УДК 621.791.725
https://doi.org/10.62595/1819-5245-2024-1-63-71

OPTIMIZATION OF PARAMETERS FOR PULSED LASER CLADDING OF 30ХГСН2А STEEL VIA GENETIC ALGORITHM

Yu. V. NIKITYUK, G. A. BAYEVICH, A. V. MAXIMENKO
Francisk Skorina Gomel State University, the Republic of Belarus

I. Yu. AUSHEV
State Educational Institution "University of Civil Protection of the Ministry for Emergency Situations of the Republic of Belarus", Minsk

The paperpresents the optimization of pulsed laser cladding of structural steel using a genetic algorithm. Using the ANSYS Workbench software, finite element modelling of laser cladding on a 30ХГСН2А steel substrate with an additive in the form of wire was conducted, considering the temperature dependence of the material's thermophysical properties. A surrogate model for pulsed laser cladding of 30ХГСН2Аsteel was developed employing a face-centered version of the central composite design experiment. The time intervals corresponding to the end time of the three fronts of the laser pulse and the diameter of the filler wire were considered as variable factors. The maximum temperatures in the treatment zone were used as responses. In order to optimize pulsed laser cladding of 30ХГСН2А steel, the maximum temperature limit values in the treatment zone were established for three moments of time that corresponded to the laser pulse fronts at the three points in the finite element model. A comparison was made between the parameters obtained from optimization and those derived from finite element modelling. When determining temperatures, the maximum percentage error of the results obtained via the genetic algorithm did not exceed 3.5 %.

Keywords: pulsed laser cladding, optimization, MOGA, ANSYS.
For citation. Parameters optimization of pulsed laser cladding of steel 30KHGSN2A using a genetic algorithm / Nikitiuk Yu. V., Bayevich G. A., Maximenko A. V., Aushev I. Yu. *Vestnik Gomel'skogo gosudarstvennogo tekhnicheskogo universiteta imeni P. O. Sukhogo*, 2024, no. 1 (96), pp. 63–71 (in Russian). https://doi.org/10.62595/1819-5245-2024-1-63-71

ОПТИМИЗАЦИЯ ПАРАМЕТРОВ ИМПУЛЬСНОЙ ЛАЗЕРНОЙ НАПЛАВКИСТАЛИ 30ХГСН2А С ИСПОЛЬЗОВАНИЕМ ГЕНЕТИЧЕСКОГО АЛГОРИТМА

Ю. В. НИКИТЮК, Г. А. БАЕВИЧ, А. В. МАКСИМЕНКО
Учреждение образования «Гомельский государственный университет имени Франциска Скорины», Республика Беларусь

И. Ю. АУШЕВ
Государственное учреждение образования «Университет гражданской защиты Министерства по чрезвычайным ситуациям Республики Беларусь», г. Минск

В работе с использованием генетического алгоритма выполнена оптимизация импульсной лазерной наплавки конструкционной стали. Конечно-элементное моделирование лазерной наплавки на основу из стали 30ХГСН2А присадкой в виде проволоки выполнялось с учетом зависимости теплофизических *свойств материала от температуры в программе ANSYS Workbench. С использованием гранецентрированного варианта центрального композиционного плана эксперимента была получена суррогатная модель импульсной лазерной наплавки стали 30ХГСН2А. В качестве варьируемых факторов эксперимента использовались временные интервалы, соответствующие времени окончания трех фронтов лазерного импульса, и диаметр присадочной проволоки. В качестве откликов использовались максимальные температуры в зоне обработки. Оптимизация импульсной лазерной наплавки стали 30ХГСН2А выполнялась при задании предельных значений максимальной температуры в зоне обработки для трех моментов времени, соответствующих фронтам лазерного импульса, в трех точках конечно-элементной модели. Выполнено сравнение параметров, полученных в результате оптимизации, и параметров, полученных в результате конечно-элементного моделирования. При определении температур максимальная относительная погрешность результатов, полученных с использованием генетического алгоритма, не превысила 3,5 %.*

Ключевые слова: импульсная лазерная наплавка, оптимизация, MOGA, ANSYS.

