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Original Empirical Research

Experimental Study and Modeling of Thermal Response in Turning a 3.5 mm Thick Shell of Metal Composite System

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Abstract

Introduction. Modern technologies of tool and mold production increasingly use metal-composite systems (MCS), which combine additively manufactured metal shells and metal-polymer fillers. This corresponds to priority areas of scientific and technological progress, such as digitalization and additive manufacturing (in accordance with the Federal Project "Development of Materials and Production Technologies" within the framework of the national program "Scientific and Technological Development"). The scope of application of MCS in industry is growing: according to industry reviews, their share in the production of high-precision components for the aerospace and automotive industries has increased by 25–30% over the past five years, providing economic benefits due to a 15–20% reduction in the weight of structures and improvement of the energy efficiency of processes. Such systems combine the strength and thermal conductivity of metal with the damping properties of polymers, yet exhibit high sensitivity to overheating during machining. Consequently, the temperature at the metal–MCPM (metal-polymer composite material) interface during turning may exceed the thermal stability threshold (170°C), resulting in thermal degradation, loss of adhesion, and shell deformation. In the literature, the problem of MCS thermal stability in turning is addressed only fragmentarily: existing studies focus on monolithic composites or general heat-transfer models, lacking detailed analysis of interfacial heating in additively manufactured systems featuring low-conductivity fillers. Therefore, research is needed to quantify the thermal response during the machining of such systems and to determine the cutting parameters that provide their thermal stability. The objective of this work is to experimentally study the temperature response during turning of MCS with a shell thickness of $\delta = 3.5$ mm and to construct a second-order regression model linking the temperature at the metal – MPCM interface with the cutting parameters.

Materials and Methods. A hardware-software measurement unit simulating the MCS structure was developed for the study. It included a replaceable bushing made of 12Kh18N10T steel, an internal insert made of Ferro-Chromium metal-polymer, three built-in type K thermocouples, and a data acquisition module based on an ESP32-WROOM microcontroller with MAX6675 converters, providing temperature recording at 5 Hz and data transmission via Wi-Fi. The accuracy of the measurements was confirmed by thermal imaging verification using FLUKE Ti400. The experiment was conducted according to the full factorial design (FFD) $2^3 + n_0$, in which cutting speed V, feed S and cutting depth t were varied. Data processing was performed by the least-squares method with adequacy validation using Fisher's F-test and coefficient significance by Student's t-test. Based on the results of processing in real physical units, a second-order regression model was constructed — model 3.5TP, designed for engineering prediction.

Results. The analysis of the experimental data showed that the thermal response of the metal–composite system was nonlinear. The depth of cut t was the dominant factor increasing the temperature, whereas within the investigated range, an increase in the feed rate S and cutting speed V led to a decrease in the interface temperature due to a shorter thermal exposure time and more intensive heat removal with the chip flow. The resulting 3.5TP model was characterized by the coefficient of determination $R^2 = 0.9513$, Fisher criterion value $F = 364.31$ and the significance level $p < 10^{-5}$, which validated its adequacy. Interpretation of the regression coefficients indicated that the depth of cut (t) had the strongest impact on the temperature rise, the feed rate (S) showed a moderate effect, and the cutting speed (V) had the least sensitivity within the investigated range. The constructed response surfaces and contour maps identified the "safe zones" of cutting conditions that satisfied the constraint $T \leq 170$°C, corresponding to the thermal stability limit of the metal–polymer filler. The average deviation between the experimental and calculated data did not exceed 7°C, that confirmed the high accuracy and predictive capability of the proposed model.

Discussion. The constructed 3.5TP model revealed the relationship between geometric and technology factors that determine the thermal load of the MCS during turning. The dominant impact of the depth of processing was due to the increase in the volume of the cut layer and heat generation in the contact zone, while the increase in feed and cutting speed was accompanied by compensating effects due to a decrease in the time of thermal contact and more intense heat removal with the chips. The results obtained indicated the need to optimize processing modes taking into account the shell thickness δ. Directions for further research were identified.
Conclusion. The conducted study demonstrates that the developed experimental setup reproduces accurately the thermal behavior of a metal–composite system composed of an additively manufactured metal shell and a metal–polymer filler. The constructed 3.5TP regression model adequately describes the temperature response during turning and can be used for engineering prediction of mechanical processing modes.

Keywords: additive technologies, metal polymer, cutting temperature, interfacial boundary

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Оригинальное эмпирическое исследование

Экспериментальное исследование и моделирование теплового отклика металл-композитной системы при точении оболочки толщиной 3,5 мм

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Аннотация
Введение. Современные технологии инструментального и формообразующего производства всё чаще используют металл-композитные системы (МКС), сочетающие аддитивно изготовленные металлические оболочки и металлополимерные наполнители, что соответствует приоритетным направлениям научно-технического прогресса, таким как цифровизация и аддитивное производство (в соответствии с Федеральным проектом «Развитие технологий материалов и производства» в рамках национальной программы «Научно-технологическое развитие»). Масштабы применения МКС в промышленности растут: по данным отраслевых обзоров, их доля в производстве высокоточных компонентов для авиакосмической и автомобильной отраслей увеличилась на 25–30% за последние пять лет, обеспечивая экономическую выгоду за счет снижения массы конструкций на 15–20 % и повышения энергоэффективности процессов. Такие системы сочетают прочность и теплопроводность металла с демпфирующими свойствами полимера, но характеризуются высокой чувствительностью к перегреву при механической обработке. Вследствие этого температура на границе «металл – МПКМ» при точении может превышать порог термостойкости (170°C), приводя к термодеструкции, потере адгезии и деформации оболочки. В литературе проблема термостабильности МКС при точении освещена фрагментарно: существующие работы фокусируются на монолитных композитах или общих моделях теплопереноса, без детального анализа межфазного нагрева в аддитивно-формованных системах с низкой теплопроводностью наполнителя. Поэтому необходимы исследования, позволяющие количественно описать тепловой отклик при обработке таких систем и определить параметры резания, обеспечивающие их термостабильность. Цель настоящей работы — экспериментальное исследование температурного отклика при точении МКС с толщиной оболочки δ = 3,5 мм и построение регрессионной модели второго порядка, связывающей температуру на границе «металл – МПКМ» с параметрами резания.

