INCREASING THE RESISTANCE OF PRECISION INSTRUMENT-MAKING ELEMENTS FROM OPTICAL GLASS TO EXTERNAL THERMO-INFLUENCES BY PRELIMINARY ELECTRON-BEAM PROCESSING OF SURFACES

ПОВЫШЕНИЕ СТОЙКОСТИ ЭЛЕМЕНТОВ ТОЧНОГО ПРИБОРОСТРОЕНИЯ ИЗ ОПТИЧЕСКИХ СТЕКОЛ К ВНЕШНИМ ТЕРМОВОЗДЕЙСТВИЯМ ПУТЕМ ПРЕДВАРИТЕЛЬНОЙ ЭЛЕКТРОННО-ЛУЧЕВОЙ ОБРАБОТКИ ИХ ПОВЕРХНОСТЕЙ

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Abstract: *The results of experimental studies to improve the properties of the surface layers of the elements of optical glass (K8, K108, K208, BK10, TF110) after their processing by mobile electron beam with density of heat exposure* $F_n = 7\cdot10^6 \ldots 8\cdot10^8$ *W/m*^{2} *and displacement speed* $V = 5\cdot10^{-3} \ldots 5\cdot10^{-2}$ *m / s (a reduction of residual microroughness height at the surface from 4 ... 6 nm (unprocessed elements) to 0.5 ... 1 nm (processed elements), the occurrence of melted layers of thickness up to 250 ... 300 microns with a modified structure, which is close to the quartz glass) are presented. It was found that the improvement of these properties increases the resistance of elements to external-heat: an increase in 1.3 ... 1.7 times of the critical value of external heat fluxes and the time of their exposure, the excess of which leads to the destruction of elements and damage to the test instrument turndown external pressure* $10^5 \ldots 10^7$ *Pa; increasing the maximum permissible values of thermal stress in the elements from 20 ... 40 MPa to 90...100 MPa heating temperatures 300 ... 1200 K;an increase of the probability of failure-free operation in the 2 ... 2.5 times by increasing the speed of the external heating from 100 K / s to 400 K / s.*

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

1. Introduction

Modern devices with elements of optical glass (K8, K108, BK 10 and so on) for measuring and thermal control of different physical nature objects (flat plates and discs as optical integrated circuit substrates, aerophoto lenses and plates of double curvature for space mirrors and aerospace applications, the input protective windows and lenses in sight for observation in the visible and infrared regions of the spectrum, optical fibers on optical monofilaments in laser medical devices for the diagnosis and treatment and so on) in operating conditions are exposed to intense external-heat (higher heating temperature and external pressure, shock thermal and mechanical stress in a shot and the flight, etc.) [1 - 3]. Under these conditions, a change in the properties of the surface layers of the optical elements up to their destruction (cracking and chipping, deep surface melting to form a sagging, undulating surfaces, changing the geometrical shape and others defects) takes place and leads to significant deterioration of the technical-operational characteristics of devices and their failure.

Therefore, the prevention of forced destruction of the optical elements of the instrument gets a significant importance in terms of their operation, taking into account the impact of external-heat.

As shown by experimental studies of various authors [4 - 8], in order to prevent the destruction of optical elements the electron-beam methods of finishing processing their work surfaces have the practical value at the manufacturing stage, and allow to improve the properties of the surface layers of elements and thus make them more resistant to external-heat, improving basic technical and operational characteristics of devices (reliability, service life and so on). However, studies of thermal exposure of the electron beam to change the properties of the surface layers of optical glass elements are currently insufficiently investigated. Therefore, the aim of this work is to prevent the destruction of optical glass elements of instruments for measuring and thermal control objects of different physical nature by improving the properties of the surface layers of the elements and increasing their resistance to external-heat by electron-beam processing.

