Evaluation of Tool Wear Characteristics during Machining Ni-Based Super-alloy (Inconel 625) Under Different Lubricating Conditions

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(h-BN) hexagonal Boron nitride
MQL-Minimum Quantity Lubrication
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ABSTRACT

Machining of Inconel 625 is associated with large amount of heat generation. This leads to sudden rise in temperature having local plastic deformation, strain hardening, excessive tool wear, results frequent change of tool etc. Excessive tool wear has become one of the most significant concerns by many manufacturing industries as it directly effects intended machining performances. Methods of lubrication play a vital role to the improvement of machining performances, as they significantly impact the control of temperature at the cutting zone hence the tool wear. This paper evaluates and compares the tribological effects, especially tool wear characteristics and chip morphology under frequently practicing lubricating methods (namely dry and wet or flooded lubricating conditions) including MQL with conventional fluid and MQL with nano cutting fluid environments during machining of Inconel 625. Then, respective tool wears and tool morphologies were recorded and analyzed.

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1. INTRODUCTION

Nickel based super-alloys (Nimonic 263, 115, 105, Inconel 600, 625, 713, 718, 751, 800, Rene 125, Waspaloy etc.) are widely used in aircraft, marine and nuclear sectors due to their superior hot strength, corrosion resistance and, excellent thermal fatigue properties. Whereas, these alloys are very difficult to machine and cause rapid wear of the cutting tools, frequent change of tools, high power consumption etc., are thus resulting in low economy and largely affects its machining performances. There are many factors like type of tool, machining parameters, use of cutting fluids

and its mode of application affect the performance of a machining operation. During machining of hard to cut materials, due to interaction (friction) between tool tip and work-piece, large amount of heat produced, thus rise in the temperature causes local plastic deformation, strain hardening and ultimately effects on tool wear, surface roughness and other machining performances. A large number of hard to cut materials (both metallic and non-metallic) pose machining challenges to machinist under various conditions. Materials like very hard super alloys, titanium, nickel alloys, cobalt-chrome especially composites are very tricky and difficult to

machine as they have anisotropic mechanical properties (varying in magnitude in the direction of measurement). In recent past many authors have studied and tabulated these challenges for variety of materials under different machining conditions. For example, Machado & Diniz [1] studied the impact of different tools on machining of hardened steel. The tool wear analysis showed that dominance of attrition and abrasion wear. Aneiro et al. [2] studied turning of hardened steel with TiCN/Al₂O₃/TiN coated carbide and PCBN tools and found that cutting parameters play significant role in machining performance as they effect tool temperature, tool wear, cutting forces, and surface roughness to a large extent. It was concluded from experiments that depth- of-cut (doc) influences the cutting force and temperature at the tool-chip interface. Dhas et al. [3] studied the performance parameters viz. surface roughness, flank wear and chip morphology during dry hard turning of AISI 4340 steel (49 HRC) using multilayer coated carbide tool. It was seen that surface roughness and flank wear significantly influenced by feed and cutting speed. Zang and Ding [4] studied the tribological behaviour during machining of Ni-superalloy (Inconel 718) and observed that mechanical, adhesive, diffusion and oxidation wear are main cause of machining difficulties. Bhatt et al. [5] investigated the finishing of Ni alloys and concluded that adhesive and abrasive wears mechanisms are dominant wears in machining of Inconel. Choudhary et al. and Li et al. [6,7] during machining of Nickel superalloys and observed that the cutting temperature significantly affects the tool wear mechanisms-chemical diffusion, abrasive wear, and notching. Zaman et al. [8] investigated the machining of another hard to cut alloy material Cobalt Chrome Molybdenum (CoCrMo) on high speed end milling (HSEM) with solid coated and uncoated tools under MQL environment. They found that the tool wear, tool life and tool wear mechanism were analyzed and they found that coated carbide tool gave better machining characteristics (hence, tool life) than uncoated carbide tool, and with a conclusion of chipping, adhesion and crack formation were the main wear mechanisms. Caggiano et al. [9] investigated the machining of fibre reinforced plastic composite. The machining marked high tool wear along with surface integrity damage. The study concluded that selection of proper tool and machining conditions (machining parameters,

