Effect of MQL, wet and dry lubrication on functional behavior of end milled nimonic-263

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Abstract. The demand for lower costs with eco-friendly characteristics has stimulated the use of alternate machining practices. The intrinsic properties of Ni-based aerospace alloy make it an uphill task to perform machining on it. The ease of machining of these alloys can be achieved by optimizing the cutting conditions with use of efficient and effective cooling mechanism. The methodology aims to predetermine the MQL performance on surface characteristics over dry and wet conditions and to determine the optimum machining parameters which provides substantial influence on functional attributes such as load bearing ability, wear resistance, etc. The feed rate (2, 20 and 50 mm/min), flow rate (5, 8 and 11 ml/min for MQL) and spindle speed (1000, 2500, 4000 rpm) were used as machining parameters (Independent variables) to govern the alterations in surface profile characteristics such as surface roughness, surface topography and surface morphology of the end milled Nimonic-263 alloy. Furthermore, the ANOVA statistical analysis shows the strong influence of the machining environment over the surface profile parameters. Additionally, the chip morphology (dry machining) was analyzed to examine the effect of variation in machining conditions over the shearing mechanism and its impact on generation of surface profiles. Finally, it has been found that the MQL with intermediate cutting conditions can be an alternative which offers better functional characteristics.

1. Introduction
Aerospace industry is among the major imperious area to be strengthened in modern day production technology. Specifically, in recent times this industry has been in huge demand due to sharp rise in aviation infrastructure. Air transport has become the go to option for any individual as there is saving in both ways, cost wise and also faster travel between places suitably. So, the need arises for design and development of jet engines which provides efficient fuel consumption and lesser degree of emissions which can be made easily possible with the recent super alloys like nickel and titanium alloys. For achieving the best performance of jet engine, the most important factor is to reach the maximum possible temperature ratio. Therefore, it becomes imperative at such elevated temperatures to use materials which have intrinsic properties of retaining mechanical and functional properties at intermediate and higher temperature working conditions [1]. The nickel alloys have remarkable characteristics such as high temperature strength, better toughness, chemically stable and corrosion resistant [2]. Machining these alloys have various issues like rapid tool wear, oxidation wear and adhesion wear which results in tool life being short [3]. Lower machinability of difficult-to-cut nickel based high temperature alloys results in easy deterioration of the surface and its subsurface.

Conventionally, the lubricant was employed for cooling which increased the tool life by lowering the wear happening at high temperature (adhesion wear and diffusion wear). Additionally, the attrition wear gets reduced when lubricant is used on the rake face of cutting edge. However, the coolant supply system is expensive to install. Furthermore, due to the chemical dissociation of cutting fluid at higher temperature, the traditional lubricant poses a hazardous exposure for the machinists along with harmful impact on the environment. These problems stimulate the investigators to look for an efficient and viable cooling methods which meet safety and economic demands. These days, dry machining and near-dry machining is preferred which uses MQL (minimum quantity lubrication) technique. This process normally requires a small quantity of lubricant (3-15 ml/min) and resulted in better results.
than dry and wet machining [4]. This technique provides higher life of the tool and lowering of surface roughness in milled AISI D2 steel as concluded from experiments [5]. The effect of cutting force and temperature on MQL assisted milling process was found to be reduced while machining of titanium alloys [6]. The application of MQL in lowering the surface roughness and cutting force on end milled Ti–6Al–4V had been experimentally found [7]. Minimum quantity lubrication method is studied along with wet lubrication in brass turning process. It was inferred from results that cost of machining and environmental hazards were significantly reduced when MQL is used [8].

The comparative advantages which MQL has over wet and dry machining brought attention of the research fraternity to explore deep into the insights of MQL and finally to clutch this competent technique of lubri-coolant application. After profound investigations, the following principal step in adapting MQL is modelling of quality performances like cutting force and surface finish. The influential factors like cutting velocity, feed and lubricant flow rate are considered as the inputs in modeling such relations. In this study, the ANOVA based regression analysis has been used for performance modeling between the input and output responses. The studies of milling process on stainless steel testified the noteworthy impact of machining input factors namely table feed and cutting velocity on surface properties [9]. Moreover, it is described that the surface roughness of machined sample is largely affected through feed which is followed by cutting speed and it was also concluded that surface finish of good tolerance can be produced under best possible machining conditions which results in achieving energy-saving machining [10]. Several researchers have concluded about favourable machining conditions offering substantial influence on the surface topography obtained. Bigerelle et al., discovered the importance of surface roughness calculation and the effect on differentiating the generated surface [11]. Again, Nieslony et al., specified that the surface roughness evaluation provides better picture in analysing the functionality of the material component [12].

