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Numerical simulation of milling of difficult-to-machine materials for cutting optimization

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Abstract

This study investigates the thermo-mechanical behaviour of titanium alloys during milling with the aim of developing a predictive approach for reducing thermal loading and improving process stability. A three-dimensional finite element model was constructed in Kompas-3D and simulated in ANSYS Workbench using the Johnson–Cook constitutive and damage model. To systematically analyse the effects of process variables, a five-level experimental design was employed, in which cutting depth, feed rate, and spindle speed were varied. The results of 25 simulation runs were processed in ANETR-5 software to establish a regression model linking cutting parameters with the workpiece surface temperature. The findings revealed that heat accumulation is strongly localised at the tool–chip interface, while subsurface temperature stabilises near 101.9 °C. Cutting forces were observed to fluctuate in all coordinate directions, reflecting the intermittent engagement of milling teeth and providing insight into potential process instability. The regression model demonstrated high adequacy with SD = 28.76%, R = 0.948, and F = 12.093. Optimisation indicated that the combination of cutting depth t = 1 mm, feed rate S = 4500 mm/min, and spindle speed n = 4162 rpm yields the most favourable thermal response. The approach provides a reliable basis for optimising titanium machining, improving tool life, surface integrity, and overall cost efficiency.

Keywords: Cutting temperature, Difficult-to-machine materials, Finite element method, Milling, Titanium alloys.

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1. Introduction

The machinability of titanium alloys (TAs) represents a long-standing scientific and engineering problem that has stimulated considerable global research efforts. The extensive use of TA as a replacement for aluminium and magnesium alloys, particularly in the aerospace industry, has led to a tenfold increase in machining labour intensity and a corresponding 10–15-fold rise in the demand for cutting tools. These challenges are further intensified by the widespread application of CNC machine tools, where high precision and process stability are required.

The strategic importance of titanium alloys in aerospace and defence has been reinforced in the past two decades, as their high strength-to-weight ratio, corrosion resistance, and fatigue performance make them indispensable in modern aircraft and engine structures [1]. In addition, titanium alloys have expanded into biomedical applications, particularly in orthopaedic implants and dental prosthetics, where machinability directly affects manufacturing costs and surface quality requirements [2]. Global consumption of titanium alloys continues to grow, with Ti-6Al-4V representing the dominant grade, accounting for more than half of titanium used in aerospace components [3, 4]. Recent comparative studies further confirm the relevance of machining optimisation for Ti-6Al-4V under various cooling and lubrication conditions, including cryogenic techniques, as a pathway to improve tool life and surface integrity [5].

The greatest technological difficulties occur during rough machining of scaled or cast surfaces, drilling small-diameter holes, thread cutting, and finishing operations. These processes demand a balance between productivity and surface integrity, as surface quality strongly affects part strength and durability. Despite numerous studies, the mechanisms underlying the reduced machinability of titanium alloys remain insufficiently understood. It is well established that cutting temperatures in TA are significantly higher than in carbon and alloy steels, accelerating tool wear and deteriorating cutting conditions [6-8].

Several authors have highlighted that drilling operations in Ti-6Al-4V often lead to severe burr formation, poor hole quality, and tool wear. For instance, conventional drilling of Ti-6Al-4V ELI experiences notable burr formation and degraded surface integrity, which can be mitigated by vibration-assisted drilling (LF-VAD) [9]. Studies of stacked materials (CFRP/Ti-6Al-4V) also found that adapting drill geometry and drilling parameters reduces damage and enhances hole dimensional accuracy [10]. For milling operations, dynamic instabilities such as chatter become more pronounced when machining Ti-6Al-4V thin-walled structures, due to high cutting forces combined with poor thermal dissipation, leading to surface waviness and elevated tool wear [11]. These issues significantly increase manufacturing cost and cycle time, especially in aerospace production where tight tolerances are mandatory.

