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ORIGINAL ARTICLE

An Improvised Method of Machinability Evaluation with Predictive Temperature Model for Inconel 625: A Holistic Machinist's Perspective

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ABSTRACT – Machinability of any material is defined as how easily it can be machined (cut) and the factors that govern this machinability comprise machining temperature, tool wear, surface roughness, and the shape of the chip. To enhance the machinability of materials, the improvement of these governing factors is a must. In this regards machinability of Nickel alloys is of great concern as they are associated with problems of high heat generation causing tool wear and poor surface finishing, which adds to the product cost. Therefore, this research aims to improve the machinability of Inconel 625 with the use of MQL assisted with h-BN nano cutting fluid. A comparative study of machining performance of h-BN NMQL with dry and MQL conventional conditions is performed. The outcomes of this study establish the superiority of h-BN over dry machining and MQL conventional machining on various machining parameters by reducing both machining temperature and tool wear. The experimental results revealed that the machining with nano h-BN MQL technique reduces the machining tool tip temperature by 25% and 12%, along with the reduction in tool wear by 67% and 47% in comparison with dry and MQL machining. Additionally, this paper also proposes a numerical model for predicting machining tool temperature using machining parameters (speed, feed and depth of cut) during turning of Inconel 625 under nano h-BN MQL technique.

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Tool wear;
Chip morphology

INTRODUCTION

In the machining process, each material has its machining requirements like machining parameters from a selection of machining tools, lubricant, and lubrication method, which affect the machinability of the material. The parameter is based on the ease with which material can be machined with an acceptable surface finish [1]. Machinability can be estimated in terms of characteristics like tool wear, chip formation, and surface finish [2] (see Figure 1). Nickel alloys are known for hard-to-machine materials, have tremendous applications in the areas of aerospace, marine, and biomedical parts because of their favourable properties such as corrosion resistance, good strength, along with superior thermal fatigue. However, the behaviour of these materials is a concern at high machining temperature as it causes excessive tool wear and poor surface finish of the product and is counted in the category of poor machinability materials [3]. A good machining process demands efficient quality of surface finish as well as in terms of economic aspects which is governed by temperature and tool wear. Therefore, machinability characteristics play an important role in manufacturing.

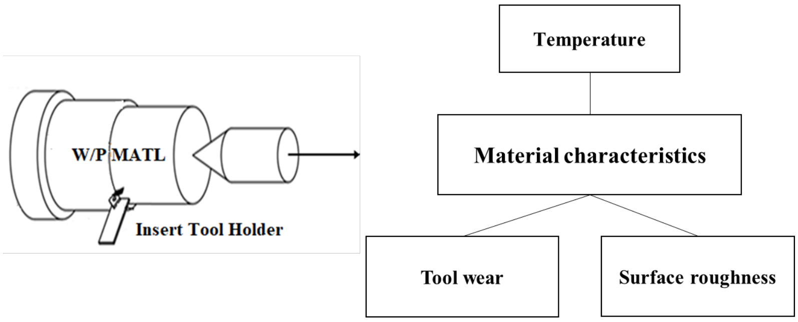

Figure 1. Illustration of the machinability performance.

For enhancement in machinability, cutting fluids are used. Cutting fluids help in reducing the friction at the machining region, subsequently improve the tool life, reduce power consumption and also flush away the chips formed during machining [4]. However, the application of cutting fluid is related to the negative effects on the environment, worker's health along with bearing a measurable amount of cost [5]. As a result, nowadays, different technologies are developed for improving the cooling techniques like MQL (minimum quantity lubrication), NMQL (nano minimum quantity lubrication), cryogenic cooling, and the use of solid lubricants. The technique of nano minimum quantity lubrication

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technique (NMQL) is one of the most effective cooling strategies, which consumes less quantity of cutting fluids leading to a reduction in storage and disposal cost along with the enhancement of the machinability characteristics [6-8]. Nano cutting fluids are synthesised by mixing nano additives in base cutting fluid, and it enhances the thermal conductivity of base cutting fluid, thus improves their cooling and lubricating functionality. NMQL is an improvised form of MQL technique in which the diminished amount of nano-cutting fluid minimises the disposal cost compared to conventional flooded lubrication [9]. Further, studies have revealed that the performance of nano MQL helps in improvising the machinability characteristics like reduction in tool wear, surface roughness, cutting force, and power consumption in comparison with dry, MQL, and cryogenic lubricating techniques. Das et al. [10] concluded with their experimentation that the application of NMQL gives superior machining characteristics like surface finishing, short and thin chips with less curl radius, lower flank wear compared to another conventional method. Similarly, Yuan et al. [11] concluded that NMQL exhibited lower values of cutting force by 10.71% and surface roughness by 14.92%, in comparison with dry and MQL machining techniques. In another study by Jamil et al. [12], it was seen that NMQL machining helps in the reduction of surface roughness by 8.72%, cutting force by 11.8%, and improves tool life by 23% in comparison with cryogenic cooling (cryogenic CO2). Figure 2 shows the advantages of NMQL in enhancing machinability parameters.

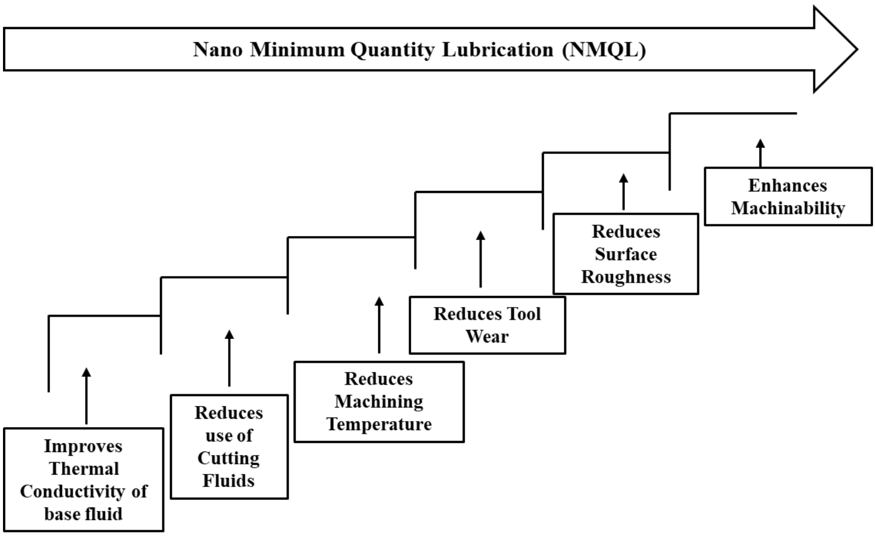


Figure 2. Advantages of NMQL in machinability characteristics.

