# Effects of the Tribological Behaviour of h-BN MQL Nano Cutting Fluid (NCF-MQL) on Turning Inconel 625

Chinmaya PADHY*,1, Pariniti SINGH[1]

*Corresponding author
[1]Center for Manufacturing Excellence, Dept. of Mechanical Engineering,
School of Technology, GITAM University,
Hyderabad, 502329, India,
padhy.gitam@gmail.com*, pariniti_singh@rediffmail.com

**Abstract:** *Minimum quantity lubrication (MQL) is currently a widely used lubricating technique during machining, in which minimum amount of lubricant in the form of mist is delivered to the machining interface, thus helps to reduce the negative effects caused to the environment and human health. Further, to enhance the productivity of machining process specifically for hard-to-cut materials, nano cutting fluid (suitably mixed nano materials with conventional cutting fluid) is used as an alternative method to conventional lubrication (wet) in MQL. In this study, h-BN nano cutting fluid was formulated with 0.1% vol. concentration of h-BN in conventional cutting fluid (Servo- 'S') for NCF-MQL technique and its tribological behaviors on machining(turning) performance of Inconel 625 were studied and compared with other lubricating conditions (dry, wet, MQL conventional). The tribological effects were analyzed in terms of tool wear analysis, chip morphology along with statistical analysis for machined surface and evolved cutting forces during machining. The optimal input machining parameters for experiments were defined by the use of Taguchi and Grey relational based multi response optimization technique. Finally, the tribological study shows that the use of h-BN NCF-MQL is a viable and sustainable option for improving machining performance of hard- to- cut material like Inconel 625.*

## 1. INTRODUCTION

Cutting fluids are one of the prime substances in today's manufacturing industries, that greatly affect the productivity during a machining process as they do influence performance parameters like-cutting force, machining temperature, tool wear and surface quality of the product. However, they are very much hazardous to environment and human health, which are associated with their use as well as their disposal. So, during investigation of other alternatives for use, a viable alternative has come across in between i.e. minimum quantity lubrication (MQL) technique, where minimal quantity of coolant/lubricant is directly fed at the cutting zones of tool and workpiece. MQL technique reduces the friction and machining temperature at the machining zone and hence improves the surface quality and life of the tool [1–3]. But with constant demand of high machining performance and

productivity, MQL requires further improvement to meet challenges in machining efficiency sought for machine hard-to-cut materials e.g. Inconel, Monel, Super-alloys etc. Many researchers [4-9] in the past studied MQL forms of different lube oils as cutting fluid and found suitable for machining.

Hwang et al. [4] investigated use of graphite nanoparticles as additive in mineral oil and found that nano graphite that reduced the friction caused by preventing direct contact between frictional surfaces. Huang et al. [5] observed that anti-wear property of paraffin oil could be improved by addition of graphite nanosheets as additives. Nam et al. [6] investigated nano diamond particles in vegetable-based oils and it was observed that addition of nano diamond particles significantly reduces the cutting forces during machining. Shen et al. [7] evaluated the performance of $MoS_2$ nano particles grinding fluid and compared its performance to those of paraffin oil and soybean oil where the results showed that $MoS_2$ nano fluid improves the machining performance by reducing the friction generated and machining forces as well.

Lee et al. [8] observed that NFMQL improves the drilling operation by increasing the number of drilled holes, reducing thrust forces. Sharma et al. [9] investigated the effects of carbon nanotubes NF-MQL on turning (AISI) D2 steel and they have concluded that NF-MQL showed improved thermal conductivity and surface integrity over conventional lubrication. The effect of $Al_2O_3$ and CuO MQL-nano fluid in grinding of Ti–6Al–4V was investigated by Setti et al. [10] and significant reduction in friction and machining temperature was observed. Discussed literatures revealed that nano cutting fluids show better machining performance in comparison to conventional cutting fluids. Recently, many researchers have proved that boron nitride is also a justifiable option as additive to enhance the properties of cutting fluid. Charoo and Wani [11] observed commendable tribological performance for nano hexagonal boron nitrate (h-BN) oil lubricants as experimental investigation showed lower friction coefficient and tool wear. Qingming Wan et al. [12] also synthesized boron nitride nano lubricant and found that nano BN oil is stable and also shows better anti-frictional and anti-wear characteristics. Cho et al. [13] investigated lubricating effects of h-BN nano particles dispersed in water and found that dispersion of h-BN nano particles improves tribological properties and it <u>is</u> a sustainable lubricant additive. Çelik et al. [14] experimented and observed that the addition of h-BN nanoparticles improves the friction coefficient and decreases the wear rate of tool. Paul and Ghosh [15] studied the effect h-BN nano-aerosol in grinding and found that h-BN nano cutting fluid improves the heat dissipation and has better lubricating property than soluble oil aerosol.