One of the characteristic features of TA is the exceptionally low value of the chip shrinkage coefficient. Several studies have reported the phenomenon of “negative shrinkage”, attributed either to gas saturation or to the low plasticity of the material, both of which contribute to segmented chip formation [12]. Elevated thermal loads on the tool are further aggravated by poor thermal conductivity and low chip shrinkage, which increase chip sliding velocity, friction forces, and heat generation at the tool–chip interface [13, 14]. In addition, chip adhesion to the tool intensifies adhesive wear, while high chemical reactivity with oxygen and nitrogen at elevated temperatures leads to embrittlement of the machined surface and further accelerates tool degradation [15-17].

Recent studies have investigated multi-objective optimisation for titanium milling, considering surface roughness, cutting forces, and cutting temperature [18] and have explored the influence of tool geometry and surface texture on reducing tool–chip contact, cutting forces, and thermal load [15]. Other works applied finite element simulations to assess the effects of cutting speed on forces in Ti-6Al-4V alloys [19] or examined material-specific optimisation strategies under minimum quantity lubrication conditions [20]. The interdependence between cutting temperature and tool wear has also been confirmed in recent milling studies of titanium alloys [21]. These contributions highlight the critical role of temperature and force prediction in achieving reliable machinability, but they rely predominantly on experimental optimisation or simplified modelling approaches.

In particular, FEM predictions of cutting forces and temperatures in Ti-6Al-4V showed close agreement with experimental data, although limitations in thermal predictions were noted due to boundary condition simplifications [22]. A grain-size-dependent constitutive model for FEM analysis under minimum quantity lubrication and cryogenic cooling, considering the ploughing effect, was also developed and validated with experimental measurements [23]. Furthermore, sub-zero milling investigations demonstrated that optimised cutting parameters significantly reduce tool wear and surface roughness [24]. These studies collectively demonstrate the growing trend of integrating FEM with experimental validation to increase predictive reliability.

Given these factors, the machining of titanium alloys with multi-tooth cutters remains problematic due to the lack of specialised equipment and insufficient development of milling and mill-turning technologies. This creates an urgent need for effective machining strategies that ensure the required surface quality while mitigating the technological challenges associated with TA. In contrast to prior research, which focused mainly on experiments and statistical optimisation, the present study integrates finite element modelling using the Johnson–Cook material law with rational experiment planning to simulate thermal and mechanical responses in the cutting zone and to determine optimal machining conditions.

Therefore, this study aims to develop and validate a methodology for numerical simulation of the milling process of titanium alloys. The proposed approach contributes to reducing the cost of full-scale experiments and improving the efficiency of machining processes for difficult-to-machine materials.

2. Materials and Methods

The milling process was modelled using the finite element method (FEM) to capture the thermo-mechanical behaviour of titanium alloy VT1-0 during high-speed cutting. A three-dimensional tool–workpiece model was created in Kompas-3D and imported into ANSYS Workbench. To reduce computational time, one quarter of the milling cutter was used. The workpiece material behaviour was described by the Johnson–Cook constitutive and damage model. Table 1 summarises the physical properties of both the TiAlSiN-coated tool and the VT1-0 titanium alloy workpiece, while Table 2 lists the Johnson–Cook parameters for the workpiece material.

Table 1.
Physical properties of the tool and the workpiece.

Parameters	**Tool**	**Workpiece**
	TiAlSiN	**VT 1-0**
Density, p	15000	7800
Young modulus, E	500	105
Poisson ratio, ν	0.235	0.32
Specific thermal conductivity, c_p	600	523
Thermal conductivity, λ	3.5	15.6
Initial temperature, T_t	22	22
Melting point, T_f	1460	1627

Table 2.
Johnson–Cook parameters for the workpiece material.

Workpiece	**A, MPa**	**B, MPa**	**C**	**n**	**m**
VT 1-0	350	250	0.25	0.02	1

The mesh was refined in the cutting zone to ensure numerical stability, and spindle rotation together with translational feed motion was applied to the workpiece as boundary conditions. Frictional contact was assigned between the cutter and the workpiece. Figures 1 and 2 illustrate the finite element mesh and boundary conditions used in the simulation.