Для цитирования. Оптимизация параметров импульсной лазерной наплавки стали 30ХГСН2А с использованием генетического алгоритма / Ю. В. Никитюк [и др.] // Вестн. Гомел. гос. техн. ун-та им. П. О. Сухого. – 2024. – № 1 (96). – С. 63–71. https://doi.org/10.62595/1819-5245-2024-1-63-71

Introduction

Currently, many technologies such as electron beam processing, ion-beam processing, and gas-flame treatment are utilized to modify the surface properties of products while maintaining the characteristics of the original material. Each of these technologies has specific areas of application; however, laser technologies are the most promising for processing mechanical-engineering parts due to their productivity, flexibility, and ability to process products of various sizes and geometries, as well as create coatings from various materials. Laser processing technologies are categorized into groups according to the heating, melting, and shock loading of materials, which are determined by the laser radiation density and the exposure time. Quenching, alloying, and cladding are among the most prevalent laser processing technologies. Utilizing solid-state lasers for laser cladding is highlighted for attaining the necessary physical, mechanical, and operational properties of surface layers. Laser cladding is known for its high bonding strength between the overlay and the substrate and minimal heat affected zone [1, 2].

Simultaneously, the formation of joints from structural steels during laser cladding might lead to cracking because of the rapid cooling rates of the melt bath. Rapid cooling rates result in the development of substantial thermal stresses, which ultimately weaken the technological strength of the overlay. Using solid-state pulsed-periodic lasers with time-varying radiation intensity and wire filler materials is recommended to tackle this problem. An essential characteristic of pulsed laser cladding is the ability to regulate the heating and cooling rate of the weld metal and the substrate by adjusting the energy and time parameters of the radiation pulses [3–6].

A substantial enhancement in the effectiveness of laser technologies employed in the processing of materials can be achieved through the optimization of the relevant technological parameters via genetic algorithms [7–18]. In this case, the temperatures generated in the laser treated area serve as parameters the determination of which provides the possibility of optimizing the laser cladding parameters.

The present study employs the MOGA (Multi-Objective Genetic Algorithm) of ANSYS Workbench to optimize parameters for pulsed laser cladding of steel 30ХГСН2А by circular laser beams with the use of filler materials in the form of wire.

Determination of optimal parameters for pulsed laser cladding of 30ХГСН2А steel

The temperatures were calculated using the ANSYS Workbench software. Simulation of laser cladding was conducted on a steel 30ХГСН2А substrate using an additive with a diameter $d = 0.2$ mm from the same material. The simulation process considered the temperature dependence of the thermal conductivity coefficient, specific heat capacity, and density on [19], along with uniform distribution of laser radiation power density over he beam cross-section. Figure 1 illustrates a schematic of laser radiation exposure on both the additive surface and the substrate surface. The finite element model shown in Fig. 1. consisted of 2120 Solid 90 elements and 10182 node units. The laser beam is focused such that the substrate metal absorbs 50 % of the energy while the additive absorbs the remaining 50 % (see Fig. 1).

