

An Experimental Investigation of the High-Speed Milling of VT1–0 Titanium Alloy and Cutting Parameter Optimization Using Numerical Modeling

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ABSTRACT

This paper presents the results of an experimental study on high-speed milling of the VT1-0 titanium alloy. A solid carbide end mill, MC089, with a diameter of 16 mm, was used as the cutting tool. The results indicated that the influence of the cutting parameters on the machined surface roughness is complex. An increase in spindle speed has a positive effect on surface roughness, whereas an increase in feed rate and depth of cut has a negative effect. The optimal cutting parameters were determined as follows: spindle speed $n_{sp}=4200$ rot/min, depth of cut $t=1$ mm, and feed rate $S=4500$ mm/min. A numerical modeling methodology was developed to determine the optimal cutting parameters for the same process. A three-dimensional model of the "tool-workpiece" system was developed using KOMPAS-3D and ANSYS Workbench, and the Johnson-Cook material failure model was selected. The contact interaction was defined, and a finite element model was developed. A numerical design of experiments was carried out using a rational planning method with variation of the main machining parameters, including depth of cut, feed rate, and spindle speed. As a result, temperature fields, contact forces, and plastic strain distributions were obtained. In addition, a mathematical model was developed to predict the workpiece temperature as a function of machining parameters. The minimization of the objective function enabled identifying the optimal cutting parameters that ensure minimal thermal impact: depth of cut $t = 1$ mm, feed rate $S = 4500$ mm/min, and spindle speed $n_{sp} = 4162$ rot/min. Comparison with the experimental results showed a slight discrepancy in the optimal cutting values. The proposed methodology can be used to reduce the cost of conducting physical experiments and improve machining efficiency.

Keywords-titanium alloys; high-speed milling; end mill; cutting tool wear; surface roughness; numerical modeling; cutting parameters

I. INTRODUCTION

The machining of difficult-to-cut materials remains a significant challenge for many mechanical engineering enterprises in Kazakhstan and is associated with high material costs and low productivity. These difficulties are largely caused by the high hardness, strength, toughness, corrosion resistance, and heat resistance of such materials combined with their low thermal conductivity, which significantly complicates cutting processes and leads to increased cutting tool consumption [1]. One of the most widely used difficult-to-cut materials in domestic industrial practice is Titanium Alloys (TA). The machinability of TA is of considerable scientific and practical interest and has been extensively studied by both domestic and international researchers.

The widespread adoption of TA as substitutes for aluminum and magnesium alloys, particularly in the aerospace industry, has resulted in a sharp increase in machining complexity. According to available estimates, the labor intensity of machining TA has increased by approximately an order of magnitude, while the demand for cutting tools has risen by 10–15 times. The relevance of this problem is further intensified by the extensive use of Computer Numerical Control (CNC) machine tools, where high requirements for accuracy and process stability must be met. The most significant technological challenges arise during rough machining of workpieces with scale or casting skin, machining of small-diameter holes, thread cutting, and finishing operations. The latter requires a combination of high productivity and high surface quality, which directly affects the strength and service life of parts. Despite the substantial volume of previous research, the mechanisms responsible for the reduced machinability of TA remain insufficiently understood. Significantly higher temperatures are generated in the cutting zone during TA machining compared to carbon and alloy steels, leading to more severe cutting conditions and accelerated tool wear [2-4].

Titanium and its alloys are difficult to machine due to the formation of thin chips, which results in a small contact area between the cutting tool and the workpiece. Authors in [5] presented the results of an experimental investigation of the influence of Minimum Quantity Lubrication (MQL) on the milling of the Ti-6Al-4V alloy, taking into account the optimization of surface roughness and machining productivity. The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method, based on the Taguchi algorithm, and Analysis of Variance (ANOVA) were employed to analyze the experimental results. The experimental findings demonstrated that MQL using vegetable oil can be successfully applied in the milling of the Ti-6Al-4V alloy.

Another characteristic feature of TA is the exceptionally low chip compression ratio. The phenomenon of "negative chip compression" has been reported, which may be attributed either to gas saturation of the material or to its low plasticity, resulting in the formation of highly segmented chips [6].

During the machining of TA, a substantial temperature rise is observed in the deformation zone due to their low thermal conductivity. An additional factor increasing the thermal load on the cutting tool is the small chip compression ratio, which leads to higher chip flow velocity along the front surface of the cutting tool, increased friction forces, and, consequently, a significant increase in heat generation in the contact zone. These conditions adversely affect tool life and cutting process stability [7, 8].

Among the key factors responsible for the poor machinability of TA is a tendency of the chip to weld to the cutting tool. This intensifies adhesive wear, and repeated tool engagement results in the detachment of tool material particles, significantly reducing tool life. This effect is observed even when modern cutting tool materials are used, severely complicating the implementation of stable and efficient cutting processes [9]. Another important feature of TA is their high chemical reactivity with environmental components,

particularly oxygen and nitrogen, and especially at elevated temperatures generated during cutting. Interaction between titanium and these gases leads to the embrittlement of both the removed material and the cooled surface layer. The formation of a hardened surface layer further accelerates cutting tool wear. The influence of oxygen and nitrogen on the machinability of TA and the associated accelerated tool degradation has been addressed in [9-11]. An increase in gas content in the metal reduces plasticity, which is accompanied by higher cutting forces, increased contact stresses on the rake face, and the occurrence of vibration, negatively affecting machining stability and accuracy.

