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Optimization of CNC Turning Parameters for Surface Roughness and Tool Wear in Machining Inconel-718 Using Response Surface Methodology (RSM)

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Abstract

Inconel-718, a nickel-based superalloy widely used in aerospace and nuclear applications due to its superior mechanical properties, high-temperature resistance, and corrosion resistance. Despite these advantages, the low machinability of Inconel-718 presents challenges in achieving high surface quality and minimizing tool wear. The objective of this research is to optimize the CNC turning process for Inconel-718 by analyzing the effects of cutting speed and feed rate on surface roughness and tool wear. The study aims to identify the optimal machining parameters that produce a smoother surface finish while minimizing tool wear. Using RSM, cutting speed and feed rate were optimized through a systematic experimental design conducted on a Doosan LYNX 220L CNC lathe machine with TiAIN-coated carbide cutting tools. The cutting speeds ranged from 20.0 m/min to 120 m/min, while feed rates varied between 0.03 mm/rev and 0.1 mm/rev. The ANOVA results showed that the models for surface roughness and tool wear were significant, with p-values of 0.0159 and 0.0037, respectively. The R^2 values were close to 1, confirming the reliability of the model. ANOVA suggested a linear model because the relationship between cutting parameters and the resulting outcomes (surface roughness and tool wear) was almost direct, with no complex interactions requiring a more intricate model. Numerical optimization revealed the optimal cutting parameters to be a cutting speed of 20.0 m/min and a feed rate of 0.030 mm/rev, achieving a surface roughness of 0.441 µm and tool wear of 2.975 µm. The linear model used in this study showed that feed rate had a more significant influence on surface roughness, while cutting speed had a greater effect on tool wear. This study delivers critical advancements in optimizing the machining of Inconel-718, significantly enhancing process efficiency, minimizing machining errors, and improving surface integrity paving the way for higher precision and productivity in the manufacturing of hard-to-machine materials.

1. Introduction

Machining parameters are paramount when it comes to producing high-quality products and maintaining a safe and efficient machining process. These parameters, which include the spindle speed and feed rate of the cutting tool, play a crucial role in determining the outcomes of machining operations. A comprehensive understanding of these parameters is indispensable for optimizing machining processes. By thoroughly analysing and adjusting these factors, manufacturers can ensure both the quality of the final product and the overall efficiency and safety of the machining operation (John et al., 2020).

The response variables, such as life and tool wear, machining forces, surface roughness, and vibration, can be utilised to conduct an analysis of the impact of cutting parameters on the quality of the finished workpiece. Therefore, these variables play a crucial role in choosing the most favourable machining condition, since they serve as indications of quality. Evaluating the impact of machining settings has consistently posed a recurring difficulty for enterprises in the sector and researchers in the field. The cutting speed parameter has a notable impact on both power consumption and vibration. The overall rise in cutting speed led to an increase in both roughness and vibration (Pinheiro et al., 2021).

In metal cutting and manufacturing industries, achieving smooth and strong product surfaces is crucial. High-quality surface finishes not only make products look better but also indicate they are well-made and durable. This attention to detail ensures that products meet high standards, making them more appealing and reliable for customers (Sahithi et al., 2019). Lathe turning is a fundamental machining technique widely utilized today, where materials are shaped into desired forms by rotating them and guiding a cutting tool along their surfaces. This method involves rotating the workpiece while precisely directing a cutting tool to achieve accurate shaping and dimensional precision (Özdemir, 2020).

To compete effectively in mass production, industries prioritize achieving a high material removal rate (MRR) without compromising product quality over time. This goal requires the use of cutting-edge cutting tools that exhibit superior wear resistance (VB), enabling faster machining processes and extending the lifespan of the tools. By employing such tools, manufacturers can streamline operations, enhance efficiency, and maintain consistent product excellence in the long run (ZHUJANI et al., 2023).

Inconel-718 has exceptional corrosion and thermal resistance, as well as the ability to retain its mechanical properties at high temperatures. Due to their great mechanical strength, low thermal conductivity, high ductility, and strain hardening, super alloys are challenging to machine. If the parameters used are incorrect, the tool will fail and shorten its lifespan. Another issue with Inconel-718 that is a material with low machinability, making it difficult to cut. Another problem that has arisen is that it is hard to get a good surface quality for the final workpiece for this material (Raju et al., 2020).