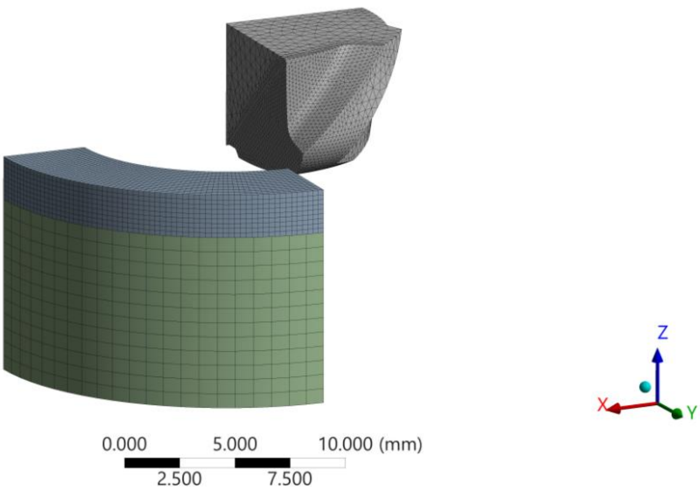


Figure 1.
Finite element mesh of the tool–workpiece model.

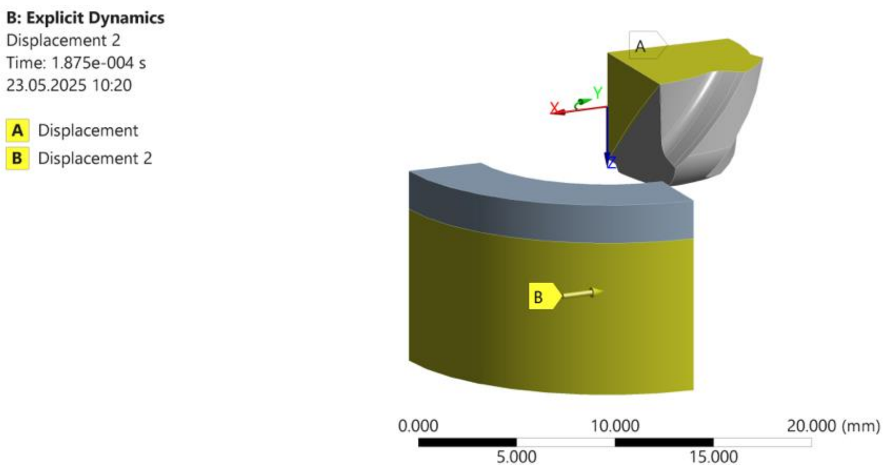


Figure 2.
Applied boundary conditions for the milling simulation.

In order to generalise the simulation results and identify optimal cutting conditions, a rational experimental planning method was employed. The approach considered three primary factors–cutting depth, feed rate, and spindle speed–each varied over five levels. This design allowed systematic investigation of parameter combinations with a reduced number of numerical experiments compared to a full factorial plan. The subsequent analysis, performed using the ANETR-5 software, enabled the construction of predictive models linking process parameters to workpiece temperature, forming the basis for optimisation presented in later sections.

3. Numerical Simulation of the High-Speed Cutting Process

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

3.1. Temperature Distribution in the Tool and Workpiece

The FEM simulations revealed the temperature distribution in both the milling cutter and the titanium alloy workpiece. Figure 3 illustrates the thermal field in the tool during engagement, showing localised heating near the cutting edge. The corresponding temperature distribution in the workpiece (Figure 4) indicates that the maximum values are concentrated in the primary shear zone, with temperatures exceeding 100 °C. The surrounding regions remain close to room temperature, demonstrating the highly localised nature of heat generation in titanium machining.