Considering that a large proportion of components produced by mechanical engineering enterprises are rotational parts, the application of multi-tooth cutting tools, such as milling cutters for machining TA, is significantly limited. This limitation is due both to the lack of specialized equipment and to insufficient development of milling and mill-turning technologies for titanium alloy shafts. As a result, there is a need to develop effective machining technologies that ensure the required surface quality without the use of grinding operations while mitigating the technological challenges inherent in cutting TA.

To address this problem, high-speed milling of TA is proposed. Until recently, the implementation of high-speed machining in domestic manufacturing was constrained by the lack of modern high-speed machine tools such as machining centers and CNC semi-automatic machines. However, most domestic mechanical engineering enterprises are equipped with machine tools from foreign manufacturers, including Victor Taichung (Taiwan), KAPP Nils (Germany), DOOSAN (Korea), MODUL (Germany), and others.

The availability of such machine tools with advanced technological capabilities enables the application of more productive machining methods, including high-speed milling. High-speed milling of difficult-to-cut materials, particularly TA, represents one of the developing research directions and remains insufficiently studied compared to other machining methods. A key challenge lies in selecting appropriate cutting parameters depending on the workpiece material and cutting tool material. Reference data for cutting parameter selection at high spindle speeds (e.g., 5000–12000 rot/min) are largely unavailable, as previously used conventional machine tools were limited to spindle speeds below 2000 rot/min [12-14]. Consequently, existing machining handbooks provide recommendations only within this limited speed range.

In this context, scientific research aimed at addressing the problem of selecting optimal cutting parameters for high-speed milling of TA is highly relevant for the domestic mechanical engineering industry.

II. MATERIALS AND METHODS

Experimental investigations of high-speed milling were carried out at a vertical CNC machining center (V-Center P76). Workpiece specimens made of the VT1–0 titanium alloy were prepared with dimensions of 160 × 75 × 32 mm. A solid carbide end mill, MC089, with a diameter of 16 mm, was used

as the cutting tool. Its technical specifications are shown in Table I.

TABLE I. TECHNICAL SPECIFICATIONS OF THE SOLID CARBIDE END MILL

Type	Solid carbide end mill
Series	089
Cutting diameter (D), mm	16
Overall length (L), mm	100
Number of flutes, z	4
Body material	Solid 30KhGSA steel
Number of regrinds	6–8 times

The experimental investigations were carried out without the use of cutting fluid. The measured roughness parameter was Ra, with a cutoff length of $\lambda_c = 0.8$ mm. Surface roughness evaluation and measurements were performed in accordance with GOST R ISO 4287-2014.

Temperature monitoring was performed during the experimental stage of the study using an electronic measuring device. The obtained experimental data were used for qualitative validation of the Finite Element Method (FEM) results. The temperature measured in the experiment characterizes the thermally accessible system response available for registration, whereas the numerical model evaluated the temperature state of the material directly within the cutting zone. Therefore, the performed comparison should be considered as a limited experimental verification of the developed model.

Figure 1 displays the technological equipment and tooling that were used, and Figure 2 presents the machining process. The dependence of the machined surface roughness on cutting parameters is illustrated in Figure 3.

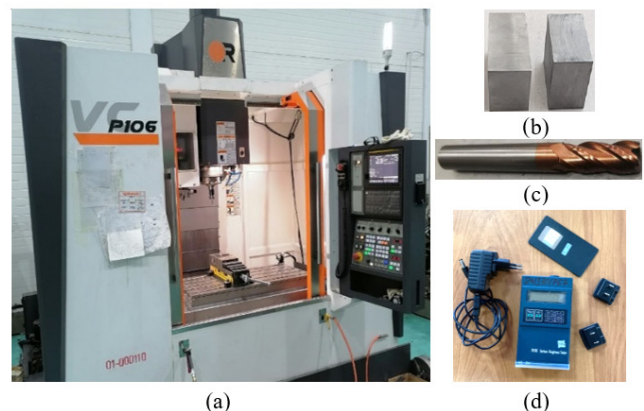


Fig. 1. Technological equipment and tooling used in the experimental investigation of high-speed milling: (a) vertical CNC machining center (V-Center P76), (b) VT1–0 titanium alloy specimens for high-speed milling, (c) solid carbide end mill MC089, (d) electronic surface roughness measuring device.

