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Original Article

Evaluation of tool wear, energy consumption, and surface roughness during turning of inconel 718 using sustainable machining technique



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ABSTRACT

Heat resistant alloys such as Inconel 718 present challenges to manufacturing industries during its machining. Machinability of such alloys can be improved using smart cutting conditions. Further, to seek improvements in the machinability of Inconel 718, this assessment evaluates industry-relevant machinability indicator, i.e., tool wear in terms of both flank and crater wear under indigenously developed cryogenic turning technique and compares the results with conventional dry and wet turning techniques. Experimental results show a massive improvement (133%) in tool life under cryogenic turning as compared with the dry turning. However, tool life obtained under wet and cryogenic turning is comparable. In the second part of this paper, industry-relevant machinability indicators namely energy consumption, chip reduction coefficient (*CRC*), and average surface roughness (R_a) were critically examined at different material removal rates (MRR) for turning of Inconel 718 under different cutting environments. A total 24 number of experiments were designed using full factorial considering two levels of cutting speed (v_c) i.e., 45 and 60 m/min, four levels of feed (f_r) i.e., 0.03, 0.06, 0.12, and 0.24 mm/rev, and three cutting conditions (dry, wet, and cryogenic). The results show that energy consumption in cryogenic turning reduced up to 8–17% when compared with dry and wet turning. R_a values for cryogenic turning also reduced up to 20–37% in comparison to dry and wet turning at various MRR. Improved tool life, reduced energy consumption, and R_a values obtained under cryogenic turning echo its potential to replace unsustainable conventional machining practices.

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Nomenclature

a_p	Depth of cut (mm)
CRC	Chip reduction coefficient
FEM	Finite element modeling
f_r	Feed (mm/rev)
MQL	Minimum quantity lubrication
MRR	Material removal rate (mm^3/s)
R_a	Average surface roughness (μm)
SEM	Scanning electron microscope
v_c	Cutting speed (m/min)

1. Introduction

High-performance alloys, for instance, Inconel 718 are used for the manufacturing of critical components for aero, marine, and defense industries. These materials are especially used in hot sections of turbines and engines [1,2]. This is mainly due to their low thermal expansion coefficient and the ability to maintain strength even at high temperatures [3,4]. However, Inconel 718 is categorized as a hard-to-cut material. It is because of its distinct characteristics such as high strength, poor thermal conductivity, and work hardening tendency [5,6]. The high strength of Inconel 718 results in a high magnitude of stress during machining. High stresses in the cutting zone cause high temperatures. Poor dissipation of heat from cutting region owing to the low thermal conductivity of the Nickel alloys leads to heat accumulation [7,8]. Gathering of heat in the cutting region leads to work hardening of material and accelerates chemical reactivity between workpiece and cutting tool. This phenomenon results in a rapid tool wear during the machining of Inconel 718 [9]. Hard abrasive particles in the microstructure of Inconel 718 also cause high abrasion wear during turning. Rapid wear of cutting edge due to abrasion results in the poor finish of the machined surface, short tool life, and an increase in energy consumption [10,11]. Carbon footprints also increase with an increase in tool consumption as high energy is consumed in making cutting tools. Hence, high tool consumption affects the sustainability of the machining processes and increase overall machining cost. Therefore, machining of heat resistant alloys is preferably done using various cooling and lubrication techniques. These techniques enable a quick heat release from the cutting zone and ensure the proper lubrication to decrease friction at chip-tool and workpiece-tool interfaces. However, workers' health hazards and environmental problems associated with the use of cooling and lubrication fluids (particularly oil-based) have motivated researchers to find greener, cleaner, and sustainable machining solutions [12,13]. The latest work of researchers is not only in the direction of machinability improvement of Inconel 718 but also to ensure the sustainability of the machining processes [14,15]. Hence, the researchers proposed a minimum quantity lubrication (MQL) machining technique [16,17]. In MQL, the minimum possible quantity of cutting fluid is supplied in the cutting region in the form of oil mist. MQL technique is effective in providing lubrication but it is unable to dissipate heat efficiently from the cutting zone [10,18]. Oil mist generates during the MQL process also create problems related to workers' health and environmental pollution [19]. Therefore, to address these issues, the cryogenic turning process was employed in this study to seek improvement in tool life and reduction in R_a and energy consumption for machining of Inconel 718. For turning heat resistant alloys, cryogenic turning can become a sustainable option to replace conventional turning techniques [20]. Cryogenic machining has the potential to address problems comes in the machining of hard-to-cut alloys [21,22]. In this technique, cryogenic fluids are employed in place of oil-based cutting fluids as a coolant and lubricant. In cryogenic machining, mostly liquid nitrogen is used. Liquid nitrogen has a low boiling point (−196 °C), it rapidly captivates heat from the cutting region and convert into vapor [23]. Liquid nitrogen does not react with tool materials and coatings due to its inert nature [24]. Hence, it is safe in terms of health aspects of workers. Efforts to improve machinability of heat resistant alloys [4,8,20] and CFRP composites [22,25] using indigenously developed sustainable machining facilities [12,26] are going on at IITRAM Ahmedabad, India by advanced manufacturing research group with other collaborators worldwide. Few important articles from literature related to machinability improvement using advanced machining techniques are discussed here.

