УДК 621.373.826 DOI: https://doi.org/10.54341/20778708_2025_4_65_98
EDN: FDSCIN

МОДЕЛИРОВАНИЕ ТЕМПЕРАТУРНОГО ПОЛЯ В ПРОЦЕССАХ ДВУЛУЧЕВОГО ЛАЗЕРНОГО ТЕРМОРАСКАЛЫВАНИЯ МАТЕРИАЛОВ ЭЛЕКТРОННОЙ ТЕХНИКИ

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MODELING THE TEMPERATURE FIELD IN DUAL-BEAM LASER THERMAL CLEAVING PROCESSES FOR ELECTRONIC MATERIALS

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Аннотация. Рассчитаны температурные поля в процессах лазерного управляемого термораскалывания хрупких неметаллических материалов с использованием двух пучков лазерного излучения в присутствии хладагента. На основании данных о распределении температуры по поверхности и в объёме материалов проведена оценка верхнего предела термического микронапряжения. Эта информация необходима для обоснованного выбора режимов лазерной обработки указанных материалов, в частности, кварцевого и силикатного стёкол, в технологических процессах микроэлектроники.

Ключевые слова: *лазерное излучения*, *температурное поле*, *микромеханические термоупругие напряжения*, *математическое моделирование.*

Для цитирования: *Моделирование температурного поля в процессах двулучевого лазерного термораскалывания материалов электронной техники* / А.Н. Купо, Ю.В. Никитюк, В.А. Емельянов, А.Н. Сердюков // Проблемы физики, математики и техники. – 2025. – № 4 (65). – С. 98–102. – DOI: https://doi.org/10.54341/20778708_2025_4_65_98. – EDN: FDSCIN

Abstract. The study presents calculations of temperature fields in controlled laser thermal cleaving of brittle non-metallic materials using two laser beams with a coolant. An estimation of the upper limit of thermal micro-stress was conducted based on the temperature distribution data across the surface and within the volume of the materials. This information is essential for the substantiated selection of laser processing parameters for the specified materials, particularly quartz and silicate glasses, in microelectronics manufacturing processes.

Keywords: *laser radiation*, *temperature field*, *micromechanical thermoelastic stresses*, *mathematical modeling*.

For citation: *Modeling the temperature field in dual-beam laser thermal cleaving processes for electronic materials* / A.N. Kupo, Yu.V. Nikityuk, V.A. Yemelyanov, A.N. Serdyukov // Problems of Physics, Mathematics and Technics. – 2025. – № 4 (65). – P. 98–102. – DOI: https://doi.org/10.54341/20778708_2025_4_65_98. – EDN: FDSCIN

Introduction

Laser cleaving is a technique for cutting brittle non-metallic materials such as silicate glasses. This procedure separates the material by initiating a crack through sequential laser heating followed by coolant application to the treated surface [1], [2]. Currently, the dual-beam laser thermal cleaving method for brittle non-metallic materials is widely employed [3]–[7]. This technique utilizes three processing tools simultaneously: radiation from a solid-state laser (1.06 μm), radiation from a CO_2 laser (10.6 μm), and a flow of air-water mixture serving as a coolant. Figure 0.1 illustrates a schematic diagram of the experimental setup for dual-beam laser thermal cleaving of glass.

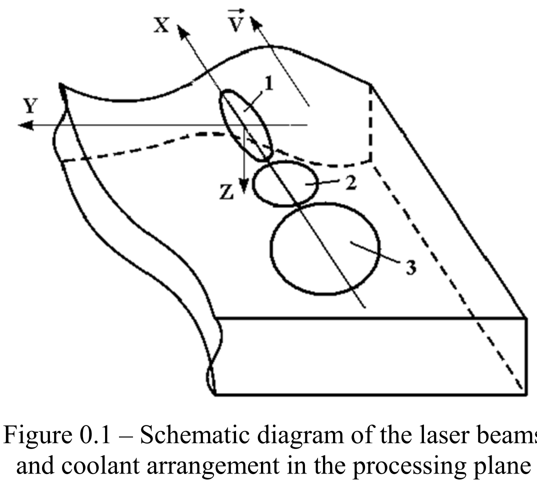


Figure 0.1 – Schematic diagram of the laser beams and coolant arrangement in the processing plane

