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PARAMETER OPTIMIZATION FOR HIGH-SPEED END MILLING ON INCONEL 718 USING UNCOATED CARBIDE TOOL

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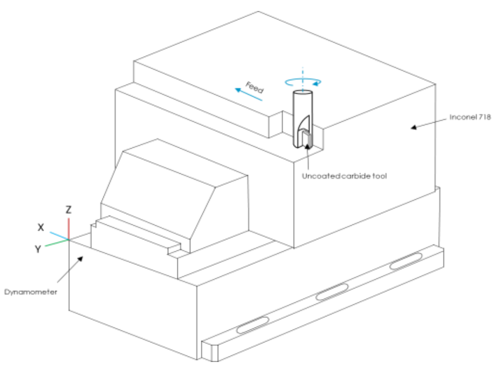
Graphical abstract



Abstract

Inconel 718 with exceptional characteristics is well known as a difficult-to-cut material especially during high-speed machining process. High cutting temperature further damaged the tool which results in low tool life. To overcome this matter, optimization on cutting parameters needed to be conducted in order to achieve longer tool life and desired cutting finish. Sets of optimized parameters consists of different cutting speed and feed rate were listed out through Research Surface Method (RSM) software which the effects and the output values were observed through high-speed end milling work on a 100 x 100 x 150 mm Inconel 718 block. The lowest cutting force and surface roughness at 776.04 N and 0.195 µm were recorded at the lowest parameter combination, while the highest results of 1,322.89 N and 0.478 µm were obtained from the highest parameter combination. Higher cutting parameter further deteriorate the cutting tool due to high heat and drastic reduction in tool life was observed, from 32 minutes of cutting process to only 2 minutes and 40 seconds. The results were further investigated through optimization work and cutting speed is the dominant factor that affected the results. The final model suggested that by using uncoated carbide tools, the lowest cutting speed and feed rate of 50 m/min and 0.05 mm/tooth can be implemented to obtain the desired cutting responses.

Keywords: High-speed machining, Inconel 718, Optimization, Uncoated carbide tool, Tool wear

Abstrak

Inconel 718 dengan sifat unggul bahan dikenali sebagai bahan yang sukar dipotong terutama ketika proses pemesinan kelajuan tinggi. Suhu pemotongan yang tinggi lebih merosakkan mata alat di mana ia menyebabkan jangka hayat menjadi rrendah. Untuk mengatasi perkara ini, pengoptimuman parameter pemotongan perlu dilaksanakan untuk mendapatkan jangka hayat mata alat yang lebih lama dan kemasan pemotongan yang baik. Beberapa set parameter yang terdiri daripada nilai kelajuan pemotongan dan kadar suapan yang berbeza disenaraikan menggunakan perisian *Research Surface Method* (RSM) di mana tindak balas diperhatikan dan nilai diperolehi melalui kerja eksperimen yang dilaksanakan pada blok *Inconel 718* bersaiz 100 x 100 x 150 mm. Daya pemotongan dan kekasaran permukaan terendah pada 776.04 N dan 0.195 µm direkodkan melalui kombinasi terendah parameter pemotongan manakala nilai tertinggi pada 1322.89 N dan 0.478 µm diperolehi melalui kombinasi tertinggi parameter pemotongan. Parameter pemotongan yang lebih tinggi semakin merosakkan mata alat dan jangka hayat dikurangkan dengan mendadak, daripada 32 minit proses pemotongan kepada 2 minit 40 saat. Keputusan disiasat dengan lebih lanjut melalui kerja pengoptimuman dan kelajuan pemotongan merupakan faktor dominan yang mempengaruhi keputusan. Model terakhir mencadangkan bahawa dengan menggunakan mata alat karbida tidak bersalut, kelajuan pemotongan dan kadar suapan terendah iaitu 50 m/min dan 0.05 mm/gigi digunakan untuk mendapatkan tindak balas pemotongan yang dikehendaki.

Kata kunci: Pemesinan kelajuan tinggi, Inconel 718, Pengoptimum, Mata alat karbida tidak bersalut, Kehausan mata alat

1.0 INTRODUCTION

Inconel 718 which belongs to nickel superalloy family, has been extensively used in many industries such as aerospace, nuclear power plants, petrochemical plants and others. Most of the applications are in high-temperature parts such as gas turbine engines, where 45-50% of the requirements are met through this alloy [1]. High yield strength of approximately 700-1200 MPa (retained up to 750 °C), high fatigue strength, high ultimate tensile strength (900-1600 MPa, maintained mechanical properties within wide range temperatures and good creep resistance are the unique attractiveness characteristics of this alloy [2, 3].

