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ОПТИМИЗАЦИЯ ЛАЗЕРНОГО РАСКАЛЫВАНИЯ СИЛИКАТНЫХ СТЕКОЛ ЭЛЛИПТИЧЕСКИМИ ПУЧКАМИ С ИСПОЛЬЗОВАНИЕМ ПАРАМЕТРОВ МЕХАНИКИ РАЗРУШЕНИЯ

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OPTIMIZATION OF LASER CLEAVING OF SILICATE GLASSES WITH ELLIPTICAL BEAMS USING FRACTURE MECHANICS PARAMETERS

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Аннотация. В рамках механики разрушения с использованием генетического алгоритма была проведена оптимизация параметров резки силикатных стекол эллиптическими лазерными пучками. С использованием языка программирования APDL были выполнены расчеты температур, термоупругих напряжений и коэффициентов интенсивности напряжений. Были построены соответствующие регрессионные модели для пяти факторов: скорости резки, мощности лазера, длины стартовой трещины и длины полуосей эллиптического лазерного пучка. Значения максимальных температур в зоне обработки, значения термоупругих напряжений и коэффициентов интенсивности напряжений K_I в вершине стартовой трещины использовались в качестве откликов. Была проведена оценка влияния варьируемых факторов на отклики. Выполнено сравнение значений откликов, полученных в результате оптимизации с использованием генетического алгоритма со значениями, полученными в результате конечно-элементного моделирования. В результате оптимизации лазерного раскалывания эллиптическими пучками были установлены значения технологических параметров, обеспечивающие повышение надежности и производительности процесса резки силикатных стекол эллиптическими лазерными пучками.

Ключевые слова: *лазерная резка*, *трещина*, *MOGA*, *ANSYS*.

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Abstract. This paper presents the optimization of cutting parameters of silicate glasses with elliptical laser beams as part of fracture mechanics using a genetic algorithm. Temperatures, thermoelastic stresses and stress intensity factors were calculated via APDL (Ansys Parametric Design Language). Corresponding regression models were built for five factors: cutting speed, laser power, initial crack length, and elliptical laser beam semi-axis length. The values of maximum temperatures in the treatment zone, values of thermoelastic stresses and stress intensity coefficients K_I at the initial crack tip were used as responses. The influence of varying factors on the responses was evaluated. The comparison of the response values, obtained as a result of optimization using a genetic algorithm with the values resulting from finite element simulation, was performed. As a result of optimizing laser cleaving with elliptical beams, the values of technological parameters were established. These parameters ensure an increase in reliability and productivity of the process of cutting silicate glasses with elliptical laser beams.

Keywords: *laser cutting*, *crack*, *MOGA*, *ANSYS*.

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Introduction

In the recent years, laser cutting of silicate glasses using laser-induced crack formation technologies has become widespread [1]–[9].

Simulation of laser cleaving processes, disregarding the initial crack, does not provide the possibility of sufficiently accurate determination of processing parameters, while simulation within thermoelasticity theory and linear fracture mechanics, taking into account the parameters of the initial defect and using the finite element mesh rebuilding technique, ensures the necessary accuracy of calculations [10]–[14].

Increasing the efficiency of laser cutting of materials, including laser cleaving methods, can be achieved by optimizing processing parameters using genetic algorithms [15]–[18].

This study uses MOGA (multi-objective genetic algorithm) of the ANSYS software to optimize the parameters of cutting silicate glasses with elliptical laser beams through laser cleaving using fracture mechanics parameters.

1 Determining the optimal parameters for laser cleaving of silicate glasses with elliptical laser beams

The calculations of temperature and thermoelastic stress fields as well as determination of the values of stress intensity coefficients K_I at the initial crack tip in silicate glasses during processing with elliptical laser beams were performed within the framework of the unrelated problem of thermoelasticity and fracture mechanics using APDL [19].

Figure 1.1 illustrates the scheme of the laser beam and refrigerant impact zones in the cutting plane. Position 1 marks the laser beam, position 2 indicates the refrigerant, and position 3 denotes the crack.

