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Optimization of finishing turning parameters for a metal–composite system with a 2-mm-thick metal external layer based on criteria of thermal load and cutting tool wear

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ABSTRACT

Introduction. The study addresses the challenge of selecting finishing turning parameters for a metal-composite system comprising a thin metal external layer (2 mm thick) produced by selective laser melting and containing an internal metal-polymer filler. The relevance of the work is driven by the need to ensure the machining quality of the outer surface while adhering to strict temperature constraints at the metal-polymer interface, imposed by the low thermal resistance of the filler material. ***Purpose of the work*** is to develop and implement a multi-criteria optimization approach for the finishing turning parameters of the metal-composite system. This approach is based on previously developed regression models for the interface temperature and cutting tool wear, and aims to minimize tool wear while satisfying temperature constraints and surface quality requirements. **Methodology.** The methodology is based on a previously developed *2T3*-type regression model for predicting temperature at the metal-metal-polymer interface and a cutting tool wear model formulated as a generalized *Fick-Taylor* equation for a cemented carbide insert (grade *AH6225*). Using these models, a mathematical programming problem with a nonlinear temperature constraint is formulated and solved via the sequential quadratic programming (*SQP*) method within specified ranges of cutting speed, feed rate, and depth of cut. **Results and discussion.** The numerical implementation of the proposed approach yielded the domains of admissible and optimal finishing turning parameters for the metal-composite system, based on criteria of thermal load and tool wear. The depth of cut was identified as the dominant factor influencing the temperature at the metal-metal-polymer interface. It was shown that the temperature constraint defines the boundaries of the admissible parameter domain. Specific combinations of cutting speed, feed rate, and depth of cut were determined that simultaneously satisfy the polymer's temperature limit and ensure an acceptable wear level for the *AH6225* carbide inserts.

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Introduction

Additive manufacturing (*AM*), and in particular selective laser melting (*SLM*), is being increasingly adopted for producing critical complex-shaped components and thin-walled shells for mechanical engineering and tooling applications. However, most metallic materials manufactured by laser powder bed fusion (*LPBF*) [1] exhibit high as-built surface roughness and pronounced property anisotropy, which necessitates finishing machining to achieve the required dimensional accuracy and surface quality [2]. It has been shown for *Ti-6Al-4V* that high-throughput finishing operations can significantly reduce surface roughness; nevertheless, the as-built condition remains unacceptable for many applications, and the effectiveness of post-processing strongly depends on build orientation and process parameters [2].

A distinct class of objects comprises thin-walled additively manufactured shells, including those with complex three-dimensional geometry. *Isaev* et al. investigated the microstructure and machinability of thin-walled titanium-alloy parts produced by *SLM*/*EBM* technologies [3]. It was shown that low structural stiffness (small stiffness radius) combined with residual stresses leads to significant deformations during milling and turning, while the choice of machining strategy and fixturing scheme critically affects geometric accuracy [4]. Studies by *Hintze* et al. on the finishing of thin-walled *SLM Ti-6Al-4V* components, taking into account support removal, demonstrated that an improper selection of milling strategy and support-removal sequence increases wall deflection and the risk of tolerance violations [5]. Research on precision turning of thin-walled *Ti-6Al-4V* parts manufactured by *SLM* has shown that, at wall thicknesses of about 1 mm, acceptable surface integrity can be achieved; however, careful control of cutting conditions and the clamping/fixturing scheme is required [6].

In addition to geometric accuracy and thin-wall deflection, the thermal loading condition in the cutting zone plays a key role in the post-processing of additively manufactured parts. The increased surface roughness, porosity, and microstructural heterogeneity typical of *SLM* components alter heat dissipation and contact stress levels, which generally degrades machinability compared to rolled or forged counterparts. In particular, when comparing the machining of additively manufactured and wrought *316L* steel, it was found that *SLM* parts require higher cutting forces [7], exhibit a different deformation pattern, and experience more intensive tool wear, especially under dry cutting conditions [8]. Similar conclusions have been reported for other additively manufactured alloys: high hardness combined with low thermal conductivity leads to elevated cutting-zone temperatures and accelerated wear of the cutting tool [9].

In most of the studies cited above, the research object is a monolithic additively manufactured workpiece. At the same time, to improve techno-economic performance, combined metal–composite structures are gaining increasing popularity [10]. In such designs, an *SLM* shell provides the strength and stiffness of the external surfaces, while the internal cavity is filled with another material — e.g., a polymer or a metal–polymer composite [11] — which serves to provide damping and to reduce mass and cost [12]. For these systems, the thermal regime at the metal–polymer interface becomes critical: exceeding the temperature limit of the polymer matrix leads to degradation of the adhesive bond, defect formation, and loss of service properties. However, the available literature contains virtually no studies devoted specifically to finishing machining of metal–polymer systems with a thin-walled metallic shell. Typically, the literature addresses either metal cutting processes or, separately, machining technologies for polymer and polymer-composite materials.

Cutting-zone temperature is traditionally regarded as one of the key parameters in turning, governing tool life, machined surface quality, and the development of residual stresses. For conventional tool–workpiece systems based on steels and titanium alloys, numerous mathematical models have been developed that relate temperature to cutting conditions (cutting speed, feed, depth of cut), material mechanical properties, and parameters of contact heat transfer. In [13], a temperature prediction model for turning biomedical stainless steel was proposed using artificial neural networks, with experimental temperature data obtained by infrared thermography. Analytical and semi-analytical models of the temperature field in turning hardened tool steels using multilayer coated tools make it possible to estimate not only the average cutting temperature but also the temperature at the coating–substrate interface, which is important for predicting tool life [14].

It has been shown that increasing cutting speed and feed generally leads to a substantial temperature rise, whereas the effect of depth of cut depends on the specific heat dissipation conditions and tool geometry.

For thin-walled parts with limited heat dissipation, the problem becomes even more acute. In a number of studies on additively manufactured thin-walled components, infrared cameras and embedded sensors were used to monitor temperature during milling and turning; it was shown that local overheating can reach levels at which the material hardness decreases significantly and tool wear accelerates [15]. However, even in these investigations, the focus is primarily on monolithic metallic parts rather than on systems with an internal polymer filler and strict temperature limits at the interface.

