

OPTIMAL GEOMETRIC PARAMETERS AND ENHANCED CUTTING PERFORMANCE OF TI(C,N)-BASED CERMET TOOLS

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Ti(C,N)-based cermet tools offer high hardness and wear resistance, yet the role of tool geometry is underexplored. Using Deform-3D simulation and response surface methodology, quadratic models for cutting force (F) and tool-tip temperature (T) were established ($R^2 > 0.98$, $p < 0.0001$). Edge radius dominates F (52.1%) and T (74.5%). Multi-objective optimization yields optimal geometry: $\gamma_0 = 9^\circ$, $\alpha_0 = 8^\circ$, $r_e = 0.02$ mm, reducing F by 5.37% and T by 3.87%.

Keywords: response surface methodology; Ti(C,N)-based cermet; parameter optimization; tool geometry

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1. Introduction

Ti(C,N)-based cermets have gained popularity as a class of tool materials for high-speed and dry machining operations due to their superior wear resistance, increased hardness, high-temperature stability, and chemical inertness when compared to conventional cemented carbides. These characteristics make them particularly ideal for machining hard materials, when heat and mechanical stresses are high[1,2]. Recent advancements in the microlevel design of Ti(C,N)-based cermets—such as the development of core-rim structures, multiscale honeycomb architectures[3], and dual-core configurations have further enhanced their mechanical strength, including breaking strength and transverse rupture strength. For instance, Wang et al. [4] systematically investigated the rupture properties of Ti(C,N)-based cermets and identified a previously overlooked "trans-rim" fracture mode using transmission electron microscopy and finite element analysis, providing new insights for toughness enhancement. When nodular cast iron is being

turned, Tong et al.'s extremely dense (Ti,W,Mo,Ta,Nb)(C,N)Co cermet tools demonstrated excellent cutting ability with a maximum tool life of 1393s, greatly outperforming traditional Ti(C,N)-based cermets [5]. Zhou et al. [6] showed that super fine grain Ti(C,N)-based cermet tools had significantly higher Rockwell hardness, flexural breaking stress, and tool life than submicron counterparts due to grain refinement strengthening, with tool wear caused by a combination of aggressive, adhesive, and oxidative wear mechanisms throughout cutting at high speeds of AISI 1045 steel.

In metal cutting processes, cutting force and tool-tip temperature are critical physical quantities that govern machining deformation, tool wear, and surface integrity [7,8]. In order to increase machinability and tool life, a significant amount of research has concentrated on improving cutting parameters. For example, Murakami et al.[9] investigated the high performance cutting qualities of Ti(C,N)-W cermet tools against S32750 SDSS at cutting speeds of 800m/min, and demonstrated that Ti(C,N)-70 wt% W cermet cutting tools exhibited the longest lifetime among all non-coated cutting tool specimens, further extended by TiAlN coating. However, while these studies have provided valuable insights into parametric optimization, they have largely overlooked the influence of tool geometry, which fundamentally alters the mechanics of chip formation, heat generation, and stress distribution on the tools-chip interface [10]. In a thorough investigation of the effects of substrate pretreatment on TiAlN-coated Ti(C,N)-based cermet tools, Wang [11] discovered that sandblasting pre-treatment improved coating hardness, residual stress, and adhesion strength, leading to a 25% longer service life than rough grinding pre-treatment. However, with Ti(C,N)-based cermet tools, the combined effects of numerous geometric parameters on cutting force and tool-tip temperature are still poorly known.

Finite element (FE) simulation has proven to be an effective tool for predicting machining responses, enabling detailed analysis of the cutting process without the cost and time associated with extensive experimental trials [12,13]. Recent studies have combined FE simulation with response surface methodology (RSM) to evaluate cutting performance [14,15]. Mekgwe et al. [16] shown the efficacy of this method for multi-parameter optimization operations by using RSM to examine the tribological characteristics of graphitized TiC_{0.5}N_{0.5}-based compounds. Despite these advances, systematic investigations integrating FE simulation with statistical modeling to establish predictive quadratic models that capture not only main effects but also interaction effects among geometric variables

for Ti(C,N)-based cermet tools are still lacking. Moreover, few studies have conducted multi-objective optimization to simultaneously minimize cutting force and tool-tip temperature, which are often conflicting objectives in machining processes.