Further, Yildirim et al. [13] studied the effect of nano-cutting fluid on tool wear, machining temperature, and roughness and concluded that NMQL improves tool wear, surface roughness, and tool life during machining of superalloy. Singh et al. [14] examined the machinability of superalloy Inconel 625 with the use of NMQL (carbon nanotube in vegetable oil) and compared them with that under dry and wet conditions. It was observed that the NMQL gave superior results for machining performance in terms of tool life and surface finish. However, all additives are not environmentally safe and appropriate for their application as additives in cutting fluids. In this regard, hexagonal boron nitride with its properties of non-toxic, good thermal stability, and high thermal conductivity is considered a suitable additive in base cutting fluids [15-16].

However, to date, there appears to be no prominent literature, tribological effects (tool wear and chip morphology, surface roughness) under the boron nitride nano cutting fluid during machining of Ni-based superalloy - Inconel 625. So, to fill this gap, the investigation of the effectiveness of h-BN NMQL with Dry, MQL and NMQL lubrication conditions in the turning of Inconel 625 are studied. Therefore, in this paper, an attempt is made to study the tool wear characteristics and formation of chips under different lubricating conditions of dry, MQL conventional, and h-BN nano MQL during machining of Inconel 625.

Experimental Setup

During experimentation, three lubrication strategies are dry, MQL, and h-BN (hexagonal boron nitride) NMQL. The base cutting fluid during MQL conventional machining is taken as servo-cut ‘S’ from IOCL (Indian Oil Corporation Limited), which has excellent working conditions in a high-temperature environment. The nano additives used are h-BN (hexagonal boron nitride) mixed with base cutting fluid (servo-cut s) for preparation of the nano cutting fluid [17]. An MQL device manufactured by KENCO was used. The MQL system was configured at 4 bar pressure and a 50 ml/h flow rate. The cutting oil was sprayed at a distance of 15 mm with a nozzle diameter of 2 mm, where the nozzle positioned at the rake face. The turning operation was done on Inconel-625 (of Ø40 mm, L350 mm). The details of the chemical composition and physical properties of the work material (Inconel-625) are illustrated in Table 1 and 2. Korloy tungsten carbide (PVD coated TiAlN) tool insert with specifications as- CCMT09T308-HMP, model-PC9030, (flat-faced rhombic shaped with corner angle- 80°, relief angle 7° and rake angle 3°, purchased from J K tools, Telangana) was used during experimentation. For determining the machining parameters, preliminary experiments and literature were used [18]. To see the impact of different lubrication regimes cutting speeds, the feed and cutting depth were kept constant (cutting speed, *v* of 60 m/min, feed rate, *f* of 0.3 mm/rev, and depth-of-cut, *d* of 0.25 mm). Cutting tool temperature was measured during each experiment at the tip of the tool with the help of a dual-wavelength (DW) infrared pyrometer. Whereas, tool wear images with their measurement and element composition were done using SEM (ZEISS GEMINI Scanning electron microscope) to get surface topography by scanning the surface with a focused electron beam. The experimental setup and process followed are shown in Figure 3.

Table 1. Chemical composition (wt. %) of Inconel 625 [14].

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

Table 2. Properties of Inconel 625 [14].

Inconel 625	Properties
Density	8.4 g/cm3
Melting point	1290 - 1350 °C
Tensile strength	880 MPa
Brinell hardness	240 HB
Modulus of elasticity	209MPa
Thermal conductivity	9.8 W/mK
Elongation	35 %

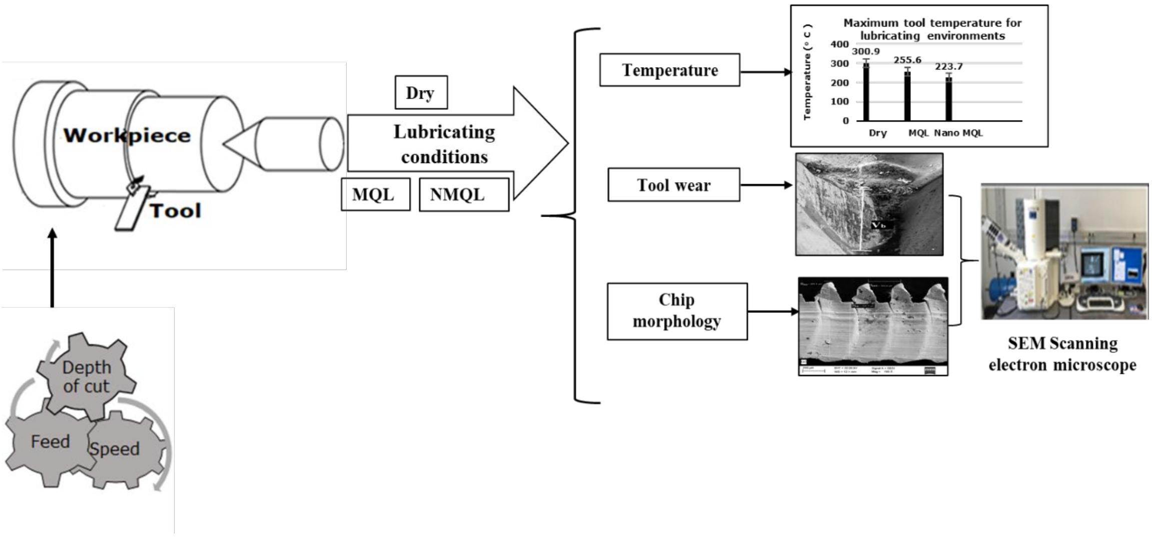


Figure 3. Experimental setup and workflow.

