Optimization of Cutting Parameters Based on Surface Roughness and Cutting Force During End Milling of Nimonic C-263 Alloy

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Abstract. The surface integrity of machined surfaces greatly influences the functional properties of the components such as fatigue life, etc. Nickel-based superalloy such as Nimonic C-263 is termed as difficult to machine material due to its unique properties as well as high strength at elevated temperatures. This study intends to optimize the cutting parameters (cutting speed, feed, depth of cut) during the end milling of Nimonic C-263 and the machining has been carried out using solid tungsten carbide tool coated with TiAlN and Vertical Machining Center. Experimentation is carried out using Taguchi L9 orthogonal array technique and based on signal to noise ratio data, optimum machining parameters were achieved for preferred observable characteristics such as cutting force and surface roughness. Additionally, Multi-purpose optimization (Grey analysis) of the observable characteristics was conducted to predict the optimum machining parameters combination which offers better producible surface finish and lowest cutting force requirement. Further, the analysis of variance (ANOVA) reveals that the feed rate is the farthest influencing factor followed by the depth of cut, cutting speed, and the variations in cutting force and surface roughness are confirmed through chip morphology using Scanning electron microscopy.

1. Introduction
Nickel-based superalloy Nimonic 263 is finding wider applications in aerospace engineering, gas turbine engines, etc. Nimonic C-263 alloy possesses superior mechanical properties such as high temperature creep resistance, unique combination of low thermal expansion coefficient and high strength at higher temperatures. The recent advances in aerospace engineering necessitated the importance of the manufacturing process. Every component which is meeting design requirements needs to undergo some sort of machining process and the surface integrity of the part greatly affects the functional characteristics such as contact friction, fatigue behavior and so on. To develop a good process understanding and thus achieve the excellent surface finish, it is therefore essential to explore the machining parameter's effects on surface integrity. Machining of superalloys is very expensive since they possess superior mechanical properties and also the requirement of tighter dimensional tolerances making them even more difficult for machining. Measurement of surface integrity is the primary characteristic for the quality of machined parts and the analysis of forces is of at most importance, as they influence the electricity consumption, machine tool vibrations, etc. Cutting forces generated during machining is responsible for residual stresses, cutting temperature and wear rate, which intern influences the performance of components during the service time [1].
Suraratchai et al have examined the impact of machined surface condition on fatigue behavior based on roughness and it provided a reliable indicator for fatigue life estimation when changing machining parameters [2]. Niharika et al have identified that solid tungsten carbide tools, when coated with TiAlN, exhibited better performance characteristics such as excellent tool life and slot geometry [3]. Gowthaman et al have studied the rake angle effects on surface characteristics during end milling and they discovered that milling cutter with a negative radial rake angle is exhibiting better surface characteristics compared to that of positive radial rake angle [4]. Ezilarasan et al have conducted turning trials to analyze machining parameters. The outcomes revealed that the depth of cut is responsible for flank wear and feed rate is for cutting forces [5]. Hamdi et al have developed a mathematical model to inspect the machining factors' effect on cutting force and surface integrity. The outcomes revealed that the feed rate and hardness of workpiece have a substantial effect on roughness parameters and additionally they concluded that the excellent surface finish obtained at maximum cutting speed and minimum feed rate [6]. Taguchi analysis is used to improve the performance characteristics to minimize the surface irregularities and microhardness during the machining of magnesium alloy and it is observed that the feed rate was the key governing factor [7]. Girish et al have reported that the grey relation method along with the RSM technique gives better results in terms of lower power consumption and better surface finish [8]. Muhammad et al., have stated that chip morphology helps to analyze the machined surface integrity [9]. Albert et at have also studied the chip morphology and they developed a procedure to classify them based on their appearance [10].

The above literature reveals the significant importance of cutting parameters on observable characteristics. Additionally, studies associated with the cutting parameters optimization and multi-purpose optimization revealed that the Taguchi technique and grey relation assessment are very useful tools. Furthermore, chip morphology has a greater influence on the machining process. The current work seeks to examine the impact of machining factors on end milled Nimonic 263 alloys surface integrity. Also, the multi-purpose optimization is performed by using grey relation analysis to discover the optimal set of cutting parameters. Scanning electron microscope images were used to study the chip morphology.