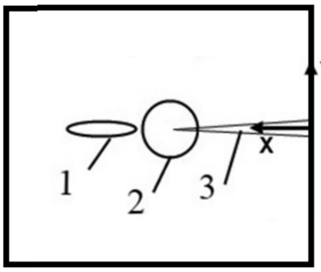

Figure 1.1 – Schematic of impact zones of laser beam and refrigerant in the cutting plane

The silicate glass properties given in [1] were used in the simulation process. The calculations were performed for a rectangular test piece with dimensions of 20×10×1 mm. The model consisted of 5968 elements (see Figure 1.2, 1.3).

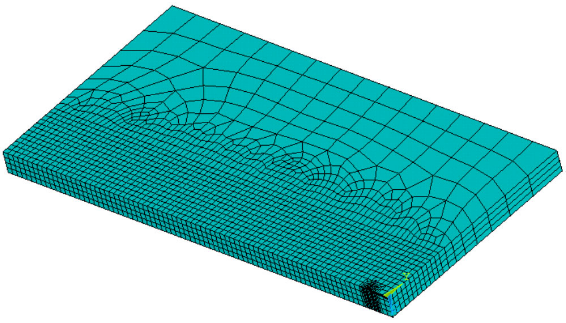

Figure 1.2 – Finite element model

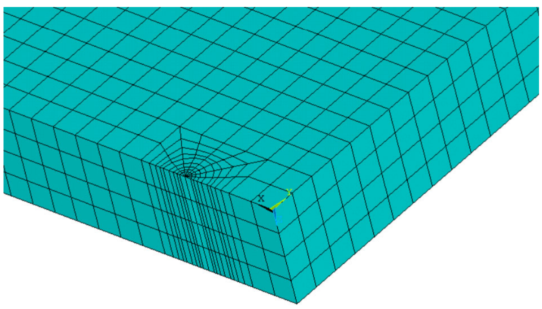

Figure 1.3 – Finite element mesh near the crack tip

The elements simulating the stress singularity at the crack tip were used to improve the accuracy of K_I calculations. Here, to obtain the root asymptotics at the crack tip, the element nodes were shifted by a quarter of the element side in the direction of the tip [19].

The calculations were performed for the laser beam with a wavelength equal to 10.6 μm. The processing speed was $V = 15 \cdot 10^{-3}$ m/s. The following values of laser beam parameters were used: major semi-axis $3 \cdot 10^{-3}$ m, minor semi-axis $B = 1 \cdot 10^{-3}$ m. The length of the initial crack was $L = 1 \cdot 10^{-3}$ m.

Figures 1.4–1.9 show the calculated values of temperature and thermoelastic stress fields.

The calculated temperatures at the initial crack tip do not exceed the glass transition temperature (for silicate glass sheet it is 789 K), which ensures the absence of thermoelastic stress relaxation.

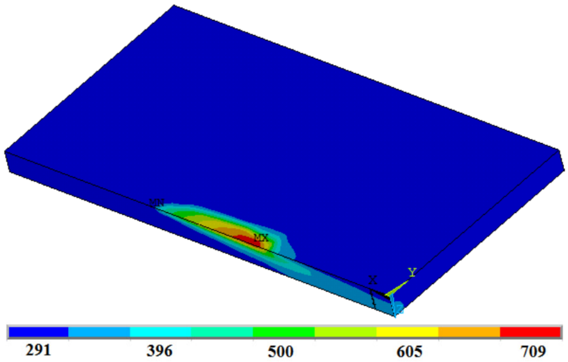

Figure 1.4 – Temperature distribution in the volume of the sample to be treated, °*K*

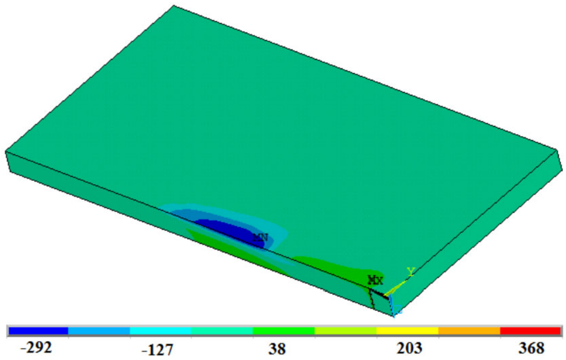

Figure 1.5 – Distribution of stresses σ_y in the volume of the sample to be treated, MPa

