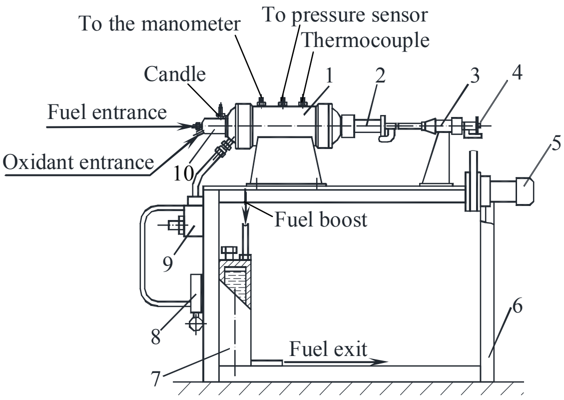


Fig. 1. Schematic diagram of the installation to study the impact of high speeds of supersonic blowing by air flow and the angular velocity of axisymmetric rotation of hemispherical cowls: 1 – chamber; 2 – variable nozzle; 3 – holder with optical element model and speed sensor; 4 – node of rotation; 5 – electric motor; 6 – bed frame; 7 – tank of fuel; 8 – electro-pneumatic valve; 9 – shut-off valve; 10 – air heater

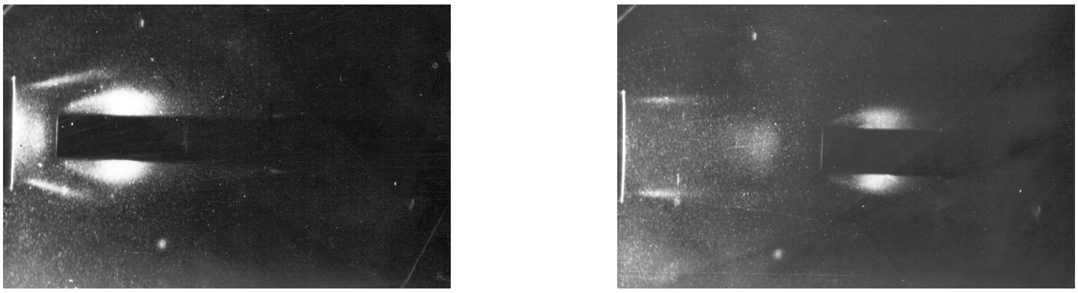
Conducted measurements have shown that the distance S_0 of straight jump from sample cut changes slightly and is between $S_0 = 1.3\cdot10^{-2}...1.5\cdot10^{-2}$ m. On the basis of the studies was selected the optimum distance from cut of sample holder to the nozzle $S_{1opt} = 5\cdot10^{-2}$ m. The analysis of the obtained images showed that supersonic gas jet has calculated flow regimes within the surveyed lengths. This maintains the structure of the initial portion of the jet, which allows in several times to increase the accuracy of calculations of blowing speeds of samples by air flow, using the known gas-dynamic functions [15].

Experimental study of surface structure and surface layers of the optical elements carried out by known methods of optical microscopy and microprobe analysis, including raster scanning microscopy, transemission electron microscopy, and atomic force microscopy [9, 16, 17]. Microhardness of surface of the optical elements was determined by Vickers method [11, 17].

To measure the quantities of thermoelastic stresses in the surface layers of cowls with optical ceramic we used diffractometer DRON-2.0 and 3.0 [9, 16].

Tensile strength of optical elements before and after electron beam processing for a range of changing of temperature of heating of 300...1200 K calculated by the method of central-circular bending [9, 14].

To assess the reliability of devices under conditions of intense external thermal actions we applied testing standard methods [3, 9], which results in accordance with DSTU 3004-95 [18] are used to find the coefficient of reliability as a criterion of efficiency of devices in their operation.



a *b*

Fig. 2. Schlieren photographs of a sample in the flowing air stream ($V = 6\cdot10^2$ m/s): a – distance from the sample to the nozzle – $1.2\cdot10^{-2}$ m; b – distance from the sample to the nozzle – $8\cdot10^{-2}$ m

