Influence of nano (h –BN) cutting fluid on machinability of Inconel 625

Pariniti Singh¹, Chinmaya P. Padhy²
¹ Research Scholar, Dept of Mechanical Engineering, School of Technology, GITAM University, Hyderabad, India
² Associate Professor, Dept of Mechanical Engineering, School of Technology, GITAM University, Hyderabad, India

E-mail: pariniti_singh@rediffmail.com

Abstract. Inconel 625 has got wide applications across industries (aerospace, petrochemical etc.) in various machining operations. During machining, large amount of heat is generated due to the friction, lowering the tool life and adding to various wear mechanism. This is sorted by conventional cooling/lubrication, but, with its harmful effect on environment and human health, it’s imperative to pursue other cleaner, greener though efficient alternatives. In this regard, MQL assisted with h-BN nano fluid is an effective option. Hexagonal Boron Nitride (h-BN) having unique structure and composition displays advanced mechanical properties which enhances its versatility in applications. To investigate effectiveness of nano (h –BN) cutting fluid on machinability, first h-BN nanofluid was prepared and characterized for its mechanical properties for nanoparticle concentrations (0.05,0.1 % Vol.). Further, the machining performance and sustainability associated with turning of Inconel-625 under different lubricating conditions viz. dry, wet, MQL with conventional cutting fluid and MQL with (h-BN) nano cutting fluid (NCF) are investigated for machining characteristics. Results showed that MQL integrated with h-BN nano cutting fluid is an effective and sustainable option.

1. Introduction

Ni-Cr alloys such as Inconel 718 or 625 are mostly used in aerospace, petrochemical, nuclear, biomedical and shipping industries. Machining of Inconel 718 has been discussed by various researchers but there are very few literatures available for effective machining of Inconel 625. Like Inconel 718, Inconel 625 is a difficult to machine material. There were mainly two problems faced in machining of super alloys (difficult to machine materials); a). possibility of less tool life due to the work hardening and abrasion properties, b.) high surface roughness and deformation caused due to high machining temperature. For this reason, application of suitable cutting fluid during machining is a wise decision to reduce friction which helps in cooling the workpiece, and washes away the chips. However, number of drawbacks like its high cost, disposal problem, environmental and occupational health hazards are associated with the use of cutting fluids. To address these problems researchers have sought alternate methods of machining, e.g. near dry machining (NDM), combining cutting fluid with additives, minimum quantity lubrication (MQL) machining etc. MQL consists of misting limited quantity of cutting fluid at flow rate of 50 to 500 ml/hour in compressed air flow straight at the cutting zone [1]. Precise application of MQL technique has been seen in machining of hard materials, super alloys etc. in aerospace, automotive, medical and nuclear industries [2-3]. However, it’s not as effective as to wet lubrication as excessive heat generation is involved during machining of hard metals. Hence it requires further improvement to meet demanding solution in high speed machining and hard machining. In this regard an attempt has taken to investigate machinability of Inconel 625 by using nano boron nitride...
(additives) cutting fluids under MQL condition to improve cooling and lubricating property. Decisive properties of boron nitride namely chemical inertness, non-hazardous and capability to lubricate at wide range of temperature and high thermal conductivity makes it a perfect option as an additive in MQL enabling enhancement of various machining parameters.

1.1. Background work on MQL with nano cutting fluid in machining
Past studies have indicated that nano MQL provide better heat transfer [4] and machining performance [5], surface roughness, tool wear and cutting temperature [6]. It is also seen that on machining of Inconel 718 with MQL improved cutting performance and lower surface roughness in comparison to dry and wet environments [7].

2. Experimental Methodology

2.1. Formation of nanofluids
Synthesis of BN nano cutting fluid is prepared with the help of dry BN powder (APS ~70-80 nm) obtained from nanoshel India. An attempt has been made to prepare the samples for BN nano-solution with 0.05 % and 0.1% vol. concentration. For this, the required quantity (measured by using eq.1) of nano particles were dispersed in deionized water and then magnetic stirred for 30 mins at 1200 rpm to obtain respective homogeneous solutions. These samples are further probe sonicated at amplitude of 40% with sonication pulse-on-off time of 50 seconds and 10 seconds respectively. The synthesized uniformly dispersed nano solutions are then added to conventional cutting fluid (Servo-S) in required quantity (95% nano fluid and 5% concentrate conventional cutting fluid) to obtain nano cutting fluid.