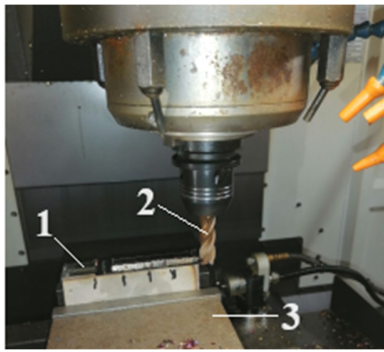


Fig. 2. High-speed milling process of the VT1-0 titanium alloy: 1) VT1-0 titanium alloy workpiece, 2) solid carbide end mill MC089, 3) machine vise.

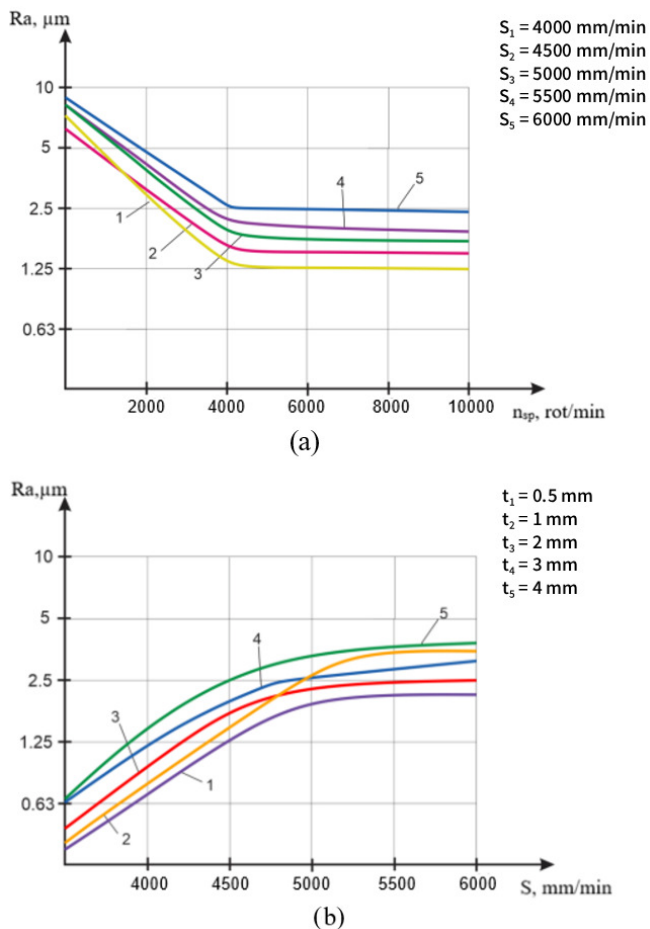


Fig. 3. Dependence of surface roughness on cutting parameters during high-speed milling with a solid carbide end mill MC089: (a) surface roughness versus spindle speed at a constant depth of cut $t = 1$ mm, (b) surface roughness versus feed rate at a constant spindle speed $n_{sp} = 4200$ rot/min.

III. RESULTS AND DISCUSSION

The experimental results demonstrated that the influence of cutting parameters on the machined surface roughness is ambiguous. An increase in spindle speed (n_{sp}) at various feed rates (S) has a positive effect on surface roughness, as demonstrated in Figure 3(a), whereas an increase in feed rate (S) adversely affects surface roughness, as exhibited in Figure

3(b). An increase in depth of cut (t) also leads to a deterioration in surface roughness. Taking into account the need to ensure adequate machining productivity, the following optimal cutting parameters for high-speed milling with an end mill were selected: spindle speed $n_{sp} = 4200$ rot/min, depth of cut $t = 1$ mm, and feed rate $S = 4500$ mm/min.

As shown in Figure 3(a), the surface roughness remains nearly unchanged within the spindle speed range of $n_{sp} = 5000$ – 10000 rot/min. This behavior can be explained by the fact that experimental investigations were not conducted at these spindle speeds due to premature tool wear. During machining at spindle speeds $n_{sp} \geq 6000$ rot/min, noticeable wear of the cutting edges of the end mill was observed. This can be attributed to a sharp increase in temperature in the cutting zone. Elevated cutting temperatures prevent further intensification of machining parameters and lead to a change in the dominant tool failure mechanism from abrasive wear to chipping and edge breakage, which significantly reduces tool life [15-18].

In the present study, the milling process was performed without the use of cutting fluid. Dry machining conditions result in increased friction and heat accumulation in the cutting zone [19]. The elevated friction level leads to more intensive mechanical ploughing of the material, thereby increasing surface roughness. Simultaneously, the generated heat accelerates tool wear mechanisms such as adhesion, abrasive wear, and diffusion, resulting in more rapid tool degradation. This issue can be addressed through the application of MQL using peanut oil during the milling of the Ti-6Al-4V titanium alloy [19].

Furthermore, the high temperature in the cutting zone can be associated with several factors [15, 18], the most significant of which include a high friction coefficient at the tool-workpiece interface, low thermal conductivity of the materials, high specific cutting forces, limited accessibility of cutting fluids directly to the cutting zone, and a "negative" chip compression ratio. This indicates the need for further studies aimed at determining the influence of the above-mentioned factors during high-speed milling.