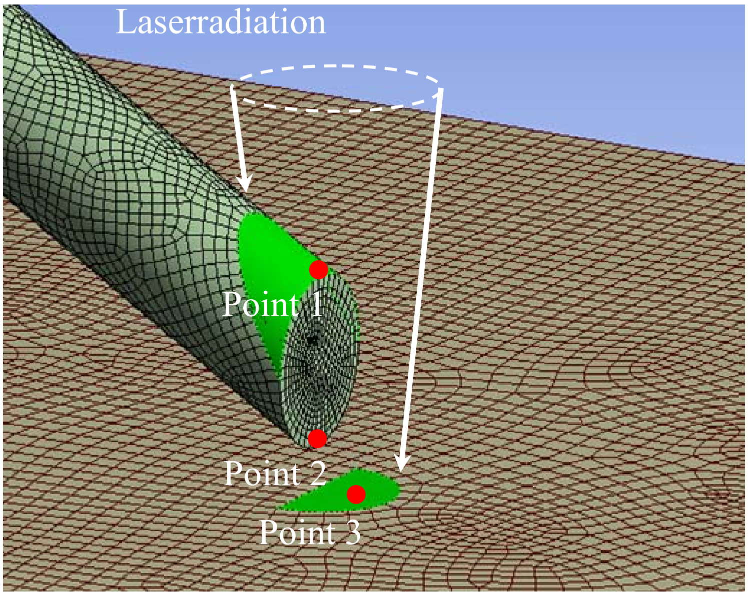


Fig. 1. Finite-element partitioning and a schematic representation of laser radiation exposure on the substrate and additive

The distribution of the laser pulse power density over time was established as follows [5, 6]:

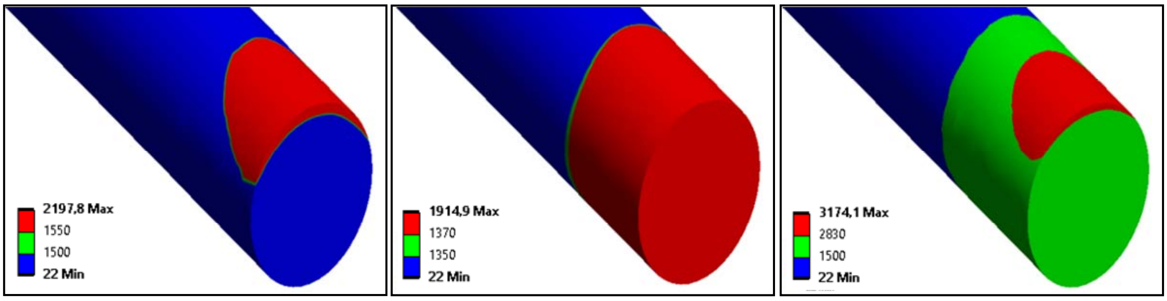
$$p(t)=\begin{cases} \dfrac{2T_m\lambda}{t_1\sqrt{\alpha\pi}}\sqrt{t}, & 0<t\le t_1, \\ \dfrac{2T_m\lambda}{t_1\sqrt{\alpha\pi}}\left(\sqrt{t}-\sqrt{t-t_1}\right), & t_1<t\le t_2, \\ \dfrac{2T_m\lambda}{(t_3-t_2)\sqrt{\alpha\pi}}\sqrt{t-t_2}+q(t_2), & t_2<t\le t_3, \end{cases}$$

where λ is the specific thermal conductivity of the additive material; α is the thermal diffusivity of the additive material; T_m is the melting point of the additive material; t_1 is the end time of the first impulse front; t_2 is the end time of the second impulse front; t_3 is the end time of the third impulse front.

The pulse has a rapidly increasing first front that causes the surface of the filler material to melt in the area exposed to the laser, followed by a decreasing second front that causes the entire volume of the filler material to melt. When the third ascending front is applied, the molten metal of the filler material undergoes detachment [5, 6]. Thus, the additive metal in the area exposed to laser radiation is thus heated and melted during the first two-time intervals t_1 and t_2, which correspond to the end of the first and second fronts of the laser pulse, respectively. At time t_3, which corresponds to the end of the third front, a droplet of molten metal falls onto the substrate.

Figure 2 displays the distributions temperature fields in the filler wire with a diameter $D = 0.2$ mm at the time moments corresponding to the end of the three fronts of the laser pulse.