The field of cutting tool wear modeling is no less developed. The classical approach is based on the *Taylor* tool-life equation, which relates cutting speed to tool life; later modifications also introduced feed and depth of cut, allowing the actual influence of cutting conditions on wear to be captured more adequately [16]. On the basis of generalized *Taylor*-type equations, tool-life prediction models are constructed for various workpiece–tool material combinations and cooling conditions, including the use of modern optimization techniques and *Bayesian* parameter updating [17]. A review [18] shows that existing wear models can be divided into two main classes: "cutting conditions–tool life" models (based on the *Taylor* equation and its modifications) and models grounded in local wear mechanisms, involving the calculation of contact stresses and temperatures. Recently, hybrid approaches have been actively developed, combining classical tool-life equations with additional informative variables—for example, cutting power consumption [19] or ultrasonic vibration parameters in vibration-assisted cutting [20].

In many studies, temperature and tool-wear models are used to optimize cutting conditions. For example, in [16], an extended *Taylor*-type equation combined with design-of-experiments methods was employed to analyze the effects of cutting speed, feed, and depth of cut on tool life in turning, and recommended parameter ranges were obtained that maximize tool life. However, such studies are typically carried out for homogeneous metallic workpieces, and the constraints considered are usually limited to surface roughness, cutting forces, or energy-related indicators.

Thus, an analysis of the recent literature indicates that finishing machining of additively manufactured thin-walled metallic parts has been studied in considerable detail with respect to geometric accuracy, wall deflection, and general machinability issues [2–7]. A wide range of cutting temperature and tool wear models has also been developed for conventional and additively manufactured metallic materials, enabling turning-condition optimization with respect to individual criteria [13–20]. However, there is a near-complete lack of studies that jointly consider a thin-walled *SLM* shell and an internal metal–metal-polymer filler under a strict temperature constraint at the interface, while simultaneously incorporating both thermal loading of the system and tool wear into the optimization criteria.

A distinctive feature of the metal–composite system (*MCS*) considered in this study is the presence of a thin-walled metallic shell with a thickness of approximately 2 mm, fabricated by SLM from a heat-resistant steel analog, and an infill based on a metal–polymer composite material for which a maximum allowable temperature level is known (170 °C). When finish-turning the outer surface of such a shell, it is necessary, on the one hand, to achieve the required dimensional accuracy and surface roughness, and, on the other hand, to prevent overheating at the metal–metal-polymer interface, which can lead to degradation of the polymer matrix and loss of adhesion. At the same time, to ensure process cost-effectiveness, the wear of the cemented carbide insert must be accounted for, and cutting conditions must be limited with respect to tool life.

It should be noted that in earlier work the authors developed and validated a regression temperature model, referred to as "***2T3***", for the metal–metal-polymer interface based on a full factorial design $\mathbf{2^3 + n_0}$. The model describes the dependence of interfacial temperature on cutting speed, feed, and depth of cut within a specified range of cutting conditions [21]. In a separate study, the influence of individual parameters on the thermal loading of the system was analyzed, permissible parameter regions were determined with respect to the temperature criterion, and the adequacy of the model was confirmed using contact temperature measurements and infrared thermal imaging. Thus, for the development of a finishing process for a metal–composite system with a 2 mm shell, a ready-to-use regression temperature model suitable for optimization calculations is already available.

In this context, a scientific and practical task arises: to develop an approach for selecting finishing turning conditions for a metal–composite system with a 2 mm-thick *SLM* shell that simultaneously accounts for the following:

1) an experimentally derived regression model of the temperature at the metal–metal-polymer interface;

2) a cutting tool wear model dependent on the cutting conditions;

3) technological constraints related to the metal–metal-polymer interface temperature limit and the quality of the machined surface.

The purpose of this work is to develop and validate a multi-criteria optimization approach for selecting finishing turning conditions for a metal–composite system with a 2 mm-thick metallic shell, aimed at minimizing cutting tool wear while satisfying temperature constraints at the metal–metal-polymer interface and meeting the required surface quality.

To achieve this purpose, the ***following tasks*** are addressed:

1. Use the previously developed ***2T3*** regression model of interfacial temperature at the metal–metal-polymer interface to determine the permissible domain of finishing turning conditions for a metal–composite system with a 2 mm-thick shell with respect to the temperature criterion, taking into account the maximum allowable temperature of the metal–polymer infill.

2. Derive analytically a *Fick–Taylor*-type regression model of tool wear to evaluate the wear progression of an *AH6225* cemented carbide insert as a function of cutting speed, feed rate, and depth of cut within the considered parameter domain.

3. Formulate a multi-criteria optimization problem for finishing turning of the metal–composite system aimed at minimizing tool wear under constraints on interfacial temperature and requirements for machined surface roughness.

4. Implement the selected mathematical programming method (sequential quadratic programming) to solve the multi-criteria optimization problem using the regression temperature and wear models, and determine rational combinations of cutting speed, feed rate, and depth of cut within the specified ranges.

5. Analyze the resulting rational domains of cutting conditions, assess the effect of the temperature and wear constraints on the selection of finishing turning parameters, and formulate practical recommendations for standardizing cutting conditions when machining metal–composite systems with a 2 mm-thick metallic shell.

Methods

The experimental basis for developing the ***2T3*** mathematical model was obtained using an MCS emulator of the metallic shell–metal- polymer type with a shell thickness of **δ** = 2 mm (Fig. 1). The maximum temperature ***T*** at the metal–*MPCM* interface was measured in the steady-state cutting region. Turning was performed on a *16K20* universal lathe using a cutting fluid (coolant–lubricant) supply system. The working fluid was a mineral oil-based water emulsion of the *I-20A* type with 5% *ED-20* emulsifier. The emulsion was supplied continuously directly into the cutting zone at a pressure of 0.25 ± 0.05 MPa with an average flow rate of 2–3 L/min.

Based on the experimental data, a second-order regression model (the ***2T3*** model) was developed in coded variables. By substituting the coded values into the regression equation and performing algebraic transformations, the ***2T3*** model was ultimately expressed in terms of the actual physical variables as follows:

$$\mathrm{3.5TP} = 1484.16 \cdot S^2 + 7.604 \cdot S \cdot V - 388.75 \cdot S \cdot t - 915.59 \cdot S +$$
$$+0.0041 \cdot V^2 - 0.4646 \cdot V \cdot t - 1.376 \cdot V + 14.84 \cdot t^2 + 85.44 \cdot t + 182.57, \quad (1)$$

It should be noted that, when developing the model using the MCS emulator, *0.12C-18Cr-10Ni-Ti* stainless steel was used as a substitute material for *EP648* steel, since it is a close analog of *EP648* in terms of thermal properties: its thermal conductivity is 14–16 W/(m·K) , which is close to 12–15 W/(m·K) for *EP648*.

