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# Hybrid cryogenic MQL for improving tool life in machining of Ti-6Al-4V titanium alloy

**Alborz Shokrani[1*], Ihsan Al-Samarrai[1], Stephen T Newman[1]**

[1] Department of Mechanical Engineering, University of Bath, Bath, BA2 7AY, United Kingdom

*corresponding author: a.shokrani@bath.ac.uk

## Abstract

It is estimated that there is a need for 37,000 new passenger aircrafts until 2037. About 15% of the modern aircrafts are made of titanium alloys due to their high strength to weight ratio. In typical aerospace manufacturing, there is a buy-to-fly ratio of 6:1 for titanium parts which identifies significant machining requirements. Machining titanium alloys is generally associated with short tool life, poor surface integrity, low productivity and high manufacturing costs. These issues have made Ti-6Al-4V a difficult to machine material.

In this study, a new hybrid cryogenic MQL cooling/lubrication technique is proposed for end milling Ti-6Al-4V using coated solid carbide tools. The effect of the proposed system on machinability of Ti-6Al-4V was studied at various cutting speeds and compared with flood, minimum quantity lubrication (MQL) and cryogenic cooling. Tool life, tool wear and surface roughness were thoroughly investigated as key machinability metrices and a new model for tool life based on tool wear is proposed. The analysis indicates a significant shift in CNC milling performance, as the new hybrid cryogenic MQL technique shows an increased tool life of 30 times is achieved together with a 50% improvement in productivity compared to state-of-the-art flood coolant machining.

**Keywords:** Machining; wear; cryogenic machining; MQL; titanium

**Highlights:**

- A new hybrid cryogenic MQL cooling and lubrication system is proposed and tested for machining Ti-6Al-4V titanium alloy. The proposed system consists of a liquid nitrogen cryogenic cooling system coupled with vegetable oil based MQL.

- A series of machining experiments were conducted and the results rigorously analysed with tool wear, tool life and surface roughness investigated under different machining environments namely, flood, minimum quantity lubrication, cryogenic and hybrid cryogenic MQL.

- The proposed hybrid cryogenic MQL system resulted in a 30 times increased tool life in end milling Ti-6Al-4V alloy compared to flood machining.

## 1. Introduction

Titanium and its alloys have enjoyed a dramatic increase in demand in aerospace, marine, chemical and medical industries in spite of the complexity of extraction processes, difficulty of melting and problems in machining and fabrication. This is due to their comparatively low density, high hot strength and hardness and superior fracture toughness and corrosion resistance [1].

These materials are extensively used in aerospace industries, for instance 14% of the aerostructure of Airbus A350-900 XWB [2], 15% of Boeing 787 [3] and 25% of GE CF6 aeroengine [4] are made from titanium alloys. It is projected that more than 37,400 new passenger aircrafts are required over the next 20 years until 2037 [5] and Airbus currently has a backlog of over 7000 orders [6]. The average buy-to-fly ratio for aerospace industry is 6:1 and can be as high as 20:1 for some complex aeroengine parts [7] indicating the significant machining requirements.

The majority of titanium alloys are notoriously classified as difficult-to-machine materials [8]. Their high hot strength and hardness cause rapid tool wear and plastic deformation of the cutting tool owing to high compressive stresses on the cutting edge resulting in premature tool failure [8]. The low thermal conductivity of titanium alloys (1/6 that for steel) prevents effective heat dissipation from the cutting zone through cutting chips and workpiece material. Therefore, the heat generated during machining accumulates at the cutting zone resulting in high localised temperatures which can easily reach beyond 1000 °C at the tool-chip interface [9]. The temperature distribution of the cutting tool when machining Ti-6Al-4V at a cutting speed 75 m/min is comparable to that when cutting carbon steel at 240 m/min [9]. This accelerates tool wear causing diffusion, plastic deformation, abrasion and attrition by weakening the cutting tool substrate and increasing chemical reactivity [10]. In addition, the high thermal gradient, caused by the small heat affected zone due to the shorter tool-chip contact length experienced in machining titanium alloys, results in excessive chipping especially if using high cooling capacity coolants such as water-based cutting fluids [11].

Since the heat generated during machining titanium alloys play a major role in tool wear, it is important to minimise heat generation and improve heat extraction at the tool-chip and tool-workpiece interfaces [12]. Various cooling/lubricating techniques have been proposed to improve the machinability of titanium alloys such as minimum quantity lubrication (MQL) [13], cryogenic machining [14], high pressure emulsion cooling [15], etc. Flood cooling using water-based coolants is the most utilised method in industry for cooling and lubrication during machining processes [16]. The effectiveness of flood cooling is limited to a low cutting speed range (30-60 m/min when machining Ti-6Al-4V) [11]. MQL has been regarded as an effective alternative to conventional flood cooling. It involves spraying a very small amount (6-100 ml/h) of mineral or vegetable oil in a mist form with compressed air stream ( normally 5-7 bar) towards the cutting zone [17]. MQL has shown encouraging performance in turning, milling and grinding due to its ability to penetrate the cutting zone providing essential lubrication, thus reducing the cutting forces and friction at the cutting zone [18]. In addition, MQL can satisfactorily reduce the cutting zone temperature by the cooling effect of the compressed pressure and the evaporation of lubricant [19]. Promising machining performance has been shown in precision machining of Ti-6Al-4V with MQL at high cutting speed and low feed conditions [20]. Kamata and Obikawa [21] investigated the machinability of Inconel 718 in turning operations using various coatings and cooling/lubrication methods. In their investigations, TiCN/Al2O3/TiN coated tool performed best in flood cooling and resulted in the longest tool life. However, unsatisfactory surface finish was achieved. The best machining performance considering both tool life and surface finish was found at a cutting speed of 60 m/min using TiCN/Al2O3/TiN coated carbide when machining Inconel 718 with different grades of coated carbide tools [21]. Further increases in cutting speed from 60-90 m/min dramatically hindered tool life and surface

finish. They suggested that the air pressure in MQL has an important effect on cutting performance and there is an optimum value of air pressure for each cutting condition that yields the longest tool life [21]. Recent studies introduced nano-platelets that are mixed with vegetable oil to enhance the machining performance when milling Ti-6Al-4V [22].

Cryogenic cooling is recognized as an effective approach for maintaining the temperature at the cutting zone well below the softening temperature range of the cutting tool materials [23]. Generally, in cryogenic machining, liquefied gases such as nitrogen at low temperatures (-196 °C) is sprayed into the cutting zone [22].  Hong and Zhao [24] noted that cryogenic machining can provide significant potential in improving tool life when machining titanium alloys due to the capability to reduce the chemical reactivity between titanium and tool material and reduce thermomechanical tool wear [24]. Cryogenic machining has demonstrated a substantial improvement in tool life. Khan and Ahmed [25] demonstrated that using $LN_2$ coolant results in a four times increased tool life in turning stainless steel 304. Shokrani et al. [26] investigated the effect of various machining parameters using different machining environments. Their analysis indicated that cryogenic cooling can improves surface integrity in milling titanium resulting in 31% reduction in surface roughness. Hong et al. [27] recorded a reduced friction coefficient at the tool-chip interface when cryogenic turning of Ti-6Al-4V. They deduced this reduction by the increased shear angle and the decreased tool-chip contact length. Hong and Ding [28] suggested that injecting a small amount of $LN_2$ simultaneously onto the rake and flank faces can significantly improve the machinability when turning Ti-6Al-4V. A fivefold increased tool life was recorded as a result of using this method when compared to flood cooling [28]. Wang and Rajurkar [29] adopted a technique of circulating $LN_2$ on a cemented carbide to indirectly reduce cutting temperature when machining Ti-6Al-4V and suggested five times reduction in flank wear at  a cutting condition; 132 m/min, 0.2 mm/rev, 1 mm. Venugopal and Chattopadhyay [11] showed that cryogenic cooling of rake and flank faces significantly reduced the wear growth at a moderate speed 70 m/min when turning Ti-6Al-4V but at higher speeds a decreased tool performance was recorded .This was attributed to the lack of penetration of $LN_2$ on the tool chip-interface. They suggested adhesion-dissolution-diffusion wear mechanism on crater and abrasion and chemical attrition flank wear [30]. However, it has been proved that the performance of cryogenic machining of titanium alloy is highly sensitive to coolant nozzle position and the optimisation of $LN_2$ spraying orientation could improve tool life up to 80% [15]. It is worth noting that the direct spraying of $LN_2$ to the cutting interfaces results in excessive hardening of titanium alloy [24] which can adversely affect the tool life.

Sun et al. [31] investigated the machining performance of $LN_2$ when machining Ti5553 in terms of tool wear, surface roughness, and cutting forces in comparison to flood cooling and MQL for various cutting speeds and feed rates. They employed EDS analysis to show the adhesion of workpiece elements on the TiCN coated tool. A 30% reduction in cutting and thrust forces compared to MQL and flooding has been recorded with good agreement to that found from FEM simulation. Sartori et al. [32] conducted an experimental study on the effect of various cooling/lubricating conditions on the machinability of Ti-6Al-4V in semi-finish turning operations. They introduced three hybrid cooling techniques; namely hybrid $LN_2$ rake+MQLflank, $LN_2$ flank+MQLrake, and $CO_2$ rake+MQL flank. It was found that the application of low temperature hybrid strategies can eliminate the tool crater wear and preserve the tool geometry whilst better surface topography was achieved in cryogenic machining. In addition, MQL reduced the flank wear through the reduction of the cutting forces and improved chip flow. The authors observed that the performance of hybrid $LN_2$/MQL was significantly affected by nozzle position. The best strategy in this combination was to direct MQL to the tool flank and $LN_2$ to the rake face. They concluded that hybrid $CO_2$/MQL provided the best performance owing to higher pressure and lower temperature of $CO_2$ compared to $LN_2$ [32].

Schoop et al. [33] investigated the feasibility of high speed precision turning of Ti-6Al-4V with PCD tools under cryogenic and hybrid MQL/cryogenic cooling/lubricating techniques. Their investigation scored 4-5 times tool wear in flood cooling more than cryogenic and hybrid conditions. Moreover, significant improvement in surface finish with cryogenic machining was reported at speeds as high as 240 m/min and low feed rate and depth of cut (0.01 mm/rev and 0.1 mm, respectively). They suggested that high speed cryogenic-finish machining of Ti-6Al-4V could replace the traditional grinding process even for slender components [33].