This study seeks to fill this research gap by systematically examining the influence of three critical tool geometry factors on cutting force and tool-tip temperature throughout the orthogonal turning of 45 steel (GB/T 699) using Ti(C,N)-based cermet tools. Deform-3D finite element simulations were combined with Box-Behnken design (BBD) and response surface methodology (RSM) to create and evaluate a quadratic regression model through analysis of variance (ANOVA). The innovation of this work lies in its extensive quantification of as well individual as interactive effects of tool geometry on machining responses, as well as the multi-objective optimization of tool factors to simultaneously minimize cutting force and temperature. The optimized geometry, which included a 9° rake angle, an 8° clearance angle, and an edge radius of 0.02 mm, resulted in 5.37% less cutting force and 3.87% less tool-tip temperature than the initial conditions, with wear morphology characterized by crater wear on the rake face and groove wear on the flank face. These findings provide a theoretical framework for the rational design of cermet tool geometries as well as a verified methodology for parameter optimization in precision machining applications.

2. Materials and Methods

2.1 Workpieces and Tool Specifications

The FE model (Fig.1) simulated orthogonal turning of 45 steel (GB/T 699) (composition: Table 1) using a Ti(C,N) cermet tool (composition: Table 2; characteristics: Table 3). Workpiece and tool meshes used tetrahedral elements (min size: 0.025 mm). Cutting conditions: speed $v_c = 100 \text{ m/min}$, feed $f = 0.15 \text{ mm/rev}$, depth of cut $a_p = 0.15 \text{ mm}$, and initial temperature $T_0 = 20^\circ \text{C}$.

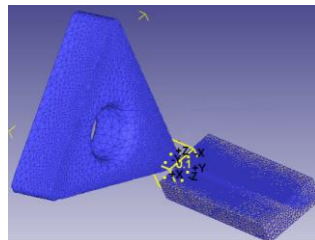


Figure 1. Cutting simulation model

Table 1. Composition of 45 steel (GB/T 699) (wt%)

C	Si	Cr	Mn	P	Ni	S
0.42-0.5	0.17-0.37	≤0.25	0.5-0.8	≤0.035	≤0.25	≤0.035

Note: Material parameters are obtained from the manufacturer's datasheet.

Table 2. Composition of Ti(C,N) ceramic (wt%)

TiC	TiN	Mo	WC	Co	Ni	C
55	10	4	15	7.5	7.5	1

Note: Material parameters are obtained from the manufacturer's datasheet.

Table 3. Mechanical and physical characteristics of Ti(C,N)

Density (kg/m ³)	Bending Strength (MPa)	Hardness	Fracture Toughness (MPa·m ^{1/2})	Heat Capacity (J/K)	Thermal Conductivity (W/(m·K))	Poisson's Ratio	Elastic Modulus (GPa)
6.264×10 ³	1642.41	92.2	17.68	84.31	45.98	0.206	456.23

Note: Material parameters are obtained from the manufacturer's datasheet.

2.2 Constitutive Model

The Johnson-Cook model described 45 steel (GB/T 699) plasticity:

$$\sigma = (A + B\varepsilon_{eq}^n) \left(1 + C \ln \varepsilon_{eq}^* \right) \left[1 - \left(\frac{T - T_0}{T_{melt} - T_0} \right)^m \right] \quad (1)$$

In the formula: A, B, n, C, m -material parameter; σ -flow stress; ε_{eq} -equivalent plastic strain; $\varepsilon_{eq}^* = \varepsilon_{eq} / \varepsilon_0$ -dimensionless equivalent plastic strain rate; ε_0 -reference strain rate; T_{melt} -materials at melting point; T_0 -room temperature, usually $T_0=20^\circ\text{C}$. Table 4 displays the Johnson-Cook model equation for 45 steel (GB/T 699).

Table 4. Johnson–Cook specifications for 45 steel (GB/T 699)

A/MPa	B/MPa	n	C	m
507	320	0.28	0.064	1.06

Note: Material parameters are obtained from the manufacturer's datasheet.

The F value of γ_0 is the smallest, α_0 is the second, and r_ε is the largest. The T rises as the blunt radius increases, because when the blunt radius is too large and the F is too high, the heat dissipation capacity increased by the blunting of the tool tip is insufficient to offset the temperature rise caused by the excessive cutting force, causing the temperature to rise further. The tool's geometric characteristics, Rake angle γ_0 , Clearance angle α_0 , and Edge Radius r_ε are chosen as independent variables to develop the model based on the single-factor experiment and principal component analysis. To obtain the three factors, each independent variable chooses three levels: -1, 0 and 1. In Table 5, the horizontal test plan is displayed.