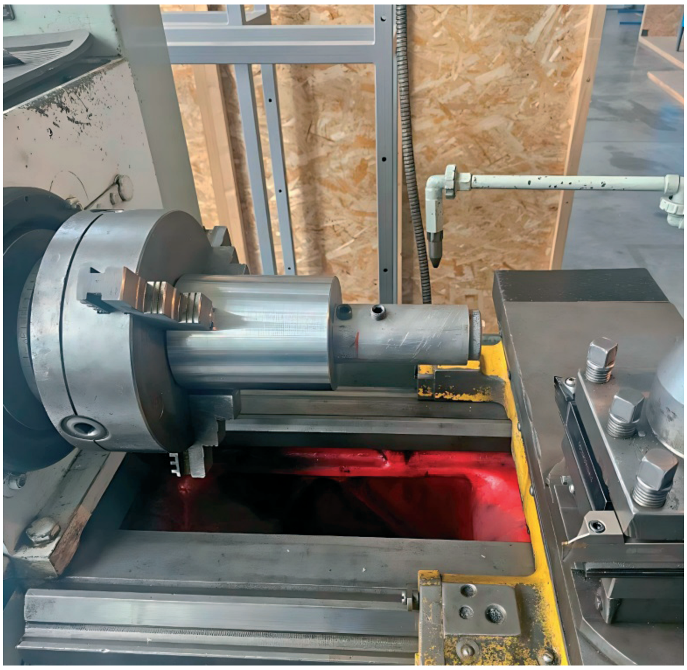

Fig. 1. Physical model of the *MCS* emulator for temperature measurement at the interface during turning, mounted in the chuck of a *16K20* lathe

In terms of heat generation during turning, the steels closest to *EP648* are *0.12C-18Cr-10Ni-Ti*, *0.08C-18Cr-10Ni-Ti*, and *0.1C-17Cr-13Ni-Mo-Cu-Ti*, as they have similar hardness and alloying levels and comparably low thermal conductivity.

The use of *0.12C-18Cr-10Ni-Ti* steel was also motivated by its close property match and its availability on the commercial market as a tube with dimensions Ø63.5 × 8 mm.

Table 1 presents a comparison of different cutting temperature models.

Based on this analysis, it can be concluded that *Kulikov* model is more suitable for rapid assessments in laboratory settings or educational work. For research studies involving detailed analysis of deformation and friction, the *Oxley* model is appropriate [22]. For modeling high-speed machining or *FEM*-based analyses, the *Komanduri* model is preferable [23].

For the purposes of the present study, given the availability of process input data and the recommendations of leading global cutting tool manufacturers, the *Oxley*/*Komanduri* (*ISO/TR 18521*) model was selected, which can be written as follows:

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Table 1

Comparison of cutting temperature models

Criterion	***Kulikov*** **model**	***Oxley*** **model**	***Komanduri*** **model**
Model basis	Empirical-analytical	Analytical (deformation + friction)	Analytical (heat transfer)
Accounts for friction	Yes	Yes	Yes
Accounts for deformation	Yes	Yes	Partially
Application	Basic estimates	General research	High-speed machining
Requires calibration	Yes	No, but requires input data	Requires *FEA* or numerical methods
Calculation speed	High	Moderate	Low

$$T_{cut} = 0.4 \cdot \frac{F_c \cdot V}{\rho \cdot c \cdot A}, °C, \quad (2)$$

where ***Fc*** is the cutting force ($F_c = k_c \cdot A$, where $A = S \cdot t$) (N); ***ρ*** is the material density (kg/m^3); ***c*** is the specific heat capacity (J/(kg·K)); ***V*** is the cutting speed (m/min).

Then:

$$T_{cut} \approx K \cdot S \cdot t \cdot V, \ °\text{C} \quad (3)$$

Based on empirical data from machining theory [24], data provided by a leading global cutting tool manufacturer [25], and approximation of the research data, the cutting temperature model can be expressed as:

$$T_{cut} = 350 + 4.5 \cdot S \cdot t \cdot V, °\text{C} \quad (4)$$

For optimization purposes, it is important to formally relate the cutting-zone temperature to a tool-wear metric. A *Fick–Taylor* model was adopted, which assumes that tool wear (e.g., flank wear) results from the combined effects of thermal and mechanical factors and can be described by the following empirical relationship:

$$Z(S, V, t) = K \cdot S^a \cdot t^b \cdot V^c \cdot e^{dT} = K \cdot S^a \cdot t^b \cdot V^c \cdot e^{\lambda \cdot S \cdot t \cdot V}, \quad (5)$$

where ***Z*** is the relative or absolute wear measure (e.g., the flank wear land width) (mm);

K is a scaling coefficient; ***T*** is the contact-zone temperature (°C);***a, b, c,*** and ***d*** are empirical exponents that depend on the workpiece material, tool material/geometry, and cutting conditions.

To predict tool wear, the tool manufacturer *Tungaloy* [26] provides the following coefficient parameters for a *Tungaloy AH6225* insert under typical stainless-steel machining conditions (Table 2).

Table 2

Values of the *Fick-Taylor* model coefficients for the *AH6225* insert during machining of stainless steels

Parameter	Value (example)
a	0.5
b	0.3
c	1.2
λ	0.015
K	0.0146

The wear model ***Z*** was adopted from the manufacturer's data and represents averaged tool-life test results obtained under the recommended operating conditions for the insert. In the present study, the cooling conditions correspond to standard emulsion supply; therefore, the ***Z*** model is treated as an engineering approximation for selecting cutting conditions in a typical finishing turning process. Refining the coefficients of the ***Z*** model for alternative cutting-fluid strategies (*MQL*, cryogenic cooling, etc.) requires separate experimental identification.