Item 1 represents the CO_2 laser beam, item 2 denotes the YAG laser beam, and item 3 refers to the coolant. The optical system forms the laser beam with a wavelength of $\lambda = 10.6$ μm into an elliptical spot on the sample surface, oriented with its major axis along the material processing line. Directly following this beam is the laser beam with a wavelength of $\lambda = 1.06$ μm, which is focused on the sample surface, with its center located on the material processing line. The coolant, in the form of an air-water mixture, is delivered directly after the beam with a wavelength of $\lambda = 1.06$ μm and is formed into a circular spot on the sample surface, whose center also lies on the material processing line.

1 Problem Statement for the Modeling

Such combined thermal impact on the surface of the processed material can be modeled by a combination of heat sources (laser radiation) and heat sinks (coolant action), as shown in Figure 1.1.

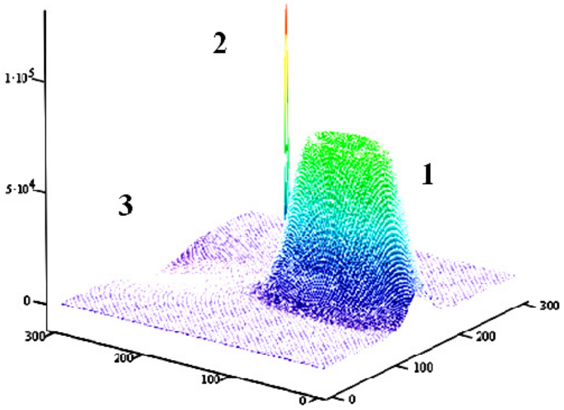


Figure 1.1 – Visualization of the laser beams and coolant model in the processing plane: 1 – CO_2 laser beam, 2 – YAG laser beam, 3 – cooling zone

In this case, the solution to the heat conduction problem can be obtained using the Green's function method. The Green's function for a semi-infinite medium, dependent on spatial coordinates $r = (x, y, z)$ and time t, is given by [8], [9]:

$$G(r,r',t-t') = \frac{Q(r,t)}{\left(2\sqrt{\pi a t}\right)^3} \times$$

$$\times \exp\left(-\frac{(x-x')^2+(y-y')^2+(z-z')^2}{4a(t-t')}\right), \quad (1.1)$$

where $a = \lambda/(c\cdot\rho)$ is the thermal diffusivity; λ is the thermal conductivity, c is the specific heat capacity, ρ is the density, $Q(r, t)$ is the volume heat generation rate, $r' = (x', y', z')$.

Thus, the solution to the heat conduction equation can be represented as:

$$T(r,t) = \int \sigma(r,t;r',t) Q(r;t') dt' d^3 r'. \quad (1.2)$$

Based on equations (1.1) and (1.2), it is possible to model the dynamics of the temperature field within the region of the described combined action. Here, the heat source model $Q(r, t)$ can be represented as a superposition of the effects from both types of laser radiation and the coolant, according to Table 1.1.

2 Evaluation of Model Parameters and Computation of Values

The calculations were conducted in the Mathcad system to represent the dynamics of the temperature field resulting from the combined action, using equations (1.1) and (1.2) along with Table 1.1. The heat source model represented a superposition of the three impacts listed in Table 1, shifted along the x-axis in the direction of the controlled thermal cleaving line formation. Figure 2.1 shows the thermal impact profile along the processing direction (left to right) for the case of $P_0 = 1\cdot0^6$ W/m^2, $A_1 = 10^{-4}$ m, $A_2 = 2\cdot A_1$, $A_3 = 3\cdot A_1$ (see Table 1.1).