Материалы и методы. Для исследования был разработан программно-аппаратный измерительный узел, моделирующий структуру МКС. Он включал сменную втулку из стали 12Х18Н10Т, внутреннюю вставку из металлополимера «Ферро-хром», три встроенные термопары типа K и модуль сбора данных на микроконтроллере ESP32-WROOM с преобразователями MAX6675, обеспечивающий регистрацию температуры с частотой 5 Гц и передачу данных по Wi-Fi. Корректность измерений подтверждена тепловизионной верификацией с использованием FLUKE Ti400. Эксперимент проводился по плану полного факторного эксперимента (ПФЭ) $2^3 + n_0$, в котором варьировались скорость резания V, подача S и глубина резания t. Обработка данных выполнялась методом наименьших квадратов с проверкой адекватности по F-критерию Фишера и значимости коэффициентов по t-критерию Стьюдента. По результатам обработки в реальных физических единицах построена регрессионная модель второго порядка — модель 3.5TP, предназначенная для инженерного прогнозирования.

Результаты исследования. Анализ экспериментальных данных показал, что температурный отклик МКС имеет нелинейный характер, при этом глубина резания t является доминирующим фактором повышения температуры, тогда как в исследованном диапазоне увеличение подачи S и скорости резания V сопровождается снижением температуры на межфазной границе за счёт сокращения времени теплового воздействия и более интенсивного выноса тепла со стружкой. Полученная модель 3.5TP характеризуется коэффициентом детерминации $R^2 = 0{,}9513$, значением критерия Фишера $F = 364{,}31$ и уровнем значимости $p < 10^{-5}$, что подтверждает её адекватность. Интерпретация коэффициентов выявила, что глубина резания t оказывает наибольшее влияние на рост температуры, подача S — умеренное воздействие, а скорость резания V — минимальное. Построенные поверхности отклика и контурные карты позволили выделить «безопасные зоны» режимов, удовлетворяющих условию $T \leq 170$°C. Средние расхождения между экспериментальными и расчётными данными не превышали 7°C, что подтверждает высокую точность модели.

Обсуждение. Построенная модель 3.5TP раскрыла взаимосвязь геометрических и технологических факторов, определяющих термонагруженность МКС при точении. Доминирующее влияние глубины обработки обусловлено увеличением объёма срезаемого слоя и тепловыделения в зоне контакта, тогда как рост подачи и скорости резания сопровождается компенсирующими эффектами за счёт уменьшения времени теплового контакта и более интенсивного выноса тепла со стружкой. Полученные результаты свидетельствуют о необходимости оптимизации режимов обработки с учётом толщины оболочки δ. Определены направления дальнейших исследований.

Заключение. Проведённое исследование доказало, что разработанная экспериментальная установка корректно воспроизводит тепловое поведение металл-композитной системы с аддитивной оболочкой и металлополимерным заполнителем. Построенная регрессионная модель 3.5TP адекватно описывает температурный отклик при точении и может использоваться для инженерного прогнозирования режимов механической обработки.

Ключевые слова: аддитивные технологии, металлополимер, температура резания, межфазная граница

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Introduction. The modern development of tool and form-forming production, particularly in the aircraft and machine-building industries, is characterized by a transition to hybrid structural solutions that combine metal and composite components. One of the promising areas in this field is the development of metal-composite systems (MCS), in which thin-walled metal shells are combined with fillers made of metal-polymer composite materials (MPCM). This provides an optimal balance of strength, thermal conductivity and damping properties [1].

In recent years, additive manufacturing (AM) technologies [2] have become widespread, allowing for the formation of complex topologically optimized (TO) shells, including structures with conformal cooling channels that provide targeted heat dissipation and increased thermal stability of products [3]. This approach is particularly important for tooling products, for example, indexable drills with internal cooling channels (Fig. 1), manufactured through selective laser melting (SLM). They improve heat dissipation from the cutting zone and increase the durability of carbide heads [4].