Thus, at the time $t_1 = 0.5$ ms, the additive is melted at the introduction of 0.01 mm (Fig. 2, *a*), at $t_2 = 4.0$ ms, the volume of metal additive in the area of laser radiation is completely melted (Fig. 2, *b*), at $t_3 = 4.5$ ms, the surface of the melt is heated to the evaporation temperature (Fig. 2, *c*).



a) *b*) *c*)

Fig. 2. Distribution of temperature fields in the additive with a diameter of $d = 0.2$ mm: $a - t_1 = 0.5$ ms; $b - t_2 = 4.0$ ms; $c - t_3 = 4.5$ ms

It is worth mentioning that in the computational case presented, the laser cladding modes were determined by selecting the durations of the fronts t_1, t_2, and t_3 of the laser pulse for a given additive diameter value. This process is time-consuming and demands significant computational resources.

At present, metamodeling is extensively employed; its implementation enables the construction of computational experiment-generated models of complex systems. Models created using this method are referred to be surrogate models or metamodels. Surrogate models are far more computationally efficient than original finite element models. An objective of surrogate modelling is to approximate the values of output parameters based on input parameters, thereby avoiding the need for full calculations. Surrogate modelling is also used to optimize the parameters of technological processes, including the implementation of genetic algorithms, using the models generated [20, 21].

The DesignXplorer module was employed to implement multicriteria optimization of pulsed laser cladding parameters for 30ХГСН2А steel with the use of filler materials in the form of wire, in accordance with the procedure outlined in [18].

A four-factor face-centered version of the central composite design experiment was used in the metamodeling. Experiment factors included the diameter *D* of the filler wire and the time intervals t_1, t_2, and t_3, which corresponded to the durations of three laser pulse fronts. The maximum temperatures in the treatment zone were considered as responses: T1 denoted the temperature on the filler wire surface in the area of laser radiation at the moment of time corresponding to the completion of the first front of the laser pulse; T2 indicated the temperature on the bottom surface of the filler wire at the moment of time corresponding to the completion of the second front of the laser pulse; T3 referred to the temperature on the substrate surface in the area of laser exposure at the moment of time corresponding to the completion of the third front of the laser pulse (Table 1).

Table 1

Experimental design and calculation results

P1 t_1, ms	P2 t_2, ms	P3 t_3, ms	P4 D, mm	P5 T1, °C	P6 T2, °C	P7 T3, °C
0.5	9.5	0.5	0.3	2026	1503	2384
0.4	9.5	0.5	0.3	2076	1508	2384
0.6	9.5	0.5	0.3	2003	1500	2384
0.5	3	0.5	0.3	2026	748	2541
0.5	16	0.5	0.3	2026	1678	2265
0.5	9.5	0.4	0.3	2026	1503	2465
0.5	9.5	0.6	0.3	2026	1503	2307
0.5	9.5	0.5	0.2	2003	1737	2384
0.5	9.5	0.5	0.4	2003	1737	2672
0.4	3	0.4	0.2	2062	1316	2642
0.6	3	0.4	0.2	1966	1311	2641
0.4	16	0.4	0.2	2062	1839	2333
0.6	16	0.4	0.2	1966	1833	2332
0.4	3	0.6	0.2	2062	1316	2465
0.6	3	0.6	0.2	1966	1311	2464
0.4	16	0.6	0.2	2062	1839	2202
0.6	16	0.6	0.2	1966	1833	2202
0.4	3	0.4	0.4	2062	1316	2816
0.6	3	0.4	0.4	1966	1311	2807
0.4	16	0.4	0.4	2062	1839	2495
0.6	16	0.4	0.4	1966	1833	2494
0.4	3	0.6	0.4	2062	1316	2674
0.6	3	0.6	0.4	1966	1311	2668
0.4	16	0.6	0.4	2062	1839	2385
0.6	16	0.6	0.4	1966	1833	2385

Figures 3 demonstrate the dependencies of input parameters on output parameters.

A response surface linking the output parameters (T1, T2, T3) to the factors (t_1, t_2, t_3, D) was created using the nonparametric regression method [22].

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

determination coefficient

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

Root Mean Square Error (RMSE):

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

where d_i is the values determined via the finite element method, y_i is the values determined using regression models.