The literature review has shown that whilst cryogenic cooling during machining can enhance machinability of Ti-6Al-4V, the process suffers from a lack of lubrication at the cutting zone. This issue is more profound in intermittent multi-point milling operations where reaching the cutting zone is more difficult. Majority of the studies in this area are concentrated on single point turning operations. Furthermore, there is no study on the effect of hybrid cryogenic MQL cooling/lubrication at various cutting speeds. In the research study reported in this paper, a new external nozzle system was designed and developed for cryogenic and hybrid cryogenic MQL machining. A rigorous methodology was developed. This study provides a comprehensive investigation of the effect of a new hybrid cryogenic MQL system and cutting speed on machinability of Ti-6Al-4V titanium alloy and compares the results with that of conventional flood cooling, MQL and cryogenic machining.

## 2. Heat transfer mechanism in machining due to coolants/lubricants

There are three sources of heat generation in machining which can be defined as (i) heat generation at the primary cutting zone due to plastic deformation of the workpiece, (ii) heat generation at the secondary zone due to the friction between the rake face of the tool and cutting chips and elastoplastic deformation of the chip and, (iii) heat generation due to the friction between the tool flank face and the machined surface and elastoplastic deformation of the machined surface. The generated heat at the cutting zone can flow through the workpiece, cutting tool and the cutting chips.

The heat transfer in machining is a combination of conductive, convective and radiation heat transfer. The heat generated at the cutting zone is conducted through and between the solid materials at the cutting zone, e.g. cutting tool, tool holder, workpiece and cutting chips. The conductive heat transfer is explained by Furrier's law shown in eq.1:

$$\dot{Q}_{Cond} = k_s A \frac{dT}{dx} \qquad (eq.1)$$

Where, $\dot{Q}_{Cond}$ is the conductive heat transfer rate (W), $k_s$ is thermal conductivity of the solid, $A$ is the cross-sectional area (m²) and $\frac{dT}{dx}$ is temperature gradient (K/m).

In the case of cryogenic cooling, changing the temperature of the body of the cutting tool and or workpiece adjacent to the cutting zone enhances heat transfer through conduction as it will increase the thermal gradient [34].

The heat is transferred from the hot surfaces in the cutting zone and tool/workpiece surface adjacent to the cutting zone to the surrounding environment and cooling/lubricating fluid by conduction as the speed of fluid in the boundary of solid-fluid is assumed zero. The heat is transferred from the boundary to the body of the fluid by convection.

The conductive heat transfer is defined by:

$$q = mC_p\Delta T \qquad (eq.2)$$

Where $q$ is the heat transfer (J), $m$ is the mass of the droplet (kg), $C_p$ is specific heat capacity (J/Kg K) and $\Delta T$ is the temperature (K) difference between the environment and the cutting zone.

Oil droplets in MQL are sprayed onto the surface of the tool. These droplets can attach to the surface of the tool and workpiece forming a film over the solid surface. They can absorb heat from the hot surfaces until they reach the saturation temperature of oil. Two different approaches can be used for analysing heat transfer namely, individual droplet heat transfer and spray cooling considering two phase homogeneous spray cooling [35]. Grissom and Wierum [36] identified that three different modes can take place in spray cooling namely, (i) dry wall state where all impinging liquid is vaporised on the heated surface; (ii) flooded where a film of liquid is formed on the surface and (iii) Leidenfrost state by forming a vapour over the heated surface.

Convective heat transfer in machining is in the form of natural convection and forced convection. However, the effect of natural convection is very small compared to forced convection [37, 38]. Assuming that the properties of the fluid is consistent throughout flow, the oil droplets in compressed air can be modelled as a two phase homogeneous forced convection heat transfer [39]. Similar assumption can be made about two phase liquid-gas nitrogen in cryogenic cooling. The convective heat transfer is expressed by Newton's law of cooling [40]:

$$\dot{Q}_{Conv} = hA\Delta T \qquad\qquad (eq.\,3)$$

Where $\dot{Q}_{Conv}$ is convection heat transfer rate, $h$ is convective heat transfer coefficient (W/m²K), $A$ is the area (m²) and $\Delta T$ is the temperature difference (K) between the coolant/lubricant's initial temperature and final temperature.

The equivalent average heat transfer coefficient of the oil droplets dispersed through compressed air can be estimated from the dimensionless Nusselt number ($Nu$) which defines the ratio of convection to conduction heat transfer in fluids and is a function of dimensionless Reynold's and Prandtl numbers [35, 40]:

$$Nu = \frac{hL}{k_f} = CRe^m Pr^n \qquad\qquad (eq.\,4)$$

$$Re = \frac{VL}{\nu} \qquad\qquad (eq.\,5)$$

$$Pr = \frac{\mu C_p}{k_f} \qquad\qquad (eq.\,6)$$

here $Nu$ is the Nusselt number, $L$ is the characteristic length (m), $k_f$ is the thermal conductivity of the fluid (W/m K), $Re$ is the Reynold's number, $Pr$ is the Prandtl number and $C$, $m$ and $n$ are constants, $V$ is velocity (m/s), $\delta$ is characteristic length (m), $\nu$ is kinematic viscosity (m²/s), $\mu$ is dynamic viscosity (Pa s) and, $C_p$ is specific heat capacity (J/kg K).

The values for constants C, m and n can be obtained experimentally, using established correlations for estimation or based on existing flow models for simple geometries.

If the temperature of the surface reaches the saturation temperature of the liquid coolant/lubricant, nucleate and film boiling heat transfer takes place. Tanveer et al. [41] identified that the cutting temperature in machining Ti-6Al-4V can reach as high as 600 °C in flood cooling. Based on their experiment for dual phase oil-compressed air flow, nucleate boiling and film boiling were the main heat transfer modes on the cutting tool at temperatures above 300 °C.

In film boiling, a layer of vapour forms between the hot surface and the coolant/lubricant liquid. The vapour commonly has a lower thermal conductivity than the liquid and acts as a thermal barrier. The heat transfer through the vapour can be modelled by conduction [41]:

$$Q = \frac{k_v A (T_s - T_b)}{\delta} \qquad\qquad (eq.7)$$

Where $k_v$ is the thermal conductivity of the vapour, $A$ is the contact area between the vapour and surface, $T_s$ is the temperature of the hot surface and $T_b$ is the boiling temperature of the coolant/lubricant liquid.

$LN_2$ in cryogenic machining has a lower saturation temperature than oil and film boiling can take place at a much lower temperature than that of MQL. The formation of the vapour film in film boiling can significantly reduce the heat transfer from the cutting zone. Pusavec et al. [42] investigated the heat transfer coefficient and the impact of nitrogen phase in cryogenic machining. Based on the experimental results, the heat transfer is maximum at 30 °C. It transforms to transition boiling when the surface temperature is 45 °C and film boiling occurs at the critical temperature of 200 °C. At this temperature, heat transfer is significantly reduced due to the Leidenfrost effect [42].

The convection heat transfer coefficient of liquid nitrogen was experimentally estimated by Hong and Ding [43] to be between 4.827 x $10^4$ and 7.495 x $10^4$ W/m²K. Boiling heat transfer of liquid nitrogen was measured by Jin et al. [44] in the range of 0-3500 W/m²K. Dix et al. [45] assumed a heat transfer coefficient of 23.3 x $10^3$ to 46.8 x $10^3$ W/m²K for liquid nitrogen. The large variation between the data reported can be due to the nozzle/cryogenic cooling setup and proportion of gas/$LN_2$ which indicates the need for further investigation.

## 3. Methodology, machining environments and procedure

In this section, the design of experiments and the procedures used for experiments and data collection are provided. Relevant procedures and standards were followed to ensure the quality of the data and minimise errors during experiments. In addition, various machining environments namely, flood, MQL, cryogenic and hybrid cryogenic MQL are explained in detail.

### 3.1. Design of experiments and procedure

In order to assess the effect of the new hybrid cryogenic MQL system on machinability of Ti-6Al-4V, a series of machining experiments were conducted. All machining experiments were conducted on a Bridgeport VMC 610xp milling centre which was retrofitted with various cooling and lubrication systems.

The machining experiments consisted of end milling of blocks of Ti-6Al-4V material with 50 mm x 50 mm x 150 mm dimension using a solid carbide end mill. The workpiece material used in this study was annealed Ti-6Al-4V with alpha-beta microstructure. The material hardness of the workpieces was measured 24 times for each block using 30 kg load for 10 s. The average material hardness was 348±11.8 HV. The blocks were supplied and cut from a single plate of material to minimise variability in material properties.

The experiments were conducted along the length of the block using a climb milling strategy as shown in figure 1. In order to minimise the effect of acceleration and deceleration on the results, the feed move started 50 mm before engagement and 50 mm after engagement with the workpiece.

Three monitoring parameters of tool wear, tool life and surface roughness were selected as predictors for the experiments. Two variables of machining environment and cutting speed were

identified for this study. A full factorial design of experiment, illustrated in figure 2, was developed for conducting machining experiments with machining environment at 4 levels and cutting speed at 5 levels. In total, 20 (4x5) machining experiments were conducted. The details of the DoE and notions are provided in table 1. Four machining environments of conventional flood, MQL, cryogenic and hybrid cryogenic MQL were used for the tests. The details of the machining environments are provided in table 2 and further discussed in section 3.2.
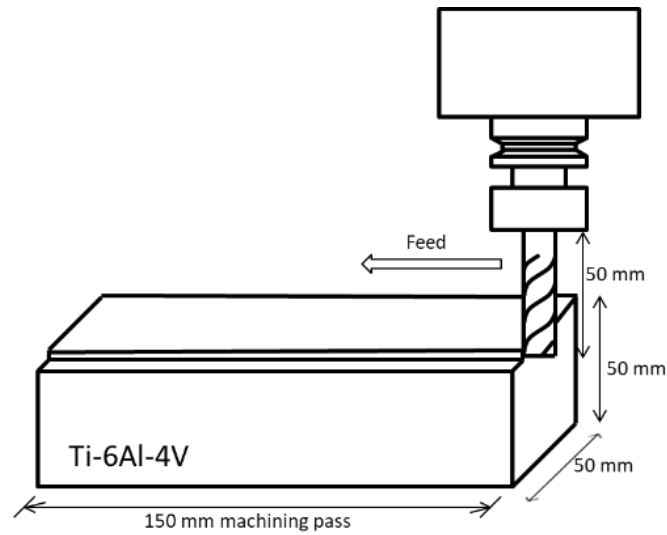