Boron Nitride (BN) volume percentage is calculated as,

\[
\frac{V_{BN}}{V_{Total}} \times 100\% = \frac{W_{BN}/\rho_{BN}}{W_{BN}/\rho_{BN} + V_{W}} \tag{1}
\]

\(V_{BN}\) - Volume of BN nanofluid, \(V_{Total}\) - Total volume of nanofluids, \(W_{BN}\) - Weight of BN nanofluids,

\(\rho_{BN}\) - Density of BN nanofluids, \(V_{W}\) - Volume of Deionized water, Calculated density of BN 2.27 gm/cm³

2.2. Thermo-Physical properties of BN nano cutting fluid
It is important to know the thermal and fluid properties (thermal conductivity (k), viscosity (\(\mu\)), surface tension(\(\sigma\))) of nano cutting fluid, which largely effects the machining of hard metals. Therefore, properties were characterized for (0.05,0.1 % Vol.) h-BN nano particles using liquid thermal property analyzer equipped with thermocouple and digital temperature indicators, Saybolt Viscometer, dynamic contact angle and tensiometer instrument (DCAT) respectively.

The increase in thermal conductivity of nano cutting fluid in comparison to base cutting fluid is observed as the dispersed nanoparticles increase the surface area and thus better heat transfer is possible. For the considered h-BN nano cutting fluid the thermal conductivity is found to increase with the increase in Vol% of nanoparticles. The viscosity of the h-BN nano fluid was tested within the temperature range of 25°C to 70°C. The experiment showed that viscosity decreases with increase in temperature and increases with increase in concentration of BN nano particles (higher viscosity was achieved with 0.1% sample of BN nano cutting fluid) The surface tension of the samples was tested by dynamic contact angle and tensiometer instrument (DCAT). Last column in Table 1 displays % improvement in various thermo physical parameters of h-BN nano-cutting fluid in comparison with conventional cutting fluid. On an average 36% improvement was seen in kinematic viscosity, ~ 37% improvement in thermal conductivity and close to 2% improvement in surface tension.
Table 1. Thermo physical properties of cutting fluid and h-BN Nano cutting fluid of varying-BN concentration

| Thermo-Physical Properties | Temperature (°C) | Conventional cutting Fluid | 0.05 % by vol. of Nano cutting fluid | 0.1 % by vol. of Nano cutting fluid | %Avg. enhancement in thermo physical properties (0.1% vol of nano fluid vs conventional(approx..)) |
|----------------------------|------------------|----------------------------|-------------------------------------|-------------------------------------|------------------------------------------------------------------------------------------------|
| Kinematic Viscosity (Stokes) | 25               | 0.0945                     | 0.0979                              | 0.1006                              | 36.3%                                                                                           |
|                            | 40               | 0.0729                     | 0.089                               | 0.0894                              |                                                                                                 |
|                            | 60               | 0.0581                     | 0.074                               | 0.0769                              |                                                                                                 |
|                            | 70               | 0.0364                     | 0.0514                              | 0.0669                              |                                                                                                 |
| Thermal Conductivity (W/m °C) | 1.818           | 2.064                      | 2.4859                              | 36.7%                               |                                                                                                 |
| Surface Tension(mN/m)     | 71.84± 0.030     | 71.309 ± 0.030             | 70.436 ± 0.020                     | 2%                                  |                                                                                                 |

2.3. Experimental Condition and Procedure

To investigate the influence of BN nano solution on turning of Inconel 625 under various operating conditions (e.g. dry, wet, MQL conventional and MQL nano cutting fluid). Coated insert (Korloy insert: CCMT09T308-HMP) Model: PC9030 is used for machining of Inconel 625. Optimization of machining parameters is done by multiple responses based on taguchi orthogonal array integrated with grey relational analysis to maximize material removal rate and minimize surface roughness. MQL technique was performed at pressure of 4 bar and flow rate of 50ml/hr during machining. The nozzle was positioned to inject cutting fluids along the formation of chip.