2. Experimental procedure

2.1. Workpiece and tool material
Nimonic 263 alloy material is studied in this paper and its chemical configuration is given in Table 1. It is mostly used in the aerospace industry for medium-range temperature applications. It has a density of 8360 kg/m³, Young's modulus of 224 GPa and a specific heat coefficient (Cp) of 461 J/kg °C. A 4-axis vertical CNC machining center (Make Agni BMV45 TC24) is used to perform end milling operation and the machining is carried out using a two-flute solid tungsten carbide tool coated with TiAlN. The cutting tool used is having a diameter of 6 mm and a 30 mm flute length. The machined workpiece is shown in figure 1.

Figure 1. End milled Nimonic 263 alloy.
2.2. Design of experiments

The machining parameters used for the experimentation were listed in Table 2. A three-factorial design of input parameters comprising of the speed (v), feed rate (f), and depth of cut (d) is employed to optimize the output response data. Taguchi’s experimental strategy is employed to perform end milling operations and an L9 orthogonal array is implemented to reduce the cost and machining time.

Table 1. Nimonic263 alloys composition.

| Elements (valves in weight %) | Co  | Cr  | Mo  | Ti  | Mn  | Ni  |
|-----------------------------|-----|-----|-----|-----|-----|-----|
| Composition                 | 21  | 19  | 5.86| 1.56| 0.43| Rest|

Table 2. Different stages of machining parameters and their values.

| Parameter       | Units | Stage 1 | Stage 2 | Stage 3 |
|-----------------|-------|---------|---------|---------|
| Speed (V)       | rpm   | 1500    | 2000    | 2500    |
| Feed rate (f)   | mm/min| 5       | 25      | 45      |
| Depth of cut (d)| mm    | 0.2     | 0.4     | 0.6     |

3. Results and discussion

Milling (dry) process is performed on Nimonic 263 alloy material and the observable characteristics were recorded i.e cutting forces, surface roughness. By using a multicomponent dynamometer (Kistler 9257B) three-component of forces generated during the milling were measured. Measurement of surface roughness (R_a) was carried out by using a 2D surface profiler (Mitutoyo SJ-410). The experimental setup and cutting force, roughness measurement setups are shown respectively in figure 2 and figure 3. In table. 3 measurement results with varying machining parameters were presented.

Figure 2. Machining setup.

Figure 3. 2D surface profiler setup.
Taguchi design uses a degree of robustness to recognize the governing factors that minimize variability by reducing the effects of noise factors. Here the governing factors may be tool geometry, cutting conditions, workpiece material, etc. The single to noise is associated with the variation in response relative to the targeted value, the greater the signal to noise ratio better will be the response. Based on the objective of the study, there are three different types available to calculate the signal to noise ratios. Larger the better criteria (Equation 1) is used if the goal is to maximize the response.

$$S / N = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^n} \right)$$ (1)

A smaller is better criteria (Equation 2) is used if the goal is to minimize the response.

$$S / N = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} y_i^n \right)$$ (2)

Where $y_i$ means response variable for the given input parameter, $n$ means the total number of response variables for a given combination of input parameters. In this study, S/N ratios are computed based on smaller the better criteria as the sole purpose of the study is to reduce the surface roughness and also cutting forces. By using the Minitab software, the graphs were plotted between input parameters and the mean values of the S/N ratio. From figure 4, at cutting speed of 2000 rpm, 5 mm/min feed rate and depth of cut of 0.6 mm the graph shows higher values of S/N ratio which means at this machining conditions Nimonic 263 alloy exhibits relatively lower $R_a$ values. Table 4 represents Taguchi analysis results based on the S/N ratios, from the table it is clear that a higher value of delta was observed for feed rate. From figure 5, the optimal parameters for reducing the cutting force ($F_x$) were observed when cutting speed is 1500 rpm, 5 mm/min feed rate and a 0.4 mm depth of cut. The delta value of