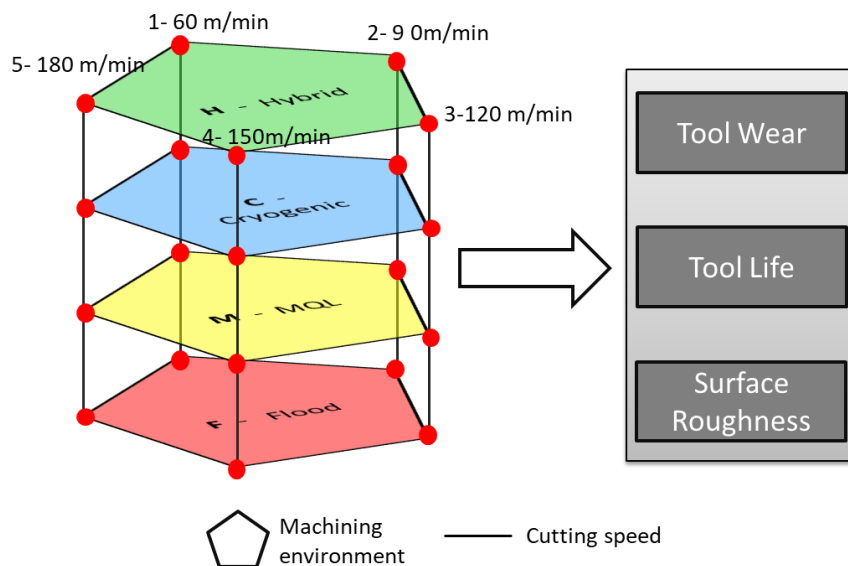Figure 1, Illustration of the machining experiment setup



Figure 2, Illustration of the DoE used for this study

Table 1, Full factorial design of experiments

| | | Cooling/lubricating conditions | | | |
|---|---|---|---|---|---|
| | | F - Flood cooling | M - MQL | C - Cryogenic | H - Hybrid |
| Cutting speed (m/min) | 60 | F1 | M1 | C1 | H1 |
| | 90 | F2 | M2 | C2 | H2 |
| | 120 | F3 | M3 | C3 | H3 |
| | 150 | F4 | M4 | C4 | H4 |
| | 180 | F5 | M5 | C5 | H5 |

Table 2, Various machining environments used for experiments

| Cooling/lubricating condition | Main effect | Brief description |
|---|---|---|
| Conventional flooding | Cooling | Water based emulsion, 8% mixing ratio |
| MQL | lubrication | Dual- nozzle sprays vegetable oil |
| Cryogenic | Cooling | Dual- nozzle sprays $LN_2$ |
| Hybrid cryogenic MQL | Cooling and lubrication | Combination of MQL and Cryogenic |

Apart from the variable parameters used in the DoE, remaining machining parameters were kept constant for all machining experiments. The constant cutting parameters are provided in table 3.

The machining experiments were interrupted regularly and the tool wear was measured throughout the experiments using an optical microscope. The machining experiments were repeated until the criterion for tool life was reached. ISO 8688-2 [46] has identified 300 μm $V_B$ or 500 μm $V_{max}$ flank wear as the tool life criterion which was used for this study.

For each machining experiment, a new cutting tool was used and the surface roughness of the machined parts was measured at the start of each machining experiment to minimise the effect of tool wear on surface roughness. The surface roughness of each sample was measured at 6 positions and was repeated 3 times. A contact profilometer with 50 nm resolution was used for measuring the surface roughness.

The cutting tools used for this study were 12 mm diameter and had a 3 μm thick TiSiN coating with 5 flutes, 12° rake angle and 40° helix angle. In order to ensure that the tools are not damaged during production, they were inspected prior to machining experiments using an optical microscope.

### *3.2. Machining environments*

Four machining environments namely, flood cooling, MQL, cryogenic and hybrid cryogenic MQL were used for this study which are described in detail below. A series of preliminary experiments were conducted for positioning of various nozzles used in this study which was also dictated by the available space in the machine tool, position of the spindle, tool changing arm and the holders. The aim was to ensure that the flow of lubricant/coolant fully covers the cutting zone.

**(i) Flood**- For flood cooling, water-based emulsion was used at 8% concentration. The coolant was delivered through the machine tool's coolant/lubrication system at 10bar. This machining environment is the most used method in industry and was defined as a control for this investigation.

Table 3, Cutting parameters used for machining experiments

| Cutting conditions | | | |
|---|---|---|---|
| Tool overhang (mm) | Chip load (mm/tooth) | Axial depth of cut (mm) | Radial depth of cut (mm) |
| 50 | 0.03 | 1 | 4 |

**(ii) MQL**- For MQL machining experiments, a dual-nozzle MQL applicator was used to spray vegetable oil at 70 ml/h flow rate and 6 bar air pressure via two nozzles. The MQL nozzles were full cone spray nozzles by Loc-line and had 2.5 mm outlet diameter and were positioned within 10 mm distance from the cutting tool. The divergence angle of the nozzle was measured to be 8°. The first nozzle was directed to the cutting zone at 110° angle to the feed direction and 60° angle to the horizon (machine's XY plane). The second nozzle was directed to the cutting tool from the opposite side to the first nozzle with 90° angle to the feed direction and 20° angle to the machine's XY plane. Figure 3 illustrates schematic of the MQL system. Loc-line flexible hose was used for the delivery of compressed air and the rapeseed oil. The oil was delivered using a positive displacement pump. Compressed air was conditioned and the pressure was regulated using a Festo filter regulator. Rapeseed oil was used as a biodegradable lubricant for the experiments. It contains long chain fatty acids and has high carbon content and viscosity with good low temperature performance making it a suitable lubricant [47-49].
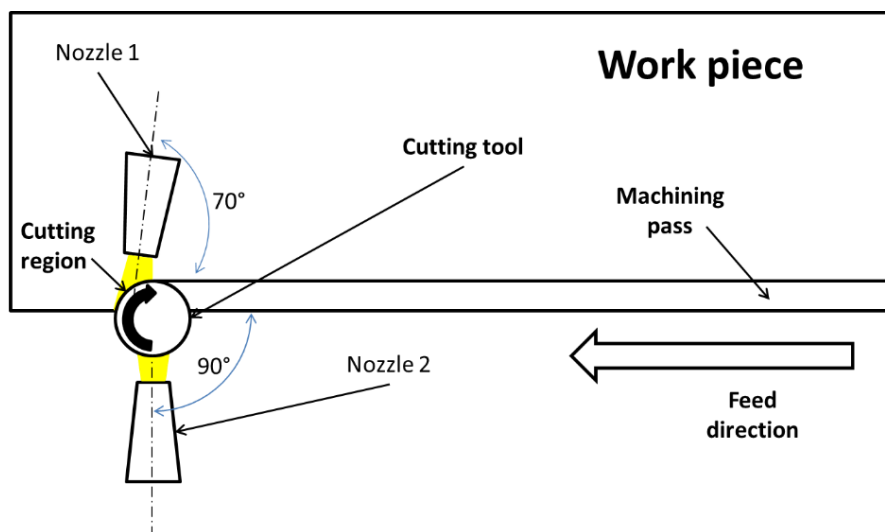


Figure 3, Schematic of the dual-nozzle MQL system

(iii) **Cryogenic machining**- Cryogenic machining with $LN_2$ was performed via a dual-nozzle external cryogenic cooling system specially designed for this purpose to be retrofitted into an existing machine tool. Each nozzle has 2 mm outlet diameter and divergence angle of 5°. They were positioned as close as 20 mm from the cutting tool periphery to ensure straight-line non-spread coolant stream and to reduce the effect evaporation of the $LN_2$ prior to reaching the cutting zone. The nozzles were set at exactly the same orientation as MQL nozzles explained in figure 3. Figure 4 illustrates the CAD models of the nozzle and the cryogenic machining setup.
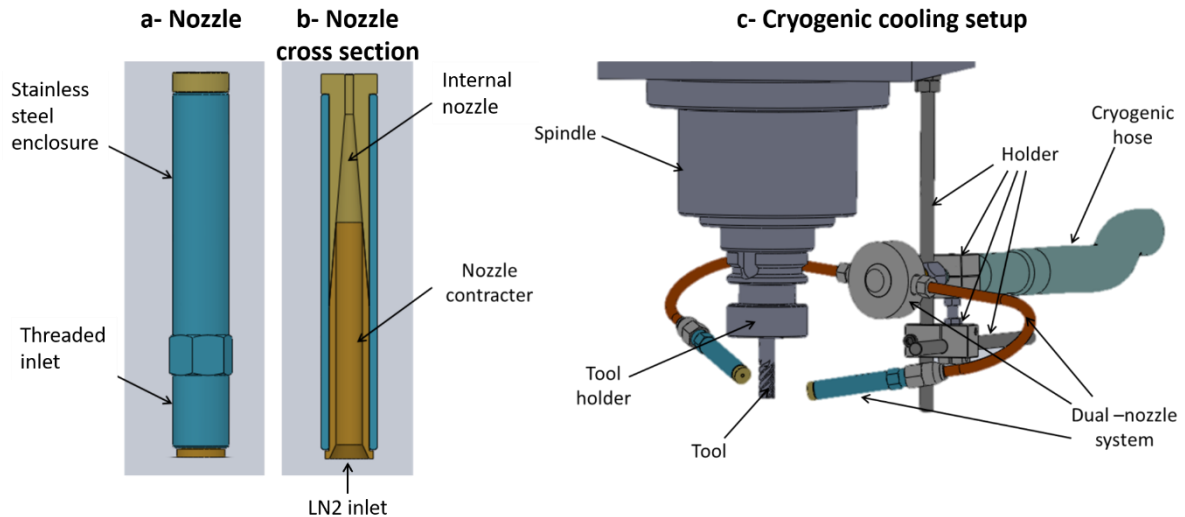
Figure 4, a) cryogenic nozzle, b) its cross section view and c) cryogenic machining setup

A cryogenic delivery system developed by Shokrani et al. [14] was adopted to deliver $LN_2$ to the dual-nozzle system at 1.5 bar and 33 l/h flow rate. The cryogenic delivery system consisted of a self-pressurised cryogenic Dewar with nominal capacity of 180 l and internal pressure of 1.5 bar, a globe valve for adjusting the $LN_2$ flow rate, a 2/2 normally closed solenoid valve and vacuum insulated flexible hoses. Figure 4 illustrates the cryogenic machining setup inside the Bridgeport VMC610 machine tool.