2. Results and discussion

As a result of experimental studies they established the following optimal ranges of electron beam parameters: $F_n = 7\cdot10^6 \ldots 8\cdot10^8$ W / m^2, and $V = 5\cdot10^{-3} \ldots 5\cdot10^{-2}$ m / s, within which there is the most significant improvement of the properties of the surface layers of the optical elements (more than in a few times).

The results of electron microscopic examination of the surface of the optical glass elements made it possible to establish that on their surfaces after machining there are such heterogeneity as scratches, cracks and unevenness, the number of which is markedly reduced after electronic processing. In addition, the surface of elements has unevenness and defects which are a result after mechanical polishing, and which are virtually absent after electron beam processing. On the unprocessed by electron beam surface portion of elements there are characteristic etch pits defect layer, while on the processed part of the surface there are much less or practically absent.

In the study of fracture surfaces (fracturegramm) of optical glass elements before and after electronic processing they revealed that the nature of the fracture is different. It is found that a fine-grained fracture occurs in the processed layer. In he elements that are exposed to the electron beam, there is a fine-grained fracture. The individual small crystals are found on the surface of the parent element. Furthermore, the nature of electron diffraction on the microdiffracturegraphs indicates crystal hexagonal structure of inclusions.

The analysis of transverse sections, chips, fractures of optical glass elements after mechanical polishing and electronic processing shows that: a clear boundary between the processed surface by electron beam and the very foundation of the element material is not observed; there is a significant difference between sides of the element - processed and unprocessed; there is a modification of the surface structure to the depth of 200 ... 220 microns with its most significant change in the sintered layer with the elements of "viscous" destruction.

The results of studies of optical glass elements surfaces by electron microscopy scanning showed that on the surface after machining, the most characteristic there is a presence of various microroughnesses - small cracks of the depth up to 0.1 ... 0.7 microns, thin scratches up to 2 ... 5 microns, as well as "tubercles" bubbles etc., a size of which $10^{-3}...10^{-2}$ microns. After electron-beam processing bubble sizes (diameters) on the elements surface are reduced in 2 ... 4 times, therefore " tubercles " and other unevenness of less than 1 ... 2 microns are not observed, that is in result of processing by electron beam the elements surface, as it were "cleaned", small defects are eliminated.

The analysis of electron-microscopic images of the surfaces of optical glass elements, the study of surfaces of the polished sections of chipped elements before and after electron beam processing indicates that in the first case the microroughness height is 30 ... 40 nm, and in the second one it is reduced to the level of 0,5 ... 6 nm.

The study of fracturegramms of optical glass elements surface layers before and after electronic processing showed that the depth of main-heat zone or the thickness of the deposited layer can be up to 250 ... 300 microns, and essentially depends on the magnitude F_n and the moving speed V of the electron flow (Fig. 1, 2). Thus, an increase of F_n from $7{\cdot}10^6$ W/m² to $8{\cdot}10^8$ W/m², when used in practice the electron flow moving speed $V = 5{\cdot}10^{-3}$ m/s leads to increasing depth of fusion from 50 microns to 230 microns for elements from optical glass K8; from 30 microns to 150 microns for elements from optical glass K108; from 25 microns to 140 microns for elements from optical glass K208; from 30 microns to 180 microns for elements from optical glass BK10; from 40 microns to 170 microns for elements from optical glass TF110. And an increase in the electron beam moving speed from 10^{-3}m/s to 10^{-2} m/s, when used in practice of F_n values already leads to a reduction of the melting depth: from 200 microns to 70 microns for elements from optical glass K8; from 160 microns to 40 microns for elements from optical glass K108; from 130 microns to 30 microns for elements from optical glass K208; from 170 microns to 80 microns for elements from optical glass BK10 and from 160 microns to 40 microns for elements from optical glass TF110.

A detailed study of scans of sections of the surface of optical glass elements after electronic processing indicates a local smoothing of irregularities, a significant dependence of the surface shape of the processing modes. So, with a deep reflow (200 ... 250 microns) it is observed a well-defined wavy surfaces. This modified melted layer has clearly oriented structure on melting depth.