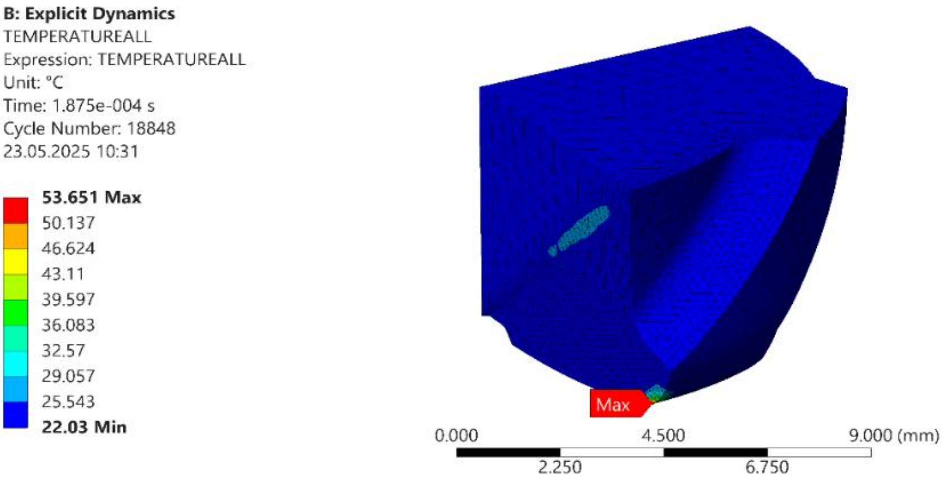


Figure 3.
Temperature distribution in the milling cutter during engagement with the workpiece.

