INVESTIGATING THE DIFFERENTIAL IMPACT OF MACHINING PARAMETERS ON TOOL WEAR USING DESIGN EXPERT 13

A.H. Norshahifudin[1], S.A. Sulaiman[1], H.F. Pahroraji[1], A.K.M.N. Amin[2]

[1] Faculty of Mechanical Engineering,
Universiti Teknologi MARA Johor Branch, Pasir Gudang Campus,
81750 Masai Johor, Malaysia.

[2]Department of Industrial and Production Engineering,
Military Institute of Science and Technology (MIST)
1216 Dhaka, Bangladesh

Corresponding Author's Email: [1]syidatul_akma7091@uitm.edu.my

Article History: Received 24 February 2026; Revised 13 April 2026; Accepted 26 June 2026

ABSTRACT: *Conventional machining at the industrial and educational levels, tool wear remains a primary cause of increased production costs and degraded surface integrity. At UiTM Pasir Gudang, the reliance on manual parameter selection for conventional lathes often leads to inefficient tool life and unpredictable wear rates during hand on session. This study targets to improve cutting parameters specifically cutting speed, feed rate, and depth of cut to minimize crater wear rates for Mild Steel workpieces using HSS 5% Cobalt tools. The research employed a Design of Experiment (DOE) approach via Response Surface Methodology (RSM) with 15 experimental runs. Data were examined using Design Expert 13 software to develop predictive mathematical models and identify significant interactions. Statistical analysis through ANOVA revealed that the depth of cut significantly dictates the progression of crater wear through a quadratic relationship with R^2 value = 0.9024. The study successfully established optimized machining zones that extend tool longevity. These findings provide a structured framework for conventional lathe operations at the Faculty of Mechanical Engineering, UiTM Pasir Gudang, to enhance machining efficiency and reduce material waste.*

KEYWORDS: *Tool Wear, Design of Experiment, ANOVA, Machining Efficiency, Crater Wear*

1.0 INTRODUCTION

In the competitive landscape of modern manufacturing, turning remains one of the most critical processes for producing high-precision components. Nevertheless, the efficiency of the machining process is frequently affected by tool wear, which may cause poor surface finish, dimensional deviations, and increased production costs [1]. Tool wear is a complex phenomenon occurring at the contact region between the cutting tool and the workpiece during the machining process, driven by high temperatures and mechanical stresses [13]. In educational settings like the Faculty of Mechanical Engineering at UiTM Pasir Gudang, conventional lathes are extensively used, making it vital to understand how cutting parameters specifically speed, feed, and depth of cut interact to determine the lifespan of High-Speed Steel (HSS) tools.

The progression of tool wear, specifically flank and crater wear, has been a central focus of machining research for decades. Previous studies by researchers such as Choudhury and Rao [2-5] have demonstrated that optimizing cutting parameters can maximize tool life by nearly 20%. Recent advancements in the field have explored the use of PVD-coated tools and Minimum Quantity Lubrication (MQL) to mitigate thermal degradation at the cutting zone

[9-10]. Furthermore, industrial patents have highlighted the development of multilayered coatings designed to resist the abrasive nature of mild steel machining [14]. While these high-end solutions exist, there is a lack of localized data regarding the optimization of standard HSS 5% Cobalt tools on conventional equipment used in university laboratories.

The primary problem identified in the workshops of UiTM Pasir Gudang is the reliance on "trial and error" or manual selection of machining parameters. This subjective approach often results in premature tool failure and material waste, as students and operators may fail to represent the non- linear relationship between cutting factors and wear rates. Without a mathematical model to predict tool behavior, the costs associated with tool replacement and machine downtime remain unnecessarily high. There is an urgent need for a systematic, data-driven methodology to replace traditional heuristic methods.

Specifically, the study targets to develop a predictive mathematical model for crater wear when machining Mild Steel. By utilizing Response Surface Methodology (RSM), this research seeks to pinpoint the optimal parameters where tool wear is minimized without compromising production time, thereby providing a clear operational guideline for the faculty's machining laboratory.

