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Prediction Surface Roughness in High-Speed Milling of Inconel 718 under Mql Using Rsm Method

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Abstract: This paper investigates the effect of cutting speed, feed rate and depth of cut on the surface roughness of Inconel 718 when milled under minimum quantity lubrication. The response surface methodology (RSM) was employed in the experiment and a Box–Behnken design was used to determine the cause and effect of the relationship between the control variables and the response. The investigated milling parameters were cutting speed (100, 135 and 170 m/min), feed rate (0.15, 0.2 and 0.25 mm/rev) and depth of cut (0.6, 0.8 and 1.0 mm). The results showed that the interaction between the feed rate, f_z and the radial depth of cut, a_e, was the primary factor controlling surface roughness. The responses of various factors were plotted using a three-dimensional surface graph. The quadratic empirical models were developed with a 95% confidence level. The optimum condition required for minimum surface roughness include cutting speed of 136 m/min, feed rate of 0.1 mm/rev, axial depth of cut of 0.5 mm and radial depth of cut of 1.38 mm. With this optimum condition, a surface roughness of 0.117 µm was obtained.

Key words: Inconel 718 · End mill · High-speed machining · Surface roughness · Response surface method · Minimum quality lubrication

INTRODUCTION

The optimization of machining conditions has become increasingly important. The traditional selection conducted by a process planner, which relies on experience or on a machining data handbook, has difficulty in satisfying manufacturing requirements and is time consuming. Therefore, optimal parameter machining selection based on multiple regression prediction models has recently been gained considerable attention. This type of mathematical modeling describes the theoretical model using mathematical language to explain the behavior of a system so as to predict the best cutting performance under certain cutting conditions [1].

Inconel 718, a nickel-based super alloy, exhibits remarkable characteristics and has consequently emerged as the material choice for high-temperature operations where creep, fatigue and environment degradation resistance are required. Owing to these properties, this material has been applied widely in the aerospace, medical and power generation industries. However, Inconel 718 was generally known to be one of the most difficult materials to be machined because of its high level of hardness, abrasiveness, retention of a high level of strength at high temperatures, chemical reactivity with tool materials and low thermal conductivity [2-4].

A large number of studies have been conducted under various conditions to determine the optimal combination of cutting parameters. The objectives of such studies were to improve tool life and surface finish. The effects of flat end milling on tool life were investigated by [5-7]. Investigations about cutting force during end milling were performed by [8, 9]. Furthermore the investigation on wear mechanism was conducted by [10], with a focus on chip formation during slot milling. The tool life of ball nose cutter with different workpiece angles were studied experimentally by [11, 12].

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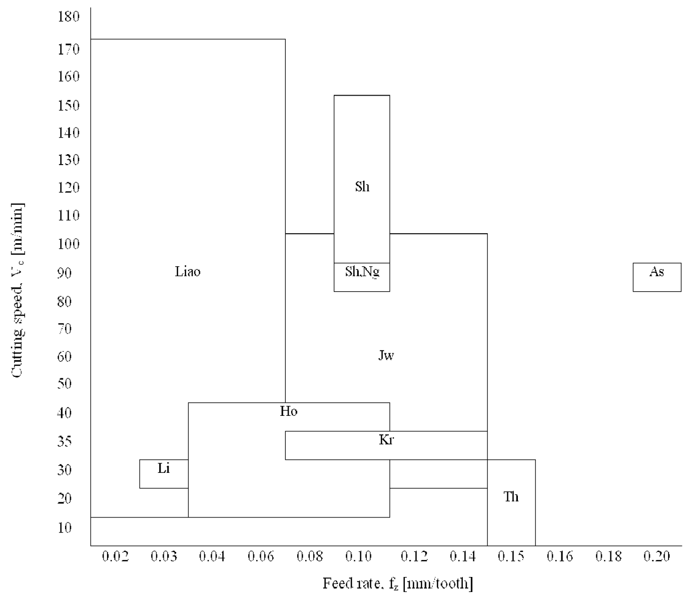

Fig. 1: Overview of cutting speed and feed rate in the literature on Inconel 718 end milling. Legend: Li [9], Ho [13], Sh [12], Ng [21], Kr [20], Jw [8], As [11], Liao [10] and Th [7].

