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Research on thermoelastic tension in two-layer structure of glassceramic ZERODUR by modulation polarimetry method

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Abstract: Thermotension induced by a thermal stream from contact heating with a capacity of 1 W at a slight temperature gradient within a sample (6-10°C) has been found in the sample consisting of two bonded plates made from the glass ceramics ZERODUR by means of the method of a modulation polarimetry. Changes in the distribution of values of tension lengthwise and crosswise in the directions of a thermal stream in the course of sample heating have been measured. The research showed that the reason of thermotension was related to a connecting layer and a distinction in values of the photoelastic constant of a nanocrystal and glass phase of ZERODUR.

Keywords: Thermoelasticity, Anisotropy, Double Refraction, Modulation of Polarization, ZERODUR

1. Introduction

As is known, lithium aluminosilicate, glassceramic materials of the ZERODUR (SCHOTT, GERMANY) kind are the composites that have nanocrystal structure in a glassy matrix. The main components of these materials are nanocrystals with the negative coefficient of thermal expansion (CTE) and glass with the positive CTE, and the structure of optical glass ceramics is optimized to obtain almost the zero value of total CTE in a wide range of temperatures. This property of materials virtually excludes the phenomenon of thermoelasticity and makes them indispensable when designing and manufacturing the main mirrors of optical telescopes, cases of laser gyroscopes and other precision optical devices geared to work in a wide range of temperature. If necessary, elements of ZERODUR design can be assembled in structural blocks or connected both with each other and other materials. This can cause some types of internal mechanical tension. First, there is the tension, which is related to the so-called "frozen" thermoelasticity and caused by characteristics of the technology of manufacturing a specific unit. Secondly, if the unit consists of elements with different CTE, thermotension, which goes deep into them, occurs in their joint. To study minimum changes in the value of photoelasticity of materials with zero CTE as an example, the method of modulation polarimetry (MT) has been used. The MT method displayed high sensitivity when tackling tasks of this kind [1].

2. The Purpose of the Study

The purpose of the study lay in experimental research on thermal tension in the sample consisting of two bonded plates made from the glass ceramics ZERODUR in the conditions of small drops in temperature along the length of a sample with the help of the MT method.

3. Experiment Techniques

The gist of the MT method is that the traditional optopolarizing scheme consisting of two crossed linear polarizers and a sample between them is supplemented by the modulator of polarization of electromagnetic radiation. This supplement has provided MT equipment with universal properties as it enables research on all the polarizing phenomena: linear and circular double refractions, as well as dichroism. Importantly, it has high sensitivity to corresponding parameter (deformation, temperature or structure gradients, etc.).

As regards the optical scheme used in this work (fig. 1a), the modulator of polarization is located after a sample for the following reasons. Linearly polarized radiation in initial U-condition (in designations a Stokes vector component of S = [I Q U V] [2]) in which the azimuth of electric field makes an angle of 45 degrees relative to the optical (anisotropic) axis of a sample, it will be generally transformed into the elliptically polarized one. The value of V-components (circular) in its structure will be in the form of IV ≈ I sin (φ) [3]. In this φ is the difference of phases of orthogonal linear components of radiation, which is defined in coordinates (fig. 1b) by the ratio

$$\varphi = \varphi_x - \varphi_y = {}^{2\pi}/_{\lambda} d(n_x - n_y) \; [4] \quad (1)$$

where λ - the length of a wave of scanning radiation, nx and ny - indicators of refraction of the material of a sample, and d - its thickness. The value of anisotropy is defined by the value and sign of the difference of main components of a tensor of tension in the direction of the corresponding axes: n_x - n_y = C (σ_x-σ_y), where C is the Brewster's photoelastic constant. Thus, the traceable signal from last radiation, being expressed by the intensity of a V-component, is the linear measure of internal mechanical tension of $I_V \approx \varphi$ at small values of a phase delay (the condition φ <<1 is well met in this experiment).

