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Optimization of parameters for double-beam laser cleaving of silicate glasses along curved paths

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This study develops regression and neural network models of double-beam laser cleaving of silicate glasses following curved paths. These models have been obtained by means of numerical experiment using the central composite design. The numerical experiment involved variable factors such as laser processing velocity, laser beam powers with wavelengths of 10,6 μm and 1,06 μm, and geometrical parameters of the elliptical laser beam with a wavelength of 10,6 μm. The values of maximum temperatures and maximum thermoelastic tensile stresses within the double-beam treatment zone were determined as responses, the calculation of which was performed via the finite element method using APDL (Ansys Parametric Design Language). TensorFlow was used to establish effective architectures for artificial neural networks in order to determine the maximum temperature and maximum thermoelastic tensile stresses in the laser-treated area. The comparison between the neural network and the regression models in the framework of double-beam laser cleaving revealed that artificial neural networks are more effective in predicting parameters related to double-beam cleaving of silicate glasses along curved paths. The genetic algorithm was employed to conduct multicriteria optimization of laser curved cutting parameters.
Keywords: laser cutting, ANN, MOGA, ANSYS.

В работе при помощи численного эксперимента с использованием центрального композиционного плана получены регрессионные и нейросетевые модели процесса двулучевого лазерного раскалывания силикатных стекол по криволинейным траекториям. При реализации численного эксперимента скорость лазерной обработки, мощности лазерных пучков с длинами волн 10,6 мкм и 1,06 мкм и геометрические параметры эллиптического лазерного пучка с длиной волны 10,6 мкм были использованы в качестве варьируемых факторов. Значения максимальных температур и максимальных термоупругих напряжений растяжения в зоне двулучевой обработки определялись методом конечных элементов с использованием языка программирования APDL в качестве откликов. При помощи пакета TensorFlow были установлены эффективные архитектуры искусственных нейронных сетей для определения максимальных температур и максимальных термоупругих напряжений в зоне лазерной обработки. Сравнение нейросетевых и регрессионных моделей процесса двулучевого лазерного раскалывания показало более высокую эффективность искусственных нейронных сетей при прогнозировании параметров двулучевого раскалывания силикатных стекол по криволинейным траекториям. Проведена многокритериальная оптимизация параметров лазерной криволинейной резки с использованием генетического алгоритма.
Ключевые слова: лазерная резка, ИНН, MOGA, ANSYS.

Introduction. The extensive use of silicate glasses in industry is attributed to their properties, with cutting being the primary procedure involved in the manufacturing of glass products. Laser cleaving technology offers several notable advantages when compared to conventional cutting processes. The advancement of laser cleaving technology for brittle nonmetallic materials was achieved during the latter half of the 20th century. Meanwhile, the investigation of cutting processes for various brittle nonmetallic materials, such as silicate glasses, using laser cleaving techniques remains relevant [1]–[4].

Laser cleaving is recognized to be an option for cutting brittle nonmetallic materials along curved paths, which is an issue in many situations. The analysis of the relevant research and publications as well as our own investigations have revealed certain disadvantages of laser cleaving technology, which are responsible for poor accuracy in processing silicate glass along curved paths [5]. One of the reasons is the use of elliptical laser beams oriented tangentially to the curved motion trajectory. The use of laser beams of this particular shape provides the necessary conditions for the formation of thermoelastic stresses in the implementation of rectilinear thermal cleaving, in contrast to circular beams. At the same time, when elliptical beams are oriented tangentially to the processing line, their use for cutting along a curved contour results in the deviation of the crack from the processing line.

To eliminate undesirable deviations of laser-induced cracks from the processing line, the suggestion was made in [6]–[7] to employ supplementary exposure to laser radiation with a wavelength of λ = 1,06 μm. Moreover, this additional bulk heating must be carried out with a specific shift from the cutting line (see figure 1).