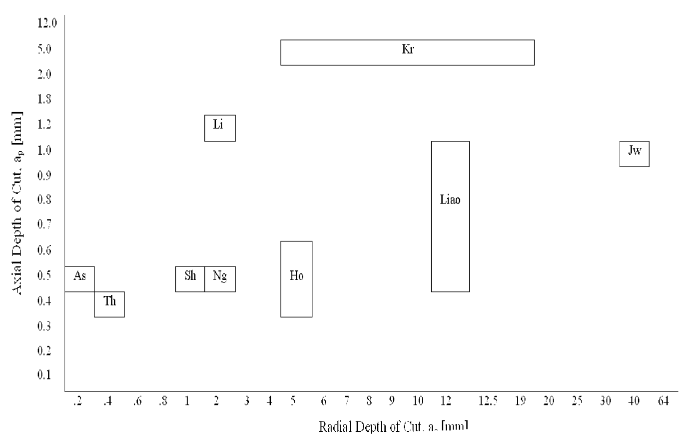

Fig. 2: Overview on axial and radial depth of cut in the literature. Legend: Li [9], Ho [13], Sh [12], Ng [21], Kr [20], Jw [8], As [11], Liao [10] and Th [7]

Hossain *et al*. [13] developed a neural network algorithm for predicting surface roughness. The most common parameters investigated by previous scholars were cutting speed, feed rate and axial depth of cut.

Surface roughness is generally known to be highly affected by feed rate, followed by cutting speed and axial depth of cut [14, 15]. The geometrical shape of the insert is another factor considered in studies on surface roughness [16, 17]. According to Iqbal *et al*. [18], who conducted a study on tool steel, found that the material inclination angle, followed by radial depth of cut, were the parameters that significantly affects surface finish after machining. Therefore, studies on surface roughness considering the radial depth of cut [19], especially on Inconel 718, are very few. The parameter settings used in previous studies are compiled in Fig. 1 and 2. Notably, [20] investigated the effect of radial depth of cut as a variable cutting parameter.

This experimental work investigates surface quality when finish milling at high cutting speed under minimum quality lubrication (MQL). Surface roughness is used to asses the performance of cutting tools under various conditions. This study aims to determine the cutting conditions that will result in the lowest value of surface roughness.

Experimental Set-up: The workpiece material used for the experiment was aged Inconel 718, AMS 5663 grade, with hardness of 42 ± 2 HRC. The block was heat treated using double aging process, where the material was hardened at 980°C for 1 h and then soaked in a water solution. Then it was subsequently reheated for another 8 h at 720°C, after which it was slowly cooled inside the furnace to 620°C. This temperature was retained for 8 h. Finally, the block was cooled using the open air procedure based on [2] and [22]. The aging treatment process was conducted to convert the Inconel from AMS5662 grade 92 HRb to AMS 5663 grade 42 HRc. The chemical compositions were 53% Ni, 18.30% Cr, 18.7% Fe, 5.05% Nb, 3.05% Mo, 1.05% Ti, 0.23% Mn and C balance (all weight percent). The end milling experiments were performed using a DMC 635 V Eco CNC milling machine with a maximum spindle speed of 8000 rpm. A 100 mm x 150 mm x 50 mm block was skimmed at a maximum of 0.5 mm on the surface to remove any surface defects or any irregularities from previous manufacturing process. Residual stress beyond a depth of 500 µm was considered relatively stable [23]. To eliminate any effect of previous cutting on the workpiece, each new layer was faced milled and then initial cut into a block, with the last cut out performed using a non-test insert. All experiments were conducted under MQL at a rate of 20 pulses/min to produce 50 ml/hr.

The cutting tools were made of tungsten carbide (WC-10%Co) coated alternately with PVD TiAlN and AlCrN to achieve a 3 um coating thickness. An insert of 10 mm in diameter was attached to the tool holder with a 16 mm of diameter and a rake angle of 3°, radial rake angle of 0° and relief angle of 11°. A constant tool overhang of 30 mm, radial run out of 10 µm and axial run out of 5 µm were maintained for all tests. Tool wear was measured using a tool maker's microscope with a micrometer for the x and y axes, each having a resolution of 1 µm. During the trial, [24] guidelines were followed, such that cutting tests were stopped when any of the following failure criteria was met: (a) average flank wear VB_1 reached 0.3 mm, (b) localized flank wear VB_3 reached 0.5 mm, or (c) catastrophic failure occurred. Workpiece surface roughness (Ra) was measured using a contact-type stylus profilometer, Mahr Perthometer M1. The stylus traversing length, L_t, was set to 5.4 mm with cut off, λ_c, at 0.8 mm. Measurements were taken parallel to the milling feed. The total minimum number of roughness measurements was nine for each cutting parameter at a random location.

