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INCREASING THE EFFICIENCY OF LASER-CONTROLLED THERMAL SPLITTING OF SILICATE GLASSES USING THE PHOTOELASTICITY METHOD

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A method for monitoring the development of a separating crack in the process of laser-controlled thermal splitting of silicate glasses is proposed. This method is based on the polarization-optical method (photoelasticity method). The method was developed on the basis of numerical modeling and experimental studies of the process using a polarized light source and a video camera with an analyzer. During the cutting process, a source of polarized light creates a stream, which, passing through silicate glass, enters a video camera with an analyzer. Analysis of the parameters of polarized light in the area of material processing allows us to draw a conclusion about the stable development or absence of the formation of a separating microcrack. Based on the information obtained, it is necessary to dynamically make corrections to the technological parameters of the laser thermal splitting process for separating silicate glasses to maintain the value of thermoelastic stresses necessary for the formation of a microcrack, or transmit a command to interrupt the process.

Keywords: laser thermal splitting, photoelasticity, thermoelastic stresses, numerical modeling.

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ПОВЫШЕНИЕ ЭФФЕКТИВНОСТИ ЛАЗЕРНОГО УПРАВЛЯЕМОГО ТЕРМОРАСКАЛЫВАНИЯ СИЛИКАТНЫХ СТЕКОЛ С ИСПОЛЬЗОВАНИЕМ МЕТОДА ФОТОУПРУГОСТИ

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Предложен метод контроля развития разделяющей трещины в процессе лазерного управляемого термораскалывания силикатных стекол, в основе которого лежит поляризационно-оптический метод (метод фотоупругости). Метод разработан на базе численного моделирования и экспериментальных исследований процесса с использованием источника поляризованного света и видеокамеры с анализатором. Во время процесса резки источник поляризованного света создает поток, который, проходя через силикатное стекло, попадает в видеокамеру с анализатором. Анализ параметров поляризованного света в области обработки материала позволяет сделать вывод об устойчивом развитии или отсутствии образования разделяющей микротрещины. По полученной информации необходимо динамически вносить коррекцию в технологические параметры процесса лазерного термораскалывания разделения силикатных стекол для поддержания значения термоупругих напряжений, необходимых для формирования микротрещины, либо передавать команду прерывания процесса.

Ключевые слова: лазерное термораскалывание, фотоупругость, термоупругие напряжения, численное моделирование.

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Introduction

Laser-controlled thermal cleaving is a highly successful technique for precisely splitting brittle nonmetallic materials. This technique relies on sequential local heating of the material via laser radiation and the subsequent cooling of the heating zone using a refrigerant, which can be a fine-dispersed air-water mixture. The formation of a splitting crack occurs in the area of refrigerant exposure [1–5].

The mechanisms of laser-induced crack formation have been thoroughly studied and documented by researchers from various parts of the world [6–10]. Theoretical calculations of temperature fields and elastic stress fields generated in work materials made it possible to analyze their spatial distribution within the material and explain the reasons for the development of a splitting crack at a given depth.

The simulation performed in the framework of linear fracture mechanics allowed obtaining the calculated profile of the laser-induced crack and to compare it with the results of experimental studies.

In [11], the numerical simulation results of laser thermal cleaving of silicate glasses were compared with thermal-imaging measurements conducted using the IR Snap Shot device.

Numerical simulation enabled us to optimize the technological parameters for laser separation of silicate glasses. However, during the implementation of this method, deviations from these parameters may arise due to the inhomogeneity of refrigerant supply, reduction in laser radiation power density, presence of defects in the processed material, and other factors. The combination of these factors results in the disruption of the splitting crack's development, necessitating continuous visual monitoring of its presence to ensure that the separation process is interrupted in a timely manner or that processing parameters are corrected.

The photoelasticity method is suggested as a means of automating the control of splitting crack development and the dynamic alteration of processing parameters during the laser cutting of silicate glasses.

Main part

One of the criteria used to analyze the initiation and development of a splitting crack is the excess of the stresses occurring in the material over the tensile strength of the material. For brittle materials, the following criteria can be chosen as stresses of this kind: the criterion for highest normal stresses, according to which the material failure is attributed to the highest (of the three main) normal stress; the criterion for maximum tangential stresses, according to which it is assumed that the limit state of the material occurs when the highest tangential stress reaches its permissible value, which is derived from tensile-compression experiments ($\sigma_{ecv} = \sigma_1 - \sigma_3$); the criterion for specific potential energy of deformation, i. e., the hazardous state occurs when the specific potential energy of deformation reaches its limit value, which is determined through simple tensile-compression experiments (comparison is based on von Mises equivalent).