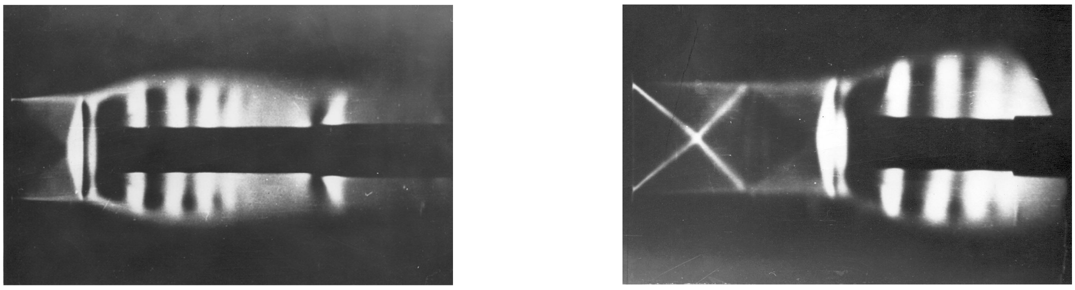


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Fig. 3. Schlieren photographs of a sample in the flowing air stream ($V = 2{\cdot}10^3$ m/s):
a – distance from the sample to the nozzle – $4{\cdot}10^{-2}$ m; b – distance from the sample to the nozzle – $7{\cdot}10^{-2}$ m

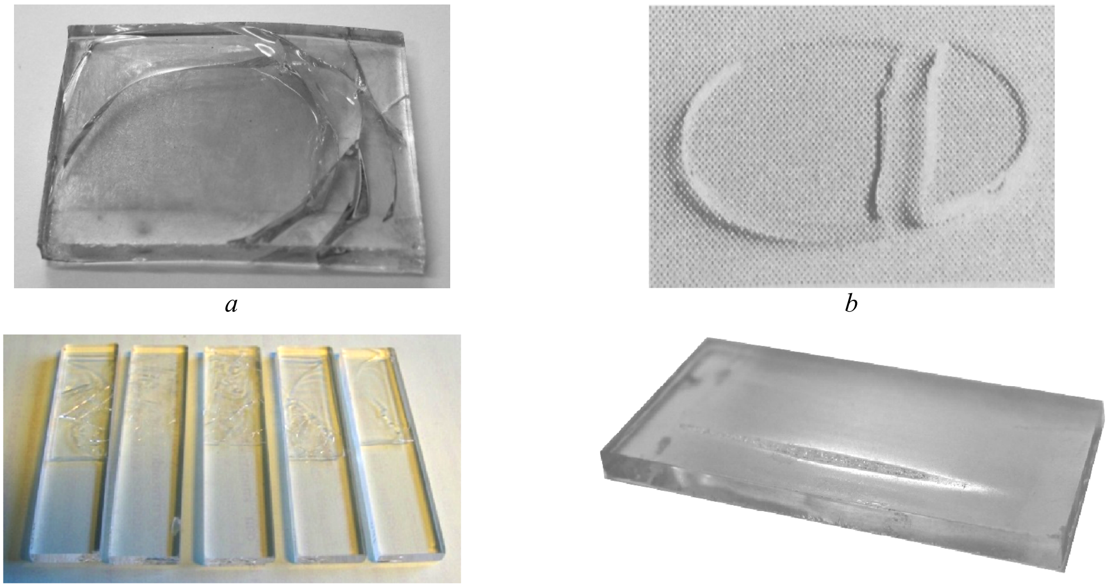
Results and Discussion. Electron microscopic studies of surfaces of optical elements (optical windows work surfaces, surfaces of hemispherical optical cowls, etc.) showed that after their standard machining there remain large number of negative defects (small cracks of 0.1...0.7 μm depths, thin scratches of length 2...5 μm, vesicles whose size up $10^{-3}...10^{-2}$ μm, etc.). It was established that these defects in the conditions of intense external thermal action (higher heating velocity up to 400 K/s, speed of supersonic blower by air flow up to $2{\cdot}10^3$ m/s, the angular velocity of axisymmetric rotation up to $4{\cdot}10^3$ rad/s, etc.), in some critical values of external heat flow q_n^* and times of action t^* are further developed. This leads to the destruction of elements (appear detachment, chips, nodules and wavy surface, areas of rapid boiling, etc.) (Fig. 4). These defects degrade device reliability when operating in conditions of thermal external action.

We found that after electron beam processing of optical elements mentioned above negative defects that remain on the surface after machining under optimal values of parameters of electron beam (density of thermal action $F_n = 7{\cdot}10^6…8{\cdot}10^8$ W/m^2 and velocity $V = 5{\cdot}10^{-3}…5{\cdot}10^{-2}$ m/s) changed the most significant. The sizes of vesicles (diameter) on the surface decrease in 2...4 times. Other micro-defects of size of less than 1...2 microns are not observed. Electron beam processing "cleans" the surface of the elements and eliminates small defects; the area occupied by these defects decreases in 1.8...2.7 times (Fig. 5, 6), and the elements surface gets atomically smooth (residual asperities do not exceed 0.5...1 nm). In this case, these destruction of optical elements are not observed.