(iv) **Hybrid Cryogenic MQL**- The cooling/lubricating strategy was built on the fact that MQL nozzle system sprays oil directly to the cutting interfaces to provide the lubrication that is essential to reduce the friction between the tool rake and chips at the secondary deformation zone and between the tool flank and the workpiece at the tertiary deformation zone. The cryogenic nozzles were mainly directed towards the cutting tool to reduce the tool temperature below the softening temperature of the tool material. The cryogenic nozzles' orientation can also provide sufficient cooling to the workpiece to reduce the chemical reactivity between titanium and solid tungsten carbide tool. In hybrid $LN_2$ cryogenic MQL setup, 4 nozzles ensure that the cutting zone is covered by both lubricant and coolant irrespective of machining direction. Unlike $CO_2$ cryogenic machining, The $LN_2$ is delivered at -197 °C. This prevents combining the cryogenic and MQL nozzles into a single hybrid nozzle as the lubricant freezes inside the delivery line blocking MQL. In the proposed hybrid cryogenic MQL setup, the position of the MQL nozzles from the MQL machining tests were kept unchanged, while the cryogenic nozzle system was turned 90 ° to the MQL position. Figure 5 shows the setup of MQL and cryogenic nozzles when hybrid cryogenic MQL machining was performed whilst figure 6 provides a pictorial view of the hybrid cryogenic MQL system.
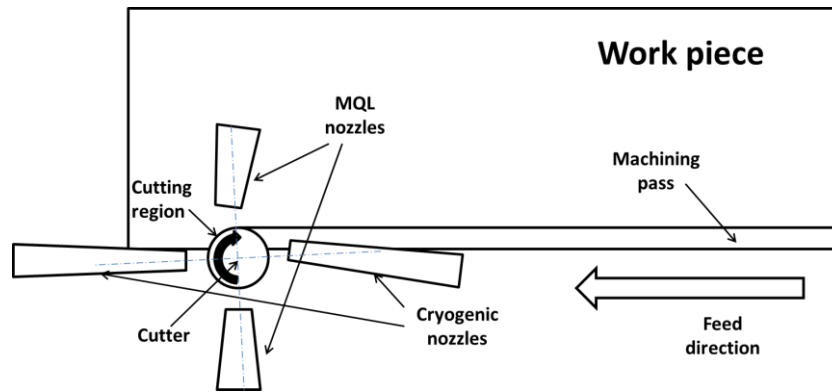
Figure 5, Hybrid cryogenic MQL setup



Figure 6, Pictorial view of the hybrid cryogenic MQL system

## 4. Results and analysis

A series of machining experiments were conducted following the DoE presented in table 1. In this section, the results from the experiments based on the proposed methodology are provided and analysed. The experimental results consist of tool life, tool wear and surface roughness.

### 4.1. Tool life:

For tool life testing in end milling, the ISO 8688-2 [46] suggests that the end of tool life is reached once the average flank wear exceeds 300 µm over all tool teeth. During the measurement of tool wear, all tool deterioration phenomena other than uniform and localised flank wear such as chipping/flaking and plastic deformation of cutting edge were treated as flank wear.

As shown in figure 7, increasing cutting speed in flood and MQL environments results in shorter tool life. It is well known that there is a direct correlation between cutting speed and cutting temperature [50]. At higher cutting speeds, the coolant/lubricant fail to reach the cutting zone effectively resulting in shorter tool life.

In contrast, in cryogenic and hybrid machining environments, increasing cutting speed from 60 m/min to 90 m/min leads to longer tool life. Using cryogenic machining environment, a further increase in tool life can also be achieved by raising the cutting speed from 90 m/min to 120 m/min. Whilst cryogenic machining generated the shortest tool life at 60 m/min compared to other machining environments, the tool life was increased by increasing cutting speed where it surpassed

the tool life from flood cooling from 90 m/min cutting speed and higher. This indicates the effect of cooling in cryogenic machining where the heat generated during machining can be effectively removed. At lower cutting speeds, the liquid nitrogen coolant reduces the workpiece temperature resulting in increased hardness. However, at higher cutting speeds, the heat generation at the cutting zone softens the workpiece material locally which is then dissipated through the cryogenic cooling.

Comparison of the tool life results at various cutting speeds between cryogenic machining and MQL environments however, indicated the role of lubrication in controlling heat generation. Bermingham et al. [15], noted that controlling heat generation by controlling cutting parameters is more significant than heat removal from the process in machining Ti-6Al-4V alloy. This is clearly demonstrated in the tool life results for MQL and cryogenic machining at 60 m/min, 90 m/min and 120 m/min cutting speeds. MQL can effectively lubricate the cutting zone at low and moderate cutting speeds and reduce the heat generation due to the friction at the secondary and tertiary deformation zones. Further increases in cutting speed diminishes the effectiveness of the MQL cooling and lubrication at 150 m/min and 180 m/min.
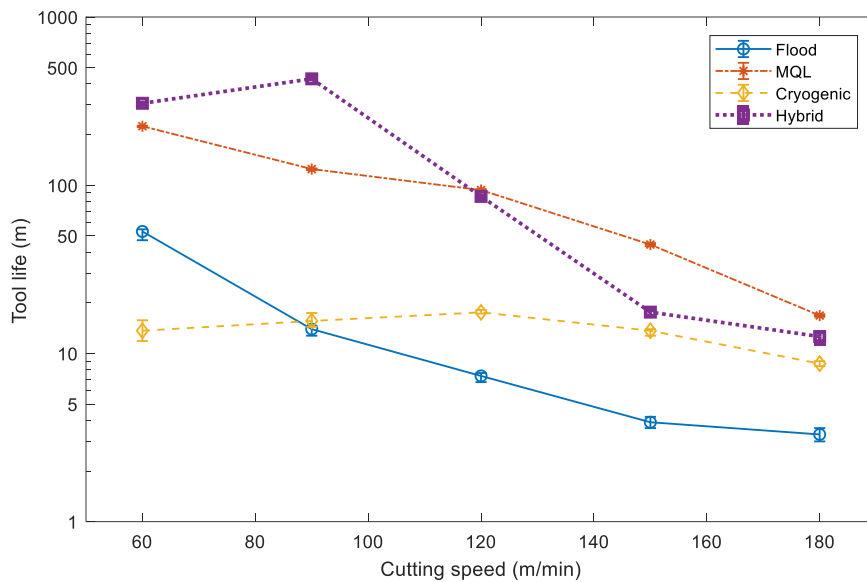


Figure 7, Tool life vs cutting speed plots for various machining environments

In the hybrid cryogenic MQL setup, the cooling effect of cryogenic machining was coupled with the lubrication effect of MQL. At 60 m/min and 90 m/min, hybrid cooling system demonstrated effective in lubricating and extracting the heat from the cutting zone where the longest tool life amongst all machining experiments was achieved at 90 m/min. At 90 m/min, the cutting tool from hybrid cooling experiment performed for 429,000 mm machining length resulting in a 30-fold increase in tool life as compared to conventional flood cooling. This is also 11 times and 2 times longer than the best result from conventional flood cooling and MQL at 60 m/min, respectively. This enables machining at a higher cutting speed without sacrificing tool life leading to 50% increased productivity. Table 4 summarises tool life in terms of cutting length, cutting time, and the improvement in machining performance relative to conventional water-based emulsion cooling.

```
                        Analysis of Variance
   Source                 Sum Sq.  d.f.  Mean Sq.     F     Prob>F
   ----------------------------------------------------------------
   Cutting speed          2.59545    4   0.64886     7.92   0.0023
   Machining environment  3.65232    3   1.21744    14.86   0.0002
   Error                  0.98343   12   0.08195
   Total                  7.23119   19
```

Figure 8, ANOVA of the tool life results

Table 4, Summary of tool wear for each cutting and machining environment

| Cooling/lubricating condition | Cutting speed (m/min) | Failure location | Time to failure (min) | length to failure (m) |
|---|---|---|---|---|
| MQL | 180 | Nose flank | 23.5 | 16.8 |
| | 150 | Nose flank | 74.4 | 44.4 |
| | 120 | Nose flank | 196.2 | 93.6 |
| | 90 | Nose flank | 348.6 | 124.8 |
| | 60 | Nose flank | 938.3 | 224.25 |
| Flood cooling | 180 | Nose flank | 4.6 | 3.3 |
| | 150 | Nose flank | 6.5 | 3.9 |
| | 120 | Nose flank | 15.4 | 7.35 |
| | 90 | Nose flank | 39 | 13.95 |
| | 60 | Nose and depth of cut flank | 149.9 | 53.1 |
| Cryogenic cooling | 180 | Nose and depth of cut flank | 12.15 | 8.7 |
| | 150 | Depth of cut flank | 22.8 | 13.65 |
| | 120 | Depth of cut flank | 36.8 | 17.55 |
| | 90 | Depth of cut flank | 43.6 | 15.6 |
| | 60 | Main and depth of cut flak | 57.1 | 13.65 |
| Hybrid cryogenic MQL | 180 | Nose flank | 17.6 | 12.6 |
| | 150 | Depth of cut flank | 29.4 | 17.6 |
| | 120 | Main flank | 179.6 | 85.8 |
| | 90 | Main flank | 1198 | 429 |
| | 60 | Main flank | 1281 | 307 |

The tool life data from all experiments were statistically analysed. The analysis indicated that the results are log normal and therefore, logarithm transformation was performed to normalise the data for further analysis. Analysis of variance (ANOVA) was performed on the normalised data as shown in figure 8 and the main effect plots where developed (figure 9).
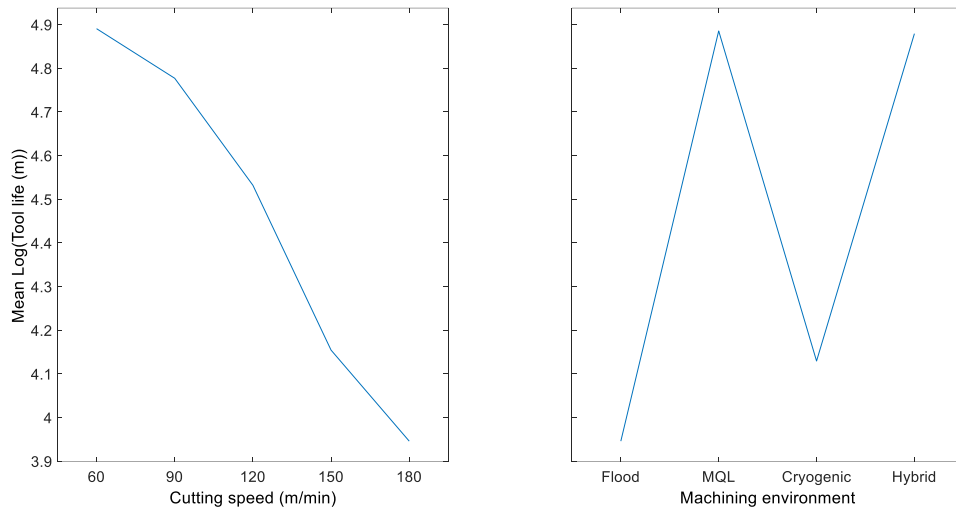
Figure 9, Analysis of means for tool life