A semiconductor laser with the length of a wave λ = 650 nanometers has been used as a source of radiation. The function of a linear polarizer consists in an increase in the extent of polarization of radiation coming out from it. The axis of a polarizer and, therefore, the direction of a field of a wave of the laser $\vec{E}$ should make such angle with axes of the ellipsoid of wave normals [5] of the investigated object as linearly polarized radiation will be most effectively transformed to the circular one. Under conditions of a phase plate, this angle is defined by equality of $E_x = E_y$ orthogonal components and it makes 45 degrees relative to the optical axis of a sample, as stated above. Since the direction of a temperature gradient (thermal stream) defines the orientation of the optical axis of a sample, it would be appropriate to set the azimuth of electric field of a wave in initial condition relative to coordinates of the sample as per to fig. 1b.

Located after a sample, the polarization modulator is the dynamic phase plate [6] in which optical anisotropy is created by the sign-variable deformation arising from a stress-strain on the quartz plate resonator attached to it. The modulator, together with the linear polarizer whose axis is turned at the angle of 45 degrees relative to optical axes of the modulator, is the dynamic analyzer of condition of the polarization of radiation. The intensity of radiation falling on a photodetector (Si-photodiode) has the variable component of frequency modulation ω defined by the value of the circular component $I_V \approx I \sin(\varphi) \sin(\omega t)$ [7].

The signal of the photodetector was measured by the lock-in-nanovoltmeter in which the value of a constant of integration was established in consideration of the parameter of dynamics peculiar to the thermal process. In the case of a slowly changing parameter its value could be increased to 3 s. If it was required to scan the distribution of tension distribution in a sample at certain moments with the help of a probing beam, this value was established at the rate of 0.1 s, and reproduction of the results of variation of the constant of integration served as a criterion of reliability.

The sample in the form of a two-layer polished plate z×y×x = 20×18×15 (mm) in size has been made from ZERODUR in accordance with the technology of bonding polished details and applying a nanodimensional layer of aluminum to ensure a diffusive joint at a temperature of up to 600°C [8,9]. One of the surfaces of a sample was fixed on glassceramic covered with the nickel film resistor that served as a source of heat. The resistor was connected to a source of direct current, which set a heat source capacity of no more than 1 W in a stationary mode, and thereby provided non-uniform heating of a sample from room temperature to the temperature that exceeded room temperature by 6-100C. Thermal contact of a sample with a resistance heater (resistor) was maintained by means of heat-conducting paste that fixed its position and excluded stress on it due to fastening conditions.

The value I_V as the function of the y-coordinate of a sample was measured at two options: 1 - at certain moments of the distribution of a thermal stream along it when its direction is perpendicular to a connection surface (fig. 1b); 2 - perpendicular to the direction of a thermal stream when it is parallel to a bonding surface (fig. 1c). In both cases the wave vector of thermal radiation was made parallel to a thermal front in order to avoid the summation of tension of opposite signs.

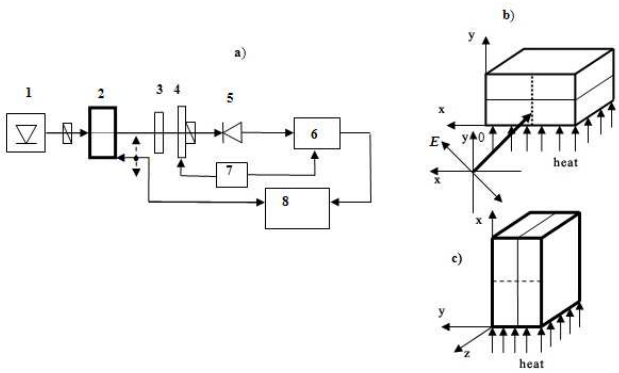

Figure 1. *The optical scheme - (a) both geometry of the experiment and orientation of a sample at the first (b) and second (c) option (a stroke designates a scanning coordinate). 1 - laser diode; 2 - sample; 3 - compensatory phase plate; 4 – polarization modulator (PM); 5 - photodetector; 6 - lock-in-nanovoltmeter; 7 - power unit of PM; 8 - personal computer; E-electric field of a wave.*

At first, residual stress caused by the non-uniform composition or structure of samples ("frozen" thermoelasticity) was measured at both options, and then the measurement of stress due to the gradient of temperature at the ends of a sample as well as due to contact heating has been taken. Thermal stress was defined as the difference of results obtained from the first and second measurements.