RESULTS AND DISCUSSION

Effect of Lubricating Conditions on Cutting Temperature

Figure 4 depicts the cutting temperature at the tool and chip contact area during machining of Inconel 625 under different lubricating conditions of dry, MQL conventional, and NMQL. The tool temperature was measured with the help of a pyrometer with an accuracy of ± 5%. The average highest recorded cutting tool temperature during the turning process was considered. It was seen that the cutting temperature at contact region is the lowest at 223.7 °C with h-BN nano MQL and increased to a maximum of 300.9 °C for dry turning and was measured as 255.6 °C for MQL conventional turning environment, making it lower by 15% in comparison with the dry condition. With the nano MQL environment, the pressurised lubricant flow (with improved thermal conductivity) helped in better heat dissipation at the cutting zone, which substantially reduces the frictional force. Over ~25% reduction in temperature over dry machining and ~12% reduction with MQL conventional was noticed with the use of h-BN NMQL.

Effect of Different Lubricating Conditions on Tool Wear

Nickel-based superalloys are subjected to excessive tool wear, which is a major concern in manufacturing industries. With poor machinability and high cutting temperatures at the cutting zone, conventionally flood lubrication, i.e. plentiful amount of lubricant, has been the focus to overcome the above problem. The high-cost factor of lubricants, along with the environmental and health risks associated with them, are the main reasons for attempting to reduce their usage [19-20]. Further, an alternative is dry machining. Nevertheless, nickel alloys are hard to be machined under this condition, which leads to high machining temperature and excessive tool wear. Hence, new justifiable and green lubrication practices are essential.

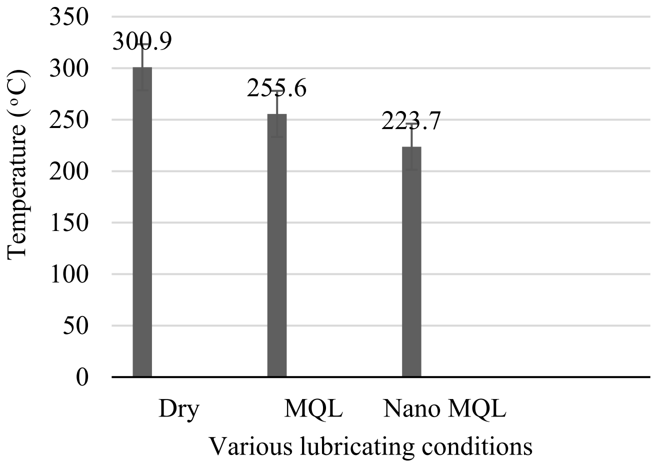


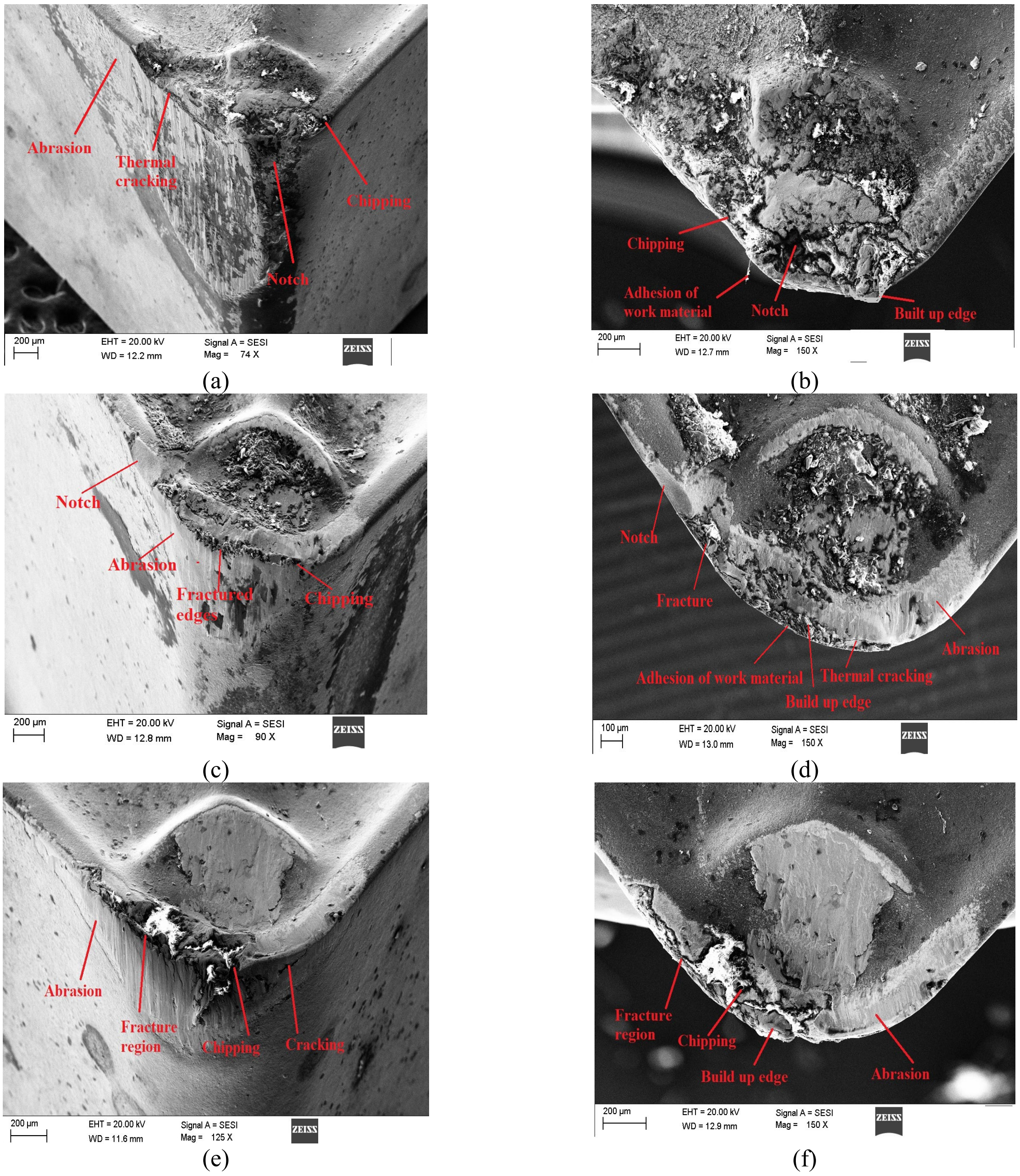
Figure 4. Maximum machining temperatures at the cutting zone.

