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ESTIMATING THE PARAMETERS OF LASER PROCESSING OF DIAMONDS USING THE FINITE ELEMENT METHOD AND ARTIFICIAL NEURAL NETWORKS

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Abstract. This paper provides the simulation of laser processing of diamonds by using a combination of artificial neural networks and the finite element method. The training data array and the data array for testing neural networks were generated in ANSYS. The calculations were performed for 600 types of input parameters, 60 of which were used to test artificial neural networks. The influence of the parameters of neural network models on the accuracy of determining temperatures in the laser processing area were studied. The parameters of neural networks were established that provide acceptable results in predicting temperatures generated by laser radiation in diamonds. The results obtained can be used to determine the technological parameters of the laser processing of diamonds.

Keywords: neural network, laser processing, diamond, ANSYS.

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ОПРЕДЕЛЕНИЕ ПАРАМЕТРОВ ЛАЗЕРНОЙ ОБРАБОТКИ АЛМАЗОВ С ПРИМЕНЕНИЕМ МЕТОДА КОНЕЧНЫХ ЭЛЕМЕНТОВ И ИСКУССТВЕННЫХ НЕЙРОННЫХ СЕТЕЙ

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Аннотация. С помощью сочетания искусственных нейронных сетей и метода конечных элементов выполнено моделирование процесса лазерной обработки алмазов. Обучающий массив данных и массив данных для тестирования нейронных сетей были сформированы с использованием программы конечно-элементного анализа ANSYS. Расчеты выполняли для 600 вариантов входных параметров, 60 из которых использовали для тестирования искусственных нейронных сетей. Исследовано влияние параметров нейросетевых моделей на точность определения температур в зоне лазерной обработки. Установлены параметры нейронных сетей, обеспечивающие приемлемые результаты при прогнозировании температур, формируемых лазерным излучением в алмазах. Полученные результаты могут быть использованы при определении технологических параметров процессов лазерной обработки алмазов.

Ключевые слова: нейронная сеть, лазерная обработка, алмаз, ANSYS.

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Introduction

The properties of diamond ensure the reliable operation of diamond-based devices under critical conditions and make it promising to use diamonds in developing new technology [1]. Laser processing of diamond has a number of advantages which include the possibility of forming narrow cuts, high productivity of the laser dimensional processing, and the possibility of automating the process of diamond cutting using laser radiation [2, 3].

At present, ANSYS is widely used to calculate the temperature fields during laser processing of materials, including diamonds [4–9]. Artificial neural networks are also effectively used to study laser processing of materials [5, 10–12]. In some cases, a combination of artificial neural networks and the finite element method is applied when simulating laser processing [13–18]. This research aims to predict the temperature fields during laser processing of diamonds via the finite element method and artificial neural networks.

Finite element analysis

The training data array and the array data for testing neural networks were generated as a result of finite element calculations with ANSYS of temperature fields during laser processing of diamonds. A model consisting of 45418 Solid 87 elements was used during the simulation process [19]. The properties of diamonds presented in [2, 20] were used for calculations. The calculations were performed for a sample with the shape of a rectangular parallelepiped with geometric dimensions of 2×3×1.5 mm, while the temperatures were determined on its surface in the center of a circular laser beam, as well as at a depth of 0.00002 and 0.00004 m.

The parameters used for finite element simulation of two-beam laser cleaning of quartz raw materials are presented in Tab. 1. Fig. 1 shows the distribution of temperature fields during laser processing of diamond. Calculations were performed for 600 types of input parameters, 100 of which were used to test neural networks (Tab. 2).

Table 1. Parameters of laser action on diamond

Parameter	Value range
Processing speed v, m/s	0.001–0.010
Laser beam radius R, m	0.00005–0.00007
Laser power density P_0, 10^{10} W/m^2	1–5

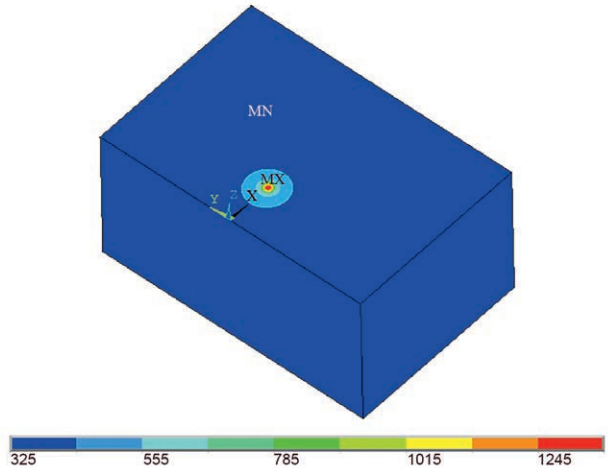

Fig. 1. Temperature distribution in the volume of diamond to be processed, K (v = 1 mm/s, R = 5 mm, P_0 = 10^{10} W/m^2)

