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Tribological Effects of H-Bn Nano Cutting Fluid - Minimum Quantity Lubrication (Nf-Mql) on Machining Inconel 625

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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 the current paper, h-BN nano cutting fluid was formulated with 0.1% vol. concentration of h-BN in conventional cutting fluid for NF-MQL technique and its tribological effects on machining performance of Inconel 625 were 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 surface roughness and cutting forces. The optimal input machining parameters for experiments were defined by the use of Taguchi and Grey relational based multi response optimization technique. The tribological effects of h-BN NF-MQL shows that it is a viable and sustainable option for improving the machining performance of hard- to- cut material like Inconel 625.

Keywords: Hexagonal Boron Nitride (h-BN), Nano Fluid Minimum Quantity Lubrication (NF-MQL), Tribological behavior

I. 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 machining of hard-to-cut materials. Many researchers [4-10] 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 which reduced the friction caused by preventing direct contact between frictional surfaces. Huang et al. [5] investigated 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 performance of MoS2 nano particles grinding fluid and compared its performance of paraffin oil and soybean oil where the results showed that MoS2 nano fluid improves the machining performance by reducing the friction generated and machining forces as well. Lee et al. [8] observed NFMQL improves the drilling operation by increasing the number of drilled holes, reducing thrust forces. Sharma et al. [9] investigated effects of carbon nanotubes NF-MQL on turning (AISI) D2 steel and saw that NF-MQL showed improved thermal conductivity and surface integrity over conventional lubrication. Effect of Al2O3 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.

Recently, many researchers have proved that boron nitride is 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 show better anti-frictional and anti-wear characteristics.

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Cho et al. [13] investigated lubricating effects of h-BN nano particles dispersed in water and found dispersion of h-BN nano particles improves tribological properties and are 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 h-BN nano cutting fluid improves the heat dissipation and lubricating property than with soluble oil aerosol.

In past, not much research has been done on 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' conventional cutting fluid [16,17] and then research is carried out for tribological behavior of h-BN NF MQL on its machining performances. For analysis turning operation is chosen on hard to cut Nickle alloy-Inconel 625 under various lubricating conditions (dry, wet, MQL conventional and h-BN NF-MQL). The optimal machining parameters are defined by Taguchi-Grey relational analysis and observations were recorded-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.

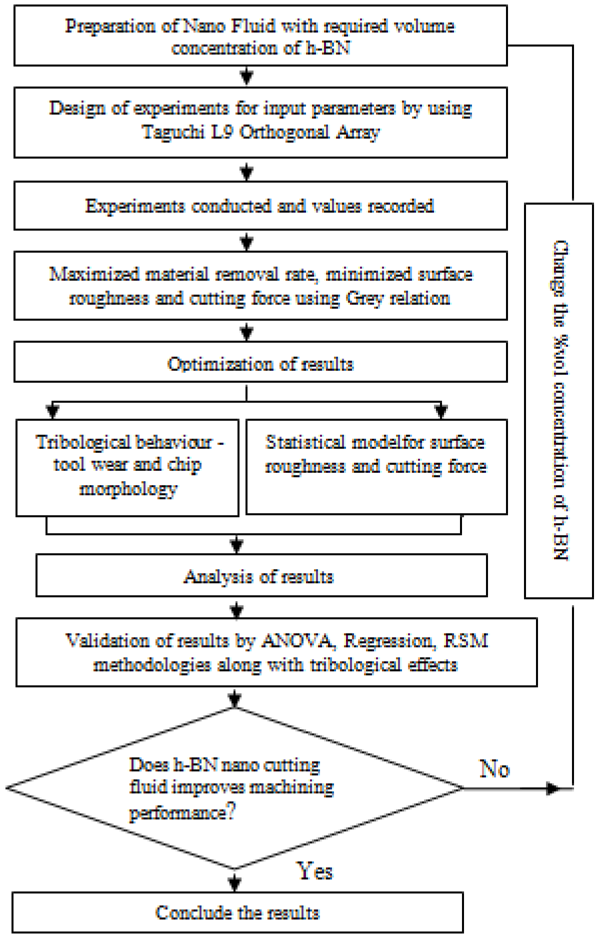

Fig. 1 Methodology followed for this research work

II. PREPRATION OF 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 I. 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 I. 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/cm3
Melting point	2973°C
Solubility in water	Insoluble
Crystal structure	Hexagonal

