Comparative studies of variation in end mill radial rake angle and cutting conditions on cutting force and surface integrity during machining of nimonic 263

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Abstract
Tool nomenclature has a profound effect on the machining of alloys and the cutting force during machining. In this study, the effect of changes in radial rake angle of end mill cutter (+7°, 0°, −7°) and machining parameters such as spindle rotational velocity (v) and table feed velocity (f) on cutting force and surface roughness were presented using regression analysis and a comparison has been made with the measured surface roughness and cutting force data. Additionally, to confirm the goodness of fit, Analysis of variance (ANOVA) has been undertaken and found that the developed empirical model is significant. The experimental outcome clearly indicates that the radial rake angle of end mill cutter is the most significant parameter, which reflect higher efficiency during machining followed by table feed velocity. Spindle rotational velocity is found to be a least significant parameter. Furthermore, the analysis of chip morphology confirmed the behavioral changes while machining due to the presence of variation in tool nomenclature and machining condition.

1. Introduction

End milling operation is one of the most common and versatile machining processes and it has been used while machining of nimonic 263 alloy in aerospace and defense industry to produce complex profiles. Currently, aerospace and defense industries are facing enormous pressure to reduce the production cost with better surface quality and it leads to improve the machining performance with favorable machining conditions. To validate the quality of machined components such as hot section of gas turbines, the factors such as machining condition and tool nomenclature which influence the cutting force are need to be analyzed and they help to improve the machining process. Dry machining possesses better environmental and economic reasons such as reduction in machining cost due to no usage of cutting fluid. But it has some disadvantages such as tool wear, tool life and high temperature at the chip and tool interfaces. Additionally, the generated chip during machining cannot be washed away and it leads to deteriorate the surface. Velchev et al have stated that, the grade of the cutting tool material plays crucial role in specific energy consumption compared to machining parameters such as feed and depth cut [1]. However, solid carbide end mills are widely used in industrial applications and Lima et al have reported that coated carbide inserts perform efficiently up to a work piece hardness of 50 HRC [2]. Zhou et al have evaluated the fluctuations in shear deformation energy through the variation in machining parameters and tool nomenclature via modified average chip thickness and it leads to enhance the surface integrity of the machined component [3]. Davoodi et al have explored the direct influence of cutting speed and uncut chip thickness on cutting force and they have also suggested that the usage of higher cutting speed and least uncut chip thickness is preferable to reduce the cutting force requirements [4]. Chinchanikar et al have studied the interactive effect of cutting speed, feed and depth of cut on surface roughness and stated that, cutting speed is the most influencing factor followed by depth of cut on surface finish. They have also suggested that the use of lower feed and depth of cut by limiting the spindle speed confirms minimum surface roughness, cutting force and tool life [5]. Wang et al have stated that, to reduce the energy consumption during machining processes, higher
In this study, the nimonic 263 is used and the chemical composition is listed in table 1. The nascent samples have been machined to sizes of 15 cm breadth, 100 cm length and 2 cm thickness using water jet machine. Moreover, Yasir et al have evaluated the influence of feed rate and spindle speed on the surface finish end-milled AISI 316L stainless steel and concluded that the spindle speed and depth of cut has negligible effect on surface distortion [7]. Saglam et al have investigated the influences of rake angle on cutting forces and the temperature rise between the tool and the chip interface and proves that the rake angle has a higher influence on cutting force and surface roughness compared to the machining conditions [8]. Zheng et al have suggested that to overcome these issues, optimum machining parameters should be found to achieve least cutting force and better surface finish with the help of mathematical models [9]. Commonly available cutting force and surface roughness models are finite element, empirical and artificial neural network and so on [10, 11]. Chuangwen et al have confirmed that feed per tooth is one of the most significant factors on cutting force during end milling of stainless steel followed by depth of cut and spindle rotational velocity through multiple factor orthogonal experiment [12]. Chen et al have suggested that the response surface methodology is found to be most compromising technique to study the influence of machining parameters such as spindle speed, feed per revolution on surface roughness and they have stated that feed rate is the most influential parameter on surface finish compared to spindle speed [13]. Further, Shao et al have proposed a mathematical model through regression method and reported the influence of cutting speed during face milling austenitic stainless steel on cutting force and surface roughness using empirical equation [14].