cutting fluid, lubrication methods) are necessary for better material removal. Li et al. [10] performed machining of sintered alumina (Al₂O₃) ceramic using chemical vapor deposition diamond coating tools on a milling machine, and later they observed for machined surface's finish, tool wear, tool life, material removal rate (MRR) and the cutting forces. Moreover, it was further seen that unexpected tool failure caused by variation in cutting forces. From above literatures it is to be noted that 'tool wear' is the centre-stage among all the machining performances and the rate of tool wear strongly depends on the cutting temperature, tool material, work material and contact forces/stresses, tool geometry, and cutting conditions etc. (Fig. 1), whereas rise in cutting temperature depends upon cutting, tool geometry, cutting conditions and including type and mode of lubrication used during machining.

Fig. 1. Process parameters effects on tool wear.

Therefore, any measures which could be applied tactfully to reduce the cutting temperature would reduce the tool wear and helps to increase the life of the cutting tool. Use of cutting fluids-lubricants and type of lubricants are one way to dealt with it. Cutting fluids have critical usage in manufacturing industries as they provide better cooling, lubrication by improving machinery lifetime and tribological behaviour which enhances the machining performance. On a note its proper application at the chosen material improvise the tribological parameters like- tool wear and friction generated at the machining

zone along with reduction in temperature at the cutting interface [11,12]. However, the critical drawback of cutting fluid is the negative effects on environment, worker's health and bearing measureable amount of cost. Over the years many alternatives were sought and developed for sustainable machining by controlling the use of cutting fluid without compromising the machining performance. However, reduction in amount of cutting fluid and alteration in its method of application with the use of MQL (Minimum Quantity Lubrication) technique is not much satisfying for particularly hard to cut materials, where a little amount of cutting oil may not perform the cooling task due to immediate evaporation of highly pressurised fluid at high temperature. So, to make a step forward to enhance the heat transfer with the machining time along with clean and green manufacturing during machining, application of nano based cutting fluid with MQL have found more suitable and emerged as a sustainable lubrication technique [13-17], it is believed that nano particles contributes to the development of tribological properties viz. friction and wear to a large extent when they come in contact with cutting tool edge and work piece surfaces. The studies have shown that addition of nano additives is observed to underpin the properties of base cutting fluid and brings about major changes in tool life, improves the machining performance and thus enhancement in productivity. But again, all these additives which influences the machining performance were not found environmentally safe [18-21]. Therefore, hexagonal boron nitrides (h-BN, also known as white graphite) has found their application as additive in base cutting fluids as they are safe to use, non-toxic, have good thermal stability along with high thermal conductivity [22]. Researches have shown that addition of boron nitride nano particles in cutting fluid improve machining processes [23-24]. However, not many literatures, besides few have been found which discusses about the tribological effects of the boron nitride nano cutting fluid during machining of Ni-based super-alloy for example, Inconel 625. It is a Ni-based super-alloy having high strength of 880 MPa, hardness 240 BHN and thermal conductivity 9.8 W/mK (Table 2), which can upload its superior consistent mechanical properties at high temperatures for longer period of time and thus it is the most commonly used material in aerospace, nuclear, automobile,

marine, oil & gas etc. [25]. Therefore, in the present paper an attempt has been made to study the tribological effects particularly, tool wear characteristics and chip formation details under different lubricating conditions viz. dry, wet and MQL conventional and h-BN nano MQL during machining of Inconel 625.