Established that the effect of electron beam ($F_n = 10^6...2{\cdot}10^7$ W/m^2, $V = 10^{-3}...2{\cdot}10^{-2}$ m/s) on elements from optical ceramic leads to increasing of microhardness of its surface depending on the parameters of the electron beam: increasing of the density of thermal action F_n from 10^6 to $1.5{\cdot}10^7$ W/m^2 leads to increasing of microhardness of ceramics surface in 1.5...1.7 times, and decreasing velocity V from $1.5{\cdot}10^{-2}$ to 10^{-3} m/s leads to increasing the microhardness of ceramic surface in 1.3...1.4 times (Fig. 7)

It was also established that the hardened layer thickness (Δ), where there the major structural changes appear and microhardness of the processed element increases, for electron beam parameters ranges from 70…90 μm to 210...230 μm in thickness of processed products $4{\cdot}10^{-3}...6{\cdot}10^{-3}$ m. The value Δ also heavily depends on the electron beam parameters: increasing of density of thermal action F_n from 10^6 to $2{\cdot}10^7$ W/m^2 leads to increasing of thickness of the hardened layer in 1.8...2.6 times, and increasing of velocity of beam movement from $1.5{\cdot}10^{-3}$ to $2{\cdot}10^{-2}$ m/s leads to reducing of the thickness of hardened layer in 1.7...2.5 times.

Determined the presence of compressive stresses up to 25...90 MPa in thin surface layers of the elements of depth 40...60 μm for the central part of the processed areas (plots size of $4{\cdot}10^{-2}...5{\cdot}10^{-2}$ m) in the considering change ranges of electron beam parameters.



a *b*

c *d*

*Fig. 4. Destruction of optical elements in excess of the parameters of the thermal action of its critical values:
a – delamination (K8 optical glass:* $q_n^*=3\cdot10^5$ *W/m*^{2}*,* $t^*>10$ *s); b – chips (KO2 optical ceramics:* $q_n^*=1{,}2\cdot10^5$ *W/m*^{2}*,* $t^*>25$ *s); c – striation, undulating surface (K108 optical glass:* $q_n^*=6\ 10^5$ *W/m*^{2}*,* $t^*>6$ *s);
d – areas of rapid boiling (K8 optical glass:* $q_n^*=6\cdot10^5$ *W/m*^{2}*,* $t^*>4$ *s)*

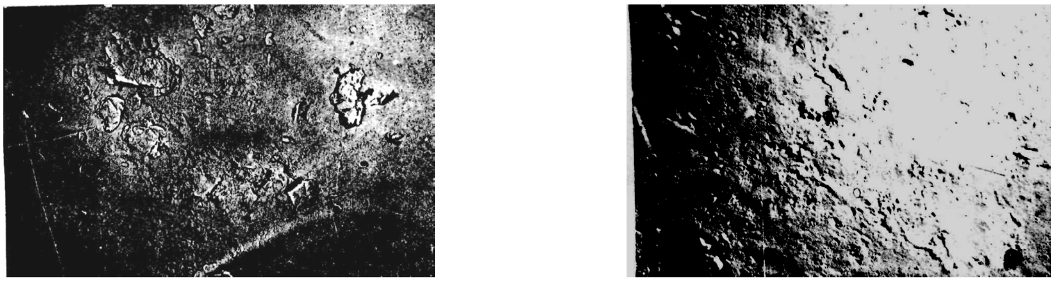


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*Fig. 5. Electron microscope images of the surface of the K8 optical glass:
a – surface after mechanical processing, × 3700; b – surface after electron processing, × 4500*