The Inconel 625 workpiece with dimensions of diameter:30mm and length:210mm was considered for experiments. By having unique properties like high temperature mechanical strength, improved corrosion resistance etc., Inconel 625 has its wide applications in industry. Being an established super alloy, it has property of rapid work hardening and low heat conductivity 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 II and III respectively. The experimental trials were conducted on NAGMATI 175 model lathe with maximum cutting speed 1200 rpm, motor 3HP. The cutting tool used for machining is as PVD coated carbide insert. Figure 2 shows the Inconel 625 stock bar used for turning , schematic layout of experimental setup and devices used to measure various response variables (surface roughness, cutting force and material removal rate) i.e. for surface roughness-Mitutoyo surface roughness tester, for cutting force measurement-lathe tool dynamometer, weighing scale for measuring weight before and after machining for calculating material removal rate.

Table II. Chemical Composition of Inconel 625

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

Table III. Physical Properties of Inconel 625

Alloy	Density	Melting Point	Tensile Strength	Brinell Hardness
Inconel 625	8.4g/cm3	1290 - 1350	760 N/mm2	< 220 HB

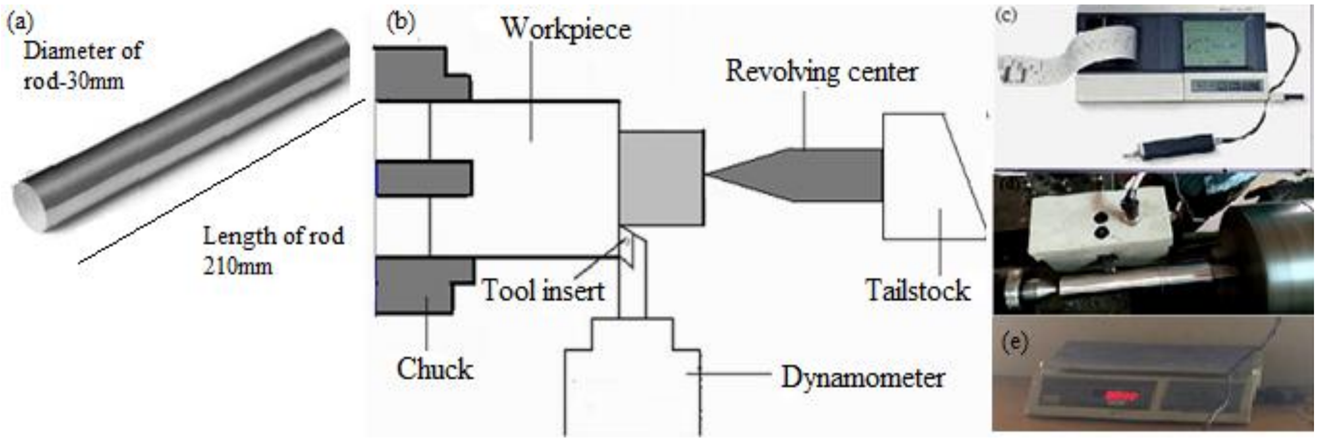

Figure. 2 (a) wok material (b) Schematic layout of experimental setup, (c) photograph of surface roughness tester, (d) photograph of experimental setup showing dynamometer attached to tool, (e) photograph of weighting scale device to measure tool weight

III. 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 table IV). 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 experimentation. Details of the test results are tabulated in table V.

Table IV. 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

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

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

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),

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

where, k is the response for i^{th} experiment and Δmin is the smallest value of $\Delta_{oi}(k)$ and Δmax is the largest value of $\Delta_{oi}(k)$. The ξ is the distinguishing coefficient is generally defined in the range zero to one [21], for current model 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). Refer table 7, and it is seen that experiment 6 has the highest grey.

