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Investigation of the thermal loading during turning of a metal–composite system as a function of cutting speed, feed rate, and depth when machining a thin-walled 2 mm metal shell

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ABSTRACT

Introduction. This paper is devoted to the study of the thermal loading of the turning process for metal–composite systems (*MCS*) consisting of a thin-walled, additively manufactured metal shell and a metal-polymer filler. **The purpose of this study** is to investigate the influence of technological turning parameters on the temperature in the cutting zone of metal-composite systems (*MCS*) with a 2 mm thick metal shell and to determine the permissible machining conditions that prevent thermal degradation of the metal-polymer filler. **Methodology.** For experimental modeling of the *MCS*, a hardware-software complex was developed, including a replaceable metal sleeve made of *0.12C18Cr-10Ni-Ti* steel, ferrochrome metal–polymer (*TU 2257-002-48460567-00*), three thermocouples with *MAX6675* analog-to-digital converters, and a wireless data transmission module based on an *ESP32*. The temperature at the metal-metal-polymer interface was recorded in real time. The results were verified using a non-contact method with a *FLUKE Ti400* thermal imager (error of 3–5 °C). The experiment was conducted according to a full factorial design $2^3 + n_0$ with variation of cutting speed V (m/min), feed rate S (mm/rev), and depth of cut $\boldsymbol{t}$ (mm), including central points for assessing the curvature of the response surface. **Results and discussion.** Based on the experimental data obtained for the 2 mm shell, a second-order regression model (*2T3*) was constructed, demonstrating high adequacy. Analysis of the model coefficients showed that the depth of cut t has the greatest influence on the temperature increase, followed by the feed rate $\boldsymbol{S}$, while the cutting speed $\boldsymbol{V}$ has the least effect within the studied range. Using the model, response surfaces and contour maps were constructed, allowing visualization of *safe* machining regions that satisfy the constraint T ≤ 170 °C — the heat resistance limit of the metal-polymer. The obtained dependencies provide a basis for standardizing finishing turning parameters for tooling components with additively formed shells and metal-polymer fillers.

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Introduction

Manufacturing of components with intensive heat exchange, such as injection-molding dies for thermoplastics and solid-body cutting tools, has increasingly relied in recent years on metal-composite systems (*MCS*) [1], which combine a thin-walled metallic shell with a filler made of metal-polymer

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composite material (*MPCM*). This approach allows integrating the high strength and stiffness of the metallic framework with the damping properties and processing advantages of *MPCM*, while simultaneously reducing the overall weight and production cost.

The key enabler behind the development of metal–composite systems (*MCS*) is the capability of additive manufacturing (*AM*) [2], particularly selective laser melting (*SLM*), to produce curvilinear (conformal) cooling channels within metallic shells [3]. For molding dies, this enables directed heat extraction from zones of maximum thermal load, uniform temperature distribution, a reduction in the molding or stamping cycle time, and improved dimensional stability.

From a technological standpoint, the process can be described as follows: a pocket is machined in the metallic base plate of the die to accommodate a replaceable forming insert; the forming insert itself is produced as a thin-walled metallic shell with integrated curvilinear cooling channels; after assembly, the cavity between the shell and the base plate is filled with a metal-polymer composite material (*MPCM*), which secures the insert, enhances thermal contact, and ensures load transfer during die operation.

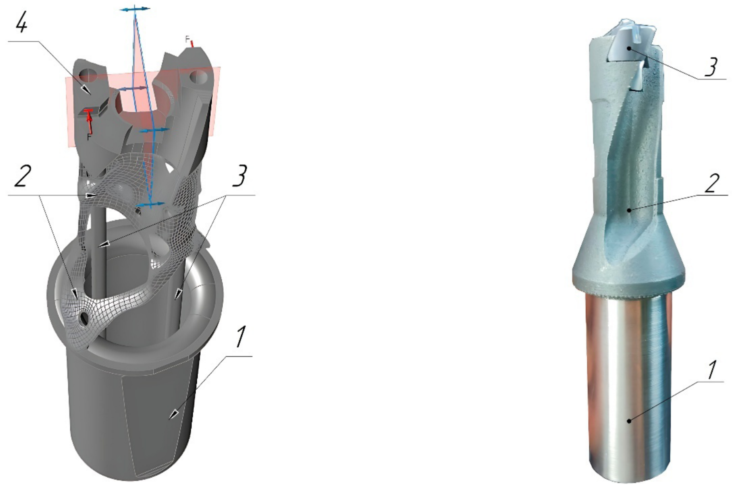
A similar design and technological concept can be implemented in cutting tools [3], for example, in a composite drill: the metallic *SLM*-manufactured shell of the drill body, featuring specially designed internal cooling channels, delivers the cutting fluid (*CF*) directly to the cutting zone, while the internal cavity formed as a result of topology optimization (*TO*) [4] is filled with metal-polymer composite material (*MPCM*). The filler absorbs volumetric loads and enhances the vibration damping of the tool. This configuration increases the durability of the carbide cutting head by improving heat removal from the cutting area.

In recent years, additive manufacturing (*AM*) has become a powerful technological solution for producing complex thin-walled shells and hollow components with integrated cooling channels. For example, the review [5] emphasizes that during the machining of *AM*-produced parts, post-processing operations such as turning play a crucial role, since the layered structure, residual stresses, and altered thermal conductivity of the material significantly affect chip formation, dimensional accuracy, and thermal loads. For a thin-walled metallic shell filled with *MPCM*, this means that turning requires consideration not only of the cutting parameters but also of the shell geometry, specific features of the additively manufactured structure, and the thermal behavior at the metal-polymer interface.