2. TRIBOLOGICAL EFFECTS OF LUBRICATING CONDITIONS ON MACHINING OF HARD TO CUT MATERIALS

Tribological aspects play a very important role in cutting processes as they encompass friction, machining temperature, tool wear, stress distribution etc. The use of cutting fluids and its mode of application affect the performance of a machining operation. Many studies about the tribological effects of different lubricants on difficult to machine materials are existing. For example, Çolak [26] investigated machinability of Inconel 718 under conventional and high-pressure cooling condition. The experimental results showed that the wear and cutting forces considerably decrease with application of high-pressure coolant at cutting phase. In another study [27], turning operation was performed on Inconel 800 with different nano-cutting fluids (aluminum oxide, molybdenum disulfide and graphite) assisted with minimum quantity lubrication technique. This result revealed that small quantities of nano graphite added in vegetable oil significantly improves the tribological properties like cutting forces, tool wear, and surface roughness. Yildirim et al., [28], studied the effect of nano cutting fluid on tool wear, machining temperature and roughness. It was seen that MQL with nano cutting fluid improves the tool wear, surface roughness and tool life. T. Singh et al. [29] investigated the machinability of super alloy Inconel 625 with the use of NMQL (carbon nanotube in vegetable oil) and they observed that the tribological behaviours greatly affects on tool life and surface finish, with comparison to other aspects of lubricating conditions viz. dry and flooded conditions. In 2009, Dhar and Kamruzzaman [30] reported that on turning of 17CrNiMo6 and 42CrMo4 under dry and high-pressure cooling conditions the high-pressure cooling enables reduction in cutting temperature up to 25 %. From the above literatures it clearly indicates that how different

cutting fluids (lubricating methods) and their chosen mode of application impacts the tribological behaviours in machining hard to cut materials to a measurable extent.

3. EXPERIMENTAL SETUP

To study the important aspects of machining performance such as tool wear and chip morphology etc. during machining with dry, wet, MQL and NMQL, a turning operation setup is established and performed on Inconel-625 (ϕ :40 mm, L:350 mm). The details of chemical composition and physical properties [31] of the work material (Inconel-625) are shown in Tables 1 and 2. The tool insert used during experiment was Korloy insert (CCMT09T308-HMP, model: PC9030) with tool holder as shown in Fig. 2 (a,b), for details and specifications Table 3. Figure 3 shows the MQL equipment used during the experiment. It is to be noted that the test was conducted at its optimal set of machining parameters viz. cutting speed (v) as 60 m/min, feed rate (f) as 0.3 mm/rev and depth-of-cut (d) as 0.25 mm for approx. 3 minutes, details of finding optimal parameters have been discussed in our earlier published work [32]. The base cutting fluid during wet and MQL conventional machining was taken as servo-cut 'S' from IOCL (Indian Oil Corporation Limited) for its excellent working condition at high temperature environment. In case of NMQL, the additives viz. h-BN (hexagonal boron nitride) nano particles with fixed proportion were mixed with base cutting fluid (servo-cut s) to prepare the nano cutting fluid [33].

Table 1. Chemical composition (wt.%) of Inconel 625 [28].

C	Mn	S	Si	Cr	Fe
0.05	0.3	0	0.25	20-23	4
Mo	Co-Ta	Ti	Al	P	Ni
9	3.5	0.3	0.3	0.15	Balance

Table 2. Physical properties of Inconel 625 [28].

INCONEL 625	Density	Melting Point	Tensile Strength	Brinell Hardness
	8.4 g/cm ³	1290 °C – 1350 °C	880 MPa	240 HB
	Modulus of Elasticity	Thermal conductivity		Elongation
	209 MPa	9.8 W/mK		35 %

Table 3. Detail specifications of cutting tool insert.