In Figure 1, position 1 corresponds to the laser beam with a wavelength of 10,6 μm, position 2 represents the refrigerant exposure area, position 3 corresponds to the cross-section of the laser beam with a wavelength of 1,06 μm

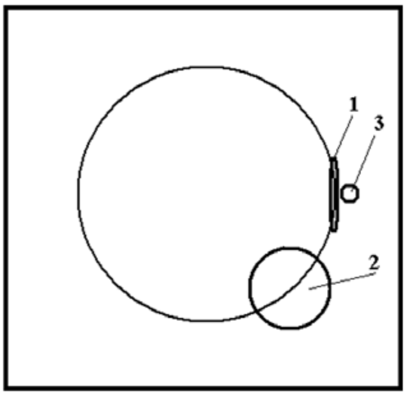

Figure 1 – Schematic depicting of the mutual arrangement of the refrigerant and laser beam exposure areas

In some cases, it is reasonable to use metamodels to optimize the parameters of laser cleaving of silicate glasses. Metamodels offer the opportunity to determine the output parameters of laser processing without performing extensive calculations, thanks to the use of regression or neural network models. Furthermore, employing genetic algorithms in metamodeling allows for the identification of the optimal values for laser cleaving parameters [8]–[16].

It is rational to further investigate the process of double-beam laser cleaving of silicate glasses along curved paths using regression and neural network models in order to ascertain the optimal modes of laser-induced crack formation.

Determination of optimal parameters for double-beam laser cleaving of silicate glasses along curved paths. Temperatures and thermoelastic stresses generated in silicate glasses during double-beam laser cleaving along curved paths were determined via the finite element method in a quasi-static formulation of the problem using APDL.

The properties of silicate glass specified in [2] were used for calculations. The displacement radius of both the centers of the elliptical beam and the refrigerant was 15 mm. The linear cutting velocity was 30 mm/s. The laser beam parameters employed in this study were as follows: the major semi-axis $A = 7 \cdot 10^{-3}$ m, the minor semi-axis $B = 1 \cdot 10^{-3}$ m for the beam with the radiation wavelength of λ = 10,6 μm and radiation power of P = 10 W; the radius of the YAG-laser radiation spot $R = 1 \cdot 10^{-3}$ m and radiation power P_0 = 40 W. The calculations were performed for a plate with geometrical dimensions of 40 × 20 × 3 mm. The model consisted of 63045 Solid 70 and Solid 185 elements used for thermal and strength analyses, respectively (see figure 2).

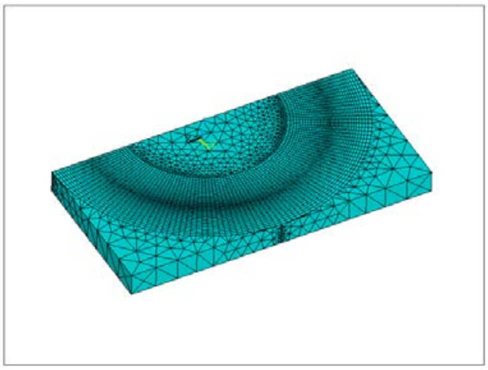

Figure 2 – Finite element model

Figures 3–4 illustrate the distributions of temperature fields and thermoelastic stress fields obtained through the finite-element modelling. Figure 4 depicts the localization of compression and tensile thermoelastic stresses within the treatment zone, which is a defining feature of laser cleaving. Here, the calculated values of maximum tensile stresses in the treatment zone, denoted as σ_r, and maximum specified temperatures, denoted as T, in the plate that underwent processing along the curved contour are equal to 34,7 MPa and 489 K, respectively, using the chosen design processing parameters.

The temperatures that do not exceed the glass transition temperature of 789 K are deemed permissible when conducting laser cleaving of silicate glass [2]. In this case, it is necessary for the values of tensile stresses σ_r to be sufficiently high, as their spatial localization and magnitude are crucial in initiating and developing laser-induced curvilinear cracks.

The numerical experiment was carried out using 27 combinations of the face-centered version of the central composite design generated in the DesignXplorer module of ANSYS WORKBENCH for five factors (P1–P5): P1 was the linear cutting velocity V, P2 was the laser power P with a radiation wavelength of λ = 10,6 µm, P3 was the laser power P_0 with a radiation wavelength of λ = 1,06 µm, P4 was the major semi-axis of the laser beam A with a radiation wavelength of λ = 10,6 µm, P5 was the minor semi-axis of the beam B with a radiation wavelength of λ = 10,6 µm.