The polarization-optical method, also known as the photoelasticity method, relies on a physical and mechanical phenomenon in which plane polarized waves undergo a phase shift or optical travel difference when they pass through a deformed element of a transparent model. The magnitude of this difference depends on the stress-strain state of the element. The interference pattern resulting from the superimposition of these waves can provide valuable information regarding the magnitude and position of stresses or deformations that occur in the work material. The practical application of this method is demonstrated in several publications [12–16].

In order to dynamically ascertain the values of thermoelastic stresses and make necessary adjustments to processing parameters, a prototype of the set-up was created. The schematic representation of this prototype can be seen in fig. 1 [17].

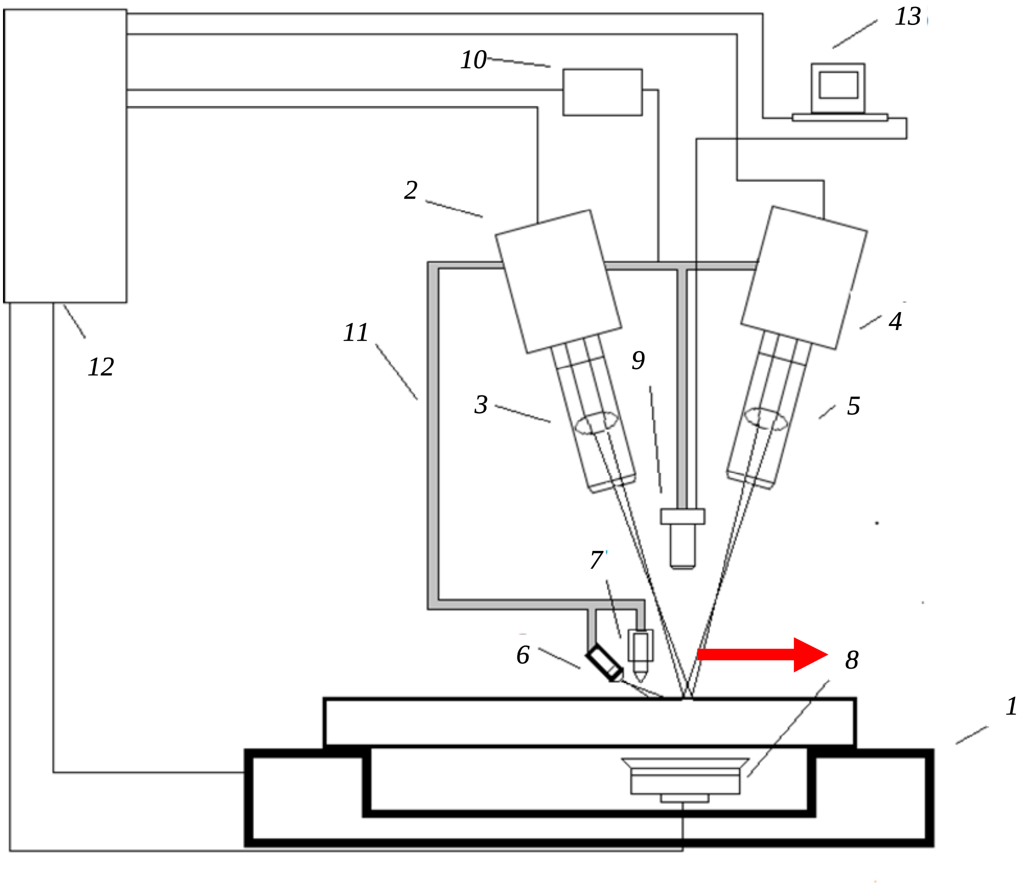
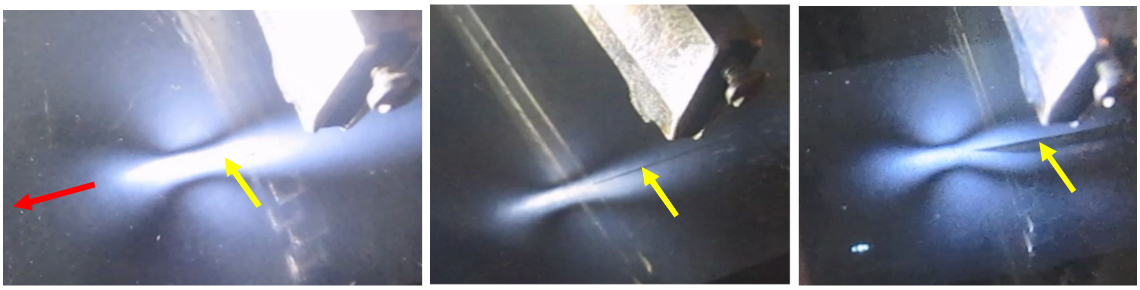


Fig. 1. Set-up for laser cutting of silicate glasses:
1 – positioning table; *2* – laser; *3* – focusing lens; *4* – laser;
5 – focusing lens; *6* – refrigerant feeder; *7* – mechanism for defect application;
8 – polarized light source; *9* – video camera with an analyzer;
10 – mechanism for vertical movement; *11* – carriage;
12 – set-up control unit; *13* – computer

A polarized light source and a video camera with an analyzer are employed to visualize the distribution of thermoelastic stresses in the designed prototype. By using the resulting image, it is feasible to examine the obtained isochromes and isoclines, with subsequent calculation of thermoelastic stresses. If required, adjustments can be made to the technological parameters of processing (radiation power density, processing speed, intensity of refrigerant supply, etc.).