Musfirah et al. [27] compared dry and cryogenic milling of Inconel 718 performance in terms of tool wear and surface integrity. Results show reduced tool wear, and cutting force (23%) and improved surface finish (88%) under cryogenic milling. Authors have also reported less contamination and changes in the microstructure of machined part at the subsurface level under cryogenic turning as compared to dry turning. However, authors have not discussed energy consumption in the presented investigation. Ucak and Cicek [28] evaluated the drilling performance of Inconel 718 under different cutting conditions. Authors reported an improvement in surface integrity and hole quality under cryogenic drilling. A decrease in cutting temperature but an increase in thrust force (up to 10%) were reported under cryogenic drilling condition in comparison to dry and wet drilling. However, improvement in the surface finish (up to 56.49%) and tool life (3–7 times) were reported under wet drilling as compared to dry and cryogenic drilling. However, authors have not discussed energy consumption and chip analysis. In another study of Inconel 718 drilling, Khanna et al. [4] reported improvement in circularity, cylindricity, and surface finish under the cryogenic condition in comparison to dry condition. Pusavec et al. [29] compared different sustainable techniques namely dry, cryogenic, MQL (near dry), cryogenic + MQL for turning of Inconel 718. Authors evaluated tool life, machined surface quality, energy efficiency, and chip breakability under these conditions. The best performance has obtained under cryogenic condition in terms of tool life, chip breakability, and surface finish. The worst performance was obtained for turning under dry condition. Authors also observed the highest cutting force values for cryogenic turning. However, tool wear in terms of crater wear was not analyzed in that study. Hribersek et al. [30] proposed finite element modeling (FEM) to predict residual compressive stress and cutting force for turning of Inconel 718 under dry, flood, and cryogenic conditions. In this study, higher cutting force (7%) was reported under

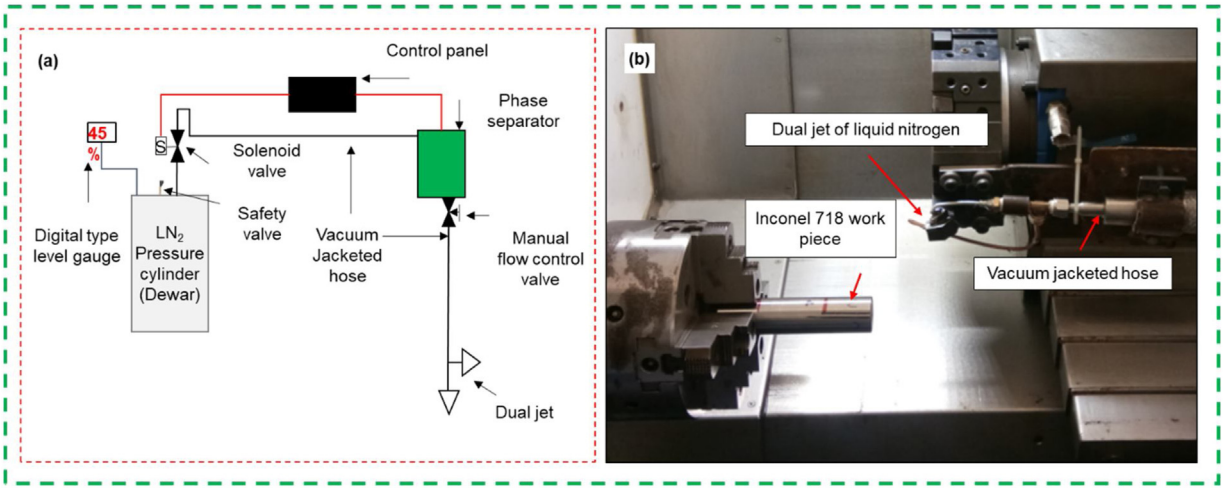


Fig. 1 – (a) schematic of the cryogenic machining setup; (b) experimental setup.

cryogenic condition as compared to flood and dry conditions. Authors also revealed better compressive residual stress was obtained when cryogenic fluid was delivered on flank face in place of rake face. In another study, a method of determining the coefficient of heat transfer between Inconel 718 and liquid nitrogen using the inverse approach was proposed [31]. However, authors have not investigated tool wear and energy consumption. Aramcharoen and Chuan [32] compared dry, wet, and cryogenic milling of Inconel 718. Authors reported the benefits of cryogenic milling in terms of increased tool life, reduced friction, reduced power consumption, and contamination-free machined surface. Kenda et al. [33] found increased residual stress under cryogenic machining condition on the machined surface which prevails at a deeper depth. Authors also reported improvement in machined component life due to increases in wear resistance and fatigue life. And claimed that it was mainly due to increased workpiece hardness (from 600 HV to 800 HV) and extended compressive stress zone. However, authors have not explored crater wear under altered machining conditions.

The above few articles available in the literature have analyzed the machinability of Inconel 718 using different machining techniques. In these studies, cryogenic machining was presented as a most promising sustainable machining solution when it comes to machine heat resistant alloys. However, only a few researchers have explored tool wear phenomena and energy consumption during cryogenic turning for Inconel 718 [4,27,29]. There is hardly any evidence for effects of cryogenic condition on crater wear in available literature. Hence, this paper presents an assessment of tool wear in terms of flank and crater wear together for turning of Inconel 718 under different cutting conditions. Furthermore, cooling methods comparison amongst dry, wet, and cryogenic was made to evaluate their suitability for turning of Inconel 718. This comparison is made in terms of industry-relevant machinability indicators such as energy consumption, chip morphology (in terms of CRC), and R_a at different MRR. For that purpose, this article offers a detailed investigation to highlight the benefits of cryogenic turning in comparison with conventional turning practices. The conclusions of this investigation demonstrate the potential of cryogenic turning to replace conventional turning practices.

2. Experimental setup and research methodology

Experimental trials were conducted on a Macpower make CNC turning center (VX 100) for dry, wet, and cryogenic turning of Inconel 718. For wet turning experiments, YBI Belcool make (EZ500) water-soluble cutting oil was used with a 5% concentration.

For cryogenic turning, the existing machine tool was retrofitted with liquid nitrogen delivery setup as shown in Fig. 1. Liquid nitrogen was stored in Dewar at a pressure of 6 bar. Liquid nitrogen was supplied from 200 L Dewar at 1.5 L/min of flow rate via two nozzles of 1.5 mm diameter each (Fig. 1). To measure the flow rate, a digital capacitance level sensor was installed on Dewar. To ensure the delivery of nitrogen in liquid form, vacuum jacketed hose and phase separator were employed in liquid nitrogen delivery system [26]. To investigate tool wear in detail, both flank and crater wear were measured. Mitutoyo make toolmakers microscope was used to quantify flank wear. To measure crater wear and to assess the wear path profile of inserts an optical profilometer (Alicona Infinite Focus G5) was used. To detect the surface morphology of inserts after the turning process a classical scanning electron microscope (SEM) Hitachi 3400 SEM was used. R_a values were measured using Taylor Hobson make S128 surface roughness tester with settings for cutoff and evaluation lengths of 0.8 and 4 mm respectively. Fluke 435 (series II) three-phase power quality and energy analyzer equipped with a data logger was employed for quantifying energy consumption during turning.