3. Results and discussion

3.1. Optimization of machining parameters

Optimization of machining parameters (Cutting velocity, Depth of cut, feed rate) in turning of Inconel 625 with multiple responses based on orthogonal array with grey relational analysis to maximize material removal rate and minimize surface roughness is discussed. The levels of the process parameters are selected in order to cover a sufficient wide range of possible cutting conditions. Table 2. shows different parameters considered for machining. Based on taguchi concept a L9 array table 3. was prepared for experimentation. The combined Grey and taguchi methods analysis gave optimal parameters with multiple characteristics. Material removal rate and surface roughness were significant characteristics considered.

Table 2. Selected Parameters in turning process

| Factors               | Units     | Levels  |
|-----------------------|-----------|---------|
| Cutting speed(V)      | Rpm       | 1 500   | 2 770 | 3 1200 |
| Feed Rate(f)          | mm/rev    | 0.05 0  | 0.1 1 | 0.2 2   |
| Depth of Cut(d)       | mm        | 0.7 0.7 | 1.0 1 | 2.0 2   |

Table 3. Orthogonal L9 Table for Response

| Trial No | Cutting Speed | Feed Rate | Depth of Cut | Material Removal rate | Surface Roughness |
|----------|---------------|-----------|--------------|-----------------------|-------------------|
| 1        | 500           | .05       | 0.7          | .126                  | 1.65              |
| 2        | 500           | .1        | 1.0          | .252                  | 1.25              |
The average grey relation grade calculated for Taguchi response. Parameters at which maximum material removal rate and minimum surface roughness was observed were labelled as optimized machining parameters. Experimental design parameters of experiment no. 6 had highest grey relation grade refer Figure 1. Thus, the optimal machining parameter were found to be as cutting speed of 770 rpm and a feed rate of 0.2 mm/rev and depth of cut as 0.7mm. The further steps of experimentation included evaluation of machining performance with different modes of lubrication (dry, wet/flooded, MQL with conventional cutting fluid, MQL with nano cutting fluid) on optimized parameters.

3.2. Chip thickness
Cutting Thickness of chip measures competence of machining process. Lower chip thickness is supposed to be given for good lubrication at machining area and improved machining efficiency [8]. Various chips were collected during the experiment and thicknesses of chips were measured using electronic micrometer. The chips for dry machining were much darker in colour owing to higher temperature along with twisted shape whereas, the chips for MQL with BN nano cutting fluid were much regular along with smooth surface which specified reduced machining temperature. The average chip thickness variation graph for modes of lubrication was plotted as seen in figure 2. which shows chip thickness is comparatively low for MQL with BN nano cutting fluid as compared with dry mode of lubrication.
3.3. Surface Roughness
Surface roughness is another parameter for evaluating machining performance. Good surface roughness results in better quality surface strength, resistance to corrosion and enhanced creep life of a workpiece. The subsequent benefits from good surface finish increases productivity with reduced re-processing of workpiece giving satisfied technical specifications. The surface roughness was recorded by Mitutoyo surface roughness tester. Results are recorded in figure 3, which shows that MQL with h-BN nano cutting fluid gives minimum surface roughness value and hence improved the surface finish.

![Surface Roughness Variation with machining Time](image)

**Figure 3.** Variation in Surface Roughness with machining time

3.4. Tool wear
Tool wear is a crucial aspect to predict tool life and effective machining process. The tool wear is measured by profile projector at varying interval of time for all lubricating conditions and is observed to increase with machining time and also adds up to high chip-tool interface temperature. High tool wear is attained for dry machining shadowed by wet, MQL with conventional cutting and minimal by MQL with h-BN nano cutting fluid due to better heat dissipation. The figure 4, shows the comparison in tool wear with various modes of lubrication.