The layers, formed by electron beam on the optical elements surface are modified to different degrees in chemical composition. Thus, the analysis of change in the elemental composition of the surface of elements of optical glass K8, K108, K208, conducted with the help of the wave dispersion spectrometer, showed a decrease of Na and O concentration, an increase of Si concentration and the constant K concentration. At the same time, by X-ray analysis on the example of untreated and treated by electron beam elements of the optical glasses BK10, TF110 it is shown that significant quantitative changes in the chemical composition of its surface are not observed, however, it is possible to make a conclusion as for the improvement of the homogeneity of the distribution of elements in micro-surface layer after electronic processing .

In the result of conducted researches, it was found that after electron beam pre-treatment of the optical elements an increase comes in the critical values of the external heat flows q_n^* and their impact time t^* in 1,5…2 times (Fig. 3).При этом увеличение внешнего давления до 10^7 Па приводит к увеличению значений q_n^* и t^* только в 1,4…1,5 раза. The increase in external pressure up to 10^7 Pa leads to reduction in the values q_n^* and t^* only in 1.4 ... 1.5 times.

In addition, it was also shown that the limit values of thermoelastic stresses $\sigma^*(T)$ at different temperatures for heating the optical elements treated by electron beam in 1.7 ... 2.3 times higher than for untreated elements (Fig. 4).

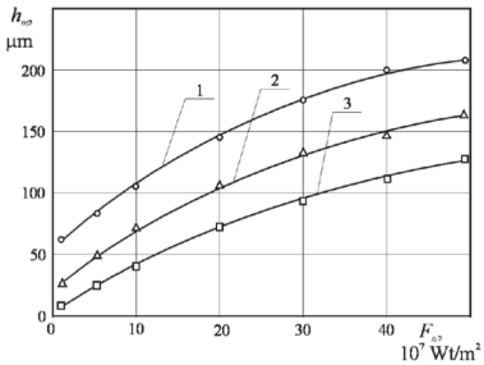


Fig. 1. The dependence of the thickness of melted layers in the elements of optical glass K8 (1), K108 (2) and K208 (3) on the density of the thermal effects of the electron beam ($V = 5{\cdot}10^{-3}$ m / s): Δ, ○, □ - experimental data.

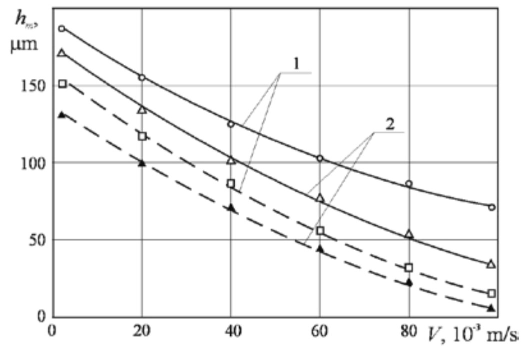


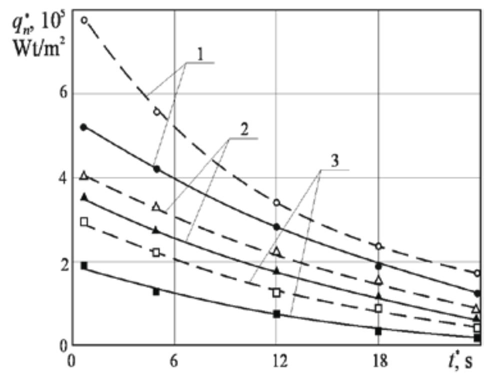
Fig. 2. The dependence of the thickness of melted layers in the elements of the optical glasses BK10 (1) and TF110 (2) on the moving speed of the electron beam: ——— – $F_n = 5{\cdot}10^8$ W / m²; – – – – – $F_n = 7{\cdot}10^6$ W / m²; Δ, ○, □, ▲ - experimental data.