From the overview of cited papers, it is clear that the machining parameters and its tool nomenclature possess crucial roles in machining. Additionally, few studies have been presented in the machining of nimonic 263 without invoke any changes in tool nomenclature. This present study is aimed to establish the empirical equation for surface roughness and cutting force under constant depth of cut due to its lowest influence compared to table feed velocity and spindle rotational velocity. Also, analyzing the cutting force during machining will help to optimize the machining parameters and tool nomenclature through regression analysis using minitab software. Furthermore, the measures of surface roughness on machined sample help to improve the surface quality. The objective of the present work is to investigate the significant effect of variation in tool nomenclature and process parameters on cutting force and surface quality. In addition, the surface morphology fluctuations have been evaluated using 3D optical profilometer and the influence of machining on chip micrographs has been presented.

### 2. Materials and methods

In this study, the nimonic 263 is used and the chemical composition is listed in table 1. The nascent samples have been machined to sizes of 15 cm breadth, 100 cm length and 2 cm thickness using water jet machine.

| Elements | Co  | Cr  | Mo  | Ti  | Mn  | Ni  |
|----------|-----|-----|-----|-----|-----|-----|
| Composition | 19.83 | 19.12 | 5.68 | 1.95 | 0.45 | Rest |
| (Values in Weight %) | | | | | | |

The received samples have been machined [Slotting operation] using end mill cutter of coated TiAlN WC cutter of 5 mm diameter. Additionally, the variation in tool radial rake angle such as $+7^\circ$ (P), $0^\circ$ (Z), $-7^\circ$ (N) produced by Axis micro tools, Himachal Pradesh without changing its axial rake angle ($10^\circ$) and helix angle ($30^\circ$) is used to analyze its resultant effect and variation in tool nomenclature is shown in figure 1.

For experimental observations, the tool nomenclature and the machining process parameters such as table feed velocity and spindle rotational velocity are identified as input operating conditions and listed in table 2. For the sake of simplicity, notation [ijk] is used where i, j and k represents radial rake angle of end mill cutter such as $+7^\circ$ (P), $0^\circ$ (Z), $-7^\circ$ (N), table feed velocity of 1 (L), 10 (M), 40 (H) mm min$^{-1}$ and spindle rotational velocity of 15.7 (L), 47.1 (M), 78.5 (H) mm min$^{-1}$, respectively.

The experiment has been carried out using CNC Vertical milling machine (Make Agni BMW 45) as shown in figure 2(a). The cutting forces in X, Y and Z direction are measured using a Kistler piezoelectric dynamometer (Type:9247 B) which is placed over a machine table and it is connected with a computer equipped with dynoware software as shown in figures 3(a) and (b). Experiments are repeated for three times over a length of 12 mm on each machining condition to obtain the similar results. Commonly used data processing methods are maximum cutting force, average cutting force and root mean square force. The forces, $F_x$, $F_y$ and $F_z$ are calculated using root mean square for the sake of simplicity and the resultant cutting force $F$ is calculated using equation (1).
Figure 1. Macroscopic images of variation in tool nomenclature. (a) Positive (b) Zero (c) Negative radial rake angle cutter.

Table 2. Machining parameters with notation under constant depth of cut of 0.5 mm.