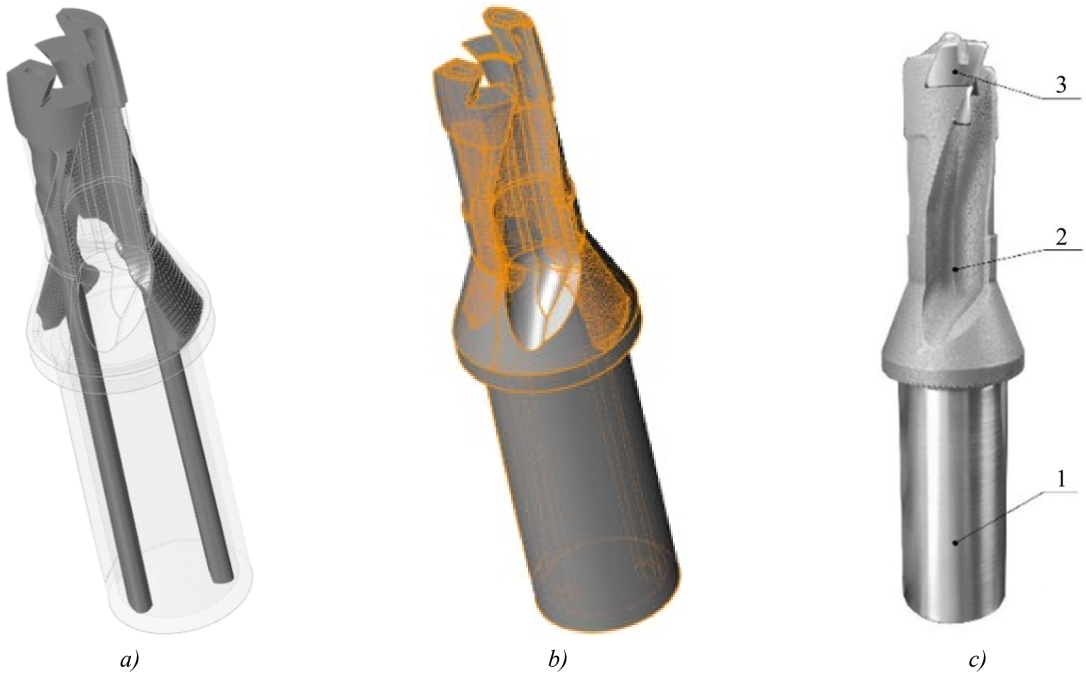


Fig. 1. Indexable drill: *a* — model of a topologically optimized part of a drill body with a setting head and curved cooling channels of the body; *b* — model of the TO drill body with a thin-walled shell forming the chip grooves and shank; *c* — physical sample of TO metal-composite indexable drill (cavity after TO is filled with MPCM), manufactured using SLM technology: 1 — machined metal-composite shank; 2 — chip grooves; 3 — cutting head of the indexable drill

The transition to hybrid metal-composite structures, despite obvious advantages, is accompanied by new technological constraints. The most significant of these are thermal processes during finishing machining, where local temperature distribution determines the strength of interfacial adhesion, geometric stability, and durability of the product. Unlike monolithic metal workpieces, the heat flow during turning of hybrid metal-composite structures is concentrated at the metal – MPCM interface, where the materials differ sharply in thermal conductivity and heat capacity [5]. Since the metal polymer is characterized by low thermal conductivity and limited heat resistance (up to 170°C), even short-term overheating can cause thermal destruction, reduced adhesion, and deformation of the shell. [6].

The analysis of the literature data shows that existing research in the field of thermal loading during cutting covers mainly homogeneous metal alloys [7] or metal-matrix composites [6], where the temperature field is described through the mechanisms of friction and hardening of surface layers. In studies on thin-walled parts [8], the main focus is on increasing rigidity and vibration resistance due to special basing systems and devices [9]. At the same time, hybrid metal-polymer structures remain virtually unexplored in terms of heat transfer patterns during turning.

Furthermore, traditional analytical and numerical heat transfer models used in cutting simulations are developed for materials with uniform thermal properties and do not take into account the discontinuity in thermal conductivity at the interphase boundary [8]. This makes it impossible to directly use known relationships to predict the temperature in the MCS where the metal and metal-polymer components interact.

Cooling and lubrication conditions, and the selection of tool materials and coatings also have an additional impact on thermal loading. It is known that the use of PVD coatings in combination with optimized conditions increases tool life when machining heat-resistant alloys [10], and modification of metalworking fluids (MWF) can reduce contact temperatures when turning titanium and aluminum alloys [11]. For additive materials obtained by surfacing, an increase in temperature gradients was noted due to differences in the thermal conductivity of the layers [12]. These effects are particularly significant when processing products with a combined metal-polymer structure.

Additively produced shells are also characterized by increased roughness and residual stresses [13], which affect local heat transfer and the generation of contact temperature [14]. This further complicates the selection of rational processing modes, requiring the construction of experimentally verified thermal response models.

Thus, in the modern scientific picture, there is a gap in knowledge due to the lack of experimentally confirmed data and validated regression models describing the temperature response of metal-composite systems during finishing. The effect of the metal shell thickness on the efficiency of heat dissipation and the nature of the temperature gradient in the metal – MPCM contact zone remains particularly understudied.

The objective of this study is to experimentally determine the temperature response of a metal-composite system with a metal shell thickness of 3.5 mm during turning, as well as to construct a regression model of the dependence of the temperature at the interphase boundary on cutting conditions (*V*, *S*, *t*).

To achieve this objective, the following tasks were completed:

– development and production of a hardware-software stand for real-time temperature recording during turning the MCS;

– conducting a series of experiments according to a full factorial design 2^3+n_0 with varying cutting parameters;

– constructing a second-order regression model and assessing its adequacy on statistical criteria;

– determining safe turning ranges that prevent overheating of the metal-polymer filler and adhesion failure.

The implementation of the set tasks is aimed at the development of an engineering-applicable methodology for selecting finishing modes for metal-composite systems, providing control of thermal loading, and preservation of the structure of the metal-polymer filler.

Materials and Methods. Experimental studies are directed at determining the thermal response patterns of a metal-composite system (MCS) during turning, taking into account the geometric parameter — the thickness of the metal shell. To simulate the actual structure of hybrid products, a hardware-software setup is developed, including a replaceable metal bushing and an internal filler made of a metal-polymer composite material (MPCM).