Insert	Korloy-insert (CCMT09T308-HMP)
Model	PC9030
Material	Tungsten Carbide
Coated	PVD (TiAlN coated)
Shape	flat-faced, rhombic
Corner angle	80°
Relief angle	7°
Rake angle	3°
Thickness (t)	3.97 mm
Radius (r)	0.4 mm
Hole dia. (d ₁)	4.4 mm
Cuting edge length (l)	8.8 mm
Insert size (d)	9.525 mm

Fig. 2. (a) Turning tool insert geometry, (b) SCLCR 121 F09- Screw type tool holder with 95° approach angle for positive 80° rhombic insert.

Fig. 3. MQL Equipment.

Fig. 4. DW laser infrared.

Fig. 5. Zeta profilometer.

Cutting temperature was measured at the cutting zone during each experiment with the help of dual wavelength (DW) infrared pyrometer (make: Williamson, model: Ratio pyrometer) shown in Fig. 4 whereas for measuring tool wear SEM (Scanning Electron Microscope) and Zeta profilometer (make: Zeta instruments) shown in Fig. 5.

4. RESULTS AND DISCUSSION

4.1 Tool wear

Excessive tool wear is one of the major concerns during machining of nickel-based superalloys.

Because of its low thermal conductivity, most of the heat produced during machining is getting transferred to the tool. Subsequently, high tool tip temperatures cause excessive tool wear. It is understood that tool wear is an inexorable process during machining and it progresses till the end of the tool life. In order to prevent or to minimize tool wear, study of wear mechanism and its causes are important. Tool wears usually occur at its rake and flank faces of a given tool (Fig. 6 for understanding tool wear area and wear volume on respective rake and flank faces) and they are termed as rake (crater) and flank wears. Prominently, it is understood that the friction at the machining interface mainly causes wear mechanism at the flank face and is a significant factor for tool failure [34].

Fig. 6. Representation of tool wears (rake-flank face) area and volume.

The major wear mechanisms during machining of hard materials like Inconel due to multiple factors and has studied by number of researchers in the past, viz. flank wear, breakage wear, notch formation, work hardening, diffusion, abrasion, chipping, adhesion, cracks, tension, high temperature distribution etc. and effectiveness of tool wear can be judged through formed BUE, BUL at the tip and edge of the tool [28,29,35-37].

4.2 Impact of different lubricating conditions on tool wear

From our preliminary studies, it is believed that overall cutting performances including tool wears are greatly affected by the kind of adopted lubricating methods to a large extent. Therefore,

here an effort is made to investigate tool wears under different (Dry, Conventional or wet, MQL conventional, NMQL) lubricating environments. Tool wear measurements were carried out by using Zeta-20 optical profilometer, refer Fig. 5. This instrument was used in the experiment to determine the absolute values of rake (crater) wear and flank wear of cutting tool. Moreover, respective tool wear images were captured and analysed for different lubricating conditions. Figures 7-10 (tool profile images obtained from SEM, ZEISS GEMINI) show the respective rake (crater) and flank wears under aforesaid lubricating conditions e.g. Fig. 7 (a,b) for Dry; Fig. 8 (a,b) for Conventional or wet; Fig. 9 (a,b) for MQL conventional and Fig. 10 (a,b) for MQL nano cutting fluid lubrication.

(a)

(b)

Fig. 7. Tool morphology during dry lubrication, (a) at the rake face and (b) at flank face of the tool insert.

(a)

(b)

Fig. 8. Tool morphology during wet lubrication (a) at the rake face and (b) at flank face of the tool insert.

(a)

Fig. 9. Tool morphology during MQL conventional lubrication (a) at the rake face and (b) at flank face of the tool insert.

Fig. 10. Tool morphology during Nano MQL lubrication (a) at the rake face and (b) at flank face of the tool insert.

Fig. 11. Maximum machining temperatures at the cutting zone.

The values shown in the bar chart (Fig. 11) are the average maximum recorded temperatures for various modes of lubrication, whereas, it is observed that the actual temperature values varied in the range of $\pm 5\%$ as indicated in the error bar.

