УДК 539.3:621.373.8

ОПРЕДЕЛЕНИЕ ПАРАМЕТРОВ ДВУХЛУЧЕВОГО ЛАЗЕРНОГО РАСКАЛЫВАНИЯ СИЛИКАТНЫХ СТЕКОЛ С ИСПОЛЬЗОВАНИЕМ РЕГРЕССИОННЫХ И НЕЙРОСЕТЕВЫХ МОДЕЛЕЙ

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Для создания нейросетевых и регрессионных моделей двухлучевого лазерного раскалывания силикатных стекол были использованы результаты численного эксперимента, реализованного в программе конечно-элементного анализа *Ansys*. В модуле *DesignXplorer* программы *Ansys Workbench* с применением гранецентрированного варианта центрального композиционного плана эксперимента были получены регрессионные модели двухлучевой лазерной резки стекла. В качестве варьируемых факторов использованы скорость обработки, параметры лазерных пучков, толщина стеклянной пластины и расстояние между зонами воздействия лазерного излучения и хладагента, а в качестве откликов – максимальные температуры и термоупругие напряжения растяжения в зоне лазерной обработки. С применением пакета *TensorFlow* реализованы построение и обучение искусственных нейронных сетей. Выполнено сравнение результатов определения максимальных температур и термоупругих напряжений в зоне лазерной обработки с использованием нейросетевых и регрессионных моделей.

Ключевые слова: лазерное раскалывание; стеклянная пластина; нейронная сеть; *Ansys*.

Образец цитирования:
Никитюк ЮВ, Сердюков АН, Аушев ИЮ. Определение параметров двухлучевого лазерного раскалывания силикатных стекол с использованием регрессионных и нейросетевых моделей. *Журнал Белорусского государственного университета. Физика.* 2022;1:35–43 (на англ.).
https://doi.org/10.33581/2520-2243-2022-1-35-43

For citation:
Nikitjuk YV, Serdyukov AN, Aushev IY. Determination of the parameters of two-beam laser splitting of silicate glasses using regression and neural network models. *Journal of the Belarusian State University. Physics.* 2022;1:35–43.
https://doi.org/10.33581/2520-2243-2022-1-35-43

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DETERMINATION OF THE PARAMETERS OF TWO-BEAM LASER SPLITTING OF SILICATE GLASSES USING REGRESSION AND NEURAL NETWORK MODELS

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The current work takes the results of the numerical experiment implemented in the *Ansys* finite element analysis program to create the neural network and regression models of two-beam laser splitting of silicate glasses. The regression models of two-beam laser glass cutting have been obtained in the *DesignXplorer* module of *Ansys Workbench* using a face-centered version of the central composite design. The processing speed, the parameters of laser beams, the glass plate thickness, and the distance between the laser radiation and the refrigerant affected zones were used as variable factors. The maximum temperatures and thermoelastic tensile stresses in the laser processing area were used as responses. The artificial neural networks have been constructed and trained using the *TensorFlow* package. The results of determining the maximum temperatures and thermoelastic stresses in the laser treatment area using the neural network and regression models have been compared.

Keywords: laser splitting; glass plate; neural network; *Ansys*.

Introduction

Laser splitting is one of the methods for cutting silicate glasses, which is carried out as a result of the laser-induced crack formation during consecutive laser heating and action of the refrigerant on the treated surface [1–5]. At the same time, the use of two-beam schemes provides an increase in the efficiency of this technology [6–8].

Artificial neural networks (ANN) provide good results when modelling complex connections between inputs and outputs of the system. The wide application of neural networks is due to their capabilities in finding non-linear dependencies in multidimensional data sets [9–11]. Currently, ANN are successfully used in various fields [9–13]. The combination of ANN and the finite element method turns out to be effective in modelling laser treatment processes [14; 15], including modelling of laser glass splitting [16; 17]. Regression models of laser processing of materials [18; 19] are also successfully used, and a comparison of neural network and regression models of laser cutting of materials was carried out in [20].

This research uses the results of the numerical experiment implemented in the *Ansys* finite element analysis program to create neural network and regression models for two-beam laser splitting of silicate glasses with subsequent comparison of their efficiency.

Finite element analysis

To determine temperatures and thermoelastic stresses in silicate glass during two-beam laser splitting (fig. 1), a calculation program was prepared in the APDL programming language (*Ansys* parametric design language).