Owing to their exceptional qualities and metallurgical traits, they are among the hardest materials to process. Due to the high cutting temperatures and forces, they can withstand at high temperatures, which results in plastic deformation and tool failure, particularly in the cutting zone area. Abrasive wear, diffusion wear, welding/adhesion of workpiece material produced built-up edge (BUE), and poor heat conductivity were frequent causes of tool failure [3-6].

Difficulties become worse when high-speed machining is implemented. Over decades, this method has been extensively implemented by researchers in their works. Grguraš [7] investigated the machining behavior of carbide and ceramic tools on high-speed machining Inconel 718 through different cooling conditions. Recent works done by Zhang *et al*. [8] investigate the effect of high-speed milling on chip formation, cutting force and tool wear using coated carbide tools. Initially, this method was in demand since it intentionally produces lower cutting forces, low energy consumption, better surface quality, and higher removal rates [9]. Despite that, this process generates high cutting temperatures, which contribute to tensile residual stress acting on the cutting tool, consequently causing rapid tool wear and, as a result, reducing the tool life.

Coated carbide tools have been used to overcome these problems by several researchers [7-10], but by considering the machining costs, the inexpensive cost of uncoated carbide tool and their suitability for high feed rates and severely interrupted cuttings, it is still used by the majority of industries [4]. However, tools behaviour must be carefully studied, especially during the milling process, which involves strong interrupted cuts and mechanical shock imparted to each cutting edge where the cutting force fluctuates due to tool rotation [9,11].

For the reason of that, cutting parameters is important in achieving optimized processes and producing the best results. By considering the advantages of high-speed machining process, it has gained interest among several researchers. Musfirah and his co-workers [11] examined how milling Inconel 718 was affected by cutting speed using carbide cutting tools. They reported that severe tool wear is obtained when high cutting speed is implemented. Surface roughness, however, improved when the cutting speed dropped between 140 to 170 m/min. Another researcher, Liu *et al*. [12], investigated cutting forces during milling on Inconel 718 with several sets of cutting parameters. As expected, cutting forces increased along with the increment of cutting speed, depth of cut and feed rate.

Reddy and Yong [13] investigate tool wear and surface roughness by implementing high-speed machining approach at different levels of depth of cut, feed rate and cutting speed. As observed at the end of the works, gradual notch wear and Built-Up-Edge (BUE) were encountered on the tool surface while the feed rate greatly influenced surface roughness. The findings were in agreement with the work by Mohd Ali [14], where the primary factor affecting the surface roughness value is feed rate, followed by cutting speed and depth of cut.

Hence, the findings from implementing high-speed cutting process on Inconel 718 using uncoated carbide tools still cannot be appropriately determined due to the various factors contributing to the finishing results and its limited cutting behavior. It is important to understand the high-speed cutting behavior during machining in order to obtain the optimum cutting parameter that is suitable to be implemented.

Due to these concerns, this paper presents the cutting force and tool wear behavior when high-speed end milling of Inconel 718 alloy is implemented using uncoated carbide tools.

2.0 METHODOLOGY

A rectangular Inconel 718 with the dimension of 100 mm x 100 mm x 150 mm was chosen as the workpiece (as shown in Figure 2). Tables 1 and 2 provide the material's chemical composition and mechanical characteristics which were obtained directly from Soonv Alloy Co. Ltd., respectively.

Table 1 Inconel 718 chemical composition (wt%)

Ni	Si	Mn	P	S	Cr	C	Mo
52.1	0.117	0.0852	0.0027	0.0024	18.41	0.028	3.01
Cu	**Fe**	**Al**	**Ti**	**Nb + Ta**	**Co**	**B**	
0.06	Margin	0.51	1.1	5.04	0.165	0.0033	

Table 2 Inconel 718 mechanical properties at room temperature

Properties	Value
Tensile strength (MPa)	1170
Yield strength (MPa)	801
Elongation (%)	31
Reduction (%)	48
Hardness (HRC)	37

Uncoated carbide inserts were used as cutting tools which manufactured by SECO. The insert type is XOEX10T308FR-E05 with a thickness of 3.80 mm, width of 6.90 mm, cutting edge effective length of 9.70 mm and 0.80 mm corner radius (Figure 1). It also has a clearance angle major of 15° and a wiper length of 1.3 mm with two cutting edges. The SECO tool holder model number is R217.69-1616.3-10-2A with a diameter of 16 mm, a maximum ramp angle is 7.5° and two inserts can be installed on the holder.