This research is highly significant as it bridges the gap between theoretical optimization and practical application within a specific educational environment. The findings will not only enhance the academic understanding of wear mechanisms in HSS tools but also provide a practical framework for the Faculty of Mechanical Engineering at UiTM Pasir Gudang to reduce operational costs. By establishing a validated set of parameters for conventional lathes, this study ensures that future machining tasks are conducted with maximum efficiency, sustainability, and tool reliability.

2.0 METHODOLOGY

The methodology of this study was structured into four primary phases: selection of machining parameters, experimental design using DOE, the physical turning process, and the microscopic measurement of tool wear.

2.1 Parameters and Materials Selection

The workpiece material used for this study was Mild Steel, due to its wide application in general engineering components. The cutting tools used were Miranda HSS 5% Cobalt square bits. Three independent input factors were selected: Cutting speed (A), feed rate (B), and depth of cut (C). These factors were chosen based on their high correlation with heat generation and mechanical resistance between the tool and the emerging chip. The output response measured was crater wear.

2.2 Design of Experiment (DOE)

To minimize the number of experimental runs while maintaining statistical accuracy, Response Surface Methodology (RSM) was employed via Design Expert 13 software. A total of 15 experimental runs were generated using a standard design matrix. This approach allowed for the analysis of both linear and quadratic interactions between the cutting parameters, which is essential for understanding the complex nature of tool degradation.

2.3 Experimental Setup and Machining Process

The machining operations were carried out at the using a WINHO S480×1000 High-Speed

Precision Lathe as in Figure 1. The lathe was calibrated to ensure stability and minimize vibration during the runs. Each of the 15 runs was conducted according to the specific combinations of RPM, feed rate (mm/rev), and depth of cut (mm) prescribed by the DOE matrix. A consistent cutting length was maintained for each run to ensure the wear observed was comparable across all tests.

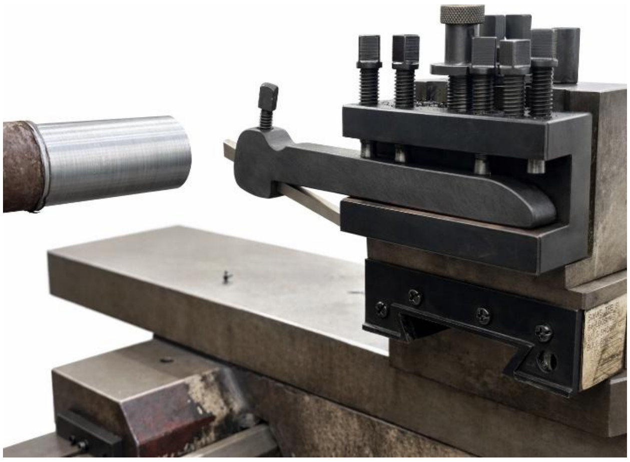

Figure 1: Experimental setup using WINHO S480x1000 precision lathe

2.4 Tool Wear Measurement and Analysis

Upon completion of each machining run, the HSS tool was removed for inspection. The wear analysis was focused on two primary regions: the flank face and the rake face. Measurements were performed using an X-80 Xoptron Optical Microscope equipped with digital imaging software. Crater wear was measured by assessing the depth and area of the depression on the top surface. The captured images were then processed to provide the numerical data required for the subsequent ANOVA and optimization phase in Design Expert.

3.0 RESULT AND DISCUSSION

The experimental results obtained from the 15 runs were examined using Design Expert 13 to determine the mathematical relationship between machining parameters and tool degradation. Statistical analysis revealed that crater wear yielded a highly significant quadratic model, providing a more precise predictive tool for machining Mild Steel with HSS 5% Cobalt.

3.1 Experimental Data and Model Fit for Crater Wear

Result from Table 1 showed a strong interaction between feed rate (B) and depth of cut (C). Cratering is observed on the tool's rake surface, where the chip slides over the surface after being sheared from the workpiece. In this study, using HSS 5% Cobalt tools on Mild Steel, the following observations were made.

Table 1: Crater wear of different parameters.