The tests of the optical elements under conditions of alternating external heating, which simulates actual operating conditions of the optical devices with the influence of external-heat showed that in the case of an electron beam-treated elements it is observed in 2 ... 2,5 times less of their destruction and failure of devices on their basis than for untreated elements (Table. 1).

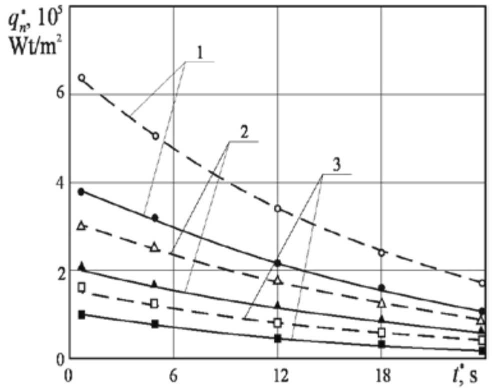
The safety factor as a measure of efficiency of the optical device at a predetermined heating rate $V_н$ (or time t, which is given to the test at a controlled heating temperature) is determined by the following formula [8]:

$$W(V_н) = 1 - N(V_н) / N_0, \quad (1)$$

where $W(V_н)$ - probability of preservation of working capacity of the device of sighting system under external thermal effects; $N(V_н)$) - the number of devices that fail at a heating rate $V_н$ (the destruction of the optical element is taken as the failure of the device as a whole); N_0 - the total number of devices that are tested.



a)



б)

Fig. 3. The dependence of the critical values of the external heat flows q_n^* from the time of their exposure t^* on the elements of optical glass K8 (1), TF110 (2) and BK10 (3) for a variety of external pressures (the thickness of the element $H = 10^{-2}$ m): a) – $P = 10^5$ Pa; b) – $P = 10^7$Pa; ——— – elements which are not processed by electron beam; – – – – processed items; ●, ○, Δ, ▲, □, ■ - experimental data.

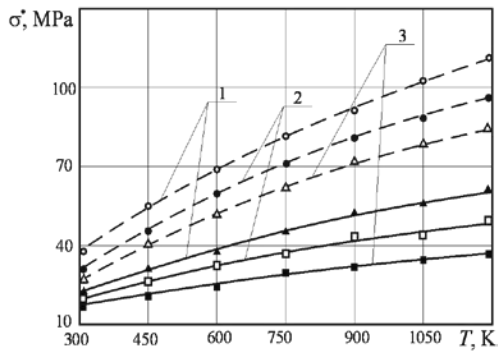


Fig. 4. The dependence of the value of the maximum allowable thermal stresses in the elements of the optical glass K8 (1), TF110 (2) and BK10 (3) on the heating temperature ($P = 10^5$ Pa, element thickness $H = 10^{-2}$ m, $F_n = 1{,}5{\cdot}10^7$ W/m², $V = 5{\cdot}10^{-3}$ m/s): ——— – elements that are not treated by electron beam; – – – – processed items; Δ, ○, □, ▲, ■, ● - experimental data.

From the formula (1) it follows that with increasing heating rate of the devices of the suggested devices (e.g., from 100 K/s to 400 K/s) leads to decrease in the probability of trouble-free operation under external-heat terms in 4.9 times; while in the case of input windows which are pre-treated by electron beam, the probability of trouble-free operation of devices increases in 2,3 times (Fig. 5).

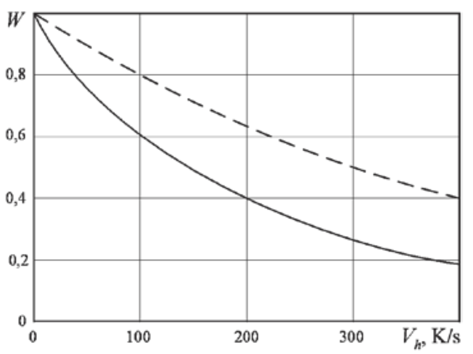


Fig. 5. The dependence of the probability of trouble-free operation of sighting devices complexes under conditions of external-heat from an external heat rate of their input protective windows: ——— – – the input windows that are not processed by electron beam; – – – – the input windows, the outer sides of which are processed by electron beam (beam parameters $F_n = 5{\cdot}10^8$ W/m², $V = 5{\cdot}10^{-3}$m/s).