A response surface methodology (RSM) experiment using the Box–Behnken approach was undertaken. A total of 29 experiments were performed.

Table 1 List of experimental factors and their levels

Control Parameters	Parameters range		
Level	-1	0	1
Cutting speed, V_c	100 m/min	120 m/min	140 m/min
Feed rate, f_z	0.1 mm/tooth	0.15 mm/tooth	0.2 mm/tooth
Axial depth of cut, a_D	0.5 mm	0.75mm	1.0 mm
Radial depth of cut, a_r	0.2 mm	1 mm	1.8 mm

The cutting conditions for this study are shown in Table 1. These parameter settings considered tool maker recommendations and settings from previous studies.

Developing the Multiple Regression Model: In this work, mathematical models have been developed using RSM based on the experiment data. Situations where the curvature in the normal operating ranges is inadequately modeled by the first-order function often occur. Thus, the quadratic response surface functions should be considered. This second-order model can be represented by the following equation [25]:

$$\hat{Y}=\beta_0+\sum_{j=1}^{k}\beta_j x_j+\sum_{i<j}\sum\beta_{ij}x_i x_j+\sum_{i=0}^{k}\beta_{jj}x_j^2+e \quad (1)$$

The proposed second-order response surface model comprises of four factors:

$$\hat{Y}=\beta_0+\beta_1x_1+\beta_2x_2+\beta_3x_3+\beta_4x_4+\beta_{11}x^2{}_1+\beta_{22}x^2{}_2+\beta_{33}x^2{}_3+\beta_{44}x^2{}_4+\beta_{12}x_1x_2+\beta_{13}x_1x_3+\beta_{14}x_1x_4+\beta_{23}x_2x_3+\beta_{24}x_2x_4+\beta_{34}x_3x_4+e \quad (2)$$

where Ŷ is the predictive Ra value; x_1, x_2, x_3 and x_4 are the coded values of V_c, f_z, a_p and a_e, respectively; e is the experimental error; and β_0, β_1, β_2 and β_4 are the model parameters to be estimated using the experimental data. The accuracy of the model will be compared with the observed value.

$$e_i=\frac{\left|Ra_{\exp}-Ra_{cal}\right|}{Ra_{exp}}x100\% \quad (3)$$

where

e_i : Percentage deviation of predicted value from single experiment data

Ra_{exp} : Measured R_a

Ra_{cal} : Calculated R_a

$$\bar{e}=\frac{\sum_{i=1}^{n}\varepsilon_i}{n} \quad (4)$$

where

ē : Average percentage error within data set

n : Number of samples

RESULTS AND DISCUSSIONS

Surface Roughness Result: The experiment results showed that end milling using a ball nose cutter can achieve good surface finish. The achieved surface roughness ranged from 0.173 µm to 0.3 µm, i.e. less than the 0.5 µm, that is equivalent to manual polishing [26]. Details on the collected experimental data and the data calculated by mathematical modeling (Equation 1) are shown in Fig. 3.

Analysis of Variance (ANOVA) for Surface Roughness: Based on the ANOVA in Table 2, the quadratic model is found to be significant with a P-value of less than 0.05 and F-value of 33.81. The cutting parameters with P-values of less than 0.05 indicate that these model terms significantly affect the response in the design space. In this case, BD, A, D^2, CD, C^2, D, AD, C, A^2, AC and B^2 are significant model terms. These terms were sorted according to F-value. A single factor alone cannot be used in the analysis because of its interaction with other factors. Given that 11 factors have P-values below 0.05, the F-value is used to determine the most significant value. Among these terms, the most dominating factor is the interaction between feedrate and radial depth of cut, BD. This parameter has the largest coefficient attributable to its highest F-value (130.83). This finding was supported by the shape of the curvature along the parameter (Fig. 4).

Values exceeding 0.1000 indicate that model terms are insignificant. The B, AB and BC terms are insignificant but not eliminated from the model to avoid a significant change in the result of the mathematical equation.