Substituting the empirical coefficient values from Table 2 into Eq. (5), the wear model is obtained:

$$Z(S, V, t) = 0.0146 \cdot S^{0.5} \cdot t^{0.3} \cdot V^{1.2} \cdot e^{0.015 \cdot S \cdot t \cdot V}, \quad (6)$$

Next, we define the interpretation of the dimensionless wear coefficient ***Z***. We establish that ***Z*** = 1 serves as a baseline reference; that is, the function ***Z (S,V,t)*** = 1 under the cutting conditions (***S*** = 0.1 mm/rev;

V = 80 m/min; ***t*** = 1.0 mm**)** corresponds to the typical/allowable wear (flank wear land width V_B = 0.3 mm) [27]. Accordingly:

Z = 0.5 indicates a safe condition where wear is below the nominal level;

Z = 1.5 indicates wear up to 50% above the nominal level, potentially reducing tool life;

Z > 2 indicates that the tool fails rapidly.

Thus, the constraint ***Z*** ≤ 1.5 means that the cutting conditions should not cause wear exceeding 50% above the allowable level.

The model can be written such that *Z* is inversely proportional to tool life.

$$Z = \frac{t_{cut}}{R}, \tag{7}$$

where ***R*** is the actual tool life (min); t_{cut} is the time for a single pass/operation (min)/

Accordingly, ***Z*** ≤ 1.5 means that the tool will sustain at least 1 / 1.5 ≈ 66% of the nominal tool life. This is acceptable for production conditions.

For optimization purposes, ***Z*** was interpreted as a dimensionless wear-risk function normalized to the reference condition. In this case:

Z ≤ 1 indicates a fully safe condition;

Z = 1 corresponds to the allowable limit;

Z = 1.5 may be acceptable for short-run machining but is undesirable for large batches;

Z > 2 indicates excessively rapid tool wear, making the condition unacceptable.

That is, the optimization constraint can be formulated as the condition that the cutting insert must not fail during a single-pass finishing operation of the *MCS*:

$$Z(S, V, t) \le 1, \tag{8}$$

The metal–polymer material used in the structure has limited thermal stability: its decomposition temperature is 170 °C [28]. Exceeding this temperature during turning may lead to degradation of the material's physical and mechanical properties, delamination, deformation, or even failure, rendering the *MCS* unsuitable for use.

Fig. 2 shows the segment of the metal-polymer sleeve between sensors (thermocouples) 1 and 2 in the experimental *MCS* emulator, where the allowable temperature level was intentionally exceeded (≈310–325 °C) after the turning experiments.

Methods for optimizing the objective function were analyzed [29], and a brief comparison is presented in Table 3.

Given the explicit analytical form of the objective function, the availability of a polynomial temperature model, the presence of explicit constraints, and the need to satisfy these constraints accurately (especially

Fig. 2. Defect (failure) of the metal-polymer composite due to exceeding the permissible temperature limit for the metal-polymer

Table 3

Comparison of optimization methods

Method	Brief Description	Why Applicable	Constraint Handling	Derivative Requirement
Sequential quadratic programming (*SQP*)	Classical constrained nonlinear optimization method	Supports nonlinear constraints and variable bounds	Yes	Desirable, but possible with auto-differentiation
Nelder-mead (Simplex) method	Gradient-free, operates via simplex geometry	Does not require derivatives, simple to implement	Only via penalty function	No
Differential evolution (*DE*)	Evolutionary global optimization algorithm	Global search capability, no gradient required	Through explicit bounds and penalties	No
Method of moving asymptotes (*MMA*)	Algorithm for constraint approximation	Fast, supports constraints via approximations	Yes (constraints via approximations)	No
Bayesian optimization (*BO*)	For expensive black-box functions	Overkill for this specific problem	Yes (through *Gaussian* process model)	No

the temperature constraint), the sequential quadratic programming (*SQP*) method was selected as the most appropriate optimization approach [29].

This method was implemented in Python using the *scipy.optimize.minimize* routine described in [29].

Results and discussion

The optimization problem was to determine turning conditions for the *MCS* that minimize insert wear while ensuring that the prescribed technological constraints are not violated. In particular, the temperature at the interface between the metallic shell and the cast metal-polymer infill must not exceed 170 °C, since exceeding this limit can result in degradation of the material structure.

The objective function is the tool-wear function for turning the MCS, expressed in terms of depth of cut, feed, and cutting speed, with allowance for the part's geometric parameters. The temperature constraint is defined using an empirical model obtained from experiments for a 2 mm wall thickness (the ***2T3*** (***S***, ***V***, ***t***) model). The model captures the nonlinear effects of feed, cutting speed, and depth of cut on temperature.

An additional surface-roughness constraint was not included, since the required roughness is achieved across the entire range of the decision variables considered, which is consistent with the cutting tool manufacturer's recommendations and the specifics of machining additively manufactured parts.

A numerical sequential quadratic programming (*SQP*) method is employed to solve the problem, as it can efficiently identify an optimum in the presence of nonlinear constraints.

In the case considered, the optimization was performed for a drill shank model with the following geometric parameters: ***L*** = 55 mm (machining length, i.e., shank length) and ***D*** = 25 mm (shank diameter).

The optimization problem was formulated as follows:

$$\begin{cases} Z(S,V,t) < 1 \to \min; \\ 2T3(S,V,t), ^\circ\mathrm{C} < 170\ ^\circ\mathrm{C}; \\ S \in [0.05; 0.15], \dfrac{\mathrm{mm}}{\mathrm{rev}}; \\ V \in [60; 120], \dfrac{\mathrm{m}}{\mathrm{min}}; \\ t \in [0.5; 1.5], \mathrm{mm}. \end{cases} \quad (9)$$

By performing optimization using the *SQP* method (Fig. 3), the optimal turning parameters were determined such that the machining time is minimized while the temperature constraint is satisfied and tool wear is minimized. The optimization results are presented in Table 4.