Run	A: Cutting Speed (rpm)	B: Feed (mm/rev)	C: Depth of Cut (mm)	Crater Wear (mm)
1	200	0.05	0.1	0.22231
2	20	0.05	1	0.3030
3	900	0.05	0.55	0.8503

4	900	0.48	1	0.8121
5	900	0.82	0.55	1.0546
6	2000	0.82	1	0.9500
7	2000	0.48	0.55	0.7354
8	20	0.82	1	0.8224
9	2000	0.82	0.1	0.4131
10	2000	0.82	0.1	0.6910
11	20	0.48	0.55	0.9762
12	900	0.48	0.1	0.6986
13	20	0.05	0.1	0.1421
14	2000	0.05	1	0.8833
15	20	0.48	0.550	0.7894

When both are high (feed 0.82 mm/rev, depth 0.55 mm) and (feed 0.82mm/rev, depth 1mm) the crater wear reached 1.0546 mm (Figure 2) and 0.9500mm. Increasing the cutting depth forces the chip to occupy more of the tool's rake surface. This traps more heat and increases the normal pressure on the tool surface. This interaction creates a wedge effect where the cross-sectional thickness of the chip forces the tool to endure maximum stress at a distance slightly away from the cutting edge, which is the classic location for a wear crater [7].

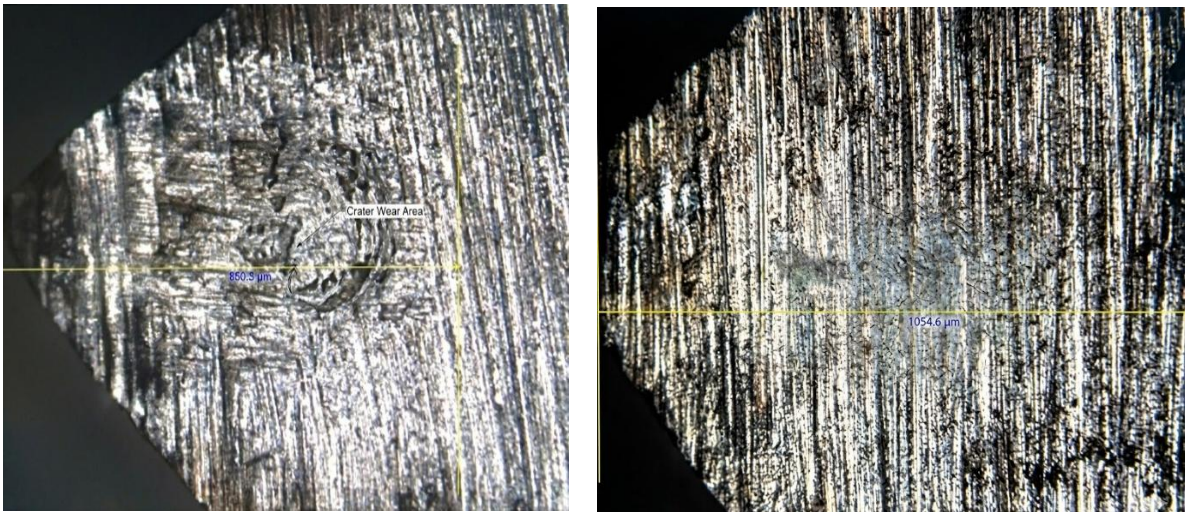

Figure 2: Microscopic image for crater wear. Left for run no 3 and right for run no 5

The relationship between cutting parameters and tool degradation is exemplified in Figure 2, which displays the rake face for run no 3 and 5 (900 rpm, 0.05 mm/rev). The microscopic analysis yields a crater wear width of 850.3 µm, precisely matching the recorded value of 0.8503 mm in Table 1. The distinct elliptical morphology and darkened surface within the wear zone suggest that diffusion and adhesion are the dominant mechanisms at this cutting speed, leading to significant material loss on the tool's rake face [8].

Table 2: Fit summary for crater wear response

Source	p-value	lack of fit p-value	R^2	adjusted R^2	
Linear	0.0674	0.3513	0.4641	0.3179	
2FI	0.1154	0.4584	0.7342	0.5349	
Quadratic	0.1427	0.6502	0.9024	0.7268	Suggested
Cubic	0.6502		0.9509	0.6561	Aliased

The Fit Summary identifies the best mathematical "fit" for the experimental data. For crater wear, the software compared several models, as summarized in Table 2. The p-value for the quadratic model is 0.142, showing that the quadratic model is the most appropriate model to represent crater wear because it is statistically significant and provides the best fit without aliasing issues. This confirms that crater wear exhibits nonlinear behavior, and second-order terms are necessary to model the response accurately. The presence of curvature in machining processes is expected due to thermal effects, tool-material interaction, and nonlinear wear mechanisms.