Chemical composition of workpiece used in this study is presented in Table 1. Cylindrical bars of $50 \times 150\,mm^2$ (diameter × length) was used as the workpiece. Kyocera made rhombic shape TiAlN coated carbide inserts of PR 1535 grade with ISO designation as CNMG120408 were used in this study. For mounting the inserts, a tool holder designated by ISO as

Table 1 – Chemical composition of Inconel 718.

Element	C	P	Ti	Co	Si	Mg	S	Cr	Mo	Nb	Fe	Al	Ni
Weight%	0.012	0.005	0.851	0.122	0.205	0.12	0.007	17.76	3.86	4.88	17.02	0.372	54.786

Table 2 – Input process parameters for tool wear analysis.

Input process parameters					
v_c (m/min)	f_r (mm/rev)	a_p (mm)	Turning conditions		
60	0.05	0.5	Dry	Wet	Cryogenic

ACLNL2525M12-A was used. The cutting tool geometry constitutes a nose radius of 0.8 mm, back and side rake angle of −6°, approach angle of 95°, and clearance angle of 15°.

First part of this study analyzes tool wear (both flank and crater wear) under different cutting conditions. Table 2 presents cutting parameters used for analyzing tool wear. These input process parameters were decided based on literature survey. Variation of energy consumption and R_a values with tool wear is also analyzed in this part.

In the second part, energy consumption, *CRC*, and R_a were analyzed at various MRR under different cutting conditions. In this part, two levels of v_c, four levels of f_r, and constant depth of cut (a_p) were considered. Experiments were designed using the full factorial technique as presented in Table 3. Two replicates were performed for each experiment to minimize random experimental errors. Average values of responses obtained in three trials were considered in the results.

3. Results and discussion

In this section results obtained for turning of Inconel 718 under different cutting conditions are presented. Subsection 3.1 presents the results of the first part, i.e., tool wear analysis. Energy consumption, *CRC*, and R_a at different MRR values are discussed in the second subsection of this section.

3.1. *Tool wear assessment in terms of flank and crater wear*

For flank wear evaluation, ISO 3685:1993 standard is considered in this study [21]. As per this standard, turning was stopped when the average flank wear width (V_b) reached 0.3 mm. In this study, flank wear was measured using a tool maker's microscope. While crater wear was analyzed using SEM microscopy and 3-D optical profilometry techniques. In the case of dry turning, tool wear reached the failure criteria quickly after turning about 150 mm of length. While, in the case of wet turning, the tool fails after turning 350 mm length. However, in cryogenic turning, the flank wear reached its criteria a little over 350 mm. Hence, flank wear results of cryogenic turning are comparable with wet turning as shown in Fig. 2.

To strengthen the above assertion, the cutting inserts were examined using the SEM images analysis as shown in Fig. 3. In those images, the rake face of the cutting inserts used for dry, wet, and cryogenic turning were examined. Cutting insert

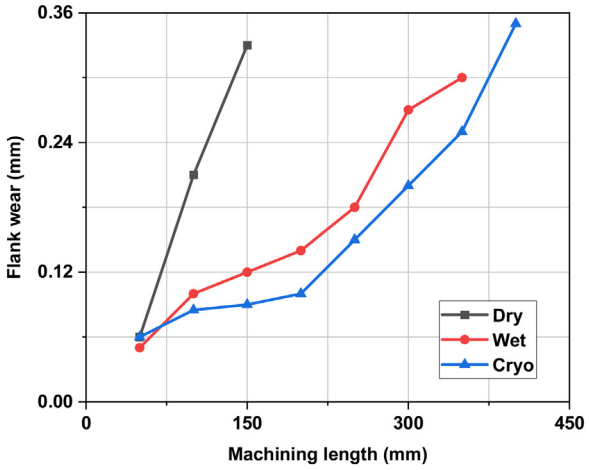


Fig. 2 – Variation of flank wear with turning length under dry, wet, and cryogenic turning.

used for the dry condition has gone under severe plastic deformation and abrasion as exposed in Fig. 3(a).

High temperature at cutting zone in case of dry turning accelerates thermally activated wear for instance high localized deformation of the tool due to work hardening [4]. This phenomenon accelerates abrasion of cutting insert under dry turning. High friction at the tool-chip interface due to sticking of chips and high tool load in case of dry turning also cause abrasion [8]. Application of cutting fluid in case of wet turning and liquid nitrogen in case of cryogenic turning have altered tool wear pattern as can be observed from Fig. 3(b, c). Evidences of interface fracture were observed in the SEM image of the insert used for wet turning as shown in Fig. 3(b). However, this fracture occurs after turning more than double length as compared to dry turning. Deposits of Nickel were observed on the insert used for cryogenic turning as shown in Fig. 3(c). This can be due to loosely connected chips on the rake face of cutting insert.

In the case of wet and cryogenic turning, chipping and adhesion mechanism was predominantly seen as a reason for tool wear. Effective cooling and lubrication at the cutting interfaces in case of wet and cryogenic turning ensured reduction in flank wear as mentioned earlier. In case of cryogenic turning, liquid nitrogen absorbs a large amount of heat from cutting zone and convert into vapor without leaving any residue on tool and workpiece. This helps in lowering the temperature in the cutting region and lessen thermally induced wear such as adhesion and diffusion wear. In this study, nearly 133% improvement in tool life was observed under wet and cryogenic conditions when compared with the result under dry condition. In brief, there were dissimilar modes of tool wear for different cutting conditions. No certain wear pattern could be recognized. In its place, it can be claimed that

Table 3 – Design of experiments.