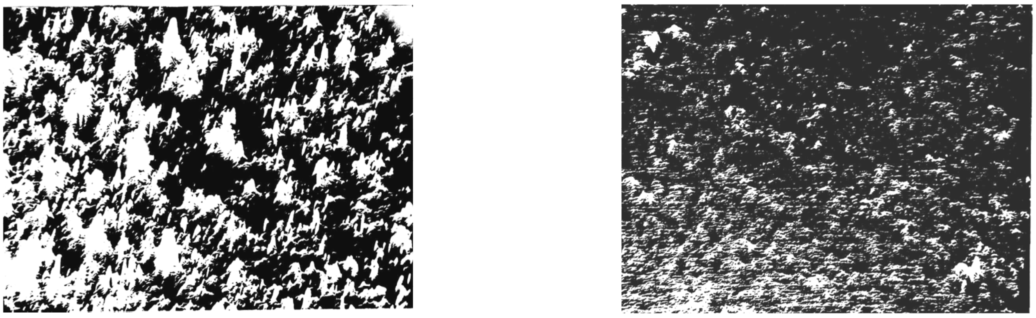

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*Fig. 6. Scanograms of the surface of the K208 optical glass:
a – surface before electron beam processing, Y-modulation, × 610;
b – surface after electron beam processing, Y-modulation, × 610*

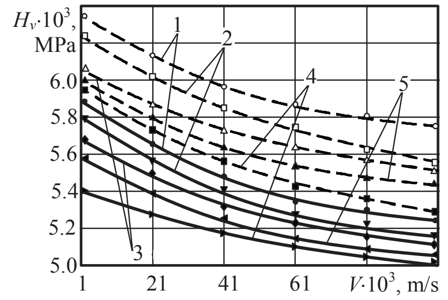

Fig. 7. Dependence of microhardness of the surface of KO12 (1), KO2 (2), KO1 (3) KO5 (4) and KO3 (5) optical ceramics on beam velocity after electron beam processing: $F_n=2.3\cdot10^6$ W/m² (————); $F_n = 1.4\cdot10^7$ W/m² (– – – –)

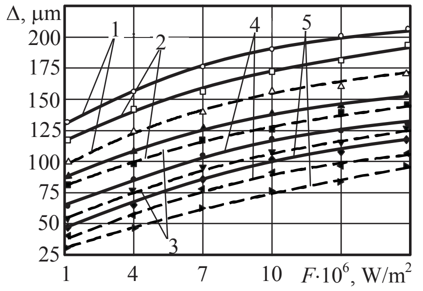

Fig. 8. Dependence of thickness of hardened layers of KO12 (1), KO2 (2), KO1 (3), KO3 (4) and KO5 (5) optical ceramics on density of thermal action after electron beam processing: $V=7\cdot10^{-3}$ m/s (————); $V = 1.5\cdot10^{-2}$ m/s (– – – –)

As a result of the research it was found that after the final electron beam processing of optical elements the critical values of external heat flow q_n^* and time of their actions t^* increase in 1.5...2 times for optical glass, and in 2...4 times for optical ceramics.

It is shown that the maximum allowable value of thermoelastic stresses at different heating temperatures 300…1200 K of optical elements, which were electron beam processed, in 1.7...2.3 times higher for optical glass, and in 1.8...2,7 times higher for optical ceramics compared with the values for unprocessed elements (Fig. 9).

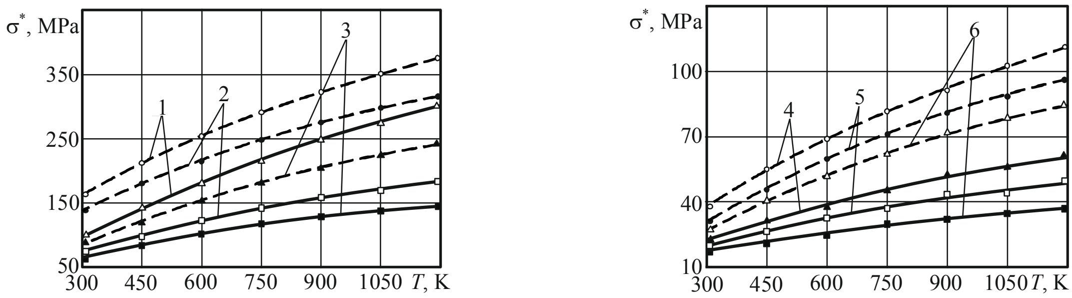

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Fig. 9. The dependence of the maximum permissible thermoelastic stresses in the optical elements on the heating temperature ($P=10^5$ Pa, thickness of element $H=4\cdot10^{-3}$ m, $F_n=1.5\cdot10^7$ W/m², $V=5\cdot10^{-3}$ m/s): a – optical glass of marks K8 (1), TF110 (2) and BK10 (3); b – optical ceramics of marks KO1 (4), KO2 (5) and KO3 (6); without electron beam processing (————); after electron beam processing (– – – –)

We conducted researches of optical windows of laser rangefinders (Fig. 10) and hemispherical cowls of IR-devices (Fig. 11) under real operation conditions.