3.2 Statistical Significance of the Quadratic Model

The ANOVA breaks down the total variation in the data into components associated with each factor. The ANOVA analysis in Table 3 evaluates the impact of the regression model and each term affecting crater wear. The results indicate that the developed quadratic model for crater wear is statistically important. The model f-value of 5.14 with a corresponding p-value of 0.00431 which is less than 0.05 demonstrates that the model is highly significant and that the probability of obtaining this result due to random noise is only 0.04%. This confirms that the selected model provides a consistent interpretation of the relationship between machining parameters and crater wear. Furthermore, the Model Sum of Squares (SS) of 1.02 is substantially higher than the residual sum of squares of 0.1108, indicating that most of the total difference in crater wear is explained by the regression model. The very small residual value suggests minimal unexplained variability, confirming good model adequacy and strong predictive capability within the studied experimental range.

Table 3: ANOVA for quadratic model

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	1.02	9	0.1138	5.14	0.00431	Significant
A-cutting speed	0.0011	1	0.0011	0.0508	0.8305	
B- feed rate	0.1616	1	0.1616	7.29	0.0427	
C-depth of cut	0.1079	1	0.1079	4.87	0.0784	
AB	0.0646	1	0.0646	2.92	0.1484	
AC	0.0473	1	0.0473	2.14	0.2037	
BC	0.0203	1	0.0203	0.9157	0.3825	
A2	0.0446	1	0.0446	2.01	0.2154	
B2	0.0002	1	0.0002	0.0110	0.9204	
C2	0.1180	1	0.1180	5.33	0.0691	
Residual	0.1108	5	0.0222			
Lack of fit	0.0550	3	0.0183	0.6574	0.6502	Not Significant
Pure error	0.0558	2	0.0279			
Cor Total	1.14	14				

3.3 Predictive Regression Equation

The final mathematical model for predicting crater wear, based on the actual machining factors, is expressed as follows:

$$\text{Crater Wear} = 0.9444 + 0.0167A + 0.2024B + 0.1211C - 0.1221AB + 0.1361AC - 0.0855C - 0.1326A^2 + 0.0099B^2 - 0.2125C^2 \quad (1)$$

The regression model implies that feed rate (B) has the strongest impact on crater wear, as its positive coefficient shows that wear increases significantly with increasing feed rate. Depth of cut (C) also contributes positively, while cutting speed (A) has a quite small influence. The strong interaction between cutting speed and feed rate highlights that crater wear is highly sensitive to their combined changes. Significant negative quadratic terms for cutting speed and depth of cut confirm nonlinear behavior, justifying the use of a quadratic model to describe the wear response. Overall, the model demonstrates that crater wear is influenced by complex nonlinear interactions between machining parameters, dominated by feed rate and strong interaction effects.