1.1 Problem Statement

Several studies have highlighted critical challenges in optimizing CNC turning operations for Inconel-718, a material known for its poor machinability due to high strength, low thermal conductivity, and rapid work hardening. Previous studies by Raju et al. (2020) and Pinheiro et al. (2021) have highlighted the persistent challenges in achieving desirable surface quality and extended tool life during the machining of Inconel-718. These difficulties are primarily attributed to the limited focus on process parameter optimization within milling operations, as most research to date has predominantly concentrated on turning processes

There is also a lack of structured optimization approaches, such as Taguchi and Response Surface Methodology (RSM), specifically tailored for this alloy, as emphasized by Sahithi et al. (2019), Özdemir (2020), and Zhujani et al. (2024). Moreover, inconsistent results across literature suggest a need for more process-specific and statistically validated models. Additional concerns include the insufficient understanding of tool coating performance under high-speed conditions, especially regarding wear and thermal effects (Zhao et al., 2021; Velraja & Srinivasan, 2023). Many studies also neglect multi-objective optimization that simultaneously considers surface roughness and tool wear, which is essential for improving overall machining efficiency. Collectively, these gaps underline the need for comprehensive and statistically driven investigations into the optimal turning parameters for Inconel-718 to enhance surface finish, reduce tool degradation, and improve production reliability.

This research gap underscores a significant opportunity for further exploration and experimentation. Optimizing these parameters is critical not only for improving machining efficiency but also for achieving superior surface finishes and extending the operational life of coated carbide tools. Utilizing advanced methodologies such as Response Surface Methodology (RSM) within the framework of Design of Experiment (DOE) offers a structured approach to systematically explore and optimize these parameters. Addressing this gap in research would enable industries and researchers to maximize the potential of Inconel-718 in various demanding applications that require precise and durable machining with coated carbide tools.

Given these considerations, addressing the machining challenges of Inconel-718 involves determining the optimal parameters that achieve superior surface roughness and minimize carbide cutting tool wear. Optimizing these turning parameters is essential to achieving optimal results in surface roughness (Ra) and tool wear.

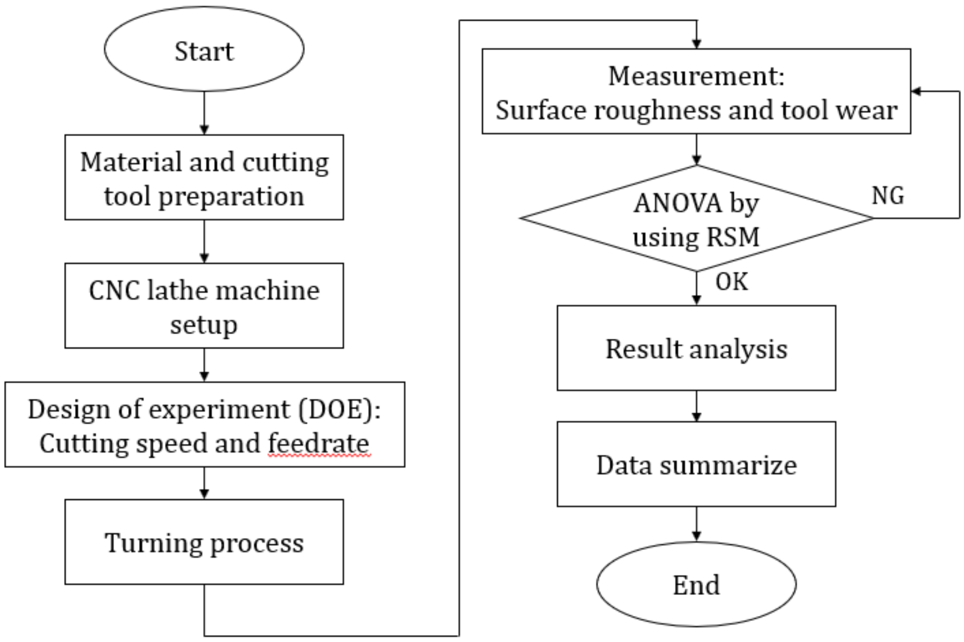
1.2 Research Objective

The primary objective of this study is to investigate and enhance the machining performance of Inconel-718, a high-strength nickel-based superalloy commonly used in aerospace and high-temperature applications. The study is conducted with three specific aims. Firstly, it seeks to analyze the surface roughness of Inconel-718 after undergoing the machining process, as surface finish is a critical quality indicator that affects the component's functionality and fatigue life. Secondly, the research focuses on examining the extent of tool wear that occurs during the machining operation, since tool degradation directly influences dimensional accuracy, surface integrity, and overall process cost. Thirdly, the study aims to determine the optimal set of machining parameters—such as cutting speed, feed rate, and depth of cut—that yield the best combination of surface finish and tool life, thereby improving the overall efficiency and sustainability of machining Inconel-718. Through this comprehensive analysis, the study aspires to contribute valuable insights for industries that frequently machine this challenging material.