Nickel alloys are known for low thermal conductivity, so heat in the machining process gets transferred to the tool. This heat generation at the tooltip subsequently causes an excess of tool wear at the cutting edge of the tool. It is a well-known fact that tool wear is an inexorable process during machining, and it progresses till the end of the tool life. To minimise tool wear, the study of wear mechanisms and their causes are important. The wear mechanisms during machining of hard materials are due to multiple factors and have been studied by some researchers in the past, viz. flank wear, breakage wear, notch formation, work hardening, diffusion, abrasion, chipping, adhesion, cracks, tension, high-temperature distribution and effectiveness of tool wear can be judged through formed BUE (built-up edge) at the tip and edge of the tool [13-14, 21]. From our preliminary studies, it is believed that overall cutting performances, including tool wear are greatly affected by the kind of adopted lubricating methods to a large extent. Therefore, an effort is made to investigate tool wears under different (Dry, MQL conventional, NMQL) lubricating environments. The tool wear was measured as seen in Figure 5. The SEM images indicate the characterisation of the wear mechanism of the cutting tool under Dry, MQL, and h-BN NMQL lubricating conditions.

As seen in Figure 5(a) and 5(b), the SEM images (flank and rake face, respectively) for dry machining tends to increase the machining tool tip temperature to 300.9 °C (refer to Figure 4). It is seen that notch formation, thermal cracking, abrasion, adhesion, chipping, and build-up edge (BUE) are major wear mechanisms caused due to developed large amount of friction, high stress, and sudden rise in temperature. The high frictional heat and stresses at the interface region cause metallic bond formation in the form of weld spots which further tend to irregular flow of chip formation. Adhesion is seen as another prominent phenomenon mainly due to the absence of cutting fluid and is caused as the tool material is carried away with the chip. It is also observed that the coating material (TiAlN) completely moves off from the surface, and the substrate material of the tool is exposed immediately to air. Notch formation occurs at the flank face of the tooltip due to the development of local thermal stress concentration causing deformation at the contact face.

Figure 5(c) and 5(d) shows the observed tool wears under an MQL-conventional environment at the flow rate of 50 ml/hr and 4 bar pressure with the position of the MQL nozzle at the rake face. The SEM analysis shows wear on cutting insert during MQL as a fractured region at cutting edge along with notch formation, abrasion, and chipping effect at the cutting edge. In addition, the embedment of chips on the tool’s surface causing adhesive wear, whereas, due to the slow build of local stress concentration, a small amount of deformation or notch is also seen 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 (15%) in comparison with dry cutting). The MQL conventional cutting reduces excessive material loss compared with dry machining. It is evident from SEM images that reduced tool wear occurred because of the pressurised conventional cutting fluid (MQL-conventional) environment, which cools down the cutting interface temperature, results in the reduction of thermal cracking, strain hardening, and other related problems.

The use of a nano-cutting fluid with the MQL technique helps to improve the performance of a machining operation by improvising better heat transfer at the machining zone, which reduces the machining temperature and improves tool wear resistance [15, 22]. In this regard, unique properties like high melting temperature and chemical stability make h-BN nanoparticles application worthy with the MQL technique [23]. The tool wear morphologies from SEM images under the h-BN NMQL technique show reduction in tool wear. This reduction in tool wear is attributed to reduced machining tool tip temperature which is measured at approximately 223.7 °C. It is assumed that the flank wear occurs in the form of abrasive and adhesive mechanism triggered due to the bursting of highly pressurised hard nano-particles and liquid droplets, which hammer at the surfaces of the chip generation and embed these chips on the tool, subsequently causing adhesion of work material on tool. At the same time, the chipping action and formation of BUE were visible at the rake/crater face of the tool. The improvement over the reduction of machining tool temperature by the use of sufficiently less (50 ml/hr) amount of lubricant led to the diminution not only in case of the tool wear but also saves significant costs.



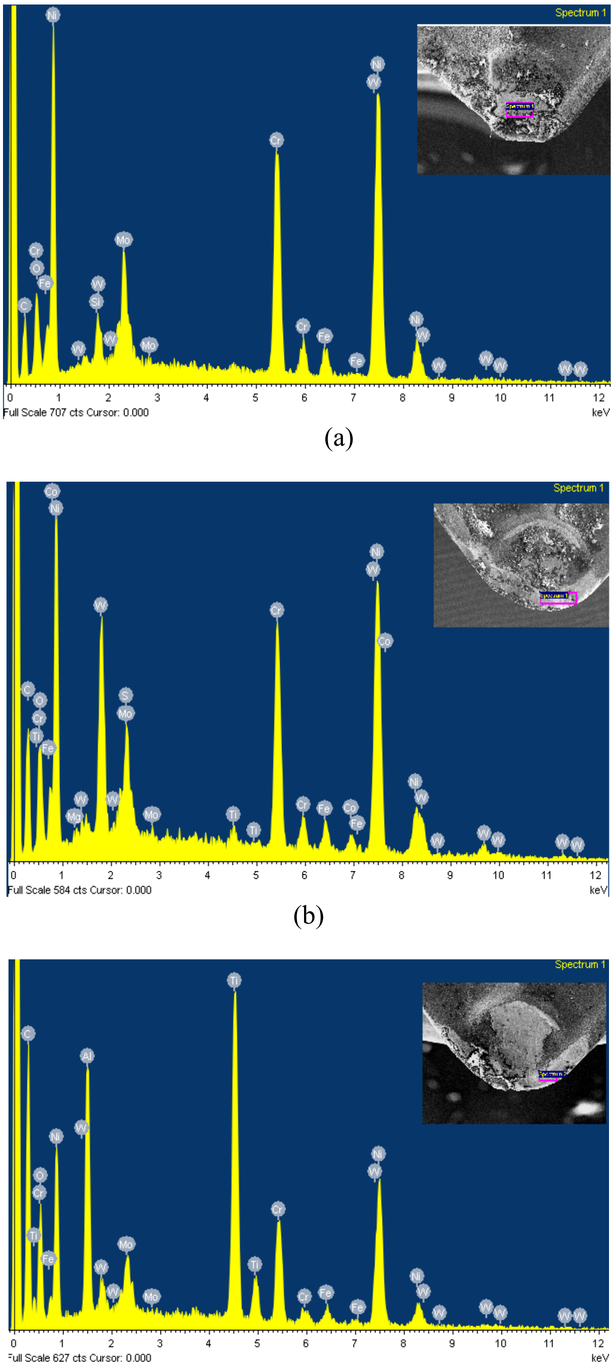
(a) (b)

(c) (d)

(e) (f)

Figure 5. SEM images of the cutting insert under (a),(b) dry, (c),(d) MQL, and (e),(f) h-BN NMQL.