IV. NUMERICAL MODELING OF THE HIGH-SPEED MILLING PROCESS

A. Development of the Tool-Workpiece 3D Model

The development of three-dimensional models does not present significant difficulties, since almost all modern CAD systems are integrated with software packages based on FEM [20]. The model of the solid carbide end mill MC089 was created using KOMPAS-3D software and subsequently imported into ANSYS Workbench, where the workpiece model was also generated in the form of a semi-cylindrical prism, as illustrated in Figure 4. To reduce computational time, the three-dimensional model of the computational domain was simplified by considering only one-quarter of the end mill.

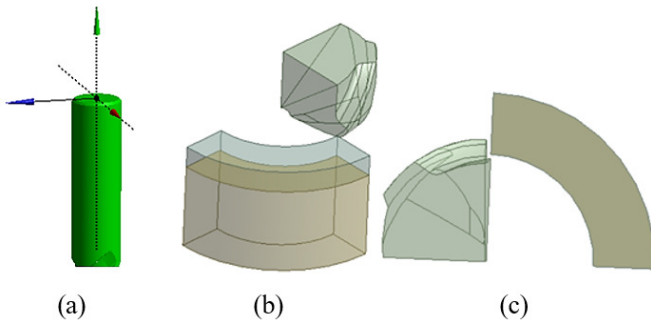


Fig. 4. 3D model of the end mill and workpiece: (a) general view, (b) simplified model, (c) simplified top view.

B. Selection of the Workpiece Material Failure Model

Machining processes remove material from the workpiece to the depth of cut. For finite element simulation of material removal and failure, various constitutive and damage models are available. In this study, the Johnson–Cook material failure model was selected. The physical properties of the workpiece material and the carbide cutting part of the end mill used in the numerical model are summarized in Table II.

TABLE II. PHYSICAL PROPERTIES OF THE CUTTING TOOL AND WORKPIECE MATERIALS

Parameter	Tool	Workpiece
	MC089	VT1-0
Density, ρ	15000	4505
Young's modulus, E	500	112
Poisson's ratio, ν	0.235	0.32
Specific heat capacity, c_p	600	540
Thermal conductivity, λ	3.5	15.6
Initial temperature, T_i	22	22
Melting temperature, T_f	1460	1668

Among the various constitutive laws describing material behavior under large deformations, the Johnson–Cook model is one of the most widely used. It accounts for adiabatic shear phenomena caused by large plastic deformations and significant temperature gradients. This constitutive law establishes the dependence of stress σ on the strain ϵ (%), strain rate, and temperature T, and can be represented in a multiplicative form as the product of three functions:

$$\sigma = (A + B \cdot \epsilon^n) \left(1 + C \cdot \frac{\ln \dot{\epsilon}}{\dot{\epsilon}_0}\right) \left(1 - \left[\frac{T - T_0}{T_f - T_0}\right]\right) \quad (1)$$

The first term describes the strain hardening phenomenon and corresponds to the flow stress at a constant strain rate. Parameter A denotes the yield strength of the material under consideration, while B and n are the linear and nonlinear strain hardening parameters, respectively.

The second term is a multiplicative factor characterizing the dynamic strengthening behavior of the material. It depends on the equivalent plastic strain rate. Parameter C is the strain-rate sensitivity coefficient. The reference strain rate was assumed to be equal to 1 s^{-1} .

The third term corresponds to the thermal softening phenomenon. Parameter T_0 denotes the initial temperature. For temperatures within the range between T_0 and the melting

temperature T_f , the flow stress decreases with increasing temperature and approaches zero at $T = T_f$. At temperatures approaching the melting point, the flow stress becomes practically zero. Thus, T_0 is the reference temperature for the thermal softening mechanism. The values of the Johnson–Cook model parameters for the workpiece materials are presented in Table III.

TABLE III. JOHNSON–COOK MODEL PARAMETERS FOR THE WORKPIECE MATERIAL [20]

Workpiece	A (MPa)	B (MPa)	C	n	m
VT1-0	350	250	0.25	0.02	1

The modified failure criterion is coupled with the Johnson–Cook constitutive law. Failure is assumed to occur for each element once the following condition is satisfied:

$$\omega = \sum \frac{\Delta \bar{\epsilon}}{\Delta \bar{\epsilon}_f} \quad (2)$$

where $\Delta \bar{\epsilon}$ is the increment of the equivalent plastic strain and $\Delta \bar{\epsilon}_f$ is the equivalent fracture strain of the material [21].

Material failure is initiated when $\omega = 1$.