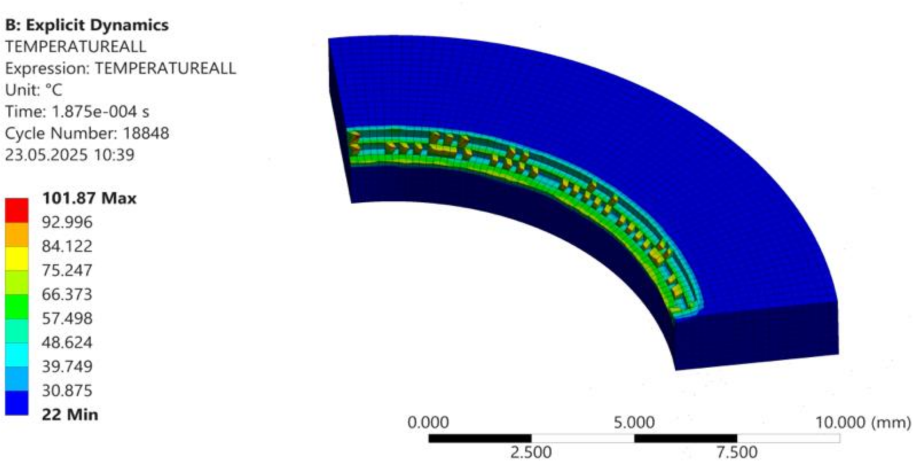
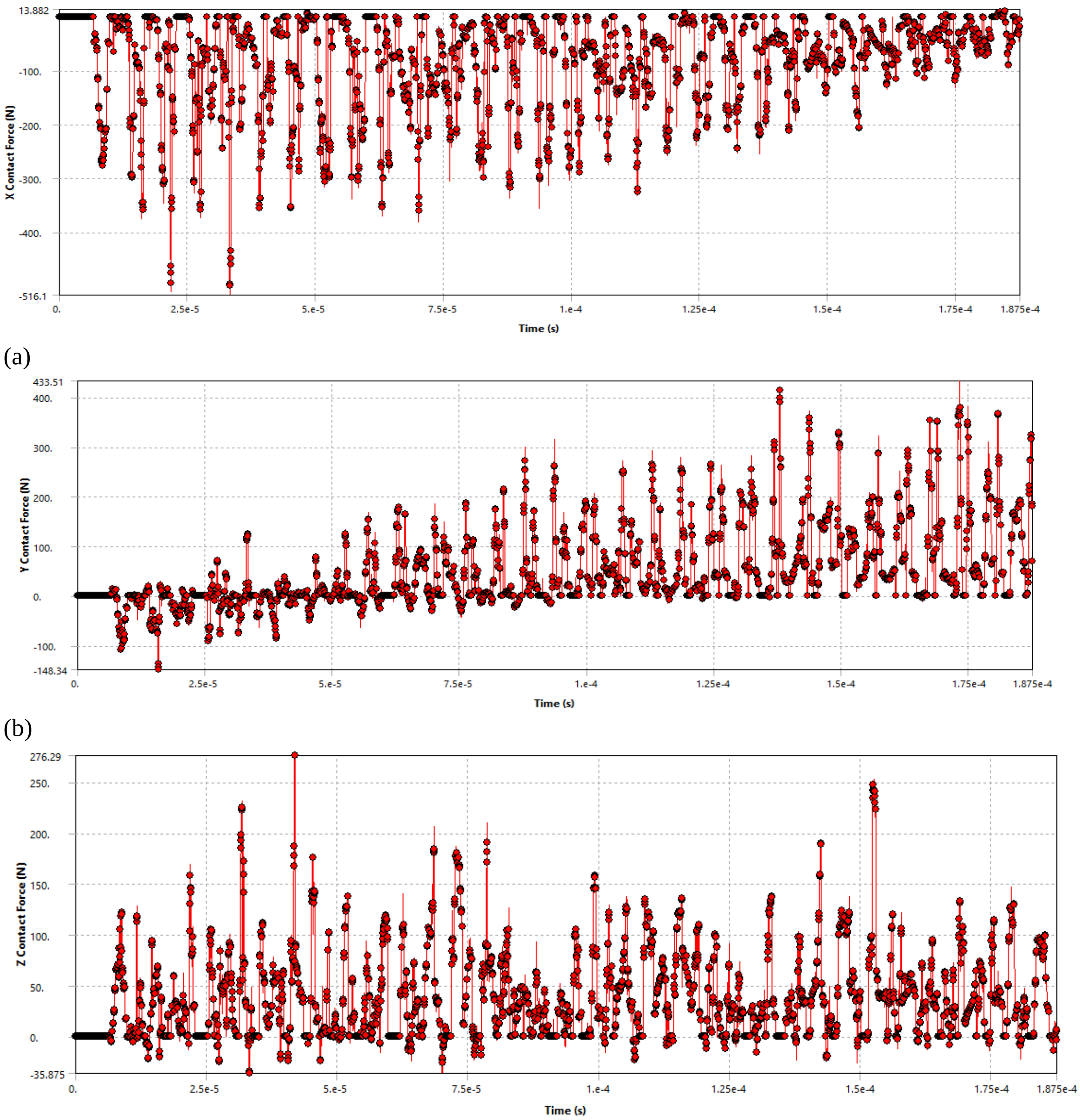


Figure 4.
Temperature field in the titanium alloy workpiece obtained from FEM simulation.

3.2. Contact Forces

The interaction forces at the tool–workpiece interface were calculated along three axes (Figure 5). The X-component exhibited the largest variation, from –13.9 N to –370 N, reflecting the dominant resistance in the cutting direction. The Y-component ranged from –148 N to +300 N, while the Z-component varied between –35.9 N and +276 N. The results show that all components fluctuate significantly during engagement, which is consistent with the intermittent nature of milling and the segmented chip formation typical of titanium alloys.



(a)

(b)

(c)

Figure 5.
Contact force components at the tool–workpiece interface: (a) X-axis, (b) Y-axis, (c) Z-axis.

3.3. Subsurface Temperature Field

In addition to surface temperatures, the simulation allowed analysis of the subsurface thermal state (Figure 6). At the onset of cutting, the temperature increased sharply and stabilised at approximately 101.9 °C, indicating the establishment of a steady-state thermal regime. This stabilisation is important for predicting tool wear and assessing the thermal impact on the surface integrity of the machined part.