Experiment number			Input process parameters			MRR = $\frac{v_c \times f_r \times a_p \times 1000}{60}$ (mm^3/s)
Dry turning	Wet turning	Cryogenic turning	v_c (m/min)	f_r (mm/rev)	a_p (mm)	
Dry - 1	Wet - 1	Cryogenic - 1	45	0.03	0.5	11.25
Dry - 2	Wet - 2	Cryogenic - 2	60	0.03	0.5	15
Dry - 3	Wet - 3	Cryogenic - 3	45	0.06	0.5	22.5
Dry - 4	Wet - 4	Cryogenic - 4	60	0.06	0.5	30
Dry - 5	Wet - 5	Cryogenic - 5	45	0.12	0.5	45
Dry - 6	Wet - 6	Cryogenic - 6	60	0.12	0.5	60
Dry - 7	Wet - 7	Cryogenic - 7	45	0.24	0.5	90
Dry - 8	Wet - 8	Cryogenic - 8	60	0.24	0.5	120

the wet and cryogenic turning demonstrated less abrasion as compared to dry turning.

The 3D optical profilometry measurements permit to detect the dimensions of crater wear in terms of width and depth. Fig. 4 plots show the 3D optical profilometry acquired for dry, wet and cryogenic machining, respectively. Further, Fig. 4(a–f) presents separately the wear scar as detected on the close view of rake face. In Fig. 4(a & b), it can be seen that the wear scar that has the profile like a groove with a depth almost of 13 μm and width of 350 μm in case of dry turning. The plastic deformation was highlighted around crater extremities caused by the high temperature released during the turning under dry condition.

Fig. 4(c & d) show wear track of insert used for wet turning. In this case, crater wear depth reduced from 13 μm under dry turning to 6 μm. In contrast, in Fig. 4(e & f) some high peaks were noted that are associated with material deposition (sticking) of Inconel 718 related to adhesion wear under cryogenic turning. There are deposits of material with dimensions of 23 μm high of which have a width of 750 μm. Therefore, the profile measurements are shown in Fig. 4(e & f) reveals almost negligible crater wear produced under cryogenic condition.

In the case of the dry turning of Inconel 718, serrated (saw-tooth) chips were obtained because of the localized adiabatic shear band formation due to thermal softening at high tem-

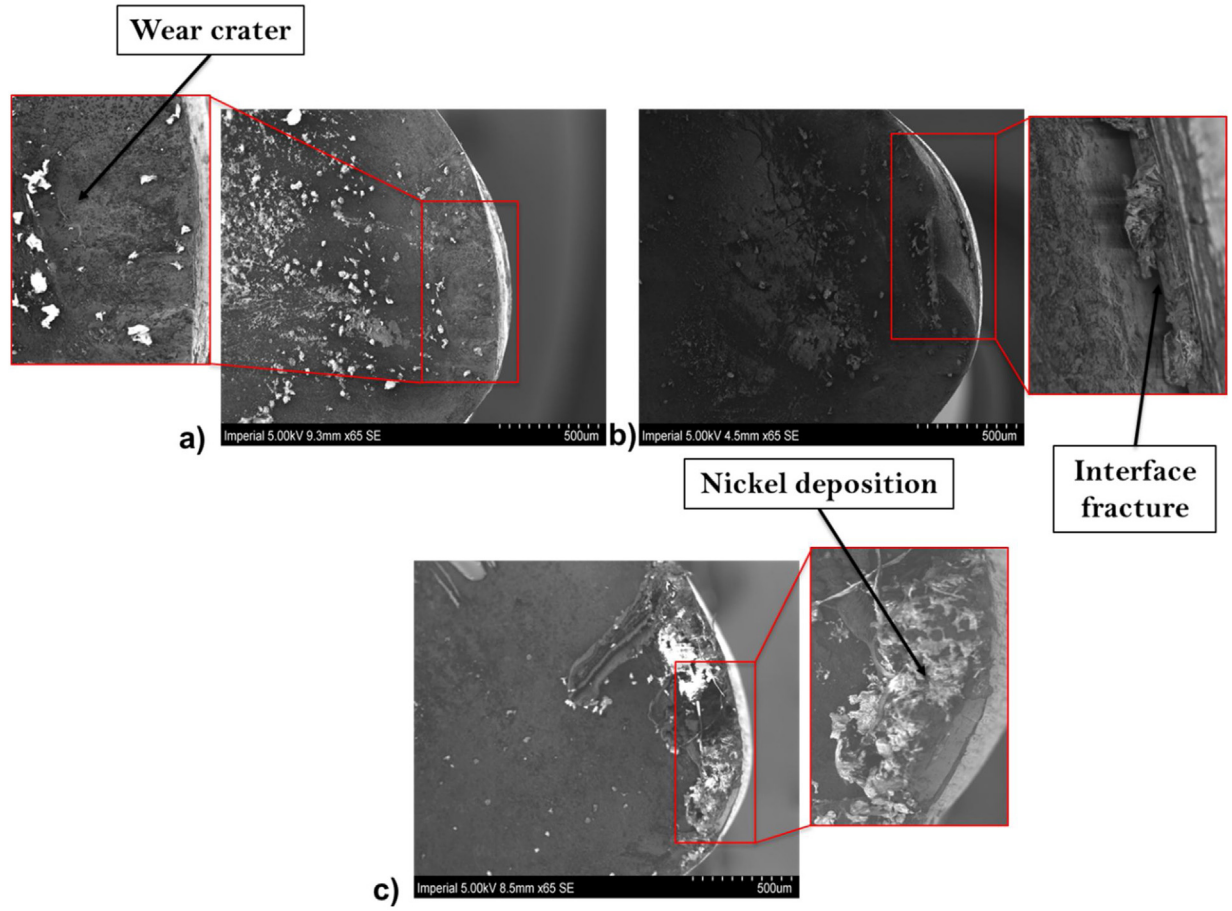


Fig. 3 – SEM images that depict the wear mechanism identified on inserts used for (a) dry, (b) wet, and (c) cryogenic turning, respectively.