The Johnson–Cook failure model considers thermomechanical processes under large deformations. The equivalent plastic fracture strain is expressed as:

$$\bar{\epsilon}_f = [D_1 + D_2 \cdot \exp(D_3 \cdot \sigma^*)] \cdot [1 + D_4 \cdot \ln \bar{\epsilon}^*] \cdot [1 + D_5 \cdot T^*] \quad (3)$$

where σ^* is the ratio of the mean stress (σ_m) to the equivalent von Mises stress ($\bar{\sigma}$); $\bar{\epsilon}^*$ is the dimensionless plastic strain rate defined using the calculated strain rate $\dot{\epsilon}$ and the reference strain rate $\dot{\epsilon}_0$, which characterizes the strain-rate sensitivity limit.; D_1 is the initial fracture strain; D_2 is the exponential factor; D_3 is the stress triaxiality factor; D_4 is the strain-rate factor; and D_5 is the thermal factor.

The dimensionless temperature coefficient T^* can be expressed as:

$$T^* = (T - T_0)/(T_f - T_0) \quad (4)$$

where T_f is the melting temperature of the material and T_0 is the initial temperature [22].

The parameters of (3) for the plastic fracture strain of the VT1-0 workpiece material are presented in Table IV.

TABLE IV. PARAMETERS OF THE PLASTIC FRACTURE STRAIN MODEL FOR VT1-0 TITANIUM ALLOY

Workpieces	D_1	D_2	D_3	D_4	D_5
VT1-0	-0.09	0.25	-0.5	0.014	3.87

C. Definition of the Tool–Workpiece Contact Zone

The interaction between the cutting tool and the workpiece was defined by specifying contact and "target" surfaces with an assigned friction coefficient, as depicted in Figure 5.

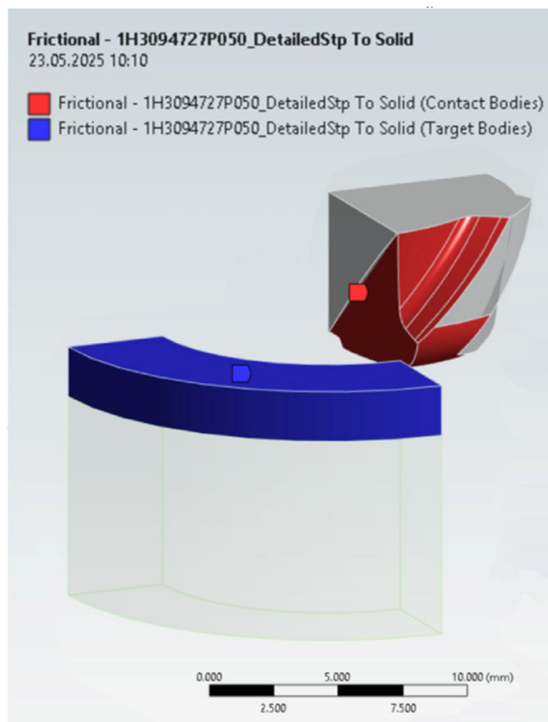


Fig. 5. Tool-workpiece contact interaction.

D. Finite Element Model Development

One of the most significant stages of finite element analysis is mesh generation. The finite element mesh used in the present study is shown in Figure 6.

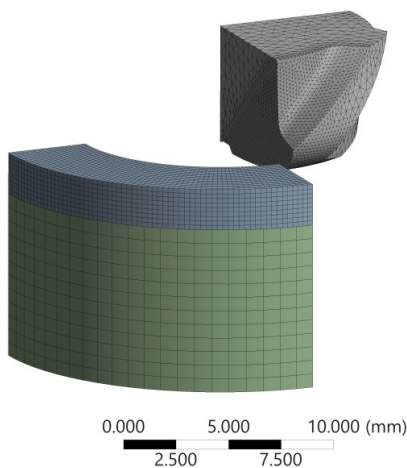


Fig. 6. Finite element mesh of the computational model.

E. Specification of Boundary Conditions

In this stage, the cutting conditions were defined by assigning rotational motion to the tool model to represent spindle speed, while the feed motion was applied through translational displacement of the workpiece, as illustrated in Figure 7.

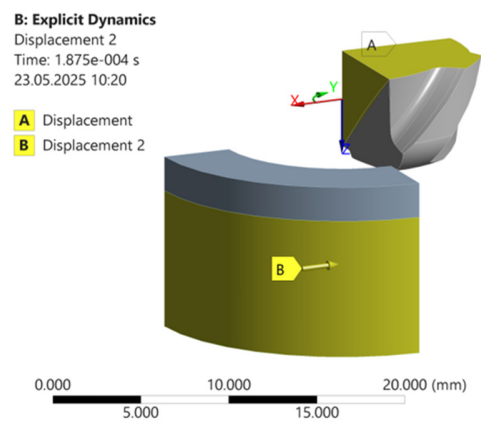


Fig. 7. Boundary conditions for the tool-workpiece system.

F. Analysis of Numerical Results

After running the solver, numerical results were obtained. Figure 8 demonstrates the temperature distribution in the cutting tool during the milling process, whereas Figure 9 presents the temperature distribution within the workpiece.

