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Research of Heat Transfer Mechanisms in Glasses Using Modulation Polarimetry Technique

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An optical method of registration of optical anisotropy (birefringence) in glasses is offered. The research of heat transfer processes was based on the occurrence and registration of the thermoelastic effect. This effect arises in the sample during radiative cooling. Change of heat balance and loss of internal energy are due to the thermal radiation. This leads to the formation of an inhomogeneous radiation, temperature, and deformation fields in the sample. The measurement method is based on the modulation of polarization of laser radiation transmitted through the anisotropic area and the definition of its anisotropy parameters by means of this modulation. Phase differences between orthogonal components of linearly polarized light are linearly dependent on a mechanical stress magnitude. The method allows obtaining several desired material parameters by measuring one stress $\sigma(t)$ value. Detectability of the modulation polarimetry technique was high and ensured the registration of the mechanical stresses during radiative cooling by a fraction of a degree. The mechanical stresses induced by the heat flow also have small values and are nonlinearly related to the temperature function. Time dependence of the stress $\sigma(t)$ in various coordinates of the sample demonstrates a complicated and variable dependence during the measurement. Components related to radiation, conductive and convective heat transfer mechanisms are obtained from the $\sigma(t)$ dependence. Relaxation parameters of these components are determined. The technique allows simulating high-temperature heating-cooling processes during the manufacture of materials and their technological application.

Keywords: Radiation cooling, Thermoelastic effect, Modulation polarimetry technique, Birefringence, Glass, Heat transfer, Mechanical stress.

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1. INTRODUCTION

High requirements are made on the theoretical level of scientific research on the physical properties of micro- and nanomaterials under the conditions of modern scientific progress and development of nanotechnology. The experimental research of the thermal, mechanical, optical, and electronic properties of materials is an important task of materials science, especially when it comes to new micro- and nanomaterials. Glass ceramics (Zerodur) is of particular interest today and has a microcrystalline uniform structure. Nanopowders are often used as activators of the bulk crystallization of glasses [1, 2] in such materials. The high chemical activity of metal nanopowders allows obtaining glass-ceramic materials of different composition and structure. However, their effective use requires a comprehensive study of various internal physical processes. Therefore, experimental studies of processes occurring in systems with nanodispersed metal powders are relevant for both physicists and technologists.

The research of the physical properties (mechanical and optical) of several types of glass and glass ceramics [3, 4] was carried out by us. And as a result of these studies, there was a question about a more detailed study of the thermal properties and heat transfer processes in a sample. A less complex in composition optical glass SF than glass ceramics was chosen to simplify understanding. Obtaining useful information about the nature of thermal processes on the example of a simple substance will provide valuable information about the understanding of thermal processes in more complex nanostructured materials.

The research of heat transfer processes was based on the occurrence and registration of the thermoelastic effect. This effect arises in the sample during radiative cooling. Change of heat balance and loss of internal energy are due to the thermal radiation. This leads to the formation of an inhomogeneous radiation, temperature, and deformation fields in the sample. The second physical circumstance in this paper is an optical method of thermoelasticity registration. This method is known as a modulation polarimetry technique [5]. The technique allows registering thermal stresses in terms off neglection of the temperature dependence of all mechanical and optical coefficients that participate in the generation of stresses and the emergence of optical anisotropy of the sample. In our paper, we use radiative cooling, which causes a small temperature gradient in the sample. As will be shown below, the temperature difference at the sample ends was a few degrees. The mechanical stresses induced by the heat flow also have small values and are nonlinearly related to the temperature function.

Today, there are not so many experimental papers on the thermoelasticity study caused by radiation cooling. For example, paper [6] shows the radiation balance in a semiconductor crystal. This balance was created by removing free electrons from the sample volume. In this case, a decrease in the sample temperature was observed. The authors ignored the formation of mechanical stresses. The authors of the monograph [7] and others gave little information about the radiative heat transfer component. Our research does not relate to work [8], where the appearance of stresses was studied in permanently frozen models and construction and to work [9], where the cold production was investigated.

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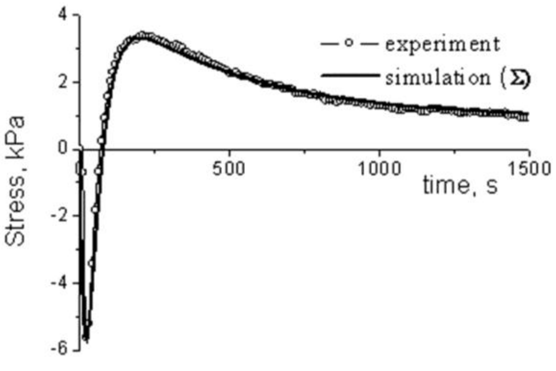


Fig. 1 – Time dependence of the experimental $\sigma(t)$ and mathematically approximated $\sigma(t)$

Our task is to continue the work [10], where the details of the radiation thermoelasticity on SF glass were studied. As noted in [11], the radiative cooling of a solid was accompanied by the appearance of mechanical stresses. Time and space distribution of the mechanical stresses must differ during the radiation cooling/heating of the sample. A detailed study of the mechanical stress distribution is of academic and practical interest. In the manufacture or heat treatment at temperatures of 1000 K [12] and 2000 K [13], the material cooling is complex. The research of the mechanical stress distribution in real time becomes problematic or impossible. Therefore, their simulation at low temperatures allows obtaining results that correspond to real conditions. Such a simulation can be obtained using modulation polarimetry techniques.