Fig. 1, *a* shows a digital model of the drill body after topology optimization (*TO*), which allowed for a 40 % reduction in metal consumption – an essential factor for ensuring the economic feasibility of applying *SLM*-based additive manufacturing (*AM*) technology in industrial production [6]. Fig. 1, *b* presents a physical sample of the topology-optimized metal-composite drill body with its internal cavities filled with *MPCM*, forming a complete metal-composite system (*MCS*).

A critical technological stage in manufacturing *MCS* is the mechanical finishing (including turning) of the outer and seating surfaces after the internal cavities have been filled with *MPCM*. Unlike homogeneous metallic workpieces, the heat flux in this case is constrained by the metal-*MPCM* interfacial boundary, while the *MPCM* itself exhibits lower thermal conductivity and limited heat resistance. Overheating during turning can lead to local thermal degradation of the polymer matrix, loss of strength, and weakened adhesion at the interface, which in turn causes deterioration of dimensional accuracy and reduced service life of the product. Meanwhile, engineering recommendations for selecting turning parameters for such hybrid shells with composite fillers remain scarce [7]. Most available data [8, 9] refer either to monolithic metallic parts or to polymer-based composites without a metallic shell.

One of the key challenges in machining thin-walled and metal-composite systems is the increase in temperature in the cutting zone and the resulting thermal loading, which leads to thermal deformations, deterioration of surface quality, and reduced dimensional accuracy of the workpiece. For instance, the study [10] demonstrated that during dry turning of aluminum-based composites reinforced with dispersed phases, thermal loading increases significantly compared to monolithic alloys: higher cutting speeds and feeds cause temperature spikes in the cutting zone. In the context of machining metallic shells with fillers – especially thin-walled ones (with thicknesses of about 2 mm or less) – the effect of thermal loading is further aggravated by reduced structural stiffness and limited heat dissipation through the workpiece.



a *b*

Fig. 1. (*a*) Digital model of the drill body with topology optimization applied (the middle part of the chip grooves is conventionally omitted):

1 – shank area (metal); 2 – load-bearing structural elements formed by topology optimization (metal); 3 – cooling channels (metal); 4 – mounting seat for a replaceable carbide cutting head (*b*) Physical sample of the topology-optimized metal–composite drill body manufactured using *SLM* technology: 1 – turned metal–composite shank; 2 – chip grooves; 3 – cutting head of the drill body

The design features of thin-walled shells and their interaction with the metal–polymer filler are important aspects of the design of metal-composite systems (*MCS*). The review [11] emphasizes that thin-walled components possess low stiffness and unstable thermal-mechanical characteristics, which impose significant constraints on cutting parameters as well as on the requirements for tooling and fixturing. When a metal-polymer filler is introduced inside the shell, an additional thermal and phase interface – metal–*MPCM* – is formed. This interface requires detailed analysis of the temperature distribution precisely at this boundary to prevent thermal degradation of the filler and to ensure that surface quality requirements are maintained.

Studies have also focused on the influence of cutting tool design and machining technology on thermal load and cutting quality. For example, the work [12] demonstrates how variations in the material and coating of the cutting insert can reduce both tool and workpiece temperatures during the turning process. It is increasingly recognized that not only the cutting parameters (speed, feed, and depth of cut), but also the tool geometry, insert material, and the applied cooling or lubrication system play a crucial role in controlling thermal loading during machining.

In recent years, cooling and lubrication strategies have been considered among the key factors determining the thermal state of the tool-workpiece system. The review [13] notes that the choice of coolant and its delivery strategy – whether conventional emulsion supply, minimum quantity lubrication (*MQL*), or the use of nanofluids – has a significant impact on cutting temperature, chip formation stability, and tool wear. For the machining of thin-walled structures and composites, where the heat flux is limited due to the low thermal conductivity and small mass of the workpiece, cooling efficiency becomes critically important. Therefore, the correct selection of coolant composition, supply pressure, and flow rate is an essential condition for obtaining reliable temperature measurements and provides an objective basis for constructing regression models of thermal loading for the turning process of metal-composite systems (*MCS*).

It is also worth noting the studies devoted to the influence of protective and anti-friction coatings of cutting tools on heat distribution and cutting temperature. For example, the paper [14] shows that the use of *PVD* coatings significantly reduces both tool and workpiece temperatures, improves surface quality, and decreases wear when machining thin-walled components. This confirms the necessity of considering not only cutting speed, feed rate, and depth of cut in the study, but also the tool properties (insert material and coating) as well as the cooling conditions.

Therefore, for the reliable implementation of metal–composite systems (*MCS*) in industrial production, a quantitative assessment of the thermal loading during the turning process is required, taking into account the actual geometry and thickness of the metallic shell, the properties of the *MPCM*, and the cutting parameters — cutting speed (***V***), feed rate (***S***), and depth of cut (***t***). Such an assessment should lead to engineering-applicable models and allowable parameter domains that ensure the required surface quality and preservation of the *MPCM* structure [15, 16].