The values of the determination coefficients for the output parameters T1, T2, T3 possess values equal to 0.9993, 0.9984, 0.9987, respectively. The RMSE values for the temperatures T1, T2, T3 are 1.1 °C, 10.8 °C, 6.0 °C, respectively.

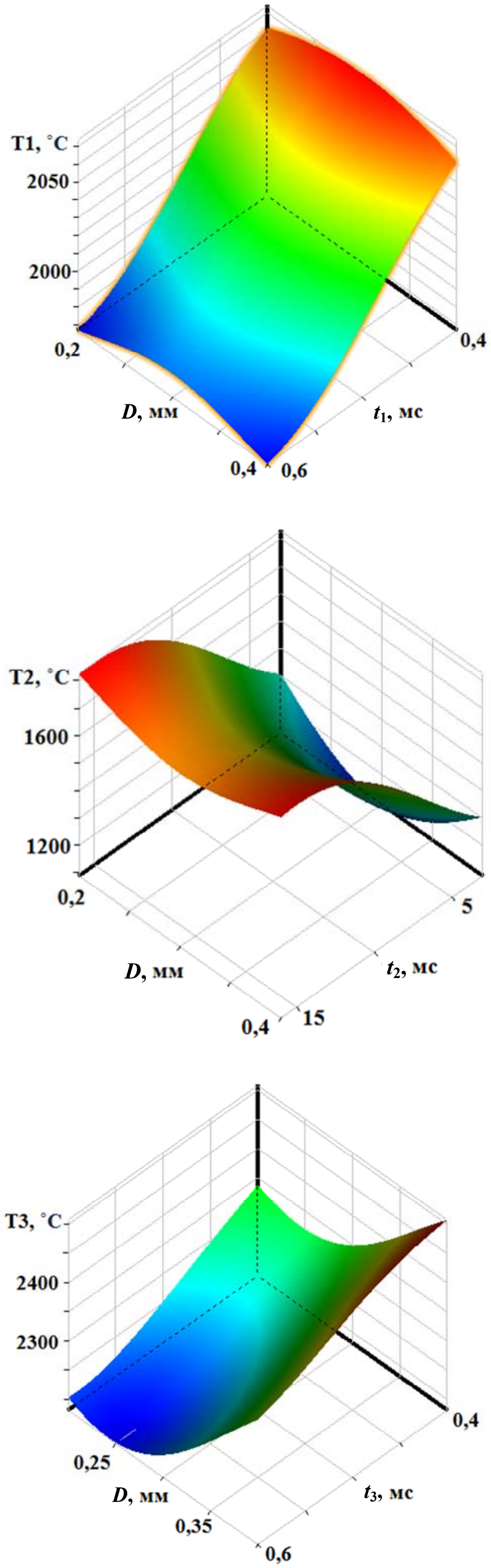


Fig. 3. Dependence of input parameters on output parameters

This may indicate the presence of the required agreement between the surrogate model and the finite element analysis data.

The optimization process was performed using MOGA of the DesignXplorer module. The number of individuals of the initial population was equal to 500 and the number of individuals per iteration was equal to 500.

The laser cladding process of 30ХГСН2А steel was optimized in accordance with the given problem formulation:

– to minimize metal evaporation during the cladding process, it is crucial that the temperature of the additive surface (Fig. 1, point 1) at the end of the first laser pulse front be above the melting temperature and below the evaporation temperature of the additive metal;

– to ensure the transfer of the molten metal of the additive to the substrate, it is necessary that that its entire volume be melted within the zone of laser radiation exposure at he moment of the end of the second pulse front. This means that the temperature of the bottom surface of the additive (Fig. 1, point 2) must not fall below the melting point of the additive metal;

– to form a reliable cladding joint, the temperature of the substrate surface (Fig. 1, point 3) at the end of the third pulse front must exceed the melting point of the substrate metal, but remain below the vaporization temperature.