Further, the formation of build-up edge, adhesion, and abrasion mechanism on the cutting insert was seen as common wear characteristics for all the considered lubricating environments in the machining of Inconel 625. Adhesion wear mechanism is further confirmed with the presence of workpiece composition obtained from the EDX analysis for all the cases (refer to Figure 6). The amount of nickel, chromium and iron, which are composition elements for Inconel 625 is found to be high on tool surface for dry turning, as referred in Figure 6(a), which is reduced with MQL in Figure 6(b), and further reduced with h-BN NMQL in Figure 6(c). Similarly, the abrasion wear mechanism is found to be higher in dry turning as the coating of TiAlN is absent from the spectrum however, few traces only can be seen in MQL follow the analogy conventional and h-BN NMQL. Similar studies have been seen by Habeeb et al. [24] in the machining of nickel alloys. The various wear mechanisms observed in this current study for turning Inconel 625 are summarised in Figure 7; it illustrates the causes and effects of various wear mechanisms, which matches almost with the previous works [14], [21], [25].



(a)

Element	Weight (%)
C K	19.31
O K	7.56
Si K	0.69
Cr K	16.22
Fe K	2.61
Ni K	44.27
Mo L	6.48
W M	2.87

(b)

Element	Weight (%)
C K	26.75
O K	9.01
Mg K	0.47
Ti K	0.66
Cr K	11.77
Fe K	1.87
Co K	1.62
Ni K	31.24
Mo L	2.43
W M	13.33

(c)

Element	Weight (%)
C K	38.76
O K	17.22
Al K	4.81
Ti K	13.10
Cr K	5.52
Fe K	0.95
Ni K	15.79
Mo L	2.22
W M	1.62

Figure 6. EDX analysis of tool surface under (a) dry, (b) MQL, and (c) H-BN NMQL.

Figure 8 depicts the measured maximum tool wear, V_b, for various lubricating conditions, where it is evident that there is a difference in wear under different lubricating conditions. The tool wear in the case of dry turning was recorded as the highest (~ 1.4 mm), followed by MQL (~ 0.863 mm), and minimum for h-BN NMQL turning (~ 0.456 mm) due to better thermal conductivity and lubricity provided by the mist of h-BN nano cutting fluid, compared to dry machining and machining with conventional cutting fluid assisted with MQL.

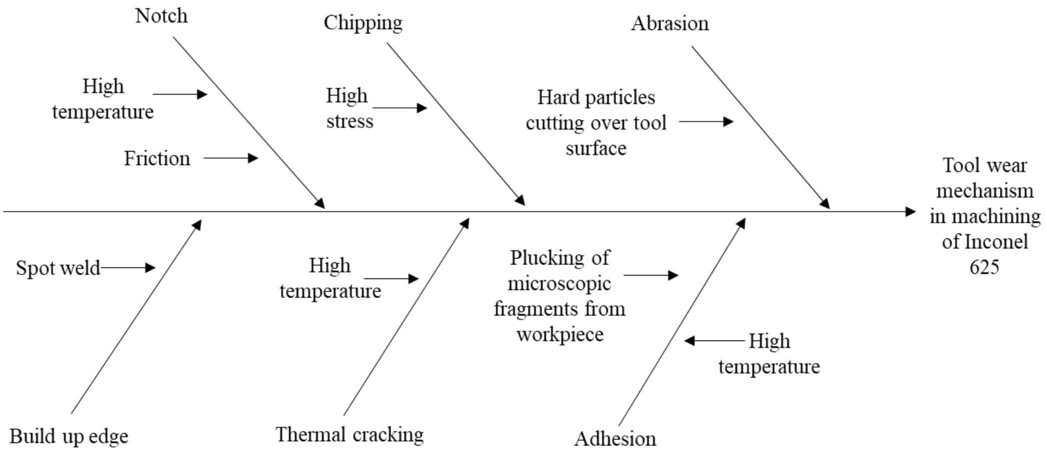
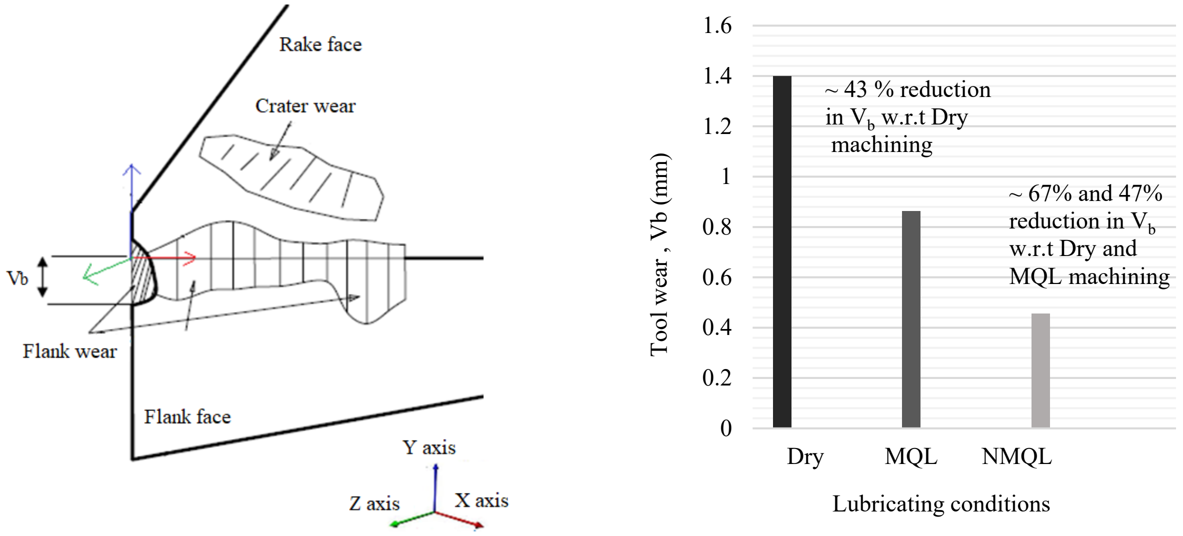


Figure 7. Cause and effect diagram for tool wear mechanism of WC insert.



