

УДК 621.9.048.7:621.791.92
DOI 10.62595/1819-5245-2026-3-29-36

PREDICTION OF THE QUALITY OF COATINGS FORMED BY PULSED LASER RADIATION ON 30XГCH2A STEEL USING METAMODELING

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The high degree of nonlinearity of the thermophysical processes of pulsed laser cladding requires the use of modern predictive analytics methods to control surface layer quality. In this study, metamodels were developed for the process of forming nichrome coatings on 30XГCH2A steel using nonparametric regression techniques. The data source consisted of results from physical experiments conducted according to a D-optimal design on a laser system featuring a controllable pump-current pulse shape. Laser pulse energy, duration, and frequency served as the input variables. Layer thickness, surface microhardness, and defect criteria (presence of pores and cracks) were evaluated as response functions. An assessment of quality metrics (RMSE, R^2) demonstrated the high adequacy of the resulting surrogate models. It was found that the geometry of the deposited bead and the susceptibility to cracking depend primarily on pulse energy, whereas minimizing porosity requires adjusting both pulse energy and pulse repetition frequency. The proposed approach enhances the efficiency of selecting processing parameters for laser coating formation on 30XГCH 2A steel while minimizing the need for physical experiments.

Keywords: laser processing, 30XГCH2A steel, metamodeling, coating defects, experiment planning.

For citation. Nikityuk Yu. V., Baevich G. A., Maksimenko A. V., Serdyukov A. N. Prediction of the quality of coatings formed by pulsed laser radiation on 30XГCH2A steel using metamodeling. *Vestnik Gomel'skogo gosudarstvennogo tekhnicheskogo universiteta imeni P. O. Sukhogo*, 2026, no. 3 (106), pp. 29–36 (in Russian). <https://doi.org/10.62595/1819-5245-2026-3-29-36>

ПРОГНОЗИРОВАНИЕ КАЧЕСТВА ПОКРЫТИЙ, ФОРМИРУЕМЫХ ИМПУЛЬСНЫМ ЛАЗЕРНЫМ ИЗЛУЧЕНИЕМ НА СТАЛИ 30XГCH2A С ИСПОЛЬЗОВАНИЕМ МЕТАМОДЕЛИРОВАНИЯ

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Высокая нелинейность теплофизических процессов при импульсной лазерной наплавке требует применения современных методов предиктивной аналитики для управления качеством поверхностного слоя. В данной работе разработаны метамоделли процесса лазерного формирования нихромовых покрытий на стали 30XГCH2A с использованием методов непараметрической регрессии. В качестве источника данных использованы результаты натурных экспериментов, проведенных по d-оптимальному плану на лазерной установке с контролируемой формой импульса тока накачки. Входными переменными выступали энергия, длительность и частота лазерных импульсов. В качестве функций отклика оценивались толщина слоя, микротвердость поверхности, а также критерии дефектности (наличие пор и трещин). Оценка метрик качества (RMSE, R^2) показала хорошую адекватность полученных surrogate-моделей. Показано, что геометрия наплавленного валика и склонность к трещинообразова-

нию в наибольшей степени зависят от энергии импульса, тогда как минимизация пористости требует регулировки энергии и частоты следования импульсов. Предложенный в работе подход позволяет повысить эффективность выбора технологических режимов при формировании лазерных покрытий на стали 30ХГСН2А при минимизации натурных экспериментов.

Ключевые слова: лазерная обработка, сталь 30ХГСН2А, метамоделирование, дефектность покрытий, планирование эксперимента.

Для цитирования. Прогнозирование качества покрытий, формируемых импульсным лазерным излучением на стали 30ХГСН2А с использованием метамоделирования / Ю. В. Никитюк, Г. А. Баевич, А. В. Максименко, А. Н. Сердюков // Вестник Гомельского государственного технического университета имени П. О. Сухого. – 2026. – № 3 (106). – С. 29–36. <https://doi.org/10.62595/1819-5245-2026-3-29-36>

Introduction

High-strength structural steels are extensively employed for manufacturing mechanical engineering components. In service, these components are often exposed to aggressive media and corrosive attack, requiring effective surface protection against such detrimental factors. Pulsed laser cladding is one of the most efficient techniques for depositing protective coatings. Compared with traditional methods, laser cladding offers minimal thermal distortion of the substrate, excellent coating adhesion, and the flexibility to adjust the physical and mechanical properties of the deposited layers [1–3].