From the above literature studies, it can be conferred that machining parameters especially the lubrication method affects the functionality-based surface parameters. Furthermore, very little work has been done on effects of various lubrication techniques under different cutting parameters on Nimonic-263. In this article, the comparative study between MQL, dry and wet cutting environment has been performed and their effect on surface characteristics like surface roughness, surface topography and chip morphology has been investigated. Also, an effort is being made to build statistical model for average surface roughness in relation with feed, cutting speed and flow rate as input parameters and their quantum of effects is evaluated using ANOVA analysis.

2. Materials and methods

2.1. Work piece Details
The material under consideration is Nimonic-263. This is a nickel based super alloy having hardness of 250 BHN. The chemical constituents of this alloy are listed in Table 1 which has wide applications across the aerospace industry.

Table 1. Elemental constituents of Nimonic-263.

| Elements | Co  | Cr  | Mo  | Ti  | Mn  | Ni  |
|----------|-----|-----|-----|-----|-----|-----|
| Content  | 19.82 | 19.10 | 5.69 | 1.96 | 0.47 | Rest |

(% by weight)

The rectangular plate having dimensions of 200 mm x 240 mm x 2 mm was sized down to 100 mm x 50 mm x 2 mm using laser cutter to execute the milling operation.
2.2. Tooling Description
The work piece is machined using TiAlN coated tungsten carbide (WC) 2-flute end-mill cutter having diameter of 6 millimetres. Machining has been carried out using Agni BMV45 TC24 4-axis Vertical Machining Centre (Bharat Fritz Werner Ltd.) as shown in Figure 1(a). The work piece is mounted on the custom-made fixture as shown in Figure 1(b). The MQL setup from DropSA was used to perform controlled lubrication machining. The coolant used was water-based SAVOOIL ISO-grade straight-cut cutting (1:20).

2.3. Design of Experiments and Process parameters
The parameters are selected based on previous research studies as feed, cutting speed and coolant flow rate. The depth of cut was kept invariably at 0.7 mm during the experiment as its significance is minimal on the output. Three levels of feed 2, 20, 50 mm/min and spindle speed of 1000, 2500, 4000 rpm were conducted with flow rates of 5, 8, 11 ml/min for MQL machining and 1800 ml/min for wet (flood) lubrication. Taguchi L9 orthogonal array is the method employed to design the experiment for each machining condition of dry, wet and MQL. The cutting parameters for performing the milling operation is shown in Table 2 and Table 3.

2.4. Response measurement
The response parameter in this study is surface roughness. It is being measured by Taly认 (Mitutoyo SJ-410). The roughness values were measured twice in along the direction of tool to reduce the experimental error and the average value is taken which is shown as Ra value in Table 2-3. Also, surface topography was analyzed using optical microscope. 3D optical profilometer (AliconaInfiniteFocus G5) was used to analyze surface morphology such as bearing area curve (BAC). The chip morphology was studied using Hitachi make Scanning electron microscope (SEM). The plasticity index (Ψ) of the attained surface after milling is done can be calculated using theory of Williamson and Greenwood which is as follows:

\[
\psi = \frac{E}{H} \sqrt{\sigma/r} \tag{1}
\]
Where $E^*$, $\sigma$, $r$ and $H$ are elastic modulus, standard deviation of peaks, average radius of the profile peaks and material hardness respectively.

**Table 2.** Design of experiment by L$_{9}$ orthogonal array for Dry and Wet machining.

| S.No | Spindle Speed (rpm) | Cutting Velocity, $V_c$ (m/min) | Feed (mm/min) | Feed/tooth, $f_z$ (mm/tooth) | $R_a$(µm) (Dry) | $R_a$(µm) (Wet) |
|------|---------------------|---------------------------------|---------------|-------------------------------|----------------|----------------|
| 1.   | 1000                | 18.84                           | 2             | 0.001                         | 0.3125         | 1.0455         |
| 2.   | 1000                | 18.84                           | 20            | 0.01                          | 1.257          | 0.301          |
| 3.   | 1000                | 18.84                           | 50            | 0.025                         | 1.1895         | 0.291          |
| 4.   | 2500                | 47.124                          | 2             | 0.0004                        | 0.543           | 0.151          |
| 5.   | 2500                | 47.124                          | 20            | 0.004                         | 0.5415         | 0.1045         |
| 6.   | 2500                | 47.124                          | 50            | 0.01                          | 0.324           | 0.133          |
| 7.   | 4000                | 75.4                            | 2             | 0.00025                       | 0.423           | 0.2895         |
| 8.   | 4000                | 75.4                            | 20            | 0.0025                        | 0.295           | 0.097          |
| 9.   | 4000                | 75.4                            | 50            | 0.00625                       | 0.4175          | 0.2835         |