4. Results and Discussion

Fig. 2 shows the result of research on dependence of the value of mechanical tension at the option (fig. 1b), which has been counted over a distribution along a thermal stream of the value of intensity of a circularly polarized radiation component. As is clear from the drawing, the sample in a thermodynamic balance ("frozen" thermoelasticity) has intense sites of compression (negative values σ) and stretchings (positive values σ). The thermal stream from a heater to which one of the flat surfaces of a sample is exposed, induces additional tension. Its distribution recorded a minute later after switching on a heater is depicted as the bold curve that has values exceeding the curve of the "frozen" component all along a sample. It means that in this case heating entails the additional normal component of a mechanical stress-strain on a sample all along its scanning.

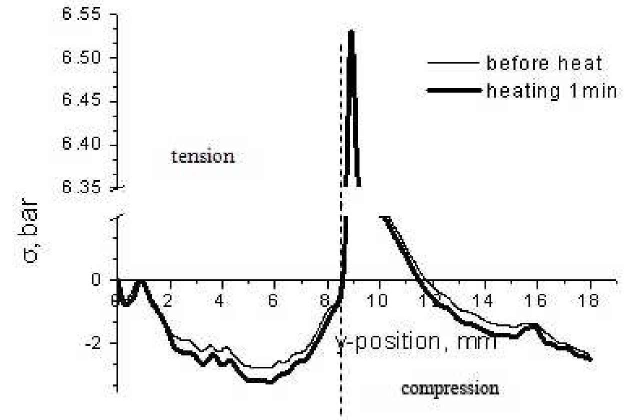

Figure 2. Distribution of the normal component of mechanical tension in a plate structure at the option (fig. 1b) along the y-coordinate of a sample without heating and 1 min later after switching on a heater.

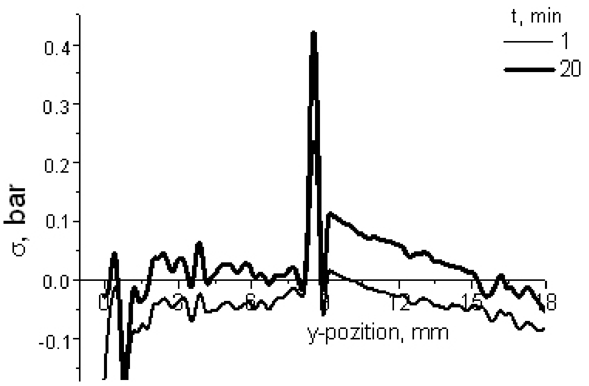

Figure 3. Distribution of the value of a normal tension component along a thermal stream in a structure at the option (fig. 1b) at the moments of 1 and 20 min after switching on a heater.

Fig. 3 shows distributions of tension of temperature origin along the coordinate, which is parallel to a thermal stream, as a result of subtraction of coordinate functions of a warm and cold sample.

Curves represent the evolution of tension at the first moments (1 min) and in conditions of the set distribution of temperature (20 min after switching on a heater). As is clear from the drawing, the situation in these two cases differs despite the identical character of curves. As distinct from the first moments, the set distribution of temperature causes mainly compressive stress except the area that adjoins the boundary of a junction of parts of a sample. Like fig. 2, the drawing also shows the general nonmonotonic dependences, which have not been related to experimental conditions or characteristics of measuring equipment. It is evidenced by the fact that the curves are fixed on the distribution of the value of a transmission of an unheated sample, which shows similar nonmonotonies (fig. 4).