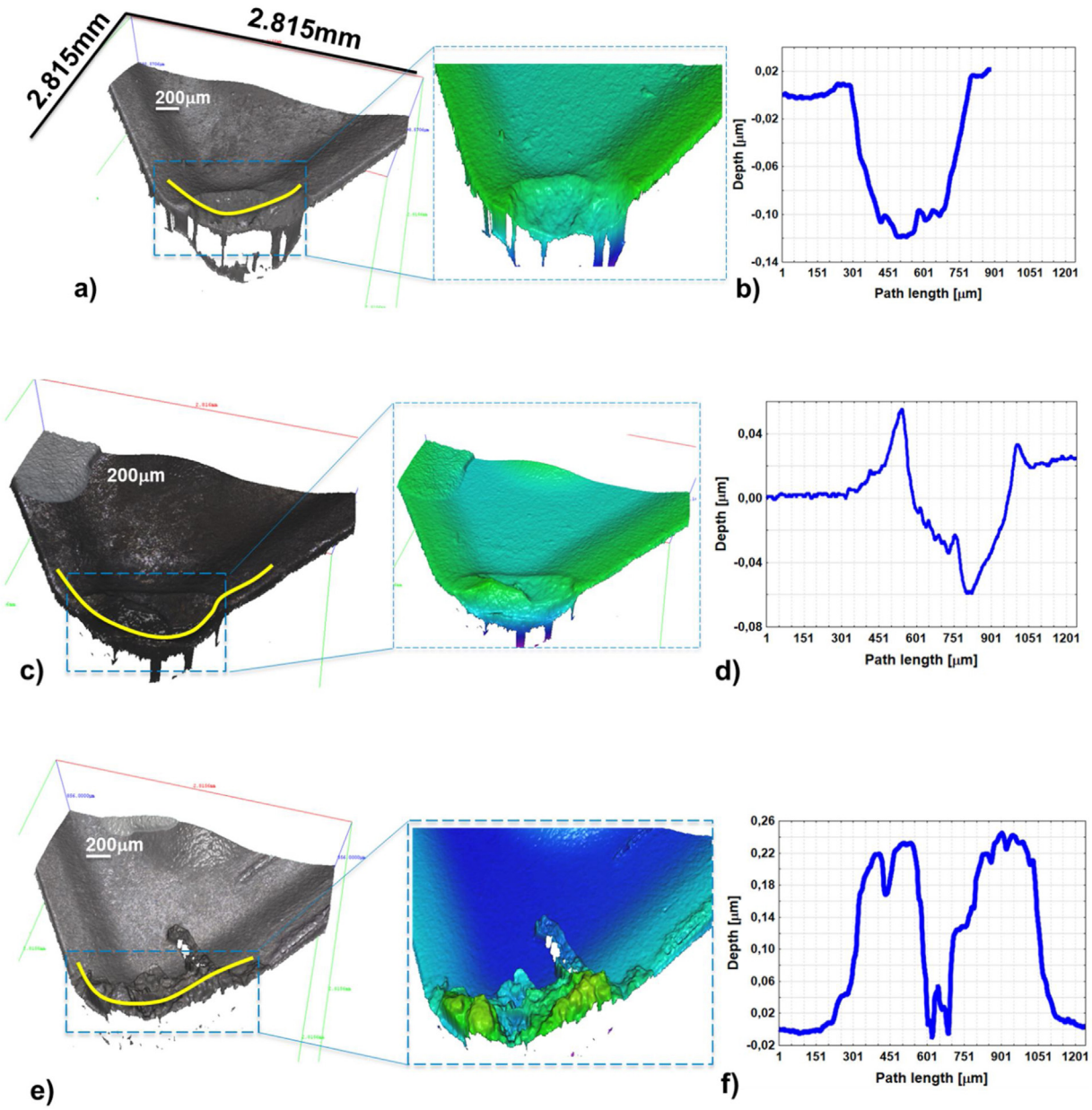


Fig. 4 – 3D optical surface profile depicting the crater wear track of inserts after turning (a, b) 150 mm of dry turning; (c, d) 350 mm of wet turning; and (e, f) 350 mm of cryogenic turning (yellow lines indicate the wear path profile measured).

perature as shown in Fig. 5(a). This can be due to severe crater wear observed under dry turning. Serrations on the chip significantly reduce under the wet condition as shown in Fig. 5(b & c). Chips obtained in turning under wet and cryogenic conditions were uniform, stable, long and loose coiled shaped. It can be due to an ample cooling effect at the cutting zone. Allu

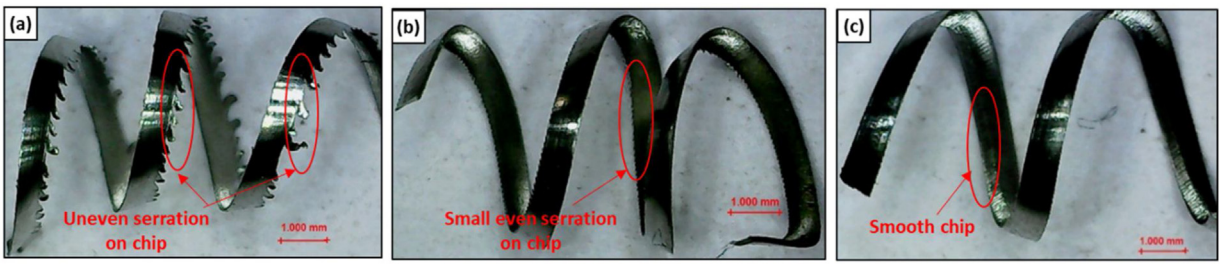


Fig. 5 – Chip obtained for turning of Inconel 718 under (a) dry; (b) wet; and (c) cryogenic condition.