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

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

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

Trial	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 are tabulated in table VI. Further, the grey relational coefficient was calculated using Eq. 3 and 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 table VII). 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 had maximum value of grey relational grade, and hence, was best experimental set of input parameters for multiple performance in machining of Inconel 625.

Table VI. 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 VII. 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 NF-MQL lubricating conditions) were studied. Statistical analysis for response factors - machining force and surface roughness are performed by using MINITAB 18.0 (a statistical software tool).

IV. TRIBOLOGICAL BEHAVIOR

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 know the tribological behavior under varied lubricating conditions. The tribological behavior shows how surfaces in contact with each other interact within a lubricating environment. Figure.3 shows the experimental setup during NF-MQL machining.

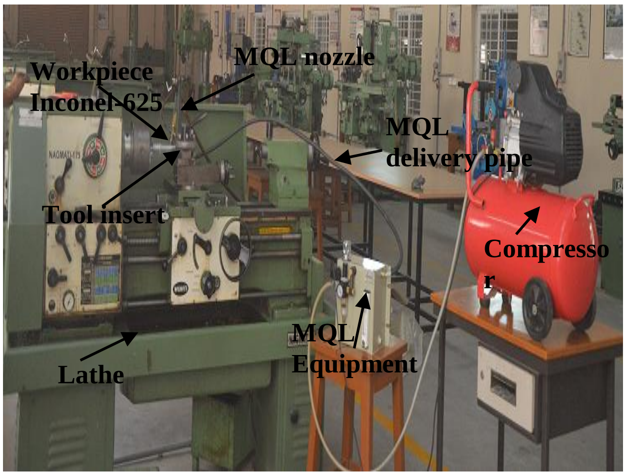

Figure. 3 Actual setups for NF-MQL machining

A. 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 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 Figure.4 during turning Inconel 625 under different lubricating conditions, where various wear patterns were observed and analyzed viz. abrasion, notching, plastic deformation and grooving.

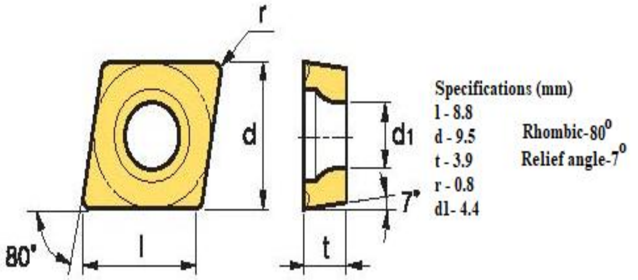

Figure 4. Tool insert geometry

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 Figure. 5 (a). This inefficient cooling and variation in temperature causes surface cracks and eventually leads to abrasion at the flank edge and causes ripping of tool parts or notch formation thus leading to tool failure, refer Figure. 5 (a) and Figure. 5 (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 Figure. 5 (g). For crater wear in dry cutting, refer Figure 5 (b) 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 Figure. 5 (f) and h-BN NMQL but the impact of grooving was much less in h-BN NMQL refer Figure. 5 (h).