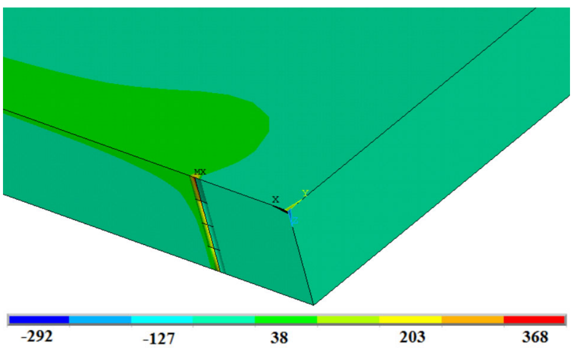

Figure 1.6 – Distribution of stresses σ_y near the crack tip, MPa

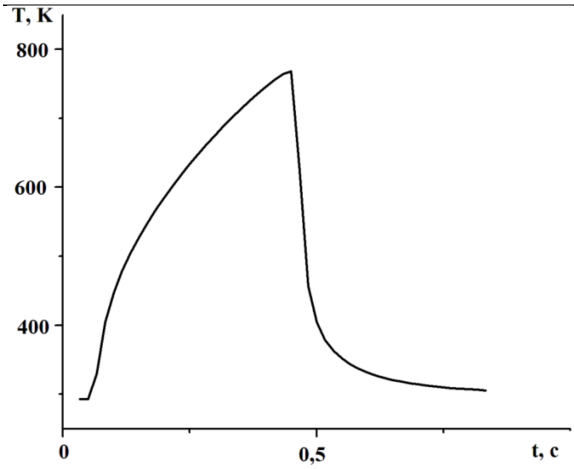

Figure 1.7 – Calculated values of temperature T at the crack tip

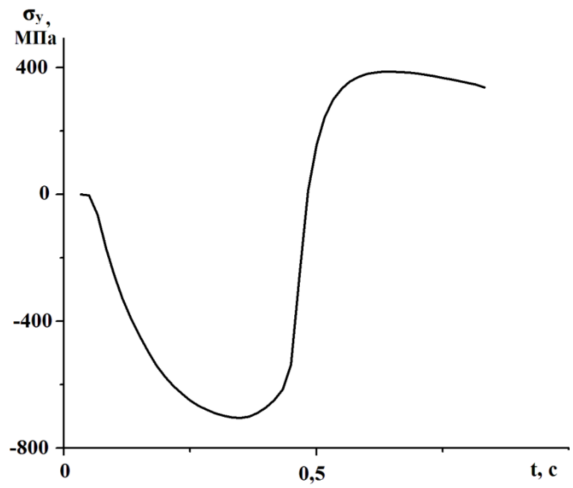

Figure 1.8 – Calculated values of elastic stresses σ_y at the crack tip

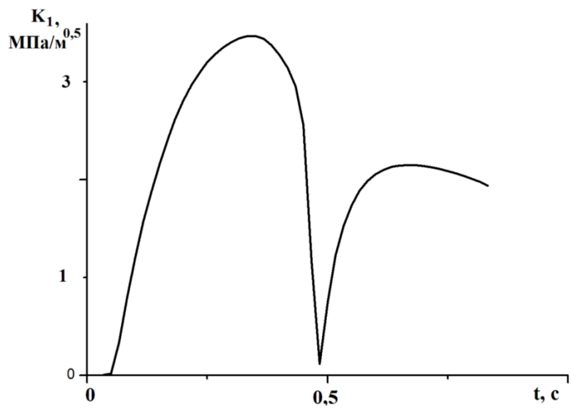

Figure 1.9 – Calculated values of stress intensity factor K_I at the crack tip

As Figure 1.8 shows, significant compressive stresses are formed at the initial crack tip as a result of laser heating with an elliptical beam. After refrigerant exposure, tensile stresses are formed there as well. At the crack tip, the values of stress intensity coefficients have reached their maximum values twice. The second maximum of the values of the stress intensity coefficients corresponds to the tensile stresses at the crack tip (see Figure 1.9). Thus, the necessary conditions for the initiation of crack development are fulfilled: $\sigma_y > 0$ and $K_I > K_{Ic}$ (for silicate glass the critical stress intensity factor is $K_{IC} = 0.5$ MPa·m$^{1/2}$).

This study used MOGA of the DesignXplorer module to optimize the cutting parameters of silicate glasses with elliptical laser beams.