4.3 Wear characteristics during dry machining

Dry machining tends to increase the machining temperature to $300.9\text{ }^{\circ}\text{C}$ (Fig. 11) along with increase in tool wear on rake and flank faces respectively, it is observed that the rake wear at the machining edge takes with the formation of larger crater, chipping and thermal cracking (Fig. 6 (a,b)) mainly because of developed large amount of friction, high stress, sudden rise in temperature and oxidation at the interface region of tool and work material. It is observed that coating material (TiAlN) layer completely moves off from the surface due to oxidation and substrate material of tool exposed immediately to air. Notch formation occurs at flank face of tool tip due to deformation because of diffusion of atoms at the contact faces. The tool wear findings in-terms of area and volume for dry machining on both rake and flank faces are shown in Figs. 12 and 13 below. The rake face and flank face wear (by area) measured were 0.660 mm^2 and 0.566 mm^2 , whereas the respective measured rake and flank face wears (by volume) were 0.407 mm^3 and 0.406 mm^3 .

Fig. 12. SEM images of rake wear during dry turning.

Zeta analysis report for tool rake face during dry turning	
Rake wear area	Rake wear volume
0.660 mm ²	0.407 mm ³

Fig. 13. SEM images of flank wear during dry turning.

Zeta analysis report for tool flank face during dry turning	
Flank wear area	Flank wear volume
0.566 mm ²	0.406 mm ³

Fig. 14. SEM images of rake wear during wet turning.

Zeta analysis report for tool rake face during wet turning	
Rake wear area	Rake wear volume
0.012 mm ²	0.007 mm ³

Zeta analysis report for tool flank face during wet turning

Flank wear area	Flank wear volume
.007 mm ²	0.0002 mm ³

Fig. 15. SEM images of flank wear during wet turning.

4.4 Wear characteristics during wet machining

In case of conventional or wet machining, it is assumed that the wear occurs mainly due mechanical friction between tool and work piece however it also seen that small amount of wear usually occurs due to chemical reaction between tool and prepared cutting fluid (it is due to presence of reagents or chemicals in the conventional base fluid), which ultimately causes debonding of atoms from its surface with time and results in very slow progressive wear [37]. The proper flushing at the machining zone along with chemical benefit from cutting fluid reduce the surface tension and hence provide good wettability and penetration during machining. The machining temperature under wet lubrication was noted to a minimum value viz. as close to 196.9 °C (Fig. 11). Though with sufficient flow of cutting fluid (50 ml/min) at the machining zone, large amount of heat generated was carried away by the cutting fluid imparting reduced wear of tool. Both rake and flank wear formed over the machining area were very small in magnitude without any formation of notches (Figs. 14 and-15) on any side. The tool wear area at the rake and flank face was measured such as 0.012 mm² and 0.007 mm², whereas the tool wear volume of rake and flank wears were measured as 0.007 mm³ and 0.0002 mm³ respectively.

4.5 Wear characteristics during MQL conventional machining

Figure 9 (a,b) shows the observed tool wears under MQL-conventional environment at the flow rate of 50 ml/hr and 4 bar pressure. In this case it is experienced that due to thermo-chemical nature of the cutting fluid, scuffing occurs at the boundary of the lubricant film causes local penetration on the tools surface, leads to localised solid phase welding called adhesive wear at the flank face of the tool, whereas, due to bursting of high pressureized lubricant droplets at the flank face, a small amount of notch is also seen including chipping at the rake side of the tool. The MQL conventional recorded a reduction in cutting zone temperature (measured as 255.6 °C, which was moderately lower (9 %) in comparison with dry cutting). MQL conventional cutting reduces excess of tool material loss compared with dry machining. With the use of zeta profilometer the respective wear areas for both rake and flank faces measured as 0.386 mm² and 0.332 mm² whereas, tool wear volumes of both rake and flank faces were recorded as 0.077 mm³ and 0.311 mm³. It is evident from Figs. 16 and 17 that reduced tool wear occurs at respective rake and flank faces because of pressurised conventional cutting fluid (MQL-conventional) environment, which cools down the cutting interface temperature, results reduction of thermal cracking, strain hardening and other related problems.