2. Methodology

An experimental flowchart is a graphical or pictorial diagram representing an experiment's overall process, system, or workflow. It will give an overview of how the experiment is done. It can improve the research's progress efficiency to complete experiments in each deadline. The experimental flow chart of the research is shown in Figure 1 below.

Figure 1 *Experiment flow chart*



The experimental procedure began with the preparation of both the Inconel-718 work material with diameter of 100mm. The Doosan LYNX 220L CNC lathe machine was set up for the turning operation and equipped with a TiAlN-coated carbide cutting tool model CNMG 120408. The machining process was conducted using flood cutting to ensure effective cooling and lubrication, thereby minimizing heat generation and reducing tool wear. A Design of Experiment (DOE) approach was applied, focusing specifically on varying cutting speed and feed rate as the main parameters. The parameters involved in this study were the cutting speed and feed rate. These parameters affected the surface roughness and tool wear. The depth of cut was kept constant throughout the experiment. This study focused only on the two variable parameters in order to obtain the optimal machining conditions for the Inconel-718 material as refer to Table 1.

Table 1 *Design schema of process parameters and their level*

Factor Symbol	Parameters	Level	
		Low	High
Vc	Cutting Speed (m/min)	20	1.20
F	Feed Rate (mm/rev)	0.03	0.1
d	Depth Of Cut (mm)	1.0	

The turning process was conducted based on the experimental matrix generated using Design Expert software, as shown in Table 2. Following each machining run, surface roughness and tool wear were measured. It specifies combinations of cutting speed (Vc), feed rate, and depth of cut used in each experimental run. The cutting speed ranges from 20.0 m/min to 140.7 m/min, covering low to high-speed machining scenarios. Feed rates vary between 0.02 mm/rev and 0.11 mm/rev to examine their effects on surface finish and tool wear. A constant depth of cut of 1.0 mm is used across most trials, ensuring consistency in material removal. This matrix systematically explores the impact of machining parameters on performance outcomes, enabling a comprehensive analysis. The experimental data were then analyzed using Analysis of Variance (ANOVA) within the framework of Response Surface Methodology (RSM). In cases where ANOVA results were not statistically significant, further refinement of the experiment was carried out. Once validated, the results were subjected to detailed analysis, and the findings were summarized to complete the experimental process.

Table 2 *Design of Experimental Matrix*

Run Order	Cutting Speed, Vc (m/min)	Feed Rate (mm/rev)	Depth Of Cut (mm)
1	20.0	0.10	
2	20.0	0.03	1.0
3	70.0	0.11	
4	70.0	0.07	
5	70.0	0.07	
6	70.0	0.07	
7	70.0	0.02	
8	70.0	0.07	
9	120.0	0.10	
10	120.0	0.03	
11	140.7	0.07	

The surface roughness tester was employed in this study to accurately measure the surface texture of the machined Inconel 718 workpieces. The Mitutoyo SJ 410 surface roughness tester as in Figure 2, was used to evaluate the surface characteristics after the roughing process. Using the device's profilometer stylus, the surface profile was traced as the stylus moved across the material's surface. Measuring tool wear was more challenging, as wear often occurred at the microscopic level. To address this, the Nikon MM-60 Tool Maker Measuring Microscope was used, enabling high-resolution visualization and precise measurement of micro-scale wear that could not be captured with conventional measuring tools. This microscope provided sharp and detailed images, essential for assessing the extent of tool wear accurately.