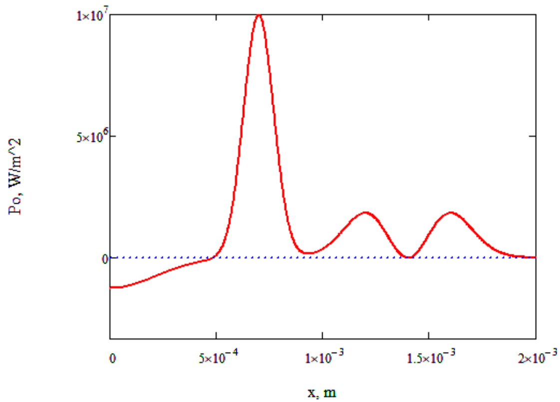


Figure 2.1– Thermal impact profile along the processing direction

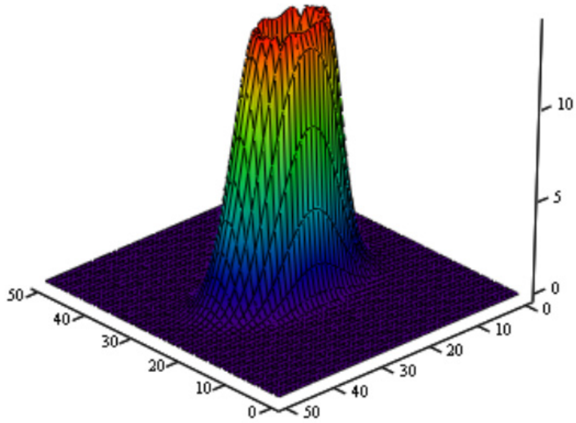
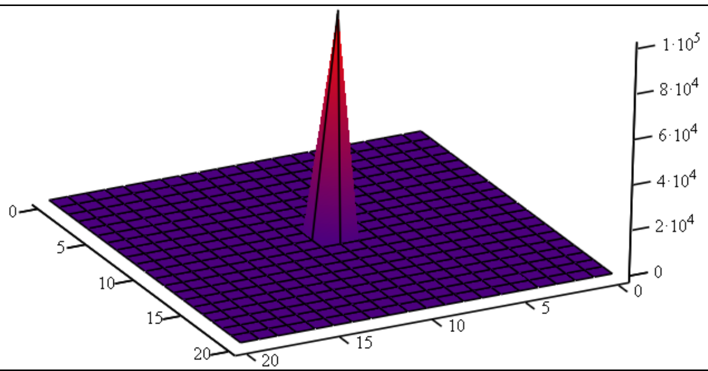
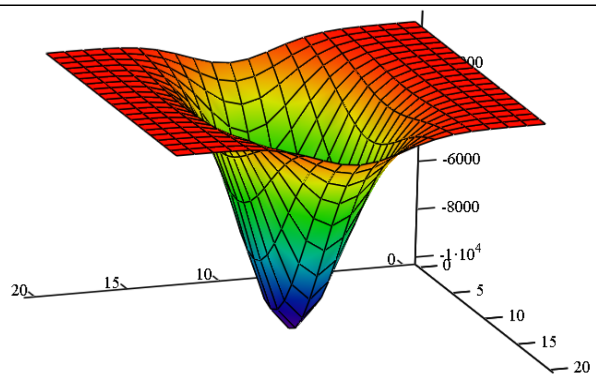
Figure 2.2 depicts the temperature distribution as a function of the distance from the center of the coolant impact zone at a processing speed of $v = 10^{-3}$ m/s at different time instances from the onset of the thermal influence on the surface of quartz glass (see Figure 2.2, a) and silicate glass (see Figure 2.2, b) with their respective thermophysical characteristics.

The primary criterion for optimizing the technological parameters, derived from the temperature field data, is the maximum temperature value in the processing zone, which determines the material fracture mechanism.