The purpose of this study was to quantitatively assess the thermal loading during the turning of metal-composite systems (*MCS*) consisting of a thin-walled additively manufactured metallic shell and a metal-polymer composite filler, to develop a model describing the dependence of temperature at the metal-*MPCM* interface on the cutting parameters (***V*, *S*, *t***), and to justify the acceptable operating range of cutting conditions that ensure the required surface quality and prevent thermal degradation of the *MPCM* in practical applications. To achieve this goal, the following ***research objectives*** were formulated:

– Development of a hardware-software setup simulating a metal-composite system (metallic shell + metal-polymer filler), enabling temperature measurement at the metal-*MPCM* interfacial boundary during external turning of a thin-walled metallic shell with a thickness of 2 mm;

– Execution of an experimental study on the turning of the simulated metal–composite model according to a full factorial experimental design of type $2^3 + n_0$;

– Construction of a regression model based on the experimental data, with evaluation of the statistical significance of the coefficients and the adequacy of the model;

– Development of graphical representations of the regression model in the form of response surface plots and contour maps, illustrating the dependence of interfacial temperature on cutting parameters for analyzing the thermal state of the cutting process.

Methods

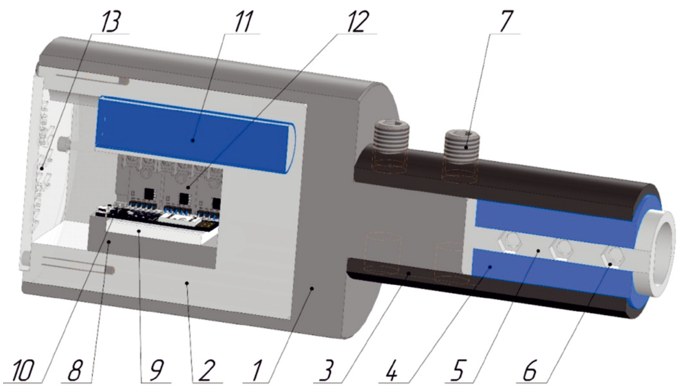


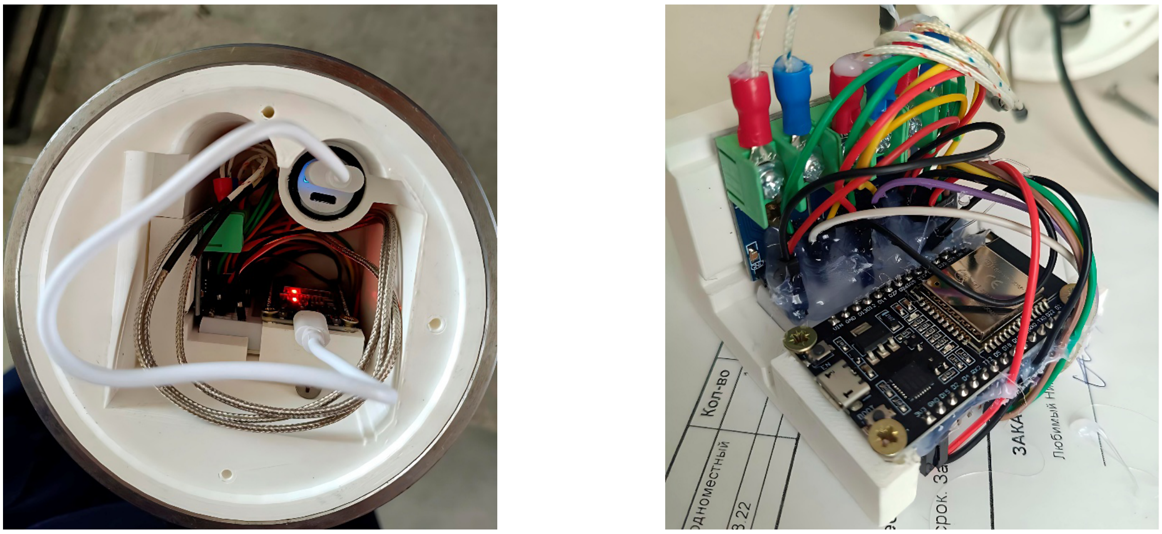
Fig. 2. 3D model of the hardware–software device for measuring temperature during turning of the metal–composite system (*MCS*), simulating a metal shell filled with *MPCM*:
1 – housing (*0.4C* steel); 2 – plastic holder for fastening electrical components inside the housing; 3 – replaceable sleeve (*0.12C18Cr-10Ni-Ti*); 4 – *MPCM* insert; 5 – plastic holder for mounting thermocouples; 6 – holes for M8 nuts; 7 – fastening screws for securing the replaceable sleeve; 8 – microprocessor enclosure; 9 – prototyping board; 10 – *ESP32* microcontroller; 11 – 2,600 mAh rechargeable battery; 12 – *MAX6675* thermocouples; 13 – cover

To study the thermal loading during the turning process, a specially developed hardware-software device was used, simulating a metal–composite system (metallic shell + metal-polymer filler). The assembly consists of a steel housing with a battery unit, a replaceable metallic sleeve, a metal-polymer insert, and three measurement channels based on *MAX6675* modules (thermocouple-to-digital converters) that transmit real-time data via Wi-Fi (*ESP32* microcontroller → *PC*). The digital model of the experimental device is shown in Fig. 2.

The design allows for quick replacement of sleeves to vary the thickness of the metallic wall and enables mounting of the workpiece in the chuck of a *16K20* lathe. The consistency of readings from the contact sensors was verified using a *FLUKE Ti400* thermal imager, with discrepancies not exceeding 3–5 °C. To ensure proper thermal contact, *KPT-8* thermal paste was applied at the sensor mounting points.

Fig. 3 shows the physical model of the developed hardware–software device used for the experimental study.

