Effect of cryogenic coolant on turning performance: a comparative study

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Abstract

In the recent years, environmental regulations became stringent in terms of disposal of chemically contaminated conventional coolants. Cryogenic cooling is an alternative technique to the conventional cooling technique with conventional coolants. In this work, new findings were reported in turning of 17-4 precipitation hardenable stainless steel (PH SS) at varying feed rate conditions under cryogenic cooling and the results were compared with the minimum quantity lubrication (MQL), conventional wet and dry cutting conditions, respectively. Turning performance considered in this work includes cutting temperature, surface roughness and tool wear. From the findings, it was noticed that a maximum of 24%, 26% and 69% reduction in surface roughness was observed in cryogenic machining when compared to MQL, wet and dry environments, respectively. Also, the maximum flank wear reduction found in cryogenic machining was 42%, 48% and 53%, respectively, over the MQL, wet and dry environments. Overall, it was concluded that cryogenic machining is a feasible method for improving the turning performance characteristics in machining of 17-4 PH SS.

Keywords Cryogenic machining · Surface roughness · Minimum quantity lubrication · Tool wear · Dry · Wet · 17-4 PH stainless steel

1 Introduction

17-4 PH SS has many emerging applications in the field of aerospace industry, nuclear industry, chemical industry and marine industry owing to peculiar properties like high corrosion resistance, high ductility and high strength [1, 2]. The presence of 17% chromium and 4% nickel as major constituents in the chemical composition of 17-4 PH SS is the reason for the aforementioned attractive properties. These attractive properties make this material an alternative to the high-cost titanium material in the aerospace industry to make stator parts of aircraft engine [3]. Productivity improvement while machining of 17-4 PH SS is a difficult work due to the limitation of higher cutting conditions. Machining of 17-4 PH SS material was associated with poor surface quality and high machining cost due to formation of built up edge (BUE) on the cutting

tool. One of the methods to overcome the above-mentioned problems is the use of coolants in conventional as well as alternative cooling methods. But conventional coolants are chemically contaminated (formaldehyde, carcinogenic, biocides) and adversely affect the health of the manual operator as well as the environment [4]. Many environmentally conscious regulations restricted the usage of conventional coolants in the metal cutting industry because of these bad effects [5].

On the other hand, some of the environmentally conscious machining processes are dry, MQL, hot and cryogenic machining. Mohanty et al. [2] have conducted machinability studies on 17-4 PH SS under the dry condition, and more adhesion wear and poor quality of machined surface were found. Similarly, Khani et al. [6] have carried out an experimental study on 17-4 PH SS under the hot machining environment and observed

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more progressive tool wear due to high temperatures at the machining zone. MQL machining is not able to avoid the accumulation of chips at the machining zone at the higher cutting conditions, and also it is not able to eliminate the health problems completely due to the presence of oil mist in the machining surroundings [7].

Cryogenic machining is an emerging manufacturing process; it avoids health and environmental issues with conventional coolants. In the present study, liquid nitrogen (LN_2) was taken as a cryogenic coolant and an intensive study has been carried out with LN_2 and the results were compared with dry, wet and MQL cooling environments. In the recent years, few researchers have used cryogenic coolants, and machinability studies were carried out during machining of different grades of materials. Jerold and Kumar [8] have utilized cryogenic coolants at the machining zone during turning of AISI 316 stainless steel and observed superior results as a function of surface roughness, tool wear, chip morphology and cutting temperature over wet and dry machining. Hong et al. [9] reported that the application of LN_2 with high pressure causes the penetration of LN_2 at the contact zone of asperities, resulting in low friction due to the microscale hydrostatic resultant force. LN_2 provides lower cutting temperatures, which changes the nature of contact from sticky to sliding, resulting in reduced effective shear strength to shear off the material. Spraying of LN_2 at the tool–workpiece zone allows the soaking of the cutting tool with LN_2 , resulting in increased hardness of the tool and hence low tool wear and maintaining good surface integrity characteristics. Hong [10] conducted experiments on five different pairs of surface and concluded that regardless of the type of pair, LN_2 generates hydrodynamic film which provides the lubrication effect. Gupta et al. [11] observed that during turning operation, superior machinability of AISI 1040 steel material can be achieved with the cryogenic machining over dry machining due to the better control of cutting zone temperatures. Biermann et al. [12] obtained improved tool life in the simultaneous application of MQL and cryogenic machining environment due to the better lubrication effect compared to the pure cryogenic environment during machining of two different grades of titanium alloys, namely Ti–6Al–4V and Ti–6Al–2Sn–4Zr–6Mo. Putz et al. [13] improved product quality, and chip morphology was observed in cryogenic machining during machining of elastomer material compared to dry machining. Mia and Dhar [14] employed two cooling methods using liquid nitrogen, namely single nozzle at rake face of the tool and dual nozzle to cool both rake and flank faces of the tool in turning of Ti–6Al4V. From the results, it has been found that dual-nozzle cooling methods significantly reduced the tool wear, surface roughness, cutting temperature and cutting force when compared to single-nozzle cooling