The analysis indicated that both cutting speed and machining environment have statistically significant effect on tool life. The analysis of means, presented in figure 9, demonstrated that generally, tool life reduced with increasing cutting speed. On average, the tool life from MQL environment was comparable with that of hybrid cryogenic MQL. Bonferroni multiple comparison test was conducted on the data to identify the significance of each combination of cutting speed and machining environment in comparison with other combinations. As illustrated in figure 10, the lower cutting speeds under MQL and Hybrid cooling is significantly different from that of cryogenic and flood cooling at moderate (120 m/min) to high (180 m/min) cutting speeds. The analysis did not indicate statistically significant differences between MQL and hybrid machining environments.
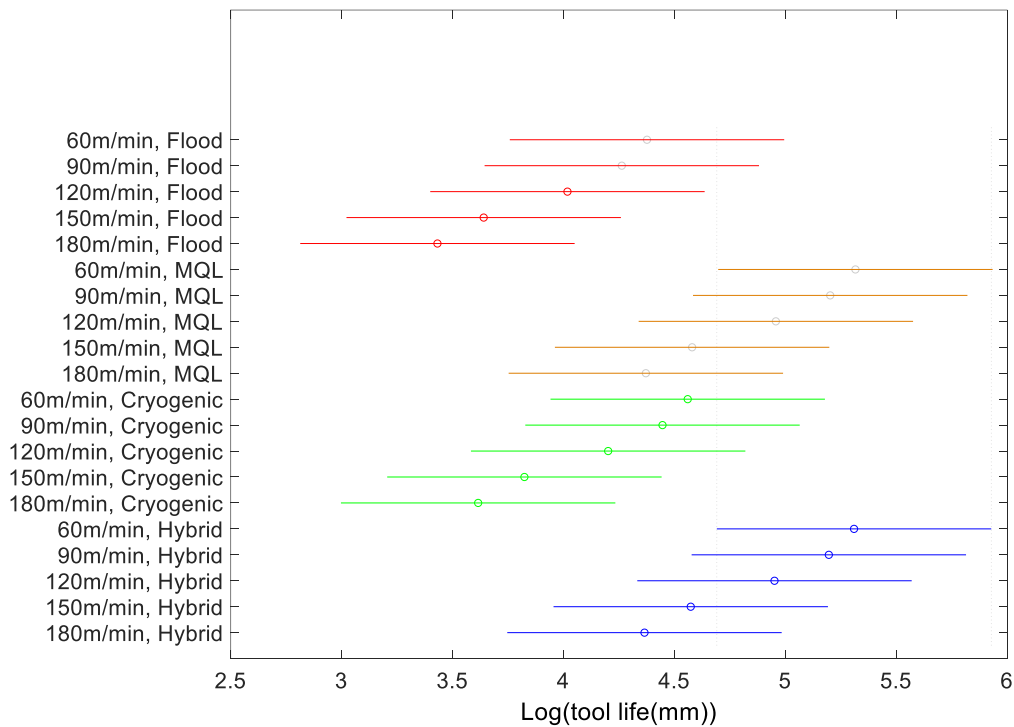


Figure 10, Bonferroni multiple comparison of the results for tool life

## 4.2. Tool wear model

The graph of average flank wear against machining length was generated and is shown in figure 11.

As illustrated in figure 11, similar wear growth pattern was observed for all machining experiments irrespective of machining environment and cutting speed. The tool wear grows gradually until the coating is removed exposing the tungsten carbide substrate. The tool wear growth increases drastically when the substrate is exposed leading to tool failure. The tool wear growth against machining length can be modelled using exponential regression. The general form of the tool wear regression can be presented as eq.8.

$$V_B = ae^{bx} \qquad\qquad (eq.8)$$

where $V_B$ is average tool wear in μm, $e$ is Euler's number, $x$ is machining length in mm and $a$ and $b$ are constants.
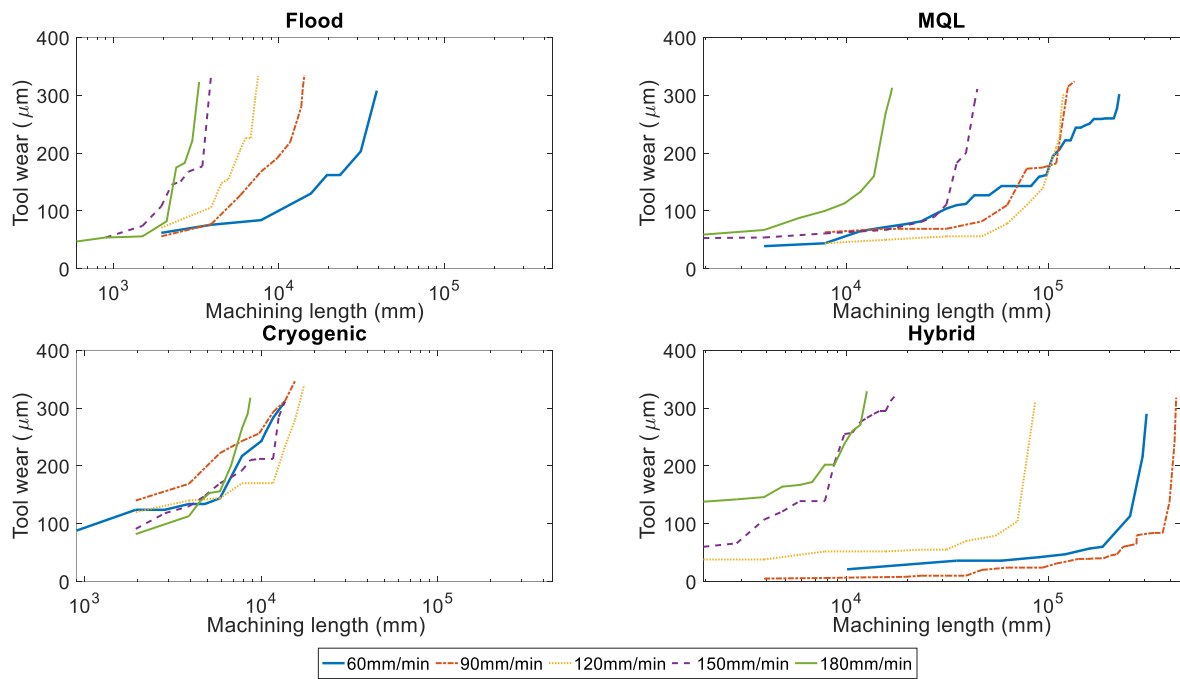


Figure 11, Flank wear against machining length at various cutting speeds for different machining environments namely, flood, MQL, cryogenic and hybrid cooling (x axis as log).

Regression analysis of the tool wear data for all machining experiments indicated that the tool wear against machining time can be confidently modelled using Eq.9. The model results in an average $R^2$ and $R^2_{adj}$ of 93% and 92%, respectively.

From the computations for cutting speed and feed rate in milling summarised in eq.9, $x$ can be developed as a function of time ($t$) as shown in eq.10.

$$f = \frac{1000\,V\,z\,n}{\pi\,D} \qquad\qquad (eq.9)$$

Machining length as a function of time and feed rate

$$x = f \times t \qquad\qquad (eq.10)$$

where $t$ is time in s.

Substituting $x$ in eq.8 with eq.9 and 10, the tool wear can be expressed as in eq.11.

$$V_B = ae^{\frac{1000\,b\,V\,z\,n\,t}{\pi\,D}} \qquad (eq.11)$$

The constants in eq.11 can be combined to for a new constant B and therefore $V_B$ will be summarised as in eq.12 and subsequently eq.14.

$$V_B = ae^{\frac{B\,V\,z\,n\,t}{D}} \qquad (eq.12)$$

$$\ln V_B = \ln a + \frac{B\,V\,z\,n\,t}{D} \qquad (eq.13)$$

Eq.13 can be rearranged for machining time t as shown in eq.14

$$t = \frac{\rho D}{B\,V\,n\,z} \qquad (eq.14)$$

Where $\rho$ is a new constant based on $V_B$ shown in eq.15

$$\rho = \ln \frac{V_B}{a} \qquad (eq.15)$$

In the above equations, a, b, A, B and ρ are constants.

The ISO 8688 [46] recommends $V_B$ = 300μm as the tool life criterion which can be used in eq.16.