As a result of the research it was found that the damage tolerance of optical windows and hemispherical cowls after electron beam processing in areas of maximum external thermal action (the most dangerous areas determined by the condition that the central angle of cowl is $\Delta\theta \approx 4°$) increases in 1.7...2.3 times compared to unprocessed devices (Table 1).

It was established that obtaining improved properties of the surface layers of the optical elements of the device increases the reliability of their operation.

Reliability factor as a criterion for efficiency of laser rangefinders at different speeds of external heat as well as IR-devices at supersonic airflow blowing determined by the following formula [18]:

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

where $W(V_i)$ – probability of maintaining efficiency of devices in terms of thermal external action;

$N(V_i)$ – number of devices that broken down under given parameters of thermal actions V_i (destruction of the entrance windows and cowls taken for failure of devices in general);

N_0 – total number of entrance windows and cowls that tested.

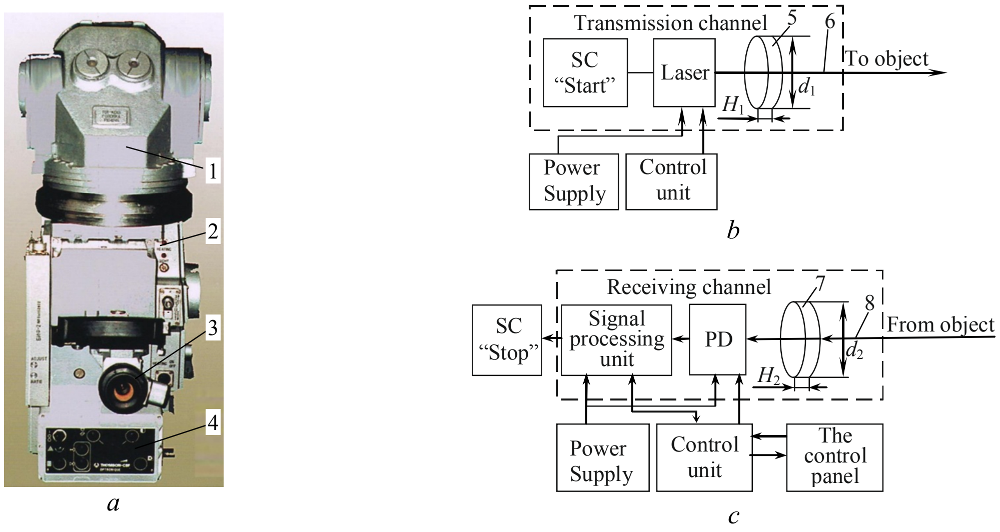

Fig. 10. General view of the sighting system unit (a) and simplified diagram of transmission (b) and receiving (c) channels of pulse laser rangefinder: 1 – optical head with laser rangefinder, 2 – opto-mechanical unit; 3 – eyelens; 4 – control panel of thermal imagery camera; 5 – outgoing optical window of transmission channel of rangefinder; 6 – IR-flux to object; 7 – incoming optical window of rangefinder receiving channel; 8 – IR-flux that scattered by object and sent to incoming optical window; PD – photo detector; SC – signal conditioner; d_1, H_1, d_2, H_2 *– diameters and thicknesses of outgoing and incoming windows (*d_1, $d_2=3\cdot10^{-2}...5\cdot10^{-2}$ *m;* H_1, $H_2=4\cdot10^{-3}...6\cdot10^{-3}$ *m);* $\lambda=1.06$ *µm – wavelength of laser radiation*