The replaceable metallic sleeves (Fig. 4) were manufactured from *0.12% C-12% Cr-18% Ni-1% Ti* (*AISI 304*) steel tubing, selected as an accessible material analog for high-alloy steel with low thermal conductivity [17].



a *b*

Fig. 3. Physical model of a device for measuring temperature data during turning Physical model of a device for measuring temperature data during turning:
(*a*) assembled device body; (*b*) assembly of the microprocessor unit

Fig. 4. Replacement sleeves processed during the experiment

The thermal conductivity of *0.12% C-12% Cr-18% Ni-1% Ti* steel is approximately 15–16 W/(m·K), which is close to that of the *EP648* heat-resistant alloy (12–15 W/(m·K)) commonly used in additive manufacturing. This ensured comparable heating conditions during the turning of the *MCS*.

The metal–polymer composite material (*MPCM*) "Ferro-Chrome" (*TU 2257-002-48460567-00*) [18] was used as the filler. This material has lower thermal conductivity than steel and limited heat resistance, necessitating temperature control during finish machining. The insert was formed by casting the compound into a mold, followed by turning to match the inner diameter of the metallic sleeve.

For the experiments aimed at developing a temperature model at the *MCS* interface, Tungaloy *DNMG150408-TF AH6225* turning inserts designed for finishing operations were used. The dimensional layout of the insert is shown in Fig. 5, and its geometric characteristics are listed in Table 1. The cutting tool material was cemented carbide *AH6225* (*WC–Co–TiC–*Al_2O_3) with a *TiAlN* + *TiN PVD* coating, providing high heat and wear resistance when machining steels.

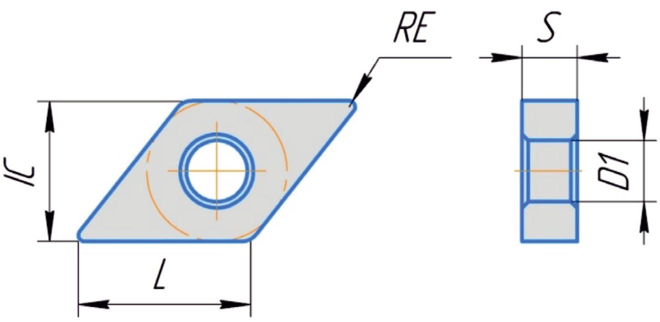


Fig. 5. Tungaloy *DNMG150408-TF AH6225* cutting insert geometry diagram

The tool holder used was *DCLNR 2020K12 – M* (medium type, with a negative rake angle).

The summarized maximum temperature values obtained for each experimental run are presented in Table 1.

The machining was carried out on a *16K20* universal lathe using a coolant and lubrication supply system (*CLSS*). The working fluid was a mineral-based water–oil emulsion of type *I-20A* with the addition of 5 % *Emulsol ED-20*, providing effective cooling and friction reduction in the tool-workpiece contact zone. The emulsion was supplied as a continuous jet under a pressure of 0.25 ± 0.05 MPa directly into the cutting zone, with an average flow rate of 2–3 L/min. The selected coolant composition and delivery parameters correspond to the standard recommendations for finish turning of structural steels.

Table 1

Geometrical and operational parameters of the cutting insert *Tungaloy DNMG150408-TF AH6225*

Designation	***Параметр / Parameter***	***Meaning***
RE	Radius at the apex	0.80 mm
IC	Inscribed circle	12.7 mm
S	Plate thickness	4.76 mm
D1	Hole in the center	5.16 mm
–	Angle of the shape	55° (rhombic)
–	Cutting edge type	*TF* (thin, finishing)
–	Class	*M* (medium negative rake angle)

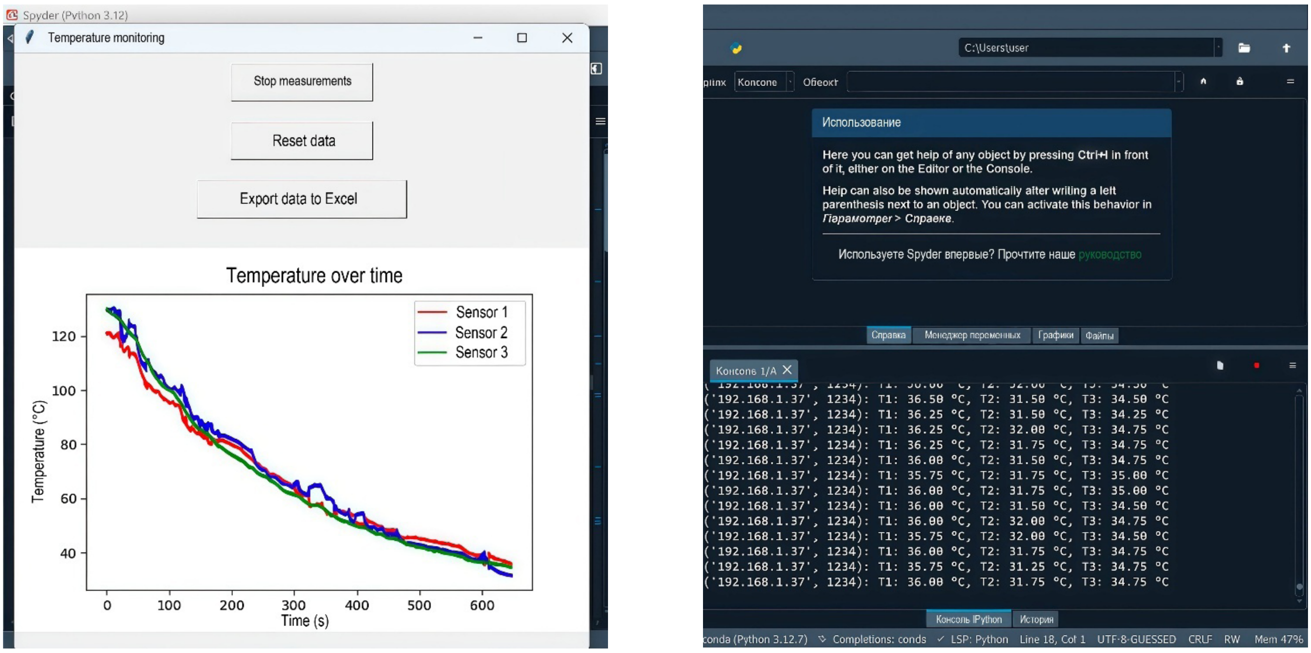
The measurement setup involved positioning three sensors near the metal–*MPCM* interfacial boundary along the sample axis. A sampling rate of 200 ms ensured recording of the temperature response during steady-state cutting. Data transmission was carried out via ***UDP*** protocol to a personal computer, while visualization and data logging were performed using a custom *Python* application (Fig. 6).