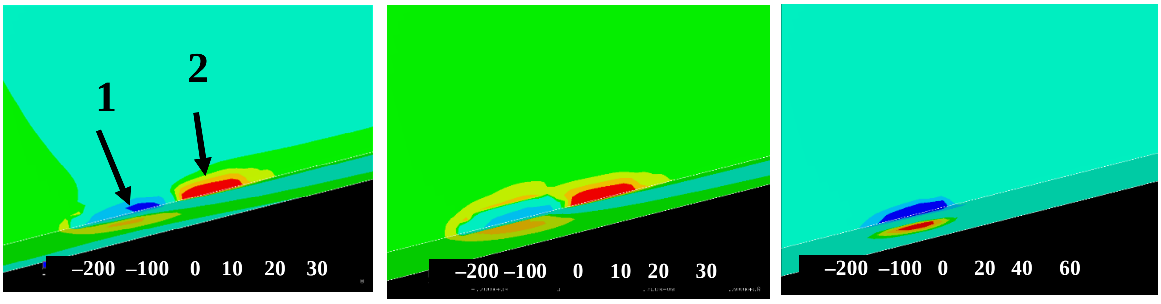
Figure 2 illustrates the interference patterns obtained during laser controlled thermal cleaving using this prototype. The patterns are obtained in the absence of a crack (fig. 2, *a*), in the presence of a non-through splitting crack (fig. 2, *b*) and in the presence of a through splitting crack (fig. 2, *c*).



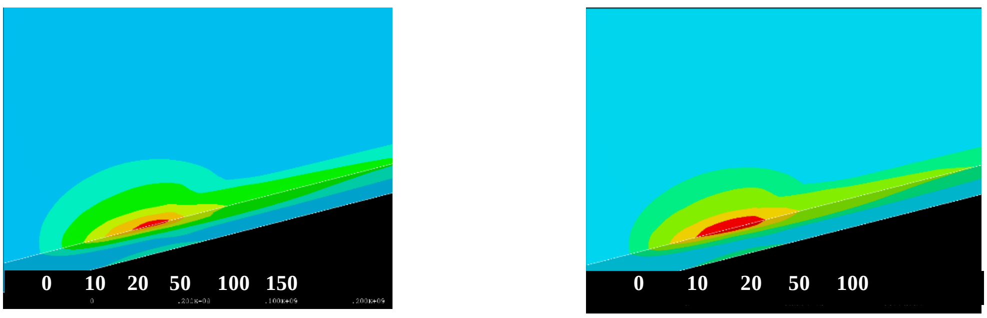
a) *b*) *c*)

Fig. 2. Photographic image of the treatment area obtained via the polarization-optical method:
a – area of laser beam and refrigerant exposure; *b* – non-through splitting crack;
c – through splitting crack

Figures 3 and 4 demonstrate the calculated stress distributions in the work sample at a specific time, both with and without the presence of a non-through splitting crack. The calculations were performed using the finite element method. The design parameters of silicate glass processing and glass properties were chosen in accordance with the experimental results. Since the beam and refrigerant move down the center of the sample, and there is symmetry on both sides of the separation plane, the field pattern is only seen for half of the sample. The front face of the sample is a cross-section in the material separation plane.



a) *b*) *c*)