The model developed in eq.15 was used to predict tool life given $V_B$ = 300 μm as shown in figure 12. The analysis indicated that the model is capable of predicting the tool life with up to 98% accuracy. The accuracy was lowest for the measured results for hybrid machining experiments with 82% accuracy. Figure 12 illustrates the results for predicted vs measured tool life for various machining environments.
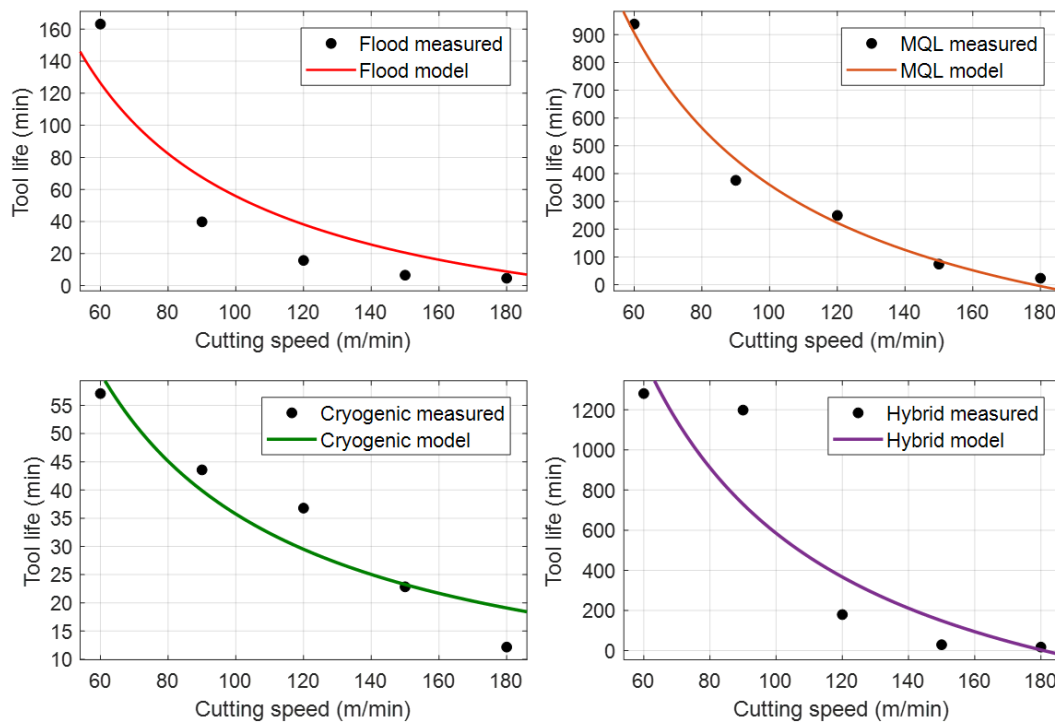


Figure 12, Measured and predicted results for tool life for different machining environments

## 4.3. Tool wear analysis

The position of the tool wear leading to failure has been summarised in table 4 and the growth of the tool wear for each experiment shown in figure 11. Rapid tool wear was detected at the start of the machining experiments as illustrated in figure 11. This was followed by a plateau of slow growth until the coating was removed exposing the tungsten carbide substrate. Rapid tool wear followed leading to tool failure. The tool failure mode for all experiments irrespective of machining environment and cutting speed was flank wear as shown in figure 13. Crater wear on the rake face was dominant (figure 14). The cutting chips adhered onto the rake face of the tool forming a built-up-edge (BUE). The BUE was removed with subsequent flow of chips taking particles from the rake face leaving a crater. Increased depth of the crater wear weakened the cutting edge leading to chipping and notch wear. This exposed the substrate on the flank face resulted in rapid flank wear. The extent of crater wear was more significant in flood cooling as demonstrated in figure 14. In flood cooling, crater wear also led to flaking on the rake surface. In cryogenic machining, chipping at the depth of cut was promoted by increased hardness due to the lower temperature on the surface of the workpiece material. The chipping was then followed by accelerated flank wear at the depth of cut.

In order to illustrate the mechanism of tool wear when end milling of titanium alloy under different cutting and cooling/lubricating conditions, it is helpful to divide the tool flank clearance face into three locations; nose flank, main flank and depth of cut flank. Nose flank represent the part of flank area in the vicinity of tool nose, while depth of cut flank is the tool flank at the depth of cut from the tool nose. The main flank is located between nose and depth of cut flanks. Images of the flank, rake and the cutting edge were taken from the cutting tools throughout the machining experiments. The images of tool flank wear, crater wear and cutting edge are provided in figure 13, 14 and 15, respectively. These figures illustrate the condition of the cutting tools at the final stage of tool life at the end of machining experiments.

It is generally well agreed that the generation of high temperature at the secondary shear zone (at rake face) can promote rapid rake crater wear by dissolution-diffusion when machining Ti-6Al-4V at moderate/high cutting speeds with straight grade tungsten carbide cutting tools with cobalt binder [9]. The bonding of titanium chips and/or workpiece onto the tool at high temperatures (beyond 900 °C when turning at 75 m/min) provides an ideal environment for the diffusion of the tool material constituents across the tool/chip and tool/workpiece interfaces [15]. Furthermore, these adhered grains of tool material can be removed or torn away by the flowing chips and/or moving workpiece could be the main contributor of flank and/or crater wear by attrition [11].

In the case of water-based flood cooling tests, there is clear evidence that both dissolution-diffusion and chipping/flaking on the rake face have occurred. At low cutting speed (60 m/min), uniform attrition wear was built thinly along the whole flank length. Then a rapid localised flank wear is developed in the vicinity of the tool nose (nose flank). This is attributed to the increase in tool tip temperature that causes loss of sharpness. This thermally related wear at nose flank is generally followed by crater chipping in the vicinity of the tool nose as shown in figure 13, 14 and 15 for F1 experiment. This is mainly due to the high levels of thermal gradient/thermal shocks [51]. With continuing the machining experiment, attrition wear was developed on the flank face near the chipped tool nose leading to the end of tool life. Attrition wear was redeveloped along the new irregular cutting edge formed from the crater chipping. Plastic deformation of the cutting edge is only noticeable at the depth of cut where no chipping was occurred. It is worth noting that crater chipping and flank attrition dominates the tool wear mechanism when milling Ti-6Al-4V alloy at low cutting speed with flood cooling.
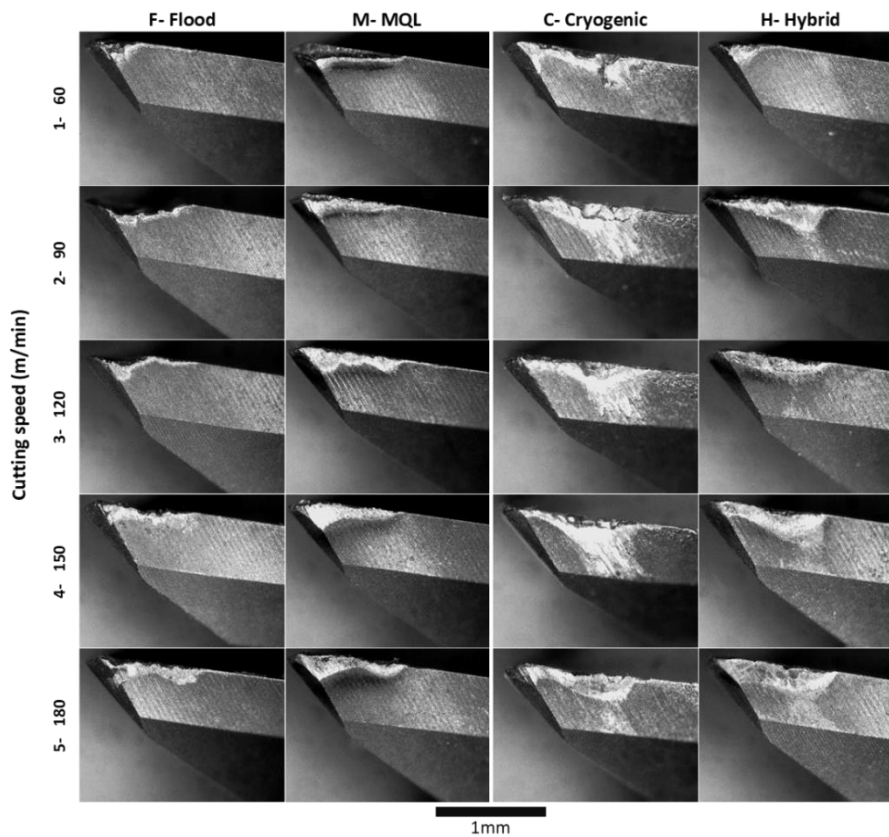
Figure 13, Images of tool flank wear at different cutting speeds and machining environments taken after the wear criterion was reached

At moderate cutting speeds, 90 and 120 m/min, the same tool wear mechanism was observed with increased crater chipping due to the increased levels of thermal gradient (experiments F2 and F3 in figure 13-15). At higher cutting speeds of 150 and 180 m/min, the crater chipping tends to spread along the depth of cut and became smaller in size as shown in figure 15 F4 and F5. The extremely high thermal stresses resulted from the existence of the seizure zone of coolant vapour shield prevents the water-based coolant from penetrating the cutting interfaces, while cooling all tool areas around the cutting zone [22]. Crater chipping and non-uniform flak attrition along the whole depth of cut dominated the tool wear mode. In all flood machining experiments there is a clear evidence of adhesion of titanium chips and/or workpiece on the tool rake face and cutting edge which caused formation of built up edge.

In the MQL experiments at low cutting speed, 60 m/min, a significant improvement in tool life has been achieved as shown in figure 7. Five folds improvement in tool life over flood cooling was recorded as listed in table 4. This enhanced machinability can be attributed to the improved lubricity in MQL environment. This resulted in reduced rubbing of tool flank onto the workpiece that causes attrition-abrasion, and between the chips and tool rake face, hence reduced adhesion-attrition wear mechanisms. At early stages of machining, a smooth crater wear due to dissolution-diffusion was built up uniformly along the rake face. The smooth dissolution in rake face can alter the shape of the cutting edge but will keep it reasonably sharp enough to efficiently resume the cutting process.
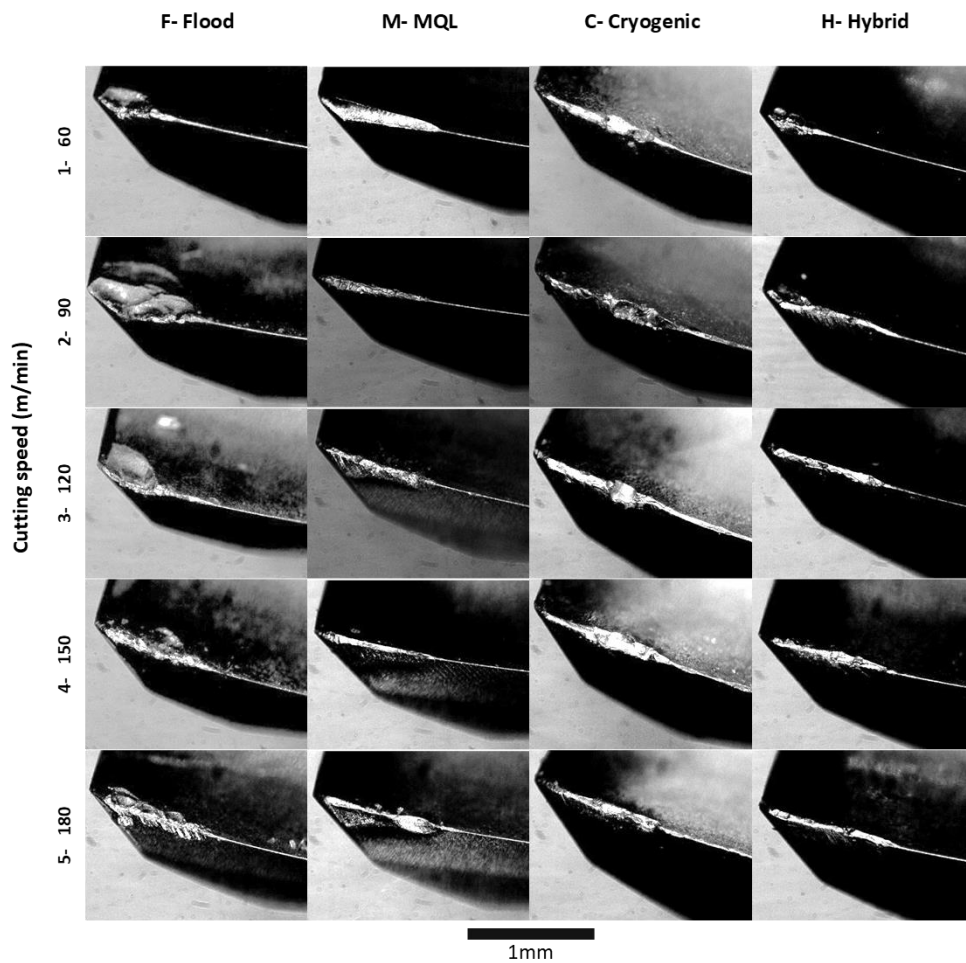
Figure 14, Microscopic images of the cutting edge for all cutting tools at different cutting speed and machining environments at the end of tool life