The development of the setup, whose model is shown in Figure 2, made it possible to simulate the conditions of turning a fragment of a hybrid part with a given wall thickness and record the temperature in real time at the interphase boundary "metal – MPCM".

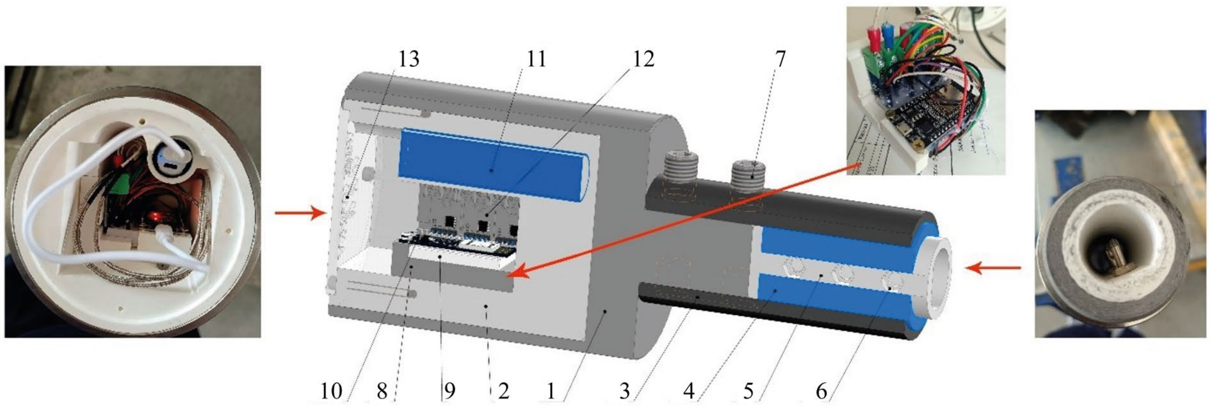


Fig. 2. Hardware-software setup for simulating real structure of hybrid products:
1 — external device housing; 2 — electronics housing; 3 — metal shell; 4 — metal-polymer filler;
5 — thermocouple housing; 6 — thermocouple mounting holes in the housing; 7 — mounting screws;
8 — microprocessor housing; 9 — breadboard; 10 — microprocessor; 11 — battery;
12 — thermocouples; 13 — cover

The major element of the setup was a housing made of grade 40 structural steel, providing secure placement in the chuck of 16K20 lathe. A replaceable bushing made of 12Kh18N10T steel (similar to AISI 321) was fixed inside the housing. This steel has low thermal conductivity (~15–16 W/(m·K)) and is resistant to high temperatures. This makes it a suitable model for high-alloy steels used in additive manufacturing [15]. The metal bushings were cylindrical with an inner diameter of 53 mm and an outer diameter of 60 mm, corresponding to a metal thickness of δ = 3.5 mm. This element simulated the metal shell of a real hybrid part and allowed for varying the geometric parameters for subsequent studies. Figure 3 shows the machined replaceable bushing.

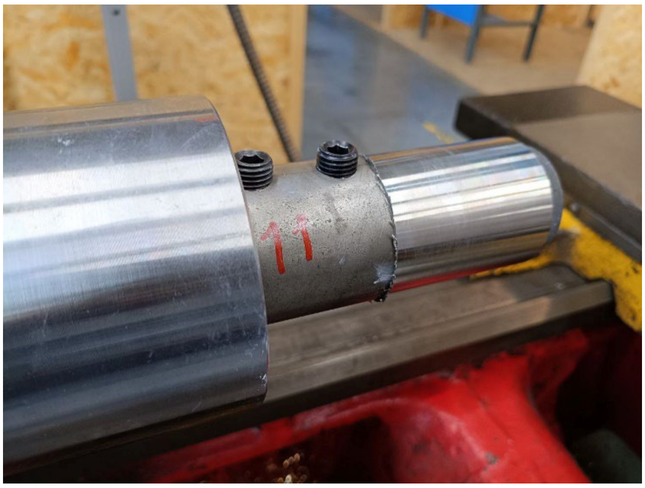


Fig. 3. Machined bushing

A Ferro-Chrom[1] MPCM insert was installed in the inner cavity of the bushing. It was pre-molded to the nominal diameter and secured with KPT-8 thermal paste to improve thermal contact. The MPCM contained a thermosetting epoxy matrix filled with powdered chromium particles. The material had a limited thermal resistance of up to 170°C and a thermal conductivity of approximately 2 W/(m·K). This combination of materials provided adequate reproduction of the thermal interaction at the metal – MPCM interface.

Three K-type thermocouples were used to record temperature. They were embedded in the wall of the bushing along the sample axis and spaced equally along the cutting zone. The thermocouple signals were fed to MAX6675 analog-to-digital converters connected to an ESP32-WROOM microcontroller, which provided digitization and wireless data transmission. The electronic components were located in a separate cavity of the housing, protected by a plastic holder. Power was supplied from a 2600 mA· h rechargeable battery, providing several hours of continuous operation.

Temperature was recorded at a frequency of 5 Hz, and data was transmitted via the UDP protocol through the built-in Wi-Fi module. On a personal computer, the data was visualized in real time using a Python 3.12 API (Fig. 4), implemented by the *PyQtGraph, Matplotlib*, and *Pandas* libraries. This allowed for rapid monitoring of temperature variation at the interface and storing the results as digital arrays for subsequent processing.