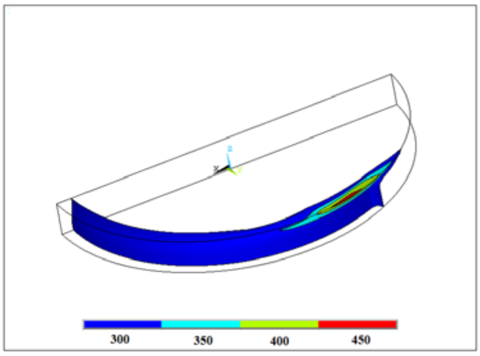

Figure 3 – Temperature distribution throughout the sample's volume, °K

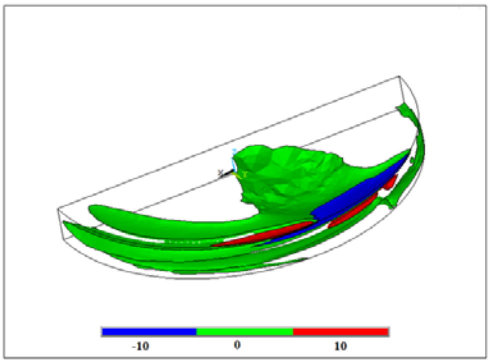

Figure 4 – Distribution of stresses σ_r throughout the sample's volume, MPa

The maximum temperature T and maximum tensile stresses σ_r in the treatment zone were determined as responses (see table 1).

Table 1 – Experimental design and calculation results

N	P1 V, m/s	P2 P, W	P3 P_0, W	P4 A, m	P5 B, m	P6 T, K	P7 σ_r, MPa
1	0,03	20	60	0,006	0,0015	600	51,8
2	0,025	20	60	0,006	0,0015	631	62,6
3	0,035	20	60	0,006	0,0015	575	43,6
4	0,03	10	60	0,006	0,0015	454	31,3
5	0,03	30	60	0,006	0,0015	746	71,4
6	0,03	20	50	0,006	0,0015	597	49,6
7	0,03	20	70	0,006	0,0015	602	53,8
8	0,03	20	60	0,005	0,0015	637	55,8
9	0,03	20	60	0,007	0,0015	573	49,0
10	0,03	20	60	0,006	0,001	717	67,4
11	0,03	20	60	0,006	0,002	532	42,3
12	0,025	10	50	0,005	0,002	447	30,7
13	0,035	10	50	0,005	0,001	516	33,6
14	0,025	30	50	0,005	0,001	1057	117,0
15	0,035	30	50	0,005	0,002	650	49,5
16	0,025	10	70	0,005	0,001	566	51,5
17	0,035	10	70	0,005	0,002	425	25,6
18	0,025	30	70	0,005	0,002	729	75,4
19	0,035	30	70	0,005	0,001	941	88,0

End of table 1

20	0,025	10	50	0,007	0,001	507	41,1
21	0,035	10	50	0,007	0,002	398	19,8
22	0,025	30	50	0,007	0,002	645	62,4
23	0,035	30	50	0,007	0,001	814	73,9
24	0,025	10	70	0,007	0,002	427	32,7
25	0,035	10	70	0,007	0,001	479	33,3
26	0,025	30	70	0,007	0,001	912	107,4
27	0,035	30	70	0,007	0,002	591	47,1

The response functions that establish the relationship between the output parameters (T, σ_r) and the factors (V, P, P_0, A, B) are expressed as follows:

$$Y_T = 6.55 + 6.54\cdot 10^{-2}\cdot P - 5.14\cdot 10^{-1}\cdot A - 5.56\cdot 10^{2}\cdot B$$
$$-2.83\cdot 10^{-4}\cdot P^2 + 1.24\cdot 10^{5}\cdot B^2 - 3.02\cdot 10^{-1}\cdot V\cdot P - 1.55\cdot 10^{3} V\cdot B$$
$$-1.33\cdot P\cdot A - 7.78\cdot P\cdot B + 1.82\cdot 10^{4}\cdot A\cdot B$$

$$T = e^{Y_T} - 1$$

$$Y_\sigma = 2.60\cdot 10^{2} - 1.43\cdot 10^{3}\cdot V + 6.03\cdot P - 4.69\cdot 10^{4}\cdot B$$
$$-3.84\cdot 10^{-2}\cdot P\cdot P + 8.33\cdot 10^{6}\cdot B\cdot B - 1.98\cdot 10\cdot V\cdot P$$
$$-4.01\cdot 10^{-3}\cdot P\cdot P_0 - 1.03\cdot 10^{2}\cdot P\cdot A - 5.41\cdot 10^{-2}\cdot P\cdot B$$
$$2.04\cdot 10^{2}\cdot B\cdot P_0 - 6.27\cdot 10^{5}\cdot A\cdot B$$

$$\sigma_r = \left(Y_\sigma\cdot 0.225 + 1\right)^{\left(\frac{1}{0.225}\right)} - 1$$

Figure 5 presents the assessment of how the input parameters affect the output parameters. Both responses that occur during double-beam laser cleaving of silicate glasses along curved paths are greatly influenced by the laser power with a radiation wavelength of λ = 10,6 μm and the size of the minor semi-axis of the laser elliptical beam B. The laser power with a radiation wavelength of λ = 1,06 μm has a significant effect on the values of the maximum tensile stresses σ_r.