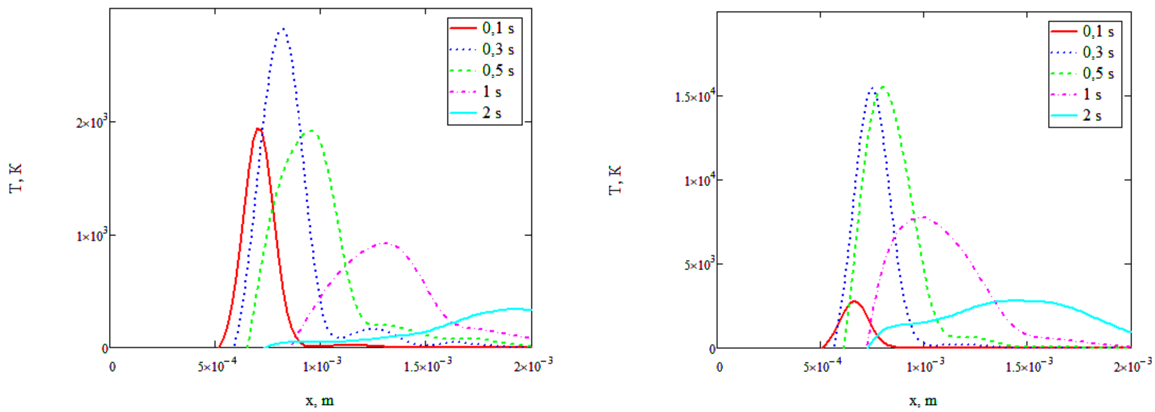
For glasses, the corresponding glass transition temperature of the specific glass grade is selected as the upper limit of allowable temperatures. Specifically, the glass transition temperature is 789 K for sheet silicate glass and 1473 K for quartz glass.

Furthermore, the information about the development of thermoelastic fracture can be obtained from the temperature distribution data through the depth of the studied materials. Figure 2.3 shows the temperature distribution across the material depth at different time instances.

Table 1.1 – Models of energy impact on the material surface during dual-beam laser thermal cleaving, implemented in the computer mathematics system Mathcad.

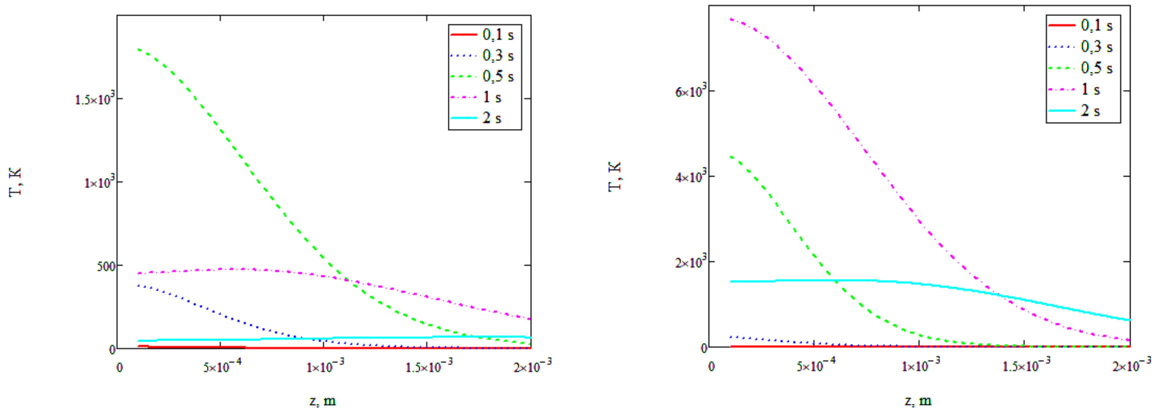
1.Type of impact	Elliptical CO_2 laser beam (λ = 10.6 μm)
Mathcad Formula	$Q_2(x,y,z,t) := \frac{\gamma P_0}{\pi A_2 B_2}\left(\frac{(x-vt)^2}{A_2^2}+\frac{y^2}{B_2^2}\right)\exp\left(\frac{-(x-vt)^2}{A_2^2}+\frac{y^2}{B_2^2}\right)\exp(-\gamma z)$
Model Visualization	
2. Type of impact	Circular YAG laser beam (λ = 1.06 μm)
Mathcad Formula	$Q_1(x,y,z,t) := P_0 \exp\left(\frac{-(x-vt)^2}{A_1^2}+\frac{y^2}{B_1^2}-\gamma z\right)$
Model Visualization	
3. Type of impact	Coolant
Mathcad Formula	$Q_x(x,y,z,t) := \frac{P_0}{10}\exp\left(\frac{-(x-vt)^2}{(50A_1)^2}-\frac{y^2}{(50B_1)^2}-\gamma z\right)$
Model Visualization	