**Table 3.** Taguchi L$_{9}$ orthogonal array for MQL machining.

| S.No | Spindle Speed (rpm) | Cutting Velocity, $V_c$(m/min) | Feed (mm/min) | Feed/tooth, $f_z$(mm/tooth) | Flow rate, Q(ml/h) | $R_a$(µm) (MQL) |
|------|---------------------|---------------------------------|---------------|-------------------------------|-------------------|----------------|
| 1.   | 4000                | 75.4                            | 2             | 0.00025                       | 300               | 0.0945         |
| 2.   | 2500                | 47.124                          | 20            | 0.004                         | 300               | 0.2815         |
| 3.   | 1000                | 18.84                           | 50            | 0.025                         | 300               | 0.506          |
| 4.   | 4000                | 75.4                            | 50            | 0.00625                       | 480               | 0.321          |
| 5.   | 2500                | 47.124                          | 2             | 0.0004                        | 480               | 0.089          |
| 6.   | 1000                | 18.84                           | 20            | 0.01                          | 480               | 0.1635         |
| 7.   | 4000                | 75.4                            | 20            | 0.0025                        | 660               | 0.3575         |
| 8.   | 2500                | 47.124                          | 50            | 0.01                          | 660               | 0.891          |
| 9.   | 1000                | 18.84                           | 2             | 0.001                         | 660               | 0.0895         |

### 3. Results and discussions

The work piece is machined under three environment namely dry, wet and MQL condition at different cutting parameters. Basically, there were 3 levels of low, intermediate and high values of input parameters. For every environment a new tool was used to avoid wear effect on the component.

To study the effect of thermal softening on the work piece at the time of machining several researchers have used Johnson Cook model. For nimonic-263 alloy both the strain-hardening effect and thermal softening effect because of rate of strain and temperature influence is present as shown in the equation below,

$$\sigma = (A + B \varepsilon^n) \left(1 + C \ln \varepsilon \right) \left[1 - \left( \frac{\theta - \theta_R}{\theta_m - \theta_R} \right)^m \right] \text{MPa} \quad (2)$$

Where $n$ is the hardening coefficient and $m$ is thermal softening coefficient, $\sigma$ is the flow stress. $\theta_m$ is melting temperature (1628 K) and $\theta_R$ is the initial temperature.
3.1. Surface Roughness

The value of a machined component is heavily influenced by the superiority of the surface generated. The advantage of the surface generated are subjected to its profile and the asperities present on that surface. Sometimes surface finish is directly affecting the functionality of the component so it needs to be evaluated in order to achieve excellent results. It is very clear from Figure 2[a-d] that the on an average the lowest value of surface roughness is obtained at lower feed and low cutting velocity.

![Surface roughness variation with different machining conditions](image)

**Figure 2.** Surface roughness variation with different machining conditions.

This may be due to the lesser thermal softening and strain hardening effect [13]. At medium and higher feed with low velocity the roughness values are increasing for dry machining [Figure 1(a)]. This is due to the increased cutting thickness and feed time getting reduced to remove unit volume of material. In Figure 2(b), there is an abrupt roughness value at low speed and 2 mm/min feed due to some experimental error caused by some irregularities or discontinuity on the work piece surface. Also, we can see that roughness values are getting increased from medium to high feed in wet machining which is because of the improper dispersion of coolant at the chip-tool interface. In Figure 1(c), it is shown that the surface roughness value is minimum when MQL flow rate of 8 ml/min is
used at medium feed. Steep rise in roughness value at 11 ml/min of flow rate may be due to effect of chatter and vibration generated due to fixture misalignment. The lowest value of surface roughness is attained at low feed and speed of 1000 rpm under MQL condition due to efficient cooling and coolant penetration near the cutting area. The chips are getting flushed out properly with the application of pressurized cutting fluid which prevents rubbing of chips on work piece surface. But low feed operation is not advisable due to its higher machining cost, overhead charges and lesser productivity. Therefore, the intermediate cutting conditions are best favourable for optimum surface finish.