It is clearly noted that the maximum tool wear occurred on the nose flank and linearly reduced until reaching minimum value at the depth of cut flank. This indicates that the lubrication is more effective at the depth of cut than at the nose of the cutting tool. In addition, higher temperatures are expected at the tool nose. Dissolution- diffusion of rake and attrition of nose flank dominate tool wear mechanism (figure 13-15, experiment M1).

With increasing the cutting speed to a moderate level, 90, and 120 m/min, it is clearly observed that the thermal-chemical wear (dissolution-diffusion) was decreased, whilst mechanical wear by attrition-abrasion in the vicinity of the tool nose became prominent. Both types dominated the tool wear mechanism at moderate cutting speeds as shown in figure 13-15 (M2, M3).

This can be attributed to the lack of cutting edge sharpness causing increased friction between the tool flank and machined surface, especially without increasing oil mist flow rate and/or pressure. At higher cutting speeds, 150 and 180 m/min, flank attrition followed by abrasion dominated the tool wear mode with clear evidence of plastic deformation of the cutting edge, as a result of high cutting temperatures at higher cutting speeds.

In all MQL machining tests, significant improvements of tool life have been achieved. The maximum improvement has been attained at moderate cutting speeds (more than 11 folds for 90 m/min and 13 folds at 120 m/min), while the maximum cutting length (224 m) was recorded at 60 m/min as depicted in table 4 and figure 7.
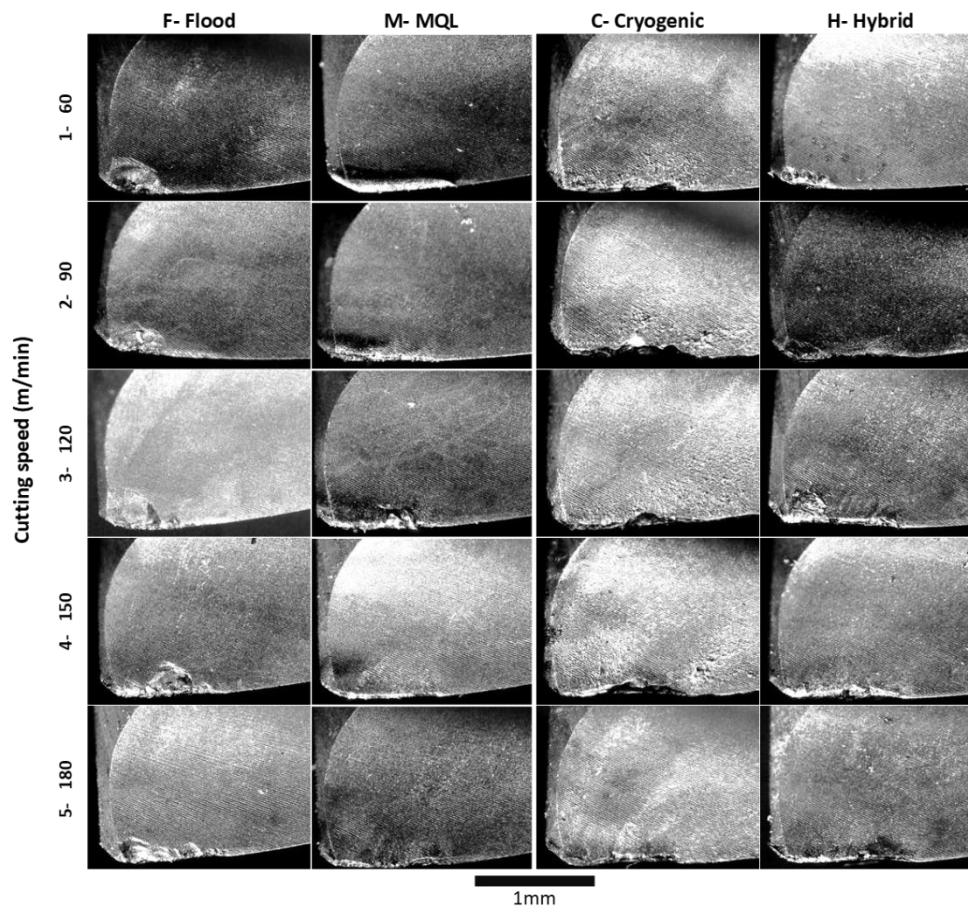
Figure 15, Microscopic images of tool rake face at different cutting speeds and machining environments at the end of tool life

Minimal adhesion on the tool flank and rake has been observed for all MQL experiments. This can be attributed to the effective penetration of oil mist into the cutting interfaces provided by the dual-nozzle MQL system which demonstrated effective lubrication even at high cutting speeds. The dark region around the tool flank wear area gives evidence that evaporation and burning of oil was occurred in all MQL machining experiments. This shows that MQL can improve the machining performance by reducing the friction induced heat generation at the cutting zone. However, the investigation revealed that MQL is not an effective cooling method for extracting heat from the cutting zone.

In the beginning of cryogenic machining at low cutting speed, the excessive cooling of the cutting zone caused significant increase in tool wear rate resulting in short tool life (figure 13-15, experiment C1). The direct spraying of the $LN_2$ into the cutting region resulted in excessive local hardening of the titanium workpiece especially at the top surface of the workpiece. This initiated chipping of the tool cutting edge at the depth of cut, while the tool nose remained sharp. The progressive loss of sharpness rapidly increased attrition-abrasion wear which was exacerbated by the poor lubricating properties of $LN_2$. This rapid development of mechanically related wear combination (attrition-abrasion) led to rapid tool failure in comparison with other machining environments. Chipping of the cutting edge and attrition-abrasion of tool flank dominated tool wear mechanism at low speed cryogenic machining.

At moderate to high speed cryogenic machining (90, 120, and 150 m/min), the rate of mechanical attrition at the depth of cut flank is increased over plastic deformation of the cutting edge due to the

increased friction at the flank face. It is noted that edge plastic deformation tends to spread along the whole depth of cut with increasing the cutting speed as demonstrated in figure 14, experiments C2, C3, and C4.  Flank attrition-abrasion dominated the wear mechanism at moderate to high speed cryogenic machining. At 180 m/min, the tool wear mode was flank attrition followed by severe abrasion as shown in figure 13, experiment C5.

Hybrid cryogenic MQL machining environment consisted of the combined application of dual-nozzle MQL and cryogenic cooling systems demonstrated significant improvement in tool life in comparison to conventional flood and cryogenic machining environments. It showed the best machining performance among all investigated cooling/ lubricating conditions and surpassed that for MQL at 60 and 90 m/min.

In all hybrid cooling experiments, crater dissolution-diffusion wear has been significantly reduced even at high cutting speeds due to the effective cryogenic cooling of the cutting tool. In addition, to avoid excessive local hardening of workpiece due to direct spraying of $LN_2$ to the cutting region, the two cryogenic nozzles were directed only on to the cutting tool as shown in figure 6. This cooling strategy has kept the tool temperature well blew the softening temperature of the cobalt binder (800 °C).  Furthermore, the inclination of the two cryogenic nozzles towards the machining surface allowed for adequate cooling of the workpiece through the reflected $LN_2$ jets from the tool. This can reduce the chemical affinity of the titanium to the tool material without considerable increase of the Ti-6Al-4V alloy's hardness. On the other hand, MQL nozzles provided the necessary lubrication and hence, significantly reduced the flank attrition wear rate and eliminated the adhesion of titanium chips and workpiece to the rake and flank faces, respectively resulted in reduced BUE.

For low speed hybrid cryogenic MQL, 60 m/min, a significant improvement in machining performance in terms of tool life in comparison to all other cooling/lubricating conditions was achieved as evidenced in table 4. The cutting tool kept its sharpness until 200 m cutting length (cutting time 840min) which was followed by chipping of the cutting edge causing loss of nose sharpness leading to localised attrition wear at the nose flank. This was then propagated and dominated the wear mode resulting in tool failure (figure 13, experiment H1).

At 90 m/min hybrid cooling, the best machining performance and the longest tool life has been achieved amongst all machining experiments. Uniform attrition wear at the whole flank initiated after 234 m of cutting length due to the effective cooling and lubricating strategy. Attrition wear propagated at the depth of cut flank and dominated the tool wear mechanism (figure 13-15, experiment H2). At the moderate and high cutting speeds of 120, 150 180 m/min, hybrid cooling failed to surpass MQL in spite of its superiority over flood cooling (table 4). Pusavec et al. [42] identified that film boiling occurs at high surface temperatures above 200 °C. Higher cutting speeds result in increased temperature at the cutting zone which can have adverse impact on cooling effect of in cryogenic machining. $LN_2$ evaporates in contact with hot surfaces forming a gaseous film which has significantly lower thermal conductivity. This gaseous nitrogen film can act as a thermal barrier between the hot surfaces and $LN_2$ resulting in increased cutting temperature. As investigated by Jin et al. [44] the boiling heat transfer of $LN_2$ can be as low as 3500 $W/m^2K$ as compared to $23.3e^3$ $W/m^2K$ defined by Dix et al. in convection. In addition,  the simultaneous application of $LN_2$ and oil mist leads to freezing of the oil droplets. Increasing the cutting speed impedes the frozen oil droplet from being adhered to the tool surface, tool/chip, and tool/ workpiece interfaces which can promote flank abrasion. This is partly due to limited speed of the droplets and also the centrifugal forces of the rotating cutting tool. Attrition-abrasion along the whole flank dominated the tool wear mechanism at moderate and high cutting speed (figure 13-14, experiments H3, H4, H5).