3.4 Parameters Interactions

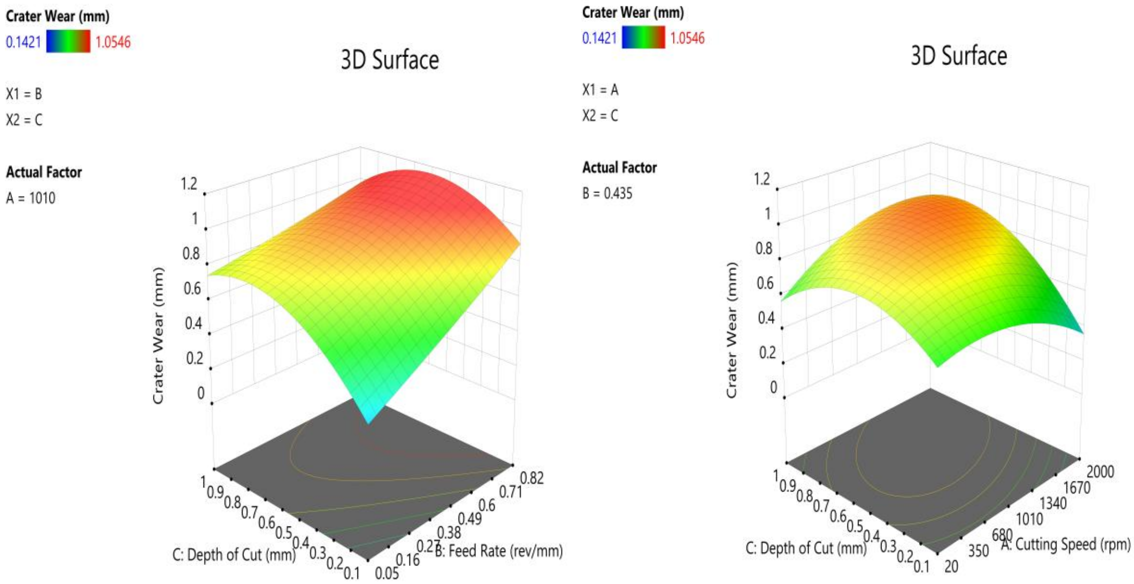

Figure 3: 3D Surface plot of interaction BC (left) and 3D surface plot of interaction AB (right).

Figure 3 demonstrates the 3D surface plot clearly demonstrates the quadratic behavior of crater wear through its curved, bowl-shaped profile. The relations between feed rate and depth of cut (BC) were found to be the most important relationship influencing cratering on the HSS tool. As shown in the 3D surface plot, the crater wear reaches its maximum peak when both the feed rate and the depth of cut are at their highest levels. When both are increased, the total volume of metal being shared per second rises sharply, leading to a massive accumulation of heat on the rake face. This confirms the strong interaction effect between these parameters, where the combined influence of thicker and wider chips intensifies mechanical stress at the tool face [11]. In addition, the relations between cutting speed and feed rate (AB) also plays a vital role in tool degradation, though its impact is more localized to the temperature gradient. The 3D surface plot indicates that at high cutting speeds (2000 RPM), increasing the feed rate leads to a steeper rise in crater wear compared to the same feed increase at lower speeds. At higher speeds, the friction between the flowing chip and the rake face generates intense localized heat weakening the tool structure and forming a deeper crater.

From the perturbation plot in Figure 4, the plot clearly shows that factor B (feed rate) has the steepest positive linear slope. This indicates that crater wear is most sensitive to changes in feed rate; as the feed increases, the wear rate rises consistently [12].

Factor C (depth of cut) exhibits a distinct downward curvature at higher deviation levels. This visual curvature confirms the significance of the C^2 quadratic term identified in the ANOVA results, suggesting that the rate of wear acceleration changes as the depth of cut increases beyond the mid-range. Lastly, factor A (cutting speed) shows a slight downward curvature like depth of cut, but with a gentler slope. This indicates that while speed does influence cratering through thermal effects, the tool is less sensitive to speed fluctuations than to changes in feed rate or depth of cut within this specific experimental range. In summary, the perturbation plot visually validates the ANOVA findings, confirming that feed rate (B) is the primary driver of crater wear, while depth of cut (C) and cutting speed (A) introduce significant non-linear (quadratic) effects to the wear mechanism