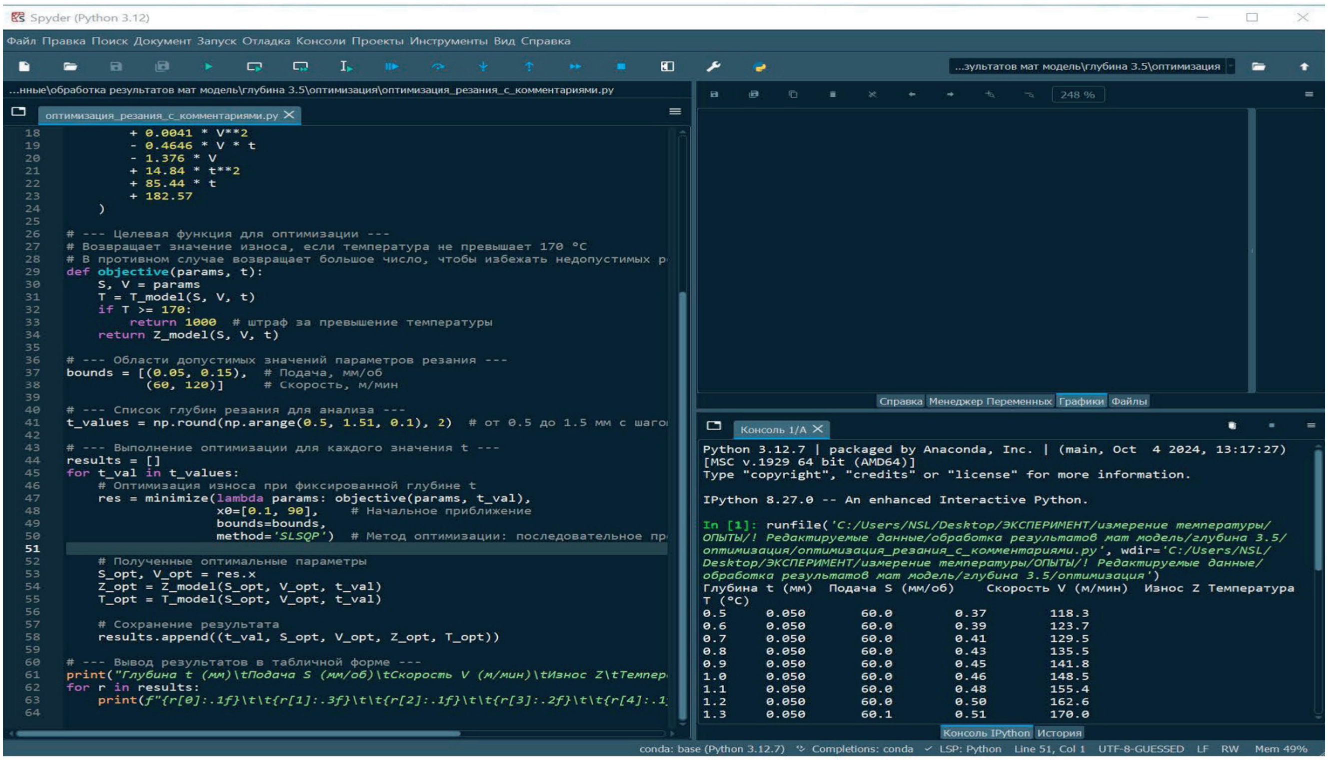

Fig. 3. Optimization of tool wear *Z* (*S*, *V*, *t*) by the *SQP* method

Table 4

Optimization results using the *SQP* method for the *2T3* model

Depth of cut, t (mm)	Feed rate, *S* (mm/rev)	Cutting speed, *V* (m/min)	Wear *Z*	Temperature, °C
0.5	0.05	60.0	0.369	153.2
0.6	0.05	60.0	0.392	148.6
0.7	0.05	60.0	0.412	146.0
0.8	0.05	60.0	0.431	145.3
0.9	0.05	60.0	0.448	146.5
1.0	0.05	60.0	0.465	149.6
1.1	0.05	60.0	0.48	154.6
1.2	0.05	60.0	0.495	161.6
1.3	0.05	60.6	0.516	170.0
1.4	0.05	72.0	0.66	170.0
1.5	0.05	87.0	0.864	170.0

The experiments showed that the characteristic temperature levels range from approximately 27 to 190 °C; under an “extreme” combination of cutting conditions, peaks of up to ~189 °C were recorded (Test No. 2), which exceeds the allowable thermal limit of the *MPCM* for finishing machining. This confirms the critical importance of selecting appropriate cutting conditions for an *MCS* with this metallic shell thickness.

Figs. 4–6 present the temperature and wear isolines at depths of cut of 0.5 mm (Fig. 4), 1.0 mm (Fig. 5), and 1.5 mm (Fig. 6), respectively.

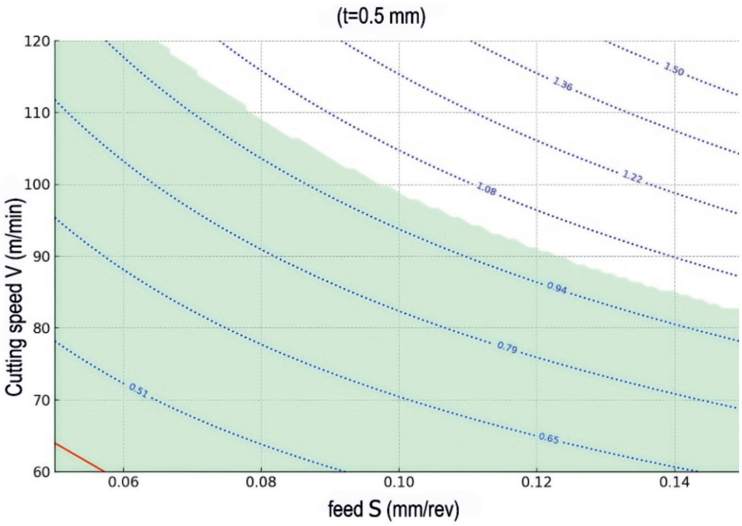

Fig. 4. Contour plot of the *2T3* (temperature) and *Z* (wear) dependencies at *t* = 0.5 mm; solid red lines – temperature (*2T3* model); dashed blue lines – tool wear (*Z* model); green area – admissible parameter domain; white area – prohibited zone with high risk of cutting insert failure