| S.No | Speed (rpm) | Feed rate (mm/min) | Depth of cut (mm) | $R_a$ ($\mu$m) | $F_x$ (N) | $F_y$ (N) | $F_z$ (N) |
|------|-------------|---------------------|------------------|----------------|-----------|-----------|-----------|
| 1    | 1500        | 5                   | 0.2              | 0.369          | 33.87     | 28.32     | 56.07     |
| 2    | 1500        | 25                  | 0.4              | 0.315          | 44.21     | 35.56     | 49.49     |
| 3    | 1500        | 45                  | 0.6              | 0.325          | 35.89     | 31.98     | 43.36     |
| 4    | 2000        | 5                   | 0.4              | 0.182          | 37.03     | 33.79     | 38.56     |
| 5    | 2000        | 25                  | 0.6              | 0.373          | 81.19     | 110.77    | 73.06     |
| 6    | 2000        | 45                  | 0.2              | 0.225          | 68.85     | 76.31     | 53.94     |
| 7    | 2500        | 5                   | 0.6              | 0.130          | 45.91     | 40.29     | 50.32     |
| 8    | 2500        | 25                  | 0.2              | 0.333          | 67.53     | 67.96     | 57.53     |
| 9    | 2500        | 45                  | 0.4              | 0.499          | 45.73     | 38.51     | 59.19     |
Table 5, clearly indicates that the highly dominating parameter is the feed rate. From the above analysis, lower values of feed rate give better results and also in both cases cutting speed is the second most influencing parameter followed by the depth of cut.

| Level | Speed (rpm) | Feed rate (mm/min) | Doc (mm) |
|-------|-------------|---------------------|----------|
| 1     | 9.485       | 13.726              | 10.389   |
| 2     | 12.107      | 9.384               | 10.596   |
| 3     | 11.409      | 9.891               | 12.016   |
| Delta | 2.622       | 4.343               | 1.627    |
| Rank  | 2           | 1                   | 3        |

Table 5. Taguchi analysis results for cutting force ($F_x$).

| Level | Speed (rpm) | Feed rate (mm/min) | Doc (mm) |
|-------|-------------|---------------------|----------|
| 1     | -31.54      | -31.74              | -34.65   |
| 2     | -35.44      | -35.90              | -32.50   |
| 3     | -34.34      | -33.69              | -34.18   |
| Delta | 3.90        | 4.16                | 2.15     |
| Rank  | 2           | 1                   | 3        |

3.1. Grey relation analysis

The complex interrelationships between the multiple responses are solved using the grey relation method. A three-stage grey relation analysis is performed. In the initial stage, the data (normalization) is pre-processed to obtain a comparable sequence. Based on the objective of the study two types of normalization are possible for instance higher the better normalization is used for maximization problems and lower the better normalization is used for minimization problems. Here lower is better normalization (Equation 3) is used.

**Figure 4.** Means of S/N ratios Vs cutting parameter plots for surface roughness.
Figure 5. Means of S/N ratios Vs cutting parameter plots for cutting force ($F_x$).

$$y_i(k) = \frac{\text{max } x_i(k) - x_i(k)}{\text{max } x_i(k) - \text{min } x_i(k)}$$

(3)

Here $x_i(k)$ are the initial values, max $x_i(k)$ stands for maximum measured value and min $x_i(k)$ stands for minimum measured values. Once the normalization is completed, the grey relation coefficients are computed by using the below formula (Equation 4).

$$\xi_i(k) = \frac{\Delta_{\text{min}} + \zeta \Delta_{\text{max}}}{\Delta_{0i}(k) + \zeta \Delta_{\text{max}}}$$

(4)

Here

$$\Delta_{0i} = \text{max } x_0(k) - x_i(k)$$

Where $\Delta_{\text{max}}$ represents the higher value of $\Delta_{0i}(k)$ and $\Delta_{\text{min}}$ is the lowest values of $\Delta_{0i}(k)$ respectively. $x_0(k)$ stands for reference series and $x_i(k)$ is for comparative series. Here $\zeta$ is known as the identification coefficient which is normally taken as 0.5. After calculating the grey relation coefficient, in the next stage grey relation grades are computed by using the below-mentioned formula (Equation 5).

$$\gamma_i = \frac{1}{n} \sum_{k=1}^{n} \xi_i(k)$$

(5)

Where $\gamma_i$ denotes the magnitude of grey relation grade. The relationship between the reference series and the comparability series is established by using the grey relation grade values. Higher the grey relation grade value better will be the multiple responses i.e the combination of machining parameters.
which are associated with higher grey relation grade gives minimal cutting force and surface roughness.