(a) (b)

Figure 1 (a) SECO tool insert, (b) schematic diagram [15]

DMG Mori DMU 50 series 5-axis CNC machine had been selected for this work. It is equipped with a 630 mm table diameter and 300 kg maximum load, 80 to 18,000 rpm of spindle speed range, a 14 kW motor drive, and an internal cooling system. A Kistler dynamometer type 9443B was mounted on the machine table for cutting forces measurement which was later analyzed through the software. The workpiece was secured on the dynamometer using a specially designed fixture and the experimental setup along with a schematic diagram, shown in Figures 2 and 3, respectively. The soluble cutting oil TL-C70 was purchased from Toyo Grease Manufacturing (M) Sdn. Bhd. and being mixed with a water-soluble oil ratio of 5% (1 : 20).

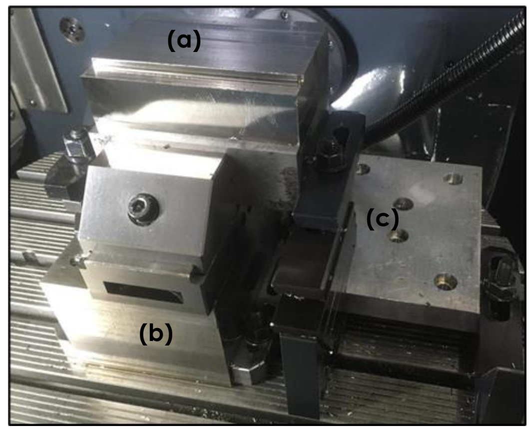


Figure 2 Experimental setup; (a) Workpiece – Inconel 718, (b) Kistler 9443B dynamometer, (c) Fixtures

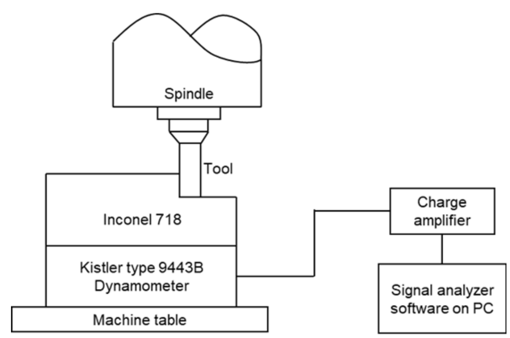


Figure 3 Schematic diagram of experimental setup

Microvisual XOPTRON XST150 microscope is being used as a device for observing and measuring tool wear. It has a zoom ratio of 12.5:1 and a magnification from 8 until 100 times. Tool rejection criteria or failure criteria were according to (a) average non-uniform flank wear ≥ 0.2 mm, (b) maximum flank wear ≥ 0.2 mm maximum on any individual tooth, (c) excessive chipping/flaking or catastrophic failure of the cutting edge, whichever occurred first as applied by other researchers [16-18]

As for surface roughness, the value was obtained directly after the machining work was done using Mitutoyo portable surface roughness tester, Surftest SJ-210 series. Down-milling operation was in favor due to the better performance compared to the up-milling [19]. Determination of the machining parameters was selected based on the review done on the previous research [20-22]. Several parameters, such as cooling method, axial and radial depth of cut, were fixed while cutting speed and feed rate were varied (Tables 3 and 4).

The selected parameters were optimized using statistical optimization software, Design Expert version 6.0.4, where the output of this work is cutting force, surface roughness and tool insert wear. Table 5 shows the suggested parameter combinations that were carried out in this work.