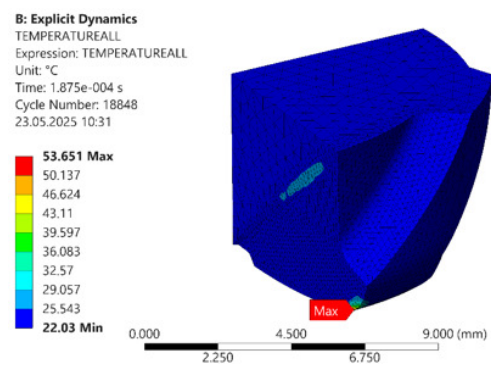


Fig. 8. Numerical simulation result for the tool.

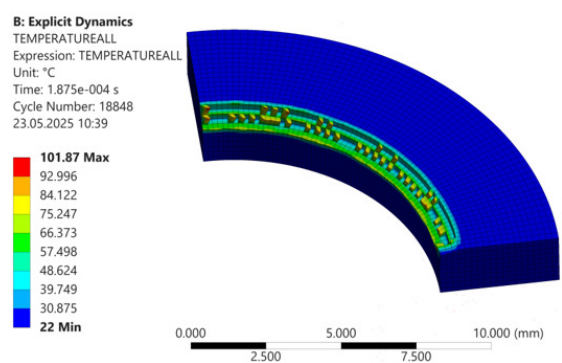


Fig. 9. Temperature distribution in the workpiece.

The ANSYS Workbench environment also enables analyzing the force interaction between the tool and the workpiece through contact forces, and the results are presented in Figure 10. All contact force components exhibit a variable character. The X-component varies within the range of -13.9 N

to -370 N, the Y-component ranges from -148 N to $+300$ N, and the Z-component varies between -35.9 N and $+276$ N.

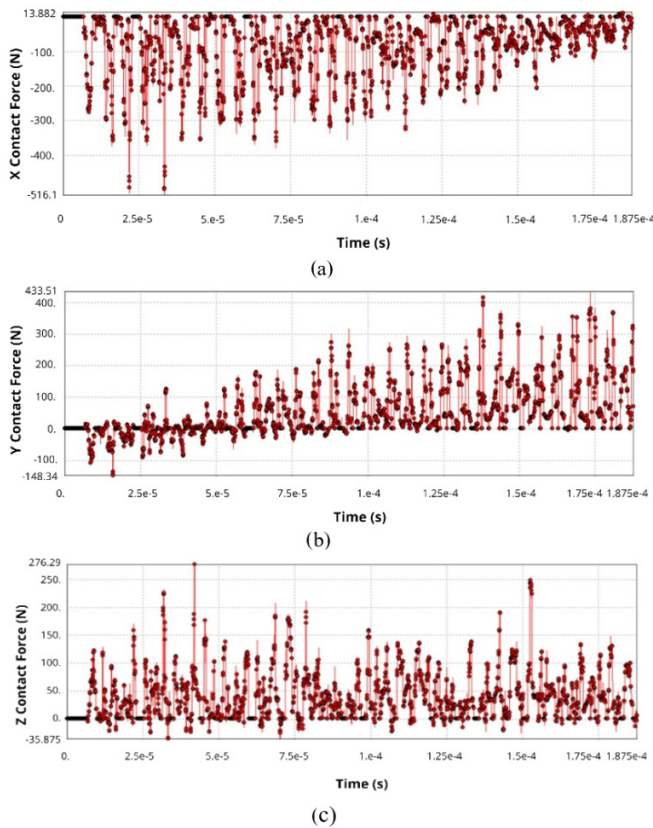


Fig. 10. Contact forces of the tool–workpiece interaction: (a) along the X-axis, (b) along the Y-axis, (c) along the Z-axis.

Figure 11 shows the temperature distribution in the subsurface contact layer of the workpiece. From the moment the end mill engages the workpiece, the temperature increases to approximately 101.87 °C and subsequently remains nearly constant.

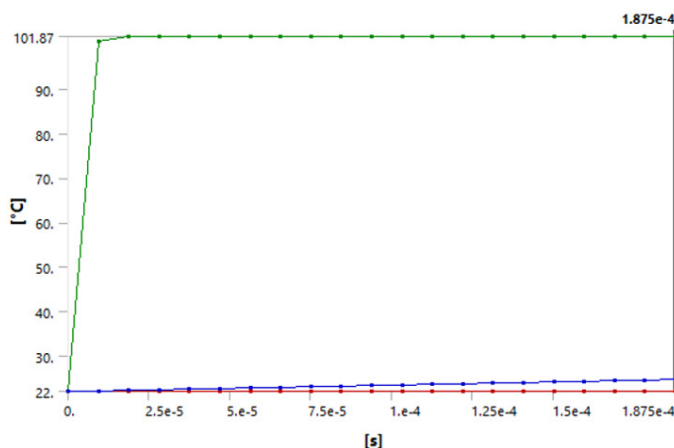


Fig. 11. Temperature distribution in the subsurface contact layer of the workpiece.

V. NUMERICAL EXPERIMENT PLANNING

The objective of the numerical experiment planning was to establish objective relationships between the temperature variation in the workpiece and the cutting parameters during milling with the solid carbide end mill MC089. The result of such an experiment is a function represented in tabular form in Table V. For planning the numerical experiment, a rational design of experiments method was selected.