The response surfaces were generated using a five-factor version of the central composite design of the numerical experiment [20]. The following factors were used as variable factors: P1 is the processing speed *V*, *P*2 is the beam power *P*, *P*3 is the large semi-axis of the laser beam *A*, *P*4 is the small semi-axis of the beam *B*, *P*5 is the length of the initial defect *L*.

The maximum temperatures *T* and thermoelastic stresses σ_y in the treatment zone, values of stress intensity coefficients K_I were determined as responses (see Table 1.1).

The response functions relating the output parameters (T, σ_y, K_I) to the factors (V, P, A, B, L) are as follows:

$$Y_T = 8.99 - 19.1V + 0.262P - 476A - 1440B -$$
$$-0.00308V^2 + 34800P^2 + 3.51\cdot10^5 A^2 - 1.33VP +$$
$$+2870VA - 11.3PA - 44.5PB + 1.27\cdot10^5 AB,$$
$$T = (0.065Y_T + 1)^{\frac{1}{0.065}} - 1,$$
$$Y_\sigma = 43.94 - 689V - 1.79P + 1870A +$$
$$+7510B + 11600V^2 + 0.0553P^2 - 2.08\cdot10^5 A^2 -$$
$$-3.11\cdot10^6 B^2 - 6.29VP - 1.04\cdot10^4 VB -$$
$$-3.12\cdot10^4 VL - 52.6PL + 1.55\cdot10^5 BL,$$
$$\sigma_y = \left(0.09Y_\sigma + 1\right)^{\frac{1}{0.09}} - 1,$$
$$Y_K = 119.7 - 8710V + 21.8P + 2.75\cdot10^4 A +$$
$$+1.01\cdot10^5 B + 1.95\cdot10^5 V^2 - 0.583P^2 - 2.66\cdot10^6 A^2 -$$
$$-3.94\cdot10^7 B^2 - 229VP - 2.26\cdot10^5 VA -$$
$$-3.52\cdot10^5 VB + 304PA - 696PL -$$
$$-1.98\cdot10^6 AL + 1.81\cdot10^6 BL,$$
$$K_I = \left(0.3Y_K + 1\right)^{\frac{1}{0.3}} - 1.$$

The following criteria were used to evaluate the resulting regression equations:

– determination coefficient

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(d_i - y_i\right)^2}{\sum_{i=1}^{n}\left(d_i - \bar{d}\right)^2},$$

– Root Mean Square Error (RMSE)

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(d_i - y_i\right)^2},$$

Table 1.1 – Experimental design and calculation results

N	P1 V, m/s	P2 P, W	P3 A, m	P4 B, m	P5 L, m	P6 T,°K	P7 σ_y, MPa	P8 K_I, MPa·m$^{1/2}$
1	0.015	7.5	0.003	0.001	0.0015	650	271	1.50
2	0.01	7.5	0.003	0.001	0.0015	708	420	2.36
3	0.02	7.5	0.003	0.001	0.0015	611	193	1.06
4	0.015	5	0.003	0.001	0.0015	531	180	1.00
5	0.015	10	0.003	0.001	0.0015	769	361	2.00
6	0.015	7.5	0.002	0.001	0.0015	738	235	1.30
7	0.015	7.5	0.004	0.001	0.0015	595	294	1.64
8	0.015	7.5	0.003	0.0005	0.0015	861	213	1.15
9	0.015	7.5	0.003	0.0015	0.0015	545	266	1.50
10	0.015	7.5	0.003	0.001	0.001	649	290	1.61
11	0.015	7.5	0.003	0.001	0.002	650	257	1.42
12	0.01	5	0.002	0.0005	0.002	852	174	9.50
13	0.02	5	0.002	0.0005	0.001	749	914	4.84
14	0.01	10	0.002	0.0005	0.001	1410	404	2.20
15	0.02	10	0.002	0.0005	0.002	1205	156	0.82
16	0.01	5	0.004	0.0005	0.001	630	245	1.36
17	0.02	5	0.004	0.0005	0.002	578	961	0.48
18	0.01	10	0.004	0.0005	0.002	968	434	2.39
19	0.02	10	0.004	0.0005	0.001	863	232	1.24
20	0.01	5	0.002	0.0015	0.001	537	248	1.41
21	0.02	5	0.002	0.0015	0.002	472	102	0.57
22	0.01	10	0.002	0.0015	0.002	782	451	2.56
23	0.02	10	0.002	0.0015	0.001	650	227	1.27
24	0.01	5	0.004	0.0015	0.002	466	286	1.63
25	0.02	5	0.004	0.0015	0.001	420	145	8.12
26	0.01	10	0.004	0.0015	0.001	637	618	3.53
27	0.02	10	0.004	0.0015	0.002	547	250	1.36

where d_i is the values determined by the finite element method; y_i is the values determined using regression models.