Calculations were performed for the plate with geometric dimensions of $30 \times 10 \times 4$ mm. The resulting model consisted of 44 160 solid 70 elements for thermal analysis and solid 185 elements for strength analysis. The processing speed for the calculations was $V = 0.02$ m/s. The following values of the parameters of laser beams were used: semi-major axis $A = 0.003$ m, semi-minor axis $B = 0.001$ m for an elliptical beam with a radiation wavelength $\lambda = 10.6$ μm and a radiation power $P = 10$ W; the radius of the beam radiation spot is $R = 0.001$ m for a beam with a radiation wavelength $\lambda = 1.06$ μm and a radiation power $P_0 = 50$ W. The distance between the action zones on the glass plate of the YAG laser and the refrigerant is $h = 0.002$ m. The refrigerant effect was believed to provide cooling of the glass surface with a heat transfer coefficient equal to 8000 W/(m^2 · K). The following properties of silicate glasses were used for the calculations: density 2450 kg/m^3, thermal conductivity 0.88 W/(m · K), specific heat capacity 860 J/(kg · K), Poisson's ratio 0.22, Young's modulus 70 GPa, linear thermal expansion coefficient $89 \cdot 10^{-7}$ °C^{-1} [2].

Figures 2 and 3 show the distribution of temperature fields and fields of thermoelastic stresses, characteristic of a two-beam laser splitting schemes of glass plates.

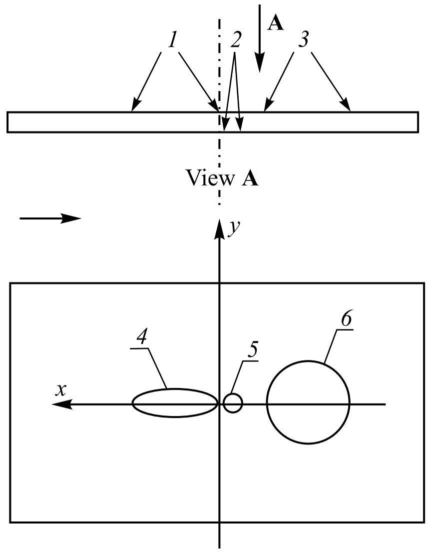

Fig. 1. Schematic of the mutual arrangement
of the laser beams and refrigerant affected zones:
position *1* corresponds to an elliptical laser beam with a wavelength of 10.6 μm,
position *2* – to a round laser beam with a wavelength of 1.06 μm,
position *3* – to the refrigerant, position *4* – to the laser beam section with a wavelength of 10.6 μm,
position *5* – to the laser beam section with a wavelength of 1.06 μm,
position *6* – to the refrigerant affected zone

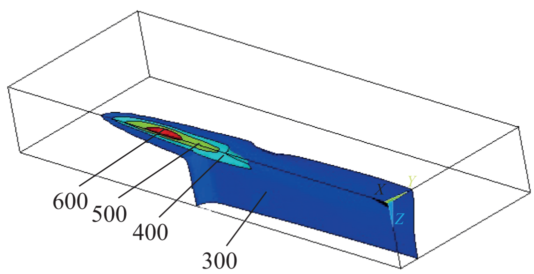

Fig. 2. Temperature distribution in the volume of the processed plate, *K*

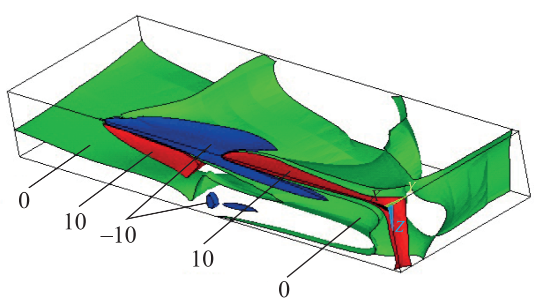

Fig. 3. Distribution of stresses σ_{yy} in the volume of the processed plate, MPa

For the selected calculation parameters, the values of the maximum tensile stresses in the treatment zone σ_{yy} and the maximum design temperatures T are 79 MPa and 689 K, respectively, with acceptable temperature values not exceeding the glass transition temperature equal to 789 K [2].