Under high-temperature micro-deformation conditions, these materials may exhibit brittle fracture. To analyze the feasibility of implementing dual-beam laser cleaving [10], [11] of glasses with subsequent formation of a laser-induced crack, it is essential to obtain information regarding the distribution of thermoelastic stresses within the volume of the materials being processed.



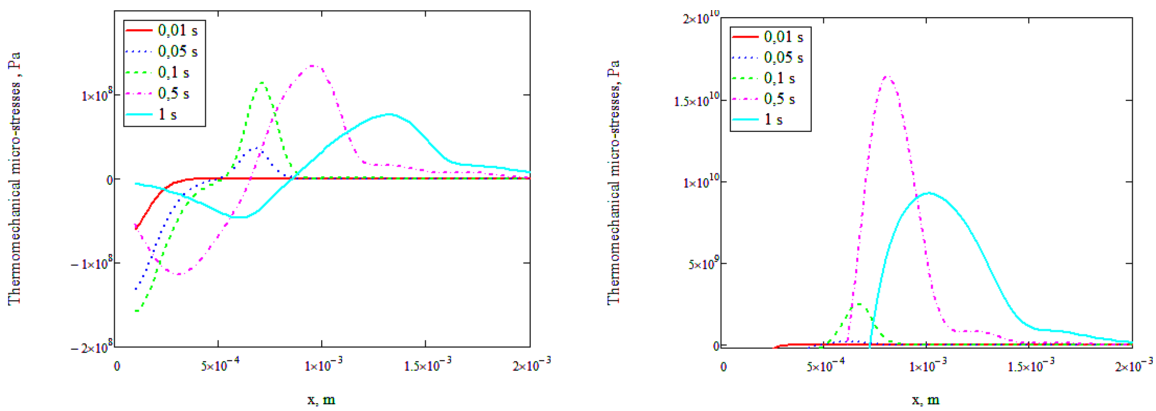
a) *b*)

Figure 2.2 – Temperature distribution profile on the surface of quartz (*a*) and silicate (*b*) glass at different processing time instances



a) *b*)

Figure 2.3 – Temperature distribution through the depth of quartz (*a*) and silicate (*b*) glass at different processing time instances



a) *b*)

Figure 2.4 – Distribution profile of thermomechanical micro-stresses along the scanning axis at different time instances for quartz (*a*) and silicate (*b*) glass

An important challenge involves studying the thermal response of a region with a time-varying boundary under heating and/or cooling. According to the methodology proposed in [12], the upper estimate of thermal micro-stress σ during surface processing along the direction *r* can be calculated using the formula:

$$\sigma(r,t)_{\max} = \frac{\sqrt{\frac{r}{R}} E\alpha(T(r,t)-T_0)}{1-2\nu},$$

where: E is the Young's modulus for diamond, α is the linear expansion coefficient, ν is the Poisson's ratio.

Figure 2.4 presents the computed values of the upper estimate of thermal micro-stress σ along the sample processing line at different time instances for a scanning speed of $v = 10^{-3}$ m/s at a depth of 10^{-4} m.

The analysis of the distribution of the upper stress estimates σ shown in Figure 2.4 reveals that the initiation of a separating micro-crack occurs in the material's surface layers, starting from a crack-like microstructural defect within the tensile stress zone generated by the coolant supply. Subsequently, the initial micro-crack begins to propagate and extends until it reaches the compressive stress zone created by the laser radiation. The distribution of compressive stresses within the sample volume determines the shape and penetration depth of the micro-crack, whose initiation and intensive development occur in the tensile stress zone generated in the coolant application area.