Table 5. Factor levels for BBD

Levels	Factor		
	A—Rake angle γ_0 /(°)	B—Clearance angle α_0 /(°)	C—Edge Radius r_ε /(mm)
- 1	6	7	0.02
0	12	11	0.06
1	18	15	0.10

Note: These parameters are defined according to the experimental design in this work.

Using the Box-Behnken Design (BBD) method, this method selects the center point, cubic point, and axial point of the design space, and its advantage is that it can evaluate the nonlinear influence of the factors. As indicated in Table 6, 17 test sample points are created using the cutting force F and the tool tip temperature T as the target response values.

Table 6. Experimental design table

Test serial number	Factor			Target Response Value	
	A—Rake angle γ_0 /(°)	B—Clearance angle α_0 /(°)	C—Edge Radius r_ε /(mm)	Cutting Force F / (N)	Tool tip Temperature T / (°C)
1	12	11	0.06	249.3	292.8
2	12	15	0.1	287.6	337.4
3	12	15	0.02	229.4	286.9
4	6	11	0.02	251.6	295.5
5	6	11	0.1	284.6	344.5
6	12	7	0.1	264.5	317.9
7	18	15	0.06	292.6	341.2
8	12	11	0.06	249.3	292.8
9	12	11	0.06	249.3	292.8
10	12	11	0.06	249.3	292.8
11	18	7	0.06	269.9	309.9
12	12	11	0.06	249.3	292.8
13	12	7	0.02	224.7	279.6
14	18	11	0.1	257.6	345.1
15	6	7	0.06	310.1	304.8
16	18	11	0.02	210.6	312.5
17	6	15	0.06	305.2	327.4

Note: The experimental scheme is generated by Box-Behnken Design.

3. Results and Discussion

3.1 Regression Modeling and Validation

The Design-Expert 13 program was used to do multiple regression analysis on the test sample points. The regression equation of the response variable F and T

on the quadratic polynomial of A-Rake angle γ_0 , B-Clearance angle α_0 , and C-Edge Radius r_ε was obtained, as shown in formulas (2) and (3)

$$F = 252.15 - 18.55 \times A - 8.55 \times B + 19.95 \times C + 3.45 \times AB + 3.5 \times AC + 2.3 \times BC + 22.35 \times A^2 + 5.7 \times B^2 - 10.55 \times C^2 \quad (2)$$

$$T = 288.66 + 3.47 \times A + 2.78 \times B + 19.77 \times C + 1.09 \times AB - 4.1 \times AC + 0.61 \times BC + 22.58 \times A^2 + 1.36 \times B^2 + 9.02 \times C^2 \quad (3)$$

The presentation will be succinct and easy to understand, and if needed, a list of the symbols used will be provided. The International System of Measurement Units will be utilized in this work. There won't be any descriptions of the equipment or installation in the paper.

Where F is the fitting value of cutting force, and T is the fitting value of tool tip temperature.

Performed variance analyses on the regression model of F and tool tip T are shown in Tables 7 and 8. Table 7 shows that the model is significant, with $F=116.63$, $P<0.0001$, reaching an exceptionally significant level. The multiple correlation coefficient R^2 is close to the corrected Adj R^2 , indicating that the experimental operation and theoretical prediction are credible, and this regression can be used as the equation replaces the true point of the test to analyze the results C.V%=1.31<10, indicates that the test has high credibility and accuracy[17]; The precision Adeq Precision=38.313>4, is considered reasonable; From the F value, it can be concluded that the factors affecting cutting the order of the main effects of force is: Edge Radius>Rake angle>Clearance angle.

Table7. ANOVA for the cutting force (F) model

ANOVA terms	Square Sum	df	F-Value	P-Value
Model	12277.63	9	116.63	<0.0001**
Rake angle	1835.21	1	156.89	<0.0001**
Clearance angle	806.65	1	68.96	<0.0001**
Edge Radius	2122.68	1	181.47	<0.0001**

Note: Multiple correlation coefficient $R^2=0.9934$, Adj $R^2=0.9849$, Pred $R^2=0.8940$, variation coefficient C.V%=1.31; Adeq Precision=38.313; ** means $P<0.0001$, the difference is extremely substantial; * means $P<0.05$, the difference is significantly[18-20].