Zeta analysis report for tool rake face during MQL turning

Rake wear area	Rake wear volume
0.386 mm ²	0.077 mm ³

Fig. 16. SEM images of rake wear during MQL conventional turning.

Zeta analysis report for tool flank face during MQL turning

flank wear area	flank wear volume
0.332 mm ²	0.311 mm ³

Fig. 17. SEM images of flank wear during MQL conventional turning.

4.6 Wear characteristics during h-BN nano MQL machining

It is to be believed that nano-MQL complements MQL conventional machining by inclusion of solid lubricants, such as nanoparticles (assumed to be uniform in size and spherical in nature) into MQL conventional machining system, which increases thermal conductivity of the base cutting fluid, also decreases direct contact (gliding) between chip and tool interface [38], results increase of better heat transfer at the cutting zone, which decreases the machining temperature, forces and delays tool wear. Thus ultimately which enhances tool life, surface finish and improvising machining performances [13, 39-41]. In this aspect, hBN with unique properties like high melting temperature and chemical stability makes it a perfect lubricant additive [16, 42-43]. The physical and chemical properties of hBN nanoparticles are tabulated in

Table 4 [28]. With the use of minimum level (just sufficient amount) of h-BN nano cutting fluid (i.e. 50 ml/hr) as lubricant along with previously discussed MQL technique, the tool wear morphologies from images show significant reduction in tool wears. It is believed that the wear at the flank side of the tool is caused due to combination of abrasive and adhesive action of highly pressurised hard nano particles and liquid droplets, which were hammering and bursting at the cutting-edge boundary of insert tool, results peeling out of material from the high stressed region (near to nose). At the same time few pullouts/troughs of carbide grain were also visible at the rake/crater face of the tool. In this context machining temperature was measured as 223.7°C, Fig. 10 which was much lower (15 %) in comparison with dry and MQL conventional machining. This remarkable improvement over reduction of machining temperature by the use of sufficiently less

(minimum) amount of lubricant, led to the significant diminution not only in case of the tool wear but also saves lot of cost (Figs. 18 and 19). From the profile pictures of rake (Fig. 18) and flank faces (Fig. 19), the rake and flank face wear

area measurements came out to be 0.100 mm² and 0.192 mm² respectively, whereas, respective wear volume measurements came out to be as 0.052 mm³ and 0.131 mm³.

Table 4. Physical and chemical properties of h-BN nanoparticles [28].

Chemical formula/Crystal structure	BN/ Hexagonal
Color	White
Melting point (°C)	3,000 dissociates
Dielectric constant (MHz)	4
Average diameter particle size (nm)	75
Density (kgm ⁻³)	2.3
Hardness (HRC)	40
Thermal stability temperature in air (°C)	1,000
Thermal conductivity (Wm ⁻¹ K ⁻¹)	27
Coefficient of Friction (COF)	0.45

Zeta analysis report for tool rake face during h-BN nano MQL turning

Rake wear area	Rake wear volume
0.100 mm ²	0.052 mm ³

Fig. 18. SEM images of rake wear during h-BN nano MQL turning.

Zeta analysis report for tool flank face during h-BN nano MQL turning

flank wear area	flank wear volume
0.192 mm ²	0.131 mm ³

Fig. 19. SEM images of flank wear during h-BN nano MQL turning.

The various wear mechanisms observed in this current study for turning Inconel 625 under different modes of lubrication are summarized in Table 5, which follow the analogy with the previous work [28,29,35-37].