**Table 6.** Grey relation grades and ranking for machining parameters.

| S. No | Ra (µm) | Fx (N) | Ra | Fx | Ra | Fx | Grey relation grade | Rank |
|-------|---------|--------|----|----|----|----|---------------------|------|
| 1     | 0.369   | 33.87  | 0.251 | 1.000 | 0.400 | 1.000 | 0.700 | 3     |
| 2     | 0.315   | 44.21  | 0.420 | 0.781 | 0.463 | 0.696 | 0.579 | 5     |
| 3     | 0.325   | 35.89  | 0.389 | 0.957 | 0.450 | 0.921 | 0.686 | 4     |
| 4     | 0.182   | 37.03  | 0.837 | 0.933 | 0.754 | 0.882 | 0.818 | 2     |
| 5     | 0.373   | 81.19  | 0.238 | 0.000 | 0.396 | 0.333 | 0.365 | 9     |
| 6     | 0.225   | 68.85  | 0.702 | 0.261 | 0.627 | 0.403 | 0.515 | 6     |
| 7     | 0.13    | 45.91  | 1.000 | 0.746 | 1.000 | 0.663 | 0.831 | 1     |
| 8     | 0.333   | 67.53  | 0.364 | 0.289 | 0.440 | 0.413 | 0.426 | 8     |
| 9     | 0.449   | 45.73  | 0.000 | 0.749 | 0.333 | 0.666 | 0.500 | 7     |

The results of grey relation analysis are recorded in Table 6. Based on grey relation grades, experiment 7 is having the higher values of grey relation grades which makes it a perfect combination of cutting parameters for minimizing the cutting force and surface roughness. In other words, experiment 7 exhibits better results for both cutting forces and surface roughness. Experiment 7 consists of a cutting speed of 2500 rpm, a feed rate of 5 mm/min and a 0.6 mm depth of cut.

### 3.2. Analysis of variance

By using the analysis of variance (ANOVA) technique it is possible to find the significance of one or more factors by relating the response variable means at different factor stages. Table 7 shows ANOVA results for grey relation grades. Usually, F > 4 indicates a significant change in observable characteristics for a corresponding variation in the machining parameters. A significant change (74.65%) in observable characteristics is observed for a corresponding variation of feed rate. Furthermore, among the other factors feed rate is having an F value greater than 4 making it a significant factor.

**Table 7.** Analysis of variance results.

| Source             | DF | Seq SS | Contribution | Adj MS | F-Value |
|--------------------|----|--------|--------------|--------|---------|
| Speed (rpm)        | 2  | 0.01312| 5.92%        | 0.006558 | 0.45    |
| Doc (mm)           | 2  | 0.01370| 6.18%        | 0.006851 | 0.47    |
| Feed rate (mm/min) | 2  | 0.16542| 74.65%       | 0.082708 | 5.64    |
| Error              | 2  | 0.02935|              | 0.014674 |         |
| Total              | 8  | 0.22158|              |         |         |
3.3. Chip morphology  

The chip morphology images of the chips produced during machining of Nimonic 263 alloy are presented in figure 6, all the images were taken at a magnification of 200X using Scanning electron microscopy (SEM).

![Chip morphology images](image)

**Figure 6.** Scanning electron microscopy images of chips produced at different levels of machining.

Based on the observation’s chips produced during machining are categorized into different groups. Smooth chips with damaged edges are related to higher cutting forces and surface roughness. Figure 6 (e), (h), (i) shows the smooth chips with damaged edges. This type of chips was produced due to the extreme strain hardening of work material in the cutting zone. From the results of grey relation analysis, the above-mentioned experimental runs are having lower grey relation grade values. Serrated chips were produced because of the poor thermal conductivity of the Nimonic 263 alloy and are shown in figure 6 (a), (b), (c), respectively. Smooth chips were observed in experiment 7, experiment 4 as shown in figure 6 (g), (d). At this cutting condition, Nimonic alloy displays a sufficient amount of ductility to produce damage free smooth surface with lesser cutting force.

4. Conclusions

To estimate the impact of cutting parameters on cutting force and surface integrity of Nimonic 263 alloy an end milling operation is performed. In this paper, three different types of cutting parameters each having three levels were chosen and a total of 9 experiments were conducted. Furthermore, statistical techniques have been employed to analyze the data and results revealed the following conclusions.

1. At a cutting speed of 2000 rpm, 5 mm/min feed rate and depth of cut of 0.6 mm Taguchi's S/N ratio analysis is giving better results for surface finish and the optimal parameters for reducing
the cutting force were observed at a cutting speed of 1500 rpm, 5 mm/min feed rate and depth of cut of 0.4 mm.

2. Grey relation analysis is employed to improve the multiple responses and the results showed that experiment 7 is having higher values of grey relation grades.

3. Based on analysis of variance feed rate is contributing around 75% and it is having an F value greater than 4 making it a significant factor for response variation.

4. The chips are categorized into different groups and with the help of chip morphology images cutting force and surface integrity were analyzed.

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