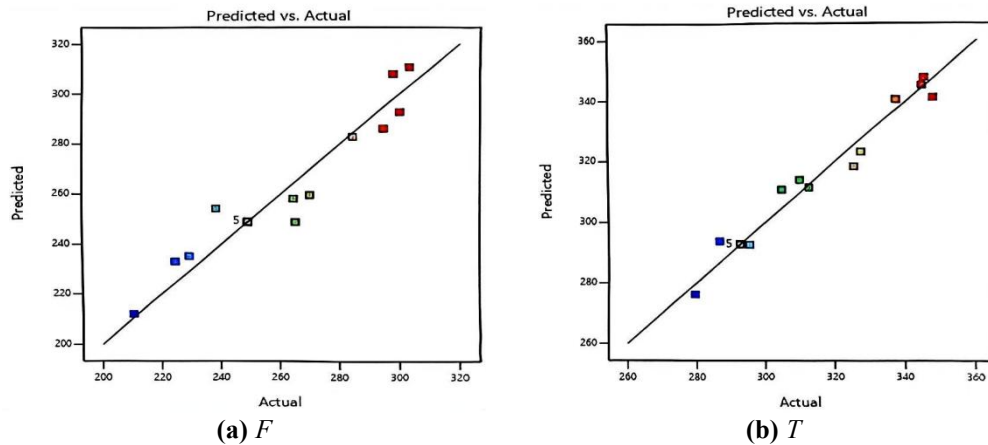
Table 8 shows that the model's $F=59.96$ and $P<0.0001$ reach a highly significant level, suggesting that the model is noteworthy. Moreover, the multiple correlation coefficient R^2 is close to the corrected Adj R^2 , indicating that the experimental operation and theoretical prediction are credible, and the regression formula can be used to examine the data, with C.V%=1.21<10. This demonstrates good credibility and accuracy of the test; Adeq Precision=24.001>4 is considered reasonable. From the F value, it can be concluded that the order of the main effects of factors on tool tip temperature is: Edge Radius>Clearance angle>Rake angle.

Table 8. ANOVA for the tool-tip temperature (T) model

ANOVA terms	Square Sum	df	F-Value	P-Value
Model	7358.02	9	59.96	<0.0001**
Rake angle	64.40	1	11.84	0.0192*
Clearance angle	84.97	1	57.86	0.0103*
Edge Radius	2085.60	1	257.96	<0.0001**

Note: Multiple correlation coefficient $R^2=0.9872$, Adj $R^2=0.9707$, Pred $R^2=0.7951$, variation coefficient C.V%=1.21; Adeq Precision=24.001; ** means $P<0.0001$, the difference is extremely substantial; * means $P<0.05$, the difference is significantly.

Figure 2 compares the simulated test values with the expected F and T target response values. The scatter points of the test values and predicted values are dispersed about the straight line in Figure 2, demonstrating the model's stability and dependability as well as its strong adaptability when fitted using the response surface approach.

**Figure 2.** Predicted vs. simulated values

3.2 Interaction Effects

Figures 3-8 present contour and 3D response surfaces of tool parameters, cutting force F , and temperature T from the quadratic model. Fixing one parameter, the plots illustrate how the other two interact to affect the response. Closer-to-ellipse contours and steeper surfaces indicate stronger interactions and greater impact.

3.2.1 Tool settings' impact on cutting force

Figure 3 shows that reducing both γ_0 and α_0 reduces the cutting force. However, when the γ_0 and α_0 patterns are compared in steepness, it is clear that the γ_0 has a substantially bigger influence on the cutting force than the α_0 .

Specifically, as the γ_0 increase, the corresponding shear angle increases, the cutting deformation of the cut part of the workpiece is reduced, and the friction resistance of the chip along the anterior face is also reduced, resulting in a reduction in the cutting force. The tool α_0 has little effect on the cutting force. The primary function of the tool α_0 is to reduce friction between the tool's flank surfaces. As a result, the cutting force falls slightly as the tool α_0 lowers.

Figures 4 and 5 show that the r_ϵ has a far bigger impact on the F than the γ_0 and α_0 , which is consistent with the F values for each response element in Table 5. That is, the F value of the r_ϵ is the biggest, followed by the γ_0 , and the α_0 of F value is the smallest. The F steadily reduces as the radius of the obtuse circle grows.