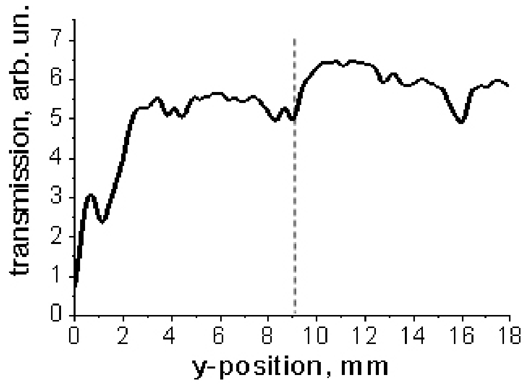

Figure 4. Coordinate dependence of the value of a transmission of probing radiation of an unheated sample.

It is worth noting that as a result of normalization, all nonmonotonies remained clearly discernible, though they became less defined. From fig. 3 it follows that a sample under investigation has the following features: local irregularities with the cross-section sizes of ~1 mm in its both parts; occurrence of similar irregularities in curves (fig. 2 and 3) fixed on the intensity of a transmission testifies to the fact that their thermoelastic properties differ from the properties of a matrix; on the average optical density of structure components, as well as their Brewster's constants $0 \leq y \leq 9$ and $9 \leq y \leq 18$ differ from each other (as is perfectly clear from the curve 1 min).

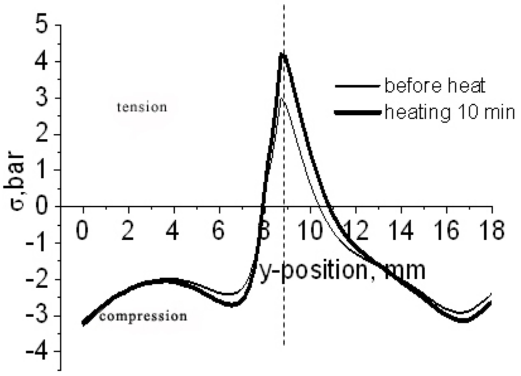

Figure 5. Distribution of the normal component of tension in a plate structure along the coordinate of a sample, which is perpendicular to the direction of a thermal stream (option fig. 1b) without heating and 10 min later after switching on a heater.

Fig. 5 shows the picture of internal mechanical tension in the absence of heating and during heating of a sample at the option (fig. 1b). However, this picture bears a superficial resemblance to the one represented in Fig. 2. Indeed, the "frozen" thermoelasticity is qualitatively in line with a corresponding curve (fig. 2), though they are not bound to be identical on the strength of a macroscopic irregularity because of a distinction in values of X-coordinate scanning (nonreproducibility).

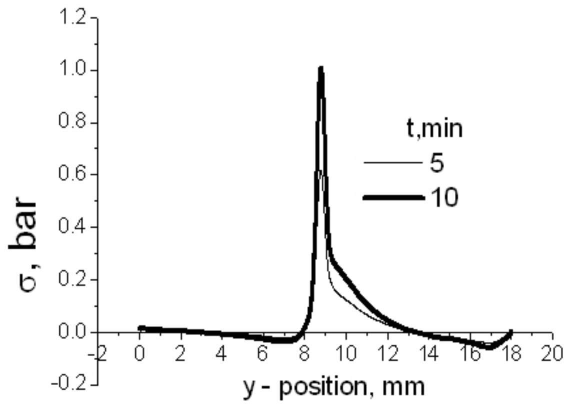

Figure 6. *Distribution of thermotension in a plate structure along the coordinate of a sample, which is perpendicular to the direction of a thermal stream 5 and 10 min later after switching on a heater.*

The curves of tension caused by a thermal stream (fig. 6) are even more dissimilar. In this case the thermoelastic curve has a positive sign in the middle only, negative sign at lateral surfaces and twice changing sign on the right side.