As illustrated in Figs. 20 and 21, following inferences can be drawn regarding improvement in tool wear area: TWA (Fig. 20) and tool wear volume: TWV (Fig. 21) by using MQL nano lubrication vis-à-vis MQL conventional and Dry lubrication methodologies. Total tool wear area in case of MQL nano lubrication has shown significant reduction of (~59 %) when compared to MQL conventional lubrication, and as close to (~76 %) reduction in comparison with dry lubrication process. Similarly, tool wear volume in case of MQL Nano lubrication has shown similar substantial

reduction of (~53 %) when compared to MQL conventional lubrication, and as close to (~77 %) reduction while compared with dry lubrication process. Also, to highlight, wet lubrication provides superior improvement in tool wear values (by area and volume) as compared to MQL nano lubrication process, but, it's negative impact on environment along with high cost involved makes it an uneconomical and non-sustainable option in the present scenario. The results of similar studies [29,44] and results of current study were found to be consistent. Hence, from the above analysis we can conclude that, MQL nano lubrication process being a sustainable and cost-effective lubrication method comes out to be a viable option as compared to Dry and MQL conventional lubrication processes during machining Ni based super alloys, especially Inconel 625.

Table 5. List of wear mechanisms observed during turning of Inconel 625 under different lubrication methods.

Lubrication method	Wear mechanisms	Factor(s) responsible for wear mechanism
Dry lubrication (Dry)	Notch wear at the flank face. Chipping and thermal cracking at the rake face	Friction, high stress and rapid increase in temperature due to absence of cutting fluid causes development of local stress concentration hence forming rapid progression of notch wear at the tool nose particularly at the side of flank face. A substantial amount of sharp, hot and high-speed chips coming out from work surface, striking repeatedly the rake face of the tool causes chipping off and develops measurable amount of thermal cracking on rake face.
Conventional/wet lubrication (Wet)	Progressive wear at both flank and rake face.	Slow (progressive) wear occurs uniformly at the rake and flank face during machining due to chemical reaction between tool and cutting fluid.
Minimum quantity lubrication with conventional cutting fluid (MQL)	Notch formation and adhesive wear at the flank face. Chipping at the rake face	High pressure flow (mist form) of conventional cutting fluid cools down the cutting interface temperature and flushes away the chips but was not sufficient to take away the high heat generated at the cutting zone, leads to a slow progress of local stress concentration, which essentially results to a formation of notch including bonding (metal fusion) of chips at flank face of the tool due to scuffing. As mentioned above, the mist form of MQL cutting fluid is not sufficient to cool down the chips properly and thus the sharp, high speed and hot chips striking the rake face continuously causes chipping off the small volume of tool from the rake face of the tool. In addition to this a large amount of bursting occurs due to breakdown of lubricants(mists) at the flank and as well as rake face continuously aids chipping mechanism.
Minimum Quantity Lubrication with h-BN nano cutting fluid (NMQL)	Adhesive wear at the flank face Pull outs at rake surface	Due to nano sized h-BN abrasive particulates and bursting phenomenon of mist droplets, very small sized chips were coming out from the cutting zone with high speed and sometimes they might attach (embed) due to bonding (metal fusion) at the flank side of tool causes the adhesive wear. Wear is caused due to bustling and bursting of highly pressurized liquid droplets at the boundary of rake side causes peeling of tool surface and in this process small amounts of carbide grains were pulled out from the rake side of tool which are under constantly high stress and pressure during machining.

Fig. 20. Tool wear area (TWA) under different lubrication conditions.

Fig. 21. Tool wear volume (TWV) under different lubrication conditions.

4.7 Chip Morphology

During turning of Inconel-625 under different lubricating conditions various chips were collected and analysed. It is observed that under dry condition (temp. 300.9 °C) the chips are saw toothed refer Fig. 22 (~length of 110 mm), dark and tubular chips were produced. During conventional or wet turning (temp. 255.6 °C) the chips obtained (Fig. 23) were clear, long and tubular (approx. length of 150 mm). For chips formed during MQL conventional refer Fig. 24 (temp. 223.7 °C) were less helical with half burnt (size of approx. length as 150 mm) while in case of h-BN nano MQL, temp. is recorded as 201.2 °C, in this case the chips generated (Fig. 25) were helical shaped with light surface having approx.

length of 150 mm. The chips generated in wet/conventional and h-BN NMQL are tubular and light coloured. It may be so due to, results to better heat transfer from the cutting zone, reduction of cutting zone temperature, reduction for possibilities of chances of strain hardening and thus improves the tribological properties.