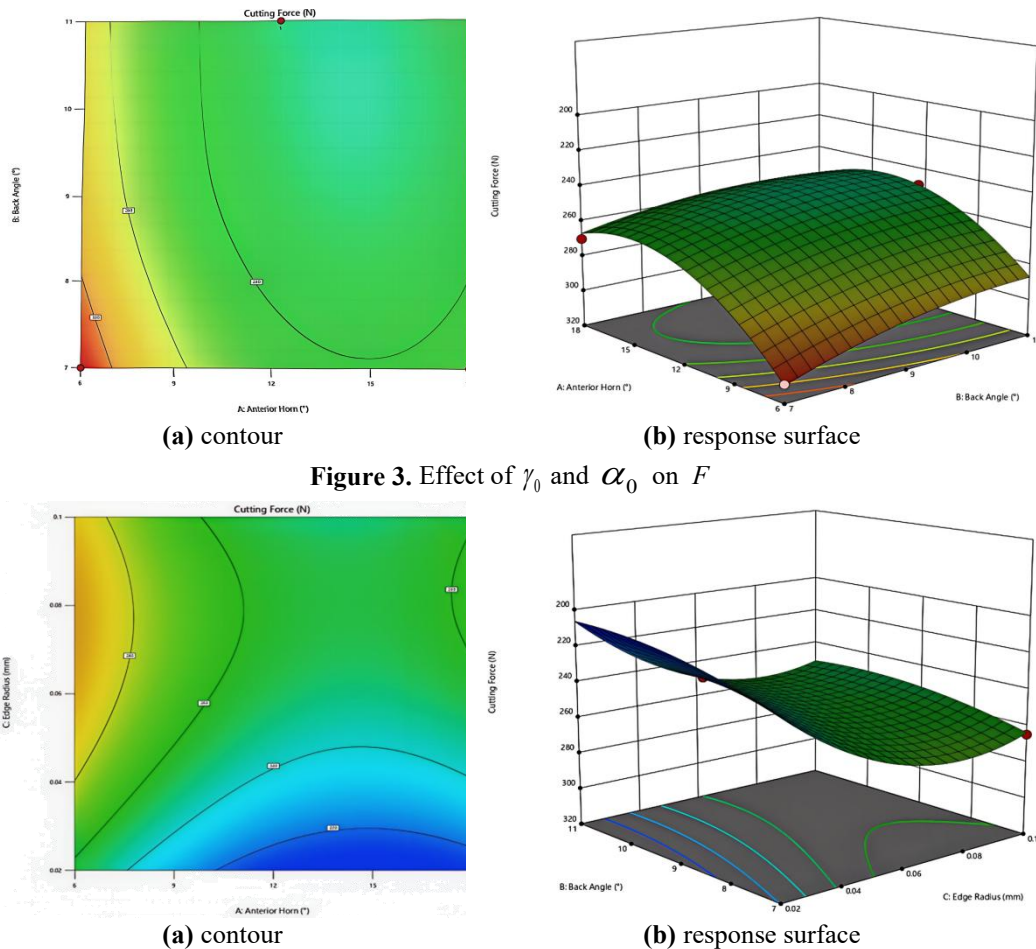


Figure 3. Effect of γ_0 and α_0 on F

Figure 4. Effect of r_ϵ and γ_0 on F

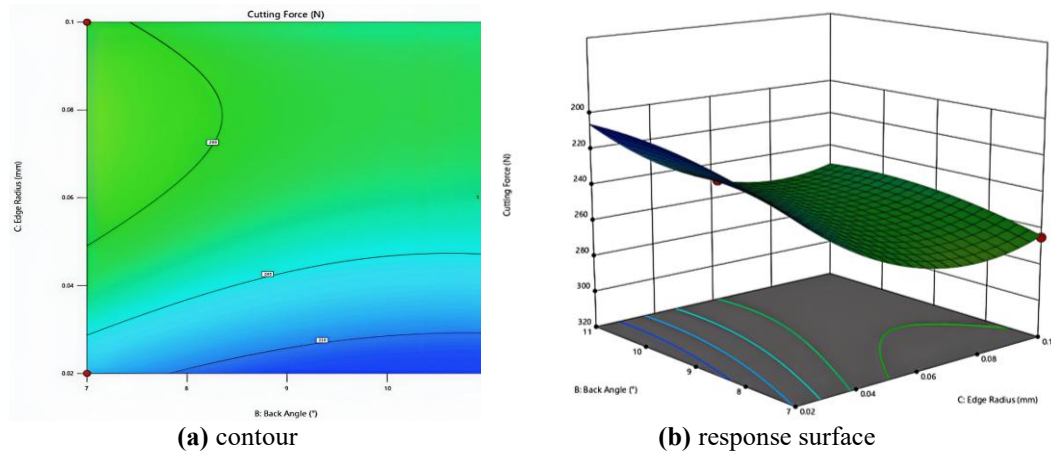


Figure 5. Effect of r_ϵ and α_0 on F

3.2.2 Tool settings' impact on tool tip temperature

Figure 6 shows that the α_0 has a far bigger impact on the T than the γ_0 , and the T progressively increases as both the α_0 and γ_0 increase. This is because the bigger α_0 , the tool's cutting edge, the sharper the tool, and the smaller the volume of the tool body, all of which hurt the tool's heat dissipation performance and cause the T to increase. The higher γ_0 , the thinner the tool body and the poorer the thermal conductivity, leading to the T to rise. Figures 7 and 8 show that, when compared to γ_0 and α_0 , r_ϵ has the highest impact on T, which is consistent with the F value for each response factor in Table 6.