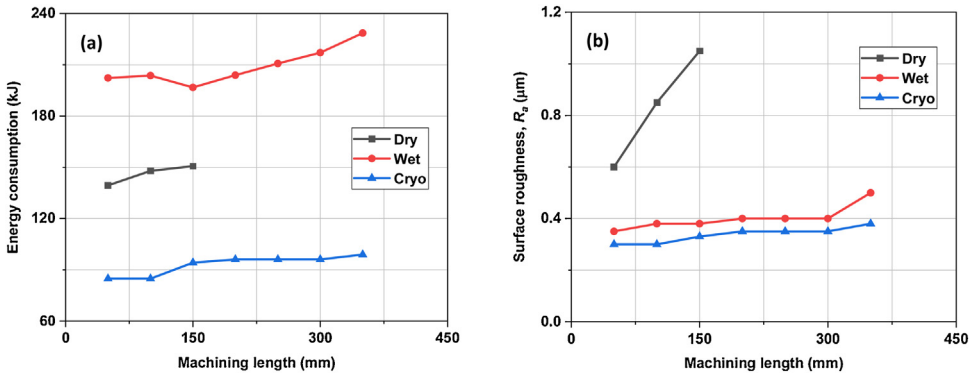


Fig. 6 – variation of (a) energy consumption and (b) R_a values with flank wear progress under dry, wet, and cryogenic turning.

et al. [34] also observed similar chips pattern for turning of Inconel 718.

Fig. 6(a) presents the energy consumption and R_a values behavior with flank wear progress during turning under different cutting conditions. From Fig. 6(a), it can be observed that energy consumption is more accentuated in the case of wet turning. This is due to excess energy used in maintaining flow, filtration, and recirculation processes during wet turning.

The energy consumption in the case of dry turning was also more as compared to cryogenic turning. This can be attributed to rapid tool wear, high friction coefficient and restricted movement of chips in case of dry turning as discussed in the previous section. Trends for the R_a values are shown in Fig. 6(b). Poor surface finish in case of dry turning is due to the rapid increase in the flank wear as shown in Fig. 2 and uneven serrations on chips (Fig. 5a). In the case of dry machining, the heat generated in the cutting zone does not dissipate through conduction mode owing to the low thermal conductivity of Inconel 718 [4]. Surface finish improved when turning under the cryogenic condition in comparison to wet (up to 24%) and dry (up to 68%) conditions.

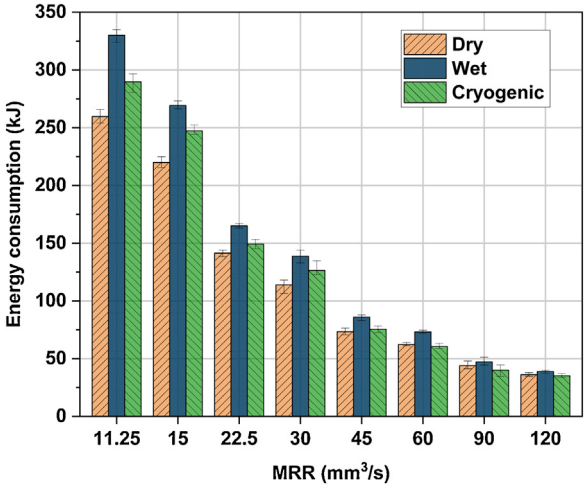


Fig. 7 – Variation of energy consumption at various MRR under different cutting conditions.

3.2. *Detail analysis of machinability indicators under dry, wet, and cryogenic turning of Inconel 718 at different MRR*

This section presents a comparison of energy consumption, CRC, and R_a values under different cutting conditions at different MRR values in consecutive subsections.

3.2.1. *Energy consumption analysis*

Energy consumption significantly varies with input process parameters and cutting conditions [35]. To reduce overall energy consumption, it is necessary to identify suitable input process parameters and cutting condition so that machine tools can be designed to consume less energy. In this study, energy consumed in turning of Inconel 718 at various MRR values was observed under different turning conditions as presented in Fig. 7.

Under all three turning conditions energy consumption decreased with increases in MRR values as shown in Fig. 7. It is because of a reduction in machining time with increase MRR values. Energy consumption was highest in the case of wet turning. It is because of extra energy is required for the functioning of the coolant system in case of wet turning. When cryogenic and dry turning were compared, it was observed that the energy consumption is high in the case of lower levels of MRR (11.25–45 mm^3/s) and low at higher levels of MRR (60–120 mm^3/s). It is because of an increase in the strength and hardness of a workpiece under cryogenic conditions [36]. Since the workpiece was exposed to cryogenic condition for a longer period at lower MRR values, an increase in hardness is expected to be more and due to this energy consumption at low MRR is high in case of cryogenic turning. However, energy consumed during turning at higher MRR value (60–120 mm^3/s) reduced up to 8% under the cryogenic condition as compared to dry condition. Energy consumed in cryogenic turning condition was up to 27% less as compared to wet turning. A similar trend in energy consumption was also presented in the existing literature [36]. Lesser energy consumption for cryogenic turning promotes its sustainable advantage over dry and wet turning. These results of energy consumption suggest that cryogenic turning can be used at higher process parameters to achieve productivity goals.

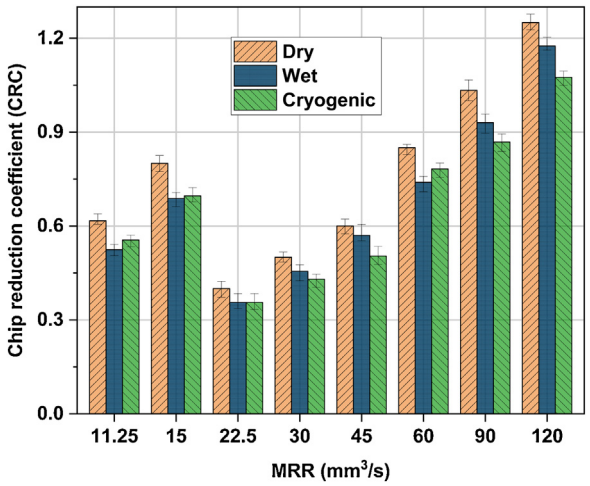


Fig. 8 – Variation of CRC at various MRR under different cutting conditions.