The need for rational experimental planning arises when a large number of influencing factors must be considered, since testing all possible combinations experimentally is practically impossible due to the excessive number of required experiments. Such an approach would involve significant time and cost expenditure. In this case, it is preferable to obtain an analytical relationship between the primary factors and the experimental results. The proposed methodology combines a rational experimental design approach with a random balance method, allowing an approximating function to be constructed with a high degree of accuracy while minimizing labor and time requirements [23].

The objective function is represented as a composition of partial functions of a single variable using a method of successive approximations. Each partial relationship is approximated by a function of one real variable, and the resulting convolution is expressed as a sum and/or product of the partial functions.

The program was tested on model problems as well as on the results of simulation experiments related to the modeling of failures in metal structures. The obtained results confirm the reliability of the program and, consequently, its suitability for practical application [23].

During the numerical experiments, a rational design of experiments method was employed, which enables selecting factor combinations such that the entire domain of possible factor interactions is covered as uniformly as possible with a minimal number of experiments [24].

The factor ranges used in the numerical experiment were intentionally expanded compared to those employed in the physical experiments. This is because numerical simulation was used not only for the interpretation of the experimental results, but also for the development of a mathematical model describing the thermal state of the process over a wider range of cutting conditions. The extended parameter range was adopted within the framework of a five-level rational experimental design, whereas the physical experiments were limited by the practical feasibility of the machining process and the tool life constraints.

When a full factorial experiment [25] is used, in order to reduce the number of experiments (which leads to a loss of accuracy), the factors are varied at two levels and, in some cases, at three levels; in the case of rational experimental planning, the factors are varied at five levels, and for three variables it is sufficient to conduct 25 experiments instead of $5^3 = 125$. In each experiment, the factors are combined at different levels.

Depth of cut t (mm), table feed S (mm/rot), and spindle speed n (rot/min) (n) were selected as independent variables X_1 , X_2 , and X_3 , respectively, and their variation ranges are presented in Table V.

TABLE V. VARIATION OF INDEPENDENT VARIABLES

Factor	1	2	3	4	5
X_1	1,0	2,0	3,0	4,0	5,0
X_2	500	1500	2500	3500	4500
X_3	4000	6000	8000	10000	12000

The three-factor experimental plan at five levels is shown in Table VI.

TABLE VI. THREE-FACTOR EXPERIMENTAL PLAN

Factors No.	X_1	X_2	X_3	Y
1	1	500	8000	101
2	1	1500	12000	104
3	1	2500	10000	104
4	1	3500	4000	97
5	1	4500	6000	96
6	2	500	10000	120
7	2	1500	4000	109
8	2	2500	12000	115
9	2	3500	6000	111
10	2	4500	8000	115
11	3	500	12000	132
12	3	1500	6000	126
13	3	2500	4000	126
14	3	3500	8000	130
15	3	4500	10000	133
16	4	500	6000	131
17	4	1500	10000	126
18	4	2500	8000	127
19	4	3500	12000	129
20	4	4500	4000	130
21	5	500	4000	138
22	5	1500	8000	127
23	5	2500	6000	133
24	5	3500	10000	127
25	5	4500	12000	133

All experiments were carried out numerically using ANSYS Workbench software. The results of the multifactor numerical experiment were processed using the ANETR-5 software [26]. The method is universal both in terms of its field of application and in the variants of model construction: the models may take the form of a sum, a product of partial dependencies, or their combinations, with sequential neutralization of the influence of priority arguments or without such neutralization. An important advantage of the method is the ability, with an appropriate level of reliability, to assess the influence of those arguments which, in traditional methods, would be excluded from the analysis as having no significant effect on the objective function (for example, according to the Fisher criterion).

The method is deterministic, i.e., it makes it possible to restrict the choice of the model using known data from the theory of the process (type of equation, limits, etc.). As an output, the program, in addition to the analytical form of the partial relationships, provides their graphs, evaluates reliability,

ranks the factors according to the strength of their influence on the result, and allows identifying the most significant influencing factors.

By changing the parameter p in the program, which can take the values $p = 0, 1, 2, 3$, and 4 , different types of generalized formulas can be obtained, both with neutralization of arguments (according to the minimum root mean squared error) and without neutralization.

The adequacy of the developed models was evaluated using the Root Mean Squared Error (RMSE):

$$\text{RMSE}\% = 100 \sqrt{\frac{\sum(Y_e - Y_c)^2}{N-1}} / \sqrt{\frac{\sum(Y_e - \bar{Y}_c)^2}{N-1}} \quad (4)$$

where Y_e is the experimental value of the response function, Y_c is the calculated value, \bar{Y}_c is the mean value of the function, and N is the number of experiments.

In addition to the RMSE, the multiple correlation coefficient R and the Fisher criterion F were calculated.

According to [27], a model is considered excellent if the RMSE is less than 20% and good if it lies between 20% and 50%.