Regression model

In the *DesignXplorer* module of the *Ansys Workbench* software, a face-centered version of the central composite plan of the experiment was generated for eight factors (P1–P8) [21; 22]: P1 is the processing speed V, P2 is the glass plate thickness H, P3 and P4 are the semi-major axis A and semi-minor axis B of an elliptical beam with the radiation wavelength $\lambda = 10.6$ μm, P5 is the radius of the radiation spot R of the beam with the radiation wavelength $\lambda = 1.06$ μm, P6 is the power P of the laser with the radiation wavelength $\lambda = 10.6$ μm, P7 is the power P_0

of the laser with radiation wavelength $\lambda = 1.06$ μm, P8 is the distance h between the action zones of the laser with the radiation wavelength $\lambda = 1.06$ μm and the refrigerant. According to the experimental plan, the calculations were performed for 81 combinations of input parameters (see version 1 in table 1), while the following output parameters were determined: the maximum temperature in the laser treatment zone T and the maximum tensile stresses σ_{yy} in the treatment zone.

Table 1

Parameters of two-beam laser glass splitting

Parameters	Values	
	Version 1 (81 combinations)	Version 2 (72 combinations)
P1 (V, m/s)	0.01; 0.025; 0.04	0.025; 0.035; 0.04
P2 (H, m)	0.003; 0.004; 0.005	0.003; 0.035
P3 (A, m)	0.002; 0.003; 0.004; 0.005	0.002 5; 0.003 5; 0.005
P4 (B, m)	0.000 5; 0.001; 0.001 5	0.001; 0.001 5
P5 (R, m)	0.000 5; 0.001; 0.001 5	0.001; 0.001 5
P6 (P, W)	5; 10; 15	7; 9; 15
P7 (P_0, W)	40; 50; 60	45; 55; 60
P8 (h, m)	0.001; 0.002; 0.003	0.001; 0.002

The regression equations obtained using the *DesignXplorer* module connecting the output parameters (T, σ_{yy}) with the factors (V, H, A, B, R, P, P_0, h) have the following form:

$$Y_1 = 7.3 - 2.7 \cdot 10^2 \cdot A - 7.6 \cdot 10^2 \cdot B +$$
$$+ 1.6 \cdot 10^{-1} \cdot P + 2.8 \cdot 10^2 \cdot V \cdot V + 1.7 \cdot 10^5 \cdot B \cdot B - 1.9 \cdot 10^{-3} \cdot P \cdot P +$$
$$+ 2.3 \cdot 10^3 \cdot V \cdot A - 6.0 \cdot 10^{-1} \cdot V \cdot P + 7.2 \cdot 10^4 \cdot A \cdot B - 5.2 \cdot A \cdot P -$$
$$- 2.4 \cdot 10 \cdot B \cdot P - 4.6 \cdot 10^3 \cdot R \cdot h,$$
$$T = \left(0.02 \cdot Y_1 + 1\right)^{50} - 1;$$
$$Y_2 = 2.3 \cdot 10^2 - 4.2 \cdot 10^3 \cdot V + 8.6 \cdot 10^4 \cdot B + 8.8 \cdot 10^4 \cdot R +$$
$$+ 5.6 \cdot P + 4.1 \cdot 10^4 \cdot V \cdot V - 3.7 \cdot 10^7 \cdot B \cdot B - 3.7 \cdot 10^7 \cdot R \cdot R -$$
$$- 5.7 \cdot 10^5 \cdot V \cdot B - 2.5 \cdot 10 \cdot V \cdot P + 7.8 \cdot V \cdot P_0 + 9.7 \cdot 10^4 \cdot V \cdot h -$$
$$- 8.4 \cdot 10 \cdot H \cdot P + 3.6 \cdot 10^5 \cdot A \cdot B + 3.9 \cdot 10^6 \cdot B \cdot R - 7.7 \cdot 10^2 \cdot B \cdot P -$$
$$- 8.3 \cdot 10^4 \cdot B \cdot h - 4.6 \cdot 10^2 \cdot R \cdot P - 4.0 \cdot 10^6 \cdot R \cdot h + 2.2 \cdot 10^{-2} \cdot P \cdot P_0,$$
$$\sigma_{yy} = \left(0.236\,6 \cdot Y_2 + 1\right)^{1/0.236\,6} - 1.$$

Neural network application

Figure 4 shows a block diagram of the ANN simulation procedure. The training and test sets were generated when solving the corresponding problems by the finite element method in the *Ansys* program. Here, 81 combinations of the central composite design were supplemented with another 72 combinations of calculations (see version 2 in table 1). Thus, neural networks training was carried out using two data sets consisting of 81 combinations of the central composite design (version A) and 135 combinations (version B) of the values of the two-beam laser splitting parameters formed by supplementing 81 combinations of version A with another 54 combinations (see 2 versions of table 1). At the same time, a test set of 18 combinations of parameters was used to test neural network and regression models (see table 2).