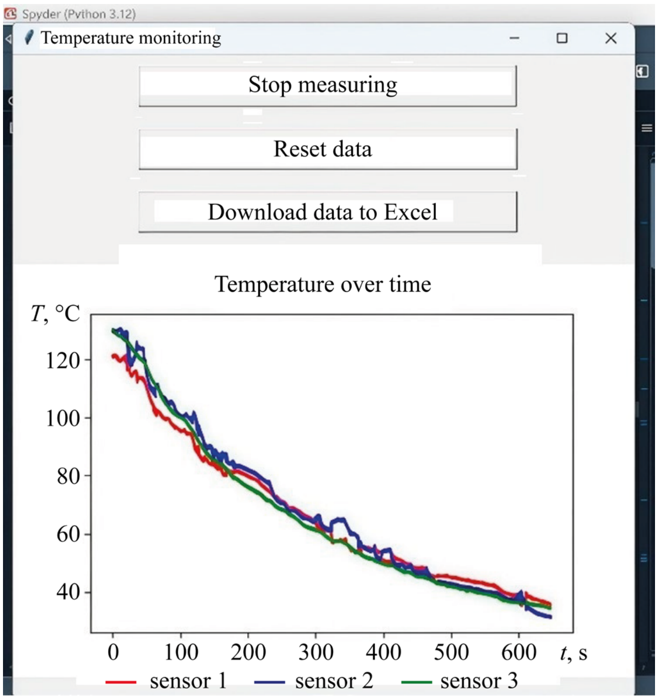


Fig. 4 Temperature Monitoring program interface on a PC (cooling process)

[1] Specifications TU 2257–002–48460567–00. *“Ferro-Chrom” Metallopolymer*. Moscow: ZAO “LEO Metal-Polymer Mmaterials”; 2000. URL: https://www.leo-polymer.ru (accessed: 01.11.2025).

To validate the operation of the thermocouples and control the temperature distribution over the surface of the bushing, thermal imaging verification was performed using a FLUKE Ti400 device [16]. The comparison results showed that the deviations between the thermocouple and thermal imaging data did not exceed ±3°C, which confirmed the reliability of the recording scheme used.

Thus, the developed setup is an autonomous measuring unit capable of recording the temperature at the interface of a metal-composite system with high frequency and sufficient accuracy. Its design allows for studies to be conducted under various shell geometric parameters and cutting conditions, that makes it possible to develop an experimentally validated model of the MCS thermal response during turning.

The experiment was designed to identify quantitative patterns in the effect of cutting conditions on the temperature response of a metal-composite system with a metal shell thickness of δ = 3.5 mm. For this purpose, an approach based on the full factorial experiment (FFE) methodology was used [17], which made it possible to study the interaction of process parameters and construct a second-order regression model suitable for engineering prediction.

The selection of this scheme is explained by the need to evaluate not only the key factors but also their interaction, since thermal loading during MCS turning is a multiparameter function dependent on cutting speed, feed, and depth. Moreover, unlike traditional metal workpieces, the behavior of hybrid systems is determined by uneven heat transfer at the interface, which increases the nonlinearity of the relationships.

The variable factors were cutting speed V (m/min), feed per revolution S (mm/rev), and cutting depth t (mm). Each factor was assigned two levels — upper and lower — corresponding to code values of +1 and –1 (Table 1).

Table 1

Experimental Factors Variation Levels

Factor	Designation	–1	0	+1
Feed, S mm/rev	x_1	0.05	0.10	0.15
Cutting speed, V m/min	x_2	60	90	120
Cutting depth, t mm	x_3	0.5	1.0	1.5

To assess possible nonlinearity and check reproducibility, five replicate experiments with zero code values (0, 0, 0) were added to the center of the design. Thus, the overall experimental structure included eight factorial and five central points (Table 2), which made it possible to construct an adequate approximation model without increasing the size of the experiments.

Table 2

Full Factorial Design

Experiment number	x_1, (S, mm/rev)	x_2, (V, m/min)	x_3, (t, mm)	Mode (code)
1	0.50	60	0.05	(–1, –1, –1)
2	0.50	60	0.15	(–1, –1, +1)
3	0.50	120	0.05	(–1, +1, –1)
4	0.50	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)

The temperature at the metal – MPCM interface was measured simultaneously by three thermocouples (T_1, T_2 and T_3), positioned along the workpiece axis. For each experiment, the maximum temperature values were determined, and the average value T_{cp}, characterizing the integral thermal response of the system, was calculated.

The experimental results were used to construct a regression function describing temperature T at the metal – MPCM interface in coded variables x_1, x_2, x_3 using equation (1):

$$T = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_1^2 + b_5 x_2^2 + b_6 x_3^2 + b_7 x_1 x_2 + b_8 x_1 x_3 + b_9 x_2 x_3. \quad (1)$$

The model coefficients were determined by the least-squares method, which minimized the sum of squared deviations between the experimental and calculated temperature values. The significance of the coefficients was tested using Student's *t*-test, and the adequacy of the model as a whole was assessed using Fisher's *F*-test at a significance level of α = 0.05, which is the standard for engineering experiments in the mechanical processing [18].

The quality of the approximation was assessed using the coefficient of determination R^2, which characterized the proportion of explained variation in the response. Values $R^2 \geq 0.95$ were interpreted as indicating high agreement between the model and the experiment. Additionally, the relative deviation ΔT was calculated from formula (2):

$$\Delta T = \frac{\left|T_{\text{эксп}} - T_{\text{мод}}\right|}{T_{\text{эксп}}} \cdot 100\%. \qquad (2)$$

Minimum values ΔT, not exceeding 7–8%, showed a good fit between the model and the observed data.