Table 2: ANOVA table for Response Surface Quadratic Model

Source	Sum of Squares	DF	Mean Square	F Value	P Value	
Model	0.088102	14	0.006293	33.80715	< 0.0001	significant
A	0.015194	1	0.015194	81.62727	< 0.0001	
B	0.000482	1	0.000482	2.587273	0.1300	
C	0.002654	1	0.002654	14.25684	0.0020	
D	0.006924	1	0.006924	37.19801	< 0.0001	
A2	0.002645	1	0.002645	14.20895	0.0021	
B2	0.001112	1	0.001112	5.973273	0.0284	
C2	0.007577	1	0.007577	40.70653	< 0.0001	
D2	0.009359	1	0.009359	50.2786	< 0.0001	
AB	0.000245	1	0.000245	1.314564	0.2708	
AC	0.001383	1	0.001383	7.431215	0.0164	
AD	0.003312	1	0.003312	17.79343	0.0009	
BC	0.00078	1	0.00078	4.191877	0.0599	
BD	0.024353	1	0.024353	130.8263	< 0.0001	
CD	0.008093	1	0.008093	43.47445	< 0.0001	
Residual	0.002606	14	0.000186			
Lack of Fit	0.002404	10	0.00024	4.748905	0.0733	not significant

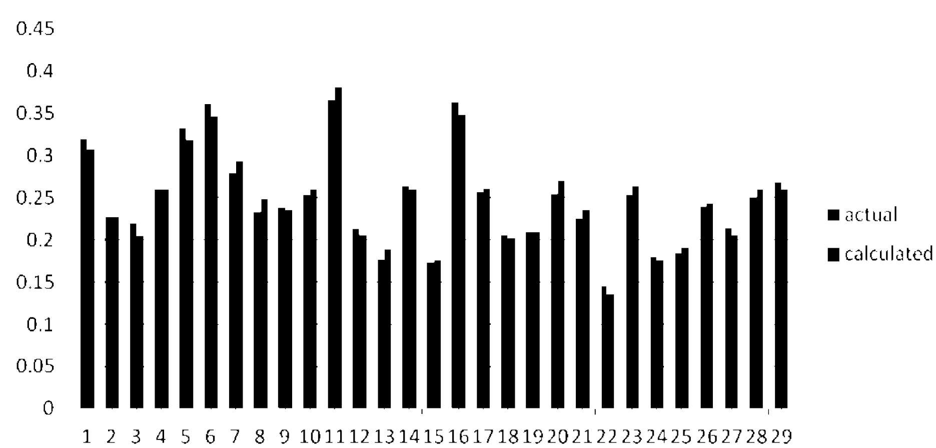

Fig. 3: Experiment results and confirmation of equation

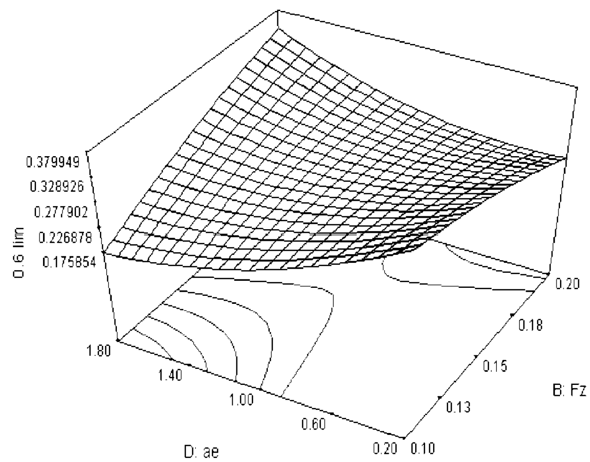

Fig. 4: Response surface for the interaction effect between feedrate and radial depth of cut, V_c 120 m/min, ap 0.75 mm

The predicted R^2 of 0.8439 is in reasonable agreement with the adjusted R^2 of 0.9425. A comparison between the range of predicted values at the design points and the average prediction error shows adequate precision. An adequate precision ratio of 24.87, which is greater than 4, is a desirable signal-to-noise ratio. Based on the regression model in Equation 1, the average error, ē, between calculated and actual values is 3%, with a maximum error of 7% (Fig. 3).