2. EXPERIMENT AND SAMPLES

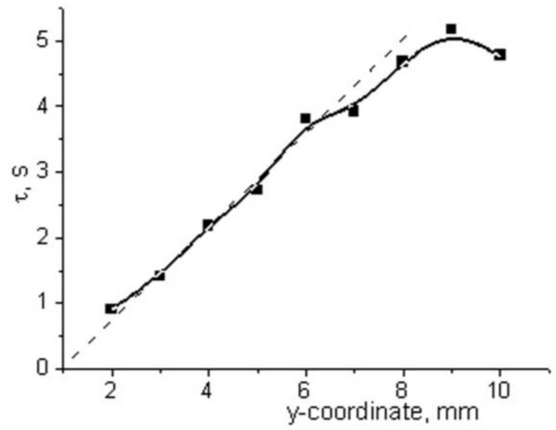
2.1 Physical Principle of the Method and Optical Scheme of the Setup

The optical scheme of equipment and its operation principle is based on the MP technique described in detail in [14, 5]. Refrigerator (thermoelectric cooler) was located above the sample at a distance of 5 mm and was of a larger dimension than the *x-z* sample surface. The temperature of the refrigerator was 6 °C and the room temperature was 20 °C.

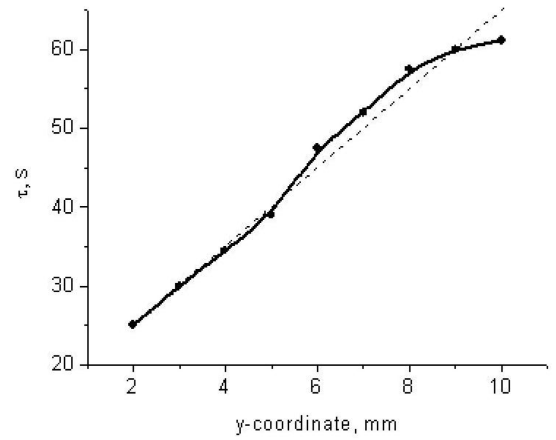
The distribution along the *y*-coordinate of the birefringence $\Delta n(y)$ and stresses $(\sigma_x - \sigma_y)$ was measured as follows. The system of values of $\Delta n_i(t)$ was registered at successive points of the y_i-coordinate in real time during the cycle: turning on the refrigerator – a steady state. Then the dependences $\Delta n(y)_t$ were produced from the set of curves $\Delta n(t)_{yi}$ by the choice of data for the corresponding time instants. The measured signal was transferred from relative to absolute units using an additional measurement. The sample was subject to an externally controlled effort (test load). After that, the relative units of mechanical stress (birefringence units) were transferred to kPa. The detectability of the setup was determined by $1 \cdot 10^2$ Pa.

2.2 Samples

Samples for measurements were made of optical SF glass as in [14].



a



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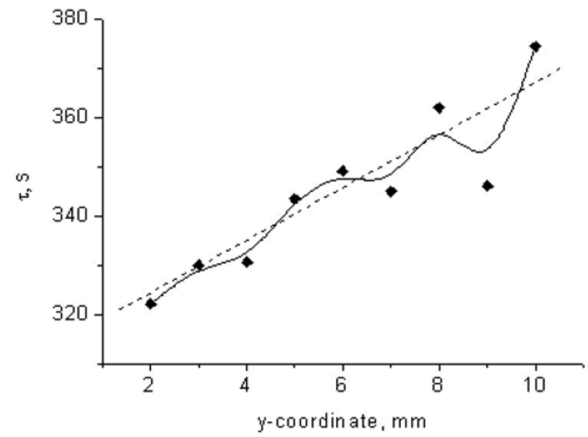

c

Fig. 2 – Coordinate dependence of the radiative (a), conductive (b) and convective (c) component relaxation time