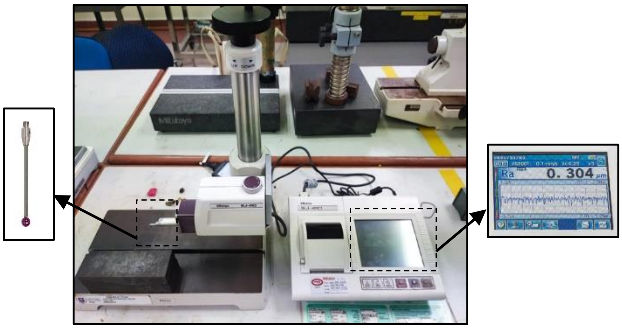


Figure 2 *Surface Roughness Tester*

3. Results and Analysis

The results and analysis encompass surface roughness evaluation, ANOVA significance testing, and parameter optimization, with Response Surface Methodology (RSM) employed to model and visualize the experimental data, enabling a deeper understanding of the machining behaviour and facilitating informed process improvements.

3.1 Surface Roughness

Surface roughness (Ra) is a critical parameter that reflects the quality of a machined surface. In machining, Ra values represent the arithmetic average of the absolute deviations of the surface profile from the mean line, offering a quantitative measure of the texture and finish. Lower Ra values indicate smoother surfaces with minimal irregularities, which are often desired for components requiring high precision and optimal performance. Conversely, higher Ra values signify rougher surfaces, typically characterized by visible tool marks or inconsistencies.

The surface roughness after machining is influenced by several factors, including the interaction between the tool and material, vibration during machining, and the thermal and mechanical conditions at the cutting interface. Achieving consistent and low Ra values is essential for enhancing the functional properties of the machined component, such as reduced friction and improved wear resistance. These values also play a vital role in determining the suitability of the surface for further operations, such as coating or assembly.

3.1.2 Measurement of Surface Roughness

Surface roughness measurement using ISO 468 involves the evaluation of surface texture by quantifying roughness parameters through a standardized approach. ISO 468 defines methods for assessing surface profiles, including the use of profilometers like the Mitutoyo SJ 410, which trace the surface with a stylus to obtain precise measurements. Key parameters such as roughness average (Ra), peak-to-valley height (Rz), and mean line deviations are computed based on the recorded surface profile. This ensures uniformity and reliability in comparing surface finishes across different materials and processes, facilitating quality control and adherence to engineering standards.

Table 3 *Result Surface Roughness*

Run Order	Cutting Speed, Vc (m/min)	Feed Rate (mm/rev)	Ra (x5) (µm)
1	20.0	0.03	0.418
2	20.0	0.10	0.635
3	70.0	0.02	0.504
4	70.0	0.07	0.536
5	70.0	0.07	0.680
6	70.0	0.07	0.573
7	70.0	0.07	0.504
8	70.0	0.11	0.975
9	120.0	0.03	0.656
10	120.0	0.10	0.684
11	140.7	0.07	0.790

Penerbit UTHM

Table 3 presents a detailed investigation into the influence of cutting speed (Vc) and feed rate on surface roughness (Ra) during machining. Measurements, based on a five-point averaging method, reveal a clear trend of increasing Ra with higher cutting speeds and feed rates, consistent with established machining principles. Notably, at a constant cutting speed of 70.0 m/min, surface roughness rises markedly from 0.504 µm at a feed rate of 0.02 mm/rev to 0.975 µm at 0.11 mm/rev, illustrating the pronounced impact of feed rate on surface quality due to coarser tool marks at higher material removal rates.

3.1.3 ANOVA Results

The results of ANOVA help in determining whether the factors under consideration (such as cutting speed and feed rate) significantly affect the outcome or whether any observed differences can be attributed to random variation. If the p-value is greater than 0.05, the factor is considered not significant, suggesting that it does not meaningfully contribute to explaining the variability in the response. In the case of a non-significant model, further analysis may be needed, or the model may require refinement or reduction. Additionally, the "Lack of Fit" tests whether the model adequately fits the data; a high p-value indicates the model fits well, while a low p-value suggests the model does not capture the data accurately. Overall, ANOVA helps in identifying the factors that influence the response variable and aids in improving model prediction.