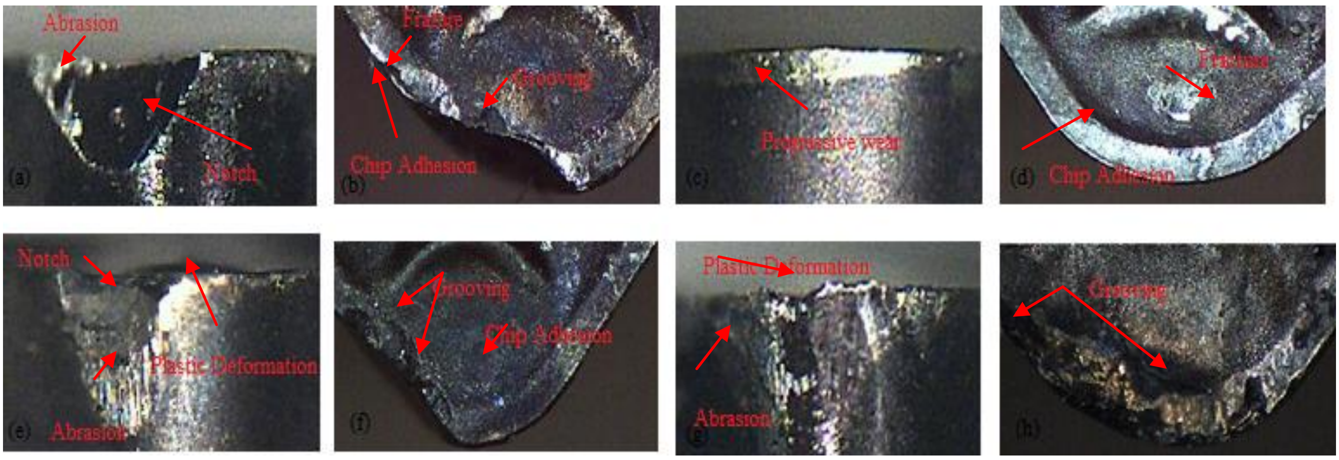

Figure 5. Tool wear images for Dry(a-b), Wet (c-d), MQL conventional (e-f), h-BN NF MQ L(g-h)

B. Chips Morphology

Chips from different machining environment (refer Figure. 6) 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 NF-MQL chips were observed to be regular shaped and burnt free. Also, was noticed that the chips coming out from h-BN NF-MQL machining were much 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.

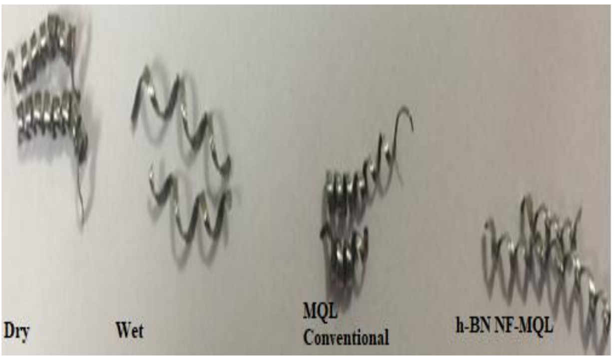

Figure 6. Chips attained for various modes of lubrication

V. STATISTICAL ANALYSIS

A. ANOVA and Regression Analysis

The predictive model was developed for MQL and h-BN NFMQL. From pertained experimental results of Taguchi L9 orthogonal array (refer table VIII), regression analysis for Fc and Ra were established (refer table IX and table X) which shows the regression model and equations for the NFMQL and MQL (cutting force and surface roughness) respectively. ANOVA analysis for cutting force and surface roughness under MQL and h-BN NF-MQL was established, refer table XI and XII respectively. It has been seen that values of R sq. (Coefficient of determination in both the cases cutting force and surface roughness were close to 100% showing that data was closely fitting the regression line.

Table VIII. 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 NF-MQL cutting force Fc (N)	MQL Surface Roughness Ra (MQL) (µm)	h-BN-NFMQL 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 IX. 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+ 0.016 67 Depth of Cut (mm)_0.25+ 0.05333 Depth of Cut (mm)_0.50- 0.07000 Depth of Cut (mm)_0.75

Table X. 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 XI. ANOVA table for MQL and NF-MQL for cutting forces

Sources		MQL				h-BN NF-MQL			
	DF	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 XII. ANOVA table for MQL and NF-MQL for surface roughness

Sources		MQL				h-BN NF-MQL			
	DF	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
Depth of Cut (mm)	2	0.079089	0.039544	9.86	0.092 Not Significant	0.24067	0.12033	27.77	0.035 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%			

B. Effect of lubricating conditions on machining

The machining parameters (speed, feed and depth-of-cut) from different lubricating conditions play an important role in order to find the quality of the product. Thus, it is wise to have a relational model among them to analyze the effects. Therefore, predictive models (MQL and h-BN NFMQL) were 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 7(a-b-c-d-e-f)) to see the potential relationships between force and (speed, feed and depth-of-cut), similarly graphs (refer Figure 8(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 Figure 7(a-b-c) for MQL and Figure 7(d-e-f) for NFMQL. Further from surface roughness plots, the surface plot for MQL refer Figure.8(a-b-c), show the rise in surface roughness with increase in feed rate and cutting speed. However, for h-BN NFMQL refer Figure 8(d-e-f), the surface roughness increases with feed rate but decreases with decrease in cutting speed.