In the past literatures, not much research has been done to the study of machining effect of nano-BN solution with titanium alloys. In this paper, an effort has been made to prepare the h-BN nano cutting fluid of 0.1 % vol. concentration of h-BN using calculated amount of Servo 'S' emulsion conventional cutting fluid [16, 17] and then an experimental investigation has carried out to study the effect of tribological behavior of h-BN NCF - MQL on its machining (turning) performances. For experimental analysis turning operation is chosen on hard to cut alloy of Nickle-Inconel 625 under various lubricating conditions (dry, wet, MQL conventional and h-BN NCF-MQL). The optimal machining parameters are defined by Taguchi and Grey relational analysis and observations were recorded-tabulated-studied for tool wear, chip formation and statistical analysis of cutting forces and surface roughness were calculated by using analysis of variance (ANOVA) and response surface method (RSM). Fig. 1 shows the complete process chart of research methodology followed for the experimental analysis.
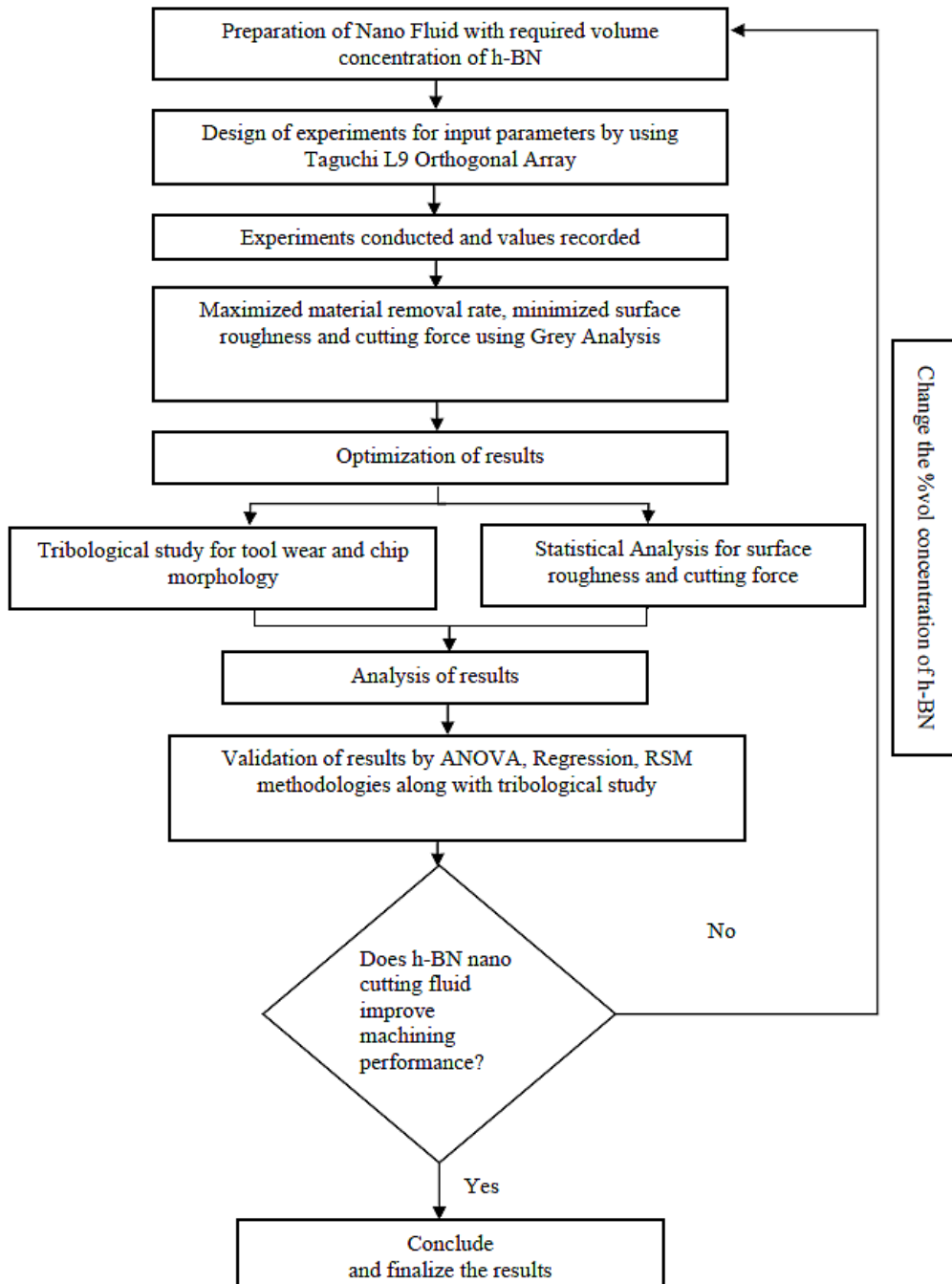
Fig. 1 Research methodology followed for experimental analysis

## 2. PREPARATION OF h-BN NANO CUTTING FLUID

Hexagonal-BN has similar structure like graphite(lamellar) and is a viable green option as an additive for enhancing the lubricating properties of base fluid [11, 18]. BN nano cutting fluid was prepared by mixing BN powder of average particle size of 70-80 nm (provided

by nanoshel, India). The details of BN nano powder used for synthesis are listed in table 1. The fluid sample was prepared with 0.1% vol. concentration of h-BN nano particles [19].

The prepared nano solution was added to conventional cutting fluid (Servo cut 'S') in required quantity (95% nano fluid and 5% concentrate conventional cutting fluid) to obtain nano cutting fluid concentration.

Table 1. Details of Supplied Boron Nitride Nano Powder

| Physical properties of Boron Nitride | |
|---|---|
| Molecular formula | BN |
| Molar mass | 24.82 gm/mol |
| Appearance | White powder |
| Density | 2.29 gm/cm$^3$ |
| Melting point | 2973$^\circ$C |
| Solubility in water | Insoluble |
| Crystal structure | Hexagonal |

The Inconel 625 workpiece is considered for experimentation. With properties like high temperature mechanical strength, improved corrosion resistance etc., Inconel 625 has wide applications. Being an established super alloy, it has the property of rapid work hardening and low heat conductivity which accompany its machining difficulty with generation of high cutting forces and temperature.

The compositional details and physical properties of Inconel 625 are listed in table 2 and 3, respectively. The experimental trials were conducted with work piece of dimensions (diameter- 30mm, Length-210mm) and using PVD coated carbide Korloy insert -model: PC9030, designation: CCMT09T308 on NAGMATI 175 model lathe with maximum cutting speed 1200 rpm, motor 3HP.

Table 2. Chemical Composition of Inconel 625

| C | Mn | S | Si | Cr | Fe | Mo | Co-Ta | Ti | Al | P | Ni |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.05 | 0.3 | 0.003 | 0.25 | 20-23 | 4 | 9 | 3.5 | 0.3 | 0.3 | 0.15 | Balance |

Table 3. Physical Properties of Inconel 625

| Alloy | Density | Melting Point | Tensile Strength | Brinell Hardness |
|---|---|---|---|---|
| Inconel 625 | 8.4g/cm$^3$ | 1290 - 1350 | 760 N/mm2 | < 220 HB |

## 3. DESIGN OF EXPERIMENTS

The initial step is to formulate the experiments and define optimal input parameter at which the experiments with varying lubrication methods were to be run. This was done using Taguchi design of experiments for the machining parameters and their levels (refer to table 4). The Taguchi's L9 orthogonal array was used to define the number of trials. The trials were performed with dry machining; each of experimental trial was replicated thrice and

average response values were considered for further study. Details of the test results are tabulated in table 5.