Verification of the surface temperature distribution was performed using thermographic method [19], and the analysis was based on the maximum cutting temperature values [20]. Fig. 7 shows the verification of temperature measurement data obtained using the thermal imager.

The experiment was carried out according to a full factorial design of type $2^3 + n_0$. The varying factors were cutting speed $\boldsymbol{V}$ (m/min), feed per revolution $\boldsymbol{S}$ (mm/rev), and depth of cut $\boldsymbol{t}$ (mm) [21]. The experimental matrix included eight factorial points (levels −1 / +1 in coded form) and $\boldsymbol{n_0}$ = 5 central runs (0, 0, 0) to estimate the reproducibility variance and to test the curvature of the response surface.

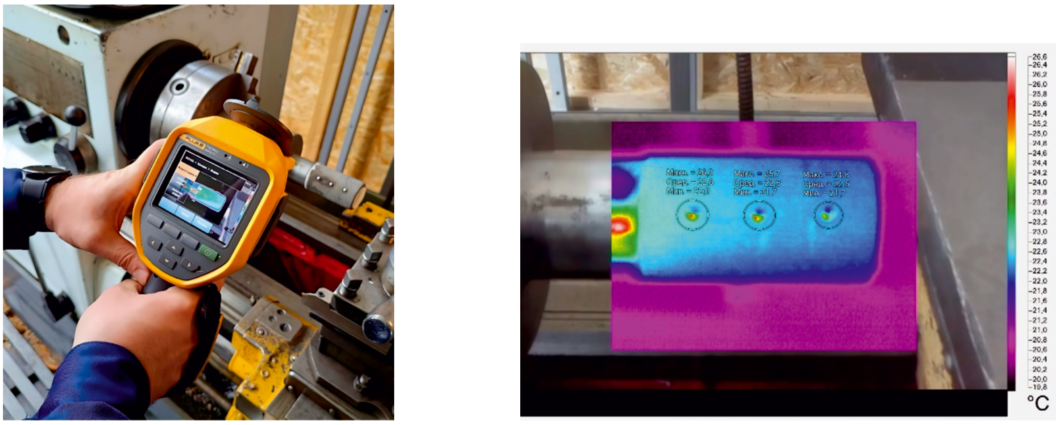
The selected range of variation for the depth of cut ($\boldsymbol{t}$ = 0.5–1.5 mm) was determined by the nominal machining allowance per side. A typical finishing allowance of 0.5 mm is recommended, which corresponds to a single finishing pass with a depth of cut of 0.5 mm, provided that a low feed rate and efficient heat removal are maintained. Machining can also be performed in two passes – e.g., 0.3 mm roughing + 0.2 mm finishing – but this approach contradicts the principle of minimizing overall machining time. However, considering the need to remove supports and surface defects associated with additive manufacturing, the depth of the defective surface layer, and consequently the machining allowance, may increase up to 2 mm. Therefore, the upper limit of the depth-of-cut range was set at 1.5 mm. Higher depths are not recommended, as further increases would lead to deterioration of surface roughness.

The variation ranges for cutting speed ($\boldsymbol{V}$) and feed per revolution ($\boldsymbol{S}$) were selected to ensure the required surface roughness of $\boldsymbol{R_a} \le 2.5$ µm. The chosen parameter ranges implicitly account for this roughness constraint across the entire domain of factor variation.



a *b*

Fig. 6. (*a*) Dialog box of the Temperature Monitoring program implemented in *Python 3.12* for recording the cutting temperature of the *MCS*; (*b*) System monitor console displaying transmitted temperature data in real time



a *b*

Fig. 7. Verification of temperature readings obtained from thermocouples using the FLUKE Ti400 thermal imager:

(*a*) thermal imager measurement; (*b*) temperature diagram

For each parameter, three variation levels were selected – minimum, maximum, and central – as presented in Table 2.

Table 2

Levels of variation of experimental factors

Factor	***Designation***	−1	0	+1
Feed rate, ***S*** (mm/rev)	x_1	0.05	0.10	0.15
Cutting speed, ***V*** (m/min)	x_2	60	90	120
Depth of cut, ***t*** (mm)	x_3	0.5	1.0	1.5

Table 3 presents the experimental design matrix (full factorial design $2^3 + n_0$). The matrix includes eight factorial points with coded levels (–1, +1) and five central runs (0, 0, 0), which allows for evaluating the curvature of the response surface and verifying the adequacy of the regression model.