(a) (b)

Figure 8. (a) Schematic diagram of the tool along with its wears and, (b) variation in tool wear depending on cooling/lubrication regime.

Chip morphology

The lubricating environment during the machining process affects the formation of the chip and its morphology [26, 27]. During machining, with an increased temperature, chips melt and stick to the cutting edge of the tool, which is also known as adhesion wear. The increase in temperature is caused by friction generated at the machining edge due to the lack of lubrication. And, the aforementioned adhesion wear leads to the formation of small spot welds, which caused obstruction at the chip surface and adds to the difficulty in the removal of the chip.

Based on the past studies [25, 28], it is evident that chip morphology transforms prominently with the changing of machining conditions, i.e. chip formation mechanism differs under different machining conditions like thermophysical property of the workpiece, machining parameters, lubrication environment. To depict a better understanding of various factors that explain the evolution of chips, a process has been outlined in Figure 9 below. It shows that continuous ribbon-shaped chips are formed under isothermal deformation, serrated chips are formed in case of ductile fracture condition, and collapsed while broken chips are formed under brittle fracture conditions.

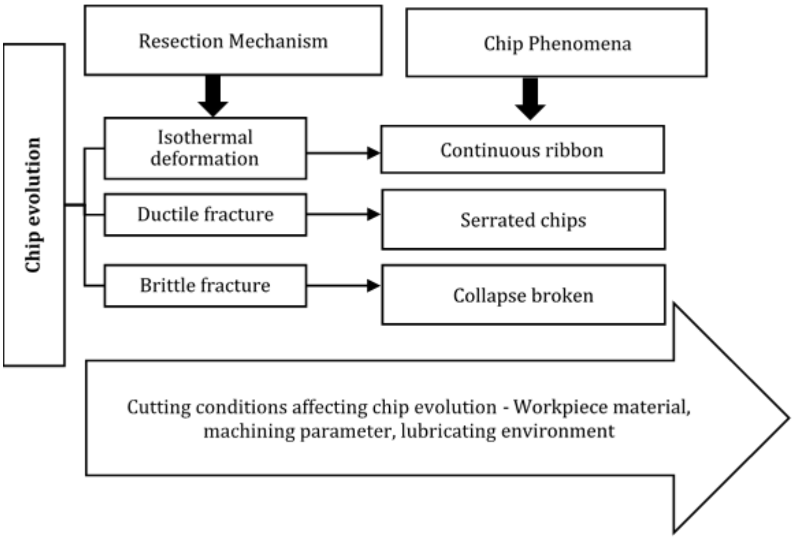
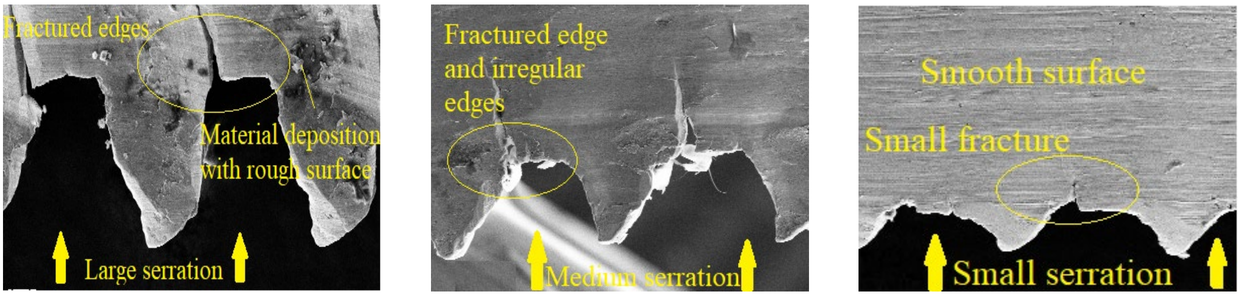


Figure 9. Chip evolution and factors governing chip morphology.

In addition to the existing studies, in the current research, the chips formed under different lubricating conditions (dry, MQL NMQL) are studied and analysed using SEM images (refer to Figure 10). These images show the formation of saw-tooth, also called chip serration, which is a major phenomenon caused due to high temperature and high localised shear at the tool-chip interface. Large serration of tooth with irregular tooth edges along with rough surface and fractured edges at the valley region, as in Figure 10(a), was observed in chips formed during dry turning. Fractured irregular edges were also seen in MQL and NMQL turning (refer to Figure 10 (b), (c)). However, in NMQL turning, the fracture and serration in the tooth were much less than in comparison with Dry and MQL machining. Wang et al. [29] explained that serrated chips are formed due to periodic expansion of cracks on the primary shear zone. Causing heat induction leading to plastic deformation, i.e., the deformation caused due to high temperature initiates the crack formation in chips. This formation and propagation of crack inside the primary shear zone of deformation cause thermoplastic instability which responsible for saw-tooth edge formation. It was also evident from the SEM images that the surface of chips was much smoother in the NMQL machining environment due to better cooling conditions and lubricity provided by h-BN cutting fluid assisted with MQL. From SEM images of chips, it is quite clear that the degree of tool wear affects the chip morphology.