Contemporary manufacturing industry faces an urgent need to replace conventional process development approaches with predictive analytics and digital simulation. The deposition of coatings onto high-strength steels is accompanied by repeated heating and cooling cycles, resulting in steep thermal gradients and the development of residual stresses. Controlling the quality of such coatings, i. e., minimizing cracks and porosity while achieving the target thickness and microhardness, is governed by the laser parameters, namely pulse energy, pulse duration, and pulse repetition rate. Given the intricate nature of hydrodynamic and thermophysical phenomena occurring within the melt pool, metamodeling emerges as the most effective tool for predicting coating characteristics [4–12].

Accordingly, this study aims to develop metamodels for predicting the geometric parameters, microhardness, and defect-related criteria of nichrome coatings deposited onto 30ХГСН2А steel by pulsed laser radiation.

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Materials and methods

Experimental investigations of coating deposition were performed using a TL-400 laser processing system. The system features a solid-state Nd : YAG laser (wavelength $\lambda = 1,064 \mu\text{m}$) based on an yttrium aluminum garnet crystal doped with trivalent neodymium ions. Laser radiation is generated in crystals of $6.3 \times 130 \text{ mm}$ in size, arranged in a master oscillator-power amplifier (MOPA) configuration. The system delivers a maximum average power of 400 W, with a beam diameter of 8 mm at the resonator output.

The system comprises a power supply and control unit, a laser head, an optical focusing system, a visual monitoring system, a water-cooling circuit, and a PC-controlled three-axis positioning system with a microstepping drive (Fig. 1).

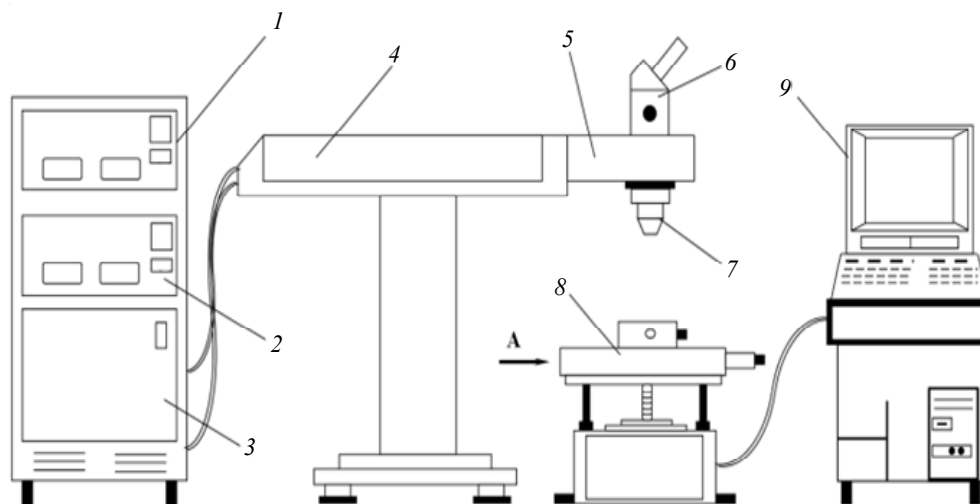


Fig. 1. Schematic layout of the laser processing system:
1, 2 – power supply units; 3 – cooling system; 4 – laser head; 5 – optical focusing attachment; 6 – visual monitoring system; 7 – focusing lens; 8 – three-axis positioning system; 9 – microstepping drive control system

A key feature of the laser system is a programmable controller that enables real-time control of the pump lamp current pulse amplitude. The electrical pulse shape is generated in discrete form as a 50-coefficient array (each coefficient ranging from 0 to 255 arbitrary units), making it possible to produce complex laser pulse profiles. The pulse duration is adjustable within the range of 0.25–20 ms, and the maximum pulse repetition rate is 100 Hz.

High-strength structural steel 30XГЧ2A was employed as the substrate. Nichrome X20H80 served as the coating material.