Figures 6–7 illustrate the dependences of maximum temperatures T and maximum tensile stresses σ_r in the treatment zone on the processing parameters.

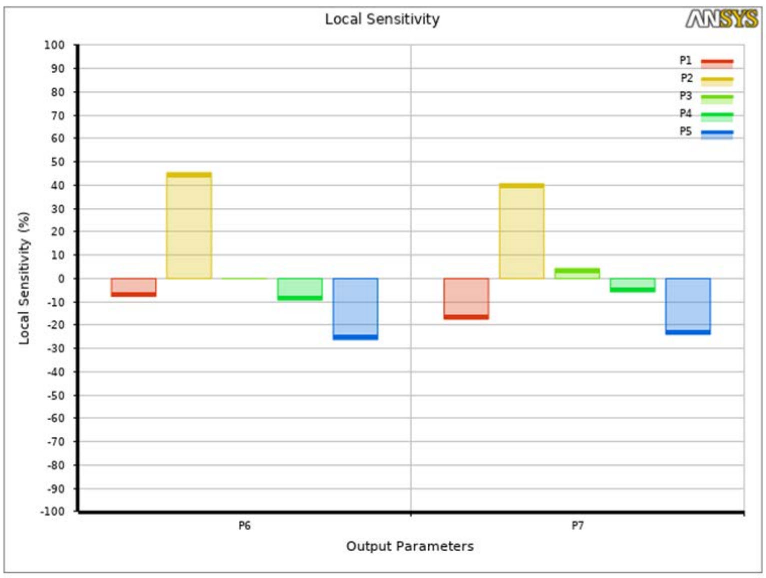

Figure 5 – Response sensitivity diagram
P1 – V, P2 – P, P3 – P_0, P4 – A, P5 – B, P6 – T, P7 – σ_r

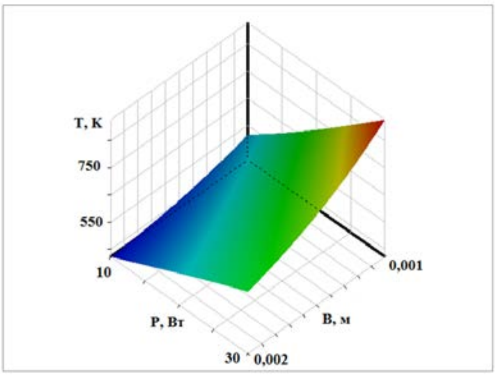

Figure 6 – Dependence of maximum temperature T, K on processing parameters P2 = P, P5 = B

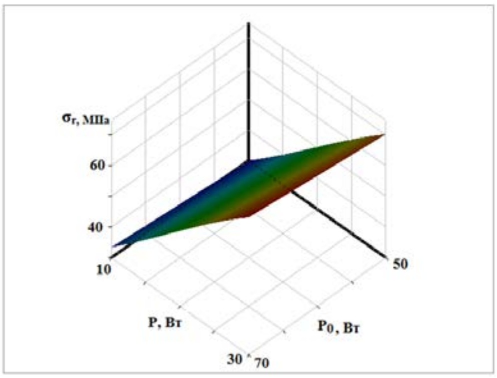

Figure 7 – Dependence of maximum stresses σ_r, MPa on processing parameters P2 = P, P3 = P_0

The TensorFlow library was used to construct artificial neural networks with two hidden layers, following the algorithm specified in reference [16].

The construction of neural networks was performed using the Adam optimizer, ReLU activation function, and MSE loss function. The neural network underwent training for a total of 500 epochs. Consequently, 16 artificial neural networks were created with the number of neurons in two hidden layers ranging from 5 to 20, with an interval of 5.

The dataset presented in table 2 was used to perform tests on regression and neural network models.

The neural network and regression models were evaluated using mean absolute error (MAE), root mean square error (RMSE), mean absolute percentage error (MAPE), and determination coefficient R^2.