## 4.4. Surface roughness

The results of the surface roughness for all machining and cooling /lubricating conditions are demonstrated in figure 16. ANOVA of the results for surface roughness indicated that both cutting speed and machining environment have significant effect on surface roughness as shown in figure 17. As demonstrated in figure 16, it can be clearly seen that for all cutting speeds, MQL outperformed all other cooling/lubricating conditions with an average surface roughness Ra of 0.2 μm even at higher cutting speed. Hybrid cooling has shown comparable results to MQL at low and high cutting speed and comparable to cryogenic at moderate cutting speeds. The highest surface roughness amongst all machining experiments was recorded for cryogenic machining which exacerbated by increasing cutting speed.

As shown in figure 16, the most repeatable surface roughness was generated in MQL machining followed by flood cooling. The standard deviation of surface roughness was highest for hybrid and cryogenic machining environments. This can be attributed to the fluctuating cooling effect of the external liquid nitrogen coolant.
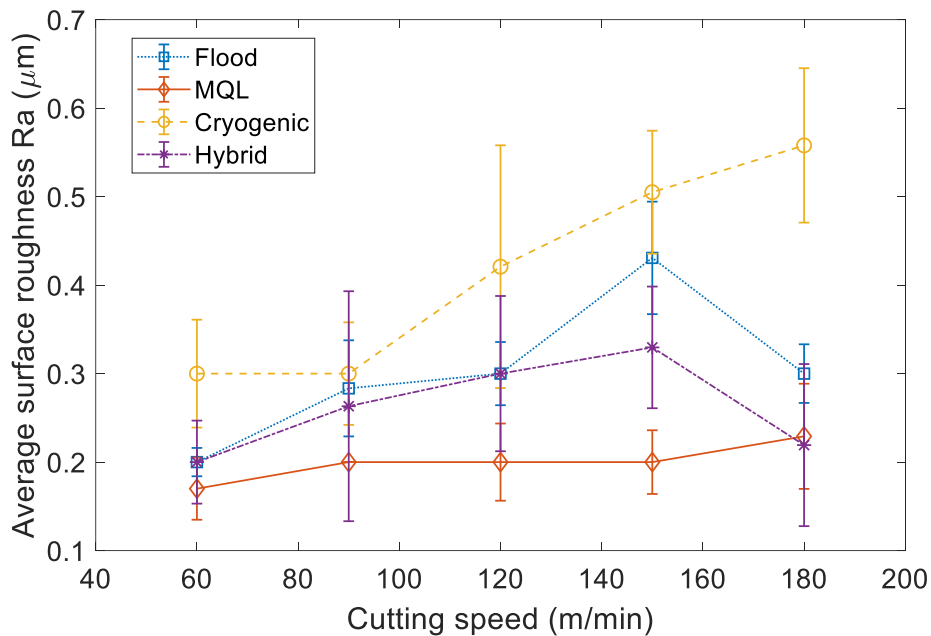


Figure 16, Average surface roughness for each cooling and cutting condition

| Analysis of Variance | | | | | |
|---|---|---|---|---|---|
| Source | Sum Sq. | d.f. | Mean Sq. | F | Prob>F |
| Cutting speed | 0.10263 | 4 | 0.02566 | 5.36 | 0.0103 |
| Machining environment | 0.24432 | 3 | 0.08144 | 17.02 | 0.0001 |
| Error | 0.05743 | 12 | 0.00479 | | |
| Total | 0.40438 | 19 | | | |

Figure 17, Analysis of variance for surface roughness

## 5. Discussion and future work

Ti-6Al-4V alloy is a difficult to machine alloy which is primarily used in the aerospace industry. Due to its inherent properties, machining this alloy is synonymous with short tool life and low productivity imposing a major restrictions and difficulties in aerospace manufacturing companies. A full factorial

design of experiments was developed to completely capture the effect of various cooling and lubricating environments on machinability of Ti-6Al-4V titanium alloy.

The analysis indicated that combining the cooling effect of liquid nitrogen in cryogenic machining with the lubrication from MQL system effectively enhances the machinability of Ti-6Al-4V alloy translating into 30 times increased tool life. This can have a significant effect on the economy of machining operations for Ti-6Al-4V alloy where higher cutting speeds of 90 m/min can be used whilst reducing the machine tool's down time for tool change and setup leading to increased productivity.

In this study, two external nozzles were used for the cryogenic machining experiments. The analysis revealed that using liquid nitrogen cryogenic coolant and employing the proposed setup has a limited effect in improving tool life when compared to conventional flood cooling. However, the improvement in tool life is limited to higher cutting speeds and significantly less than that of MQL and hybrid machining environments. Whilst these results are comparable with that of published literature [52-54], the extent of the improvements was significantly smaller. This can be explained by the fact that in this study, two external nozzles were used for delivering liquid nitrogen. Whilst it successfully reduced the cutting temperature, it also reduced the workpiece material temperature and hence resulted in increased material hardness and strength. This is evident by the chipping of the tool at the depth of cut, due to the increased workpiece hardness on the surface. Astakhov [55] explained that minimum tool wear and improved surface finish can be achieved at an optimum cutting temperature irrespective of how this temperature has been achieved. Increasing cutting speed results in increased cutting temperature. The use of lubricants can reduce heat generation in machining due to friction. Coolants can effectively remove heat from the cutting zone and control the cutting temperature. The use of $LN_2$ coolant and MQL in this study allowed increasing cutting speed to 90 m/min. However, further increasing of cutting speed and therefore heat generation surpassed the effectiveness of hybrid cryogenic MQL.

In addition, it is observed that the tool coating at both flank and rake faces have been adversely affected by the direct spraying of $LN_2$ onto the cutting tool which has weakened the bonding between the coating and the tool substrate due to the variation in thermal expansion coefficient (figure 13-15). Bermingham et al. [15, 56] investigated the cryogenic machining of Ti-6Al-4V alloy and noted that controlling the heat generation has more significant effect on tool life than heat removal using cryogenic machining. They suggested controlling heat generation by strategic selection of cutting parameters. However, this method resulted in the employment of lower cutting speeds and feed rates and hence lower productivity. In this research, vegetable oil lubricant was introduced during cryogenic machining using an MQL system to reduce the friction between contact surfaces and reduce friction induced heat generation. This has proven to be effective in hybrid cryogenic MQL machining environment as 11-fold increased tool life was achieved at the higher cutting speed of 90 m/min.

A new tool life model was introduced based on the tool wear against machining length. The analysis indicated that this model is capable of predicting tool life based on cutting parameters with a good accuracy. Teitenberg et al. [57] proposed an analytic mechanistic model for cutting forces for worn tools. Attanasio et al. [58] developed a model for predicting tool wear using a response surface methodology (RSM) and artificial neural network (ANN). The model was based on series of experiments and fitting a polynomial regression model. The tool life model proposed by Taylor [59] was only based on cutting speed and machining time and had very limited application in milling operations. The proposed model in this paper is based on the relationship between tool wear and machining length. By defining a tool wear limit, the tool life can be predicted. The authors recognise

that further investigations are required to validate this model and extend its application to other materials and cutting conditions.

The effect of various cutting environments and cutting speed on surface roughness was also investigated. The analysis showed that cryogenic cooling produced the highest surface roughness as compared to flood, MQL and hybrid machining environments. This is in contrast to the findings in literature [23, 26, 60-62] where improved surface integrity and surface roughness has been reported as a result of using cryogenic cooling when compared to flood cooling. The cryogenic setup in this study consisted of two external nozzles targeting the cutting zone and workpiece. The use of two external nozzles resulted in over cooling of the workpiece material as explained by [63] which exacerbated the surface roughness. This is in line with findings from Uehara and Kamagai [64] that used workpiece cooling for cryogenic machining. Sun et al. [31] also reported that cryogenic cooling failed to outperform MQL in terms of surface roughness. They attributed this to the improved lubrication and lower friction as a result of using MQL during machining.

It is recognized that the position of the nozzles and cooling/lubrication parameters can affect the performance of the proposed hybrid cooling/lubrication system as it can affect the Reynold's and Nusselt numbers and therefore convection heat transfer. Optimisation of the position of the nozzles alongside the pressure and flow rate of the coolants/lubricants will be further investigated.

## 6. Conclusions

A new hybrid cryogenic MQL system has been introduced in this paper for enhancing machinability of Ti-6Al-4V alloy in finish end milling operations. A comparison of different cooling/lubricating techniques, namely MQL, cryogenic, and hybrid cryogenic MQL machining with conventional flood cooling at different cutting speed was made to investigate their machining performance in terms of tool wear, tool life and surface roughness. Key results show:

• Both MQL and Hybrid cryogenic MQL are highly effective cooling and/or lubricating technologies in extending the tool life up to 30 times over commonly used flood cooling. The hybrid machining environment at low and moderate cutting speed was superior in achieving the longest tool life equivalent to 1198 min due to the effective cooling and lubrication of the cutting tool and the cutting zone that enabled significant reduction in thermomechanical tool wear.

• Hybrid cryogenic MQL significantly reduced dissolution-diffusion and controlled the rate of tool attrition-adhesion due to the effective cooling and lubricity. Cryogenic machining enabled substantial reduction in dissolution-diffusion wear through the control of the machining temperature at all cutting speeds. However, the increased hardness of the workpiece material due to direct spraying of $LN_2$ jet resulted in increased plastic deformation of cutting edge, and the non-satisfactory lubricity of $LN_2$ significantly increased friction and promoted adhesion-attrition.

• MQL recorded the best surface roughness among all cooling/lubricating conditions with stable value of surface roughness Ra almost 0.2 μm even at higher cutting speeds thanks to the effective lubricity that minimised adhesion and reduced attrition-abrasion through the reduction of friction forces.

This significantly extended tool life when machining titanium Ti-6Al-4V alloy using the multi-nozzle hybrid cryogenic MQL technology shows strong potential for the adoption of the technology for industrial application, especially with an increase in productivity of 50%, it will have a major impact on aerospace manufacturing.

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