Table 2

Test set of parameters

No.	P1 (V, m/s)	P2 (H, m)	P3 (A, m)	P4 (B, m)	P5 (R, m)	P6 (P, W)	P7 (P_0, W)	P8 (h, m)	T, K	σ_{yy}, MPa
1	0.035	0.003 5	0.002 5	0.001	0.001	9	55	0.002	577	47.5
2	0.035	0.003	0.002 5	0.001 5	0.001 5	9	55	0.001	486	35.3
3	0.025	0.003	0.003 5	0.001 5	0.001 5	7	45	0.001	454	40.0

Ending table 2

No.	P1 (V, m/s)	P2 (H, m)	P3 (A, m)	P4 (B, m)	P5 (R, m)	P6 (P, W)	P7 (P_0, W)	P8 (h, m)	T, K	σ_{yy}, MPa
4	0.035	0.003	0.002 5	0.001	0.001	7	45	0.002	514	37.9
5	0.035	0.003 5	0.002 5	0.001	0.001	7	55	0.002	514	41.5
6	0.025	0.003	0.003 5	0.001	0.001	7	55	0.002	526	57.1
7	0.035	0.003	0.002 5	0.001	0.001	9	55	0.002	577	47.8
8	0.035	0.003	0.002 5	0.001	0.001	9	45	0.001	577	44.0
9	0.035	0.003	0.002 5	0.001 5	0.001 5	9	45	0.001	486	32.6
10	0.025	0.003 5	0.002 5	0.001	0.001	7	55	0.002	560	56.2
11	0.035	0.003 5	0.002 5	0.001	0.001	9	60	0.002	577	49.3
12	0.035	0.003	0.002 5	0.001 5	0.001 5	15	55	0.001	615	48.9
13	0.04	0.003	0.003 5	0.001 5	0.001 5	7	45	0.001	417	25.2
14	0.035	0.003 5	0.005	0.001	0.001	7	55	0.002	460	42.4
15	0.04	0.003	0.003 5	0.001	0.001	7	60	0.002	476	39.3
16	0.035	0.003	0.005	0.001	0.001	9	45	0.001	508	45.8
17	0.035	0.003	0.002 5	0.001 5	0.001 5	9	60	0.001	486	36.7
18	0.04	0.003 5	0.002 5	0.001	0.001	7	55	0.002	497	36.7