Table 4. Machining parameters with experimental design and their results

| Factors | Units | Levels | | |
|---|---|---|---|---|
| Cutting Speed | m/min | 42 | 60 | 108 |
| Feed | mm/rev | 0.1 | 0.2 | 0.3 |
| Depth of Cut | mm | 0.25 | 0.5 | 0.75 |

For evaluating optimal solution by grey relational approach, different machining performances as experimental results (cutting force, surface roughness, material removal rate) were at first normalized and then grey relational coefficient was calculated from the normalized values for expressing relationship between the desired and actual experimental data. It is an eminent fact that lower the value of cutting forces and surface roughness along with higher value of material removal rate results into improved machining performance. Hence, for efficient machining operation with Grey model "larger-the-better" (LB) is featured for material removal rate and "smaller the- better" (SB) for cutting forces and surface roughness.

The surface roughness and cutting forces performance characteristics must be minimized, hence signal to noise ratio $(\frac{S}{N})$ is expressed as in equation (1) and for material removal rate is expressed as in equation (2). For formulating grey relation grade, normalization of S/N ratio is done, for converting the random input data to a comparable form. Linear normalization of this ratio lies between zero and one, and is known as the grey relational generation [20]. Table 6 shows the calculated S/N ratio for the set of experimental results.

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

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

where, $y_{ij}$ is the observed experimental value, n is the number of experiments. Further the grey relational coefficient (GRC)is calculated and is expressed as in equation (3),

$$\gamma\big(x_0\,(k), x_i(k)\big) = \frac{(\Delta min + \xi\Delta max)}{(\Delta_{oi}\,k + \xi\Delta max)} \tag{3}$$

where, $k$ is the response for $i^{th}$ experiment and $\Delta min$ is the smallest value of $\Delta_{oi}(k)$ and $\Delta max$ is the largest value of $\Delta_{oi}(k)$.

The $\xi$ is the distinguishing coefficient and it is generally defined in the range zero to one [21], for current study the distinguishing factor is taken as 0.5. Next step was to determine grey relation grade [GRG]. The complete multiple performance evaluation is grounded on the grey relational grade which is mean sum of grey relational coefficients [22] as expressed in equation (4). Referring to table 7 it is seen that experiment 6 has the highest grey.

$$\gamma(x_0\,, x_i) = \frac{1}{m}\,\gamma\big(x_0\,(k), x_i(k)\big) \tag{4}$$

where, $\gamma(x_0, x_i)$ is the grey relational grade.

The effect of cutting speed(v), feed rate(f) and depth- of- cut(d) on cutting forces (Fc), surface roughness (Ra), material removal rate (MRR) on machining of Inconel 625 was observed and analyzed.

Table 5 shows the detailed experimental results pertaining to set of input machining parameters as per Taguchi L9 orthogonal array.

Table 5. Values of response variables attained with Taguchi L9 array machining parameters

| Trial No | Machining Parameters | | | Average Response Values | | |
|---|---|---|---|---|---|---|
| | Cutting Speed (m/min) | Feed Rate (mm/rev) | Depth-of-Cut (mm) | Cutting Forces Fc (N) | Surface Roughness Ra (μm) | Material Removal Rate (MRR) |
| 1 | 42 | 0.1 | .25 | 230 | 1.63 | .126 |
| 2 | 42 | 0.2 | .5 | 195 | 1.25 | .252 |
| 3 | 42 | 0.3 | .75 | 300 | 1.13 | .270 |
| 4 | 60 | 0.1 | .5 | 240 | 1.01 | .380 |
| 5 | 60 | 0.2 | .75 | 220 | .663 | .712 |
| 6 | 60 | 0.3 | .25 | 340 | .998 | .786 |
| 7 | 108 | 0.1 | .75 | 215 | 1.255 | .860 |
| 8 | 108 | 0.2 | .25 | 265 | .865 | .918 |
| 9 | 108 | 0.3 | .5 | 235 | .834 | 1.14 |

The S/N ratio for each of the response variables (cutting force, surface roughness and material removal rate) are tabulated below in table 6. Further, the grey relational coefficient was calculated using Eq. 3 and as equal weightage is given to all process parameters, the coefficient ζ is taken as 0.5.

Next, the grey relational grade was calculated by Eq. 4 for each set of L9 orthogonal array (refer to table 7). Higher grey relational grade attained for set of input machining parameter showed that the corresponding S/N ratio was nearer to the ideal normalized S/N ratio. It was observed that experiment 6 has maximum value of grey relational grade, and hence, has best experimental set of input parameters for multiple performance in machining of Inconel 625.

Table 6. The S/N ratio for the set of experimental results

| Experiment No. | S/N ratio Cutting Force (SB) | S/N ratio Surface Roughness (SB) | S/N ratio Material Removal Rate (LB) |
|---|---|---|---|
| 1 | -47.2 | -4.24 | -17.9 |
| 2 | -45.8 | -1.93 | -11.9 |
| 3 | -49.54 | -1.06 | -11.3 |
| 4 | -47.6 | -0.08 | -8.4 |
| 5 | -46.8 | 3.6 | -2.9 |
| 6 | -50.6 | 0.01 | -2.09 |
| 7 | -46.6 | -1.97 | -1.3 |
| 8 | -48.4 | 1.25 | -0.74 |
| 9 | -49.0 | 1.57 | -1.13 |

Table 7. Grey relational coefficients and grade

| Experiment No. | GRC Cutting Forces | GRC Surface Roughness | GRC Material Removal Rate | Grey Relation Grade GRG | Rank |
|---|---|---|---|---|---|
| 1 | .413 | 1 | .332 | .581 | 5 |
| 2 | .333 | .476 | .436 | .415 | 9 |
| 3 | .694 | .398 | .450 | .514 | 7 |
| 4 | .444 | .335 | .539 | .439 | 8 |
| 5 | .387 | .766 | .822 | .658 | 3 |
| 6 | 1 | .33 | .897 | .742 | 1 |
| 7 | .377 | .480 | .833 | .563 | 6 |
| 8 | .528 | .445 | .956 | .602 | 4 |
| 9 | .606 | .440 | 1 | .682 | 2 |

Further the tribological behaviors like tool wear, chip morphology, surface rough ness and cutting forces were obtained during machining of Inconel 625 under different working conditions (i.e. dry, wet, MQL conventional and h-BN NCF-MQL lubricating conditions) were studied.