Metallographic specimens were prepared from the cross-sections of the clad beads for microstructural analysis. The prepared surfaces were successively ground and polished with abrasives of decreasing grit size: 60-40, 10-17, 7-5, 1, and 0.1 μm , until a final surface roughness of $R_a \leq 0.2 \mu\text{m}$ was achieved. To reveal the microstructure of the substrate material, the heat-affected zone (HAZ), and the clad layer, the specimens were chemically etched using a 3–5 % solution of nitric acid in ethanol (nital).

Surface morphology, as well as the macro- and microgeometry of the coatings, were examined using an EPIQANT automatic structure analyzer (Carl Zeiss, Jena) at $\times 100$ magnification. Linear measurements (namely, the thickness of the deposited layer and the extent of the HAZ) were performed on digital images using a stage micrometer with a scale division of 0.01 mm. Coating defectiveness was evaluated by counting the number of pores and microcracks in the cross-sections of the clad beads.

Microhardness measurements of the various structural zones were carried out using the Vickers method on a Kason-59-HV microhardness tester. The applied load was 0.4905 N, with a dwell time of 10 s. The indentation diagonal was measured at $\times 400$ magnification.

To establish the relationships between the laser parameters and the properties of the resultant coatings, a D-optimal experimental design was employed. The input factors varied in the experiments were pulse duration (t , ms), pulse energy (E , J), and pulse repetition rate (f , Hz). This design is particularly effective for investigating complex nonlinear thermo-physical phenomena in laser processing, as it offers the flexibility to specify the required number of experimental runs and provides an accurate description of the multivariate response space [13].

The response functions evaluated in this study included coating thickness (h , μm), surface microhardness (HV , kgf/mm^2), crack count (N_c), and pore count (N_p). The experimental data were approximated, and surrogate models were constructed using nonparametric regression [14].

Results and discussion

The first stage involved assessing the feasibility of producing defect-free coatings via pulsed laser irradiation. Figure 2 presents a cross-sectional view of the laser-affected zone on a 30XГCH2A steel sample with a nichrome coating.

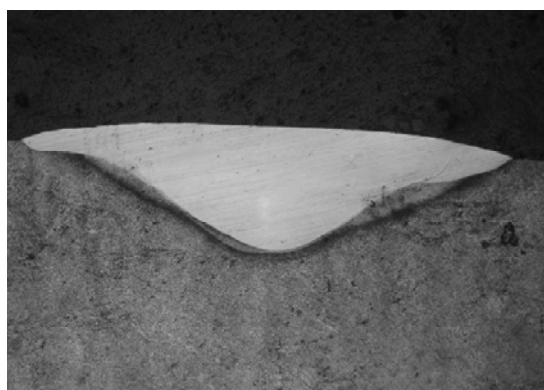


Fig. 2. Cross-sectional overview of the laser-affected zone in the specimen

Metallographic examination of the specimens showed that, under the selected baseline laser processing conditions, a characteristic lens-shaped melt pool is formed. Visual inspection confirmed the absence of defects such as lack of fusion, delamination, and large pores at the coating-substrate interface, indicating that a sound metallurgical bond was achieved between the deposited layer and the substrate. Microhardness profiling revealed a complex variation in mechanical properties across the structural zones. Immediately beneath the coating, a dark rim, i. e., the heat-affected zone, is visible, measuring approximately 0.2 mm in thickness. A notable feature of the system under study is significant hardening of the HAZ metal. This phenomenon is explained by the inherent characteristics of laser processing: ultra-high cooling rates, due to rapid heat dissipation into the cold substrate bulk, induce a self-quenching effect in the steel, promoting the formation of martensitic microstructures. Meanwhile, the hardness of the coating itself is about 200 kgf/mm^2 , which ensures adequate ductility of the clad layer while preserving its high corrosion resistance.

Table 1 presents the design matrix of the D-optimal experiment and the corresponding response values.