Table 4 *ANOVA for Surface Roughness*

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.1473	2	0.0736	7.27	0.0159	significant
A-Cutting Speed	0.0435	1	0.0435	4.30	0.0719	
B-Feed Rate	0.1038	1	0.1038	10.25	0.0126	
Residual	0.0810	8	0.0101			
Lack of Fit	0.0687	5	0.0137	3.36	0.1740	not significant
Pure Error	0.0123	3	0.0041			
Cor Total	0.2283	10				

The ANOVA table as in Table 4 provides insights into the factors influencing Ra during machining. The model is statistically significant, as indicated by a p-value of 0.0159, which is below the typical threshold of 0.05. This means that the variation in Ra is significantly explained by the factors included in the model for cutting speed (A) and feed rate (B). The F-value of 7.27 further supports the model's strength in explaining Ra compared to random error.

$$Surface\ Roughness = 0.293498 + 0.001729\ (A) +\ 3.25391\ (B) \tag{1}$$

A = Cutting Speed
B = Feed Rate

The given equation helps predict surface roughness Ra based on cutting speed Vc and feed rate using their actual units. This means you can directly input cutting speed in m/min and feed rate in mm/rev to estimate the surface roughness in. It's a practical tool for machining, allowing you to forecast surface finish quality for specific parameter settings and adjust them as needed to meet your goals.

3.1.4 Contour Plot for Surface Roughness

In Response Surface Methodology, contour and 3D surface graphs are essential tools for analysing and visualizing the relationships between variables. The contour graph, or contour plot, displays responses on a two-dimensional plane, mapping them against combinations of numerical factors and mixture components. This type of graph illustrates how variables interact and influence the outcome, with contour lines highlighting regions of similar response values, making it easier to identify optimal conditions. The 3D surface graph provides a more detailed visualization by projecting the contour plot into three-dimensional space, offering deeper insight into the surface's shape and the interactions between variables. These visual tools are crucial for pinpointing parameter combinations that yield the most favourable results.

Figure 3 presents a contour plot created using Response Surface Methodology (RSM) to depict the relationship between cutting speed and feed rate on surface roughness (in microns). The color gradient shows the predicted surface roughness values within the cutting speed range of 20–120 m/min and feed rate range of 0.03–0.10 mm/rev. Regions in blue correspond to lower surface roughness values, whereas green and yellow areas indicate higher roughness levels.

The diagonal contour lines highlight the combined influence of cutting speed and feed rate. Surface roughness tends to increase with a rise in feed rate, as indicated by the shift toward green and yellow shades at the top of the plot. Similarly, higher cutting speeds cause a slight increase in roughness, though feed rate has a more significant effect. A red dot represents a specific experimental point, showing its position relative to the contour lines and indicating a surface roughness value close to the surrounding predictions. This plot is useful for identifying optimal machining parameters to minimize surface roughness, emphasizing areas with lower feed rates and moderate cutting speeds.

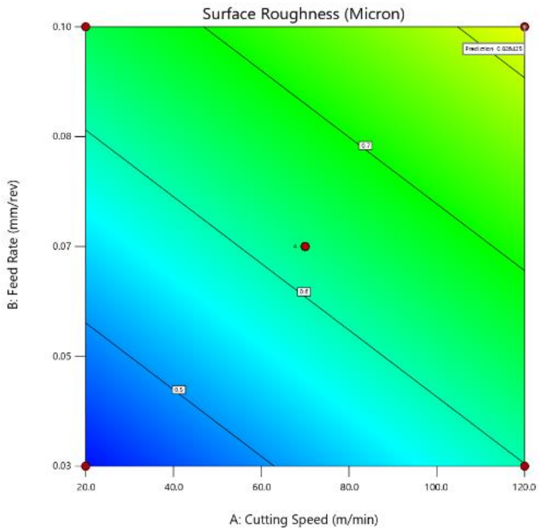


Figure 3 Contour Plot for Surface Roughness

3.1.5 Optimization of Parameter

Design Expert 13 is a robust software designed to optimize parameters in experimental designs, enabling users to determine the best combination of factors to achieve specific objectives. It utilizes advanced statistical methods, RSM, to model the relationships between input variables and outcomes. By defining goals and setting constraints for each parameter, users can apply Design Expert's optimization algorithms to explore the design space and identify optimal solutions.

The software uses desirability functions to consolidate multiple responses into a single value, helping users select parameter settings that maximize performance or meet defined criteria. This streamlined process allows researchers and engineers to save time, minimize costs, and enhance the reliability of their results by effectively fine-tuning experimental parameters. surface roughness is targeted for minimization, with acceptable values restricted between 1.556 µm and 1.856 µm. The goal is to achieve the smoothest surface possible while staying within the specified range.