All statistical processing was performed in Excel and Python using built-in regression analysis tools and the statsmodels package. This approach provided reproducible calculations, clear graphical representation, and the ability to subsequently validate the model in automated engineering analysis systems.

Thus, the selected experimental design scheme allowed us to generate a statistically reliable database required for constructing the 3.5TP regression model and subsequent analysis of the thermal behavior of the metal-composite system. The resulting relationships served as the basis for determining critical cutting conditions that preserved the structure of the metal-polymer filler and the stability of the shell geometry.

Research Results. The experiments yielded a set of data reflecting the dynamics of temperature variation at the metal-composite interface during turning of specimens with a shell thickness of 3.5 mm. Processing of the results revealed that the temperature response of the metal-composite system was nonlinear, and it was determined by a combination of cutting conditions. It was found that increasing the cutting depth t led to a growth of temperature, while in the studied range, increasing the feed rate S and cutting speed V was accompanied by a decrease in temperature at the interphase boundary. Moreover, the impact of the parameters was interrelated, therefore the nature of the temperature variation should be assessed using the response surfaces.

Figure 5 shows a typical temperature dependence obtained with fixed machining parameters. The curve demonstrates the initial heating phase, followed by a brief temperature increase to a steady-state level, after which thermal equilibrium is observed. The average duration of the transient mode was 2–5 minutes, corresponding to the time it took for the heat flow in the cutting zone to stabilize, followed by slow cooling.

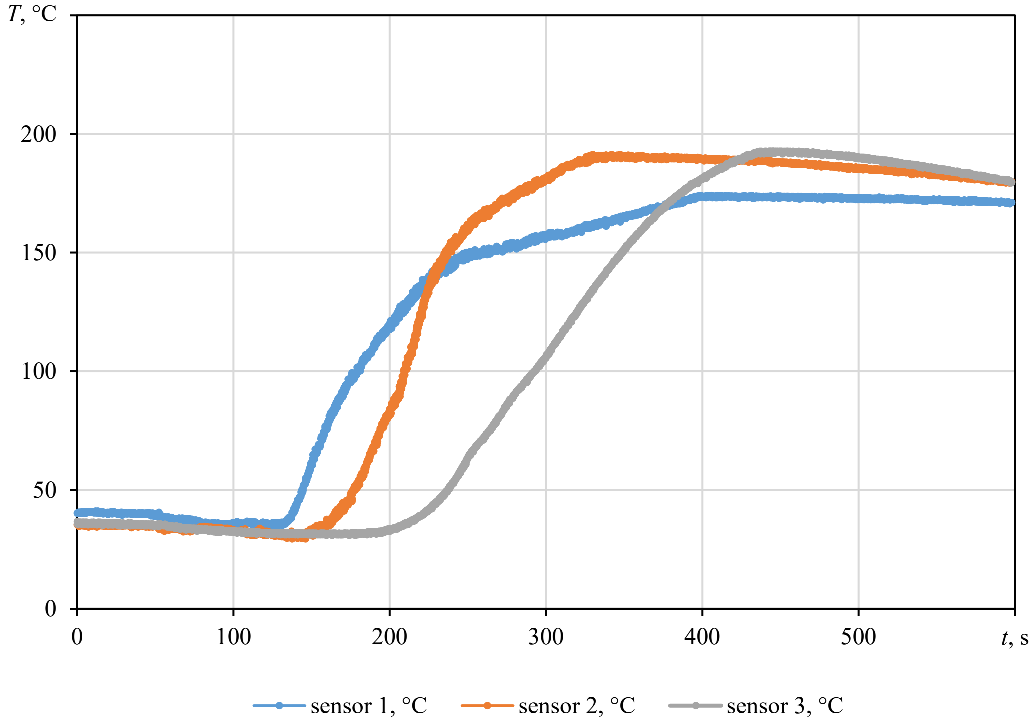


Fig. 5. Temperature change graph during turning, experiment no. 2, δ = 3.5 *mm*

Average temperatures T_{cp}, calculated from the results of 13 full factorial experiments, ranged from 90 to 186°C. The highest temperatures were observed under conditions with increased cutting depth t combined with reduced S and V values (within the studied levels), while temperature reduction was achieved with increased feed and speed at a fixed cutting depth.

The maximum temperatures at the interphase boundary are shown in Table 3.

Table 3

Maximum Temperature Values for Thermocouples with a Metal Thickness of 3.5 mm

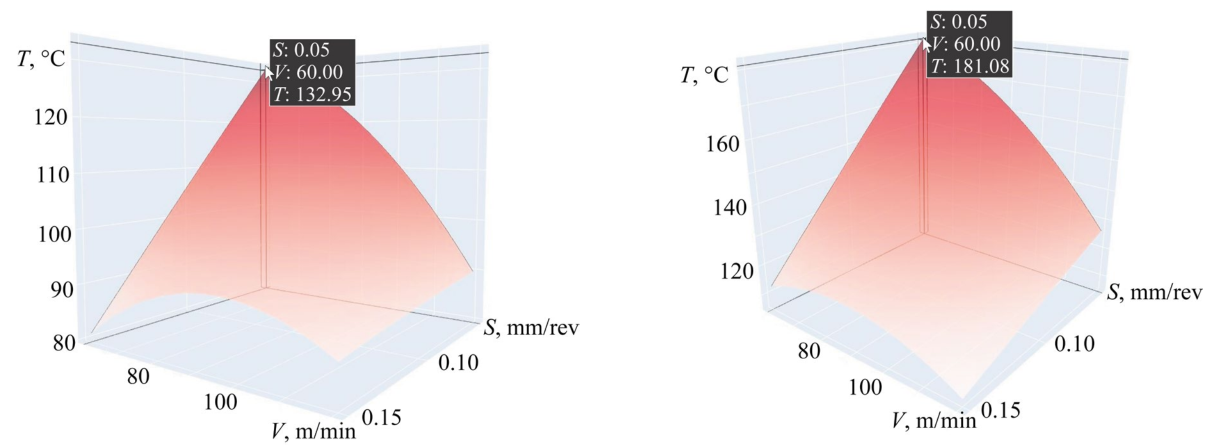
Experiment no.	Thermocouple 1, °C	Thermocouple 2, °C	Thermocouple 3, °C	Average, °C
1	120.00	116.75	111.75	116.17
2	174.25	191.50	192.75	186.17
3	97.00	90.50	95.75	94.42
4	120.75	121.25	122.50	121.50
5	95.50	87.00	89.25	90.58
6	112.25	106.50	105.00	107.92
7	103.50	95.25	92.50	97.08
8	118.50	111.25	106.75	112.17
9	104.25	103.00	99.75	102.33
10	109.00	101.50	101.50	104.00
11	112.75	106.25	102.75	107.25
12	111.50	104.00	102.00	105.83
13	113.75	108.50	111.00	111.08