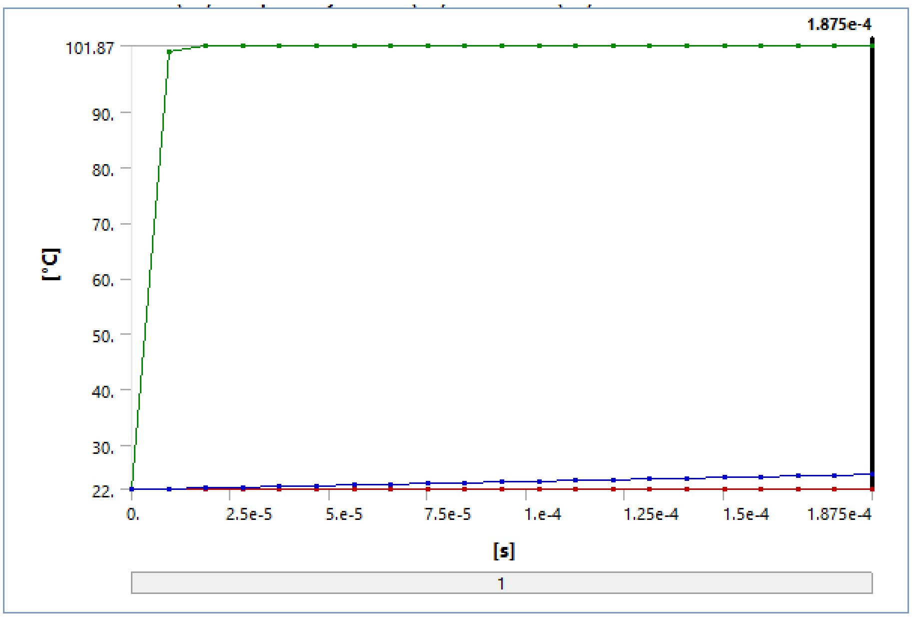


Figure 6.
Subsurface temperature distribution beneath the tool–workpiece contact zone.

4. Design of Numerical Experiments

The objective of the experimental design was to determine the effect of cutting parameters on the temperature distribution in the titanium alloy workpiece during high-speed milling. Since testing all possible combinations of parameters would be computationally prohibitive, the method of rational planning was applied. This approach allows a systematic study of multiple factors with a reduced number of experiments while maintaining adequate coverage of the factor space [25, 26]. Three independent variables were considered: cutting depth (X_1, mm), feed rate (X_2, mm/rev), and spindle speed (X_3, rpm). Each variable was varied at five levels, as presented in Table 3.

Table 3.
Changing independent variables.

Factors	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

A three-factor experimental plan at five levels was adopted, resulting in 25 simulation runs. The experimental matrix is presented in Table 4, where the response variable Y corresponds to the workpiece surface temperature.

Table 4.
Plan of a three-factor experiment.

Factors / Experiment No.	X_1	X_2	X_3	Y
1	**2**	**3**	**4**	**5**
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 simulations were performed in ANSYS Workbench, and the resulting datasets were processed using the ANETR-5 software package [27]. This tool enables the construction of predictive models and ranking of factor influence. To assess the adequacy of the obtained models, several statistical criteria were applied, including the standard deviation (SD), the multiple correlation coefficient (R), and the Fisher criterion (F). The standard deviation was calculated according to Equation 1:

$$SD\% = 100\sqrt{\frac{\sum (Y_e - Y_c)^2}{N-1}} \Bigg/ \sqrt{\frac{\sum (Y_e - \bar{Y}_{av})^2}{N-1}}\ , \qquad (1)$$

where Y_e is the experimental value of the response function (coating quality parameter); Y_c is the calculated function value; $\bar{Y}_{av}$ is the average function value; N is the number of experiments.