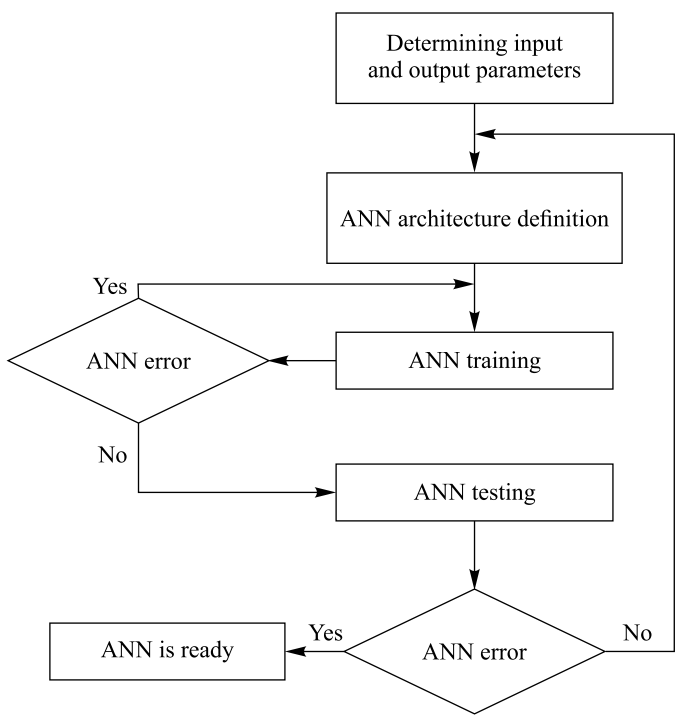

Fig. 4. Block diagram of the simulation procedure using the neural network

Fully connected neural networks with architecture [8–50–30–10–2] were used to determine the values of temperatures and thermoelastic stresses during two-beam laser splitting. The networks were formed using the *TensorFlow* machine learning library [10]. The networks used the ReLU (rectified linear unit) activation function, the Adam optimiser, which is a version of the stochastic gradient descent algorithm, and the MSE (mean squared error) loss function, which calculates the square of the difference between the predicted and target values. The number of epochs during network training was 500.

Results and discussion

The following criteria were used to evaluate the resulting regression and neural network models: determination coefficient

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

mean absolute error

$$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n}\left|d_i - y_i\right|,$$

root mean square error

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

mean absolute percentage error

$$\text{MAPE} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{d_i - y_i}{d_i}\right| \cdot 100,$$

where d_i is the finite element values; y_i is the values determined using regression and neural network models.

The criteria values used to assess regression and neural network models are presented in tables 3–5.

Accordingly, the obtained data lead to a conclusion that the regression and neural network models have the necessary consistency with the results of finite-element analysis.

Table 3

Results of evaluating regression models

Criterion	Test set		Central composite plan dataset (81 combinations)	
	T	σ_{yy}	T	σ_{yy}
RMSE	8	$1.71 \cdot 10^6$	13	$4.55 \cdot 10^6$
MAE	7	$1.20 \cdot 10^6$	9	$3.31 \cdot 10^6$
MAPE	1.3	2.7	1.3	5.3
R^2	0.9768	0.9649	0.9983	0.9849

Table 4

Results of evaluating the neural network model (version A)

Criterion	Test set		Training set (81 combinations)	
	T	σ_{yy}	T	σ_{yy}
RMSE	14	$2.82 \cdot 10^6$	5	$0.72 \cdot 10^6$
MAE	11	$2.36 \cdot 10^6$	4	$0.50 \cdot 10^6$
MAPE	2.1	5.4	0.6	0.9
R^2	0.9284	0.9039	0.9997	0.9996

Table 5

Results of evaluating the neural network model (version B)

Criterion	Test set		Training set (135 combinations)	
	T	σ_{yy}	T	σ_{yy}
RMSE	8	$1.15 \cdot 10^6$	5	$0.76 \cdot 10^6$
MAE	6	$0.84 \cdot 10^6$	3	$0.49 \cdot 10^6$

Ending table 5

Criterion	Test set		Training set (135 combinations)	
	T	σ_{yy}	T	σ_{yy}
MAPE	1.2	2.0	0.4	0.8
R^2	0.9777	0.9839	0.9996	0.9994

At the same time, for the datasets used to create regression models and train neural network models, the values of the average absolute percentage errors of MAPE when determining the maximum temperatures and tensile stresses in the laser processing zone turned out to be the highest for regression models. They amounted to 1.3 % for temperatures and 5.3 % for tensile stresses. Furthermore, for this dataset, the RMSE, MAE and R^2 values of the regression models exceeded the values of the corresponding criteria of neural network models. The results of the neural network trained on a set of parameters of the central composite plan turned out to be worse than the results of the regression models. In this case, for the test dataset, the results of the neural network model trained with 135 combinations of parameter values of the two-beam laser splitting (version B) proved to be the best.

The suggested architecture of the neural network model, trained with a small dataset, proved to be better at predicting the parameters of two-beam laser splitting compared to the suggested regression models. Thus, as in [20], it follows that the use of neural network models is preferable for predicting laser cutting parameters, including two-beam laser splitting.

Conclusions

The research performed by us shows the possibility of determining the modes of two-beam laser splitting of silicate glasses based on a combination of the finite element method, regression and neural network models. The numerical experiment brought about identifying the architecture of neural networks, which gives an acceptable result when determining the values of thermoelastic stresses and temperatures in the laser processing zone. A higher efficiency of neural network models in predicting the parameters of two-beam laser glass splitting compared to regression models has been shown.

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Received 25.11.2021 / revised 04.01.2022 / accepted 04.01.2022.