| S.no | Notation | Radial rake angle of tool (degree) | Table feed (mm/tooth) (f) | Table feed velocity (m min$^{-1}$) ($f_v$) | Spindle rotational velocity (m min$^{-1}$) (v) |
|------|----------|-----------------------------------|---------------------------|------------------------------------------|---------------------------------------------|
| 1    | PLL      | +7                                | 0.0005                    | 1                                        | 15.7                                       |
| 2    | PLM      | +7                                | 0.000167                  | 1                                        | 47.1                                       |
| 3    | PLH      | +7                                | 0.0001                    | 1                                        | 78.5                                       |
| 4    | PML      | +7                                | 0.005                     | 10                                       | 15.7                                       |
| 5    | PMM      | +7                                | 0.001667                  | 10                                       | 47.1                                       |
| 6    | PMH      | +7                                | 0.001                     | 10                                       | 78.5                                       |
| 7    | PHL      | +7                                | 0.02                      | 40                                       | 15.7                                       |
| 8    | PHM      | +7                                | 0.006667                  | 40                                       | 47.1                                       |
| 9    | PHP      | +7                                | 0.004                     | 40                                       | 78.5                                       |
| 10   | ZLL      | 0                                 | 0.00005                   | 1                                        | 15.7                                       |
| 11   | ZLM      | 0                                 | 0.000167                  | 1                                        | 47.1                                       |
| 12   | ZLH      | 0                                 | 0.0001                    | 1                                        | 78.5                                       |
| 13   | ZML      | 0                                 | 0.005                     | 10                                       | 15.7                                       |
| 14   | ZMM      | 0                                 | 0.001667                  | 10                                       | 47.1                                       |
| 15   | ZMH      | 0                                 | 0.001                     | 10                                       | 78.5                                       |
| 16   | ZHL      | 0                                 | 0.02                      | 40                                       | 15.7                                       |
| 17   | ZHM      | 0                                 | 0.006667                  | 40                                       | 47.1                                       |
| 18   | ZHH      | 0                                 | 0.004                     | 40                                       | 78.5                                       |
| 19   | NLL      | −7                                | 0.0005                    | 1                                        | 15.7                                       |
| 20   | NLM      | −7                                | 0.000167                  | 1                                        | 47.1                                       |
| 21   | NLM      | −7                                | 0.0001                    | 1                                        | 78.5                                       |
| 22   | NML      | −7                                | 0.005                     | 10                                       | 15.7                                       |
| 23   | NMM      | −7                                | 0.001667                  | 10                                       | 47.1                                       |
| 24   | NMH      | −7                                | 0.001                     | 10                                       | 78.5                                       |
| 25   | NHL      | −7                                | 0.02                      | 40                                       | 15.7                                       |
| 26   | NHM      | −7                                | 0.006667                  | 40                                       | 47.1                                       |
| 27   | NHH      | −7                                | 0.004                     | 40                                       | 78.5                                       |

Figure 2. (a) CNC Vertical Milling Machine (b) 3D optical profilometer (c) End mill cutter.
Measurement of surface roughness is performed through a 3D optical profilometer (Taylor Hobson) using the principle of infinite focus and the Mountains Map 7.1 software has been used to collect the real information from the surface topography. Additionally, scanning electron microscope is employed to analyze the qualitative contribution of tool nomenclature and machining process parameters on chip and surface morphology.

3. Results and discussion

The behavioral changes during the end milling process, due to the variation in radial rake angle are demonstrated in figure 4.

3.1. The influence of cutting parameters and tool nomenclature on cutting force

The measured cutting forces from the experiment are analyzed to understand the performance of machining process under various tool nomenclature and machining conditions. The data measured using dynamometer is statistically analyzed to emphasize the influence of tool nomenclature and the machining parameters on cutting force [15, 16].

Measured values of the resultant cutting force under various tool nomenclature and machining conditions are listed in table 3. Based on the experimental responses, the lowest values of the cutting force are encountered in a tool with a negative radial rake angle machining condition which results due to the resultant effect of positive axial rake angle and helix angle. This trend is similar irrespective of the machining conditions. Simultaneously, an increase of cutting force value is observed in positive radial rake angle machining condition followed by zero radial rake angle end mill.

The resultant cutting force $F$ listed in table 3 shows typical changes in tendency with respect to decreasing radial rake angle. Cutting force is the lowest under machining with a table feed velocity of 1 mm min$^{-1}$ due to the lowest strain hardening and temperature effect but it leads to increase the machining cost and overhead

$$F = \sqrt{Fx^2 + Fy^2 + Fz^2}.$$ (1)