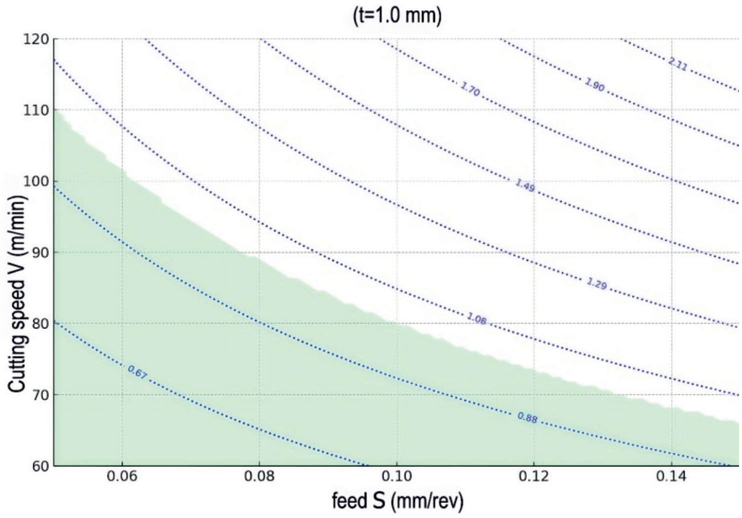

Fig. 5. Contour plot of the *2T3* (temperature) and *Z* (wear) dependencies at *t* = 1.0 mm; solid red lines – temperature (*2T3* model); dashed blue lines – tool wear (*Z* model); green area – admissible parameter domain; white area – prohibited zone with high risk of cutting insert failure

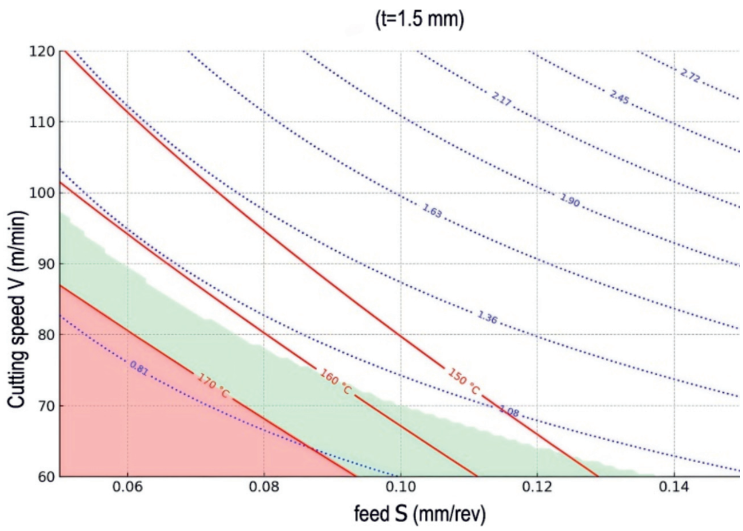

Fig. 6. Contour plot of the *2T3* (temperature) and *Z* (wear) dependencies at *t* = 1 mm; solid red lines – temperature (*2T3* model); dashed blue lines – tool wear (*Z* model); green area – admissible parameter domain; white area – prohibited zone with high risk of cutting insert failure

To enable a consistent comparative analysis of the results in Figs. 4–6, a unified visualization logic was used for permissible cutting conditions in the (***S***, ***V***) plane at a fixed depth of cut ***t***. Each plot shows temperature isolines calculated from the ***2T3*** regression model (solid red lines) and tool-wear isolines from the ***Z***(***S***, ***V***, ***t***) model (dashed blue lines). The green region denotes the set of cutting conditions that simultaneously satisfy the adopted constraints on the metal-polymer temperature and the wear-risk criterion (the permissible domain). The white region indicates conditions under which the allowable wear-risk level for the cutting insert is exceeded.

The threshold for critical thermal exposure of the metal–polymer was set at 170 °C as the maximum allowable temperature for the material. In addition, Fig. 4 includes the 150 °C isoline, which marks the onset of technologically significant (pronounced) heating of the metal–polymer. Note that for t = 0.5 mm (Fig. 4) and t = 1.0 mm (Fig. 5), temperatures T > 170 °C are not reached within the investigated (S, V) range; therefore, no metal–polymer overheating zone appears in these plots. For t = 1.5 mm (Fig. 6), the temperature exceeds the 170 °C threshold over part of the factor space, which is visualized as a red overheating region.

The color coding in Figs. 4–6 reflects compliance with the technological constraints adopted for the optimization of cutting conditions. The green region corresponds to the set of (S, V) combinations for which both T < 170 °C (no overheating of the metal-polymer) and $Z(S, V, t) \le Z_{allow}$ (allowable wear-risk level of the cutting insert) are satisfied simultaneously. The white region corresponds to cutting conditions that violate the wear constraint ($Z > Z_{allow}$), i.e., conditions associated with an increased risk of accelerated insert wear; in this region, the temperature may still remain below 170 °C.

A physical interpretation of the observed trends indicates that the interfacial temperature increases due to the total heat generation in the chip-formation zone and from friction at the tool–workpiece contact surfaces, followed by heat transfer through the metallic shell to the metal-polymer infill. In general, increasing cutting speed V, feed rate S, and depth of cut t leads to higher temperature levels, which is consistent with established machining theory and recent experimental studies on turning.

For the metal-composite system considered, analysis of the ***2T3*** model coefficients indicates that, within the selected parameter ranges, the depth of cut t has the strongest effect on temperature rise, followed by the feed rate S, while the cutting speed V has the weakest effect. This ranking can be explained physically by the fact that increasing t directly increases the material removal volume and the specific cutting power, thereby intensifying the heat flux into the system; by contrast, within the investigated V range, the contribution of cutting speed is partially “smoothed out” due to stable heat dissipation and fixed contact conditions.

The contour maps in Figs. 4–6 illustrate how the permissible domain evolves as the depth of cut increases:

1. t = 0.5 mm (Fig. 4): the temperature constraint T < 170 °C is not activated within the considered S and V ranges (no overheating occurs); therefore, the boundary of the permissible region is determined mainly by the tool wear criterion. In practical terms, at a small depth of cut the thermal risk for the metal-polymer is minimal, and optimization reduces to a trade-off in tool life while maintaining the required surface quality.

2. t = 1.0 mm (Fig. 5): the absence of an overheating zone T > 170 °C is retained within the selected S and V range; however, the overall temperature levels increase compared to t = 0.5 mm. The permissible region is still largely limited by tool wear, while the “temperature margin” decreases.

3. t = 1.5 mm (Fig. 6): the temperature constraint becomes dominant: an overheating region appears, and the boundary of allowable cutting conditions is governed by two mechanisms: (1) metal-polymer overheating at T > 170 °C and (2) an increased tool-wear risk. Thus, at larger t, the temperature criterion imposes a “hard” cutoff in the factor space, highlighting the dominant influence of depth of cut on the system’s thermal loading.