5. Results and Discussion

5.1 Numerical Simulation Results

The finite element simulations provided detailed insight into the thermo-mechanical behaviour of the titanium alloy workpiece during high-speed milling. The predicted temperature field in the milling cutter (Figure 3) indicated that heat accumulation was highly localised around the cutting edge, particularly at the rake face in the immediate vicinity of the tool–chip contact. Such localisation is consistent with the low thermal conductivity of Ti-6Al-4V, which prevents efficient dissipation of heat into the bulk material. In contrast, steels or aluminium alloys typically demonstrate a more distributed temperature field due to their higher thermal diffusivity. The results therefore emphasise the inherent difficulty in controlling temperature during titanium machining.

In the workpiece, the maximum temperature exceeded 100 °C (Figure 4), concentrated within the primary shear zone where severe plastic deformation occurs. Although this level of heating is moderate compared to conditions observed at higher cutting speeds in experimental studies, it highlights the sensitivity of titanium alloys to even short cutting engagements. The accumulation of heat in this region has direct implications for microstructural stability, since repeated thermal cycling may cause localised softening, phase transformations, or oxidation at the machined surface. These factors ultimately reduce fatigue resistance and dimensional accuracy.

The simulated cutting forces revealed significant fluctuations in all three coordinate directions (Figure 5). The dominant component was observed along the cutting direction (X-axis), ranging from –13.9 N to –370 N, while oscillations in the Y and Z components were smaller but still considerable. This behaviour reflects the intermittent nature of the milling process, where each tooth periodically engages and disengages with the workpiece. The magnitude of force oscillations is particularly important, since it indicates the level of dynamic excitation acting on the machine–tool–workpiece system. Large fluctuations can excite structural resonances, promoting chatter vibrations that deteriorate surface finish and accelerate tool wear. Thus, even in simulations without explicit dynamic modelling of the spindle–tool assembly, the force patterns provide indirect evidence of potential process instability.

A more detailed examination of the force components shows that the radial (Y-axis) forces contribute to lateral tool deflection, which in turn affects dimensional accuracy of the milled slot or surface. The axial (Z-axis) forces, while smaller, are important for predicting the load on the spindle bearings and for assessing the risk of tool pull-out in high-speed applications. The strong variation of forces across different cutter teeth also suggests uneven load sharing, which may result in accelerated wear of the leading teeth and limit tool life.

Subsurface thermal analysis (Figure 6) further highlighted that the temperature beneath the contact layer increased rapidly upon tool entry, stabilising at approximately 101.9 °C. The establishment of this steady-state regime is critical for predicting the onset of thermally driven phenomena such as workpiece surface softening, oxidation, or damage to protective tool coatings. The steady-state values also provide a basis for correlating thermal conditions with surface integrity indicators such as hardness variation, residual stress distribution, or microstructural alterations. From a manufacturing perspective, understanding the time required to reach steady-state is essential, since it defines the minimum engagement period at which reliable temperature predictions can be made.

Another important observation is the concentration of heat at the rake face rather than in the tool bulk. This finding implies that tool coatings with enhanced thermal resistance or surface treatments designed to reduce friction could play a significant role in mitigating tool degradation. Similarly, the observed subsurface temperatures indicate that coolant delivery strategies should target the cutting edge more effectively, for example through internal coolant channels or high-pressure nozzles directed at the shear zone. While not explicitly simulated in this study, such measures could significantly alter the thermal balance and extend tool life in practical applications.

Overall, the simulation results underline three major points. First, the poor thermal conductivity of titanium alloys ensures that heat remains confined near the cutting zone, making thermal management a primary concern. Second, the oscillatory nature of cutting forces is intrinsic to milling and cannot be eliminated, but its magnitude can be controlled by careful selection of cutting parameters. Finally, the steady-state temperature distribution provides a reliable reference for evaluating thermal damage mechanisms and for guiding experimental validation in future work.