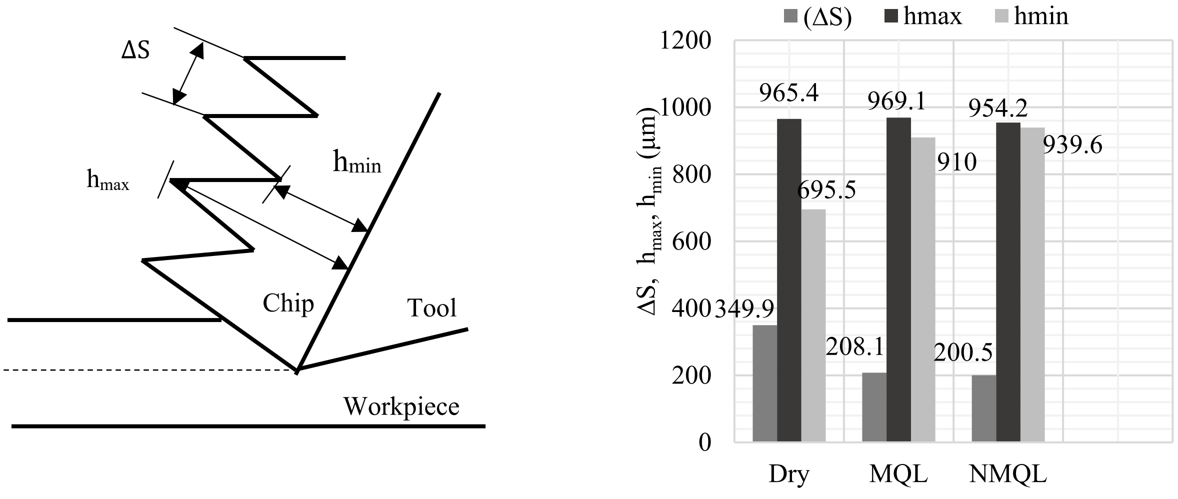


(a) (b) (c)

Figure 10. SEM images of chip cross-section formed under (a) dry, (b)MQL and (c) NMQL environment.

For better understanding, the geometry of serrated tooth is explained in terms of maximum, and minimum height of chip referred to as h_{max}, h_{min} respectively and pitch of saw/ serrated tooth (ΔS) (distance between two successive teeth), as in Figure 11(a). Figure 11(b) shows the chip morphology (ΔS, h_{max}, h_{min}) under different lubricating conditions. The pitch of serrated chips(ΔS) affects the chip segmentation. The chip segmentation frequency of serrated chip (saw-tooth) is defined as reciprocal of the pitch of the serrated chip. Chip segmentation frequencies obtained for MQL conventional and NMQL were in a close range and nearly double the chip segmentation frequency of dry machining. Further, the difference between the h_{max} and h_{min} corresponding to dry turning is much higher indicates large serrations in comparison to MQL and NMQL machining. In dry turning conditions, the depth of the saw-tooth is approximately 28% of the height of the chip. Whereas, for MQL conventional machining, the depth of saw tooth formation is 6 % of the chip height and only 2.6% of chip height in the case of h-BN NMQL machining. The rest of the chip is removed by ductile-type deformation. From the above analysis, it is clear that large serrated tooth formation occurs in dry turning whereas, in MQL conventional turning, the serration is reduced and small serrated chips are formed in NMQL turning.

Large serrations with fractured edges and rough surfaces of chips were observed in dry turning, while comparatively smaller chip serration along with smooth chip edge and smooth surface was observed in MQL and NMQL machining. Based on these findings, it can be stated that the high deformation of chips is due to the high temperature and gets reduced with effective cooling during MQL and NMQL machining.



(a) (b)

Figure 11. (a) Geometry of serrated chip formation and, (b) chip morphology (ΔS, h_{max}, h_{min}) under different lubricating conditions.

Development of a Predictive Model for Interface Temperature

The usefulness of a predictive temperature model is highly desirable from a machinist's perspective. It helps in forecasting machining temperature and taking preemptive steps for a smooth machining operation. For reconnoitring this, the potential cause that affects machining performance (temperature) the experimental analysis was done, and the predictive mathematical model was built for tool temperature (dependent variable) with three input parameters under consideration (speed, feed, and depth of cut as independent variables). For the development of the model, the variables are oriented into 27 experimental runs of nano minimum quantity lubrication (NMQL) cutting. The experiments were generated by a full factorial design plan, as shown in Table 3.

Table 3. Experimental design for cutting temperature.

Sr. No	Speed (m/min)	Feed (mm/rev)	Depth of cut (mm)	Experimental temperature (°C)
1	42	0.1	0.25	197.66
2	42	0.1	0.5	200.15
3	42	0.1	0.75	201.33
4	42	0.2	0.25	203.77
5	42	0.2	0.5	204.4
6	42	0.2	0.75	206.23
7	42	0.3	0.25	211.72
8	42	0.3	0.5	212.2
9	42	0.3	0.75	213.46
10	60	0.1	0.25	210.7
11	60	0.1	0.5	215.9
12	60	0.1	0.75	211.26
13	60	0.2	0.25	213.51
14	60	0.2	0.5	215.7
15	60	0.2	0.75	221.3
16	60	0.3	0.25	223.7
17	60	0.3	0.5	224.52
18	60	0.3	0.75	225.23
19	108	0.1	0.25	226.34
20	108	0.1	0.5	227.8
21	108	0.1	0.75	228.8
22	108	0.2	0.25	235.2
23	108	0.2	0.5	237.45
24	108	0.2	0.75	239.76
25	108	0.3	0.25	231.58
26	108	0.3	0.5	232.6
27	108	0.3	0.75	233.76

The data in Table 3 is expected to be fitting into the general equation for the least square method [30] given as in Eq. (1).

$$Y = a_0 + a_1X + a_2U + a_3W \tag{1}$$

The experimental data can be written as in the following Eq. (2).

$$Y_i = 1 * a_0 + x_ia_1 + u_ia_2 + w_ia_3 + e_i \tag{2}$$

where e_1 is the error, a_0 is the constant for temperature; x_i, u_i, w_i represent speed, feed, depth of cut, and $a1$, $a2$, and $a3$ are the coefficients for speed, feed, and depth of cut, respectively. Further, Eq. (2) is converted to matrix form as follows:

$$\begin{vmatrix} Y_1 \\ Y_2 \\ Y_3 \\ \cdot \\ \cdot \\ \cdot \\ Y_i \end{vmatrix} = \begin{vmatrix} 1 & x_i & u_i & w_i \end{vmatrix} \begin{vmatrix} 1 & x_1 & u_1 & w_1 \\ 1 & x_2 & u_2 & w_2 \\ 1 & x_3 & u_3 & w_3 \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ 1 & x_i & u_i & w_i \end{vmatrix} * \begin{vmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{vmatrix} + e_i$$

The least-square solution for the equation is defined as Eq. (3).

$$(X^T * X)^{-1}\, X^T * Y \tag{3}$$

This can be solved as in Eq. (4).

$$\begin{vmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{vmatrix} = \varnothing_{least\ sq} = (X^TX)^{-1}\, X^T\, Y \tag{4}$$

On solving the above model for experimental data, the final equation in terms of factors:

$$\text{T} = 178.81 + 0.38 * \text{X (Speed)} + 49.356 * \text{U(Feed)} + 5.98 * \text{W (Depth of cut)} \tag{5}$$

Figure 12 shows the graphical representation of predicted temperatures for corresponding experimental trial obtained derived from the predicted model equation. Further, the derived mathematical model in Eq. (5) was validated by experimental data and the error in temperature measurement was found to be less than 10%. Figure 13 is for a graphical representation of variation between experimental and predicted values from the model for temperature.