After the micro-crack reaches its maximum penetration depth, unsteady crack growth ceases, and its subsequent propagation is determined by changes in the spatial distribution of tensile and compressive stress zones. The observed changes result from the relative movement between the processed material, laser radiation, and coolant.

Conclusion

The constructed model for dual-beam thermal cleaving of brittle non-metallic materials provides a straightforward means to assess the feasibility of forming thermoelastic micro-stress fields both on the surface and within the material volume. This enables informed selection of laser processing parameters for silicate glasses and other brittle non-metallic materials in electronics technologies.

REFERENCES

1. *Kondratenko*, *V.S.* Precision Cutting of Glass and Other Brittle Materials by Laser-Controlled Thermo-Splitting (Review) / V.S. Kondratenko, S.A. Kudzh // Glass and Ceramics. – 2017. – № 74. – P. 75–81. – DOI: https://doi.org/10.1007/s10717-017-9932-1.

2. *Nikityuk*, *Yu.V.* Laser cleaving of brittle non-metallic materials / Yu.V. Nikityuk, A.A. Sereda, A.N. Serdyukov. – Gomel: Francisk Skorina Gomel State University, 2025. – 217 p.

3. *Two-beam laser thermal cleavage of brittle nonmetallic materials* / S.V. Shalupaev, E.B. Shershnev, Yu.V. Nikityuk, A.A. Sereda // Journal of Optical Technology. – 2006. – Vol. 73, № 5. – P. 356–359. – DOI: https://doi.org/10.1364/JOT.73.000356.

4. *Nikityuk*, *Yu.V.* Physical regularities of laser thermal cleaving of silicate glasses and alumina ceramics / Yu.V. Nikityuk // Abstract of Ph. D. thesis. – Minsk, 2009. – 24 p.

5. *Dual laser beam revising the separation path technology of laser induced thermal-crack propagation for asymmetric linear cutting glass* / C. Zhao, H. Zhang, L. Yang, Y. Wang, Y. Ding // International Journal of Machine Tools and Manufacture. – 2016. – Vol. 106. – P. 43–55. – DOI: https://doi.org/10.1016/j.ijmachtools.2016.04.005.

6. *Nikitjuk*, *Y.V.* Determination of the parameters of two-beam laser splitting of silicate glasses using regression and neural network models / Y.V. Nikitjuk, A.N. Serdyukov, I.Y. Aushev // Journal of the Belarusian State University. Physics. – 2022. – № 1. – P. 35–43. – DOI: https://doi.org/10.33581/2520-2243-2022-1-35-43.

7. *Nikityuk*, *Yu*. Optimization of two-beam laser cleavage of silicate glass / Yu. Nikityuk, A. Serdyukov, I. Aushev // Journal of Optical Technology. – 2022. – Vol. 89, № 2. – P. 121–125.

8. *Carslaw*, *H.S.* Conduction of Heat in Solids / H.S. Carslaw, J.C. Jaeger. – Moscow: Nauka, 1964. – 487 p.

9. Green's Function for Boundary Value Problems [Electronic resource]. – Access mode: https://tkachenko-mephi.narod.ru/pdfs/DIUlec2.pdf. – Date of access: 14 Aug 2025.

10. *Advances in thermal laser separation: process monitoring in a kerf-free laser-based cutting technology to ensure high yield* / M.C. Baretto [et al.] // Procedia CIRP 74. – 2018. – P. 645–648.

11. *Shershnev*, *E.B.* Features of Manufacturing High-Temperature Electronics Component Base Using Laser Radiation / E.B. Shershnev // Doklady BGUR. – 2025. – Vol. 23, № 2 . – P. 77–83. – DOI: https://doi.org/10.35596/1729-7648-2025-23-2-77-83.

12. *Nenakhov*, *E.V.* Estimates of Thermal Stresses in Dynamic Thermoelasticity Models / E.V. Nenakhov, E.M. Kartashov // Herald of the Bauman Moscow State Technical University. Series Natural Sciences. – 2022. – № 1. – P. 88–106.

The article was submitted 04.11.2025.

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