The determination coefficients for the output parameters T, σ_y and K_I are 0.9993, 0.9997 and 0.9996, respectively. The RMSE values for T, σ_y and K_I are 5.8° K, 2.2 MPa and 0.013 MPa·m$^{1/2}$, respectively. This allows concluding about the necessary correspondence of regression models to finite element analysis data.

The data presented in Figure 1.10 also confirm the adequacy of the resulting regression equations. The graph shows the normalized values obtained by finite element simulation on the abscissa and the corresponding normalized values obtained by regression equations on the ordinate. The accuracy of the regression model is higher when the points are closer to the diagonal of the graph.

The study on the influence of input parameters on output parameters has revealed that the laser beam power and its geometrical parameters have the most significant effect on the maximum values of temperature T in the treatment zone, while the processing speed and the laser power have the greatest effect on the maximum thermoelastic stresses σy and the values of stress intensity coefficients K_I. Here, the length of the initial crack also affects considerably these responses (see Figure 1.11).

Figures 1.12–1.14 illustrate the diagrams showing how the maximum temperature in the treatment zone T, tensile stresses σ_y and stress intensity factors at the crack tip depend on the factors.

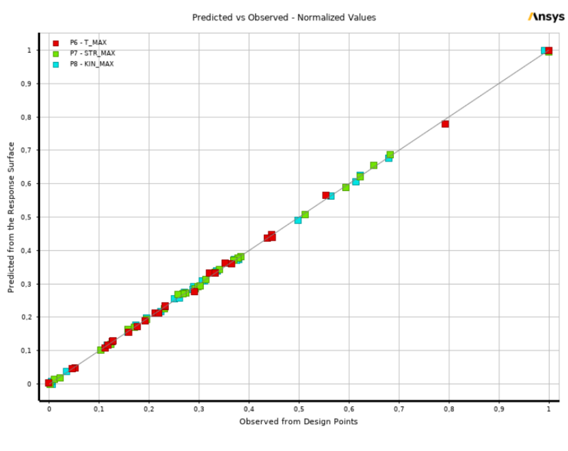

Figure 1.10 – Adequacy test of regression equations P6 – T, P7 – σ_y, P8 – K_I

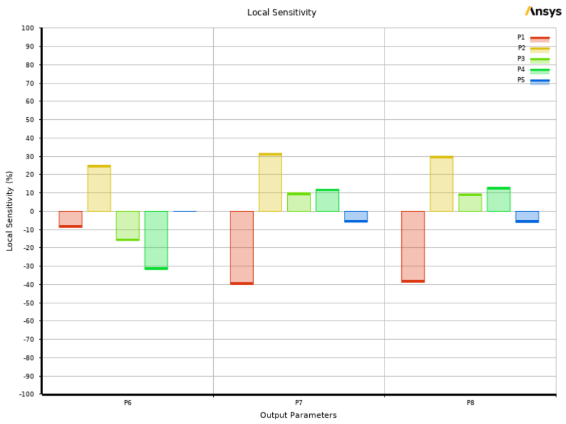

Figure 1.11 – Response sensitivity diagram P1 – V, P2 – P, P3 – A, P4 – B, P5 – L