with liquid nitrogen and dry cutting conditions, respectively. Islam et al. [15] supplied liquid nitrogen through the end mill tool and found superior end milling performance in machining of hardened EN 24 steel when compared to dry and flood cutting conditions, respectively. In the literature, few optimization studies have been carried out on various difficult-to-cut materials under sustainable machining techniques [16–20]. In the literature, most of the comparative analyses of various performance characteristics were only performed either under the dry, cryogenic machining or wet, cryogenic environments. Very limited work was carried out under the cryogenic, MQL and dry environments [21, 22] while cutting machining of superalloys.

In the recent times authors carried out experimental investigation in turning of 17-4 PH SS at varying cutting velocity and depth of cut conditions under cryogenic, MQL, dry and conventional cooling conditions [23, 24]. Further, Sivaiah and Chakradhar investigated the effects of novel external cryogenic spray method on turning of 17-4 PH SS [25]. From the literature, it has been observed that limited effort has been put on comparative evaluation of turning performance during machining of 17-4 PH SS under the cryogenic, MQL, wet and dry environments, respectively, at varying feed rate conditions. 17-4 PH SS has many applications in various emerging fields, so there is a necessity to carry out the extensive experimental investigation on it. Hence, the current work is carried out at varying feed rates and at constant cutting velocity and depth of cut of 78.5 m/min and 1 mm, respectively, while machining 17-4 PH SS under different cooling environments (cryogenic, MQL, wet and dry). Cutting temperature, surface roughness and tool wear were taken as turning performance characteristics.

2 Experimental work

Conventional lathe (Make: Kirloskar; Model: Nagmati-175) has been used to conduct the experiments on 17-4 PH SS under all machining environments. Before performing the actual experiments, the received workpiece was fixed at the headstock and facing operation as well as the center drill was done to overcome the overhanging problem. In the received material, microcracks on the surface as well as wobbling were present, which can badly affect the machining quality. Therefore, to eliminate these effects, 1 mm of top layer was removed from the received material. Selection of cutting tool was done based on the manufacturer's recommendation (SNMG120408 MP). For each experiment, a new cutting edge was chosen for observing the tool wear for a constant time of 4 min. Table 1 lists the experimental details considered for the present

Table 1 Experimental conditions

Workpiece material and size	17-4 PH SS round bar and ($\varnothing$ 50 mm $\times$ 300 mm)
Workpiece chemical composition	(Ni—3.546%, Cr—16.179%, Cu—3.177%, Mn—0.744%, Si—0.360%, C—0.042%, P—0.028%, S—0.011% and Fe—balance)
Cutting inserts	AlTiN PVD-coated KC5010, tungsten-coated carbide inserts (an ISO designation of SNMG120408 MP), Kennametal made
Tool holder	ISO specification of PSBNR 2020 K12
Working insert tool geometry	Inclination angle: -6° , rake angle: -6° , clearance angle: 6° , nose radius: 0.8 mm, major cutting edge angle: 75°
Turning process parameters	Cutting velocity (v): 78.5 m/min; feed rate (f): 0.048, 0.096, 0.143, 0.191 and 0.238 mm/rev; depth of cut (d): 1 mm
Environments and coolants used	Cryogenic cooling (LN_2); dry (no coolant); MQL and wet (emulsion-based flood cooling: 1:20 soluble oil)
Cutting fluid supply	Cryogenic cooling—compressed air: 4 bar, flow rate: 0.45 kg/min MQL cooling—compressed air: 4 bar, flow rate: 70 ml/h (through external nozzle) Wet cooling—flow rate: 6 l/min (through external nozzle)
Nozzle diameters used to spray coolant for different environments	Cryogenics and MQL: $\varnothing$ 1 mm, wet: $\varnothing$ 10 mm