Table 3 Fixed parameters of the experiments

Parameter	Value
Axial depth of cut, a_p (mm)	4.0
Radial depth of cut, a_e (mm)	1.0
Number of tool teeth, z	2
Tool holder diameter (mm)	16.0
Workpiece material	Inconel 718
Cooling method	Flood

Table 4 Variable parameters used in experiments

Parameter	Level		
	Low	Mid	High
Cutting speed, V_f (m/min)	50	75	100
Feed rate, f_r (mm/tooth)	0.02	0.035	0.05

Table 5 Input parameters and output value

Run	Level of input parameter		Output value				
			Cutting time (sec)	Resultant cutting force, N	Surface roughness, Ra (µm)	Tool wear (mm)	
	V_r (m/min)	f_r (mm/tooth)				Tool 1	Tool 2
1	50	0.05	1920	776.04	0.195	0.21	0.16
2	75	0.10	896	1110.75	0.227	0.22	0.20
3	75	0.10	960	1063.41	0.213	0.22	0.25
4	75	0.05	960	774.34	0.226	0.23	0.23
5	75	0.10	800	977.47	0.248	0.21	0.19
6	75	0.10	800	1036.37	0.191	0.25	0.22
7	75	0.15	506	1161.88	0.234	0.24	0.19
8	100	0.15	160	1322.89	0.478	0.26	0.26
9	50	0.15	800	1503.29	0.261	0.21	0.18
10	100	0.05	864	1138.13	0.451	0.27	0.22
11	50	0.10	960	1196.27	0.194	0.20	0.18
12	100	0.10	360	1371.59	0.337	0.24	0.28

3.0 RESULTS AND DISCUSSION

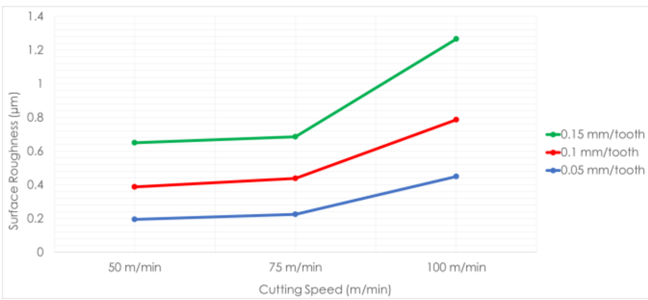
3.1 Machining Responses

As depicted in Table 5 show, the results obtained after the tool rejection criteria were reached. The results pattern is different for each parameter combination. The lowest combination of cutting speed and feed rate, 50 m/min and 0.05 mm/tooth, respectively, recorded the longest cutting tool life of 32 minutes. On the other hand, the highest parameters produced the lowest tool life, 2 minutes and 40 seconds, with relatively high cutting force and surface roughness, 1,322.89 N and 0.478 µm, respectively.

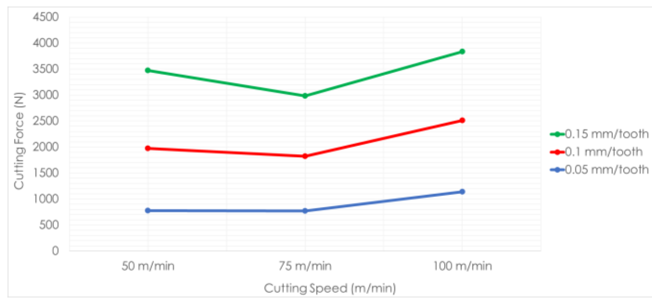
To enhance the accuracy of the estimations and measure the variability of the results, repetitions were conducted at the midpoint of the cutting parameters [22]. The tool insert demonstrated durability within a range of 12 minutes 40 seconds to 16 minutes, with the maximum cutting force ranging from 1,036.37 N to 1,161.88 N and surface roughness ranging from 0.191 µm to 0.248 µm. These results fell within the anticipated average range, and it was observed that higher cutting speeds led to increased cutting force and surface roughness, as depicted in Figure 4.

According to the findings of a previous study [24], both feed rate and cutting speed significantly impact the surface roughness of the workpiece. Figure 4(a) illustrates the resulting surface roughness, revealing that the tools experience slight wear at cutting speeds of 50 and 75 m/min, but the situation worsens when a cutting speed of 100 m/min is employed. A similar trend is observed for the feed rate, whereby higher feed rates lead to further deterioration of surface roughness. This phenomenon occurs because the ability of the lubricant to penetrate the cutting area diminishes with higher cutting speeds. Consequently, as the cutting temperature rises, the cutting tool is subjected to excessive heat, causing the material to soften and the tool to wear rapidly. Figure 4(b) depicts the corresponding cutting forces, demonstrating a decrease in force as cutting speed increases. However, as high speeds and feed rates are implemented, the uncoated carbide tool sustains greater damage and becomes unable to maintain its performance, resulting in increased cutting forces and surface roughness.