Measurement of surface roughness is performed through a 3D optical profilometer (Taylor Hobson) using the principle of infinite focus and the Mountains Map 7.1 software has been used to collect the real information from the surface topography. Additionally, scanning electron microscope is employed to analyze the qualitative contribution of tool nomenclature and machining process parameters on chip and surface morphology.
charges, due to less productivity. Cutting force at medium table feed (10 mm min\(^{-1}\)) offers moderate level of cutting force for all spindle rotational velocities and this trend occurs irrespective of tool nomenclature. At medium table velocity cutting force first increases for spindle rotational velocity increment from 15.7–47.1 m min\(^{-1}\), due to pronounced effect of increment in chip load and deformation resistance. On further increment in spindle rotational velocity, the cutting force requirement is the lowest among various machining conditions due to increment in thermal softening behavior of the work piece due to lowest thermal evacuation at the cutting zone and it has also been quoted by other researchers also\[17\]. Under higher table feed condition, the cutting force behavior is not similar like medium table velocity machining due to the effective work done by the tool to shear the work piece which obscures the thermal softening effect. Further, the chip takes utmost heat at higher table feed machining condition due to less available time for heat conduction and it leads to invalidate the thermal softening effect.

Material constitutive model such as Johnson cook model (J-C) has been used by many researchers to analyze the thermal softening behavior of the work piece during machining. A J-C model for nimonic 263 alloy which includes strain hardening effect, the strengthening effect due to strain rate and the temperature effect is shown in the following equation.

\[
\sigma = 450 + 1700e^{0.65} (1 + 0.017 \ln \dot{\varepsilon})(1 - \left(\frac{T - T_m}{T_r - T_m}\right)^{1.3}) \text{MPa}
\]

Where \(T_m = 1573 \text{ k}\) and \(T_r = 303 \text{ k}\)

The temperature effect term in the J-C model measures the thermal softening behavior of the work piece which results due to the temperature rise in shear zone and this rise is estimated using oxley’s theory\[18\]. The flow stress has been calculated under various machining conditions which clearly reveals the increment in chip

### Table 3. Cutting force as a function of machining parameters.

| S.No | Notation [ijk] | Cutting force F (N) |
|------|----------------|---------------------|
| 1    | PLL            | 25.94               |
| 2    | PLM            | 26.65               |
| 3    | PLH            | 37.13               |
| 4    | PML            | 109.63              |
| 5    | PMM            | 122.33              |
| 6    | PMH            | 99.56               |
| 7    | PHL            | 123.57              |
| 8    | PHM            | 138.56              |
| 9    | PHH            | 147.88              |

### Table 4. Surface roughness as a function of machining parameters.

| S.no | Notation [ijk] | Surface roughness Sa (\(\mu\)m) |
|------|----------------|-------------------------------|
| 1    | PLL            | 0.256                         |
| 2    | PLM            | 0.424                         |
| 3    | PLH            | 0.987                         |
| 4    | PML            | 0.897                         |
| 5    | PMM            | 0.399                         |
| 6    | PMH            | 0.313                         |
| 7    | PHL            | 0.834                         |
| 8    | PHM            | 0.753                         |
| 9    | PHH            | 0.621                         |

Figure 5. Work piece images of zero radial rake angle machined samples.
load and it leads to thermal softening behavior in shear zone. The cutting force requirement is normally higher in end milling with a negative radial rake angle cutter end but in this study, it offers less cutting force due to the interactive effect between negative radial rake angle, positive axial rake angle and helix angle. From the evidence it is noted that, it is more preferable to machine the work piece with a cutter having negative radial rake angle, positive axial rake angle and helix angle, due to the lowest force requirement.

3.2. The influence of cutting parameters and tool nomenclature on surface roughness

Figure 5 clearly illustrates the influence zero radial rake angle cutter along with varying machining condition on nimonic 263 work piece and table 4 reveals the pronounced effect of thermal softening compared to strain hardening on surface roughness.

Lowest surface roughness is encountered during machining with a table feed velocity of 1 mm min\(^{-1}\) at 15.7–47.1 m min\(^{-1}\) spindle rotational velocity, due to the lowest strain hardening and temperature effect. But it’s not preferable, due to economic considerations such as higher machining cost, overhead charges with lowest productivity. At medium and higher table feed under lower spindle rotational velocity machining condition, the surface quality gets deteriorated and then, the surface quality becomes better with the increment in spindle rotational velocity. This increment in residual height arises due to the reduction in feed time for removing per unit volume of material and it leads to increase the surface roughness. Additionally, increasing table feed induces increment in cutting thickness and plastic deformation volume on the metal surface which results in higher surface roughness [19, 20]. Moreover, the variations in surface roughness are also evident as a function of table feed. From the table 4, it can be concluded that with the medium table feed velocity of 10 mm min\(^{-1}\) and spindle