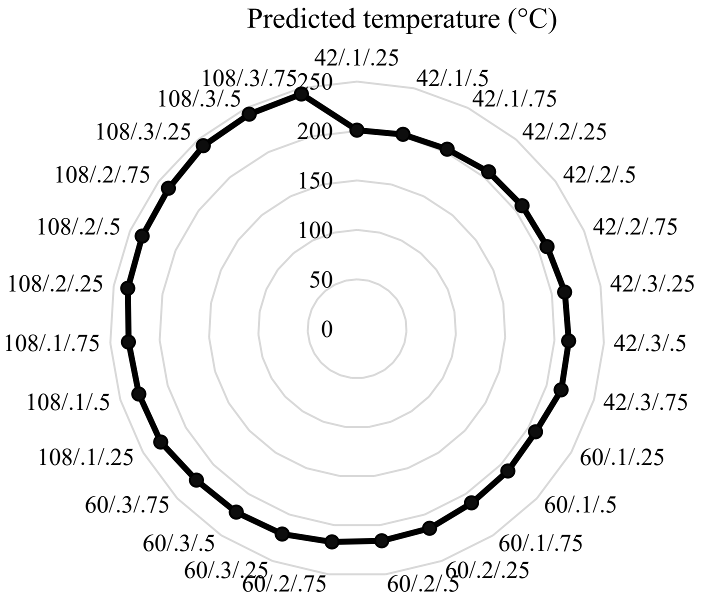


Figure 12. Predicted temperature to corresponding experimental trials.

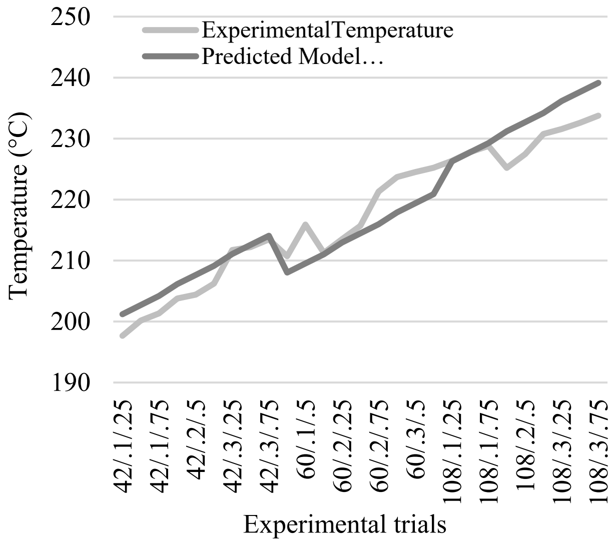


Figure 13. Experimental temperature vs predicted temperature for corresponding experimental trials.

CONCLUSION

This paper highlights the role of lubrication by conducting the turning of Inconel 625 under different lubricating conditions of dry, MQL, h-BN NMQL for finding the effect on tool wear characteristics and chip morphology which are essential in improving machinability in the case of difficult to machine material. The key findings from this investigation are summarised below.

i. During dry machining, a sudden rise in temperature at the tooltip was observed to its maximum level (~300.9 °C), which stimulated excessive tool wear. SEM images showed that major parts of the tool insert from both the rake and flank face is scooped out, causing tool damage and thus reducing tool life.
ii. In MQL conventional machining, the amount of heat generated at the machining tooltip is reduced by ~15 % in comparison to dry machining due to the controlled supply of pressurised cutting fluid. The resulting tool wear was found to reduce by 38% in comparison with dry turning.
iii. In the case of h-BN nano MQL, most of the heat gets dissipated with the use of nano cutting fluid assisted with MQL, thus reducing the machining tool tip temperature to ~25% in comparison with dry turning and by ~ 12% in comparison with conventional MQL environment. This is due to the superior thermal conductivity of h-BN (hexagonal boron nitride) additives in base cutting fluid in nano form to make it an efficient cutting fluid.
iv. With the controlled supply of efficient h-BN nano cutting fluid (NMQL) at high pressure on cutting zone, resulting in the reduction of tool wears by ~ 67% than dry and by ~ 47% than MQL conventional, ultimately which qualifies to be the most suitable lubricating method among others for machining Ni-based superalloys like Inconel 625.
v. From SEM images of tool wear, it is revealed that various wear mechanisms occurring during dry turning are - notch formation, chipping, abrasion, adhesive, and thermal cracking with BUE as main wear modes, whereas comparative smaller notching, abrasion, and adhesion wear with BUE are the prominent wear modes in MQL conventional machining conditions. However, turning under h-BN NMQL environment results in lesser adhesion, abrasion, plastic deformation, and chipping as wear modes compared to the dry and MQL machining environments. Adhesion of work material was observed as common wear phenomenon during machining under dry, MQL, and NMQL environments and was proven well by EDX analysis.
vi. The SEM images of chips showed the formation of rough irregular, fractured edges of the chip due to the severe friction between the tool rake surface and the chip in dry turning of Inconel 625. It was found that under MQL and NMQL environments, the chips have a smooth surface with less fractured edges along with smaller serration.
vii. The derived model for temperature prediction gives an insight to the machinist about machining temperature and possible consequences beforehand.
viii. From the above encouraging results, it can be inferred that the h-BN NMQL technique provides a viable base for sustainable manufacturing with improvised machinability in the machining of hard-to-cut materials, such as Inconel 625, as this technique considerably lowers the machining temperature leading to less tool wear which helps in enhancing the tool life.

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