Table 1

Experimental design and measured responses

N	P1 t , ms	P2 E , J	P3 f , Hz	P4 h , μm	P5 HV , kgf/mm^2	P6 N_c	P7 N_p
1	4	6.4	2	40	224	1	0
2	4	12.9	2	200	191	0	3
3	4	12.9	3	220	209	4	0
4	4	6.4	5	50	201	0	4

<i>N</i>	P1 <i>t</i> , ms	P2 <i>E</i> , J	P3 <i>f</i> , Hz	P4 <i>h</i> , μm	P5 <i>HV</i> , kgf/mm ²	P6 <i>Nc</i>	P7 <i>Np</i>
5	4	12.9	5	250	186	3	0
6	6	4.6	2	30	213	0	0
7	6	12.6	2	220	205	0	1
8	6	9.1	4	130	214	0	0
9	6	4.6	5	40	192	0	0
10	6	12.6	5	260	208	2	3
11	8	9.8	2	30	193	0	0
12	8	12.8	2	120	217	2	3
13	8	12.8	4	130	194	2	3
14	8	9.8	5	40	189	0	0
15	8	12.8	5	140	228	0	1

Experimental data processing and surrogate model development (response surface construction) were carried out using the Design Explorer module of the Ansys Workbench software. The data were fitted using a nonparametric regression algorithm.

The quality of the resultant models was evaluated through the following metrics:

– Root Mean Square Error (RMSE):

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

and the coefficient of determination:

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

where d_i – denotes the experimentally measured values; y_i – denotes the corresponding metamodel predictions.

Table 2 summarizes the results of the model evaluation.

Table 2

Metamodel evaluation results

Criterion	P4	P5	P6	P7
RMSE	0.15	0.41	0.04	0.04
R^2	0.9988	0.9989	0.9990	0.9992

Figure 3 illustrates a Predicted vs Observed plot of the normalized values, generated to visualize the quality of the developed metamodels.

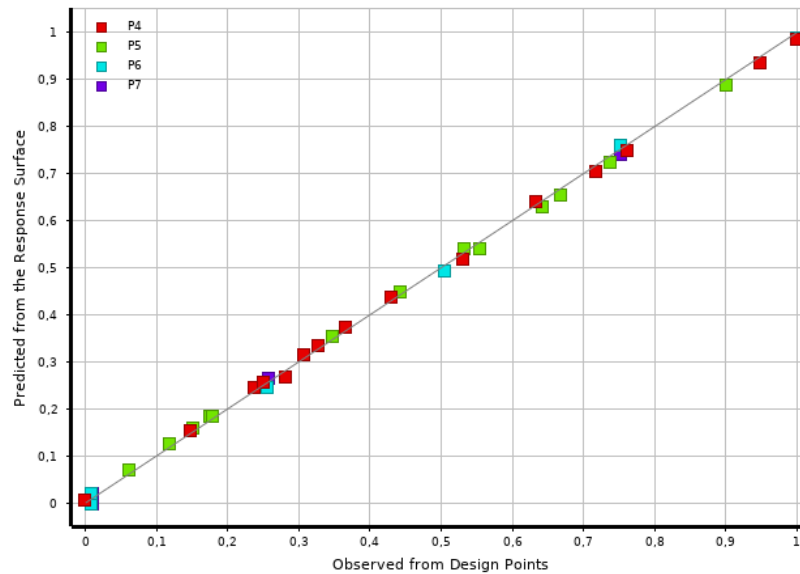


Fig. 3. Predicted vs observed values for the response parameters

Figure 3 clearly illustrates that the data points for all four response parameters (coating thickness, microhardness, and the numbers of pores and cracks) closely cluster around the diagonal line of ideal correlation. The absence of significant deviations and the high values of the coefficient of determination indicate good predictive capability of the constructed metamodels. The models adequately capture the complex nonlinear behavior of the laser cladding process and are suitable for integration into practical engineering workflows.

To gain insight into the physical phenomena governing laser coating deposition and to quantify the individual influence of each process parameter on coating quality, a local sensitivity analysis was performed using the Ansys Design Explorer environment.

Local sensitivity quantifies the rate at which the surrogate response function Y changes in response to small variations in a single independent input parameter X_i , while all other parameters are held constant at a specified level. To facilitate comparison between parameters of different physical nature and units, the absolute values of the partial derivatives are normalized. The normalized local sensitivity S_i for the i -th factor is computed as:

$$S_i = \frac{\partial Y}{\partial X_i} \frac{\Delta X_{i\max}}{\Delta Y_{\max}} 100 \%,$$

where $\frac{\partial Y}{\partial X_i}$ is the partial derivative of the response function evaluated at a given operating point, $\Delta X_{i\max}$ is the full variation range of the i -th input factor in the design matrix; $\Delta Y_{\max}$ is the maximum spread of the response function values.