Statistical analysis for response factors - machining force and surface roughness are performed by using MINITAB 18.0 (a statistical tool software).

## 4. TRIBOLOGICAL STUDY

Machining performance is significantly affected by lubricating condition which includes both selection of an appropriate lubricant and its application technique. The lubrication environment affects the overall machining efficiency by reducing premature tool failures and hence increasing the tool life.

Thus, it's essential to study and investigate tribological behavior under varied lubricating conditions.

The tribological study shows how surfaces in contact with each other interact within a lubricating environment. Fig. 2 shows the experimental setup during NCF-MQL machining.
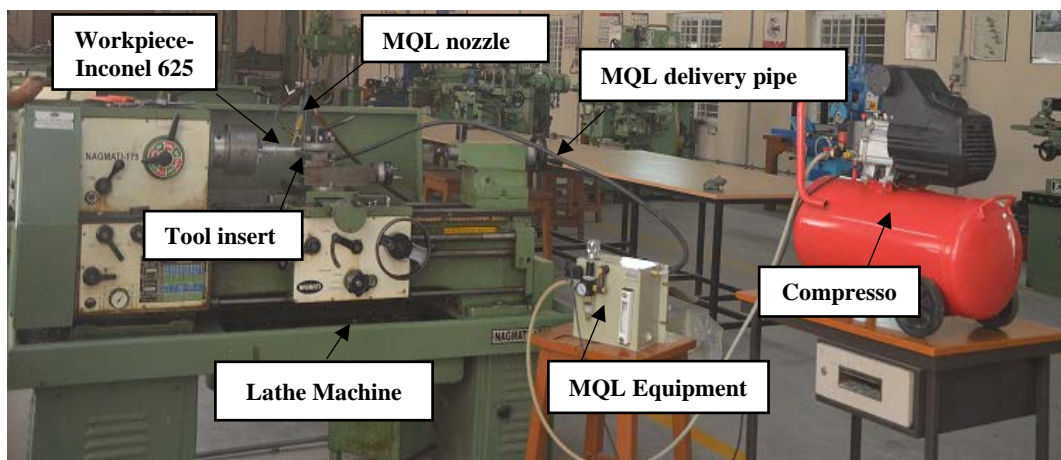


Fig. 2 Actual setups for NCF-MQL machining

### 4.1 Tool Wear

Tool wear is unwanted detonation of cutting tool which results in lowering of machining precision.

There are various types of wear caused due to lubricating condition, type of cutting tool and workpiece material [23] and the major factor that contributes to tool wear/failure is the elevated machining temperature [24].

Tool wear continuously impacts the geometry of tool, machining temperature, cutting forces and surface roughness of work piece. The tool wear might occur on flank or rake face.

This paper analyzes the tool wear patterns for PVD coated carbide tool (Korloy insert -model: PC9030) with tool geometry as shown in fig. 3 during turning Inconel 625 under different lubricating conditions, where various wear patterns were observed and analyzed viz. abrasion, notching, plastic deformation and grooving.



Specifications (mm)
l - 8.8
d - 9.5          Rhombic-80$^0$
t - 3.9          Relief angle-7$^0$
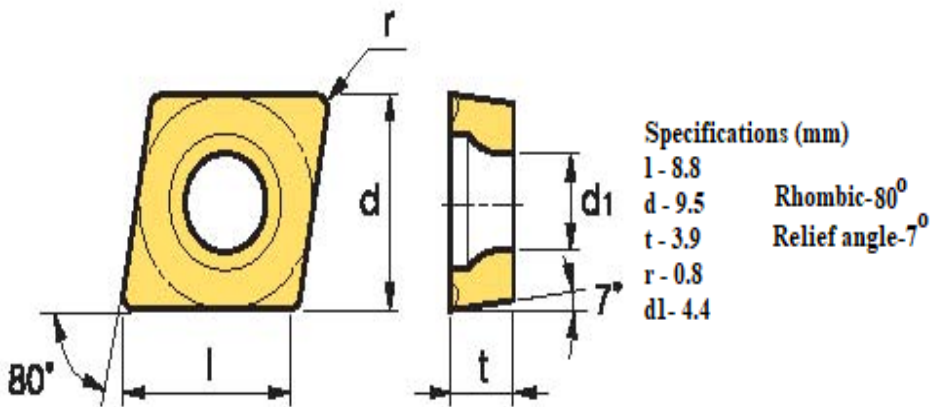r - 0.8
dl- 4.4

Fig. 3 Tool insert geometry

The tool wear images during turning of Inconel 625 at optimal machining parameters (cutting speed of 60 m/min and a feed rate of 0.3 mm/rev and depth-of-cut as 0.25 mm) were taken by Rapid – I microscope.

Due to inefficient cooling and intense rubbing, the machining zone deteriorates the tool surface leading the contact area to increase and form a notch caused due to sharp rise in temperature as shown in fig. 4 (a).

Due to inefficient cooling the variation in temperature causes surface cracks and eventually leads to abrasion that occurs at the flank edge and causes ripping of tool parts or notch formation thus leading to tool failure, refer fig. 4 (a) and fig. 4 (e) shows the tool wears at cutting edge for dry and MQL machining respectively causing poor surface finish as well as wears out tool at a higher rate.

Notch formation is dominant in dry and MQL conventional whereas h-BN NMQL causes plastic deformation and adhesion at cutting edge, refer to fig. 4 (g).

For crater wear in dry cutting, refer to fig 4 (b) which shows chip adhesion, fracture and grooving as main wear due to the flow of chips at high temperature thus exacerbating the rake face.