Development of the Second-order Surface Roughness Model: The second-order equation describes the effect of the four cutting parameters on the finishing process. The following equation is in fitted quadratic form, that is, a second-order polynomial equation (Equation 2). This multiple regression is expressed in both actual factor and coded factors:

$$Ra_{exp}(\text{actual}) = -0.639 + 0.014V_c - 0.353F_z + 1.150a_p - 0.394a_e - 5.048\text{x}10\text{-}5\ V_c^2 - 5.237F_z^2 - 0.54686a_p^2 + 0.059352a_e^2 + 7.82143\text{E-}003V_c.F_z - 3.71925\text{E-}003V_c.a_p - 1.79848\text{E-}003V_c.A_e - 1.11735F_z.a_p + 1.95067F_z.a_e + 0.22490a_p.a_e \quad (1)$$

$$Ra_{exp}\ (\text{coded}) = +0.26 - 0.036A + 6.335\text{E-}003B - 0.015C - 0.024D - 0.020A^2 - 0.013B^2 - 0.034C^2 + 0.038D^2 + 7.821\text{E-}003AB - 0.019AC - 0.029AD - 0.014BC + 0.078BD + 0.045CD \quad (2)$$

The interaction effect of radial depth of cut, a_e and feed rate, f_z, is shown in the contour graph in Fig. 4. The cutting speed and axial depth of cut were set at 120 m/min and 0.75 mm respectively. This plot indicates that the best value of surface roughness can be obtained at high f_z and low a_e, as well as high a_e and low f_z.

Fig. 5 shows the effects of cutting speed and feed rate on Ra. The slope of the plot was shown to vary with the radial depth of cut. The curvature line was more significant at ae of 1.0 mm (Fig. 5b) followed by ae of 1.8 mm (Fig. 5c). Generally, the surface roughness improved with increasing cutting speed. However, this condition cannot be applied with ae of 0.2 mm (Fig. 5a), where the slope was found to be insignificant.

0.15mm/tooth, ap 0.75 mm

Fig. 6 shows the interaction effect between cutting speed and radial depth of cut. The relationship exhibits a curvature shape, with the minimum Ra near the mid-range of a_e and maximum V_c. Cutting speed curvature is steeper above 120 m/min. Subsurface fracture is frequently observed when cutting at low, rather than high speeds.

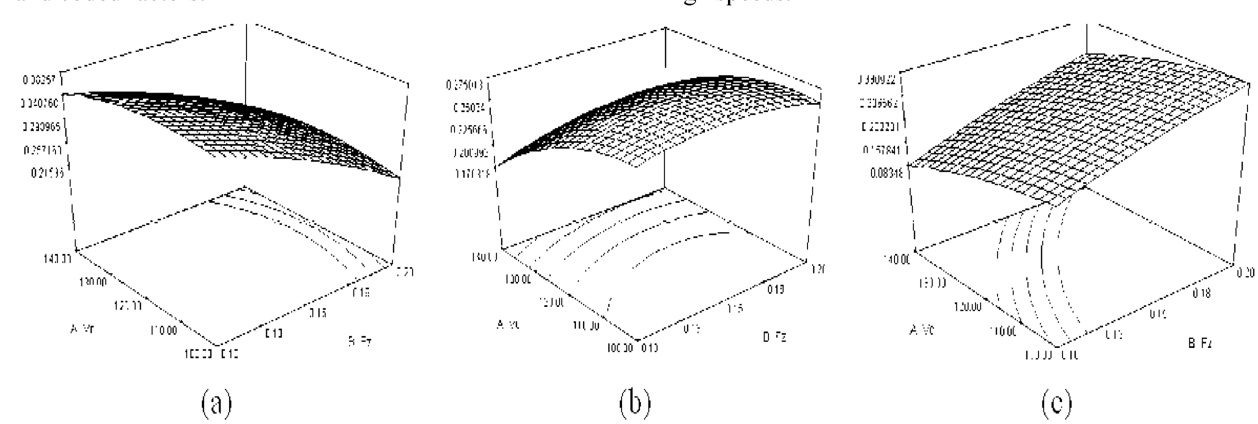

Fig. 5: Interaction effect between cutting speed V_c and feed rate f_z at various radial depth of cut a_e, where the axial depth of cut a_p is constant at 0.75 mm (a) a_e = 0.2 mm, (b) a_e = 1.0 mm and (c) a_e = 1.8 mm