Table 3

Levels of variation of experimental factors

No.	x_1, (***S***, mm/rev)	x_2, (***V***, m/min)	x_3, (***t***, mm)	Mode (code)
1	0.5	60	0.05	(–1. –1. –1)
2	0.5	60	0.15	(–1. –1. +1)
3	0.5	120	0.05	(–1. +1. –1)
4	0.5	120	0.15	(–1. +1. +1)
5	0.15	60	0.05	(+1. –1. –1)
6	0.15	60	0.15	(+1. –1. +1)
7	0.15	120	0.05	(+1. +1. –1)
8	0.15	120	0.15	(+1. +1. +1)
9–11	0.10	90	0.10	(0. 0. 0)

As a result of each experimental run, time-dependent datasets of cutting temperature were obtained. For every run, the maximum temperature ***T*** at the metal-*MPCM* interfacial boundary was recorded using three sensors.

The regression model was constructed using coded variables $\boldsymbol{x_1}$, $\boldsymbol{x_2}$, and $\boldsymbol{x_3}$ [22]. A second-order model with pairwise interaction terms was considered:

$$T = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_1^2 + b_5x_2^2 + b_6x_3^2 + b_7x_1x_2 + b_8x_1x_3 + b_9x_2x_3 \quad (1)$$

The coefficients were estimated using the least squares method. The statistical significance of the coefficients was evaluated using the ***t***-test ($\alpha = 0.05$), and the model adequacy was verified using the ***F***-test, with calculation of the coefficient of determination (R^2). For engineering visualization [23], response surfaces ***T***(***V***, ***S***) were constructed at fixed values of ***t***.

Results and Discussion

Based on the series of experiments conducted for the *MCS* with a metallic shell thickness of $\delta = 2$ mm, simultaneous temperature measurements were taken using three sensors (T_1, T_2, T_3), resulting in a total of 39 observations (three temperature maxima per experimental run). Fig. 8 shows the temperature plot for the second experimental run.

The summarized maximum temperature values for each experimental run are presented in Table 4.

The experiment showed that the characteristic temperature levels ranged from approximately 27 °C to 190 °C, with peak values up to ~189 °C observed under the most aggressive combination of cutting parameters (Run No. 2). This exceeds the technological heat resistance limit of the *MPCM* for finish machining operations, confirming the critical importance of proper selection of cutting conditions for *MCS* with this metallic shell thickness.

When constructing the model based on experimental data with thermocouples embedded at a depth of 2 mm, only the data obtained from thermocouple No. 3 were used. This model was designated as *2T3*, where ‘2’ denotes the thickness of the metallic shell, and ‘T3’ refers to the thermocouple from which the valid data were obtained. This decision was made because thermocouples No. 1 and No. 2 produced evidently unreliable readings in certain trials. For example, in Run 8, thermocouple No. 1 recorded a maximum temperature of 27.3 °C, which did not reflect the actual cutting conditions. Similarly, thermocouple No. 2 showed inconsistent readings during Runs 1, 4, 6, and 8.

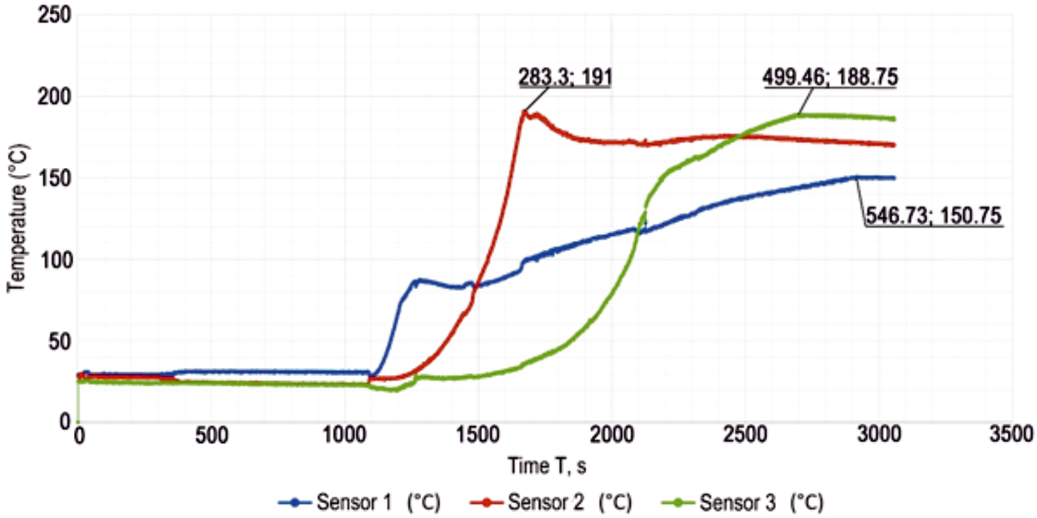


Fig. 8. Graph of temperature change during turning, experiment No. 2 (**δ** = 2 mm)

Table 4

Maximum temperature values from thermocouples for the 2 mm *MCS* metal shell

No.	Thermocouple 1, C	Thermocouple 2, ℃	Thermocouple 3, ℃	Average, ℃
1	96.8	75	155.75	109.2
2	150.8	191	188.75	176.8
3	112.0	113	111.75	112.3
4	153.3	106.25	148.5	136.0
5	108.5	106.5	102.25	105.8
6	100.5	77.5	140.5	106.2
7	96.5	90.25	86.75	91.2
8	27.3	70	97	64.8
9	105.8	112	103	106.9
10	108.5	109.25	104	107.3
11	80.0	68.75	96.25	81.7
12	84.8	73.58	101.1	86.5
13	83.9	72.63	100.1	85.5

Table 5 presents the values of the calculated polynomial coefficients obtained from the physical data. The least squares method was applied, which provides coefficient estimates through statistical procedures that account for effects such as parameter correlations.