Similar wear of rake surface was observed in MQL conventional, refer to fig. 4 (f) and h-BN NMQL but the impact of grooving was much less in h-BN NMQL, refer to fig. 4 (h).
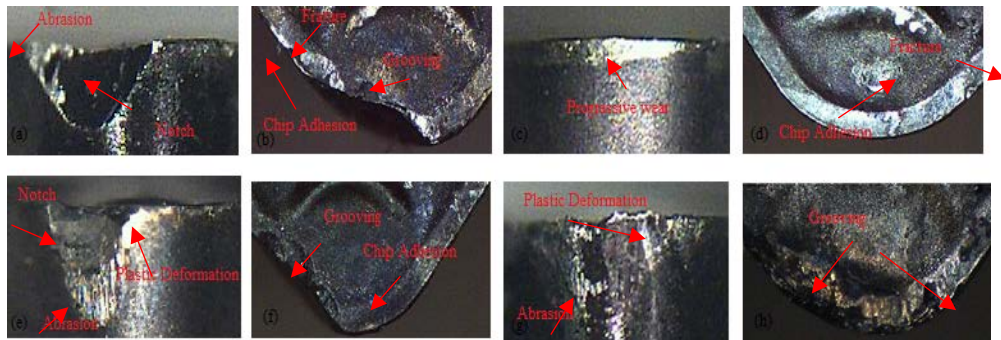
Fig. 4 Tool wear analysis for (a-b) dry, (c-d) wet, (e-f) MQL with conventional metal working fluid, (g-h) MQL h-BN nano metal working fluid

## 4.2 Chips Morphology

Chips from different machining environment (refer fig. 5) were analyzed, and it was observed that: chips under dry machining were more twisted, overlapped and dark, due to the surface burns caused by high machining temperature. The chips obtained from MQL conventional cutting appeared with minor darkness of burnt but were of irregular shape whereas, in conventional (Wet) and h-BN NCF-MQL chips were observed to be regular shaped and burnt free. Also, it has been noticed that the chips coming out from h-BN NCF-MQL machining were more segmented than others. This proves that the machining with h-BN nano fluid reduces the machining temperature as well as provides better interaction of chip and tool.
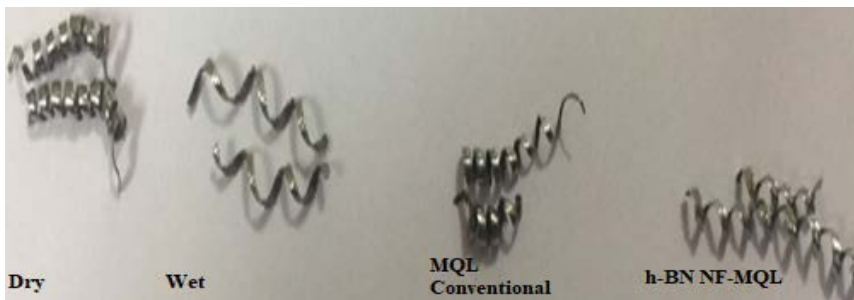


Fig. 5 Chips attained for various modes of lubrication

# 5. STATISTICAL ANALYSIS TO STUDY EFFECT OF h-BN NCF-MQL ON SURFACE ROUGHNESS AND CUTTING FORCES

## 5.1 ANOVA and Regression analysis

The predictive model was developed for comparison between MQL and h-BN NCFMQL. From pertained experimental results of Taguchi L9 orthogonal array (refer table 8), regression analysis for Fc and Ra were established (refer table 9 and table 10) which shows the regression model and equations for the NCFMQL and MQL (cutting force and surface roughness) respectively. The ANOVA analysis for cutting forces and surface roughness under MQL and h-BN NCFMQL model was established, refer table 11 and table 12 respectively. It has been seen that the values of R sq. (coefficient of determination) in both cases - cutting force as well as surface roughness were close to 100% showing that data were closely fitting the regression line.

Table 8. Machining parameters with L9 orthogonal array and their results in turning of Inconel 625

| Trial No | Cutting Speed (m/min) | Feed Rate (mm/rev) | Depth of Cut (mm) | MQL Cutting Forces Fc (N) | h-BN NCF-MQL cutting force Fc (N) | MQL Surface Roughness Ra (MQL) (µm) | h-BN NCF-MQL Surface Roughness Ra (µm) |
|---|---|---|---|---|---|---|---|
| 1 | 42 | 0.1 | .25 | 228 | 176 | 1.53 | .52 |
| 2 | 42 | 0.2 | .5 | 247 | 185 | 1.17 | .80 |
| 3 | 42 | 0.3 | .75 | 265 | 198 | .93 | .86 |
| 4 | 60 | 0.1 | .5 | 230 | 181 | 1.2 | .68 |
| 5 | 60 | 0.2 | .75 | 251 | 192 | .58 | .77 |
| 6 | 60 | 0.3 | .25 | 266 | 208 | .86 | 1.03 |
| 7 | 108 | 0.1 | .75 | 258 | 195 | 1.08 | .56 |
| 8 | 108 | 0.2 | .25 | 277 | 210 | .82 | .90 |
| 9 | 108 | 0.3 | .5 | 295 | 225 | .79 | 1.08 |

Table 9. Regression Model (in terms of actual factors)

| MQL Conventional | Fc (N) | 257.444-10.778 Cutting Speed (m/min)_42-8.444 Cutting Speed (m/min)_60+ 19.222 Cutting Speed (m/min)_108-18.778 Feed Rate (mm/rev)_0.1+0.889 Feed Rate (mm/rev)_0.2+17.889 Feed Rate (mm/rev)_0.3-0.444 Depth of Cut (mm)_0.25-0.111 Depth of Cut (mm)_0.50+0.556 Depth of Cut (mm)_0.75 |
|---|---|---|
| | Ra (µm) | 0.9956+0.2144 Cutting Speed (m/min)_42-0.1156 Cutting Speed (m/min)_60-0.0989 Cutting Speed (m/min)_108+0.2744 Feed Rate (mm/rev)_0.1-0.1389 Feed Rate (mm/rev)_0.2-0.1356 Feed Rate (mm/rev)_0.3+0.0744 Depth of Cut (mm)_0.25+0.0578 Depth of Cut (mm)_0.50-0.1322 Depth of Cut (mm)_0.75 |
| h-BN NMQL | Fc (N) | 197.000-10.67 Cutting Speed (m/min)_42-3.33 Cutting Speed (m/min)_60+14.00 Cutting Speed (m/min)_108-13.00 Feed Rate (mm/rev)_0.1-1.33 Feed Rate (mm/rev)_0.2+14.33 Feed Rate (mm/rev)_0.3+1.00 Depth of Cut (mm)_0.25+1.00 Depth of Cut (mm)_0.50-2.00 Depth of Cut (mm)_0.75 |
| | Ra (µm) | 0.80000-0.07333 Cutting Speed (m/min)_42+0.02667 Cutting Speed (m/min)_60+0.04667 Cutting Speed (m/min)_108-0.21333 Feed Rate (mm/rev)_0.1+0.02333 Feed Rate (mm/rev)_0.2+0.19000 Feed Rate (mm/rev)_0.3+0.01667 Depth of Cut (mm)_0.25+0.05333 Depth of Cut (mm)_0.50-0.07000 Depth of Cut (mm)_0.75 |