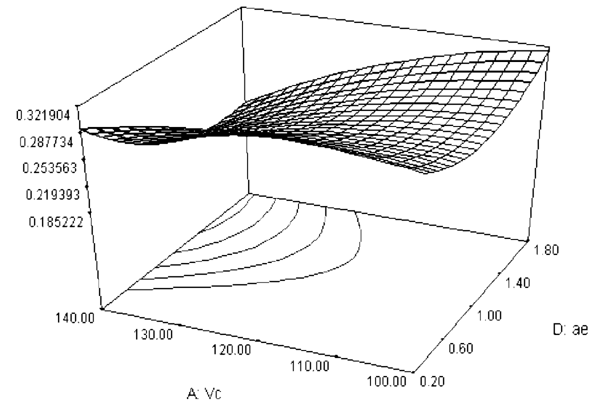

Fig. 6: Interaction effect between cutting speed and radial depth of cut. F_z

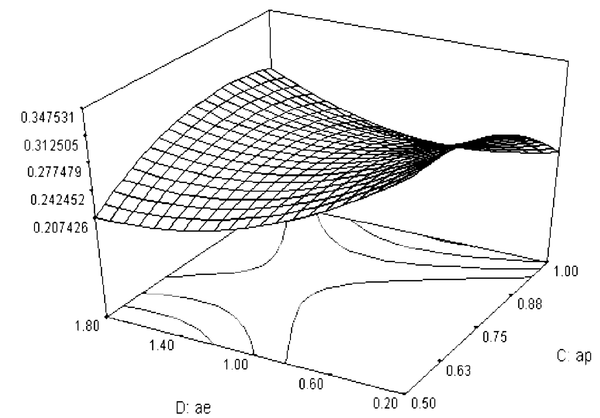

Fig. 7: Interaction effect between axial depth of cut and radial depth cut. V_c 120 m/min, f_z 0.15 mm/tooth

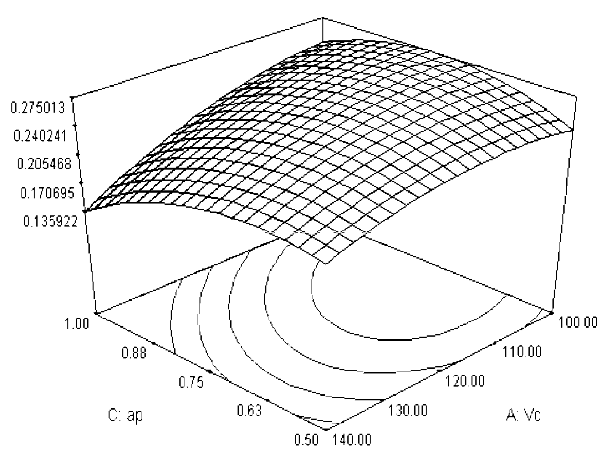

Fig. 8: Interaction effect between cutting speed and axial depth of cut. F_z 0.15 mm/tooth and a_e 1.00 mm

Fig. 7 shows the interaction between axial and radial depths of cut. Higher surface roughness could be achieved when machining at the extreme points of a_e (0.5 and 1.8 mm) when a_p is 0.75 mm.

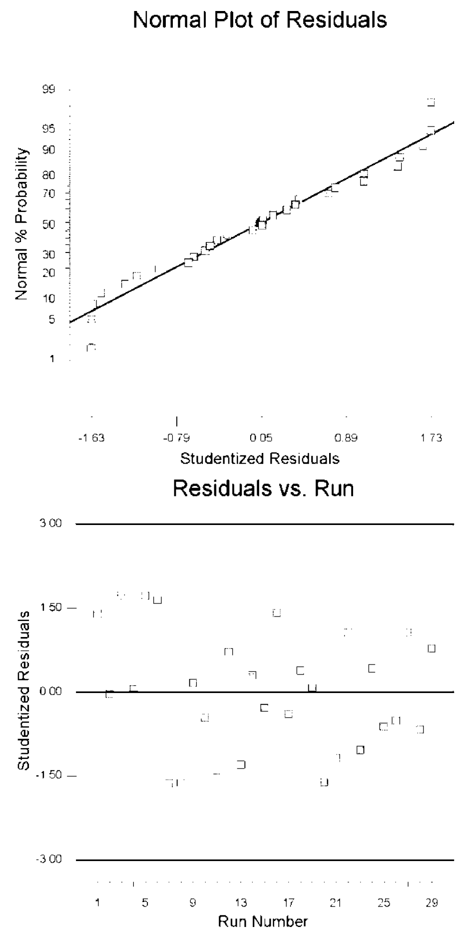

Fig. 9: (a) Studentized residual plot and (b) residual vs run

Fig. 8 shows the interaction between cutting speed and axial depth of cut. The lowest Ra is shown to be achieved at the peak point of V_c and a_p. The effect of the primary machining parameters on surface roughness was found to be comparable with that reported by [19].