For the *2T3* model, the statistical metrics are: $\boldsymbol{R^2} = 0.98534$, $\boldsymbol{F} = 22.4$, $\boldsymbol{p} = 0.01336$ (< 0.05). The resulting *2T3* regression model has the following form:

$$2T3 = 292.497 - 509.117S - 1.433\mathrm{V} - 134.602t - 98.166S^2 + 0.005\ V^2 +$$

$$+96.488t^2 + 2.104SV - 106.205St - 0.202Vt. \qquad (2)$$

The interpretation of the estimated coefficients in coded variables shows a consistent physical meaning of the main effects: the linear terms for feed ($\boldsymbol{x_S}$), cutting speed ($\boldsymbol{x_V}$), and depth of cut ($\boldsymbol{x_t}$) are negative (i.e., an increase in ***S***, ***V***, and ***t*** within the investigated ranges leads to a decrease in ***T***). Nonlinearity is expressed by the quadratic terms: one of the quadratic coefficients is significantly negative, while the other two are positive. Another quadratic term ($\boldsymbol{V^2}$) lies at the boundary of statistical significance. The pairwise interaction terms exhibit borderline significance, indicating a moderate but noticeable interdependence of the factors,

Table 5

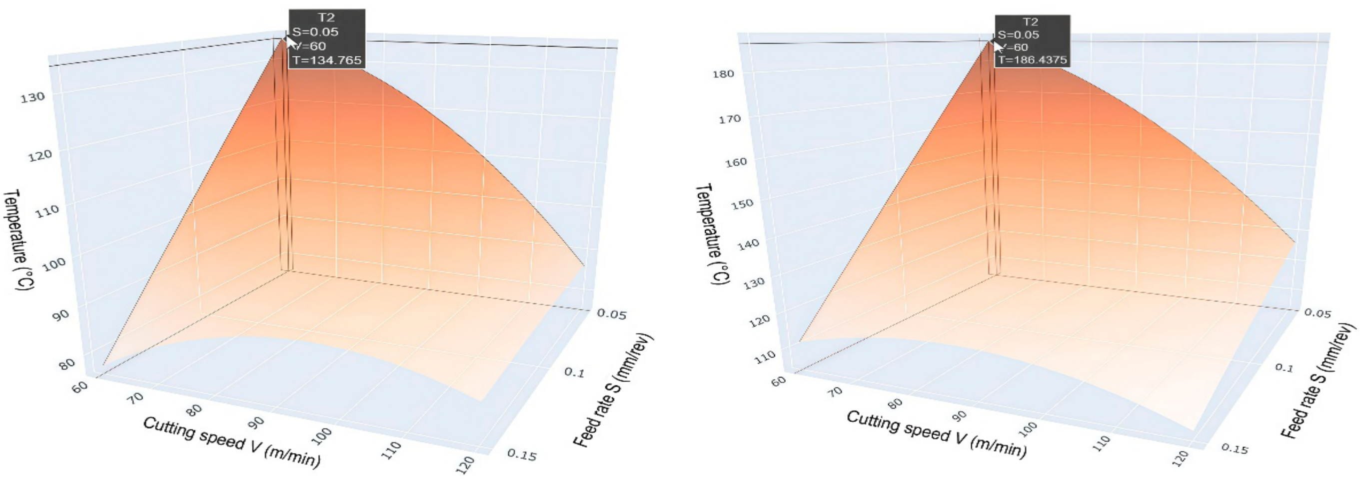
Evaluation of the significance of the coefficients of the *2T3* mathematical model

Symbol	Coefficient	Standard error SE_i	***t***-statistic	***p***-value	Interpretation
b_0	292.49651	29.17582	10.02530	0.00017	The coefficient is statistically significant (***p*** < 0,05)
b_1	−509.11672	144.98610	−3.51149	0.01707	The coefficient is statistically significant (***p*** < 0,05)
b_2	−1.43312	0.44609	−3.21259	0.02366	The coefficient is statistically significant (***p*** < 0,05)
b_3	−134.60192	16.56281	−8.12676	0.00046	The coefficient is statistically significant (***p*** < 0,05)
b_4	−98.16642	28.83137	−3.40485	0.01915	The coefficient is statistically significant (***p*** < 0,05)
b_5	0.00460	0.00233	1.97237	0.10560	The coefficient is not statistically significant
b_6	96.48846	6.11772	15.77196	0.00002	The coefficient is statistically significant (***p*** < 0,05)
b_7	2.10417	1.34301	1.56676	0.17795	The coefficient has low statistical significance
b_8	−106.25000	80.58035	−1.31856	0.24448	The coefficient is not statistically significant
b_9	−0.20208	0.13430	−1.50471	0.19273	The coefficient is not statistically significant

primarily between cutting speed and depth of cut, and between feed and cutting speed. Taken together, this means that for **δ** = 2 mm, the temperature is most sensitive to changes in depth of cut, followed by feed, and to a lesser extent cutting speed, which is consistent with the observed heating behavior in the experiments.