investigation. Trial experiments have been performed for selection of range of each process parameter. In the present investigation, machinability studies at various cooling environments like cryogenic, MQL, wet and dry conditions were performed and comparison of turning performance characteristics at the various feed rates was made keeping other input parameters constant. Feed rate is an important parameter because it has proportional relationship with material removal rate; hence, in the present study machinability characteristics were investigated at varying feed rate conditions. Table 2 shows the experimental results. In the literature, researchers have adapted similar experimental plan to study the machinability characteristics [11, 26].

LN_2 was sprayed at the tool tip and workpiece interface by using a fabricated low-cost external cryogenic jet cooling setup. The developed cryogenic machining setup consists of Indian Oil Corporation Ltd (IOCL)-made 'TA-55' Dewar tank to store the LN_2 at -196°C , and compressed air has been utilized to take out the LN_2 from the tank and supply it to the machining using external nozzle in the jet form. For MQL experimentation, air coolant mist was supplied at the tool tip–workpiece interface by using 'Dropco156' model MQL machining setup. Figure 1 depicts the machining zone images under different cutting environments.

For tool wear analysis, each experiment was conducted with a 4-min constant time. 'ZEISS-made AXIO LAB A1' model optical microscope was used to measure the tool wear. Average surface roughness (R_a) was considered as surface quality characteristic and was measured by using 'MITUTOYO SJ301' surface tester. For each machined sample, five respective R_a readings were noted down with a cutoff length (λ_c) of 4 mm and the average was considered

as actual surface roughness parameter. Surface morphology and tool wear mechanisms have been investigated by using 'JEOL-JSM-6380 LA' model scanning electron microscope (SEM). 'CENTER 350'-type calibrated infrared thermometer was used to measure the maximum machining zone temperatures. The machining zone temperatures obtained in the present work may not represent the actual value because chips and coolants at the machining zone interrupted the infrared ray of the thermometer.

3 Results and discussion

3.1 Effect of cooling environment and feed rate on cutting temperature

As shown in Fig. 2, as the feed rate increases, cutting temperature at the machining zone increases. The reason might be that as feed rate rises, the friction between the tool and workpiece increases, which causes the rise in heat generation at the contact asperities, resulting in the generation of high temperature at the machining zone. Figure 2 depicts that at a low feed rate of 0.048 mm/rev, the corresponding temperature values for the dry, wet, MQL and cryogenic machining were 74, 64, 61 and 23°C , respectively. At this point, MQL and wet machining conditions have developed almost equal temperature. At this situation, the cryogenic machining reduced the cutting temperatures by 69%, 64% and 62%, respectively, over the dry, wet and MQL machining conditions. Similarly, the respective temperature drop in cryogenic machining was 72%, 52% and 45% compared to dry, wet and MQL machining conditions at a high feed rate of 0.238 mm/rev. From the obtained results, it

Table 2 Experimental results

S. no.	Cutting velocity (m/min)	Feed rate (mm/rev)	Doc (mm)	Temperature (°C)				Surface roughness (μm)				Flank wear (μm)				Rake wear (μm)			
				Dry	Wet	MQL	Cryo	Dry	Wet	MQL	Cryo	Dry	Wet	MQL	Cryo	Dry	Wet	MQL	Cryo
1	78.5	0.048	1	74	64	61	23	2.23	0.93	0.91	0.69	65	56	47	38	216	189	167	142
2	78.5	0.096	1	80	75	68	30	1.96	1.68	1.43	1.25	98	87	78	49	237	218	192	151
3	78.5	0.143	1	102	81	73	36	2.57	1.81	1.72	1.68	129	113	99	64	268	256	226	167
4	78.5	0.191	1	127	86	76	40	3.21	2.41	2.3	2.19	187	168	153	88	319	287	252	174
5	78.5	0.238	1	155	89	78	43	3.94	3.65	3.46	2.78	273	251	215	131	367	325	291	192

was observed that significant machining zone temperature reduction was found in cryogenic machining over the other machining environments. These favorable results are owing to the spraying of low-temperature LN_2 at the machining zone, which led to low temperatures. These favorable cryogenic results indicate that it reduces the friction between the contact asperities. As a whole, the temperature drop range found in cryogenic machining was 63–72%, 52–64% and 45–62%, respectively, compared to dry, wet and MQL machining environmental conditions with an increase in feed rate from 0.048 to 0.238 mm/rev, respectively. In the literature, Gupta [11] observed 93.5% reduction in cutting temperature during turning of AISI 1040 medium-carbon steel under cryogenic condition over dry cutting condition. The obtained results from the present work are in good agreement with the literature results.