Table 10. Regression Equations for NMQL and MQL responses cutting force and surface roughness

| Regression Equation | | |
|---|---|---|
| NMQL | Fc (N) | 148.50+0.3548 Cutting Speed (m/min) + 131.67 Feed Rate (mm/rev) - 6.00 Depth of Cut (mm) |
| | Ra (µm) | 0.376+0.001529 Cutting Speed (m/min) + 2.017 Feed Rate (mm/rev) - 0.173 Depth of Cut (mm) |

| MQL | Fc (N) | 186.20 + 0.4797 Cutting Speed (m/min) + 183.3 Feed Rate (mm/rev) + 2.00 Depth of Cut (mm) |
|---|---|---|
| | Ra (µm) | 1.871 - 0.00370 Cutting Speed (m/min) - 2.050 Feed Rate (mm/rev) - 0.413 Depth of Cut (mm) |

Table 11. ANOVA table for MQL and NCF-MQL for cutting forces

| Sources | DF | MQL | | | | h-BN NCF-MQL | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Adj SS | Adj MS | F-Value | P-Value | Adj SS | Adj MS | F-Value | P-Value |
| Cutting Speed (m/min) | 2 | 1670.89 | 835.44 | 1074.14 | 0.001 (Significant) | 962.67 | 481.333 | 76 | 0.013 (Significant) |
| Feed Rate (mm/rev) | 2 | 2020.22 | 1010.11 | 1298.71 | 0.001 (Significant) | 1128.67 | 564.333 | 89.11 | 0.011 (Significant) |
| Depth of Cut (mm) | 2 | 1.56 | 0.78 | 1 | 0.5 (Not Significant) | 18 | 9 | 1.42 | 0.413 (Not Significant) |
| Error | 2 | 1.56 | 0.78 | | | 12.67 | 6.333 | | |
| Total | 8 | 3694.23 | | | | 2122 | | | |
| S | | 0.881917 | | | | 2.51661 | | | |
| R-sq | | 99.96% | | | | 99.40% | | | |
| R-sq(adj) | | 99.83% | | | | 97.61% | | | |
| R-sq(pred) | | 91.50% | | | | 87.91% | | | |

Table 12. ANOVA table for MQL and NCF-MQL for surface roughness

| Sources | DF | MQL | | | | h-BN NCF-MQL | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Adj SS | Adj MS | F-Value | P-Value | Adj SS | Adj MS | F-Value | P-Value |
| Cutting Speed (m/min) | 2 | 0.207356 | 0.103678 | 25.85 | 0.037 Significant | 0.0248 | 0.0124 | 28.62 | 0.034 Significant |
| Feed Rate (mm/rev) | 2 | 0.338956 | 0.169478 | 42.25 | 0.023 Significant | 0.246467 | 0.123233 | 284.38 | 0.004 Significant |
| | 2 | 0.079089 | 0.039544 | 9.86 | 0.092 | 0.24067 | 0.12033 | 27.77 | 0.035 |

| Depth of Cut (mm) | | | | Not Significant | | | | Significant |
|---|---|---|---|---|---|---|---|---|
| Error | 2 | 0.008022 | 0.004011 | | 0.000867 | 0.000433 | | |
| Total | 8 | 0.633422 | | | 0.2962 | | | |
| S | | 0.0633333 | | | 0.0208167 | | | |
| R-sq | | 98.73% | | | 99.71% | | | |
| R-sq(adj) | | 94.93% | | | 98.83% | | | |
| R-sq(pred) | | 74.35% | | | 94.07% | | | |

### 5.2 Effect of lubricating conditions on machining

It is important to study the effect of different lubricating condition while machining. The machining parameters (speed, feed and depth-of-cut) from different lubricating conditions play an important role in order to find the surface quality of the product. Thus, it is wise to have a relational model among them to analyze the effects on quality. Therefore, from the above two predictive models (MQL and h-BN NCFMQL) a study was conducted for the changes of variation of cutting forces and surface roughness by using surface plotter with the help of Minitab software.

Different surface plots of force vs (speed, feed), force vs (speed, depth-of-cut), force vs (feed, depth-of-cut) were plotted (refer figure 6 (a-b-c-d-e-f)) to see the potential relationships between force and (speed, feed and depth-of-cut), similarly graphs (refer figure 7 (a-b-c-d-e-f)) for surface roughness were plotted. The cutting forces were analyzed from the surface plot and it was noticed that cutting forces have reduction tendency with the rise in cutting speed and decrease in feed rate, refer fig. 6 (a-b-c) for MQL and fig. 6 (d-e-f) for NCFMQL. Further from surface roughness plots, the surface plot for MQL refer fig. 7 (a-b-c), show the rise in surface roughness with increase in feed rate and cutting speed. However, for h-BN NCFMQL refer fig. 7 (d-e-f), the surface roughness increases with feed rate but decreases with decrease in cutting speed.
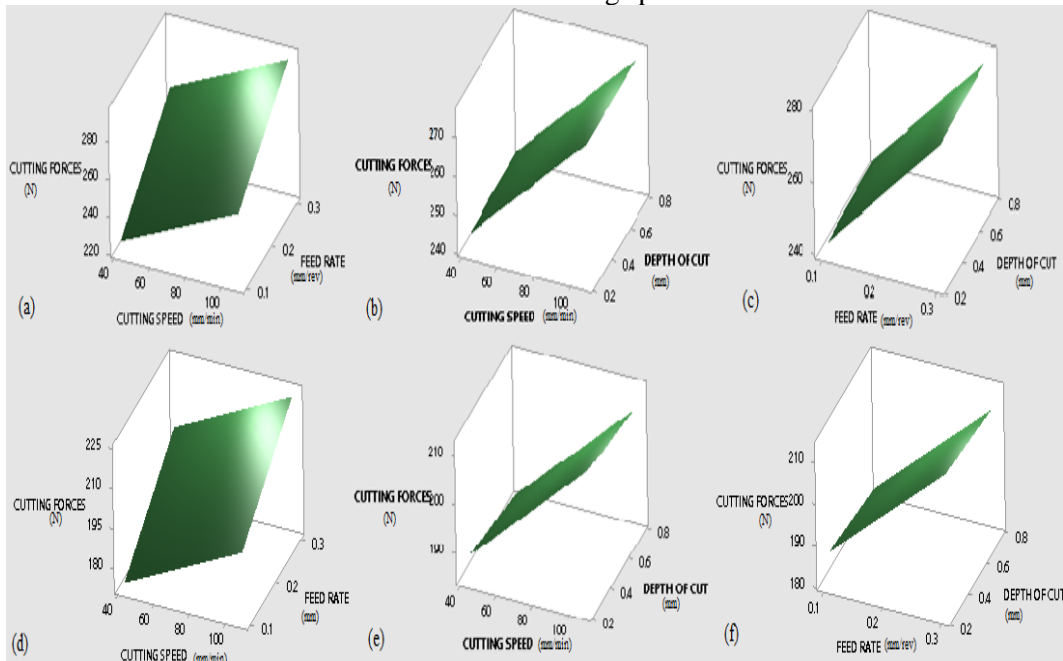