Further evidence supporting the impact of cutting parameters on tool wear can be observed through the analysis of tool wear progression, specifically during the final cut (Figure 5). Nose radius wear emerges as the predominant wear factor, accompanied by visible notch and flank wear on the tool surface. At a cutting speed of 50 m/min, the flank wear progresses steadily until it reaches the rejection criterion of 0.2 mm. However, as the cutting speed increases, the tool's behavior changes, particularly when the feed rate exceeds 0.10 mm/tooth. With further increments in the cutting parameters, the tool sustains even greater damage, such as tip breakage and visible burn marks at the edge of the wear surface. These observations provide additional support for the detrimental effects of higher cutting speeds and feed rates on tool wear and performance.



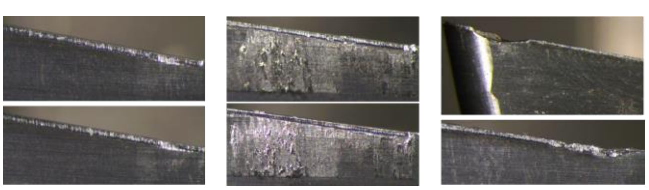
(a)



(b)

Figure 4 Resultant (a) surface roughness, (b) cutting force against cutting speed

Towards the trailing edge of the relief face, a slight rubbing surface and a small fracture are observed. This is primarily attributed to the increased temperature and material loss rate from the deformation zone. Since the cooling agent cannot effectively penetrate the cutting area at higher speeds, the tool has to endure a significant amount of heat generated by friction. Consequently, tool adhesion on the rubbing surfaces becomes more pronounced, leading to increased friction and wear rate. Furthermore, the presence of abrasive particles in Inconel 718 exacerbates tool wear, particularly when uncoated carbide tools are used. Deng *et al*. [25] demonstrated that abrasion wear, caused by small wear particles acting on the tool face, leads to crack development and the formation of plastically deformed grooves. At the maximum implementation of cutting parameters (100 m/min and 0.15 mm/tooth), tool chipping occurs due to the low strength of the tool, which cannot withstand the forces and heat generated. This chipping phenomenon becomes a significant contributor to tool failure.



(a) (b) (c)

Figure 5 Tool insert wear progression; (a) 50 m/min, (b) 75 m/min, (c) 100 m/min at 0.15 mm/tooth

As for cutting force, the highest cutting parameters produced the highest cutting force and the trend obtained for all parameter conditions is similar to the findings by previous researchers [26-29]. Due to the softening of workpiece materials, cutting forces tend to decrease when cutting speed is increased because of the increase in cutting temperature. When the tool reaches the end of its life, the cutting forces significantly rise because of increased friction brought on by heavy tool wear and correspondingly higher temperatures. However, the uncoated carbide tool cannot sustain the heat at a certain level, hence further damaging the tool.

3.2 Parameter Optimization

Response Surface Method (RSM) which stated by Montgomery [30], is a simple collection of mathematical and statistical techniques that are useful for modelling and analysis problems in which a response of interest influenced by several variables quantifies relationships among one or more measured responses and the main objective is to optimize the responses. Through this method, the results obtained earlier were further analyzed and the responses were listed in the ANOVA table (Tables 6 and 7).

Since the "Prob>F" value is less than 0.05, it is possible to conclude that the regression model is significant and that the variables in the model significantly affect the response. According to the previously obtained results, all of the parameters have a substantial impact on the model for the cutting force (F) response. The model is desirable, as evidenced by the insignificant lack-of-fit and the value of R^2 is high, close to 1.

As for the surface roughness (Ra) ANOVA table, several responses can be eliminated through the backward elimination procedure in order to demonstrate that the model is still significant. It determines that the main effect of cutting speed (A) and the two-level interaction of cutting speed (A^2) were the significant model terms. This is expected since, from experimental observations, due to the reduced lubrication penetration into the cutting zone at a higher speed, the cutting speed has a greater impact on the finishing surface roughness than the feed rate. While raising the feed rate causes the material flow rate to increase and the temperature to rise, higher cutting speed makes the machining work difficult by reducing the cooling agent's ability to penetrate the cutting zone, further damaging the tool and deteriorating the surface.