Table 5 *Numerical Optimization of Parameters for Surface Roughness*

Number	Cutting Speed (m/min)	Feed Rate (mm/rev)	Surface Roughness (µm)	Desirability	
1	20.000	0.030	0.426	0.986	Selected
2	24.070	0.030	0.433	0.974	
3	24.874	0.030	0.434	0.971	

The first row as in Table 5 selected as the optimal solution, specifies a cutting speed of 20 m/min and a feed rate of 0.030 mm/rev, yielding a surface roughness of 0.426 µm with a desirability score of 0.986. This combination strikes the best balance between minimizing surface roughness and meeting the defined constraints, making it the most favourable solution.

3.2 Tool Wear

Wear refers to the process of material being gradually removed from the active surfaces of a cutting tool during the machining operation, primarily due to friction, pressure, and thermal effects. Among the different types of wear, flank wear holds the greatest significance, as it occurs universally on the cutting edges of all types of tools and serves as a critical indicator for determining the tool's lifespan.

3.2.1 Measurement of Tool Wear

Flank wear is a critical parameter in assessing tool life and performance during machining processes. Using the Nikon MM-60 Tool Maker Measuring Microscope, the wear on the tool's flank surface can be accurately measured and analyzed. This microscope provides high-resolution imaging and precise measurement capabilities, enabling the detection of wear patterns and quantification of wear dimensions. Flank wear occurs due to the friction and interaction between the tool and the workpiece material, resulting in material removal from the tool's cutting edge over time. Factors such as cutting speed, feed rate, depth of cut, and the material properties of both the tool and the workpiece influence the extent and rate of flank wear as result may refer to Table 6 below.

Table 6 *Result for Tool Wear*

Run Order	Cutting Speed, Vc (m/min)	Feed Rate (mm/rev)	Flank Wear (µm)
1	20.0	0.03	4.15
2	20.0	0.10	4.556
3	70.0	0.02	3.913
4	70.0	0.07	8.219
5	70.0	0.07	8.303
6	70.0	0.07	11.245
7	70.0	0.07	15.453
8	70.0	0.11	13.535
9	120.0	0.03	9.79
10	120.0	0.10	19.255
11	140.7	0.07	15.493

3.2.2 ANOVA Result

Table 7 *Anova for Tool Wear*

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	199.87	2	99.94	12.23	0.0037	**significant**
A-Cutting Speed	130.97	1	130.97	16.03	0.0039	
B-Feed Rate	68.91	1	68.91	8.44	0.0198	
Residual	65.35	8	8.17			
Lack of Fit	30.61	5	6.12	0.5285	0.7512	**not significant**
Pure Error	34.74	3	11.58			
Cor Total	265.23	10				

The analysis in Table 7 above shows that the overall model, which includes both cutting speed and feed rate, is statistically significant with a p-value of 0.0037. This means that the combination of cutting speed and feed rate has a meaningful impact on tool wear. Cutting speed (A) is the most significant factor, with a p-value of 0.0039 and an F-value of 16.03, indicating that changing the cutting speed has a strong effect on tool wear. Feed rate (B) also significantly influences wear, but its impact is slightly less, with a p-value of 0.0198 and an F-value of 8.44.

$$Tool\ Wear = -2.34701 + 0.094890(A) + 83.25201(B) \quad (2)$$

A= Cutting Speed
B= Feed Rate

The given equation predicts tool wear based on two factors: cutting speed and feed rate. The coefficients associated with each factor show how much tool wear is expected to change when the values of these factors change. Specifically, the coefficient for cutting speed indicates that for each increase in cutting speed, tool wear increases by a certain amount, while the coefficient for feed rate shows that increases in feed rate lead to a much larger increase in tool wear.

3.2.3 Contour Plot for Tool Wear

In Response Surface Methodology (RSM) for tool wear analysis, the Contour Graph and 3D Surface Graph are essential tools for visualizing and understanding the combined effects of multiple parameters on tool wear. These graphs reveal how variations in input factors influence tool wear and help identify optimal conditions for minimizing wear. The Contour Plot, shown in Figure 3, illustrates the relationship between cutting speed (Vc) and feed rate (mm/rev) with contour lines representing varying levels of flank wear. By analysing these contours, regions of minimal and maximal tool wear can be identified, aiding in the selection of optimal machining conditions.