![Surface morphologies of machined sample under (a) PLL (b) ZLL (c) NLL conditions.](image)
rotational velocity of 78.5 m min\(^{-1}\), a controlled surface roughness is produced and this trend happens irrespective of tool nomenclature. Amongst various tool nomenclatures and machining conditions, the cutter with a negative radial rake angle, table feed velocity of 10 mm min\(^{-1}\) and spindle rotational velocity of 78.5 m min\(^{-1}\) has produced a controlled surface finish. Hence, it is more preferable to machine the workpiece with a cutter having negative radial rake angle, positive axial rake angle and helix angle due to better surface finish. The surface morphologies of the machined samples under various machining conditions and tool nomenclature are shown in figure 6.

3.3. The influence of cutting parameters and tool nomenclature on chip morphology
The micrographs of chips obtained during various machining conditions are demonstrated in figure 7. In the case of similar machining conditions with various tool nomenclatures, the variation of chip size is observed as a result of variation in shear angle and chipping process. The chip morphologies are amorphous, loose and fan based chips in zero radial rake angle cutter machining due to more discontinuous deformation on the machined surface has resulted the prevention of continuous flow of chips compared to positive and negative radial rake angle cutter machining. It clearly indicates the lowest dominance of thermal softening compared to strain hardening effect which leads to maximize the cutting force requirement and thermal evacuation at the cutting zone during machining. Additionally, the conversion of chip morphology is taken place from discontinuous to continuous chips with a minor increase in curl length under increment in cutting spindle rotational velocity which results from variation in shear angle in the cutting zone and chipping process [21]. Amongst various machining conditions, the cutter with a negative radial rake angle produces continuous chips which lead to reduce the cutting force through decrement in the thermal evacuation at the cutting zone and it offers better surface finish.

3.4. Establishing empirical model based on the power function
The experimental responses are analyzed with the help of regression and ANOVA to observe the effect of machining parameters and tool nomenclature on the measurable characteristics such as surface finish and cutting force and it also helps to perceive the most influencing parameter on the measurable characteristics [17]. The experimentally measured values of the surface roughness and cutting force shown in tables 3 and 4 can be used for the determination of equations and they help to describe the machining process. The empirical model is developed based on power function model type I [22, 23].
The generalized equation to describe the investigated phenomena R can be written as equation (2)

\[ R = k \times a_1^{x_1} \times a_2^{x_2} \]  

(2)

Where R is the investigated phenomena, \( a_1 \) and \( a_2 \) are the independent parameters and \( x_1 \) and \( x_2 \) are constants. The equation (2) can be rearranged for cutting force equation as

\[ F_i = k f^{x_1} \nu^{x_2} \]  

(3)

Where \( F \) represents cutting force in N, \( f \) and \( V \) are table feed in mm/tooth and spindle rotational velocity in m min\(^{-1}\), respectively. \( k, x_1, \) and \( x_2 \) are constants which influence the investigated parameter on ith condition. The equation (3) can be linearized using ln function and the modified equation as follows

Table 5. ANOVA table for cutting force with Positive radial rake angle end mill.

| Source   | DF | Adj SS | Adj MS | F-Value | P-Value |
|----------|----|--------|--------|---------|---------|
| Regression | 2  | 3.8985 | 1.9492 | 34.20   | <0.001  |
| \( f \)   | 1  | 3.8662 | 3.8663 | 67.84   | <0.001  |
| \( \nu \) | 1  | 0.9180 | 0.9180 | 16.11   | 0.007   |
| Error    | 6  | 0.3420 | 0.0569 |         |         |
| Total    | 8  | 4.2405 |  |         |         |

Table 6. ANOVA table for cutting force with zero radial rake angle end mill.