The following equations are the final empirical models in terms of coded factors which obtained from optimized parameters:

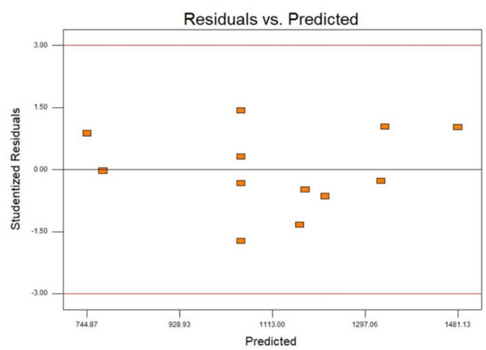
Cutting force:

$$F = 1050.33 + 59.50A + 216.59B + 226.95A^2 - 88.87B^2 - 135.62AB$$

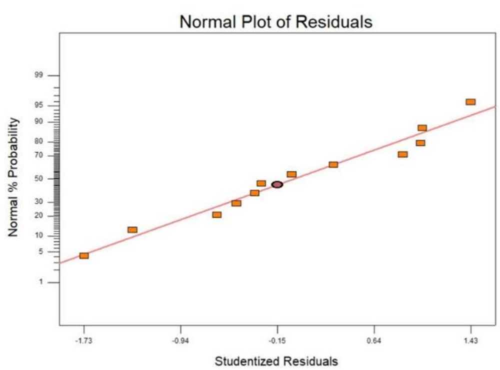
Surface roughness:

$$R_a = 0.21 + 0.10A + 0.017B + 0.081A^2 + 0.046B^2 - 9.917\times10^{-3}AB$$

Where:
A = cutting speed
B = feed rate



(a)



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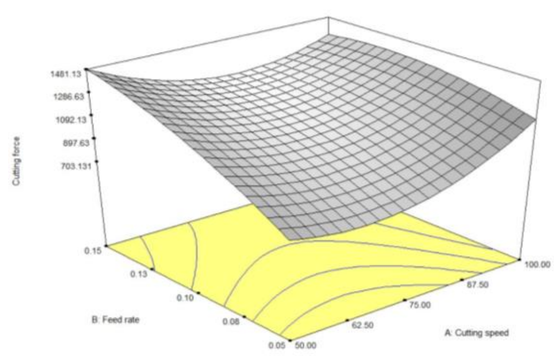


(c)

Figure 6 Diagnostics and model graphs for cutting force, F

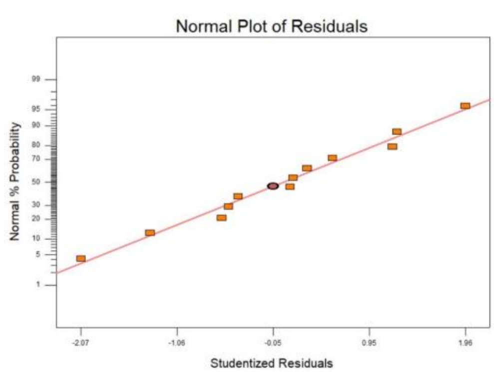
Table 6 ANOVA table (partial sum of squares) for response quadratic models (response: cutting force, F)

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	5.142E+005	5	1.028E+005	45.75	0.0001	*significant*
A	21241.83	1	21241.83	9.45	0.0218	
B	2.815E+005	1	2.815E+005	125.22	<0.0001	
A^2	1.374E+005	1	1.374E+005	61.11	0.0002	
B^2	21059.25	1	21059.25	9.37	0.0222	
AB	73574.90	1	73574.90	32.73	0.0012	
Residual	13487.05	6	2247.84			
Lack of Fit	4206.66	3	1402.22	0.45	0.7337	*not significant*
Pure Error	9280.39	3	3093.46			
Cor Total	5.227E+005	11				
S.D.	47.41	R^2	0.9744			
Mean	1119.37	Adj. R^2	0.9531			
C.V.	4.24	Pred. R^2	0.8912			
PRESS	57984.03	Adeq. precision	21.962			