Conclusion

The use of the previously developed ***2T3*** regression model for a 2 mm-thick *SLM* shell made it possible to quantify the thermal response of the metal-composite system to variations in depth of cut, feed, and cutting speed. It was shown that, within the investigated range of cutting conditions, the characteristic interfacial temperatures lie approximately between 27 and 190 °C; under “extreme” parameter combinations, the temperature reaches ~189 °C, which exceeds the thermal stability threshold of the metal–polymer (≈170 °C). This confirms the need for a strict temperature constraint when selecting cutting conditions and demonstrates the suitability of the ***2T3*** model for a priori delineation of the permissible domain based on the temperature criterion.

Based on the empirical *Fick–Taylor* relationship and the parameters recommended by the manufacturer of the *AH6225* cemented carbide insert for machining stainless steels, a regression wear model $\boldsymbol{Z}(\boldsymbol{S}, \boldsymbol{V}, \boldsymbol{t})$ was obtained. A dimensionless interpretation of the wear coefficient $\boldsymbol{Z}$ was introduced, where $\boldsymbol{Z} = 1$ corresponds to a typical (allowable) wear level, and the constraint $\boldsymbol{Z} \leq 1.5$ implies that the tool life is at least ~66% of the baseline value. This formulation enables a direct linkage between cutting conditions and operational tool life, allowing the wear model to be used in engineering optimization problems.

Based on the coupled "***2T3*** temperature model + *Fick–Taylor* wear model", a multi-criteria optimization problem for finishing turning of the *MCS* was formulated and reduced to minimizing the wear function $\boldsymbol{Z}(\boldsymbol{S}, \boldsymbol{V}, \boldsymbol{t})$ subject to a nonlinear temperature constraint ***2T3***$(\boldsymbol{S}, \boldsymbol{V}, \boldsymbol{t}) \leq 170$°C and technological bounds on feed, cutting speed, and depth of cut. No additional surface-roughness constraint was introduced, since the specified parameter ranges ensure the required surface quality. This formulation captures the practical conflict between reducing tool wear and preventing overheating of the metal-polymer infill.

Implementing the sequential quadratic programming (*SQP*) method in *Python* for the developed model demonstrated its effectiveness in the presence of nonlinear constraints. For the specific case of a drill shank ($\boldsymbol{L} = 55$ mm, $\boldsymbol{D} = 25$ mm), a set of rational cutting conditions was obtained that simultaneously satisfies the temperature constraint and provides an economically acceptable level of tool wear. The optimal solutions fall within the range of moderate depths of cut ($\boldsymbol{t} \approx 0.5$–1.0 mm) at the minimum feed ($\boldsymbol{S} \approx 0.05$ mm/rev) and a cutting speed close to the lower bound of the investigated range ($\boldsymbol{V} \approx 60$ m/min), yielding $\boldsymbol{Z} < 1$ and an interfacial temperature well below 170 °C.

Analysis of the temperature and wear isolines showed that depth of cut is the dominant factor governing the temperature rise at the interfacial boundary, whereas the effect of cutting speed is less pronounced. In all cases considered, the temperature constraint determines the boundaries of the permissible cutting-condition domain and limits increases in cutting speed and feed; for $\boldsymbol{t} \geq 1.0$–1.2 mm, the temperature margin is rapidly exhausted, and the risk of exceeding the thermal stability threshold of the metal–polymer becomes unacceptable. In practical terms, this means that for finishing machining of an *MCS* with a 2 mm-thick shell, it is reasonable to use depths of cut on the order of 0.5–1.0 mm with a coordinated selection of feed and cutting speed. The proposed approach can be extended to other shell thicknesses and *MCS* configurations after calibrating the temperature model using experimental data.

References

1. Huber F., Rasch M., Schmidt M. Laser powder bed fusion (PBF-LB/M) process strategies for in-situ alloy formation with high-melting elements. *Metals*, 2021, vol. 11 (2), p. 336. DOI: 10.3390/met11020336.

2. Fan F., Jalui S., Manogharan G. Mass finishing of additively manufactured Ti6Al4V parts: An investigation of surface finish dependency on build orientation and processing conditions. *Manufacturing Letters*, 2023, vol. 35, pp. 439–449. DOI: 10.1016/j.mfglet.2023.08.095.

3. Isaev A., Grechishnikov V., Pivkin P., Kozochkin M., Ilyuhin Y., Vorotnikov A. Machining of thin-walled parts produced by additive manufacturing technologies. *Procedia CIRP*, 2016, vol. 41, pp. 1023–1026. DOI: 10.1016/j.procir.2015.08.088.

4. Isaev A., Grechishnikov V., Pivkin P., Ilyukhin Y., Kozochkin M., Peretyagin P. Structure and machinability of thin-walled parts made of titanium alloy powder using electron beam melting technology. *Epitoanyag – Journal of Silicate Based and Composite Materials*, 2016, vol. 68, pp. 46–50. DOI: 10.14382/epitoanyag-jsbcm.2016.8.

5. Hintze W., Wenserski R., Junghans R., Carsten S. Finish machining of Ti6Al4V SLM components under consideration of thin walls and support structure removal. *Procedia Manufacturing*, 2020, vol. 48, pp. 485–491. DOI: 10.1016/j.promfg.2020.05.072.

6. Le Coz G., Fischer M., Piquard R., D'Acunto A., Laheurte P., Dudzinski D. Micro cutting of Ti-6Al-4V parts produced by SLM process. *Procedia CIRP*, 2017, vol. 58, pp. 228–232. DOI: 10.1016/j.procir.2017.03.326.

7. Kitay O., Kaynak Y. Machining and deformation response of wrought and additively manufactured 316L stainless steel under cryogenic cooling and dry condition. *The International Journal of Advanced Manufacturing Technology*, 2025, vol. 137, pp. 1791–1809. DOI: 10.1007/s00170-025-15152-3.

8. Polishetty A., Nomani J., Littlefair G. Evaluating and comparing secondary machining characteristics of wrought and additive manufactured 316L stainless steel. *Materials Today: Proceedings*, 2023. DOI: 10.1016/j.matpr.2023.05.404.

9. Arnés-Urgellés P., Bayas J., Salazar E.R., Maldonado F., Helguero C., Amaya J. Machinability study of polymeric parts fabricated by additive manufacturing under a dry milling process. *Advanced Structured Materials*, 2021, vol. 149, pp. 139–148. DOI: 10.1007/978-3-030-68277-4_10.