3. RESULTS AND DISCUSSION

In the paper, special attention was given to research of the time ratios of stresses of radiation, conductive and convective components (mechanisms) in the glass sample during radiative cooling. There is a claim that these components are inseparable [15]. Single cases of placing the sample in a vacuum for the exclusion of the convective component [16] do not contradict the previous statement. Contrary to this view, the separation of the stress components from radiation, conductive and convective heat transfer in space was carried out by us. For this, we used the experimental time dependences σ(t), which were described in the paper [14] and obtained at discrete points of the y-coordinate of the sample. The method of analyzing one of the $\sigma(t)$ dependencies is also described in detail. The method is based on the mathematical approximation of the complex dependence $\sigma(t)$. This dependence has the features of three components with strongly varying parameters of relaxation. $\sigma(t)$ was approximated by a curve that consists of three exponents. Amplitudes and relaxation parameters of exponentials were determined from the analysis of experimental data. This information became the basis for the decomposition of the $\sigma(t)$ dependencies on the components in the form of three mechanisms of heat transfer – radiation $\sigma_{\mathrm{rad}}(t)$, conductive $\sigma_{\mathrm{cond}}(t)$ and convective $\sigma_{\mathrm{conv}}(t)$.

Fig. 1 shows the comparison of the experimental curve with the mathematically approximated curve in y-coordinate at 7 mm from the sample surface cooled. A curve with dots is an experiment. The solid curve is the sum of three mathematically approximated curves $\sigma = \sigma_{\mathrm{conv}} + \sigma_{\mathrm{cond}} + \sigma_{\mathrm{rad}}$. The technique of mathematical approximation is described in detail in [14]. Fig. 1 shows a good agreement between experiment and mathematical approximation. We have studied more than 10 y-coordinate positions and made sure that they have a similar tendency. Therefore, only 1 coordinate position is shown here. As a consequence, the ratio between the stress components and the relaxation time at all points in the sample will differ.

If we have several time dependences of the mechanical stress at the positions of the y-coordinate, then it is easy to determine the relaxation times of each section of the dependence. Each section corresponds to a certain mechanism of heat transfer.The relaxation time of the radiative, conductive and convective heat transfer components was determined in each coordinate ($y = 2\div10$ mm) (Fig. 2a-c). The relaxation time τ is the time during which the initial value of the mechanical stress $\sigma(t)$ is reduced by e times. These dependencies were approximated by a straight line, whose slope angle characterizes the heat flux rate. The slope of the dependence can be interpreted as a constant velocity of the radiation, conductive and convective component, at least within the sample coordinates $y = 0$-10 mm. The figure shows that the three curves have almost linear dependencies. Nevertheless, because of the different nature of the heat transfer component, the curves have certain features. The continuation of research on the features of the heat transfer mechanisms is a difficult task and will be carried out in the next research paper.

4. CONCLUSIONS

The practical importance of research results has a dual meaning. Firstly, the diagnostics of the heat-conduction, radiation, and optical properties of the material can be performed by changing the sample material while maintaining all the external conditions. And secondly, external radiation and convective effects can be tested knowing the reaction of the sample material relatively to external conditions. The technique allows experimentally registering and mathematically modulating (approximate) the various temperature processes of heating-cooling materials; separate and analyze mechanical stresses caused by individual heat transfer mechanisms; determine the thermal, mechanical and optical parameters of a solid.

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Дослідження механізмів теплообміну в склі з використанням методу модуляції поляризації

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Запропоновано оптичний метод реєстрації оптичної анізотропії (двопроменезаломлення) у склі. Дослідження процесів теплообміну засновано на появі та реєстрації термопружного ефекту. Цей ефект виникав у зразку під дією радіаційного охолодження. Зміна теплового балансу і втрата внутрішньої енергії відбувалась за рахунок теплового випромінювання. Це призводило до утворення неоднорідного радіаційного, температурного та деформаційних полів у зразку. Метод вимірювання базується на модуляції поляризації лазерного випромінювання, що проходить крізь анізотропний зразок, та визначення параметрів анізотропії за допомогою цієї модуляції. Різниця фаз між ортогональними компонентами лінійно поляризованого світла лінійно залежали від величини механічного напруження. Метод дозволяє отримати кілька параметрів матеріалу шляхом вимірювання одного значення напруження $\sigma(t)$. Висока виявна здатність методу модуляції поляризації забезпечувала реєстрацію механічних напружень при радіаційному охолодженні на частки градусу. Механічні напруження, викликані тепловим потоком, також мають малі значення і нелінійно пов'язані з функцією температури. Часова залежність напруження $\sigma(t)$ в різних координатах зразка демонструє складну та знакозмінну залежність під час вимірювання. Компоненти, пов'язані з радіаційним, кондуктивним та конвективним механізмами теплопередачі, отримані з $\sigma(t)$ залежності. Визначено параметри релаксації цих компонент. Методика дозволяє моделювати високотемпературні процеси нагріванняохолодження при виготовленні матеріалів та їх технологічному застосуванні.

Ключові слова: Радіаційне охолодження, Термопружний ефект, Техніка модуляційної поляриметрії, Двопроменезаломлення, Скло, Теплообмін, Механічні напруження.