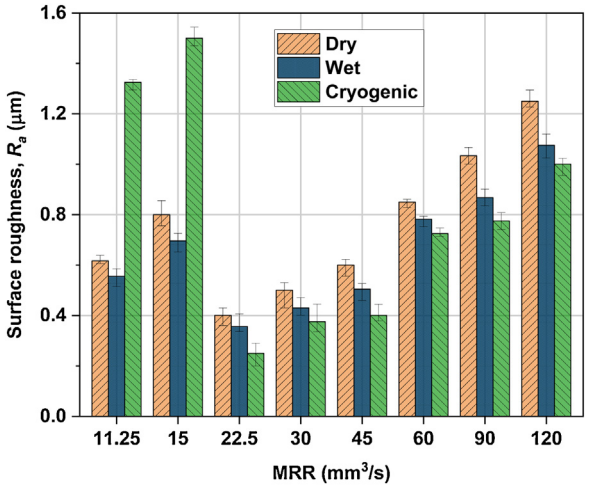


Fig. 9 – Variation of R_a at various MRR values under different cutting conditions.

3.2.2. *CRC analysis*

As per established relation between chip thicknesses (t_c), shear plane angle, and coefficient of friction, thin chips are an indication of better machinability. This is due to less force needed to shove off the material. Thin chips represent a low friction coefficient. In this study, chips are analyzed in terms of *CRC*.

$$CRC = \frac{t_c}{f_r \times Sin\,\emptyset} \tag{1}$$

An analytical expression for the *CRC* is presented in Eq. 1. It is a relation between t_c, f_r, and primary cutting edge angle (Ø). The primary cutting edge angle of cutting insert used in this study is 95°. Fig. 8 shows *CRC* variation obtained for turning Inconel 718 at various MRR under different cutting conditions. *CRC* values reduce up to 14% under wet and cryogenic conditions as compared to dry turning. Reduction in *CRC* values in the case of wet and cryogenic turning indicates a reduction in friction coefficient at the cutting interface. This is because of the reduction in the temperature of cutting region and improvement in lubrication at the chip-tool interface under wet and cryogenic conditions. However, *CRC* values under cryogenic condition were observed to be least at most of the MRR values in comparison with dry and wet conditions. It can be due to the assistance of the cryogenic condition in restricting the change in the microstructure of chips. Park et al. [36] have also reported increased stability of chips under cryogenic environment for turning of Ti-6Al-4V when compared with dry and wet environments. Lower values of *CRC* for turning under cryogenic condition suggest its suitability over dry and wet turning in terms of providing necessary lubrication and cooling effects.

3.2.3. *R_a analysis*

Variation of R_a values for turning of Inconel 718 at various MRR under different cutting conditions is presented in Fig. 9. It was observed that R_a values increase with an increase in MRR except at very low MRR under all three cutting conditions. Best surface finish values were obtained under cryogenic turning followed by wet and dry turning respectively.

R_a values reduce up to 37% as compared to dry and 20% as compared to wet turning under cryogenic turning. This can be due to improvement in *CRC* under the cryogenic condition in comparison with dry and wet conditions. Reduction in tool wear under cryogenic condition can also be a primary reason for the decrement in R_a as compared to dry condition. Uneven serrations on the chips in case of dry machining as shown in Fig. 5(a) due to high heat generation can be the reason for poor surface characteristics. Although, *CRC* and R_a have

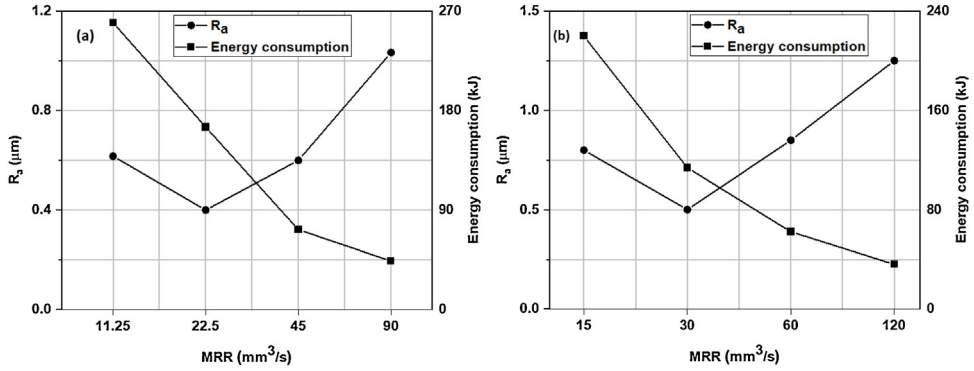


Fig. 10 – Interaction of R_a and energy consumption for turning under dry condition at (a) v_c = 45 m/min; (b) v_c = 60 m/min.

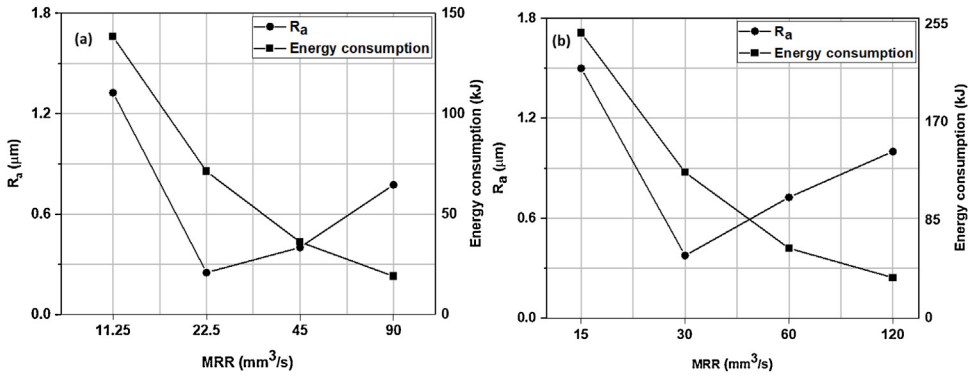


Fig. 11 – Interaction of R_a and energy consumption for turning under wet condition at (a) v_c = 45 m/min; (b) v_c = 60 m/min.