![Variation in tool wear with machining Time](image)

**Figure 4.** Variation in Tool Wear with Machining Time

3.5. Cutting forces
Cutting forces in machining are directly affected by lubrication during machining. An appropriate cushion of lubricant formed by MQL with h-BN nano cutting fluid at tool workpiece interface reduces the machining temperature along with cutting forces. The cutting forces are measured by lathe tool dynamometer and is seen that cutting force get reduced with h-BN nano cutting fluids refer figure 5.
3.6. Chip tool Interface Temperature

Cutting zone temperature is another important parameter affected by lubrication method. It is evident by study of thermo physical properties of BN nano cutting fluid that it shows improved thermal conductivity in comparison with conventional cutting fluid. This factor adds on to its lubricious property. The Extech dual laser infrared thermometer is used for measuring the temperature which showed that interface temperature for Dry machining is much higher when compared to the cutting temperature for wet, MQL (conventional cutting fluid) and MQL with nano cutting fluid. It is also seen that relative difference between wet, MQL (conventional fluid) and MQL (BN cutting fluid) is also less. It is inferred from figure 6 that the MQL with BN nano cutting fluid gives minimum cutting interface temperature.

![Figure 5. Variation in cutting force with different lubrication condition](image)

![Figure 6. Variation in Tool cutting interface temperature with various lubrication modes](image)

4. Conclusion

Various aspects of machining performance and green technology have been taken into consideration to reach at the best sustainable lubrication in machining. The effect of h-BN nano-fluids in enhancing the MQL lubrication capabilities during machining of Inconel-625 has been investigated and results pertaining to machining of Inconel - 625 under dry, wet, MQL (conventional fluid) and MQL (h-BN nano cutting fluid) are listed below to arrive at inference regarding preeminence of MQL with h-BN nano cutting fluid.

- Surface of chip achieved for MQL conventional is much smooth comparison to tangled chips of dry machining. Also, chip thickness for MQL with h-BN nano cutting fluid was much less in comparison to other lubricating techniques.
- During machining of Inconel-625 surface finish is significantly affected due to intense stress and temperature at tool workpiece interface. The surface roughness was found to be much lower for MQL with BN nano cutting fluid application due to effective enhancement of lubricating properties in comparison to other methods.
- Application of MQL with h-BN nano cutting fluid resulted into lower tool wear. The h-BN nano cutting fluid with lower viscosity and improved thermal conductivity gives better heat dissipation on the interface and hence reduces the tool wear to greater extent.
Application of MQL with h-BN nano cutting fluid helps in better lubrication and adds up to lower down cutting forces compared to dry and MQL conventional lubricating technique.

MQL with BN nano cutting fluid helps in lowering machining temp. (due to increase in K value) and better lubrication adds up to reduced cutting forces as compared to other techniques.

Based on the above inferences, it is evident that the employed h-BN nano cutting fluid with MQL application showed significant improvement in machining performance and thus MQL integrated with h-BN nano cutting fluid is a sustainable and greener lubricating option in machining.

5. References

[1] R. Autret and S. Y. Liang. (2003) “Minimum quantity lubrication in finish hard turning,” in Proc. International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment, and Management, 26-28.

[2] Y. Kamata, T. Obikawa. (2007) “High speed MQL finish-turning of Inconel 718 with different coated tools” Journal of Materials Processing Technology 192–193.

[3] D. G. Thakur, B. Ramamoorthy, and L. Vijayaraghavan. (2009) “Optimization of Minimum Quantity Lubrication Parameters in High Speed Turning of Superalloy Inconel 718 for Sustainable Development”, World Academy of Science, Engineering and Technology, 54, 224-226.

[4] Hwang Y, Park HS, Lee JK, Jung WH. (2006) “Thermal conductivity and lubrication characteristics of nanofluids”. Curr Appl Phys 6:67–71.

[5] Shen, B., Shih, A.J., Tung., S.C., (2008) “Application of nanofluids in minimum quantity lubrication grinding” Tribology Transactions, 51, 730–737.

[6] M Amrita, RR Srikant, AV Sitaramaraju, MMS Prasad, P Vamsi Krishna. (2014)“Preparation and characterization of properties of nano graphite-based cutting fluid for machining operations” in Materials Manufacturing Process;29, 600-605,

[7] Bikash Chandra Behera, Chetan, Sudarsan Ghosh, P Venkateswara Rao. (2014), “Effects on forces and surface roughness during machining Inconel 718 alloying using Minimum Quantity Lubrication”, 5th International & 26th All India Manufacturing Technology, Design and Research Conference.

[8] L.B Abhang, Hameedullah M. (2010), “Experimental Investigation of Minimum Quantity Lubricants in alloy steel turning”. International Journal of Engineering and Technology”, Vol.2(7),3045-3053