Using the genetic algorithm, the three optimal variants of laser pulse front duration for the additive with a diameter of $D = 0.25$ mm were identified (refer to Table 2). The values of parameters derived through finite-element calculations are enclosed in brackets. When determining temperatures, the maximum percentage error of the results determined via MOGA did not exceed 3.5 %.

Table 2

Optimization results

P1 t_1, **ms**	**P2** t_2, **ms**	**P3** t_3, **ms**	**P4** *D*, **mm**	**P5** **T1, °C**	**P6** **T2, °C**	**P7** **T3, °C**
0.54	15.44	0.56	0.25	1997 (2026)	1756 (1753)	2173 (2205)
0.58	14.98	0.55	0.25	1986 (1993)	1759 (1743)	2187 (2210)
0.42	14.22	0.55	0.25	2066 (2076)	1763 (1734)	2199 (2229)

Conclusion

This work provides the finite element modeling of pulsed cladding of 30ХГСН2А steel with filler material in the form of wire. A surrogate model of the process under study was created using a four-factor face-centered version of the central composite design of numerical experiment and the nonparametric regression approach. By employing MOGA, this research established the feasibility of multicriteria optimization of parameters for pulsed laser cladding of steel with a maximum percentage error no more than 3.5 % in determining the temperatures within the laser treatment zone. The parameters of the laser pulse were found through multicriteria optimization to effectively carry out the process of laser cladding of steel 30ХГСН2А.

References

1. Grigoryants A. G., Shiganov I. N., Misyurov A. I. *Technological processes of laser processing.* Moscow, MGTU Bauman Publ., 2006. 664 p. (in Russian).

2. Devoyno O. G., Kardapolova M. A., Kalinichenko A. S., Zharsky V. V., Vasilenko A. G. *Technology of formation of wear-resistant coatings on the iron base by laser processing methods.* Minsk, Belorusskii natsional'nyi tekhnicheskii universitet, 2020. 280 p. (in Russian).
3. Maksimenka A. V. *Technology of restoration of details surfaces of aviation technics pulsing laser weld deposit. Abstract of Ph. D. thesis.* Minsk, 2011. 27 p. (in Russian).
4. Maximenko A. V., Myshkovets V. N., Bayevich G. A. Influence of laser pulse duration on the properties of welded high-strength steels. *Vestnik Gomel'skogo gosudarstvennogo tekhnicheskogo universiteta imeni P. O. Sukhogo*, 2013, no. 2, pp. 61–66 (in Russian).
5. Bayevich G. A., Maximenko A. V., Myshkovets V. N. Dynamics of thermal cycles formation during pulsed laser welding and cladding of high-strength structural steels. *Vestnik Gomel'skogo gosudarstvennogo tekhnicheskogo universiteta imeni P. O. Sukhogo*, 2016, no. 1, pp. 38–44 (in Russian).
6. Bayevich G. A., Maximenko A. V., Myshkovets V. N. Perculiar features of chromium additive melting depending on the shape of laser radiation pulse in welding and cladding processes. *Avtomaticheskaya svarka = Automatic Welding*, 2015, no. 2 (740), pp. 28–31 (in Russian).
7. Bessmeltsev V. P., Bulushev E. D. Optimization of Laser Micromachining Regimes. *Avtometriya*, 2014, no. 6, pp. 3–21 (in Russian).
8. Parandoush P., Hossain A. A review of modeling and simulation of laser beam machining. *International Journal of Machine Tools and Manufacture*, 2014, no. 85, pp. 135–145.
9. Nikitjuk Yu. V., Serdyukov A. N., Aushev I. Y. Optimization of two-beam laser cleavage of silicate glass. *Journal of Optical Technology*, 2022, no. 89, pp. 121–125.
10. Nikitjuk Yu., Sereda A., Serdyukov A., Shalupaev S., Aushev I. Parametric optimization of silicate-glass-based asymmetric two-beam laser splitting. *Journal of Optical Technology*, 2023, vol. 90, iss. 6, pp. 296–301. https://doi.org/10.1364/JOT.90.000296
11. Nikitjuk Yu. V., Serdyukov A. N., Ma J., Wang L., Aushev I. Y. Optimisation of parameters for laser cleaving of silicate glasses using U-shaped beams. *Vestnik Gomel'skogo gosudarstvennogo tekhnicheskogo universiteta imeni P. O. Sukhogo*, 2023, no. 4, pp. 30–39.
12. Nikitjuk Yu. V., Prokhorenko V. A., Kulyba A. I. Multi-criteria optimization of quartz glass laser cutting parameters using neural network simulation and genetic algorithm. *Problemy fiziki, matematiki i tekhniki*, 2023, no. 3, pp. 26–31 (in Russian).
13. Nikitjuk Yu., Prokhorenko V., Semchenko A., Kovalenko D. Multi-criteria optimization of quartz glass laser cleaving parameters via neural network simulation and genetic algorithm. *2023 7th International Conference on Information, Control, and Communication Technologies (ICCT)*, Astrakhan, Russian Federation, 2023, pp. 1–3. https://doi.org/10.1109/ICCT58878.2023.10347113
14. Nikitjuk Yu., Prokhorenko V., Semchenko A., Kovalenko D. Optimization of quartz sol-gel glass cutting parameters by elliptical laser beams using neural network simulation and genetic algorithm. *Recent Advances in Technology Research and Education. Inter-Academia 2023. Lecture Notes in Networks and Systems*, vol. 939. Springer, Cham. https://doi.org/10.1007/978-3-031-54450-7_34
15. Nikitjuk Yu., Bayevich G., Myshkovets V., Maximenko A., Aushev I. Characterization of lasercladding of steel 30ХГСН2А by combining artificial neural networks and finite element method. *Research and education: traditions and innovations. Inter-Academia 2021.*