Verification of Model Adequacy: Based on ANOVA, another residual analysis is necessary to confirm that the assumptions are correct and the observations are adequately described by the model. An examination of residuals, that is, subtracting the value of the observed responses from that of the predicted responses [25], was thus conducted.

Fig. 9a shows that the studentized residual plot is in straight line, indicating that the error of distribution is normal. This finding was supported by residual vs. run plot (Fig. 9b), with all values having 95% confidence limits. The random scatter value indicates that the residuals produced by the model have a normal distribution.

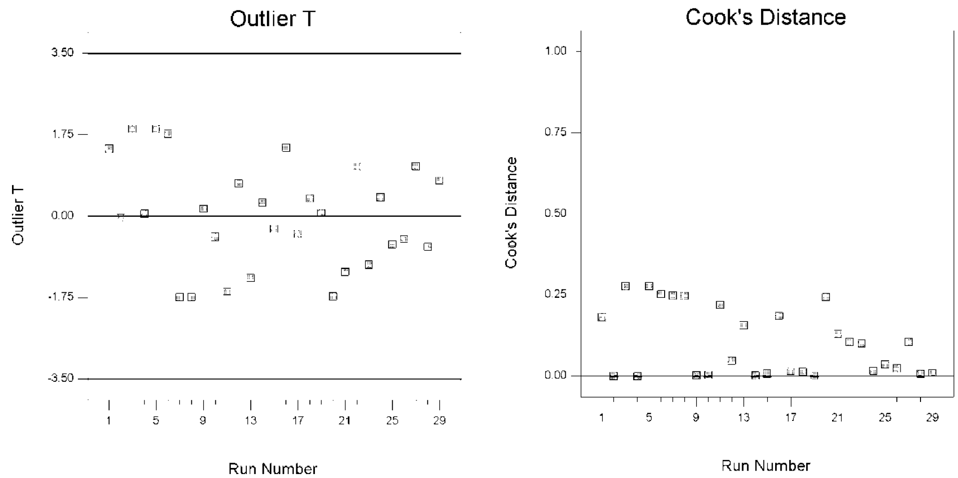

Fig. 10: Outlier T Plot, External studentized residual and (b) Cook’s Distance plot

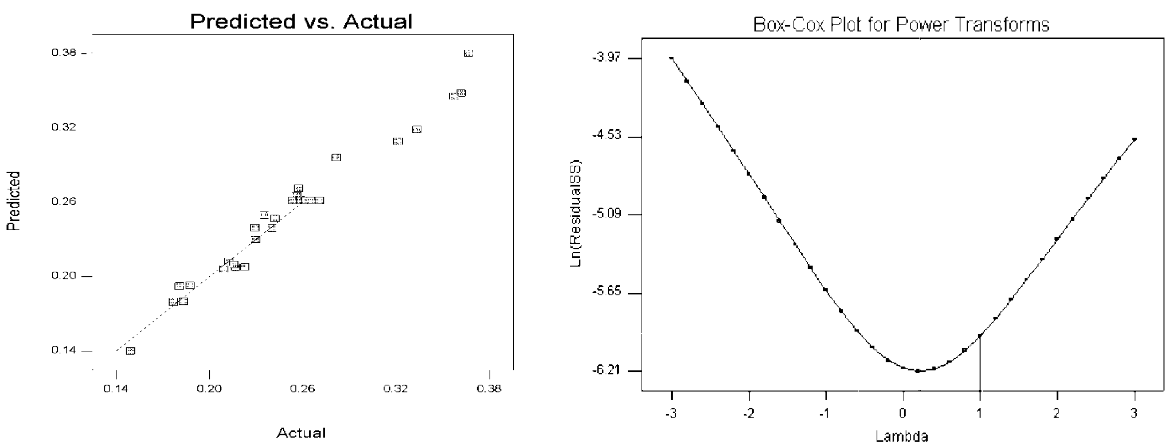

Fig. 11: (a) Pedicted vs actual values and (b) Box–Cox plot

The outlier T plot (Fig. 10a) measures the standard deviations of the actual from the predicted value. All specific design points are shown to fit the model. Normally, values greater than 3.5 indicate the run to be an outlier that should be examined. Such a value is considered extreme among those in the dataset [27]. The presence of one or more outliers can seriously alter the ANOVA results. The outlier T plot was supported by Cook’s distance plot, as shown in Fig. 10b. The Cook distance plot determines the number of outliers appearing inside the run number. The Cook distance graph helps in measuring the extent of the effect on the regression if one particular run is omitted from the analysis. The far value of runs may be affected during fitting and should be examined for recording errors or an incorrect model. Based on Cook’s distance plot, the outlier and its distance was found to be very the close to zero. Thus, the small actual value was shown to deviate from the predicted value.