![BAC for Dry Machining](image1)

![BAC for Wet Machining](image2)

![BAC for MQL Conditions](image3)

**Figure 3.** Bearing area curves for different machining environment (The legends are numbered as per L₀ array cutting conditions).

3.2. Bearing Area Curve

When functional attributes are defined qualitatively by equivalent surface texture characteristics, the functionality-based performance of produced component can be projected and correlated [14]. The
Bearing area curve (BAC) is one of those parameters. It basically represents the amount of solid contact at different profile height. By analyzing this curve, we can decide the load bearing ability, wear resistance, plasticity index and lubricant retention properties. Figure 3a represents BAC for dry machining, the curves for medium and high cutting conditions provide better results. In wet machining also the curve no. 5 [Figure 3(b)] shows overall contact at various heights. But in MQL the best results are shown by curve no. 2 at intermediate feed and 300 ml/min. The comparative analysis is done at a speed of 2500 rpm for all machining environment as shown in Figure 4 which concludes that MQL provides best results under given cutting conditions. From the analysis it is clear that intermediate cutting conditions with MQL is providing optimum results.

Figure 4. Bearing area curves at same speed for different machining condition.

The surface topography provides the aesthetic value to the machined surface. We can discriminate somewhat by having a glance at it. Figure 5 provides the surface topography at 100 µm scale of the milled surface. It can be deduced from Figure 5(a) that pits are being formed at the surface due to the ploughing action of tool onto the work piece resulting in poor surface finish which is shown with the roughness profile. During wet machining rubbing action of excess coolant develops cutter marks on the surface [Figure 5(b)]. It is inferred from the Figure 5c that MQL provides good aesthetic surface with better surface finish.

3.3. Chip Morphology
Chips are an important factor in controlling surface finish. Therefore, they are studied to differentiate the machined surface. SEM is used to study the chips by generating high resolution images up to micron level. At low feed the chip segments are not closely held during dry machining [depicted by arrows in Figure 6(a)]. Furthermore, a larger saw tooth is noticed which indicates high cutting happening at machined area. But at higher feed value, chip segments are closely held [shown by arrows in Figure 6(c)] due to faster cutting action and dominance of shearing action against ploughing of work surface. Also, smaller notched tooth is obtained which results in better finish at higher feeds. During flood machining black color chips were produced depicting higher thermal stress being produced due to lack of penetration of lubricant at chip tool interface. In MQL machining the cutting temperature is significantly reduced thereby making the chips brittle and easy to break. Also, it facilitates minimum chip thickness which prevents the side flow and ploughing caused by chips generating good surface finish.
3.4. Statistical analysis of Surface Roughness

By means of ANOVA method, evaluation of machining parameters and their effects on surface roughness is studied. From this observation it is found that there is substantial contribution of the input factors on surface roughness. On the basis of values recorded during experiment final equations are derived using regression analysis taking individual and interactive effect into consideration [16]. These equations are used to calculate some predicted values and then they are compared with the recorded values. The equations to describe average surface roughness under dry, wet and MQL environment are as follows:

**Figure 5.** Surface topography of machined surface with their respective roughness profiles.
For dry machining,
\[ Ra = 0.225 + 175.1 \times f_z + 0.0005V_c - 3589 f_z \times f_z + 0.000036 V_c \times V_c - 2.61 f_z \times V_c \] .... (3)

For wet machining,
\[ Ra = 2.107 - 147.2 \times f_z - 0.0615 V_c + 3047 f_z \times f_z + 0.000474 V_c \times V_c - 2.61 f_z \times V_c \] .... (4)

For MQL conditions,
\[ Ra = 0.120 + 0.03101 V_c - 0.00446Q + 58.2 f_z - 0.00277 V_c \times V_c + 0.000005 Q \times Q - 1119 f_z \times f_z \] .......... (5)

where \( f_z \), \( V_c \) and \( Q \) are feed per tooth(mm/tooth), cutting velocity(m/min) and lubricant flow rate(ml/h) respectively. The significance of machining parameters is verified by using F-test in regression model using ANOVA with m no. of experimental factors and n no. of experiments at 95% level of significance. Tables 4, 5 and 6 represents the ANOVA analysis of surface roughness for different machining environment. The regression model with F-value more than 5.14 (95% confidence level) predicts that developed model is significant for all functions. Further, P-value lesser than 0.05 depicts that particular input response is having greater significance with 95% confidence [15].