Discussing results, we would like to begin with the fact of detection of thermoelasticity in the substance in which it should be absent because the temperature coefficient of its linear expansion is close to zero. Nevertheless, its registration promoted two equivalent circumstances. Mentioned in the introduction, the first circumstance consists in high sensitivity of the techniques of modulation polarimetry in relation the value of double refraction. The second circumstance lies in properties of the structure of a sample, which consists of two connected components of the same nature, although the components have slightly different optical and mechanical constants (different batches of manufacturing). This is evidenced by figures 2 and 5, which show how deformation (tension) caused by a local stress-strain on the boundary of a joint extends to its both sides with differing lengths of attenuation. As a matter fact, the third component with the connecting material, namely an aluminum layer 100 nanometers thick, is also present in this structure. This layer (fig. 4, an extremum at the intersection with a stroke) creates main tension, therefore it forms anisotropy in ZERODUR layers adjoining to it. And the response of this structure to a thermal stream in the form of induced tension turns out to be comparable with the value of the "frozen" thermoelasticity, which occurs in the absence of heating. Also, the existence of this layer explains the increased value of tension of temperature origin during a measurement at the option of figure 1c. The layer of aluminum that is directly exposed to a heater at this option, possessing higher heat conductivity, brings the additional component into the coordinate function of a temperature. In its turn, this leads to a greater difference in the thermal expansion of components of a structure and big deformations.

Particular emphasis should be put on the transmission characteristic in which a significant optical irregularity causes strong dispersion and, as a result, low transparency. Probably, angular dependences of the intensity of scattered radiation, as well as its condition of polarization at various lengths of waves could provide data on the structure and nature of scattering centers that would be a separate task.

5. Conclusions

It has been shown in this work that the method of modulation polarimetry possesses so high sensitivity in relation to the value of tension (optical anisotropy), that it is possible to observe kinetics and dynamics of thermal tension at insignificant temperature gradients within a sample even in materials of the ZERODUR kind with almost zero CTE. The additional circumstance, which helps manage the set task, has the physical nature and consists in the availability of the crystal component of the structure of glass ceramics. As is known, the Brewster's constant acquires great values in crystals, compared with glass, that provides a raised signal caused by stress on them during non-uniform heating of local irregularities. As far as further research is concerned, the above circumstance can be used as a tool to control uniformity of both products made from ZERODUR and parameters of the technological process of their manufacturing.

References

[1] I. E. Matyash, I. A. Minailova, O. N. Mishchuk, B. K. Serdega "Kinetics and dynamics of heat-flow-induced birefringence in a glass: modulation polarimetric representation," Physics of the Solid State, FTT, 2013, Volume 55, Issue 5, pp. 1003-1010

[2] A. Gerard, J.M. Burch, "Introduction to matrix methods in optics," 1975. A Wiley-Intersc. Public. London-N-Y-Sydney-Toronto. There is the translation of this work from English into Russian. Moscow: Mir. 1978. p. 342.

[3] B.K. Serdega, Ye.F. Venger, Ye.V. Nikitenko. "Thermoelasticity in Ge due to nonuniform distribution of doping impurity studied by light polarization modulation technique," Semic.Ph., Quant.El.&Opt. - 1999. - V. 2, No. 1. - pp. 153-156.

[4] M. Born, E. Wolf. "Principles of Optics Cambridge, Cambridge University Press," 1968, p. 952.

[5] G. S. Landsberg "Optics," Moscow: GITL. - 1957. - p. 760

[6] S.N. Jasperson, S.E. Schnatterly "An improved method for high reflectivity ellipsometry based on a new polarization modulation technique," Rev Sci Instrum. - 1969. - V. 40 (6). - pp. 761-767..

[7] I.E. Matyash, B.K. Serdega. "Features of polarizing modulation diagnostics of dielectric anisotropy of materials," Optoelectronics and semi-conductor equipment, V. 40, pp. 155-161 (2005).

[8] V. Maslov. Development of technology for joining glassceramic parts with zero thermal expansion//OE. - 47 (2), 023401, (February 2008). - pp. 023401-1-023401-4.

[9] V. Maslov. Unknown properties of aluminum nanolayer in unglue assemblage of ZERODUR parts//American Journal of Nanoscience and Nanotechnology - 2013; 1 (3): pp. 70-73.