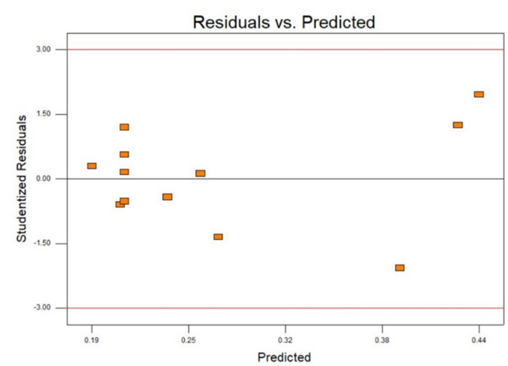
Table 7 ANOVA table (partial sum of squares) for response quadratic models (response: surface roughness, R_a)

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	0.099	5	0.020	14.09	0.0029	*significant*
A	0.063	1	0.063	45.14	0.0005	
B	1.711E-003	1	1.711E-003	1.22	0.3110	
A^2	0.017	1	0.017	12.50	0.0123	
B^2	5.536E-003	1	5.536E-003	3.96	0.0938	
AB	3.934E-004	1	3.934E-004	0.28	0.6149	
Residual	8.393E-003	6	1.399E-004			
Lack of Fit	6.64E-003	3	2.221E-003	3.85	0.1485	*not significant*
Pure Error	1.729E-003	3	5.763E-004			
Cor Total	0.11	11				
S.D.	0.037	R^2	0.9215			
Mean	0.27	Adj. R^2	0.8561			
C.V.	13.79	Pred. R^2	0.4387			
PRESS	0.060	Adeq. precision	9.745			

Figures 6 and 7 illustrate that the normal probability graph displays normally distributed errors that typically fall along a straight line. There is no discernible pattern or unusual structure observed in both the residuals versus predicted response data. This indicates that the proposed models are adequate and that neither the assumption of independence nor the assumption of constant variance has been violated. The fitted quadratic model aligns with the curvilinear profile of the 3D surface graphs, effectively capturing the relationships between the factors and the responses. This relationship is further evident in the cutting force and surface roughness contour plot.



(a)



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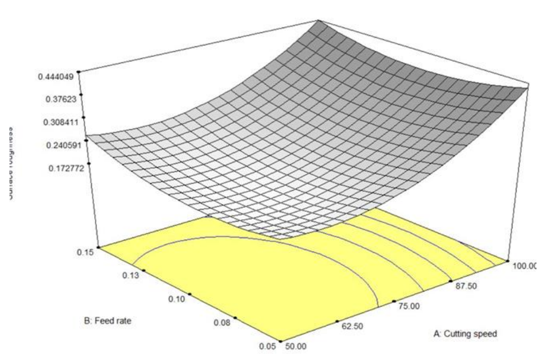

(c)

Figure 7 Diagnostics and model graphs for surface roughness, R_a

Based on the analysis conducted, it can be concluded that higher values of cutting parameters lead to increased cutting force, which in turn reduces tool life. To achieve the best surface finish, it is recommended to maintain the cutting speed within the range of 50 to 62.5 m/min, accompanied by a feed rate of 0.09 mm/tooth. Beyond a cutting speed of 70 m/min, the surface roughness is likely to deteriorate even further. Therefore, it is advisable to adhere to these optimal parameter values to attain the desired surface finish while minimizing cutting force and extending tool life.

4.0 CONCLUSION

This study aimed to optimize the cutting parameters for high-speed machining of Inconel 718 using uncoated carbide tools. The findings of this study demonstrate the significant impact of cutting speed and feed rate on the machining results. As cutting speed and feed rate increase, there is an increase in cutting force and a deterioration of the machined surface. These effects are mainly attributed to the high cutting temperature generated during machining. Furthermore, in intermittent cutting processes, it was observed that the cutting fluid is unable to fully penetrate the cutting zone, leading to inadequate heat reduction.

Based on the results, it is evident that the use of uncoated carbide tools should be limited to cutting speeds below 75 m/min and feed rates below 0.10 mm/tooth to avoid further damage to the tool when machining Inconel 718. The predominant types of tool wear observed in this study were flank wear, notch wear, abrasive wear, and tool chipping. According to the optimization model, the most optimal cutting parameters for machining Inconel 718 with uncoated carbide tools are a cutting speed of 50 m/min and a feed rate of 0.05 mm/tooth. By implementing these parameters, desired cutting force and surface roughness can be achieved, along with an extended tool life. These optimized parameters can serve as a benchmark for high-speed machining of Inconel 718 using uncoated carbide tools.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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