Lecture notes in networks and systems, vol. 422. Springer, Singapore. https://doi.org/10.1007/978-981-19-0379-3_28

16. Nikitjuk Yu. V., Bayevich G. A, Maximenko A. V., Myshkovets V. N., Aushev I. Yu. Application of finite element method and artificial neural networks for determining parameters of laser treatment of 12X18H9T steel. *Vestnik Gomel'skogo gosudarstvennogo tekhnicheskogo universiteta imeni P. O. Sukhogo*, 2022, no. 1, pp. 48–55 (in Russian).
17. Nikitjuk Yu. V., Bayevich G. A., Myshkovets V. N., Maximenko A. V., Aushev I. Yu. Optimization of parameters of 12X18H9T steel processing using circular laser beams. *Vestnik Gomel'skogo gosudarstvennogo tekhnicheskogo universiteta imeni P. O. Sukhogo*, 2022, no. 2, pp. 17–24 (in Russian).
18. Bayevich G. A., Nikitjuk Yu. V., Myshkovets V. N., Maximenko A. V., Aushev I. Yu. Optimization of 12X18H9T-steel processing by ring laser beams. *Nauka i tekhnika = Science & Technique*, 2023, no. 22 (3), pp. 186–192. https://doi.org/10.21122/2227-1031-2023-22-3-186-192 (in Russian).
19. Zinoviev V. E. *Thermo physical properties of metals at high temperatures: handbook.* Moscow, Metalurgia Publ., 1989. 384 p. (in Russian).
20. Koziel S., Leifsson L. *Surrogate-based modeling and optimization.* New York, Springer Publ., 2013. 412 p.
21. Jiang P., Zhou Q., Shao X. *Surrogate model-based engineering design and optimization.* Berlin, Heidelberg, Springer Publ., 2020. 240 p.
22. Santner T. J., Williams B. J., Notz W. I. *The design and analysis of computer experiments*. New York, Springer New York Publ., 2003. 285 p. https://doi.org/10.1007/978-1-4757-3799-8

Поступила 05.03.2024 г.