Figures 8–9 show heat maps illustrating the distribution of validation errors in determining the maximal values of temperature and tensile stresses during double-beam laser cleaving of silicate glasses following curved paths. The number of neurons in the first and second hidden layers of the artificial neural network are shown by the vertical and horizontal axes, respectively. The intensity of color coding represents the extent of error: the error increases from light to dark.

Table 2 – Test dataset

N	P1 V, m/s	P2 P, W	P3 P_0, W	P4 A, m	P5 B, m	P6 T, K	P7 σ_r, MPa
1	0,026	20	53	0,007	0,002	527	44,70
2	0,031	27	65	0,006	0,002	605	51,60
3	0,032	15	63	0,006	0,001	605	50,00
4	0,029	16	55	0,005	0,0015	575	47,80
5	0,026	14	66	0,007	0,0015	511	44,10
6	0,031	28	56	0,005	0,002	652	53,70
7	0,032	12	58	0,005	0,0015	498	34,60
8	0,025	12	59	0,006	0,001	579	52,80
9	0,034	25	58	0,006	0,002	567	42,90
10	0,033	15	54	0,006	0,0015	514	35,60

The neural network with the architecture [5-20-10-2] demonstrated superior performance in determining the values of maximum temperatures T in the area of double-beam laser treatment, whereas the neural network with the architecture [5-15-20-2] achieved the highest accuracy in calculating the maximum tensile stresses σ_r.

Table 3 displays the estimation outcomes of both the regression and neural network models.

Table 3 – Evaluation results of regression and neural network models

Criterion	Regression models		Neural network models	
	T	σ_r	T	σ_r
RMSE	6,4 K	1,13 MPa	3,6 K	0,97 MPa
MAE	5,4 K	0,86 MPa	3,0 K	0,51 MPa
MAPE	1,0 %	1,8 %	0,5 %	1,1 %
R^2	0,9819	0,9685	0,9663	0,9771

The evaluation results of the generated neural network and regression models demonstrate a significant consistency with the outcomes obtained from the finite element computations. The neural network models have superior efficacy in predicting the parameters of double-beam laser cleaving of silicate glasses along curved paths.

The MOGA algorithm of the DesignXplorer module was used to perform multicriteria optimization of parameters for double-beam laser cleaving of silicate glasses along curved paths. The optimization procedures were conducted following the algorithm described in references [8]–[9].

The following optimization criteria were chosen: V → max, σ_r → max, T ≤ 789 K. The optimization results are provided in Table 4. The values of temperatures and tensile stresses derived from the finite element calculations are presented in brackets. The maximum relative error of the results did not exceed 2 %. These results were obtained using the genetic algorithm when determining the responses.

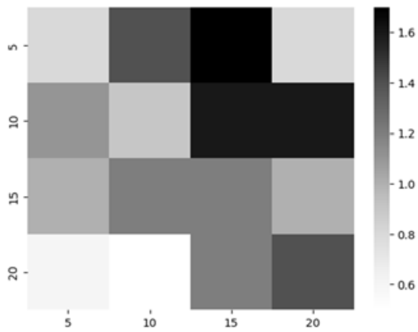

Figure 8 – Heat map of MAPE distribution when determining T

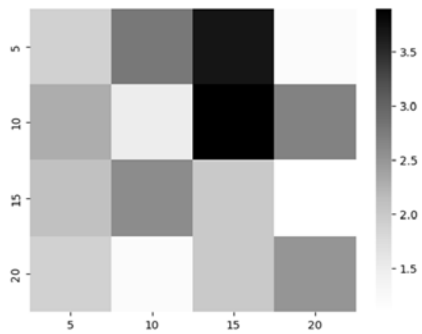

Figure 9 – Heat map of MAPE distribution when determining σ_r

Table 4 – Optimization results

P1 V, m/s	P2 P, W	P3 P_0, W	P4 A, m	P5 B, m	P6 T, K	P7 σ_r, MPa
0,035	27,8	65,3	0,007	0,001	787 (780)	72,8 (71,8)

Conclusion. This paper presents the development of regression and neural network models of double-beam laser cleaving of silicate glasses along curved paths. Efficient architectures of artificial neural networks were identified, the accuracy of which was found to be higher than that of regression models. Efficient parameters for double-beam laser cleaving were determined through multicriteria optimization utilizing the genetic algorithm in order to ensure the effective formation of laser-induced cracks along curved paths.

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