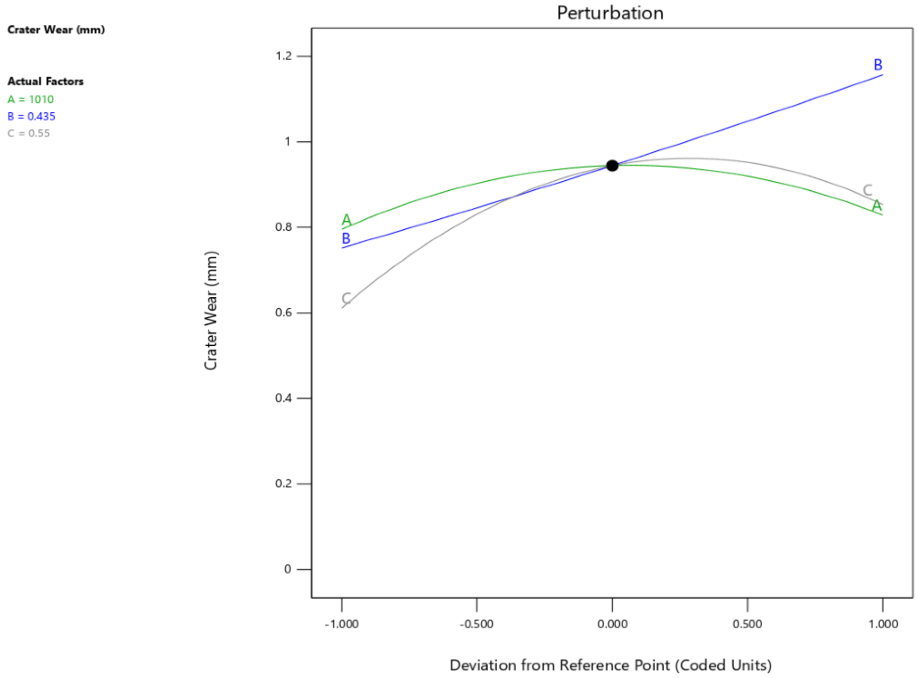

Figure 4: Perturbation interaction between cutting speed, feed rate and depth of cut

3.5 Optimization and Experimental Validation

The software's optimization algorithm generated a solution with a desirability value of 1.000. The suggested optimized parameters for machining Mild Steel with HSS 5% Cobalt tools at the UiTM workshop represented in Table 4 below.

Table 4: Optimized parameters suggested by DoE

Cutting Speed (rpm)	Feed Rate (mm/rev)	Depth of Cut (mm)	Crater Wear (mm)	Comparison	Percentage error
1752.54	0.5718	0.671	0.9596	Predicted	15%
1752.54	0.5718	0.671	1.1065	Experimental Validation	

To verify the accuracy of the model, a validation experiment was conducted using the exact parameters suggested by the optimizer. The comparison between the predicted theoretical value and the actual laboratory measurement is presented in Table 4. The numerical optimizer in Design-Expert 13 recommended an optimal cutting speed of 1752.54 RPM. However, during validation, a practical limitation occurred because the WINHO S480×1000 Lathe uses a stepped pulley system with fixed gear ratios, allowing only specific spindle speeds instead of continuous adjustment. Therefore, the closest available speed of 2000 RPM was selected for the experiment. This increase in speed (about 14%) caused higher frictional heat and kinetic energy at the tool–chip interface, leading to slightly greater crater wear than predicted. As a result, the percentage error recorded was 15%. Despite this deviation, the result still demonstrates that the model provides a reasonably reliable operational guideline under practical machining constraints.

4.0 CONCLUSION

This study successfully optimized cutting parameters to minimize tool wear during the turning of mild steel using HSS 5% Cobalt cutting tools through the application of Design of Experiment (DOE) and Response Surface Methodology (RSM). The statistical analysis confirmed that crater wear is best represented by a quadratic model ($R^2 = 0.9024$), indicating a strong nonlinear relationship between machining parameters and wear behavior. Depth of cut was discovered as the most influential factor causing crater wear, while cutting speed had minimal influence on crater wear. Significant interaction effects, particularly between feed rate and depth of cut, were observed, where simultaneous increases intensified thermal and mechanical stresses at the cutting interface, accelerating tool degradation. The developed predictive equations provide a reliable mathematical framework for parameter selection in machining applications, particularly for laboratory use at the Faculty of Mechanical Engineering, UiTM Pasir Gudang. These models support improved tool life and enhanced manufacturing sustainability by reducing tool consumption and waste. For future research, incorporating vibration analysis and surface roughness measurements is recommended to develop a comprehensive multi-objective optimization model for conventional lathe operations.

ACKNOWLEDGMENTS

The authors wish to express their deepest gratitude to the Faculty of Mechanical Engineering, Universiti Teknologi MARA (UiTM) Johor Branch, Pasir Gudang Campus, for providing the laboratory facilities, equipment, and technical support necessary to complete this research. Special thanks are also extended to the laboratory technicians for their assistance during the experimental setup and microscopic analysis.