Based on the experimental data processing for samples with a metal shell thickness of $\delta = 3.5$ mm, several regression models of the temperature response T were constructed: separately for each sensor (T_1, T_2, T_3), for the average temperature value, and for the combined sample. The comparative analysis showed that the models constructed on individual measurement channels were characterized by high determination coefficients ($R^2 \approx 0.96$–0.97) and statistically significant coefficients at the $p < 0.5$ level. However, the most robust and informative model was the combined (extended) model, which took into account the combined data from all three thermocouples. This model, designated as 3.5TP, tripled the observation volume, increasing its statistical power and the reliability of engineering predictions.

For the 3.5TP model, the determination coefficient was $R^2 = 0.9513$, and the Fisher's exact test value was $F = 364.31$, with a significance level of $p < 10^{-5}$, indicating high adequacy of the model to the experimental data. Based on the estimated coefficients, regression equation in physical units was obtained (3):

$$3.5TP = 1484.16 \cdot S^2 + 7.604 \cdot S \cdot V - 388.75 \cdot S \cdot t - 915.59 \cdot S + 0.0041 \cdot V^2 - \\ -0.4646 \cdot V \cdot t - 1.376 \cdot V + 14.84 \cdot t^2 + 85.44 \cdot t + 182.57. \quad (3)$$

Based on the obtained 3.5TP model, surface graphs were constructed reflecting the interaction of factors (Fig. 6).



a) *b)*

Fig. 6. Temperature surface graphs for 3.5TP model: *a* — cutting depth of 1 mm; *b* — cutting depth of 1.5 mm

The constructed 3.5TP model is characterized by high approximation accuracy. Validation against the full observation matrix showed that the deviation between the calculated and experimental temperature values (ΔT) in most cases did not exceed 1–7 °C. Only in certain combinations of modes, deviations of the order of 10–12 °C were observed, which was due to local inhomogeneity of heat transfer at the metal – MPCM boundary and differences in the emissivity coefficient when compared with thermal imaging verification data [19]. Overall, the level of discrepancies is considered acceptable for engineering tasks of prediction and construction of temperature maps.

Figure 7 shows a contour map of the temperature fields constructed using equation (2) for a cutting depth of 1.5 mm.

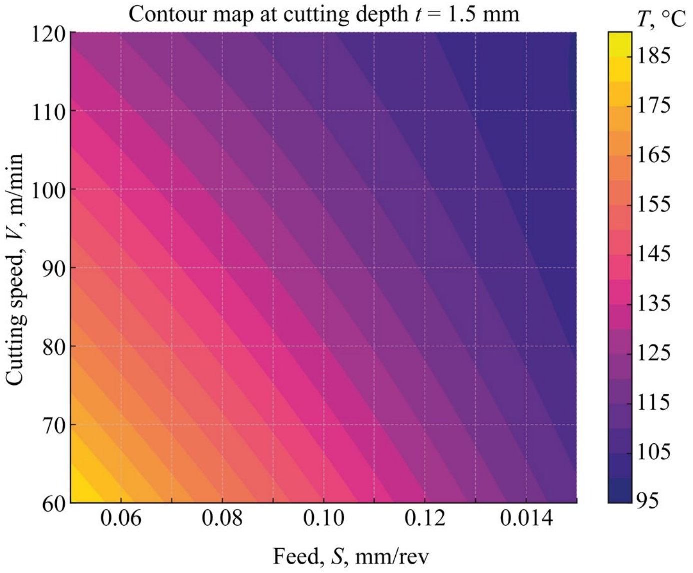


Fig. 7. Temperature contour graph for 3.5TP model, with cutting depth of 1.5 mm

The constructed 3.5TP regression model reliably describes the thermal behavior of a metal-composite system with a metal shell thickness of 3.5 mm during turning. The model has high predictive power and can be used to determine safe machining conditions that prevent the 170°C threshold from being exceeded.

Discussion. The analysis of the obtained coefficients has shown a consistent physical meaning for each term of the equation. The linear coefficients for feed and speed ($-915.59S$ and $-1.376V$) have negative values, indicating a decrease in temperature as these parameters increase over the studied range. This effect is explained by the fact that increasing cutting speed reduces the time of thermal contact between the tool and the workpiece surface, while the increase in supply contributes to a more intensive heat removal from the chips. Meanwhile, the coefficient for depth of cut is positive ($+85.44t$), which corresponds to the observed increase in temperature with increasing cross-section of the cut layer.