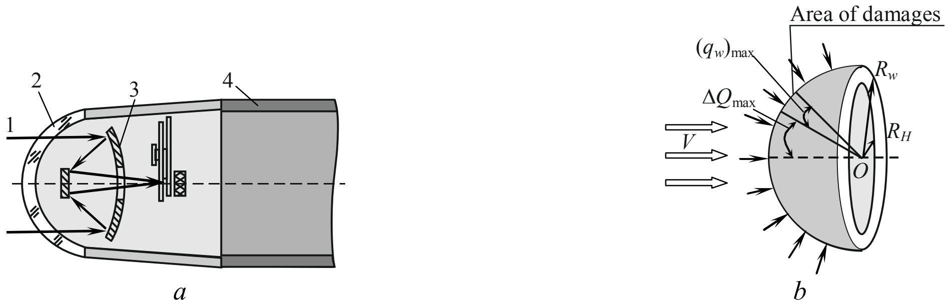

Fig. 11. Scheme of IR homing device (a) with optical cowl (b): 1 – incoming IR-flux from observed object; 2 – cowl (optical ceramics); 3 – function circuit of IR device; 4 – general view of IR homing device: central angle of cowl within of which damages happen $\Delta\theta\approx4°$ *(*$\theta_{max}\approx19...23°$*); outer cowl radius* $R_w=2\cdot10^{-2}$ *m; thickness of hemi-spherical shell of cowl* $H=4\cdot10^{-3}$ *m; maximum density of external heat action* $(q_w)_{max}=3\cdot10^5...2.5\cdot10^6$ *W/m*^{2}*; supersonic speed of air flow* $V=7\cdot10^2...2.5\cdot10^3$ *m/s*

Calculations by the formula (1) made it possible to establish that increasing of the heating velocity of the entrance windows in laser rangefinders (from 100 to 400 K/s) and blowing by air flow of the cowls in IR-devices under consideration ($7\cdot10^2$ to $2\cdot10^3$ m/s) in real conditions leads to increased reliability of these devices in 1.3...1.9 times provided the final electron beam processing of their surfaces (Fig. 12, 13).

Table 1

Impact of electron beam processing of devices surfaces on the amount their damage $\bar{k}$[*] *(%) depending on the parameters of the thermal action (heating velocity V_1 (K/s) for windows of K8 optical glass, and blowing velocity V_2 (m/s) for cowls of KO2 optical ceramics)*

Entrance window V_1, K/s	$\bar{k}$, %	
	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
Cowls V_2, m/s	$\bar{k}$, %	
	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

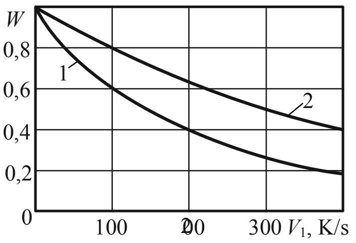

Fig. 12. Dependence of the probability of faultless work of laser sighting systems during the external thermo actions on velocity of external heat of their optical windows of K8 optical glass: without electron beam processing (1); after electron beam processing ($F_n = 5\cdot10^8$ W/m^2, $V = 5\cdot10^{-3}$ m/s) (2)

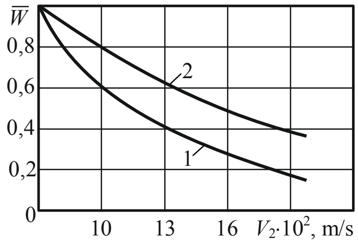

Fig. 13. Dependence of faultless work of IR devices on the speed of supersonic blowing by air flow to the hemispherical cowls of KO2 optical ceramics: without electron beam processing (1); after electron beam processing ($F_n = 2\cdot10^7$ W/m^2, $V = 10^{-3}$ m/s) (2)

Conclusions. The results of the research determined the optimal range of change of parameters of the electron beam (density of thermal action $F_n = 7\cdot10^6...8\cdot10^8$ W/m^2 and the velocity $V = 5\cdot10^{-3}...5\cdot10^{-2}$ m/s) within which observed substantial improvement of the properties of the surface layers of the optical elements of glass (K8, K208, BK10) and ceramics (KO1, KO2, KO3, KO5, KO12):

– the surface is cleaned from the various negative defects (scratches, bubbles, small cracks, etc.) that remain after standard machining, and becomes atomically smooth;

– the surface microhardness of optical elements increases in 1.3... 1.7 times and forms the hardened layers of thickness of 70... 230 μm with compressive stresses of 25...90 MPa;

– increase the critical importance of external heat flow and the time their actions in 1.5…4 times;

– increases the maximum allowable value of thermoelastic stresses in optical elements at temperatures of 300…1200 K in 1.7...2.7 times.

Established that final electron-beam processing of the optical windows surfaces of laser range-finder in sighting system and external surfaces of cowls of IR-devices by increasing of their surface layers resilience to external thermal actions leads to an increase in 1.3...1.9 times the reliability of devices during their operation in conditions intense external thermal action (high speed external heating of the optical window surfaces (up to 400 K/s) and thermal shock effects of supersonic air flow (flow rate up to $2\cdot10^3$ m/s) to the cowls).

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[*] Note: $\bar{k} = k/k_0$, where k_0, k – the total number of tested entrance windows and cowls, and the number of devices, which had been destroyed, respectively. The angular velocity of axisymmetric rotation of cowls in the considered range of change ($4\cdot10^3$ rad/s) does not affect the amount of their damage.

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