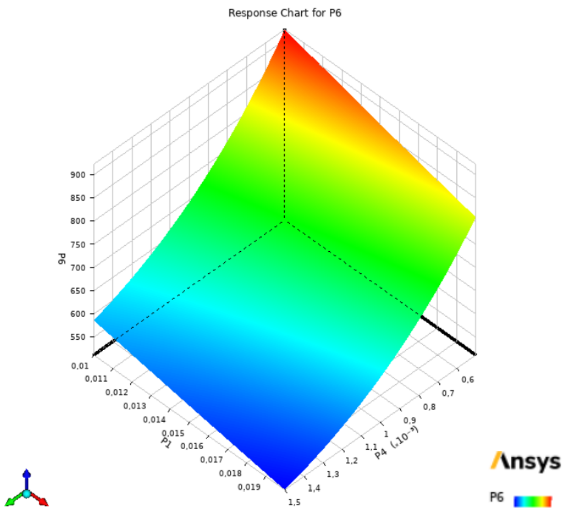

Figure 1.12 – Dependence of maximum temperature T, K on processing parameters P2 – P, P4 – B

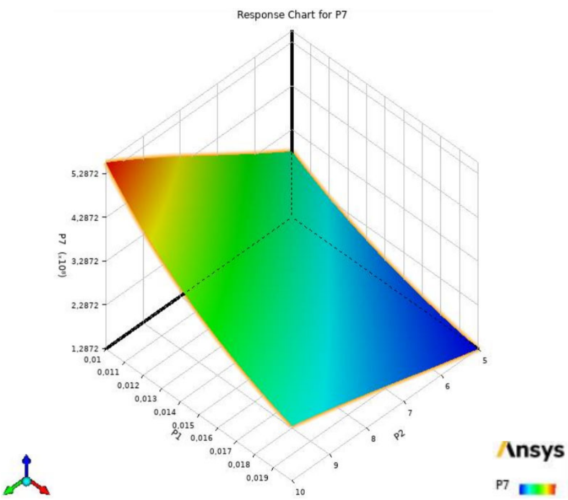

Figure 1.13 – Dependence of stresses at the crack tip σ_y, MPa on processing parameters P1 – V, P2 – P

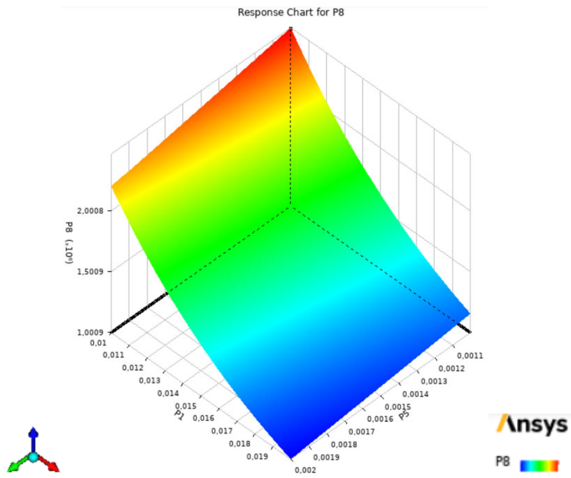

Figure 1.14 – Dependence of stress intensity factors at the crack tip K_I , MPa·m$^{1/2}$ on processing parameters P1 – V, P5 – L

2 The optimization of laser cleaving of silicate glass with elliptical laser beams

The optimization of laser cleaving of silicate glass with elliptical laser beams was performed using MOGA of the DesignXplorer module with an initial population of 500 individuals and the number of individuals per iteration also equaling 500.

The optimization was done following the criterion of processing speed maximum $V \to \max$ at the maximum temperature in the treatment zone $T \le 789\text{K}$ and the minimum values of stress intensity factors at the crack tip exceeding the values of the critical stress intensity factor $K_I > K_{Ic}$.

The optimization results are given in Table 2.1, where the parameter values obtained by finite element simulation are given in brackets. Here, the maximum relative error of the results obtained using MOGA did not exceed 8% when determining the responses.

Table 2.1 – Optimization results

N	1
P1 V, m/s	0.02
P2 P, W	8.9
P3 A, m	0.002
P4 B, m	0.0015
P5 L, m	0.0012
P6 T,°K	601 (554)
P7 σ_y, MPa	214 (231)
P8 K_I, MPa·m$^{1/2}$	1.17 (1.26)

Conclusion

This paper demonstrated the possibility of optimizing silicate glass processing parameters as part of thermoelasticity and fracture mechanics theory using a genetic algorithm. The regression models of glass thermal cleaving using the central composite experimental design were obtained. The correspondence between regression models and finite element analysis results was established. The numerical experiments resulted in the determination of the optimal parameters for thermal cleaving of silicate glass by elliptical laser beams based on fracture mechanics criteria.

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