| Source   | DF | Adj SS | Adj MS | F-Value | P-Value |
|----------|----|--------|--------|---------|---------|
| Regression | 2  | 6.8834 | 3.4417 | 89.58   | <0.001  |
| \( f \)   | 1  | 6.8789 | 6.8789 | 179.04  | <0.001  |
| \( \nu \) | 1  | 0.9951 | 0.9951 | 25.90   | 0.002   |
| Error    | 6  | 0.2305 | 0.0384 |         |         |
| Total    | 8  | 7.1139 |  |         |         |

Table 7. ANOVA for cutting force with negative radial rake angle end mill.

| Source   | DF | Adj SS | Adj MS | F-Value | P-Value |
|----------|----|--------|--------|---------|---------|
| Regression | 2  | 3.4890 | 1.7445 | 204.83  | <0.001  |
| \( f \)   | 1  | 3.4110 | 3.4110 | 400.49  | <0.001  |
| \( \nu \) | 1  | 1.0027 | 1.0027 | 117.73  | <0.001  |
| Error    | 6  | 0.0511 | 0.0085 |         |         |
| Total    | 8  | 3.5401 |  |         |         |
This equation is modified to regression form using the following notation

\[ \ln F_1 = \ln k + x_{11} \ln f + x_{12} \ln v. \]  

(4)

This equation is modified to regression form using the following notation

\[ \ln F_1 = Y_1, \ln k = A_1, \ln f = A_2, \ln v = A_3. \]  

(5)

A new equation (6) can be facilitated using the notation written in equation (5) as

\[ Y = A_1 + X_1 A_2 + X_2 A_3 = AX. \]  

(6)

The values of A1, A2 and A3 are assumed (Machining condition, independent factors) and the value of Y is measured. The equation (6) has been used to analyze the influence of independent variables (f and v) on the experimental response or investigated phenomenon (F and Sa).

\[
\begin{bmatrix}
Y_1 \\
Y_2 \\
Y_3 \\
\vdots \\
Y_9
\end{bmatrix} = \begin{bmatrix}
1 & X_{11} & X_{12} \\
1 & X_{21} & X_{22} \\
1 & X_{31} & X_{32} \\
\vdots & \vdots & \vdots \\
1 & X_{91} & X_{92}
\end{bmatrix} \begin{bmatrix}
A_1 \\
A_2 \\
A_3 \\
A_4
\end{bmatrix},
\]

(7)

\[ A = X^{-1}Y = (X^T X)^{-1}XY. \]  

(8)

On the basis of experimental values and the aforementioned equations, the coefficients of each cutting parameter could be obtained and the final equations (9) and (10) help to describe the surface roughness and cutting force under variable machining cutting conditions with positive radial rake angle tool is

\[ F = 187.91 f^{0.431} v^{0.519}. \]  

(9)

\[ Sa = 0.62 f^{0.1044} v^{0.083}. \]  

(10)

For the cutter with zero radial rake angles, equation (11) describes the cutting force F, and equation (12) explores the surface roughness Sa.

\[ F = 609.11 f^{0.57} v^{0.54}. \]  

(11)

\[ Sa = 1.4 f^{0.16} v^{0.012}. \]  

(12)

Similarly, for the cutter with negative radial rake angles, equation (13) describes the cutting force F, and equation (14) presents the surface roughness Sa.

\[ F = \ldots \]  

\[ Sa = \ldots \]  

(13)

(14)
Where $f$ and $v$ are feed per tooth (mm/tooth) and spindle rotational velocity in m min$^{-1}$, respectively. The comparisons of the experimentally measured cutting force and the surface roughness with the values obtained from the mathematical equations (9)–(14) is shown figures 8(a) and (b).

For the mathematical model, the biggest error of the cutting force $F$ value for the positive radial rake angle cutter equals 40% related to the measured value and in surface roughness, it equal to 50% related to the measured value. In the case of the zero radial rake angle cutters, the biggest error equals 27% in cutting force and 55% in surface roughness. Similarly, for the negative radial rake angle cutter, the biggest error equal to 16% in cutting force and 60% in surface roughness. In case of the entire mathematical model, the total errors do not exceed the value of 22% in cutting force and 35% in surface roughness. The surface roughness model shows higher error percentage, due to the abrupt nature of measured values and this abrupt nature leads to induce inhomogeneity in work piece.