The nonlinearity of the dependence is expressed by the quadratic terms S^2, V^2 and t^2, among which the positive coefficient for S^2 is particularly significant, reflecting the effect of optimal feed: after reaching a certain level, increasing the feed again leads to a growth of temperature due to increased cutting force and friction on the flank of the tool. One of the quadratic terms is negative, indicating a saturation effect, and another is at the border of statistical significance.

The paired relations of $S \cdot V$, $S \cdot t$ and $V \cdot t$ demonstrate moderate but significant factor interactions. The most pronounced interdependence was between cutting speed and depth ($-0.4646Vt$), reflecting compensation for the thermal effect due to increased heat transfer across the shell thickness. The interaction of feed and speed ($+7.604SV$) indicates the presence of regions where a coordinated increase in these parameters contributes to temperature stabilization, which is confirmed experimentally (Fig. 6).

The results obtained confirm the high sensitivity of the thermal response of the metal-composite system to the combination of process parameters and demonstrate the significance of the geometric and thermophysical characteristics of the structure. The constructed 3.5TP model shows that even with a relatively small shell thickness of $\delta = 3.5$ mm, heat transfer processes in the cutting zone are determined by the complex interaction of cutting parameters and the material properties of the metal – MPCM system. This allows us to assert that further development of research should be aimed at expanding the scope of applicability of the obtained patterns and increasing the universality of the proposed model.

A promising direction is the parametric study on the effect of metal shell thickness on the thermal behavior of the MCS during turning. The variation of δ affects the heat rejection rate and the temperature field pattern, thus allowing the overheating resistance of the metal-polymer to be controlled. Systematic variation of the shell thickness will make it possible to construct a generalized *"δ–T"* relationship, enabling the prediction of thermal risks for various hybrid component configurations.

An equally important task is to validate the constructed model on alternative types of metal-polymer composites with different thermal conductivity, heat capacity, and temperature rating. Conducting similar experiments with composites based on aluminum or nickel fillers, as well as using other grades of structural steel, will help determine universal heat transfer patterns and refine the applicability limits of the regression relationships.

The next direction should be a comprehensive study of the relationship between temperature, surface roughness, and tool wear, supplemented by recording cutting forces and vibroacoustic characteristics. This coupled analysis will enable the development of integrated maps for permissible machining conditions, where thermal constraints are considered alongside surface quality and tool life indicators. This will lay the groundwork for multi-factor optimization of the process parameters.

The impact of metalworking fluids (MWF) on reducing temperature extremes in the cutting zone deserves special attention. The experiment used a standard MWF supply, but it would be advisable to further explore alternative technologies, such as minimum quantity lubrication (MQL), aerosol cooling, and cryogenic techniques. These methods can provide localized temperature reduction and reduce the thermal impact on the metal-polymer filler, specifically when working near the 170°C threshold.

An important area for further research is the identification of heat transfer mechanisms and the degradation of adhesive bonds at the metal – MPCM interface under cyclic thermomechanical loads. Monitoring this effect will enable a quantitative evaluation of the contact zone stability and a more precise definition of the durability criteria for hybrid components in service.

Finally, numerical 3D models of thermal processes and digital twins of metal-composite systems offer significant potential for improving prediction accuracy. Their development and calibration using the experimental data obtained in this work will open up the possibility of rapid engineering calculation of temperature fields under production conditions and the implementation of the method in an adaptive process control system.

Pursuing the outlined directions will enable the transformation of the proposed approach into a standardized methodology for assigning mechanical processing modes for metal-composite systems, providing robust control of the thermal load and durability of tooling products.

Conclusion. The conducted research has confirmed the feasibility of accurate experimental simulation of the thermal behavior of metal-composite systems (MCS), which comprise an additively manufactured metal shell filled with a polymer composite, by means of the developed measuring assembly. The experimental apparatus was designed to provide reliable temperature measurements at the metal–polymer composite interface, enabling a quantitative evaluation of the thermal load during turning under conditions representative of practical engineering applications.

The application of a full factorial experimental design provided the identification of the major effects of cutting parameters, the determination of their interactions, and the detection of nonlinearities through introducing central points. The constructed second-order regression model for the shell thickness variant of δ = 3.5 mm (3.5TP model) demonstrated high statistical adequacy ($R^2 = 0.9513$, $F = 364.31$, $p < 10^{-5}$) and good agreement with the results of thermal imaging verification, validating the experimental methodology.

Engineering interpretation of the model coefficients has shown that the depth of cut t is the decisive factor affecting the temperature increase, whereas the feed rate S has a moderate effect, and the cutting speed V exhibits the lowest sensitivity within the ranges studied. These relationships provide a clear understanding of the contribution of each parameter to the thermal response and can be applied to optimize the machining parameters.

Based on the 3.5TP model, response surfaces and a contour map of temperature fields are constructed, allowing for the identification of "safe zones" of turning modes in which the temperature at the metal-polymer composite interface does not exceed the limit value of T ≤ 170°C. The introduction of this technological constraint prevents thermal degradation of the metal-polymer composite and confirms the feasibility of finish turning of MCS without damaging the filler.

The developed model is of significant applied value for engineering prediction and standardization of process modes for the machining of hybrid components — both for shaping molds with conformal cooling channels and for composite bodies of indexable drills. Practical implementation of the proposed approach reduces the risk of thermal damage to metal-polymer structures, improves the reproducibility of product quality characteristics, and guarantees their operational durability while maintaining high process efficiency.

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