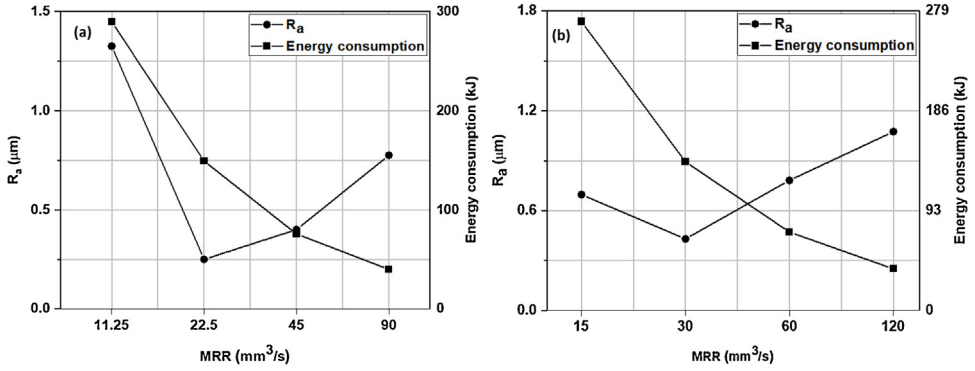


Fig. 12 – Interaction of R_a and energy consumption for turning under cryogenic condition at (a) v_c = 45 m/min; (b) v_c = 60 m/min.

shown significant reduction under wet turning as compared to dry turning. However, cryogenic turning proved most effective for achieving lower R_a as compared to conventional turning practices.

Interaction plots of R_a values and energy consumption are shown in Fig. 10, Fig. 11, and Fig. 12 for dry, wet, and cryogenic turning respectively. These graphs are plotted at different v_c i.e., 45 and 60 m/min under different cutting conditions. As the MRR is the product of v_c, f_r, and a_p. At constant v_c and a_p, MRR will increase with the increase in f_r values. It can be observed from the graphs that R_a is increasing with the increase in MRR values except at very low MRR values. However, energy consumption is decreasing with an increase in MRR due to a decrease in machining time.

Interactions plots can suggest an optimum MRR that can be used for a particular v_c and cutting condition. In the case of wet and cryogenic conditions interaction points move towards higher MRR. However, energy consumption under wet turning is substantially high as compared to dry and cryogenic turning. Surface characteristics under dry turning and energy consumption in case of wet turning are also not promising. Hence, cryogenic turning can be projected as the greener, cleaner, and sustainable machining technique for turning of Inconel 718.

4. Conclusions

This study investigates the machinability of Inconel 718 in terms of tool wear (flank and crater wear), energy consumption, *CRC*, and R_a using cryogenic turning and compared the performance under dry and wet turning. Following conclusions can be drawn from this study:

- The highest tool life was obtained for cryogenic turning, while the lowest tool life was obtained for dry turning. Tool life was significantly improved by nearly 133% for wet and cryogenic turning when compared with dry turning.
- Assessment of SEM images of cutting inserts reveal that the abrasion wear is the main reason for high flank wear in case of the dry turning of Inconel 718. However, in the case of wet and cryogenic turning, chipping and adhesion mechanism were predominantly seen as a reason for tool wear.
- Crater wear assessment using 3D optical profilometry offers detail regarding the wear width and depth under different cutting conditions. Noticeable large crater wear width and depth were seen under the dry condition from the close view of the rake face as compared to wet and cryogenic conditions. Wear mechanism noted for dry operation is associated with abrasion wear. Besides, on the crater extremities, some hills were seen with an accentuated peak that can be attributed to plastic deformation progress. These are produced because of elevated temperature in the cutting region during the dry turning. Some specific peak hills associated with adhesion wear were detected under cryogenic condition.
- Variation of R_a and energy consumption with tool wear were also noted. Higher R_a and energy consumption were

observed in the case of dry and wet turning in comparison with cryogenic turning.

- At higher MRR (60–120 mm^3/s), energy consumed for cryogenic turning decreases up to 8% in comparison to dry turning. This is due to decrement in the *CRC* under cryogenic condition and improved tool life. However, at lower MRR (11.5–45 mm^3/s) energy consumption was high for cryogenic turning as compared to dry turning. This can be due to the extreme cooling of the workpiece at low MRR.
- Energy consumption in cryogenic turning also reduced up to 17% as compared to wet turning. This is due to high energy consumption in the coolant system in case of wet turning. The further decrement in *CRC* values obtained under cryogenic condition also suggests better cooling and lubrication as compared to wet turning can also be a reason for reduced energy consumption.
- R_a values found poor at low MRR (11.5 and 15 mm^3/s) in the case of cryogenic turning. This can be due to the extreme cooling of the workpiece at low MRR. However, at higher MRR (22.5−120 mm^3/s), R_a was reduced under cryogenic turning when compared with dry (up to 37%) and wet turning (up to 20%). Reduction in *CRC* values up to 14% under cryogenic turning as compared to dry and wet turning can also be a reason for a reduction in R_a values.

Conflict of interest

The authors confirm that this work has not been published elsewhere and also it has not been submitted simultaneously for publication elsewhere.

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Navneet Khanna: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing - review & editing, Formal analysis. **Chetan Agrawal:** Methodology, Conceptualization, Data curation, Writing - original draft, Formal analysis, Software. **Manu Dogra:** Formal analysis, Resources, Writing - review & editing. **Catalin Iulian Pruncu:** Formal analysis, Writing - review & editing.

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