REFERENCES

[1] R. N. Elshaer, A. A. El-Aty, E. M. Sayed, A. F. Barakat, and A. S. Sobh, "Optimization of machining parameters for turning operation of heat-treated Ti-6Al-3Mo-2Nb-2Sn-2Zr-1.5Cr alloy by Taguchi method," *Scientific Reports*, vol. 14, no. 1, pp. 1–14, 2024.

[2] S. K. Choudhury and I. V. K. Appa Rao, "Optimization of cutting parameters for maximizing tool life," *Int J Mach Tools Manufacturing*, vol. 39, no. 2, pp. 343–353, 1999.

[3] D. Yue, A. Zhang, C. Yue, X. Liu, M. Li, and D. Hu, "Optimization Method of Tool Parameters and Cutting Parameters Considering Dynamic Change of Performance Indicators," *Materials*, vol. 14, no. 20, p. 6181, 2021.

[4] O. Kayabasi, "Optimization of cutting parameters using the online method to minimize tool wear," *Journal of Engineering Research and Applied Science*, vol. 9, no. 1, pp. 1335–1340, 2025.

[5] A. Adamu, M. A. Bawa, and A. M. Abioye, "Optimization of Cutting Parameters of Tool Wear in Turning Operations: A Review," *Saudi Journal of Engineering and Technology Abbreviated Key Title: Saudi J Eng Technol*, vol. 6, no. 9, pp. 2415–6264, 2021.

[6] G. Jovicic *et al.*, "Optimization of Dry Turning of Inconel 601 Alloy Based on Surface Roughness, Tool Wear, and Material Removal Rate," *Metals 2023, Vol. 13, Page 1068*, vol.

13, no. 6, p. 1068, 2023.

[7] A. Yıldız, L. Uğur, and İ. E. Parlak, "Optimization of the Cutting Parameters Affecting the Turning of AISI 52100 Bearing Steel Using the Box-Behnken Experimental Design Method," *Applied Sciences (Switzerland)*, vol. 13, no. 1, pp.1-22, 2023.

[8] A. T. Abbas, E. A. Al Bahkali, S. M. Alqahtani, E. Abdelnasser, N. Naeim, and A. Elkaseer, "Fundamental Investigation into Tool Wear and Surface Quality in High-Speed Machining of Ti6Al4V Alloy," *Materials 2021,* Vol. 14no. 23, p. 7128, 2021.

[9] T. F. Ariff and U. A. Ismail, "Reducing Tool Wear with Hybrid Microwave Treated TiCN Coated Tool and Recycled Cooking Oil in MQL Machining of T6061 Aluminium Alloy," *Jurnal Kejuruteraan*, vol. 499, no. 1, pp. 499–506, 2025.

[10] M. Z. Siddique *et al.*, "Parametric Analysis of Tool Wear, Surface Roughness and Energy Consumption during Turning of Inconel 718 under Dry, Wet and MQL Conditions," *Machines 2023,* vol. 11, no. 11, p. 1008, 2023.

[11] M. Yildirim *et al.*, "An Investigation of Factors Influencing Tool Life in the Metal Cutting Turning Process by Dimensional Analysis," *Machines 2023,* vol. 11, no. 3, p. 393,2023.

[12] M. Sengottaiyan, P. S. kumar, P. N. Surendhar, K. Vasanth, and P. Vimalraj, "Effect of cutting parameters on wear behavior of coated tool with titanium nitride," *International journal of Intellectual Advancements and Research in Engineering Computations*, vol. 7, no. 2, pp. 2589–2593, 2019.

[13] A. K. M. N. Amin, S. A. B. H. Subir, and M. D. Arif, "Optimization of Tool Wear Using Coupled RSM-GA Approach in Turning of Stainless Steel AISI 304 with Magnetic Damping of Tool Shank," *Advance Material Research*, vol. 1115, pp. 117–121, 2015.

[14] V. Schier and W. Engelhart, "Wear-Resistant PVD Tool Coating Containing TiAlN Sublayers," *European Patent Specification*,2020.