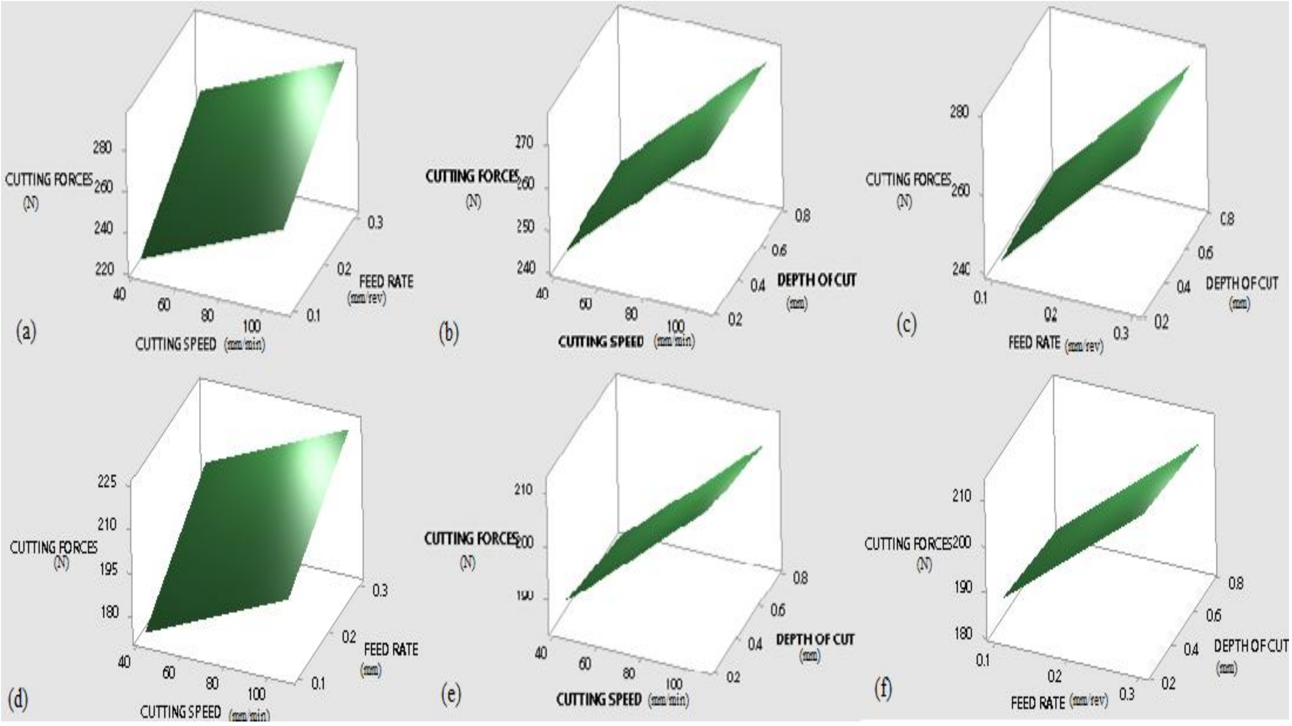

Figure 7. Effect on cutting forces under MQL-(a), (b), (c); h-BN NF-MQL (d), (e), (f)