Table 1

The influence of electron beam processing of working surfaces of the elements in the form of plates of optical glass K8 on the dependence of the relative amount of their damages (k) from the heating rate *)

Input protective window / External heating rate, K/s	k, %	
	unprocessed by electron beam	processed by electron beam
100…150	40…50	20…30
150…200	50…60	30…40
200…300	60…70	40…50

*) Note. $k = k_p/k_0$, where k_0, k_p - a total number of test elements and the number of exposed to fracture respectively.

It is shown that the use of the results in the design and manufacture of new instruments, as well as the modernization of serial devices to considered optical elements for measuring and thermal control of the objects of different physical nature (optical integrated circuits substrates, aerophoto lenses, laser sights for observation in the visible and infrared regions of the spectrum , laser medical devices etc.) allows to improve basic technical characteristics (the reliability, service life and durability) when used in accordance with the influence of external-heat, for example during storage or transport under the conditions of occurrence of high-temperature fire sites, as well as the design of products with infrared devices in a shot and the flight (external thermal shock effects and others).

3. Conclusions

1. It was found that after the pre-treatment of the working surfaces of the elements of optical glass (K8, K108, K208, BK10, TF110) by mobile electron beam for change ranges of its settings (density of the heat effect $F_n = 7{\cdot}10^6…8{\cdot}10^8$ W/m² speed of its movement $V = 5{\cdot}10^{-3}…5{\cdot}10^{-2}$m/s) the basic properties of the surface layers are improved:

– after electron beam processing the surface of elements are completely cleared of defects, which were obtained by the mechanical polishing (fine cracks sized 0.1 ... 0.7 microns, long thin scratches 2 ...5 microns and other defects in size $10^{-3}...10^{-2}$ microns); thus there is a smoothing of irregularities, substantial dependence of the surface shape from the processing modes (with deep reflow (up to 200 ... 250 microns) a well-defined wave-like surface is observed, and the modified melted layer has clearly oriented structure for melting depth);
– the electron-beam processing of the elements of optical glass by melting leads not only to homogenization of the surface, but also to oriented restructure near the surface of the silicon-oxygen grid, which is becoming close to the quartz glass structure, which considerably increases the resistance of the elements to external-heat;
– the depth of the main-heat zone or the thickness of the melted layer can reach 250 ... 300 microns and essentially depends on the density of heat exposure of the beam F_n and its moving speed V: for example, increasing F_n from $7{\cdot}10^6$ W/m² to $5{\cdot}10^8$ W/m² and decreasing V from $5{\cdot}10^{-3}$ м/с до $5{\cdot}10^{-2}$s leads to an increase in depth of melting from 20…60 microns to 130…220 microns.

2. It was found that improvement of the properties of the surface layers of the optical elements after electron beam processing leads to increase their resistance to external-heat:
– increase in 1.5 ... 2 times the critical values of the external heat flows and times of their effects that lead to destruction of elements; thus increasing the external pressure from 10^5 Pa to 10^7 Pa reduces the critical values of these parameters in 1,3 ... 1,4 times;
– increase in 1.7 ... 2.3 times the value of the maximum permissible thermal stress in the optical elements processed by

electron beam, to change the heating temperature range 300 ... 1200 K.

3. It was found that electron beam pre-treatment of plates of optical glass used in the devices for measuring and thermal control of objects of different physical nature, reduces the amount of damage in the 2 ... 2.5 times and increases the probability of failure-free operation in 1.9 ... 2.3 times under variable external heating conditions.

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