5.2 Analysis of Experimental Design Results

The dataset obtained from the 25 simulation runs (Table 4) was processed using the ANETR-5 software to construct predictive models linking the cutting parameters to the thermal response of the workpiece. The resulting regression function expressed the dependence of surface temperature (Y) in the cutting zone on the cutting depth (X1), feed rate (X2), and spindle speed (X3), as given in Equation (2). This mathematical representation allowed quantitative assessment of how process parameters contribute to the thermal state of the material and the stability of the machining process.

$$Y = (-2.37976 \cdot X_1^2 + 21.2918 \cdot X_1) + \frac{240.465}{X_2} + \left(\frac{3.9 \cdot 10^{-4}}{X_3}\right) + 81.70103, \quad (2)$$

The adequacy of the model was confirmed using statistical criteria introduced in Section 4. The standard deviation was calculated as SD = 28.76%, the correlation coefficient was R = 0.948, and the Fisher criterion was F = 12.093. These values indicate a strong correlation between predicted and simulated results, while the deviation lies within acceptable limits for machining studies. According to the established classification [28] the model can be considered “good,” as it provides a reliable tool for predicting thermal outcomes under varying cutting conditions.

Analysis of the regression coefficients demonstrates the relative influence of each parameter. Cutting depth exerts the strongest effect, with both linear and quadratic terms significantly shaping the predicted temperature. This finding is consistent with the physical expectation that deeper engagement of the tool produces larger shear zones and higher rates of heat generation. Feed rate shows an inverse relationship, suggesting that higher material removal rates contribute to reduced surface temperature, possibly due to shortened contact time and improved chip evacuation. Spindle speed exerts a weaker effect, but its role is still important for balancing thermal load and cutting efficiency.

Optimisation of the regression function in Mathcad 15 provided the combination of cutting parameters that minimises surface temperature: cutting depth t = 1 mm, feed rate S = 4500 mm/min, and spindle speed n = 4162 rpm. This parameter set highlights the delicate balance required in titanium milling–small changes in depth or feed can significantly alter the thermal state of the workpiece. From a technological perspective, these optimised parameters are particularly valuable for improving surface quality, enhancing tool life, and reducing the likelihood of thermally induced surface defects.

The modelling results also indicate that no single parameter can be adjusted independently without affecting the overall thermal response. For example, while higher feed rates reduce surface temperature, they may also increase cutting forces, thereby raising the risk of tool deflection or chatter. Similarly, reducing cutting depth lowers heat generation but decreases material removal efficiency. Therefore, the optimisation task is inherently multi-objective, requiring compromise between thermal stability, tool wear, productivity, and dimensional accuracy.

In practical applications, the regression model provides a framework for selecting process windows that balance these competing requirements. It also offers a predictive basis for adaptive process control systems, where real-time monitoring of cutting forces and temperatures could be used to adjust parameters dynamically. Thus, beyond the immediate insights into the present simulations, the results form a methodological foundation for integrating finite element modelling with process optimisation tools in advanced titanium alloy machining.

6. Conclusions

- A finite element method for simulating the milling of difficult-to-machine materials was developed in Kompas-3D and ANSYS Workbench using the Johnson–Cook fracture model;
- The simulations provided thermo-mechanical insights, including temperature fields, contact forces, and plastic strain distributions, which revealed the influence of cut-ting parameters on thermal loading in the cutting zone;
- A rational experimental design enabled the construction of a mathematical model describing the dependence of workpiece temperature on cutting depth, feed rate, and spindle speed with a reduced number of numerical experiments;
- The model demonstrated good adequacy SD=28.76%, R=0.948) and can be used to predict thermal characteristics and guide parameter selection;
- Optimisation of the regression model identified the cutting depth of 1 mm, feed rate of 4500 mm/min, and spindle speed of 4162 rpm as the conditions minimising thermal impact;
- The proposed methodology can be applied for the preliminary selection of cutting conditions for difficult-to-machine materials, reducing the cost of full-scale experiments while improving accuracy and efficiency.

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