In Fig. 11a, the poins of all 29 samples are randomely scattered between the observed and predicted Ra. The trend line indicates a linear relationship. The group of points along the straight line indicates better prediction. The Box–Cox analysis in Fig. 11b indicates the most appropriate power law transformation that can be applied to the response data. The red line indicates a 95% borderline confidence interval. The blue model line falling between the confidence interval lines indicates that the current transformation is fitted. The Lambda value of 1 indicates that no power law transformation is required.

Optimum Parameter: For the end milling of Inconel 718, the optimum condition is required to achieve the best surface roughness within predetermined parameters. The minimum values are cutting speed of 135.92 m/min, feed rate of 0.1 mm/tooth, axial depth of cut of 0.55 mm and radial depth of cut of 1.38 mm. At this cutting condition, a surface roughness of 0.117 µm was obtained (Fig. 12).

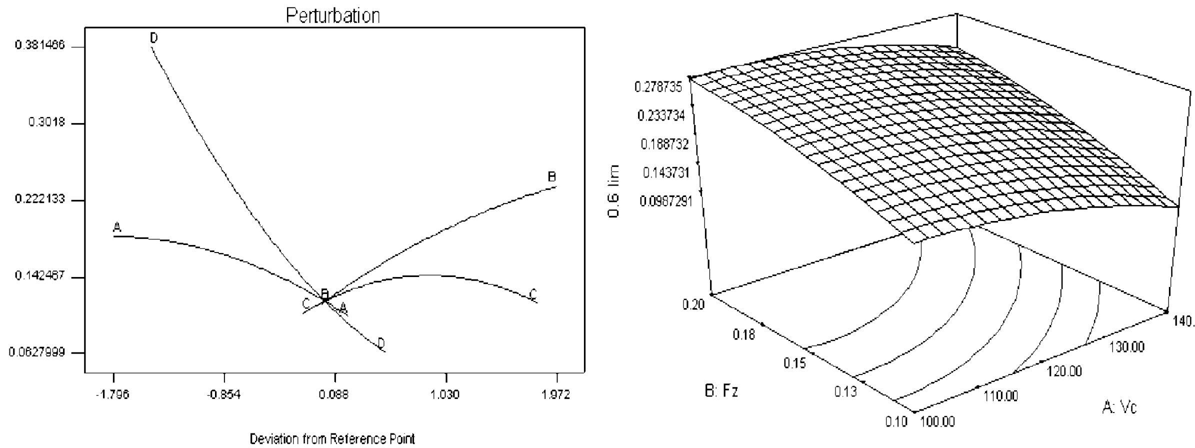

Fig. 12: (a) Pertubation plot indicating the minimum point of surface roughness. V_c 135.92, f_z 0.1, a_p 0.55, a_e 1.38 and (b) interaction effect for minimum surface roughess

The minimum response, Ra, is located at the intersection of the four curvature factors. This perturbation plot (Fig. 12a) is used to indicate the effect of particular factors on the response in the design space. The steepest curvature indicates the factor that most significantly affects the response, whereas the relatively flat line suggests insensitivity to change.

CONCLUSIONS

A series of experiments using RSM were conducted to investigate the factors affecting the surface roughness of Inconel 718 during end milling. The effect of spindle speed, feed rate, as well as radial and axial depth of cut was studied. The following conclusions can be drawn:

- This study demonstrated that end milling can be a part of the final machining process. A surface finish ranging from 0.173 µm to 0.3 µm adequately complies with high finishing requirements.
- This study shows the interaction between radial depth of cut and feed rate to be the most dominant factor affecting the surface roughness. No main factor contributed to this response.
- The average deviation between predicted and observed surface roughness value was approximately about 3%.
- Radial depth of cut mitigates the effect of feed rate. The interaction between these factors significantly affects surface roughness.
- The best surface finish was achieved when cutting at V_c of 135.92 m/min, f_z of 0.1 mm/tooth, a_p of 0.55 mm and a_e of 1.38 mm.

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