10. Lubimyi N.S., Polshin A.A., Gerasimov M.D., Tikhonov A.A., Antsiferov S.I., Chetverikov B.S., Ryazantsev V.G., Brazhnik J., Ridvanov I. Justification of the use of composite metal-metal-polymer parts for functional structures. *Polymers*, 2022, vol. 14 (2), p. 352. DOI: 10.3390/polym14020352.

11. Lubimyi N.S., Chepchurov M., Polshin A.A., Gerasimov M.D., Chetverikov B.S., Chetverikova A., Tikhonov A.A., Maltsev A. Reducing the cost of 3D metal printing using selective laser melting (SLM) technology in the manufacture of a drill body by reinforcing thin-walled shell forms with metal-polymers. *Journal of Manufacturing and Materials Processing*, 2024, vol. 8 (2), p. 44. DOI: 10.3390/jmmp8020044.

12. Lubimyi N., Voronenko V., Polshin A., Gerasimov M., Antsiferov S., Öztürk O.K., Chetverikov B., Tikhonov A., Ryazantsev V., Shumyacher V., Melentiev N. What is the economic feasibility of manufacturing a metal-metal-polymer composite part compared to other technologies? *Australian Journal of Mechanical Engineering*, 2022, vol. 22 (2), pp. 314–325. DOI: 10.1080/14484846.2022.2094533.

13. Petkovic D., Madić M., Radovanović M., Janković P., Radenkovic G. Modeling of cutting temperature in the biomedical stainless steel turning process. *Thermal Science*, 2016, vol. 20, pp. 1345–1354. DOI: 10.2298/TSCI16S5345P.

14. Zhang J., Zhanqiang L., Xu C., Jin D., Guosheng S., Zhang P., Meng X. Modelling and prediction of cutting temperature in the machining of H13 hard steel of multi-layer coated cutting tools. *The International Journal of Advanced Manufacturing Technology*, 2021, vol. 115 (11–12), pp. 3731–3739. DOI: 10.1007/s00170-021-07417-4.

15. Garcia-Llamas E., Sandoval G., Fuentes M., Vidales E., Pujante J. Exploring post-machining alternatives under dry conditions for thin-walled additive manufacturing components aided by infrared thermography. *Processes*, 2025, vol. 13, p. 717. DOI: 10.3390/pr13030717.

16. Rao C.J., Sreeamulu D., Mathew A. Analysis of tool life during turning operation by determining optimal process parameters. *Procedia Engineering*, 2014, vol. 97, p. 241–250. DOI: 10.1016/j.proeng.2014.12.247.

17. Batista M., Davim P., Salguero J., Gomez-Parra A., Marcos M. Taylor's model based analysis of turning inserts tool-life in the dry turning of UNS R56400 alloy. *ASME International Mechanical Engineering Congress and Exposition. Proceedings (IMECE)*. Vol. 1, Montreal, Quebec, Canada, 2014. DOI: 10.1115/IMECE2014-38710.

18. Salvatore F. Sofiane S., Hamdi H. Modeling and simulation of tool wear during the cutting process. *Procedia CIRP*, 2013, vol. 8, pp. 305–310. DOI: 10.1016/j.procir.2013.06.107.

19. Lee Y.J., Yoon H.-S. Modeling of cutting tool life with power consumption using Taylor's equation. *Journal of Mechanical Science and Technology*, 2023, vol. 37 (6), pp. 3077–3085. DOI: 10.1007/s12206-023-0531-5.

20. Zhang X., Peng Z., Liu L., Zhang X. A tool life prediction model based on Taylor's equation for high-speed ultrasonic vibration cutting Ti and Ni alloys. *Coatings*, 2022, vol. 12, p. 1553. DOI: 10.3390/coatings12101553.

21. Pol'shin A.A. Razrabotka tekhnologii izgotovleniya metall-kompozitnykh korpusov sbornykh sverl v usloviyakh importozameshcheniya [Development of technology for manufacturing metal-composite bodies of prefabricated drills in the conditions of import substitution]. *Transportnoe mashinostroenie = Transport Engineering*, 2025, no. 10 (46), pp. 27–35. DOI: 10.30987/2782-5957-2025-10-27-35.

22. Oxley P.L. *The mechanics of machining: An analytical approach to assessing machinability*. Sydney, Halsted Press Publ., 1989. 242 p.

23. Komanduri R., Hou Z.B. Thermal modeling of the metal cutting process: Part I – Temperature rise distribution due to shear plane heat source. *International Journal of Mechanical Sciences*, 2000, vol. 42 (9), pp. 1715–1752. DOI: 10.1016/S0020-7403(99)00070-3.

24. Kalpakjian S., Schmid S. *Proizvodstvennaya inzheneriya i tekhnologii (SI-edinitsy)* [Manufacturing engineering and technology (SI Units)]. Moscow, Logos Publ., 2022. 1360 p.

25. Tungaloy Corporation. *A new generation of PVD grade for stainless steel turning: AH6225*. Available at: https://tungaloy.com/wpdata/wp-content/uploads/540-u_AH6225.pdf (accessed 14.01.2026).

26. Tungaloy Corporation. *Latest grade series for stainless steel turning with AH6200*. Available at: https://tungaloy-rus.ru/upload/iblock/ae2/ae25807696423260679c5e78743e3f79.pdf (accessed 14.01.2026).

27. Grechishnikov V.A., Tarasov A.V., Ganshin V.K., Zhivodrov O.G. Razrabotka metodiki diagnostirovaniya sostoyaniya rezhushchego instrumenta v rezhime real'nogo vremeni pri sverlenii otverstii v khrupkikh materialakh [Development of methods of diagnosis state of cutting tool real-time in drilling brittle materials]. *Sovremennye materialy, tekhnika i tekhnologii = Modern Materials, Equipment and Technology*, 2016, no. 4 (7), pp. 45–51.

28. Borovkov A.I., Vafaeva K.M., Vatin N.I., Ponyaeva I. Synergistic integration of digital twins and neural networks for advancing optimization in the construction industry: A comprehensive review. *Construction Materials and Products*, 2024, vol. 7 (4). DOI: 10.58224/2618-7183-2024-7-4-7.

29. Virtanen P., Gommers R., Oliphant T.E. SciPy 1.0: Fundamental algorithms for scientific computing in Python. *Nature Methods*, 2020, vol. 17, p. 1–12. DOI: 10.1038/s41592-019-0686-2.

Conflicts of Interest

The authors declare no conflict of interest.