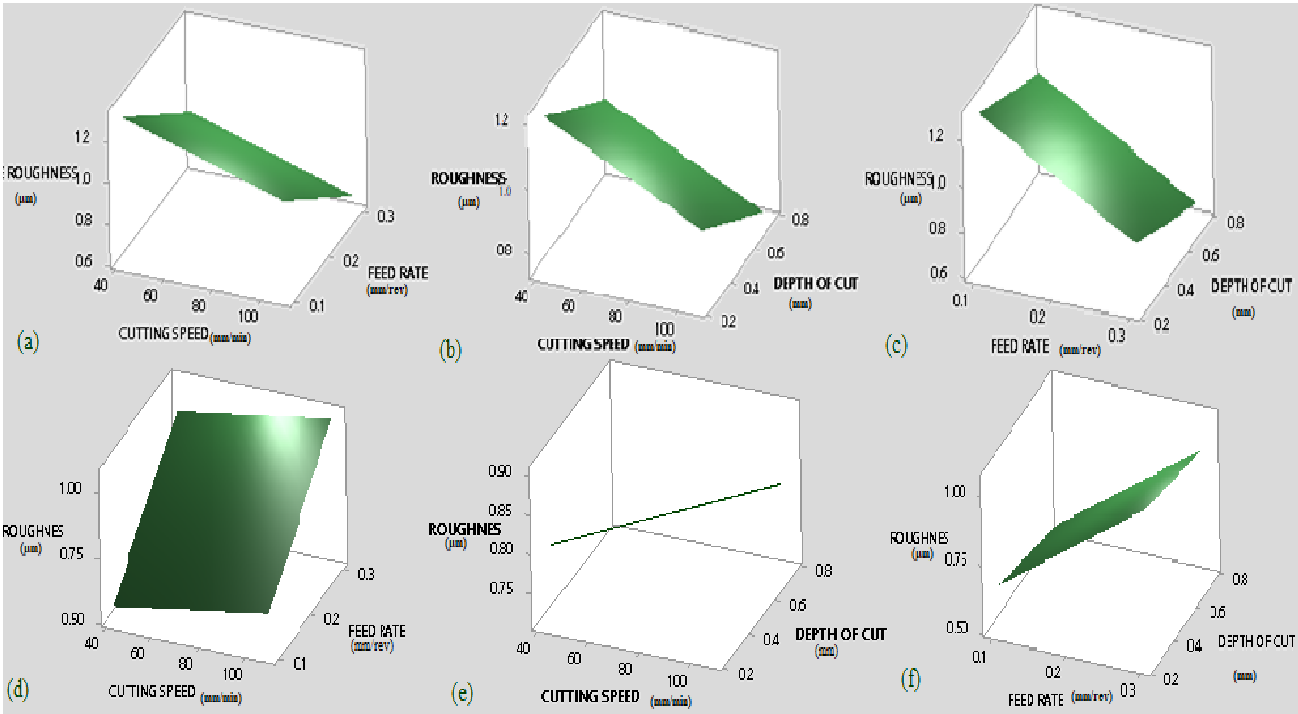

Figure 8. Effect on surface roughness under MQL-(a), (b), (c); h-BN NF-MQL-(d), (e), (f)

VI. CONCLUSION

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 NF-MQL and wet lubrication., there was minimal formation of notch and abrasion wear in tool was also significantly less, which implies the superiority of NF-MQL.

2. Groove formation - Number of grooves formed at the cutting faces were very less in case of NF-MQL as compared to dry machining.
3. Plastic deformation - Fewer traces of plastic deformation of tool cutting edge were seen in h-BN NF- MQL technique vis-a-vis MQL conventional method.

➢ Chip Morphology

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

➢ Statistical relationship between predictive models (h-BN NF-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 NF-MQL machining environment as compared with conventional MQL.
2. Cutting forces – Results showed that cutting force increased with cutting speed and feed rate for both h-BN NF-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 model for surface roughness and it showed feed rate and cutting speed impacted surface roughness significantly and was directly proportional to increase in these values. However, depth-of-cut(d) displayed some marginal effect on surface roughness for h-BN NF-MQL lubricating condition, while it is insignificant in case of conventional MQL.
4. From ANOVA it is quite clear that the values of R sq. (coefficient of determination) close to 100% in both the cases - cutting force as well as surface roughness showing that the data is closely fitting the regression line, which show that developed equation modes will give satisfactory response values.

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