Table 2. Test dataset

No	*v*, m/s	*R*, m	P_0, W/m^2	T_1, K	T_2, K	T_3, K
1	0.00584	0.00006	16600000000	2411	1774	1374
2	0.00669	0.00006	29600000000	4067	2931	2218
3	0.00791	0.00007	40200000000	6302	4713	3641
4	0.00639	0.00005	10200000000	1361	986	775
5	0.00309	0.00006	24300000000	3408	2475	1890
6	0.00116	0.00007	46700000000	7445	5599	4353
7	0.00462	0.00005	47800000000	5305	3548	2558
8	0.00144	0.00007	10900000000	1953	1523	1232
9	0.00494	0.00006	15000000000	2209	1633	1272
10	0.00104	0.00007	13300000000	2336	1811	1456
11	0.00786	0.00007	39000000000	6123	4582	3541
12	0.00521	0.00005	25500000000	2965	2028	1500
13	0.00852	0.00006	40500000000	5450	3896	2920
14	0.00608	0.00007	11600000000	2030	1571	1262
15	0.00230	0.00007	24500000000	3995	3026	2373
16	0.00174	0.00005	44600000000	5009	3369	2446
17	0.00701	0.00007	14600000000	2477	1900	1511
18	0.00339	0.00006	23300000000	3277	2383	1822
19	0.00851	0.00006	26100000000	3617	2615	1986
20	0.00414	0.00005	16400000000	2014	1411	1071
21	0.00797	0.00006	31600000000	4318	3105	2344
22	0.00207	0.00007	41200000000	6528	4899	3800
23	0.00761	0.00005	36700000000	4132	2783	2023
24	0.00140	0.00006	48600000000	6590	4724	3554
25	0.00999	0.00005	17400000000	2111	1471	1111
26	0.00513	0.00005	39900000000	4475	3008	2182
27	0.00899	0.00007	30000000000	4774	3588	2788
28	0.00201	0.00007	37400000000	5955	4477	3479
29	0.00612	0.00007	17700000000	2943	2244	1772
30	0.00981	0.00006	28900000000	3970	2861	2165
31	0.00188	0.00007	22200000000	3658	2780	2188
32	0.00939	0.00005	29100000000	3334	2264	1662
33	0.00485	0.00006	36300000000	4930	3537	2663
34	0.00510	0.00005	41800000000	4674	3137	2272
35	0.00632	0.00006	37600000000	5089	3646	2740
36	0.00566	0.00005	49500000000	5478	3659	2633
37	0.00402	0.00005	34000000000	3861	2611	1907
38	0.00401	0.00007	38900000000	6135	4598	3560
39	0.00941	0.00006	10500000000	1629	1226	973
40	0.00765	0.00006	37100000000	5020	3596	2702
41	0.00108	0.00005	49700000000	5591	3763	2734
42	0.00350	0.00007	12900000000	2233	1723	1379
43	0.00867	0.00006	44400000000	5946	4242	3173
44	0.00945	0.00007	45900000000	7146	5332	4107
45	0.00839	0.00005	17800000000	2154	1500	1131
46	0.00261	0.00006	19900000000	2848	2084	1605
47	0.00327	0.00007	48700000000	7621	5696	4397
48	0.00996	0.00005	40200000000	4493	3015	2182
49	0.00146	0.00006	39400000000	5394	3881	2932
50	0.00345	0.00005	21900000000	2594	1788	1335
51	0.00905	0.00006	32000000000	4366	3138	2367
52	0.00674	0.00006	30600000000	4195	3020	2283
53	0.00660	0.00006	42600000000	5725	4090	3064
54	0.00497	0.00005	38700000000	4350	2927	2125
55	0.00888	0.00007	34400000000	5431	4072	3154
56	0.00599	0.00007	45600000000	7122	5319	4103
57	0.00483	0.00007	24000000000	3892	2944	2304
58	0.00431	0.00007	15600000000	2635	2018	1602
59	0.00845	0.00006	26000000000	3604	2606	1980
60	0.00846	0.00005	19500000000	2332	1615	1211

Neural network application

The key feature of artificial neural networks is that they are trained, not programmed. At the same time, neural networks are effective in simulating complex associations between input and output parameters [21]. As mentioned earlier, the training data array and the array data for testing neural networks were generated as a result of solving the corresponding problems in ANSYS. After training, the artificial neural network, dealing with new sets of laser processing parameters, can determine accurately the maximum temperatures at different depths in diamond crystals.