The plot in Figure 4 provides a detailed visualization of how cutting speed (20–120 m/min) and feed rate (0.03–0.10 mm/rev) influence tool wear (measured in microns). The colour gradient highlights wear levels, with blue indicating lower wear (approximately 3.913 microns) and red showing higher wear (up to 19.255 microns). The analysis reveals that cutting speed has a more significant impact on tool wear compared to feed rate. As cutting speed increases, particularly near the upper limit of 120 m/min, tool wear rises sharply, as evident from the transition from blue to red. Feed rate also contributes to increased wear, with higher values intensifying wear effects, especially when combined with elevated cutting speeds. The combined influence of both parameters results in maximum wear at the upper right of the plot. These findings emphasize the critical role of optimizing cutting speed and feed rate to minimize tool wear and improve tool life. RSM proves invaluable in understanding these interactions and identifying ideal machining settings for enhanced performance. A study by Bahari et al. (2024) confirmed that feed rate has the most significant influence on surface roughness, while cutting speed is the dominant factor affecting tool wear.

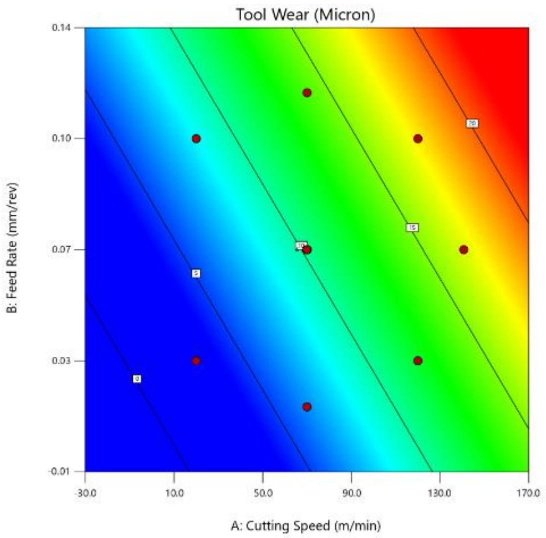


Figure 4 *Contour Plot for Tool Wear*

3.2.4 Optimization of Parameter

The selected optimal solution as in Table 8, highlighted in row 1, suggests a cutting speed of 20 m/min and a feed rate of 0.030 mm/rev, resulting in the lowest tool wear value of 2.066. This combination is chosen as the most favourable due to its exceptional performance in reducing tool wear while adhering to the desired parameter ranges.

Table 8 *Numerical Optimization of Parameters for Tool Wear*

Number	Cutting Speed (m/min)	Feed Rate (mm/rev)	Tool Wear (μm)	Desirability	
1	20.000	0.030	2.066	1.000	**Selected**
2	31.492	0.037	3.729	1.000	
3	33.594	0.032	3.558	1.000	
4	22.732	0.040	3.195	1.000	
5	30.084	0.034	3.349	1.000	
6	29.901	0.035	3.384	1.000	
7	33.450	0.036	3.876	1.000	
8	20.727	0.036	2.647	1.000	

4. Conclusion

This study provides a comprehensive analysis of machining Inconel 718, addressing critical challenges such as poor machinability, high cutting forces, rapid tool wear, and maintaining surface quality. The findings highlight the significant influence of machining parameters, particularly feed rate and cutting speed, on surface roughness and tool wear. Feed rate is identified as a dominant factor affecting surface quality, with higher feed rates leading to coarser finishes due to more prominent tool marks. On the other hand, cutting speed plays a more substantial role in determining tool wear, as elevated speeds generate higher temperatures and mechanical stresses that accelerate wear. These results emphasize the need for a balanced approach when selecting machining parameters to achieve both optimal surface quality and extended tool life.

The use of RSM proved invaluable in modelling the interactions between cutting speed, feed rate, and their effects on tool wear and surface roughness. By employing RSM, optimal parameter combinations were identified, ensuring reliable results while maintaining machining efficiency. Furthermore, the integration of TiAlN-coated tools showcased their superior performance in high-speed and high-stress environments, enhancing tool life and reducing wear significantly. These tools demonstrated sustainable benefits, such as lower material waste and improved energy efficiency, aligning with modern manufacturing priorities to international standards, such as ISO 3685:1993, further reinforced the reliability of the study by maintaining tool wear well below the permissible limits, achieving values as low as 2.066 μm.

This research provides a robust framework for machining Inconel 718 by leveraging advanced optimization techniques, sustainable tooling strategies, and international machining standards. The findings serve as a valuable guide for improving machinability, enhancing tool life, and ensuring superior surface quality, which are critical in high-precision industries.

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