3.2 Effect of cooling environment and feed rate on tool flank wear

From Fig. 3, it is observed that as feed rate increases, flank wear increases under the all cooling environments. This trend is due to the higher cutting temperatures caused by higher material removal rates at higher feed rates, which results in more tool flank wear. It is seen from Fig. 3 that at a low feed rate of 0.048 mm/rev, the respective tool flank wear measurements was 65, 56, 47 and 38 μm for dry, wet, MQL and cryogenic machining. At this point, the respective tool flank wear reduction found in cryogenic machining was 42%, 32% and 19% over the dry, wet and MQL machining conditions. However, at this same condition, the respective flank wear reduction in MQL machining was 28% and 16% compared to dry and wet machining. The flank wear reduction found at a high feed rate of 0.238 mm/rev was 52%, 48% and 39%, respectively, compared to dry, wet and MQL machining, as shown in Fig. 3. At this condition, 21% and 14% reduction in tool flank wear was found in MQL compared to dry and wet machining, respectively. This resulting reduction in cutting zone temperatures offered by LN_2 causes less built up edge (BUE) on the cutting tool edge. Figure 4 depicts the SEM images of tool flank wear obtained at the respective given conditions. It is evident from the SEM analysis that less adhesion wear (BUE) was found in cryogenic machining compared to other machining environments in the respective given conditions. In cryogenic machining, the major tool wear mechanism found was abrasion only, whereas in other machining environments it was adhesion and abrasion mechanisms. Similar results were obtained in the literature [21, 27]. In overall, the tool flank wear reductions found in cryogenic machining were in the range of

Fig. 1 Machining zone at different environments: **a** cryogenic, **b** MQL, **c** wet, **d** dry

Fig. 2 Effect of cooling environment on cutting temperature at varying feed rates

42–53%, 32–48% and 19–42%, respectively, over the dry, wet and MQL machining conditions when the feed rate varies from 0.048 to 0.238 mm/rev.

Fig. 3 Effect of cooling environment on tool flank wear at varying feed rates

3.3 Effect of cooling environment and feed rate on tool rake wear

Figure 5 depicts the effect of feed rate on tool rake wear, and it shows an increasing trend when feed rate rises.

Fig. 4 SEM images of tool flank wear at $v=55$ m/min, $f=0.238$ mm/rev and $d=1$ mm under different cooling environments: **a** cryogenic, **b** MQL, **c** wet, **d** dry

Fig. 5 Effect of cooling environment on tool rake wear at varying feed rates

This rise in the tool–chip contact length at high feed rates causes high cutting temperatures and hence more rake wear [28]. It is observed from Fig. 5 that at a low feed rate of 0.048 mm/rev, the tool rake wear values for dry, wet, MQL and cryogenic machining were 216, 189, 167 and 142 µm, respectively. At this situation, the tool rake wear

reduction found in cryogenic machining was 34%, 25% and 15%, respectively, over the dry, wet and MQL machining condition. Similarly, MQL machining also substantially reduced the tool rake wear by 23% and 12% over the dry and wet machining conditions, respectively. Similarly, tool rake wear reduction obtained in cryogenic machining at a high feed rate of 0.238 mm/rev was 48%, 41% and 34%, respectively, compared to dry, wet and MQL machining, as depicted in Fig. 5. Likewise, at this condition, 21% and 10% reduction in tool rake wear was found in MQL machining over the dry and wet machining, respectively. From the obtained results at all the feed rates, it was found that cryogenic machining substantially reduced the tool rake over the other machining conditions. This is because of the reduction in friction at the contact asperities, which results from an effective control of machining zone temperatures with LN_2 cooling, and the reduction in tool–chip contact length leads to less rake wear [28]. Another reason might be the effective control of adhesion between the tool and workpiece due to the better control of machining zone temperatures. As a whole, when feed rate varies from 0.048 to 0.238 mm/rev, the tool rake wear reduction range in cryogenic machining was 34–48%, 25–41% and 15–24%, respectively, over the dry, wet and MQL machining. Figure 6 depicts the tool wear mechanism observed using