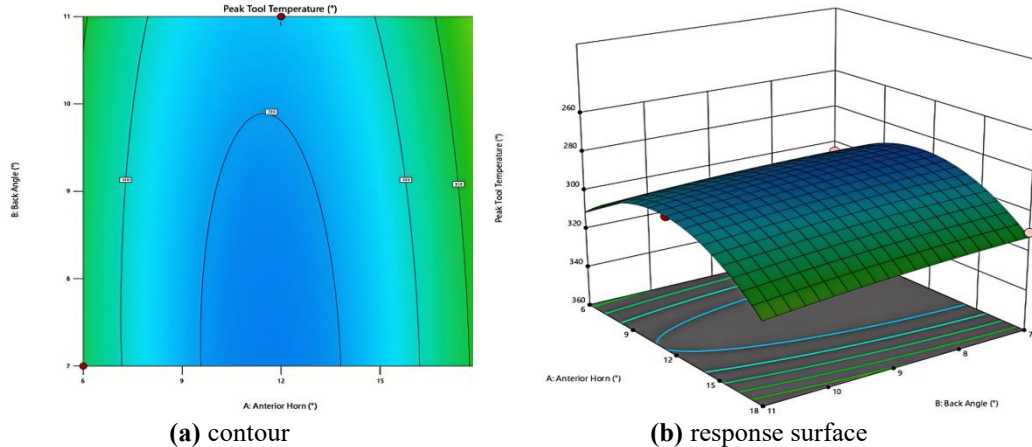


Figure 6. Effect of γ_0 and α_0 on T

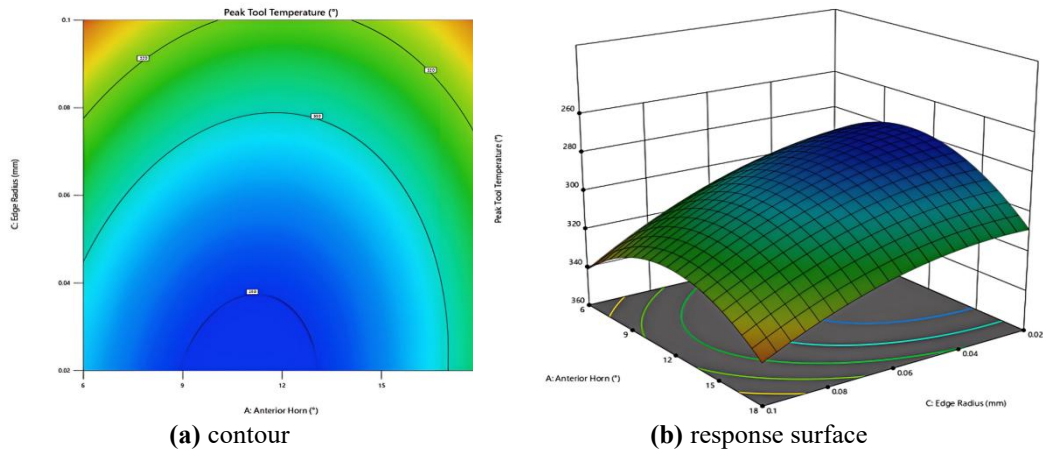


Figure 7. Effect of γ_0 and α_0 on T

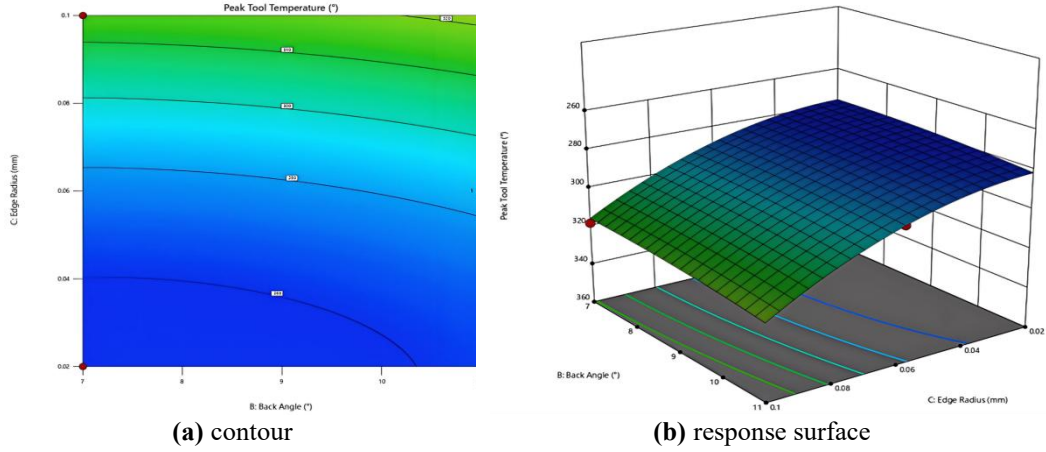


Figure 8. Effect of r_e and α_0 on T

The F value of γ_0 is the smallest, α_0 is the second, and r_e is the largest. The T rises as the blunt radius increases, because when the blunt radius is too large and the F is too high, the heat dissipation capacity increased by the blunting of the tool tip is insufficient to offset the temperature rise caused by the excessive cutting force, causing the temperature to rise further.

3.3 Multi-Objective Optimization

The Design-Expert software's optimization module is used to optimize the tool settings while taking into account the impact of F and T in order to attain the minimum value of the two responses. The ideal parameters for the tool are: $\gamma_0 = 9^\circ$, $\alpha_0 = 8^\circ$, and $r_e = 0.02mm$. Figure 9 displays the F and T under ideal tool

conditions. Table 9 displays the prediction and simulation results after the ideal tool parameters are simulated and confirmed. The prediction model may accomplish the final goal of lowering cutting force and surface roughness, minimizing expenses, and enhancing processing quality and production efficiency with a very small error.

Table 9. Optimization results

Parameter	Optimization degree	Optimized tool parameters			Expected Response	Simulation Response	Error (%)
		Rake angle	Clearance angle	Edge Radius			
F / (N)	minimum	9°	8°	0.02	238.656	226.498	5.37
T / ($^\circ\text{C}$)	minimum				277.765	264.535	3.87

Note: These parameters are defined according to the experimental design in this work.