### 3.5. Statistical analysis of cutting force and surface roughness

The significance of the regression equation was verified with the help of F value test using ANOVA with m experimental factors and n - no of experiments. The level of significance was preset to 0.05. There is no presence of linear relationship between machining parameters and observable characteristics such as cutting force and surface roughness if $F < F_{0.05} (m, n-m-1)$. Furthermore, it meant that the mathematical regression equation was not true. Additionally, there is a significant linear relationship is confirmed if $F_{0.05} < F < F_{0.01} (m, n-m-1)$. Moreover, if $F > F_{0.01} (m, n-m-1)$, confirmed that there is strong linear relationship between machining parameters and observable characteristics such as cutting force and surface roughness. In this study $m = 2$ and $n = 9$ is considered and it could be found that $F_{0.05} (2,6) = 5.14$ and $F_{0.01} (2,6) = 10.92$ from the F-distribution table. Tables 5–7 shows the F- value of cutting force under positive, zero and negative radial rake angle machining and tables 8–10 shows the F- value of surface roughness under positive, zero and negative radial rake angle machining. The F value for the resultant cutting force were higher than $F_{0.05} (2,6) = 5.14$ which confirms

\begin{align}
F &= 122.3 f^{0.4} v^{0.54}, \quad (13) \\
S_x &= 0.72 f^{0.078} v^{-0.09}, \quad (14)
\end{align}
that the regression equations are significant. It concludes that the reliability of the developed empirical equations is higher and helps to predict the required cutting force based on machining conditions and tool nomenclature. It also shows that the table feed velocity has greater influence on the cutting force and spindle rotational velocity.
have a less contribution with the level of significance of less than 0.05. A similar effect is observed on surface finish also and this trend is irrespective of tool nomenclature like cutting force.

The contour plot helps to analyze the influence of table feed and spindle rotational speed on cutting force and surface roughness in the graphical perspective. For the sake of simplicity and clear visualization, the table feed is taken in mm min\(^{-1}\) for plotting contour profiles.

Figures 9 and 10 shows the changes in surface roughness and cutting force with changing spindle rotational velocity and table feed. The changes in contour interval prove the interaction between the spindle rotational velocity and the table feed is significantly affecting the surface roughness and cutting force. Furthermore, it is proved that this contour interval variations are not similar between various radial rake angle, due to the significant effect of radial rake angle on temperature effect and it clearly indicates the influence of radial rake angle on surface roughness and cutting force compared to the machining parameters\[24\].

The surface morphology machined samples under different machining conditions are shown in figure 11. It clearly shows the impacts of machining parameters and tool nomenclature on surface morphology. The severe plastic deformation leads to form plastically deformed pits which lead to increase its surface finish. These variations have happened, due to the variation in chipping process and shear angle during machining and it is confirmed through the analysis of chip morphology.

### 4. Conclusion

In the present study, the analysis of variation in radial rake angle and machining parameters during end milling of nimonic 263 alloy has been studied. The main attention has been focused on the surface roughness and the cutting force component. The study reveals the following conclusions:

1. The dependency of surface roughness and cutting force on tool nomenclature and machining parameters has been established using regression analysis and validated with the experimental results.

2. ANOVA observation has confirms that the table feed has higher influence followed by spindle rotational velocity during end milling with a positive radial rake angle cutter but this influence is much higher in zero radial rake angle cutter followed by negative radial rake angle cutter, due to the influence of radial rake angle.

3. Changes in contour plot interval proved the interaction between the spindle rotational velocity and the table feed per tooth is significantly affects the cutting force and surface finish.

4. Amongst various machining conditions, the cutter with a negative radial rake angle at a table feed velocity of 10 mm min\(^{-1}\) and spindle rotational velocity of 78.5 m min\(^{-1}\) produces better surface finish along with lowest cutting force.

5. The cutting force requirement is normally higher in end milling with a negative radial rake angle cutter end but it consumes less cutting force, due to the interactive effect of negative radial rake angle \((-7^\circ)\), positive axial rake angle \(10^\circ)\) and helix angle \(30^\circ)\).

6. Through the observation and contour plot, it can be demonstrated that the end mill cutter with a negative radial rake angle has a great potential and alternative in machining of alloys has been used in defense and aerospace application and increases its productivity with lowest production cost.

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