| Source | DF | Adj SS | Adj MS | F-Value | P-Value |
|--------|----|--------|--------|---------|---------|
| Regression | 5  | 0.961764 | 0.192353 | 5.54 | 0.047 |
| \( f_z \) | 1  | 0.300720 | 0.300720 | 6.47 | 0.044 |
| \( V_c \) | 1  | 0.000022 | 0.000022 | 0.00 | 0.984 |
| \( f_z \times f_z \) | 1  | 0.171078 | 0.171078 | 3.68 | 0.151 |
| \( V_c \times V_c \) | 1  | 0.001464 | 0.001464 | 0.03 | 0.870 |
| \( f_z \times V_c \) | 1  | 0.256604 | 0.256604 | 5.52 | 0.100 |
| Error | 3  | 0.139513 | 0.046504 | | |
| Total | 8  |        |        | | |
Table 5. ANOVA for average surface roughness under wet machining.

| Source   | DF | Adj SS   | Adj MS   | F-Value | P-Value |
|----------|----|----------|----------|---------|---------|
| Regression | 5  | 0.64193  | 0.12839  | 8.79    | 0.052   |
| $f_z$     | 1  | 0.21250  | 0.21250  | 14.55   | 0.032   |
| $V_c$     | 1  | 0.38204  | 0.38204  | 6.15    | 0.094   |
| $f_z*V_c$ | 1  | 0.12328  | 0.12328  | 8.44    | 0.062   |
| $V_c*V_c$ | 1  | 0.24744  | 0.24744  | 6.94    | 0.066   |
| $f_z*V_c$ | 1  | 0.15565  | 0.15565  | 10.66   | 0.047   |
| Error     | 3  | 0.04382  | 0.01461  |         |         |
| Total     | 8  |          |          |         |         |

Table 6. ANOVA for average surface roughness under MQL condition.

| Source   | DF | Adj SS   | Adj MS   | F-Value | P-Value |
|----------|----|----------|----------|---------|---------|
| Regression | 6  | 0.53170  | 0.088616 | 13.81   | 0.049   |
| $V_c$     | 1  | 0.11032  | 0.110318 | 4.19    | 0.154   |
| $Q$       | 1  | 0.03525  | 0.035250 | 15.49   | 0.044   |
| $f_z$     | 1  | 0.12320  | 0.123196 | 19.20   | 0.048   |
| $V_c*V_c$ | 1  | 0.08644  | 0.086437 | 3.47    | 0.167   |
| $Q*Q$     | 1  | 0.05059  | 0.050591 | 7.88    | 0.087   |
| $f_z*V_c$ | 1  | 0.02495  | 0.024949 | 8.89    | 0.094   |
| Error     | 2  | 0.01283  | 0.006416 |         |         |
| Total     | 8  |          |          |         |         |

Clearly, it can be concluded that for dry and wet machining, feed has greater influence on surface roughness following which the interactive effect of quadratic term of feed effects the output response. In MQL, the flow rate has the highest weightage followed by feed rate. The error percentage between predicted and recorded values for wet, dry and MQL machining was found out to be 28.65%, 26.38% and 19.27% respectively. On the whole, we can say that MQL condition with intermediate machining parameters provide better surface characteristics thereby producing component of high functional performance.
4. Conclusion
The given Nimonic-263 alloy was machined under different environment of wet, dry and lubrication with different feed, speed and flow rate with constant depth of cut. The experimentation, modeling and statistical analysis of the outcomes has revealed the following conclusions:

1. The influence of machining conditions and environment has been recognized by numerical analysis with the help of analysis of variance (ANOVA) which tells that feed is the most influencing parameter when machining is done under dry and wet lubrication method whereas lubricant flow rate is most significant when machining is performed under MQL condition.
2. From the surface integrity analysis, it can be concluded that at intermediate cutting condition of feed value 20 mm/min and cutting speed of 47.12 mm/min under MQL flow rate of 8 ml/min desirable surface characteristics were obtained.
3. Average two-dimensional surface roughness (Ra) was brought down by 47% under MQL condition. It is because of the disintegration of lubricant into small particles which effectively penetrates to chip-tool interface. Also, the decline of cutting temperature facilitates better surface finish.
4. The bearing area curve (BAC) depicts that the load bearing ability, wear resistance is considerably high for medium feed under MQL conditions.
5. Chip morphological studies shows cutting process was less at medium and higher feed depicted by low saw tooth. This is because of less impact of tool at these parameters which enables smoother surface generation.
6. Lastly, closely held chip are formed at higher value of feed which facilitates better surface finish.

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