Fig. 6 SEM images of tool rake wear at $v=55$ m/min, $f=0.238$ mm/rev and $d=1$ mm under different cooling environments: **a** cryogenic, **b** MQL, **c** wet, **d** dry

SEM analysis under different cooling conditions. From SEM analysis, it is evident that at all the feed rates, less adhesion wear (BUE) was found in cryogenic machining compared to other machining cooling conditions. At higher feed rates, the major wear mechanisms found in cryogenic, MQL and wet machining were of adhesion type, whereas adhesion and abrasion type was found in dry machining. In the literature, Kaynak et al. [27] also noticed adhesion as a major tool wear mechanism in dry and MQL turning NiTi Alloy.

3.4 Effect of cooling environment and feed rate on average surface roughness

In the present study, an investigation was carried out on the effect of feed rate on average surface roughness and it showed an increasing trend with varying feed rates as depicted in Fig. 7. It is well known that feed rate and surface roughness have a proportional relationship. Another reason might be the generation of more tool wear at high feed rates due to high cutting zone temperature, resulting in more toolmarks on the machined surfaces. At all the feed rates, cryogenic machining generated lower

Fig. 7 Effect of cooling environment on surface roughness at varying feed rates

surface roughness values than the other cooling environments. The measured surface roughness values found at a low feed rate of 0.048 mm/rev in dry, wet, MQL and cryogenic machining were 2.23, 0.93, 0.91 and 0.69 μm ,

respectively. At a low feed rate of 0.048 mm/rev, the reduction in surface roughness obtained was 69%, 26% and 24%, respectively, in cryogenic machining over the dry, wet and MQL machining. At this same point, MQL machining also reduced surface roughness by 59% and 2%, respectively, compared to dry and wet machining. The reduction in surface roughness in cryogenic machining was due to the less adhesion of workpiece material to the cutting tool (BUE) and retain of cutting tool edge, which are results of the spraying of low-temperature LN_2 . Figure 8 depicts the surface morphology obtained on this given condition. From the SEM analysis, it was found that less side flow of material from the tool cutting edge and less adhered chip particles contributed to low surface roughness in the cryogenic machining. Particularly, the more side flow of material was found in dry machining due to the high cutting temperatures compared to other cooling environments. In the same way, at a high feed rate of 0.238 mm/rev, 29%, 24% and 20% respective reduction in surface roughness was found in cryogenic machining compared to dry, wet and MQL machining, as shown in Fig. 7. Similarly, at this point, MQL machining reduced the surface roughness by 12% and 5% over the dry and

wet machining, respectively. Overall, the range of surface roughness reduction in cryogenic machining was found to be 29–69%, 7–26% and 2–24%, respectively, compared to dry, wet and MQL machining. Similar results were obtained in the literature [21, 29].

4 Conclusions

- The maximum temperature drop found in cryogenic machining was 72%, 64% and 62%, respectively, compared to dry, wet and MQL machining.
- The maximum tool wear reduction found in cryogenic machining was 53%, 48% and 42%, respectively, over the dry, wet and MQL machining conditions.
- The maximum surface roughness reduction in cryogenic machining was found to be 69%, 26% and 24%, respectively, compared to dry, wet and MQL machining.
- Better surface finish was found in cryogenic machining over the other cooling environments; hence, cryogenic machining increases the fatigue resistance of the product.

Fig. 8 SEM images of surface morphology at $v=55$ m/min, $f=0.048$ mm/rev and $d=1$ mm under different cooling environments: **a** cryogenic, **b** MQL, **c** wet, **d** dry

- Overall, at all the feed rates, cryogenic machining yields better performance characteristics compared to dry, wet and MQL conditions by satisfying the health and environmental issues.
- Metal cutting industries could use the cryogenic machining technique as an alternative to conventional cooling technique to improve productivity during machining of 17-4 PH SS.

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Compliance with ethical standards

Conflict of interest The author declares no conflict of interest.

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