As a result of data processing, the following relationship was obtained for the surface temperature in the cutting zone T ($^{\circ}\text{C}$):

$$Y_1 = (-2,37976 \cdot X_1^2 + 21,2918 \cdot X_1) + (2404,65 \cdot 10^{-1}/X_2) + (3,9 \cdot 10^{-4}/X_3) + 81,70103 \quad (5)$$

For this model, the RMSE was 28.76%, and the correlation coefficient was $R = 0.948$.

The calculated Fisher criterion $F = 12.093$ is less than that for the 1% significance level, $F(0.01) = 2.636$, and for the 5% significance level, $F(0.05) = 1.977$.

The obtained mathematical model, which relates spindle speed (n_{sp}), feed rate (S), and depth of cut (t), enables controlling the temperature distribution in the workpiece and determining the optimal machining parameters that ensure high machining accuracy.

The application of numerical investigation methods for machining difficult-to-cut materials allows a significant reduction in the cost of physical experiments.

Subsequently, the minimum of the developed mathematical model was determined using Mathcad 15 software.

$$f(x, y, z) = -2.37976x^2 + 21.2918x + \frac{2404.65}{y} + \frac{3.9 \cdot 10^{-4}}{z} + 81 \quad (6)$$

where $1 < x < 5$, $500 < y < 450$, and $4000 < z < 1200$.

As a result of minimizing the temperature distribution function with respect to the cutting parameters, the following conditions were obtained: depth of cut $t = 1$ mm, table feed $S = 4500$ mm/min, and spindle speed $n_{sp} = 4162$ rot/min.

A quantitative comparison showed that the discrepancy between the experimentally determined optimal spindle speed (4200 rot/min) and the value obtained through numerical optimization (4162 rot/min) is 38 rot/min, or 0.9%. No discrepancy was observed for the depth of cut and feed rate parameters ($t = 1$ mm, $S = 4500$ mm/min). The obtained difference in spindle speed can be considered engineeringly insignificant; however, it reflects the presence of simplifying assumptions adopted in the numerical model.

VI. CONCLUSIONS

This study presents a comprehensive investigation into the high-speed milling characteristics of the difficult-to-machine VT1-0 titanium alloy. By integrating physical experiments with finite element modeling, the complex relationships between cutting parameters, surface quality, and thermomechanical phenomena at the tool-workpiece interface were established. Based on the findings, the following conclusions can be drawn:

- As a result of experimental studies of the high-speed milling process of the VT1-0 titanium alloy, it was established that an increase in the spindle speed n_{sp} at various feed rate values S has a positive effect on the surface roughness of the machined surface, whereas an increase in the feed rate S and depth of cut t has a negative effect on the surface roughness.
- The optimal cutting parameters for high-speed milling with an end mill were determined as: spindle speed $n_{sp} = 4200$ rot/min, depth of cut $t = 1$ mm, feed rate $S = 4500$ mm/min.
- It was established that during high-speed milling at spindle speeds exceeding $n_{sp} \geq 5000$ – 7000 rot/min, wear of the cutting part of the tools is observed.
- To clarify the factors that have a significant influence on tool wear during high-speed milling at spindle speeds in the range $n_{sp} = 5000$ – 10000 rot/min, additional studies are required.
- A methodology for numerical simulation of the milling process of difficult-to-machine materials was developed and implemented based on the construction of a three-dimensional finite element model of the "tool-workpiece" system in the KOMPAS-3D and ANSYS Workbench environments using the Johnson-Cook damage model.
- Thermomechanical processes were simulated, including the determination of temperature fields, contact forces, and plastic strain distributions, which made it possible to qualitatively assess the influence of cutting parameters on the thermal load in the cutting zone.
- A rational experimental design method was applied, which made it possible, with a minimal number of numerical experiments, to obtain a reliable mathematical model of the dependence of the workpiece temperature on the depth of cut, feed rate, and spindle speed.
- The constructed mathematical model demonstrated a good degree of adequacy (RMSE = 28.76%, $R = 0.948$) and can be used to predict the temperature characteristics of the high-speed milling process and to select the optimal cutting parameters.
- As a result of numerical optimization, optimal high-speed milling parameters ensuring minimal thermal impact on the workpiece were established: depth of cut $t = 1$ mm, feed rate $S = 4500$ mm/min, spindle speed $n_{sp} = 4162$ rot/min. A comparison of the optimal cutting parameters obtained from experimental studies and numerical optimization shows a slight discrepancy in the spindle speed values.

Consequently, the proposed methodology can be effectively utilized for the preliminary selection of cutting parameters when processing difficult-to-machine materials. This approach significantly reduces the temporal and financial costs associated with physical trial-and-error experiments while enhancing the overall accuracy and efficiency of mechanical machining operations.

DECLARATION OF COMPETING INTERESTS

The authors declare no competing interests.

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DATA AVAILABILITY

Methodology and acquired data are given within the article.

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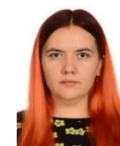
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