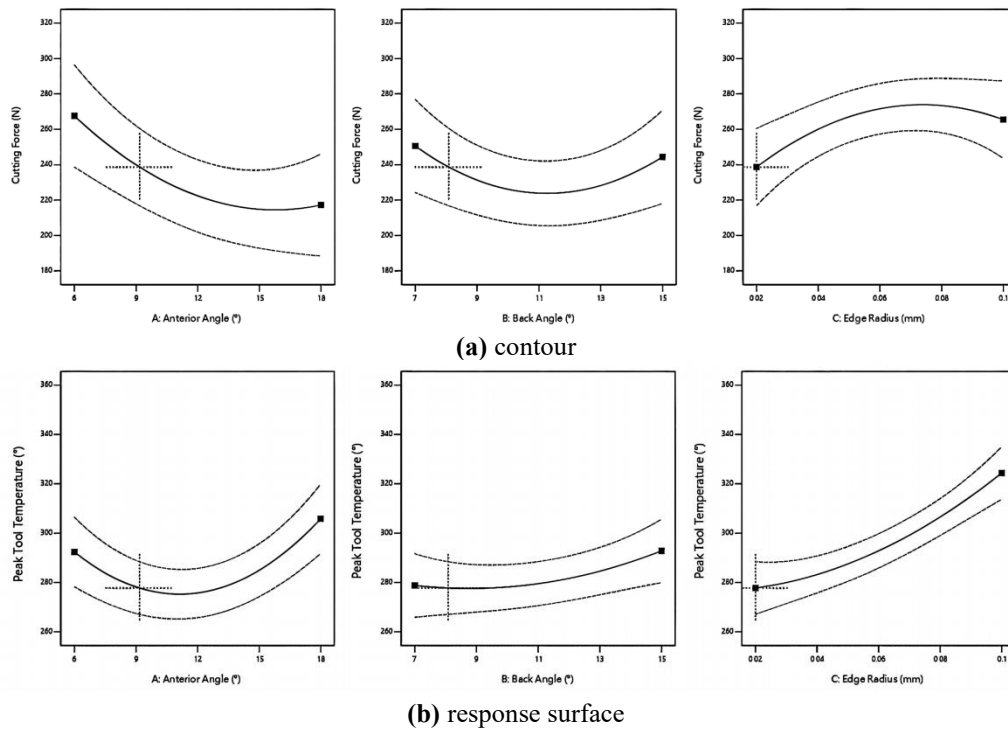


Figure 9. Optimal tool performance

Figure 10 shows the abrasive look of the best knife parameter SEM image. Figure 10(a) depicts the wear on the front knife surface. The concave pit in the image represents the so-called "crescent depression" wear. The primary reason for this wear pattern is cutting heat, as the crescent depression appears when cutting. Where the temperature is highest, wear the most and form a "concave nest," i.e. crescent lying. It is evident from Figure 10 (b) that knife tip wear, normal wear, and groove wear region make up the majority of the rear knife surface wear. The tip and

groove wear area has more wear than the regular wear area. The largest of these is the ditch wear area.

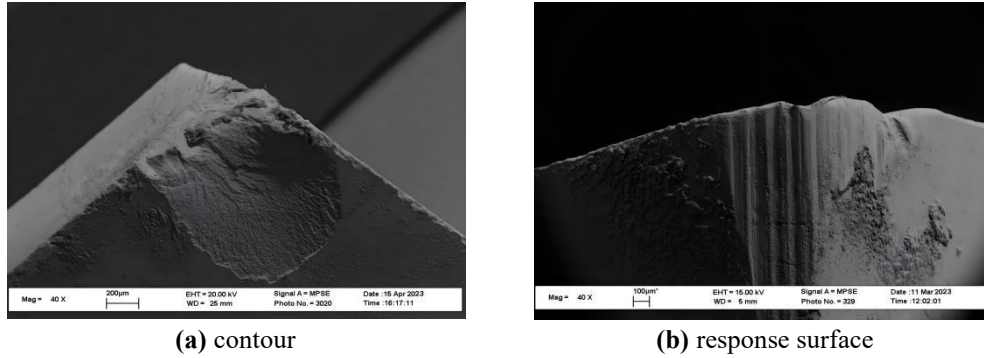


Figure 10. Tool wear morphology

4. Conclusions

It was investigated how tool settings affected cutting force and tool tip temperature. Regression analysis was performed using the response surface method and cutting simulation. Response analysis was used to create a quadratic model. To improve the tool parameters, the influence trend of several elements on the indicators was examined, and interacting effects were taken into account. It is possible to reach the following conclusions:

(1) Quadratic RSM models for F and T demonstrated high accuracy ($R^2 > 0.98$) and significance ($P < 0.0001$).

(2) Edge radius r_e dominated both F (52.1% contribution) and T (74.5%), followed by rake angle γ_0 and clearance angle α_0 .

(3) Optimal parameters ($\gamma_0 = 9^\circ$, $\alpha_0 = 8^\circ$, $r_e = 0.02\text{mm}$) minimized F (226.5 N) and T (264.5°C), improving tool life and efficiency.

Author Contributions

Data curation, Writing-original draft, G C.Xu; Writing-review & editing, W W.Zhang.; All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

Data supporting the findings of this study are available upon reasonable request from the corresponding author.

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Conflicts of Interest

The authors declare no conflict of interest.

Artificial Intelligence Disclosure

No artificial intelligence-based or generative tools were used in the preparation of this manuscript.

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