The resultant value, expressed as a percentage, represents the relative contribution of each input parameter to the overall response. The sign of S_i indicates the direction of the effect: positive values correspond to a direct correlation, meaning that an increase in the input parameter yields a higher response; conversely, a negative sign denotes an inverse correlation, whereby the response decreases as the parameter increases.

The computed sensitivity bar chart is presented in Fig. 4.

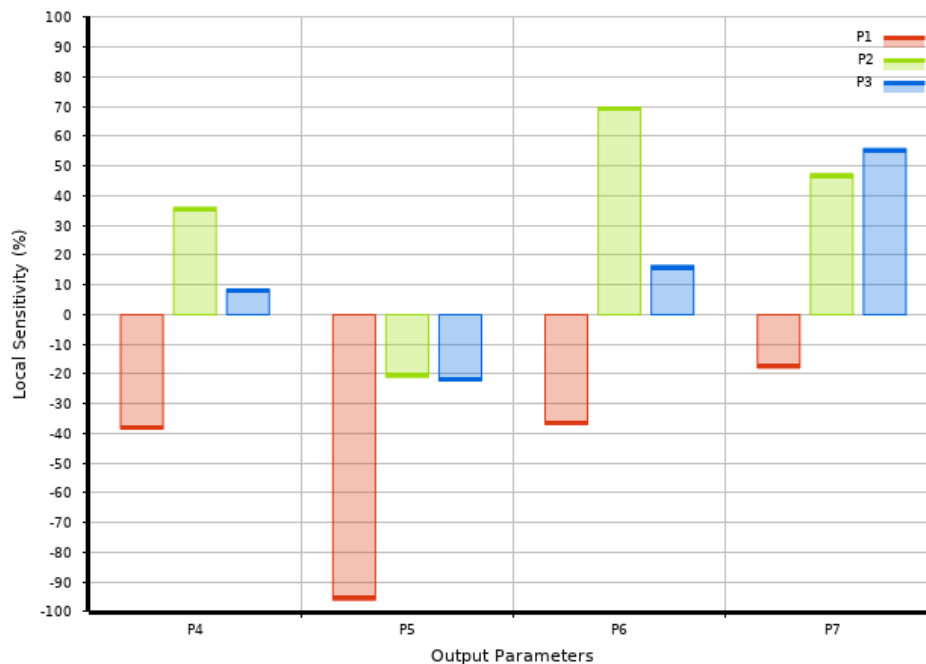


Fig. 4. Bar chart showing local sensitivity of the response functions to the laser input parameters

The analysis of the sensitivity chart revealed several important trends.

Increasing pulse energy naturally leads to greater coating thickness, owing to the larger volume of melted material. However, longer pulse duration exerts a comparable negative influence, attributable to diminished peak power density and, thus, a shallower penetration depth when the pulse is prolonged.

Pulse duration was found to be the dominant factor affecting coating microhardness. This behavior is explained by the fact that longer irradiation durations reduce both the thermal gradient and the cooling rate of the melt pool. The lower heat extraction rate hinders the full development of martensitic transformations during quenching from the liquid state, leading to a decrease in microhardness of the heat-affected zone.

Microcrack generation is largely governed by the input energy level: high energy induces substantial thermal stresses at the coating-substrate interface. Conversely, increasing the pulse duration has a favorable effect by promoting localized tempering and relieving residual stresses. Porosity, on the other hand, arises from the combined influence of pulse repetition rate and pulse energy.

Conclusion

This study presents the development and validation of metamodels for the pulsed laser cladding of protective nichrome coatings onto 30X1CH2A steel. The models enable the prediction of coating thickness, microhardness, and defect formation.

Crack generation in the clad layers was found to be critically dependent on pulse energy, which governs the heat input: excessive energy increases the thermal gradient and cooling rates, thereby promoting the development of residual thermal stresses.

The constructed metamodels offer a reliable tool for producing defect-free protective coatings while significantly minimizing the need for full-scale experiments.

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Поступила 20.07.2026 г.