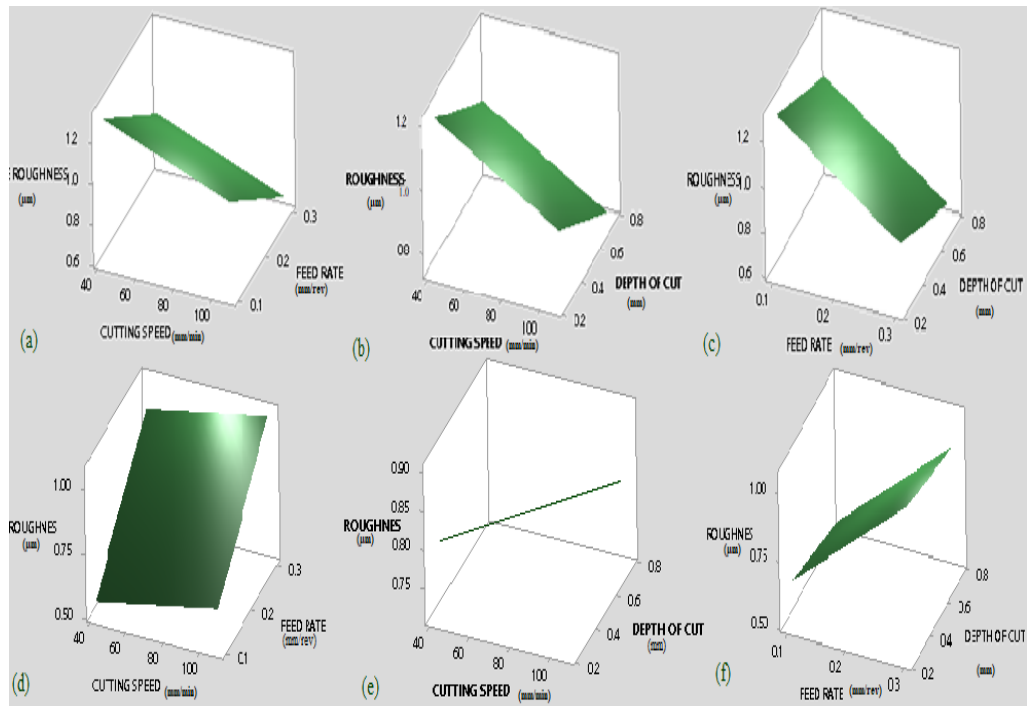Fig. 6 Effect on cutting forces under MQL-(a), (b), (c); h-BN NCF-MQL (d), (e), (f)

Fig. 7 Effect on surface roughness under MQL-(a), (b), (c); h-BN NCF-MQL-(d), (e), (f)

## 6. CONCLUSIONS

This paper concludes that in the machining of Inconel 625 using MQL technique, the addition of h-BN nano particles in conventional cutting fluid (mixture of Servo cut 'S' lube oil and water) provides better tribological performances (reduction in tool wear, cutting force & surface roughness along with improved chip morphology). To summarize the results, following inferences were drawn based on the attained results as discussed in above sections:

➢ Tool Wear

1. Notch formation and abrasion - Notch formation and abrasion were found to be dominant in dry and MQL conventional machining. However, in case of h-BN NCF-MQL and wet lubrication., there was minimal formation of notch and abrasion wear in tool was also significantly less, which implies the superiority of NCF-MQL.
2. Groove formation - Number of grooves formed at the cutting faces were very small in the case of NCF-MQL as compared to dry machining.
3. Plastic deformation - Fewer traces of plastic deformation of tool cutting edge were seen in h-BN NCF- MQL technique compared to MQL conventional method.

➢ Chip Morphology

1. Chip formation in case of h-BN NCF-MQL exhibited significant improvement owing to reduced machining interface temperature and more interaction of chip with tool. The chips formed under both wet and NCF-MQL conditions were burn free and segmented unlike dry and MQL conditions.

> ➤ Statistical analysis between predictive models (h-BN NCF-MQL Vs Conventional MQL)

　　1. Machining results indicate that, there is a significant improvement (on an avg. of 14 % and 24%) in the values of surface roughness and cutting forces by using h-BN NCF-MQL machining environment as compared to conventional MQL.

　　2. Cutting forces - Statistical analysis showed that cutting force increased with cutting speed and feed rate for both h-BN NCF-MQL as well as conventional MQL. Depth-of- cut(d) shows having not much impact on cutting forces.

　　3. Surface Roughness - The response plots achieved during statistical analysis for surface roughness showed that the feed rate and cutting speed impacted the surface roughness significantly and were directly proportional to the increase of these values. However, depth-of-cut (d) displayed some marginal effect on the surface roughness for h-BN NCF-MQL lubricating condition, while it is insignificant in the case of the conventional MQL.