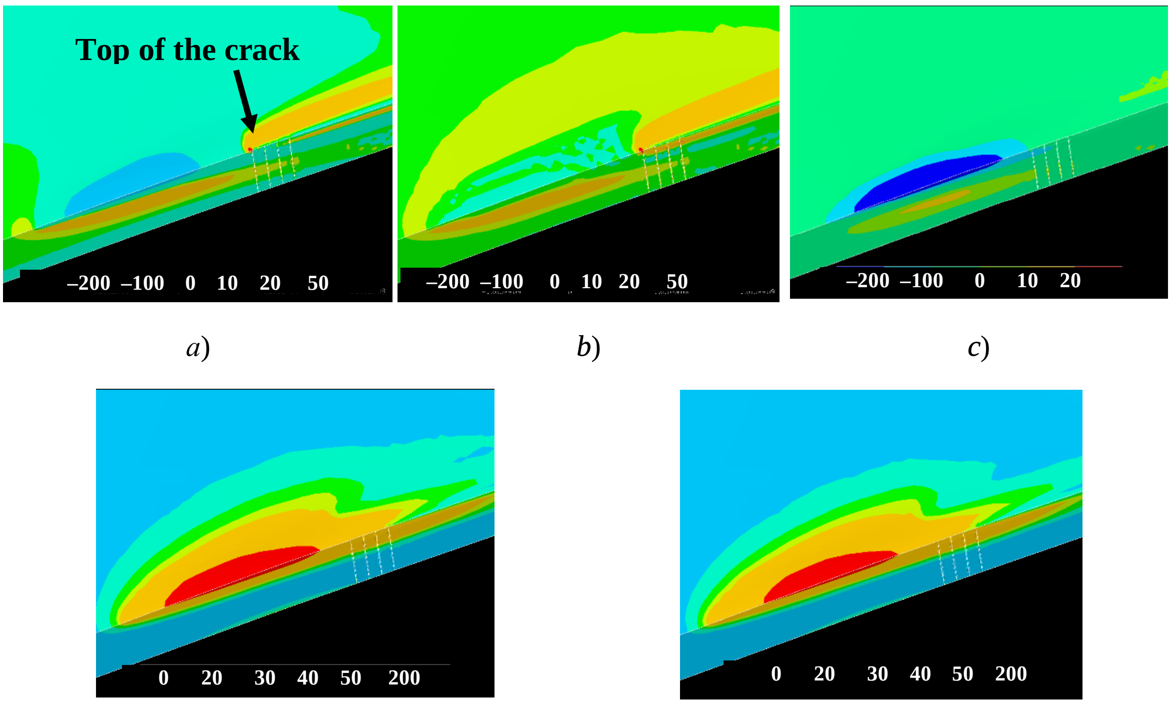


b) *e*)

Fig. 3. Distribution of thermoelastic fields in the sample (MPa) during laser processing
in the absence of a splitting crack:
a – stresses σ_{22} perpendicular to the plane of separation; *b* – primary stresses σ_1;
c – primary stresses σ_3; *d* – stress intensity $\sigma = \text{MAX}\left(|\sigma_1 - \sigma_2|, |\sigma_2 - \sigma_3|, |\sigma_3 - \sigma_1|\right)$;
e – von Mises equivalent: *1* – laser exposure area; *2* – refrigerant exposure area

The analysis of fig. 3, *a*, *b* reveals the presence of a region characterized by intense tensile stresses on the surface of the material in the area of refrigerant supply, where sharp cooling of the material occurs. In this scenario, the maximum in the value of stresses arises on the exposure line of the laser beam or beams and the refrigerant. Crack initiation takes place on the surface of the material. The area of tensile stresses, caused by the action of the refrigerant, extends deep into the material and is restricted underneath by the areas of compressive stresses generated by laser beams. These areas limit the development of the initiated crack deep into the material.

In the interference pattern, the area of strong compressive and tensile stresses is expressed by an area with increased intensity of transmitted light. By comparing this picture with the computed distribution of stress intensity (namely, the maxima of the difference between primary stresses) and the distribution of von Mises equivalent, we may deduce that the intensity of transmitted light is directly dependent on the value of stresses. The higher the magnitude of the stresses, the higher the intensity of the transmitted polarized light. However, it is difficult to separate the region of compressive and tensile stresses in these pictures, due to the very small width of the isotropic line (region).



a) *b*) *c*)

b) *e*)

Fig. 4. Distribution of thermoelastic fields in the sample (MPa) during laser processing in the presence of a splitting crack in the material:
a – stresses σ_{22} perpendicular to the plane of separation; *b* – primary stresses σ_1;
c – primary stresses σ_3; *d* – stress intensity $\sigma = \mathrm{MAX}\,(|\sigma_1 - \sigma_2|, |\sigma_2 - \sigma_3|, |\sigma_3 - \sigma_1|)$;
e – von Mises equivalent

Figures 2, *a*, *b* demonstrate that when a splitting crack is present, a dark band can be visible along its boundaries. This phenomenon can be attributed to two factors: the presence of a free surface that is perpendicular to the treated surface of the material, which alters the path of the rays travelling through it, and the value of stresses close to zero in the area of the crack edges. Confirmation is provided through numerical simulation within the context of linear fracture mechanics, as depicted in fig. 4.

Conclusions

Thus, by analyzing the intensity of the transmitted polarized light in the area of refrigerant exposure, we can conclude about the presence or absence of a splitting crack. A pronounced dark band along the line of material processing indicates the presence of a crack, whereas a homogeneous intensity area confirms its absence. This enables the development of a computer program that dynamically ascertains the presence of a splitting crack during the controlled laser thermal cleaving of silicate glasses by analyzing the image obtained from the video camera. The program then either makes adjustments to the technological parameters of processing or interrupts the technological process if necessary.

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