Feedforward neural networks created in TensorFlow were provided to determine the temperature value during laser processing [22]. While generating networks, the Adam optimizer, the MSE loss function, and ReLu activation function were used. The number of epochs for training networks was 100. Neural networks with the architecture shown in Fig. 2 were used to determine the temperature values during laser processing.

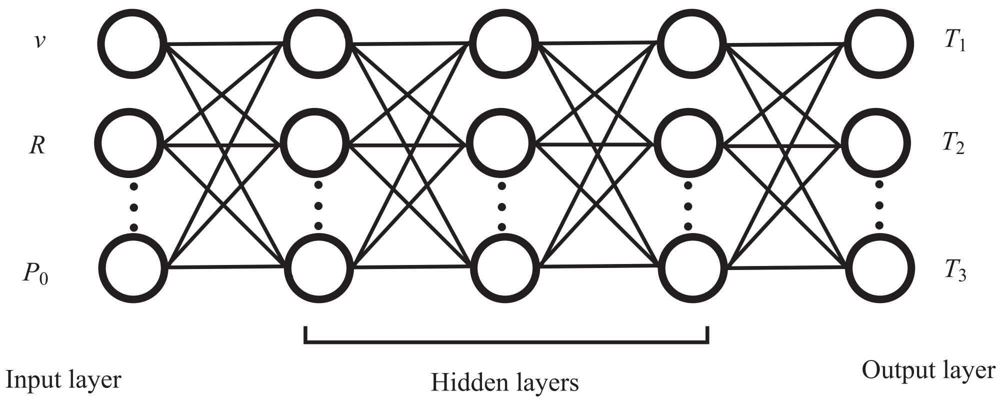

Fig. 2. Neural network architecture

To assess the efficiency of neural networks, the following criteria were used:

– coefficient of determination

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

– mean absolute error

$$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n}\left|d_i - y_i\right|; \tag{2}$$

– root mean square error

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(d_i - y_i\right)^2}; \tag{3}$$

– mean absolute percentage error

$$\text{MAPE} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{d_i - y_i}{d_i}\right|100, \tag{4}$$

where d_i is the desired network output; y_i is the actual network output.

The outcomes of the resulting neural networks are provided in Tab. 3.

Table 3. Neural network testing outcomes

No		Network architecture	RMSE	MAE	MAPE	R^2
1	a	[3-5-3]	38.0	27.1	1.0	0.9989
	b		35.9	26.5	0.9	0.9991
2	a	[3-10-3]	15.8	11.4	0.4	0.9998
	b		14.7	10.6	0.3	0.9998

Ending of Tab. 3

No		Network architecture	RMSE	MAE	MAPE	R^2
3	a	[3-15-3]	22.4	17.8	0.7	0.9996
	b		21.7	16.7	0.6	0.9996
4	a	[3-5-5-3]	23.4	16.8	0.7	0.9995
	b		19.1	14.5	0.6	0.9997
5	a	[3-10-5-3]	34.9	28.0	1.0	0.9991
	b		31.3	24.9	0.9	0.9993
6	a	[3-5-10-3]	11.7	8.7	0.3	0.9998
	b		10.4	7.9	0.3	0.9999
7	a	[3-10-10-3]	10.2	7.9	0.3	0.9999
	b		9.7	7.6	0.3	0.9999
8	a	[3-10-15-3]	21.8	15.8	0.6	0.9996
	b		17.7	13.3	0.6	0.9997
9	a	[3-15-10-3]	9.1	6.6	0.2	0.9999
	b		7.3	5.4	0.2	0.9999
10	a	[3-15-15-3]	17.3	13.4	0.6	0.9997
	b		15.5	8.7	0.5	0.9998

In testing, the best results were obtained for option 9 of the neural network configuration with two hidden layers. MAPE did not exceed 0.2 %, and MAE and RMSE did not exceed 10 K.

Conclusion

The current paper shows the possibility of predicting the modes of laser processing of diamonds using a combination of the finite element method and artificial neural networks. Based on numerical experiments, the neural network architecture has been established, which ensures a better outcome when determining the temperature values in the laser action area. The results can be used to determine the technological parameters of laser processing of diamonds.

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Authors' contribution

Emelyanov V. A. and Shershnev E. B. developed a model of laser processing of diamonds.

Nikitjuk Y. V., Sokolov S. I. and Aushev I. Y. carried out a numerical experiment using a model of laser processing of diamonds and performed the optimization of the corresponding parameters.

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