　　4. From ANOVA analysis it is clear that the values of R sq. (coefficient of determination) are close to 100% in both cases - cutting force as well as surface roughness showing that the data are closely fitting the regression line, which shows that developed equation modes will give the satisfactory response values.

## REFERENCES

[1] M. M. A. Khan, M. A. H. Mithu, N. R. Dhar, Effects of minimum quantity lubrication on turning AISI 9310 alloy steel using vegetable oil-based cutting fluid, *J Mater Process Technol.*, Vol. **209**, no.15–16, pp. 5573–5583, 2009.

[2] E. A. Rahim, H. Sasahara, A study of the effect of palm oil as MQL lubricant on high speed drilling of titanium alloys, *Tribol. Int.*, Vol. **44**, no. 3, pp. 309–317, 2011.

[3] Y. Kamata, T. Obikawa, High speed MQL finish- turning of Inconel 718 with different coated tools, *Journal of Materials Processing Technology*, vol. **192**, pp.281-286, 2007.

[4] Y. J. Hwang, C. G. Lee, Y. M. Choi, An Investigation on Tribological Properties and Lubrication Mechanism of Graphite Nanoparticles as Vegetable Based Oil Additive, *Science and Technology*, Vol. **25**, no. 11, pp. 2853–2857, 2011.

[5] H. D. Huang, J. P. Tu, L. P. Gan, and C. Z. Li, An investigation on tribological properties of graphite nanosheets as oil additive, *Wear*, vol. **261**, no. 2, pp. 140–144,2006

[6] J. S. Nam, P. H. Lee, S. W. Lee, Experimental characterization of micro-drilling process using nanofluid minimum quantity lubrication, *International Journal of Machine Tools and Manufacture*, Vol. **51**, pp. 649-652, 2011.

[7] B. Shen, A. P. Malshe, P. Kalita, A. J. Shih, Performance of novel MoS2 nanoparticles-based grinding fluids in minimum quantity lubrication grinding, *Transactions of NAMRI/SME*, Vol. **36**, pp. 357–364, 2008.

[8] Pil-Ho Lee, J. S. Nama, S. W. Lee, Experimental characterization of micro-drilling process using nanofluid minimum quantity lubrication, *International Journal of Machine Tools and Manufacture*, Vol. **51**, no. 7–8, 649-652, 2011.

[9] P. Sharma, B. S. Sindhu, J. Sharma, Investigation of effects of nanofluids on turning of AISI D2 steel using minimum quantity lubrication, *Journal of Cleaner Production*, Vol. **108**, Part A, 72-79, 2015.

[10] D. Setti, M. Kumar, S. S. Ghosh, V. R. Paruchuri, Performance evaluation of Ti-6Al-4V grinding using chip formation and coefficient of friction under the influence of nanofluids, *International Journal of Machine Tools and Manufacture*, Vol. **88**, 237-248, 2015.

[11] M. S. Charoo, M. F. Wani, Tribological properties of h-BN nanoparticles as lubricant additive on cylinder liner and piston ring, *Lubrication Science*, Vol. **29**, no 4, 241-254, 2017.

[12] Q. Wan, Y. Jin, P. Sun,Y.g Din, Tribological behaviour of a lubricant oil containing boron nitride nanoparticles, *Procedia Engineering*, Vol. **102**, pp.1038 – 1045, 2015.

[13] D. H. Cho, J. S. Kim, S. H. Kwon, C. Lee, Y. Z. Lee, Evaluation of hexagonal boron nitride nano-sheets as a lubricant additive in water, *Wear*, Vol. **302**, pp. 981–986, 2013.

[14] O. N. Çelik, N. Ay, Y. E Göncü, Effect of nano hexagonal boron nitride lubricant additives on the friction and wear properties of AISI 4140 steel, *Part. Sci. Technol*, Vol. **31**, pp. 501–506, 2013.

[15] S. Paul, A. Ghosh, Grinding of WC-Co cermets using hexagonal boron nitride nano-aerosol, *International Journal of Refractory Metals and Hard Materials*, Vol. **78**, pp. 264-272, 2019.

[16] S. Khandekar, M. R. Sankar, V. Agnihotri, and J. Ramkumar, Nano-Cutting Fluid for Enhancement of Metal Cutting Performance, *Materials and Manufacturing Processes*, Vol. **27**, pp. 1–5, 2012.

[17] S. Chinchanikar, A. V. Salve, P. Netake, A. More, S. Kendre, R. Kumar, Comparative evaluations of surface roughness under dry and water based and vegetable oil-based cutting fluid, *Procedia Materials Science*, Vol. **5**, pp. 1966 – 1975, 2014.

[18] A. Lipp, K. A. Schwetz, K. Hunold, Hexagonal Boron Nitride: Fabrication, Properties and Applications. *J Eur Ceram Soc*, Vol. **5**, no. 1, pp. 3-9, 1989.

[19] P. Singh, and C. P. Padhy, Study on the rheological properties of h-BN nano cutting fluid in MQL machining of Inconel 625, *i-manager's Journal on Material Science*, Vol. **6**, no. 4, pp. 59-66, 2019.

[20] C. C. Tsao, Grey- Taguchi method to optimize the milling parameters of alluminium alloy, *Int J Adv Manuf Technol*, Vol. **40**, 41-18, 2009.

[21] K.W. Ng. David, Grey system and grey relational model, *ACM SIGICE Bulletin*, Vol. **20**, no. 2, pp. 1–9, 1994.

[22] J. L. Lin, K. S. Wang, B. H. Yan, Y. S. Tarng, Optimization of the electrical discharge machining process based on the Taguchi method with fuzzy logics, *J Mater Process Technology*, Vol. **102**, pp. 48–55, 2000.

[23] G. Poulachon, B. P. Bandyopadhyay, I. S. Jawahir, S. Pheulpin, E. Seguin, Wear behavior of CBN tools while turning various hardened steels, *Wear*, Vol. **256**, pp. 302-10, 2004.

[24] S. Hernandez, J. Hardell, H. Winkelmann, M. R. Ripoll, B. Prakash, Influence of temperature on abrasive wear of boron steel and hot forming tool steels, *Wear*, vol. **338-339**, pp. 27-35, 2015.