The tribological behaviour (tool wear and machining chips) indicated that reduction in cutting temperature under conventional or wet and nano based MQL lubrication (NMQL) techniques give appropriate cooling and reduction in machining temperature, which ultimately improves the tool life with reduced flank wear and provides the improved machining performance.

Fig. 22. Saw tooth shaped chips obtained under dry lubrication.

Fig. 23. Long tubular chips obtained under wet lubrication.

Fig. 24. Helical burnt chips obtained under MQL conventional lubrication.

Fig. 25. Long helical chips obtained under h-BN nano MQL lubrication.

5. CONCLUSION

This paper highlights the role of lubrication on finding tool wear characteristics and controlling tribological parameters which are essential in improving machining performances in case of difficult to machine material.

The key findings from this investigation are summarized as below.

Tool Wear

- During dry machining a sudden rise in temperature at tool-workpiece interface was observed to its maximum level ($\sim 300.9^\circ\text{C}$), which stimulated excessive tool wear. In both rake and flank face the major part of tool insert is scooped out causing tool damage and thus reduces tool life.
- In MQL conventional machining high heat is generated due to insufficient cooling at the cutting edge, which $\sim 15\%$ reduction in temperature than dry is machining. The resulting TWA and TWV were found to be reduced by 41 % and 52 % in comparison with dry turning.
- In case of h-BN nano MQL, though the rake face showed burnt marks but most of the heat got dissipated thus shows a reduction of max. temp. to 25 % than dry and 12 % than MQL lubrication methods. This may be due to the presence of superior thermal conductivity of h-BN (hexagonal boron nitride) additives in base cutting fluid in nano form to make it an efficient cutting fluid. Pressurised flow of cutting fluid with hard particles of nano additive causes prominent amount of adhesive and abrasive wears at flank face with small amount of pull outs of carbide grains on rake face.
- With controlled supply of efficient h-BN nano cutting fluid (NMQL) at high pressure on cutting zone, resulted into the reduction of tool wears (TWA as 76 % and TWV as 77 %) than dry and similarly, (TWA as 59 % and TWV as 53 %) than MQL conventional, ultimately which qualifies to be the most suitable lubricating method among others for machining Ni-based super alloys (e.g. here, Inconel 625).

- Machining with wet lubrication gives lowest machining temperature ($\sim 196.9^\circ\text{C}$) in comparison with dry, MQL conventional and NMQL technique along with minor tool wear due to continuous excess flow of lubricant during the machining. But moving ahead towards green sustainable machining option the wet lubrication cannot be considered as a viable option due its negative impact on environment and worker's health along with high cost of disposal.

Chip Morphology

- The chips obtained in dry machining condition were discontinuous saw shaped edges along with dark surface due to high machining temperature. During Wet machining the chips generated were long, tubular with clear surface of chip. The chips obtained in MQL conventional turning were less spiral with saw shaped edges. However, in h-BN nano MQL the chips generated were similar to chips generated under wet lubrication with smooth edged and spiral shape. The length of the chips under wet, MQL conventional and h-BN NMQL turning were in close range of 150 mm, with increase in length of 36 % than dry machining.
- In h-BN MQL tubular shaped sooth edged chips were obtained due to better thermal conductivity of h-BN nano cutting fluid which aided in efficient dissipation of heat at the cutting zone leaving clean smooth finished work surface, thus reducing machining temperature and improving machining process by enhancing the tribological properties.

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