The constructed *2T3* model is presented in real physical units for engineering applications. Validation of the model using the full set of experimental observations demonstrated good agreement [24]. The maximum deviation between the calculated and experimental temperatures did not exceed 5 °C, which falls within the established allowable range. Overall, the level of discrepancy was deemed acceptable for predicting the threshold of 170 °C and for constructing temperature distribution maps [25, 26].

Visualization of the response surface ***T***(***V***, ***S***) at fixed values of ***t*** demonstrates a monotonic decrease in temperature ***T*** with increasing ***V*** and ***S***, as well as a shift of the isotherms toward more restrictive regions with increasing ***t*** (Fig. 9).



a *b*

Fig. 9. Temperature surface graphs for model *2T3*:

(*a*) cutting depth of 1 mm; (*b*) cutting depth of 1.5 mm

On the contour map for a cutting depth of t = 1.5 mm (Fig. 10), which corresponds to the most thermally loaded condition, an acceptable zone of cutting parameters can be identified, along with regions where the temperature potentially exceeds 170 °C.

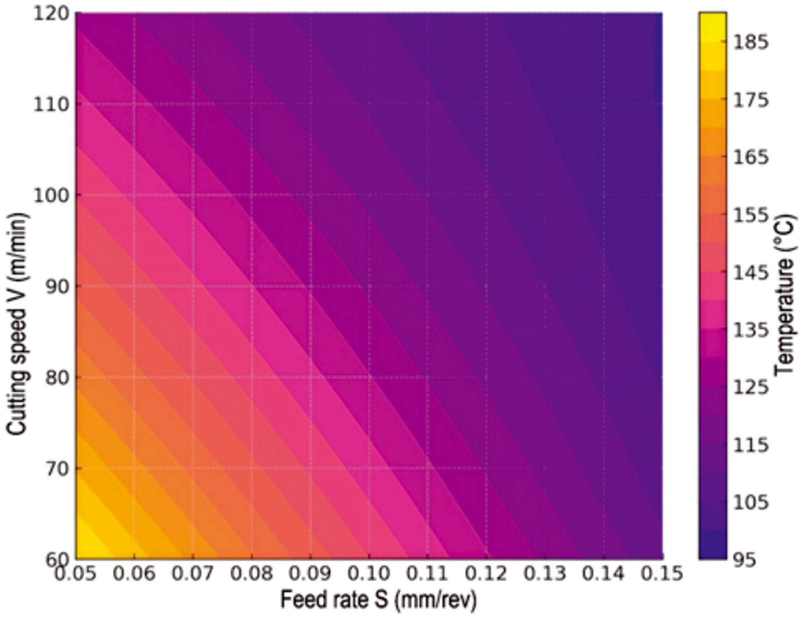


Fig. 10. Temperature contour graph for model *2T3*, with a cutting depth of 1.5 mm

Further research should be aimed at expanding the applicability of the obtained results:

1. Parametric investigation of the influence of shell thickness (**δ**) on the thermal response during turning;
2. Validation of the developed models on alternative grades of metal-polymer composites with different thermal conductivities and temperature limits, as well as on various structural steels;
3. Coupled analysis of the “temperature-surface roughness-tool wear” relationship, including the recording of cutting forces and vibroacoustic signals to construct integrated maps of permissible cutting conditions;
4. Although the experiment was conducted with the application of coolant and lubrication fluids (*CLF*), it is advisable to investigate the role of advanced cooling and lubrication techniques (such as minimum quantity lubrication (***MQL***) and cryogenic cooling) and their effect on reducing peak temperatures;
5. Identification and monitoring of heat transfer at the interfacial boundary, including the effect of adhesion degradation under cyclic thermomechanical loading;
6. Development of numerical 3D thermomechanical models and digital twins, calibrated using experimental data, to enable rapid prediction of optimal cutting conditions in industrial applications.

The implementation of these directions will allow the proposed approach to evolve into a standardized methodology for determining machining parameters for metal-composite systems (*MCS*) in tool engineering applications.

Conclusion

A hardware–software device has been developed and experimentally validated, accurately simulating a metal-composite system (*MCS*) comprising a thin-walled metallic shell and a metal-polymer composite filler. This setup enabled the direct measurement of the temperature response at the metal-*MPCM* interfacial boundary during the turning process.

The implemented full factorial experimental design $2^3 + n_0$ yielded statistically reliable data, allowing for the identification of the main effects and interactions of the cutting parameters (***V*, *S*, *t***) and accounting for nonlinear dependencies through the inclusion of central points.

The constructed second-order regression model for a shell thickness of **δ** = 2 mm (designated as model *2T3*) adequately describes the temperature at the interface and is consistent with the results of thermal imaging verification.

It was established that, within the investigated parameter ranges, the depth of cut (***t***) has the greatest influence on the temperature rise, the feed rate (***S***) has a moderate effect, and the cutting speed **(*V*)** has the least effect.

Based on the developed model, response surfaces and contour maps have been constructed. These allow for the identification of acceptable machining parameter regions that satisfy the condition **T** ≤ 170 °C, corresponding to the heat resistance threshold of the metal–polymer composite.

It was demonstrated that maintaining the technological constraint ***T*** ≤ 170 °C is achievable through a rational combination of parameters ***V*, *S*,** and ***t***. This confirms the feasibility of finish turning metal-composite systems without causing thermal damage to the polymer matrix of the filler.

The obtained results provide a scientifically grounded basis for standardizing the machining parameters of tool-engineering components, such as forming dies with conformal cooling channels and composite drill bodies, thereby reducing the risk of defects and improving product quality repeatability.

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Conflicts of Interest

The authors declare no conflict of interest.